BUILDING PHYSICS

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ir. A.C. van der Linden
ir. I.M. Kuijpers-Van Gaalen
ir. A. Zeegers

Authors
mw. ir. I.M. Kuijpers-Van Gaalen, DGMR, Arnhem

- *Energy and energy performance*
- *Sustainable construction*

mw. ir. A. Zeegers, Central Government Real Estate Agency, The Hague

- *Heat, heat transport, thermal insulation*
- *Moisture, moisture transport, condensation*
- *Heat and moisture transport in practice*
- *Acoustics*
- *Sound insulation and sound proofing*
- *Applied sound insulation*

ir. A.C. van der Linden, Delft University of Technology

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- *Lighting*
- *Thermal comfort*
- *Ventilation and infiltration*
- *Solar gain and solar control*
- *Acoustics*
- *Sound insulation and sound proofing*
- *Applied sound insulation*
- *Fire safety*

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Editing
ir. A.C. van der Linden

Revised layout
M.J.C. van der Klooster

Faculty of Architecture and the Built Environment
Architectural Engineering and Technology
Group Building Physics and Building Services
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Preface

The daily use quality of a building depends to a large extend on the performance achieved with respect to indoor climate: thermal comfort, air quality, day light, artificial light, acoustics, etc. There also is a strong relation between the way these performances are achieved and the energy use of the building. Furthermore one takes it for granted that the building structures (facade, roof) fulfill their function for many years and are not damaged by interstitial condensation or other problems. All these aspects are subject of the study of Building Physics. Energy conservation, a careful choice of building materials and a healthy indoor climate are very important with regard to sustainability.

Building Physics bridges different knowledge domains. For this reason it is of importance for all parties involved in building: project developer, architect, consultants on structural design, building services, building contractor, etc. Basic knowledge on Building Physics is built up in this book step by step and made applicable by examples from building practice.

The book is meant for higher technical education as well as BSc-students in building sciences at universities. After studying the basics the book remains very useful as reference book when making assignments and graduate projects. For students and also for those who are working in building practice special attention is paid to rules of thumb and figures to be used, material properties, etc.

To give an entrance to the use of standards and legislation in practice examples of the way Building Physics aspects are treated in these documents are given. These examples comes from the Dutch situation, but since only the principles that form the bases are discussed these examples also give an entrance to European standards and standards and legislation overall.

The Dutch version of the book has been already used for many years. The content of this English edition is equal to the content of the eighth Dutch edition.

In this edition of Building physics examples in all chapters are actualized and topics are renewed or further elaborated. In chapter 6 the principles of natural ventilation are treated more extensively. Chapter 8 Buildings and climate installations was repealed. Chapter 9 (now chapter 8) is completely renewed and is now called Energy and energy performance. The new chapter 9 deals with Sustainable Building and shows how this topic works out on the work of all parties in the (re)development of buildings with, of course, special attention payed to building physics. New ways of expressing sound insulation and sound proofing are given in chapter 11 and 12. In chapter 13, finally, the development of a fire is added and the sequence of the topics is adapted.

Hopefully also this English version will not only provide the knowledge needed in education but also give a clear view how to use this knowledge in practice.

The main goal is realizing new or renovated buildings that are 'fit for purpose', provide a healthy living or working environment thus contributing to sustainable building. Building Physics plays an important role in this field and it inspires me to work in this field with sustainable enthusiasm.

March 2018
Kees van der Linden

In Memoriam: Kees van der Linden

Kees van der Linden, a pioneer in building physics, sadly passed away in April 2024. We will remember Kees for his passion and dedication to advancing and promoting the field of building physics. Throughout his active career and the many years that followed, Kees tirelessly contributed to numerous associations and organisations in this field. As a tribute to Kees, we will continue and update this English version.

Group Building Physics and Building Services
Faculty of Architecture of the Delft University of Technology
Delft, June 2024

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1 Heat, heat transport, thermal insulation

A.C. van der Linden; A. Zeegers

This chapter deals with the basic terms relating to heat and heat transport. The use of these terms, and their application in constructions in practice are covered in Chapter 3, 'Heat and vapour transport in practice'.

In addition to the basic principles, this chapter also includes information on heat resistance and the effect of temperature in constructions, as well as the phenomena of heat accumulation, thermal bridges and thermal stress.

1.1 Basic principles of heat transport

Heat is a form of energy. Heat will move (flow) from areas with a high temperature to areas with a lower temperature in order to attain a state of balance. This movement of heat can take place in three ways: through convection, through radiation and through conduction.

Convection

In case of heat transfer through convection (flow), heat is taken along by a flowing medium. Convection is possible only in liquids and gases.

> Example
> Blow on your hot soup you have just been served and it will cool down.

Radiation

Each object or body with a temperature higher than 0 K (–273 °C) radiates 'heat' in the shape of electromagnetic vibrations. These vibrations are turned into heat when they come into contact with an object or body. The amount of 'heat' that is radiated depends on the temperature of the object. Colder items radiate less heat than warmer items. When two surfaces with different temperatures are placed opposite each other, the warm object will radiate more heat than the cold object. As a result, the cold object will heat up and the warm object will cool down. Radiation does not require a medium.

> Example
> Because heat radiation does not require a medium, the sun can heat up the earth.

Conduction

Heat conduction takes place because of molecules in a solid are in vibration. As the temperature rises, the molecules will start to vibrate faster. This vibration is passed on to bordering molecules. Liquids and gases are poor conductors, while conduction is the only method for solids to transport heat.

The total amount of heat transported as a result of convection, radiation and conduction is called heat transport. The unit of heat transport is watt (W) or joule per second (J/s).

> Example
> If you pour boiling water in a single-walled cold mug, the mug will heat up to such an extent that it will be hard to handle without burning your fingers. The hot water passes on the heat to the cold mug making its temperature rise.

When assessing a particular construction, you look at the heat flow density. That refers to the amount of heat flowing through one square metre in the construction. Heat flow density q is therefore expressed as $W/(m^2)$. If a wall has a surface area of 15 m^2, then the total heat loss through the wall in watts (joule/second) is 15 times the heat flow density.

To further explain the terms regarding heat transport we will use an aquarium as example (see figure 1.1).

When a 25-watt heating element is placed in this aquarium, the water temperature will always be around 6 °C higher than the room temperature. The electrical energy which is added to the heating element heats up the water, and by conduction via the glass the water gives off the heat to the air in the room by convection and radiation. From the aquarium there is therefore a heat flow of ϕ = 25 watt = 25 joule/second to the air in the room.

Heat transport through convection

Heat transport through convection in the example, the heat element heats up the water in the aquarium. The water where the heat element is located will heat up. Because of the density difference (the warm water weighs less than the cold water) the water will start to flow through the aquarium. Therefore, to transport the heat, a medium is used – the water. The same thing happens in the space where the aquarium is situated. The glass of the aquarium has a higher temperature than the air in the room. Colder air that passes along the warmer surface of the aquarium glass will be warmed up. In this case, the transport medium is air. This type of heat transport is called convection.

To warm up a room with a radiator, convection (among other means) is used with the help of air. The air flows past a radiator and is warmed up as it does so. The warmer air gives off this heat to cold glass surfaces and other walls in the room. It is clear that the degree to which heat is transferred depends on the speed of the flow of the transport medium (air or wind speed) and the difference in temperature between the object and the medium that is flowing past. This is expressed using the following formula:

$$q_c = a_c \cdot (T_1 - T_2) \text{ [W/m}^2\text{]}$$

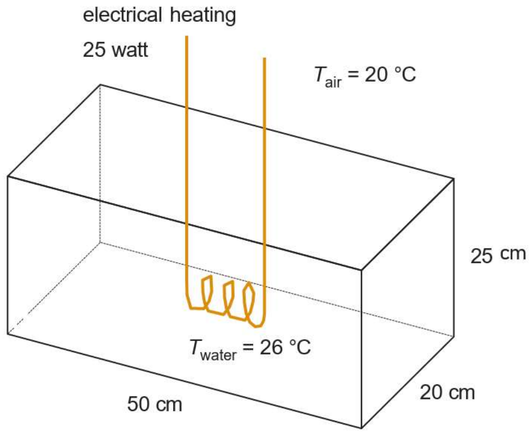


Figure 1.1 Example of heat flow

The meaning of the symbols is:

q_c the heat flow density in W/m²

a_c the heat transfer coefficient in W/(m²·K)

$T_1 - T_2$ the difference in temperature (ΔT) between for example the surface of the construction and the air flowing past in °C or K

Common values for a_c are:

- indoors: a_c = 2 to 2.5 W/(m²·K);
- outdoors: average wind a_c = 19 to 20 W/(m²·K), strong wind a_c = 100 W/(m²·K).

Heat transport through radiation

Heat transport through radiation is part of the electromagnetic spectrum.

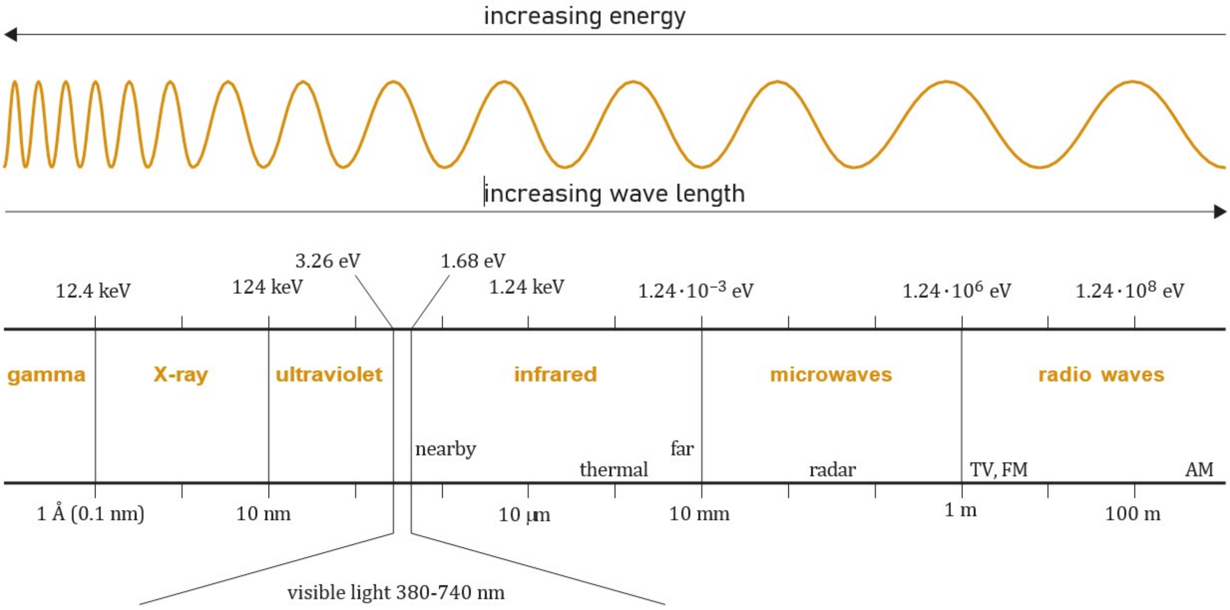


Figure 1.2 Electromagnetic radiation

As a result of molecule vibration in the material, all objects (bodies) radiate infrared radiation which is experienced as heat. Not until 0 K (approx. –273 °C) this radiation ceases (at this temperature all molecules are still). With an infrared camera you can measure the temperature of a surface.

As an object gets hotter, the molecules in and at the surface of the object will start to vibrate faster. This causes more energy to be radiated. Colder objects radiate less heat. A person experiences a cold surface as ‘cold radiation’ but this is not actually the case. People radiate heat and so does the glass. Because the glass is colder, a person radiates more heat (energy) than he receives back from the glass. This is why the glass surface is experienced as ‘cold radiation’.

By placing a warm radiator underneath the glass, for example, it can be made warmer. In the example of the aquarium, the warm glass of the aquarium radiates heat out onto the colder walls in the room. The quantity of heat that is given off by a particular surface can be calculated with the following formula:

$$q_s = \varepsilon \cdot 56.7 \cdot 10^{-9} \cdot T^4 \text{ [W/m}^2\text{]}$$

The meaning of the symbols is:

q_s the heat flow density of the radiation that is given off in W/m²

ε the emission coefficient of the surface of the material

T the absolute temperature in K

Figure 1.3 Temperature portrayed by an infrared camera

Emission and absorption coefficient

For most building materials, the emission coefficient is ε = 0.9 to 0.95. This value also applies to all paint colours (so white paint, as far as heat radiation is concerned, is just as 'black' as green). Only metallic paints, such as aluminium lacquer, have a value of ε = 0.35 to 0.40. For anodised aluminium, the emission coefficient is ε = 0.4 to 0.5 and for blank aluminium with a surface with a smooth finish ε = 0.07 to 0.09. The book of tables includes the coefficient values for various materials.

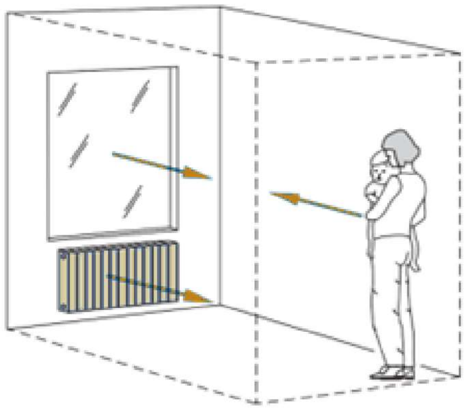


Figure 1.4 Emissions of radiation from person, glass and radiator

In figure 1.4, the heat radiation is given for three different temperatures in common situations (calculated with ε = 0.9):

- window, surface temperature around 0 °C, q_s = 290 W/m²;
- person, body surface temperature around 30 °C, q_s = 430 W/m²;
- radiator, surface temperature around 50 °C, q_s = 555 W/m².

When long-wave heat radiation falls onto a surface, it is partly reflected and partly absorbed. It is very rare for anything to pass through. Also glass is impervious to long-wave heat radiation. Only a small amount of 'short-wave' heat radiation (infrared > 3-5 µm) from the sun can permeate through glass.

In general, the portion of the radiation that is absorbed is equivalent to the emission coefficient. This emission coefficient is therefore automatically the absorption coefficient as well.

Visible light

Heat radiation is very different to visible light (also energy), although it belongs to the same family of electromagnetic radiation (see figure 1.2). A surface that is painted white absorbs around 90% of radiated heat, but the proportion of visible light absorbed is only about 20%. A brown or black surface absorbs some 90% of radiated heat, and 90% of visible light. Most of the energy in solar radiation is found in visible light. That is why houses in southern European countries are often whitewashed. As far as heat radiation is concerned, the heat given off by a radiator will not be increased by painting it black or brown. But painting a radiator with a metallic paint will have a detrimental effect on the amount of heat it gives off.

Greenhouse effect

Glass is opaque for longwave infrared radiation, but permeable for sunlight. As a result, the energy emitted by the sunlight will enter the home and 'passively' heat up the enveloping surfaces in this space. These surfaces in turn will give off heat in the shape of longwave infrared radiation. For this type of radiation, however, glass is 'opaque'. The home will therefore heat up. This is positive in winter, but undesirable in summer.

Greenhouses also make use of this principle. Energy emitted by the sunlight will warm up the greenhouse. In order to prevent the greenhouse from overheating, the windows in the greenhouses are often painted white.

Figure 1.6 White paint preventing overheating

Radiation	Transmission	Reflection	Absorption
Sunlight	86%	9%	5%
Heat radiation	0%	10%	90%

Figure 1.5 Transmission, reflection and absorption normal glass

Radiative heat transfer

Two objects, two surfaces at different temperatures, both emit heat radiation, absorbing part of each other's heat radiation, and reflecting some of it as well. Some of the radiation that is reflected is re-absorbed by the other surface, and so on. On balance, though, heat will flow from the surface with the higher temperature to the one with the lower temperature. Heat transfer through radiation between two parallel and infinitely long surfaces can be calculated using the following formula:

$$q_s = \frac{\varepsilon_1 \cdot \varepsilon_2}{\varepsilon_1 - (\varepsilon_1 \cdot \varepsilon_2) + \varepsilon_2} \cdot 56{,}7 \cdot 10^{-9} \cdot (T_1^4 - T_2^4)\ [\mathrm{W/m^2}]$$

The meaning of the symbols is:

q_s the net radiation transfer in W/m²

$\varepsilon_1 - \varepsilon_2$ the emission coefficient of surface 1 and 2 respectively

$T_1 - T_2$ the temperature of surface 1 and 2 respectively, in K

When aluminium foil radiation screens are placed between radiators and glass, or poorly insulated outer walls (see figure 1.7), the effect of the various emission coefficients is used. The low emission coefficient of the aluminium foil will restrict the radiative exchange. However, the effectiveness of the screen will diminish as a result of dirt. It should therefore be cleaned regularly or replaced after a few years. Using the above formula will give you a rough idea of the effect of radiation foil in a cavity wall or behind a radiator. This principle is also used in the application of low-emissivity windows (low-E window). By applying an emission lowering coating, the radiant heat exchange is limited.

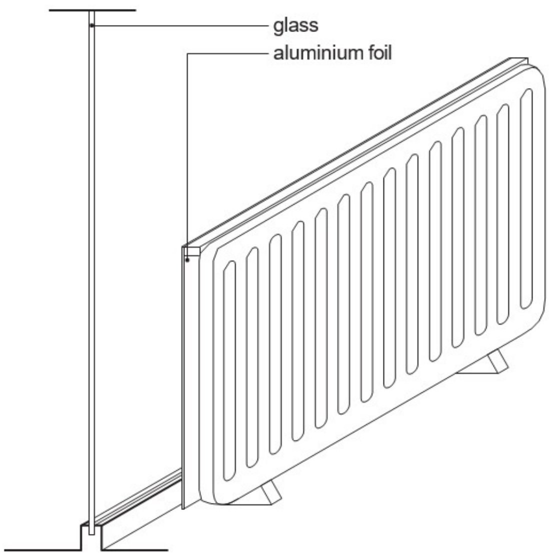


Figure 1.7 Heat shield behind radiator

The formula for radiative transfer is simplified in practice. Heat transport resulting from radiation is expressed with the use of a heat transfer coefficient.

$$q_s = \alpha_s \cdot (T_1 - T_2)\ [\mathrm{W/m^2}]$$

The meaning of the symbols is:

q_s heat transfer through radiation in W/m²

a_s heat transfer coefficient in W/(m²·K)

$T_1 - T_2$ difference in temperature (ΔT) between both surfaces in °C or K

In normal building practice, the value of a_s is often 4.7 to 5.2 W/(m²·K). Simplifying the formula with regard to radiation transfer is wrong in principle, but the error that is made is generally only slight.

When calculating the radiative transfer, you need to look carefully at what outside temperature you are working with. There is the potential to make a serious error here. For example, the roof of a car may be frozen in the morning, even though the outside air temperature has not been below zero degrees. If you are using the outside air temperature as your starting point, you cannot explain this phenomenon, but if, instead of the outside air temperature, you were to use the 'sky' temperature in the calculation, then you can explain it. If there is a clear sky, the roof is 'facing' a temperature of approximately –30 °C. This makes the roof surface cool down to a temperature lower than the temperature of the environment. Outside the Earth's atmosphere, you 'face' –273 °C (0 K). The atmosphere lets us keep a little heat.

Heat transport through conduction

Heat can only be conducted through a construction if there is a difference in temperature. It always 'flows' from the high-temperature location to the low- temperature one. In the example of the aquarium (figure 1.1), there is water at 26 °C, on one side of the glass, and on the other, air at 20 °C. Therefore heat will 'flow' through the glass. The heat moves from one part of the glass to the next. This kind of heat transport, in a material, is known as conduction. An example of this is the copper rod in a soldering bolt. The rod is heated on one side, and the heat moves through the rod towards the soldering point.

Heat conduction coefficient

The heat conduction coefficient λ (lambda) shows how much heat 'flows' through a layer of material 1 m thick and with a surface area of 1 m², where the difference in temperature is 1 K (1 °C). The unit of λ is therefore: W/(m²·K). Different materials have their own heat conduction capacity, that is, some materials conduct heat better than others. The greater λ is, the more easily the material can conduct heat. In figure 1.8, the heat conduction coefficients of several different materials are compared.

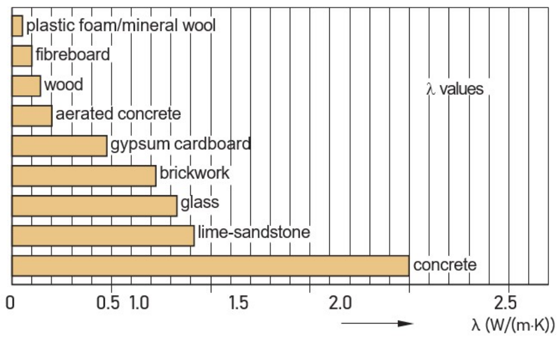


Figure 1.8 Comparison of the heat conduction coefficients of several different materials

In laboratories, the heat conduction coefficients of a variety of materials are measured under conditioned dry circumstances (λ_{dr}). These circumstances will rarely occur in practice. The heat conduction coefficient will in practice always be higher than the laboratory value due to the influence of moisture, aging etc. If laboratory values are used, these have to be multiplied by a factor dependent of the type of material. These factors can be found in standards. The values used for calculations are represented as λ_{calc}.

Heat resistance

The heat resistance of a layer of material of a particular thickness can be found by multiplying the reciprocal of the heat conduction coefficient $1/\lambda$ by the thickness (d).

$$R_m = \frac{1}{\lambda} \cdot d = \frac{d}{\lambda} \; [\mathrm{m^2 \cdot K/W}]$$

The table in figure 1.9 shows the heat resistance of commonly used thicknesses of several materials. It appears from the table that the heat resistance of chipboard with a thickness of 18 mm is as great as that of concrete that is 180 mm thick. The heat resistance of 100 mm of insulation material is almost 30 times greater.

	Heat conduction coefficient	Thickness	Heat resistance
Material	λ [W/(m·K)]	d [m]	$R_m = d/\lambda$ [W/(m²·K)]
Concrete	2.0	0.18	0.18 / 2.0 = 0.09
Chipboard	0.2	0.018	0.018 / 0.2 = 0.09
Insulation material	0.04	0.10	0.10 / 0.04 = 2.50

Figure 1.9 Examples of heat resistance levels

Heat transport as a result of conduction is expressed with the help of the following formula:

$$q_g = \frac{1}{R_m} \cdot (T_1 \cdot T_2) \text{ [W/m}^2\text{]}$$

The meaning of the symbols is:
q_g the heat flow density as a result of conduction in W/m²
$T_1 - T_2$ the difference in temperature (ΔT) throughout the relevant construction in °C or K
R_m the heat resistance in (m²·K)/W

The greater the difference in temperature (ΔT), the greater the heat flow density (q_g). Conversely, the greater the heat resistance (R_m), the smaller the heat flow density (q_g) (in other words, 'the less heat goes through the construction').

1.2 Heat resistance of constructions

Layered constructions

Most constructions consist of more than one layer. See the example of the roof in figure 1.10.

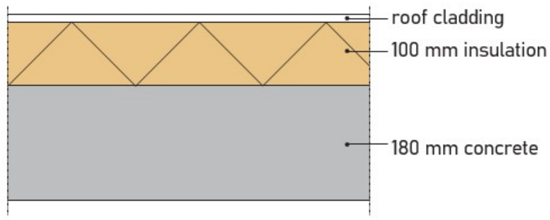


Figure 1.10 Multi-layered construction

If you are dealing with a construction of the same thickness throughout, the heat resistance can be calculated for every layer. The total heat resistance can be found by adding up the resistance values of the individual layers:

$$R_c = R_{m1} + R_{m2} + R_{m3} + ...$$

The meaning of the symbols is:
R_c the heat resistance of the total construction in (m²·K)/W
$R_{m1}, R_{m2}, R_{m3}, ...$ the heat resistance of the individual layers in (m²·K)/W

In the example with the roof, the figures are those in the table in figure 1.11.

Layer	Heat resistance R_m [W/(m²·K)]
Roof covering	0.04
Insulation	2.50
Concrete	0.09
	$R_c = 2.63$

Figure 1.11 Heat resistance roof construction

There are minimum requirements in the building provisions of the Buildings Decree that apply to the R_c value of external partition constructions.

Heat transfer resistance

The heat resistance of the layered constructions examined above refers to the heat transfer from one surface (on the inside) through the material to the other surface (on the outside). Of course, heat transfer also occurs from the air on the inside to the surface on the inside, and from the outside surface to the outside air. This heat transfer takes place through radiation and convection. The role of conduction on the surface of the construction is virtually nil. Convection depends, among other things, on the speed of the air flow over the surface. The level of heat transfer through convection will be greater on the outside than on the inside because of the wind. To be able to calculate what the total heat transfer between the inside air and the outside air will be, you therefore have to consider the heat transfer on the surface of the construction (both inside and outside). For this, the heat transfer coefficient on the surface of the construction should be expressed in terms of heat resistance: the heat transfer resistance (R_s). A distinction is made in the heat transfer resistance on the inside (R_{si}) and the heat transfer resistance on the outside (R_{se}) of the construction. The heat transfer resistance is inversely proportional to the heat transfer coefficient (R = 1/α).

The transfer resistances are strongly dependant on the circumstances. However, for calculations they are standardised and the following principles are employed:

- On the outside, the radiative temperature is equal to the air temperature (e.g. a cloudy night sky).
- In an enclosed room, the radiation temperature is equal to the inside air temperature.
- The speed of air brushing past outside surfaces is 4 m/s.
- The speed of air brushing past inside surfaces is lower than 0.2 m/s.

For vertical constructions bordering the outside air the following values are used:
R_{si} = 0.13 (m^2·K)/W
R_{se} = 0.04(m^2·K)/W

These values are based on the following assumptions for convection and radiation transfer of heat: α_{csi} = 2 W/(m^2·K); α_{ssi} = 5.7 W/ (m^2·K); α_{cse} = 20 W/(m^2·K); α_{sse} = 5 W/(m^2·K). With $R_s = 1/(\alpha_c + \alpha_s)$ [m^2·K/W] the values for R_{si} and R_{se} are then easily calculated.

The total heat resistance of a construction can then be calculated as follows:

$$R_T = R_{si} + R_c + R_{se}$$

The meaning of the symbols is:

R_T total heat resistance of the construction [m^2·K/W]
R_{si} heat transfer resistance at the inside surface [m^2·K/W]
R_c heat resistance of a (construction) part [m^2·K/W]
R_{se} heat transfer resistance at the outside surface [m^2·K/W]

For horizontal constructions, account must be taken of the direction of the heat flow. A distinction is made here between a heat flow aimed upwards and one aimed downwards. Warm air is lighter than cold air. This results in warm air rising (an upward convection flow). If the heat flow is aimed upwards (for example, towards a roof), the heat flow and the convection flow are moving in the same direction. If the heat flow is aimed downwards (for example, towards a floor), the heat flow is in the opposite direction to the convection flow. The warm air will more or less remain where it is under the warm floor, which will involve less strong convection flows and therefore a greater level of heat resistance. Standards give calculation values for these situations (see the table in figure 1.12).

Direction of heat flow	Construction part	R_{si} [m²·K/W]	R_{se} [m²·K/W]
Downward (horizontal construction deviating up to 60° from horizontal)	Floors above outside air	0.17	0.04
	Floors above unheated space	0.17	0.17
	Floors in contact with ground	*	*
Horizontal (vertically placed construction, slanting up to 30°)	Partition construction bordering on outside air	0.13	0.04
	Internal partition construction	0.13	0.13
Upward (horizontal constructions deviating up to 60° from horizontal	Outside partition construction on top of heated space	0.10	0.04
	Internal partition construtions	0.10	0.10

* Heat loss due to ground level floors, via a crawlspace or immediately on the bottom is a complex matter. See calculation methods provided in manuals and standards.

Figure 1.12 Heat transfer resistance of construction parts in different heat flow directions

Cavity constructions

All types of heat transfer occur with cavity constructions: conduction, radiation and convection.

Vertical cavity

We will first look at the vertical cavity (see figure 1.13).

Air is a good insulator. The following applies to still air: λ = approx. 0.025 W/(m·K). This means that a 50-mm layer of air would have a heat resistance of:

$$R_m = \frac{d}{\lambda} = \frac{0.05}{0.025} = 2 \text{ m}^2\cdot\text{K/W}$$

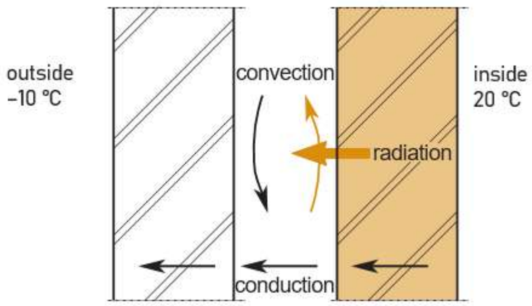


Figure 1.13 Heat transfer in cavity constructions

That is very high. However, the air in a cavity construction unfortunately does not remain still. There is a flow present – convection, that is – even if the cavity is not ventilated. The air is heated up next to the 'warm' cavity leaf. The warm air rises, cools off when next to the outer cavity leaf, becomes heavier, and falls. A rotating convection flow is thus created in the cavity, which transfers heat from the inner to the outer cavity leaf. Because the surface temperatures of the cavity leaves (on the cavity side) are different, heat transfer also takes place through radiation. It is clear that the large level of heat resistance in the air is significantly reduced through radiation and convection. This is of course not helped by the cavity ventilation that is so often to be found.

So how great is the heat resistance of a cavity? Conduction and convection depend on the width of the cavity. Convection flows will not be able to develop so easily in a very narrow cavity, and that is a good thing. The α_c therefore decreases. On the other hand, the layer of air will be so thin that levels of heat resistance against conduction will be very low. The α_g therefore increases. The proportion taken up by radiation does not depend on the width of the cavity, but it is affected by the surface temperatures in the cavity leaves. The reverse applies to wider cavities. Because of these conflicting effects, the heat resistance of a vertical cavity is relatively dependent on the thickness (see figure 1.14). It is only with very narrow cavities that heat transport sharply increases through conduction.

For this reason, the cavity of low-E windows is not filled with air but with a different gas (argon, krypton), which has a lower heat conduction coefficient than air. For lightly ventilated or unventilated cavities of ≥ 20 mm, heat resistance R_{sp} = 0.17 m²·K/W can be used. This value results from the assumptions for transfer through conduction, convection and radiation: α_{gsp} = 0.5 W/(m²·K); α_{csp} = 0.5 W/(m²·K); α_{ssp} = 5.0 W/(m²·K).

From this we can derive $R_{sp} = 1/(\alpha_{gsp} + \alpha_{csp} + \alpha_{ssp}) = 1/(0.5 + 0.5 + 5.0) = 0.17$ m²·K/W. This is of course a global value. The transfer coefficients will differ in different situations. The influence on R_{sp} is seldom more than a couple of hundredths, except when there is a radiation screen in the cavity as is the case with insulation sheets cached with aluminium foil, radiation screens of plastic foil with deposited aluminium and double glazing with a deposited metal layer on one of the window panes. The radiation transfer can then drop significantly to α_{ssp} = 0.1 W/(m²·K)or lower, for example. The heat resistance of the cavity will then be R_{sp} = 1/(0.5 + 0.5 + 0.1) = 0.9 m²·K/W or more. For all kinds of specific situations values are provided in standards and reference books.

Horizontal cavity

As with transfer resistances, the direction of the heat flow plays an important role with horizontal cavities (see figure 1.15). If the heat flow is in an upward direction, like the convection flow, the heat resistance will be lower than when the heat flow is moving in a downward direction, that is, against the convection flow. In the standards values are included which should be used in calculations. A distinction is made between cavities that are not, lightly or strongly ventilated (see figure 1.16). For cavities that are not or lightly ventilated, these specified values differ only slightly from the numbers given here.

Besides the cavity width and any possible air flow in the cavity, standardisation also takes account of the effect of placing reflecting material in the cavity.

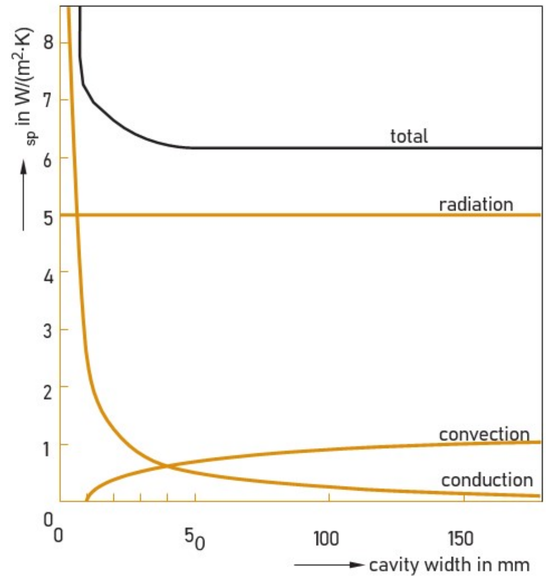


Figure 1.14 Heat transport through vertical air cavities through conduction, radiation and convection, depending on width of cavity: approximate indication of transfer coefficient α_{sp}

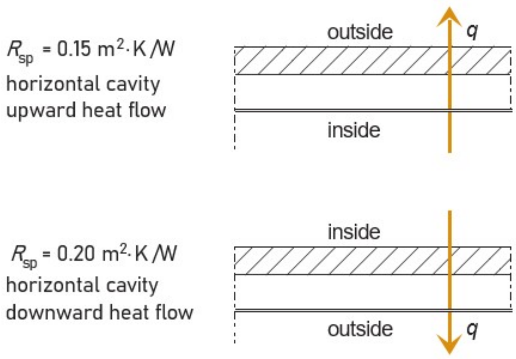


Figure 1.15 Heat resistance of horizontal cavity

Calculating heat resistance for constructions with a cavity

The total heat transfer for constructions with a cavity (both vertical as horizontal) can be obtained by adding the individual heat resistances of the inside cavity sheet (R_{bibl}), the outside cavity sheet (R_{bubl}), the insulation (R_{iso}), the cavity resistance (R_{spw}) and the surface resistance inside (R_{si}) and outside (R_{se}). This can be represented with the following formula:

$$R_T = R_{si} + R_{bibl} + R_{iso} + R_{spw} + R_{bubl} + R_{se}$$

The meaning of the symbols is:

R_T	total heat resistance of the construction
R_{si}	the inside surface resistance
R_{bibl}	the heat resistance of the inside cavity sheet [m²·K/W]
R_{iso}	the heat resistance of the insulation [m²·K/W]
R_{spw}	the cavity resistance [m²·K/W]
R_{bubl}	the heat resistance of the outside cavity sheet [m²·K/W]
R_{se}	the outside surface resistance [m²·K/W]

If there is a strongly ventilated layer of air in a construction, the calculations of R_c must include only the specific heat resistances of those layers on the inside of the relevant layer of air. From this point, you use a replacing heat transfer resistance R_{se} = 0.13 m²·K/W in calculations, in which R_{spw}, R_{bubl} and R_{se} are combined.

Heat transmission coefficient

When you want to calculate the amount of heat lost by a construction (for example when fitting a heating system), you should use the heat resistance of the total construction (R_T), which is composed of the heat resistance of the construction, the heat resistance of a cavity – if there is one – and both transfer resistances. However, it is not the heat resistance of the total construction (R_T) that is used at international level, but the U_T value. The U_T value is the opposite of the heat resistance of the total construction.

Cavity	Definition	Description openings
not ventilated cavity	no or small openings; no or hardly any air flow	< 500 mm^2/m measured in horizontal direction in case of vertical cavities < 500 mm^2/m^2 cavity surface area in case of horizontal cavities
slightly ventilated cavity	limited openings present in aid of air flow	≥ 500 mm^2/m but < 1500 mm^2/m measured in horizontal direction in case of vertical cavities ≥ 500 mm^2/m^2 but < 1500 mm^2/m^2 cavity surface area in case of horizontal cavities
strongly ventilated cavity	openings present in aid of air flow	≥ 1500 mm^2/m measured in horizontal direction in case of vertical cavities ≥ 1500 mm^2/m^2 cavity surface area in case of horizontal cavities

Figure 1.16 Definition of not, slightly and strongly ventilated cavities

The U_T value shows how great the heat-flow density is through a construction where the difference in temperature is 1 K. In other words, how much heat passes through a particular construction where there is a difference in temperature of 1 K. The heat-flow density, for a random difference in temperature through the construction, is then:

$$q = U_T \cdot \Delta T \, [W/m^2]$$

As an illustration, the table in figure 1.17 shows the heat resistance (R_c and R_T) and the heat transmission coefficient (U_T) for a number of constructions with R_{si} = 0.13 $m^2 \cdot K/W$ and R_{se} = 0.04 $m^2 \cdot K/W$.

The building regulations in the Buildings Decree include requirements for the U_T value of windows, doors and frames in partition constructions. The amount of heat passing through the surface to be considered at a temperature difference of 1 K, is called the heat loss through transmission coefficient (H_T).

	R_c [$m^2 \cdot K/W$]	R_T [$m^2 \cdot K/W$]	U_T [$W/(m^2 \cdot K)$]
single glazing (4 mm)	0.005	0.175	5.7
double glazing (4–12–4 mm)	0.16	0.33	3.0
cavity wall (50 mm, uninsulated)	0.35	0.52	1.9
cavity wall (50 mm, insulated)	1.43	1.60	0.6
cavity wall (100 mm, fully insulated)	2.68	2.85	0.35

Figure 1.17 Example of heat resistance (R_c and R_T) and heat transmission coefficient (U_T) of a number of constructions

Average heat transmission coefficient

External partition constructions often consist of not one, but several elements, in which case it could be useful to work out roughly what the average heat transmission coefficient (U_T value) is. How this is done is explained using the drawing of the wall fragment in figure 1.18.

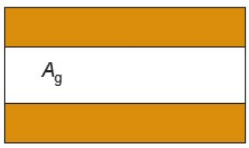


Figure 1.18 Calculation of total heat flow through a surface made up of different constructions

The starting point is that there is no lateral exchange of heat and that the individual constructions comply with the following conditions:

- The direction of the heat flow is perpendicular to the surfaces.
- The heat flow density is the same everywhere.

- The surfaces parallel to the main surface are isothermal (i.e. the same temperature).

The total heat loss (H_T) at a temperature difference of 1 K through the wall fragment in the drawing can be calculated as follows:

$$H_T = H_{glass} + H_{wall} = (A_g \cdot U_g) + (A_w \cdot U_w) = A_{total} \cdot \bar{U}_{outside\ wall} \text{ [W/K]}$$

The calculation of the total heat flow through a fragment of an outside wall leads to the following formula, for the average U value of that fragment:

$$\bar{U}_{outside\ wall} = \frac{(A_g \cdot U_g + A_w \cdot U_w)}{A_{total}} \text{ [W/m}^2\text{·K]}$$

The meaning of the symbols is:
H_T the total heat flow in W
A_g the surface area of glass in m²
A_w the surface area of the non-open parts of the outside wall in m²
A_{total} the total surface area of the outside wall (A_g + A_w) in m²
U_g the U value of the glass in W/m²·K
U_w the U value of the non-open parts of the outside wall W/m²·K
$\bar{U}_{outside\ wall}$ the average U value of the outside wall in W/m²·K

This calculation is intended for a simple, flat, external partition construction, assuming there is no lateral exchange of heat. In reality, the influence of lateral heat exchange and thermal bridges will play a role and will therefore have to be compensated. Calculation rules are provided for this in standards and reference books.

1.3 Temperature progression in constructions

The total heat resistance can be calculated for a construction that consists of various layers. This can be used to determine the heat flow density. Assuming that the building is already heated and that a uniform (stationary) situation has been achieved, the heat flow density (q) will be the same in every layer of the construction. After all, there will be no heat left in the construction, nor will there be any heat generated in it. The following applies to each layer:

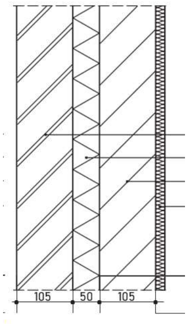
$$q = \frac{\Delta T}{R} \text{ [W/m}^2\text{]}$$

This means that where q is the same, the difference in temperature in a layer with a high level of heat resistance should also be greater than in the case of a layer with a low level of heat resistance. The difference in temperature throughout the construction is distributed evenly across the various layers, according to the levels of heat resistance of the layers. The jump in temperature in a layer can be calculated using the following formula:

$$\Delta T_{m;i} = \frac{R_{m;i}}{R_T} \cdot \Delta T \text{ [°C]}$$

The meaning of the symbols is:
$\Delta T_{m;i}$ the jump in temperature across layer i
$R_{m;i}$ the heat resistance of layer i
ΔT the difference in temperature between the air on both sides of the construction
R_T the total heat resistance of the total construction (air to air)

As an example, the table in figure 1.19 shows a calculation of the progression of the temperature in a completely insulated cavity wall in an existing dwelling (< 1970).



Construction layer	d [m]	λ [W/(m·K)]	$R_{m;i}$ [m²·K/W]	$\Delta T_{m;i}$	T [°C]
Ouside air					-10
R_{se}			0.04	0.73	-9.3
Brickwork	0.105	1.2	0.09	1.6	-7.7
Insulation material	0.05	0.04	1.25	22.89	15.2
Sand-lime brick	0.105	0.95	0.11	2.02	17.2
Plaster layer	0.01	0.50	0.02	0.37	17.6
R_{si}			0.13	2.38	
Inside air					20
Total			1.64		30

Figure 1.19 Calculation of progression of the temperature in a completely insulated cavity wall

It is also possible to determine temperature progression using graphs, where the wall is drawn on the scale of the heat resistance (see figure 1.20). The temperature progression is then depicted by a straight line. By linking the temperatures that are known (inside and outside) to this straight line, you can read the temperature at all the intermediate locations.

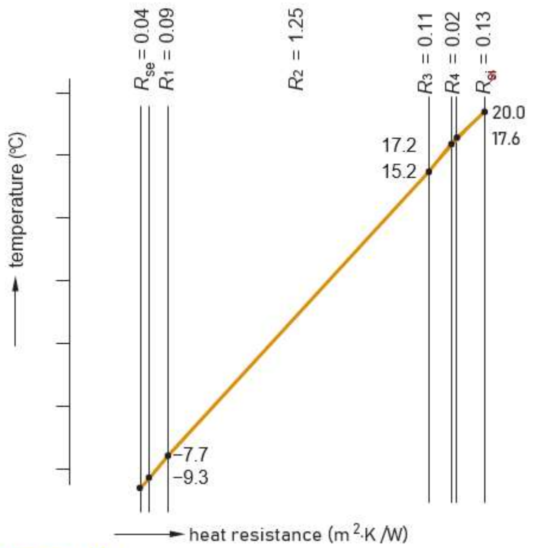


Figure 1.20 Determining the temperature progression using graphs

In figure 1.21, the temperature progression of a construction that was calculated in figure 1.19 is compared with a non-insulated cavity wall and that of a cavity of 100 mm, completely filled with insulation material. Also shown are the heat resistance of the total construction (R_T), the heat transmission coefficient of the constructions and the heat loss in the case of the stated 30 °C difference in temperature.

You can see that the surface temperatures of the non-insulated cavity wall, the 50-mm cavity wall, and the cavity wall with 100 mm of insulation material are 13.0 °C, 17.6 °C and 18.6 °C respectively.

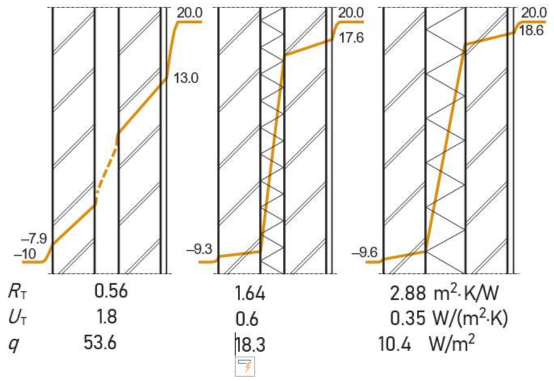


Figure 1.21 Temperature progression, heat resistance, heat transmission coefficient and heat loss (heat flow density) at 30 °C for several cavities

Knowing the overall temperature progression in a construction is important in connection with being able to determine whether, and if so where, interstitial condensation will occur in the construction (see Chapter 2). Better insulation will not only restrict heat loss, but the temperature of the inner surface will increase too with the greater level of insulation. This makes the spaces concerned considerably more comfortable. Modern building assumes higher heat resistances than shown here. Values of R_T = 5 or 6 m²·K/W are normal up to R_T = 10 or 12 m²·K/W in 'passive houses'.

The temperature progression and surface temperature of different types of glazing can be determined in the same way as with a cavity wall (see figure 1.22).

Glass has a fairly high heat conduction coefficient (λ = 0.8 W/(m·K). As a result the total thermal resistance of the construction (R_T) is determined primarily by the levels of heat transfer resistances and the cavity. The thickness of the glass has only a slight influence. In the case of single-glazing, the surface temperature falls to –2.3 °C in the situation described (outside temperature of –10 °C), to 8.2 °C in the case of double-glazing, and with high-efficiency glass (with a coating for reducing emissions, and with argon gas in the gap), it is 14.2 °C, very important in the scope of thermal comfort. The surface temperature determines whether condensation forms on the window pane (see Chapter 2).

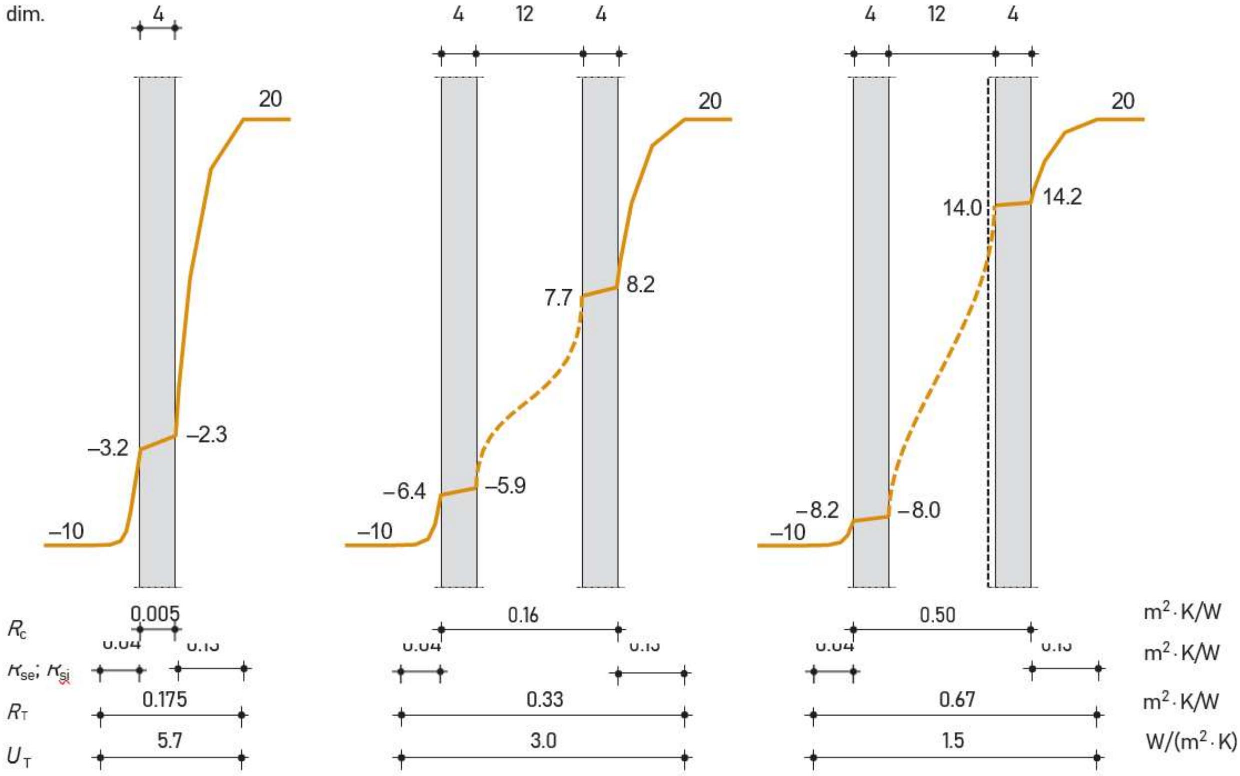


Figure 1.22 Temperature progression in single-glazing, double-glazing and high-efficiency glass

1.4 Heat accumulation

In order to be able to calculate the heat transport and the temperature progression in a construction, your starting point should be a stationary situation, in other words where the situation has been the same for a long time, so that there is an overall balanced position. However, this will not be the case in practice. If, in the evening, the heating is turned down before it is time to go to sleep, the inside temperature at night will be lower than during the day. The outside temperature is also lower at night than in the daytime. This will affect the progression of the temperature in the construction. The temperature progression in the construction will adapt itself more slowly or more quickly to the new situation, depending on the mass of the construction.

In summer

Heat accumulation refers to the phenomenon where a large, sturdy building (such as an old church or a bunker) remains relatively cool by day and by night during the summer, while a light wooden building gets very warm in the daytime and cold at night. This is caused by the difference in mass of the buildings. When the outside temperature rises or the sun starts to shine, the whole of the building begins to warm up. In the case of a light building, this does not take much time. Within just a few hours, it is warm not only due to the rising temperature of the inside air, but also the heat radiation from the walls, to the point where it affects levels of comfort for those inside. Things are different with large, sturdy buildings. Because of their greater mass, they require much more heat in order to be warmed up, but before they get much warmer, the day is over and they start to cool down again. As a result, the temperature in large buildings is almost the same as the average outdoor temperature measured over a few days or a week. If you know that the average temperature in the month of July is around 17 °C, then it is not surprising that old churches are often so pleasantly cool during the summer.

In winter

In the winter, too, heat accumulation plays a role. A light building warms up quickly when the heating is switched on, a process that takes several hours or even a few days in the case of a building with more thermal mass. In some offices with a not or not sufficient insulated floor above outside air, it is not until the afternoon that it starts to feel comfortable if the heating has been off during the weekend. For example, if the heating comes on at 6 o'clock on Monday morning, the air temperature may be warm enough by 9 o'clock, but the walls and floor will still be cold, resulting in a feeling of cold radiation. Nevertheless, buildings with more thermal mass are more pleasant. Changes in the outside temperature are not so noticeable thanks to heat accumulation. The heating system, the effect of which can take time to be felt anyway, does not need to respond so quickly, and the result is a much more constant indoor temperature. Mass is also necessary if you wish to use passive sun energy and internal heat sources in the building. The indoor temperature of a small building will quickly rise when the sun shines through the windows, even when the outdoor temperature is low (5 to 10 °C). Any excess heat is removed through ventilation, or perhaps with a cooling system. The temperature in a larger building will not rise as quickly, as the construction itself has to be heated as well. If, for example, a 3 to 4 °C rise in indoor temperature is allowed for, then there is no excess heat to be removed. The heat is conserved – it accumulates – in the building itself until such time that it is needed. At night this heat keeps the temperature of the building up, so that in the morning there is hardly any necessity, if at all, to provide extra heating. For that reason, thermically open ceilings are often used in offices where the mass of the construction is generally light (because of the use of plasterboard walls and carpets on the floor). The free-hanging ceilings are about 20% open so that the heat can be stored in the floor above. However, the top side of the ceiling has to be kept clean to prevent the build up of dust.

Position of insulation

Using insulation, as well as its position, affects the heat accumulation features of the building (see figure 1.23).

A lot of heat is stored (accumulated) in walls where the insulation is on the outside (see figure 1.23-1). This results in equable conditions indoors. It is also possible for the heating to be switched off for an hour without any problems – there is, after all, enough heat in the walls. It goes without saying that the process of heating up a building like this takes a long time.

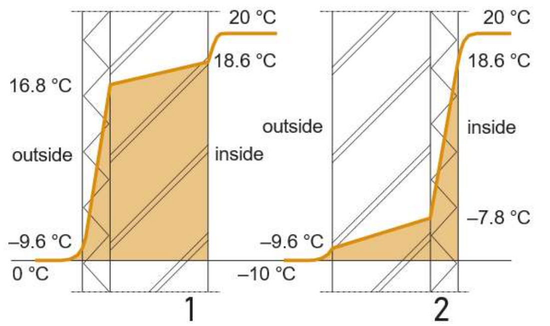


Figure 1.23 Insulation on the inside and outside of the wall, influence on heat accumulation

When the inside is insulated (see figure 1.23-2), only a small amount of heat is stored in the walls, and the heat stored in the insulation material is of little significance: it has virtually no mass. In a building of this type, the heating has to be able to respond quickly. The heat- regulating stone mass is, as it were, outside, and the time taken for warming up the building is of course short. This offers advantages to buildings which are only used for a few hours a week, given that less fuel is needed. In general, the situation in figure 1.23-1 is more favourable: the building has a large interior capacity. With regard to the situation in figure 1.23-2 (insulation on the inside), the stone mass hardly has any effect. It should not be forgotten either that floors and interior walls must be included in the overall calculations. These are even more important, because they have a far bigger surface and therefore have more mass.

The amount of heat that is accumulated in any particular layer can be calculated with the following formula:

$$Q = \rho \cdot c \cdot d \cdot \Delta T \,[\mathrm{J/m^2}]$$

The meaning of the symbols is:

Q the amount of heat that is accumulated in the construction layer per m²

ρ the density of the material in kg/m³

c the specific heat in J/(kg·K)
d the thickness of the layer in m
ΔT the rise in temperature of the layer in K of °C

Values for ρ and c for various materials are shown in the book of tables. You can use the above formula to calculate how much heat has been accumulated in different situations, such as the one in figure 1.23.

The length of time roughly needed for a construction to be heated up can be calculated with the following formula:

$$\tau = \frac{Q_{acc}}{q} \text{ [s]}$$

The meaning of the symbols is:
τ the length of time needed to heat up the construction in s
Q_{acc} the amount of accumulated energy in J/m^2
q the amount of energy 'supplied' to the construction in W/m^2

Example
Given

- We are working on the basis of the constructions described in figure 1.23.
- We are assuming that, at the beginning, the temperature throughout the construction is –10 °C.
- To bring the construction up to temperature, 250 W/m^2 is being 'supplied'.

	d [m]	ρ [kg/m^3]	c [J/kg·K]
Brickwork	0.21	1900	840
Insulation material	0,1	200	840

We can now calculate the amount of accumulated energy and the time needed to heat up the construction. First, we determine the average temperature in the construction for figure 1.23-1. For the insulation material, this is:

$$\frac{-9.6 + 16.8}{2} = 3.6 \text{ °C}$$

And for the brickwork:

$$\frac{-9.6 + 16.8}{2} = 17.7 \text{ °C}$$

We can now work out the amount of accumulated energy. The rise in temperature of the insulation material is 13.6 °C, from –10 at the beginning, to 3.6 °C, so:

Qacc = 0.1 · 200 · 840 · 13.6 = 228 · 103 J/m2

For the brickwork, the rise in temperature from the situation at the beginning is 27.7 °C, from –10 to 17.7 °C, so:

$$Q_{acc} = 0.21 \cdot 1900 \cdot 840 \cdot 27.7 = 9284 \cdot 10^3 \text{ J/m}^2$$

This means the total accumulation is:

$$Q_{acc;tot} = 228 \cdot 10^3 + 9284 \cdot 10^3 = 9512 \cdot 10^3 \text{ J/m}^2$$

The time needed to heat up the construction is therefore

$$\tau = \frac{9512 \cdot 10^3}{250} = 38{,}048 \text{ seconds, or } 10.6 \text{ hours}$$

With figure 1.23-2, too, we first need to determine the average temperature in the construction as a whole. For the brickwork:

$$\frac{-9.6 - 7.8}{2} = -8.7\ °C$$

And for the insulation material:

$$\frac{-7.8 + 18.6}{2} = 5.4\ °C$$

We then calculate the amount of accumulated energy. The increase in temperature of the brickwork is 1.3 °C, from -10 at the beginning to -8.7 °C, so:

$$Q_{acc} = 0.21 \cdot 1900 \cdot 840 \cdot 1.3 = 436 \cdot 10^3\ J/m^2$$

For the insulation material, the rise in temperature is 15.4 °C, from -10 at the beginning to 5.4 °C, so:

$$Q_{acc} = 0.1 \cdot 200 \cdot 840 \cdot 15.4 = 259 \cdot 10^3\ J/m^2$$

The total accumulation is therefore:

$$Q_{acc;tot} = 436 \cdot 10^3 + 259 \cdot 10^3 = 695 \cdot 10^3\ J/m^2$$

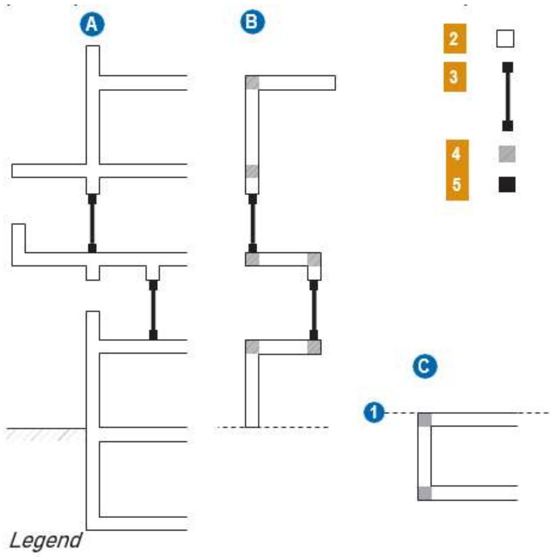
The length of time needed to head up the construction is now:

$$\tau = \frac{695 \cdot 10^3}{250} = 2780 \text{ seconds, or } 0.8 \text{ hours}$$

1.5 Schematization of a construction; thermal bridges

Earlier, we addressed simple construction parts without accounting for the context of the construction. In section 1.2 we determined an average heat transmission coefficient under the precondition that no lateral heat exchange takes place. In reality, we will want to calculate the heat loss coefficient through transmission (H_T) for an entire home where lateral heat exchange does in fact take place. Standardization extensively describes which conditions must be taken into account. Discussing all the details involved goes beyond the scope of this book. Only the basic principles will be discusses in this chapter.

Which surface do you have to include in order to calculate the heat loss coefficient (H_T) for the entire home: the inside or the outside surface? In standardization, rules have been agreed for this. Figure 1.24 describes how the building surfaces must be determined. The surface obtained is called the projected surface.



Legend
A actual situation
B model approach NEN_EN_ISO 13789
C model approach NEN_EN_ISO 13370

1 heat loss through the floor
2 flat construction elements
3 rooms, doors, window frames
4 linear elements
5 window frame connections (as linear element)

Figure 1.24 Modelling of the building casing (NEN 1068)

The connections between floor or roof on the facade are considered separate linear elements. This linear element is approached as a linear thermal bridge, whose linear heat loss coefficient needs to be determined. Besides the linear thermal bridges, the heat loss coefficient of point thermal bridges also needs to be taken into consideration. Think for example of anchors or other point bushings.

The direct heat loss coefficient between the heated inside space and the outside air (H_D) in W/K is calculated as follows:

$$H_D = \sum_i (A_{T;i} \cdot U_{C;i}) + \sum_k (l_k \cdot \psi_k) + \sum_j X_j$$

The meaning of the symbols is:

- $A_{T;i}$ the projected surfaces of the level element *i* of the outside partition construction [m2]
- $U_{C;i}$ the heat transmission coefficient of the level element *i* of the outside partition construction [W/(m²·K)]
- ℓ_k the length of the linear thermal bridge *k* [m]
- ψ_k the linear heat loss coefficient of the thermal bridge *k* [W/(m²·K)]
- X_j the heat loss coefficient of the point thermal bridge *j* [W/K]

The $U_{C;i}$ value is equal to the U_T value ($U_T = 1/R_T$) added by an additional factor for the difference between theory and practice where the heat loss can be slightly higher due to matter not included in the calculation. Think for example of fasteners and the quality of the realisation.

Thermal bridge

A thermal bridge is a part of the building envelope which has a rather low insulation value compared to the overall value. Examples are a concrete column, which starts inside and ends outside, a storey floor which directly goes through as a balcony, or a cavity anchor forming a thermal leak in an insulated cavity which, at this location, results in a lower surface temperature due to the poor insulation.

Influence on heat transport

The problem with thermal bridges is not just the localised reduction of heat resistance, leading to a greater level of heat transport at that location, but also the influence they have on their surroundings: heat is drawn towards the thermal bridges so that the actual level of heat loss is greater than you would at first think (see figure 1.25). Furthermore the temperature at the thermal bridge itself will become somewhat higher because of the lateral heat transport. Nevertheless it will remain low so condensation and mould grow still may occur (see Chapter 2).

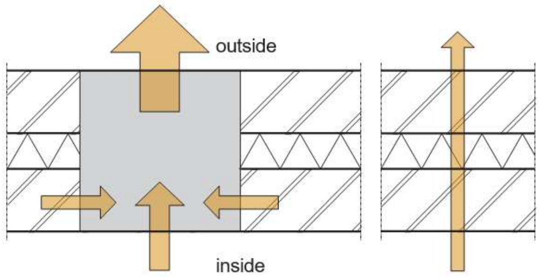


Figure 1.25 Extra heat loss at thermal bridge through indirect supply of heat

The better-insulated building constructions are, the more influential thermal bridges on heat loss become, in percentage terms. Calculating heat loss through thermal bridges is a fairly complex matter, one which actually requires a computer. If you nevertheless wish to be able to estimate what the R_c value of a construction would be, you can use the following approximation.

We are using the thermal bridge described in figure 1.26, to which the following generally apply:

- depth of the construction: 1 m'
- brickwork: λ = 1.0 W/(m·K)
- insulation: λ = 0.04 W/(m·K)
- heat transfer resistance on inside: R_{si} = 0.13 m²·K/W
- heat transfer resistance on the outside: R_{se} = 0.04 m²·K/W

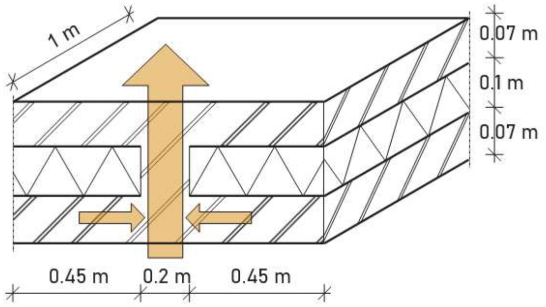


Figure 1.26 Thermal bridge

First, we calculate the R value of the thermal bridge as if there were no indirect flow. To do this, we insulate the thermal bridge from the rest of the construction through a fictitious application of a material with an infinitely high level of heat resistance (see figure 1.27). Obviously this approximation is far too high. The resulting R' value will be the maximum possible.

The construction is divided into sections, perpendicular to the ground surface. Each section has the same profile, and each is made up of one or more layers of material. The heat flows will now travel as shown in figure 1.27. Two sections can be distinguished: the well-insulated section a and the thermal bridge (section b).

Calculate the heat resistance $(\Sigma R_m)_a$ and $(\Sigma R_m)_b$ with formula $R_m = d/\lambda$ for all sections. Calculate the heat transfer coefficient U_a and U_b with the formula $U = 1/(R_c + R_{si} + R_{se})$. Next determine the replacing heat resistance R' by means of the formula:

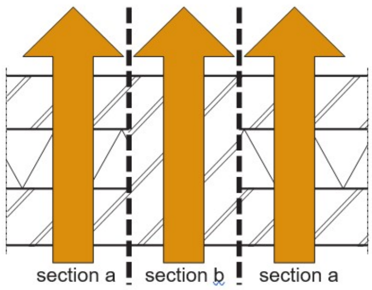


Figure 1.27 Heat flows R' value

$$R' = \frac{A_{con}}{A_a U_a + A_b U_b}$$

The meaning of the symbols is:

A_{con} the projected surface area of the partition construction
A_a, A_b the projected surface area of the sections a and b
U_a, U_b the heat transmission coefficients of the sections a and b

We can now calculate the heat resistance of section a for the thermal bridge from figure 1.26:

$$A_a = 0.9 \cdot 1 = 0.9\ \text{m}^2$$

$$(\Sigma R_m)_a = \frac{0.07}{1} + \frac{0.1}{0.04} + \frac{0.07}{1} = 2.6 \text{ m}^2\cdot\text{K/W}$$

And the heat resistance of section b:

$$A_b = 0.2 \cdot 1 = 0.2 \text{ m}^2$$

$$(\Sigma R_m)_b = \frac{0.24}{1} = 0.24 \text{ m}^2\cdot\text{K/W}$$

The heat transfer coefficient for both sections then follows from:

$$U_a = \frac{1}{(\Sigma R_m)_a + R_{si} + R_{se}} = \frac{1}{2.6+0.13+0.04} = 0.36 \text{ W/(m}^2\cdot\text{K)}$$

$$U_b = \frac{1}{(\Sigma R_m)_b + R_{si} + R_{se}} = \frac{1}{0.24+0.13+0.04} = 2.44 \text{ W/(m}^2\cdot\text{K)}$$

The maximum heat resistance of the total construction then amounts to:

$$R' = \frac{A_{con}}{A_aU_a + A_bU_b} + \frac{0.9 + 0.2}{0.9 \cdot 0.36 \cdot 0.2 \cdot 2.44} = 1.37 \text{ m}^2\cdot\text{K/W}$$

Second, we base our calculations on a situation where there is an endless supply of heat to the thermal bridge. We divide the construction into layers – that is, the construction is divided into a system of imaginary layers parallel to the ground surface with the same profile in each layer, all of which are made up of one or more layers of material (see figure 1.28).

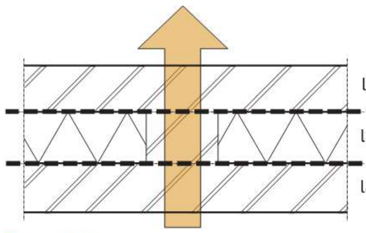


Figure 1.28 Determining the *R''* value

We now assume that an infinitely thin layer of very conductive material ($\lambda = \infty$) is applied to the locations where the sections border each other. The effect of this is that the surface temperature will be the same at these points. The heat flow will therefore be greater than in reality. In other words the outcome is too negative. The resulting *R* value will be the minimum possible value.

In order to be able to determine the heat flow for the whole construction, we have to work out the average λ value for each layer. This is done as follows:

$$\lambda'' = \frac{\lambda_{a;i} \cdot A_a + \lambda_{b;i} \cdot A_b + \dots}{A_a + A_b + \dots}$$

The meaning of the symbols is:

λ''	the average heat conduction coefficient of imaginary layer j in W/(m·K)
$\lambda_{a;j}$, $\lambda_{b;j}$, ...	the heat conduction coefficients of the materials of section a, b, ... in layer j in W/(m·K)
A_a, A_b, ...	the surface areas of sections a, b, ... in m²

The minimum resistance of the construction is now:

$$R'' = \sum \frac{d_j}{\lambda_j''}$$

For figure 1.28, we can determine the λ'' values of layers 1, 2 and 3 respectively as follows:

$$\lambda_1'' = 1 \text{ W/(m}\cdot\text{K)}$$

$$\lambda_2'' = \frac{0.04 \cdot 0.9 + 1 \cdot 2.1}{0.9 + 0.2} = 0.21 \text{ W/(m}\cdot\text{K)}$$

$\lambda_3'' = 1$ W/(m·K)

The minimum heat resistance of the construction is then:

$$R'' = \frac{0.07}{1} + \frac{0.1}{0.21} + \frac{0.07}{1} = 0.62 \text{ m2·K/W}$$

The actual heat resistance R_c of the construction will lie somewhere between the most positive and the most negative approximation, and is calculated as follows:

$$R_c = \frac{a' \cdot R' + R_{si} + R_{se} + R''}{1 + 1.05 \cdot a'} - R_{si} - R_{se}$$

The weighting factor a' is given in the table of figure 1.29.

Condition	a'
a $R' \leq 1.05 \cdot (R'' + R_{si} + R_{se})$	0
b the construction includes an insulation layer which is interrupted by parts consisting of a material with a heat transfer coefficient larger than 0.30 W/(m·K), without those parts being directly thermally shielded of on at least one side by an insulation layer of at least 20 mm width	0
c the construction includes an insulation layer which is interrupted by parts consisting of a material with a heat transfer coefficient larger than 0.15 W/(m·K) but not exceeding 0.30 W/(m·K) without those parts being directly thermally shielded of on at least one side by an insulation layer of at least 20 mm width	0.5
d the construction includes an insulation layer which is interrupted by metal parts where those parts are directly thermally shielded of on at least one side by an insulation layer of at least 20 mm width, but not exceeding 30 mm	0.5
e all other situations	1

Figure 1.29 Determining weighting factor a′

Condition e applies to our example so that a' equals 1. R_c then amounts to:

$$R_c = \frac{1.37 + 0.13 + 0.04 + 0.62}{1 + 1.05} - 0.13 - 0.04 = 0.88 \text{ m}^2\text{·K/W}$$

The above calculation was carried out for a relatively simple thermal bridge. In practice, thermal bridges will be more complex. Then, it becomes necessary to make use of computer programs. Thermal bridges as calculated here do exist (or used to exist) in practice – see figure 1.30 and 1.31. This type of thermal bridge probably belongs to the past.

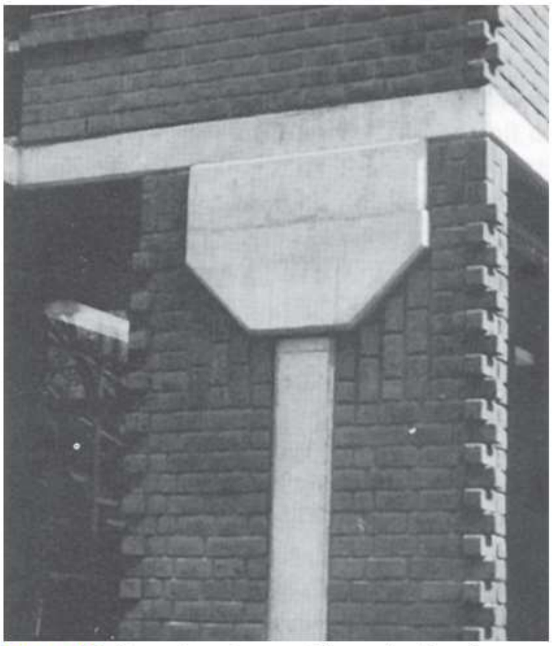


Figure 1.30 Concrete column and floor edge forming a thermal bridge

Figure 1.31 The same situation as in figure 1.30, but seen here from the inside

Influence on the surface temperature

Figure 1.32 shows a cross-section of a continuous floor-to-balcony layer of concrete. As a result of the high level of heat conduction through the concrete, the surface temperature at the corners indicated may be very low. This may result in condensation from vapour, causing circles to appear on the ceiling, or carpets to rot. Constructions of this type are therefore no longer built.

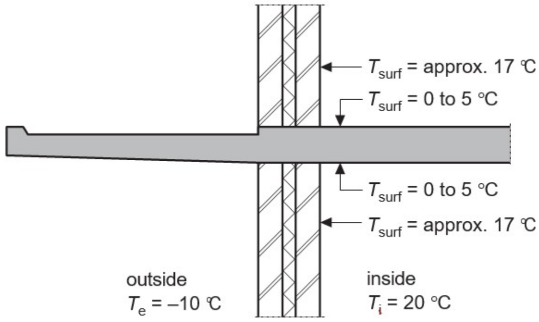


Figure 1.32 Concrete cantilever

Steel window profiles – and to an even greater degree, aluminium ones – can cause very cold surfaces. The heat conduction coefficient of aluminium is so high (λ = 200 W/(m·K) that the entire profile assumes virtually the same temperature. This means the profile depends strongly on the relationship between the part facing outwards and the part facing inwards (see figure 1.33).

If the largest part of the profile is on the outside, it acts as a kind of cooling fin, and the – much smaller – inside part will become very cold. If the proportions are reversed, the temperature of the profile will be higher. This example is shown here to demonstrate the mechanism. In practice, in heated buildings you find separated aluminium profiles, with insulation material located between the two parts.

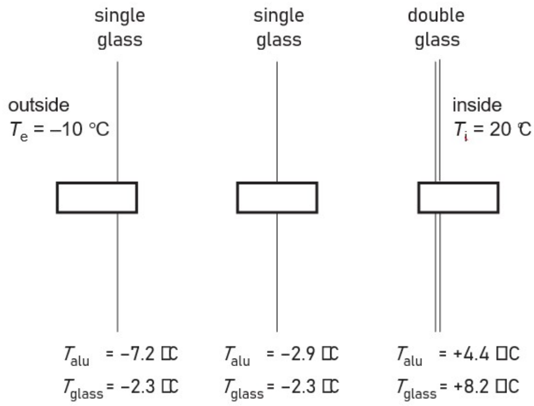


Figure 1.33 Influence on surface temperature of presence of aluminium hollow cross-section

Points to note during the design process

During the design process, the architect and the construction engineer must avoid the creation of thermal bridges as much as possible. Critical points here are:

- foundations
- brickwork supports
- balconies and galleries
- roof edges

Foundations

Possible solutions for the foundations are:

- lay the foundations deeper;
- thermal layers in the floor supports (using foam glass, polystyrene insulation or felt or rubber).

Brickwork supports

Possible solutions for brickwork supports are:

- adding insulation between the ridges of the band of concrete and the part of the construction behind it (bear in mind the dimensions of the ridges: the width of the ridge, the distance from the ridges, and the thickness of the insulation);
- stainless-steel anchoring of prefab insulated bands of concrete instead of steel (the heating conduction coefficient of steel is greater than that of stainless steel);
- applying stainless steel profiles instead of steel ones (bear in mind the heart to heart distance of the brackets).

Balconies and galleries

Possible solutions for balconies and galleries are:

- mounting balconies and galleries using insulated stainless steel starter bars;
- restricting the number of ridges and the surface area of ridges when mounting the balcony (bear in mind the heart to heart distance and length of the ridges);
- completely separating the balcony or the gallery (separate support construction).

Roof edges

A possible solution for roof edges is to, at least partly, brick up the roof edge with cellular concrete or to apply a rim of cellular glass.

1.6 Thermal stress

Expansion of various materials

Materials expand when subject to rises in temperature. The degree to which this happens varies from one material to another. It is expressed in the linear expansion coefficient ?. This indicates how many metres a one-metre rod of a particular material will expand when subjected to a temperature increase of one Kelvin (1 °C). See the table in figure 1.34.

Material	Linear expansion coefficient α [m/m·K)]
Brick	$5 \cdot 10^{-6}$ (0.000005)
Concrete	$10 \cdot 10^{-6}$
Steel	$12 \cdot 10^{-6}$
Aluminium	$23 \cdot 10^{-6}$
Polystyrene foam	$70 \cdot 10^{-6}$
Polyurethane foam (laminated sheeting)	$27 \cdot 10^{-6}$
Foam glass	$9 \cdot 10^{-6}$

Figure 1.34 Expansion of various materials

If fluctuations in temperature become too great, cracks can appear. This can also happen if two layers in a construction have different expansion coefficients.

Influence of the position of the insulation

In view of thermal stress, the position of the insulation in a construction is important. This applies especially to roofs. Because of solar radiation, roof surfaces that are not protected by a layer of tiles or gravel or something similar, can reach temperatures of up to 80 °C.

As an example, figure 1.35 shows the temperature progression in the summer and winter of two roof constructions. This clearly highlights the influence of the position of insulation on the average difference in temperature between summer and winter of the concrete layer: ΔT = 12.8 °C insulation on top of the concrete layer and ΔT = 76.7 °C when the insulation is placed under the concrete layer. In the case of a roof 30 m long, this will result in a change in length as follows:

- $\Delta L = 10 \cdot 10^{-6} \cdot 12.8 \cdot 30 = 0.004$ m with insulation at the top;
- $\Delta L = 10 \cdot 10^{-6} \cdot 76.7 \cdot 30 = 0.023$ m with insulation at the bottom.

A change in length of just a few millimetres can often be accommodated, either with or without the help of special features in the construction. However, this is no longer the case where the change in length is 23 mm. The risk of cracks forming is then a distinct possibility.

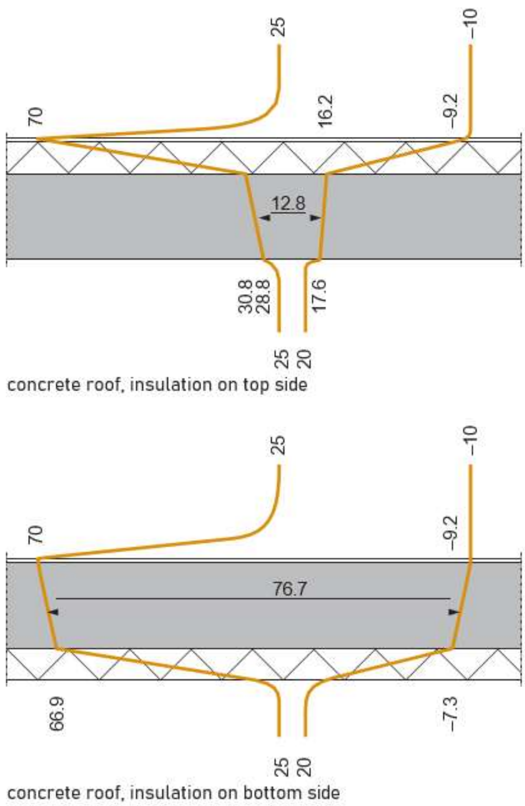


Figure 1.35 Insulated concrete roof temperature distribution

Choice of insulation material

Top-side insulation is therefore favourable for thermal stress in a concrete construction. However it does place demands on the way roofs are covered and the choice of insulation material. In the same example (figure 1.35), the daily difference in temperature in the insulation layer is around 30 °C. If polystyrene foam plates measuring 1.20 m in length are chosen, the daily change in length of each plate will be about 2.5 mm. If the roof covering is attached completely to the plates, this change in length has to be accommodated at the point where the plates meet. This puts a very heavy burden on the roof covering. With this type of construction, the roof covering should only be attached in a few places in order to spread the change in length over a wider area. In the case of a tiled or gravel roof, there is less solar radiation – and therefore less difference in temperature – in the insulation layer. However, the change in length nevertheless remains so great that it would be wrong to totally attach the roof covering. The gravel load does mean the roof covering can be laid loosely, though. Where foam glass has been used, for example ($\alpha = 8.5 \cdot 10^{-6}$ m/m·K), the change in length for each plate of around 0.60 m long is just 0.15 mm. The roof covering can be attached completely to this type of material. An unusual version is the inverted roof, where the insulation is laid onto the roof covering and weighed down by gravel or by tiles. The changes in temperature that the roof covering undergoes in this case are notably small. In addition, loose lying plastic foil can be used as a watertight layer.

2 Moisture, moisture transport, condensation

A.C. van der Linden; A. Zeegers

This chapter deals with the basic terms relating to moisture, condensation and moisture transport in constructions and similar objects. The subject matter is illustrated using practical examples.

Moisture can occur in three aggregation phases:

- gaseous phase (vapour)
- liquid phase (water)
- solid phase (ice)

All three phases can cause their own specific problems in the construction industry. Often in a particular process it is not easy to distinguish one specific phase from another, in which case we talk about moisture.

2.1 Vapour transport

Vapour concentration and vapour pressure

Vapour is gaseous, invisible and behaves just like all other gases. As well as oxygen, nitrogen, carbon and so on, air can also contain a quantity of vapour. The quantity is relatively small, around 10 grammes in every cubic metre of air in average indoor circumstances. The quantity of vapour in every cubic metre of air is known as the absolute air humidity, or the vapour density (c in kg/m³). As well as using the vapour density, you can express the amount of vapour on the basis of its contribution to the total air pressure: the partial vapour pressure (p in N/m² or Pa). The total air pressure (barometer pressure) is the same as the sum of the partial pressures of the individual gases (Dalton's Law). The relationship between vapour concentration and vapour pressure is shown by the Boyle- Gay Lussac Law:

$$p = \frac{m}{V} \cdot R \cdot T \text{ [Pa]}$$

The relationship between the mass and the volume is the same as the concentration, so that the formula becomes:

$$p = c \cdot R \cdot T \text{ [Pa]}$$

The meaning of the symbols is:

p the vapour pressure in Pa
m the mass of a gas in kg
V the volume in m³
R the specific gas constant (for vapour: R = 462 J/(kg·K))
T the absolute temperature in K
c the concentration in kg/m³

Note: these formulas do not apply when you are too close to the point of condensation (see below).

The vapour pressure therefore depends on the amount of moisture in the air and the temperature of the air. The maximum level of vapour that the air can hold is not infinite, but is determined by the temperature.
The table in figure 2.1 shows several values for this maximum vapour pressure (see the book of tables for more details). As well as the maximum level of vapour pressure, the maximum vapour density is given.

θ [°C]	p_{max} [Pa]	c_{max} [g/m³]
35	5627	39.56
30	4245	30.34
25	3169	23.05
20	2340	17.28
15	1706	12.85
10	1229	9.40
5	872	6.83
0	611	4.84
-5	401	3.26
-10	260	2.15
-15	165	1.41
-20	103	0.90

Figure 2.1 Maximum vapour pressure and vapour concentration

The approximate values for pmax can be calculated using the following formula:

$$p_{max} = 100 \cdot e^{\left(18.956 - \frac{4030.18}{\theta + 235}\right)}$$

The meaning of the symbols is:

p_{max} the maximum vapour pressure in Pa
θ the temperature in °C

Relative humidity

If the vapour pressure is at its maximum level in any given situation, this means the air is 100% saturated with vapour. For that reason, the maximum level of vapour pressure is also known as the saturated vapour pressure. If there is less vapour in the air, this can be expressed in terms of relative humidity. This is the relationship between the prevailing vapour pressure (p) and the maximum possible level vapour pressure in Pa (N/m^2) of vapour pressure (p_{max}) for that temperature. This relationship is expressed as a percentage (%):

$$\phi = \frac{p}{p_{max}} \cdot 100\%$$

Figures 2.2 to 2.5, 2.8 and 2.9 plot the relative humidity with the temperature and the vapour pressure. The temperature is shown on the vertical axis and the vapour pressure on the horizontal axis.

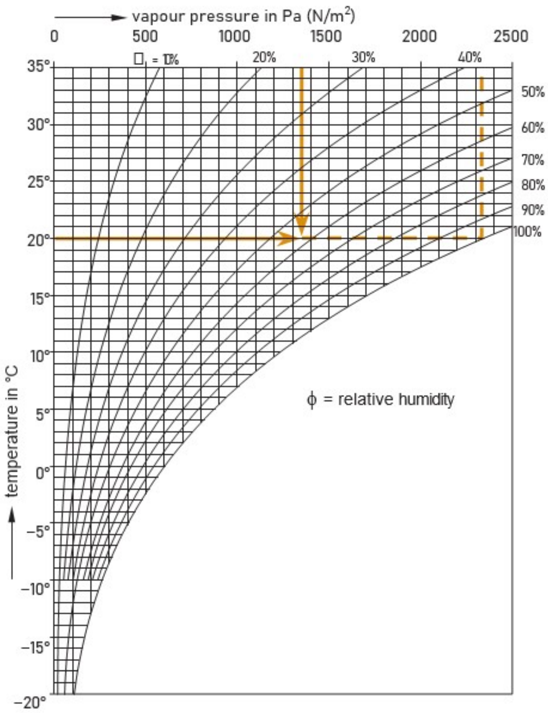


Figure 2.2 Vapour pressure p = 1350 Pa, relative humidity ϕ = 58%

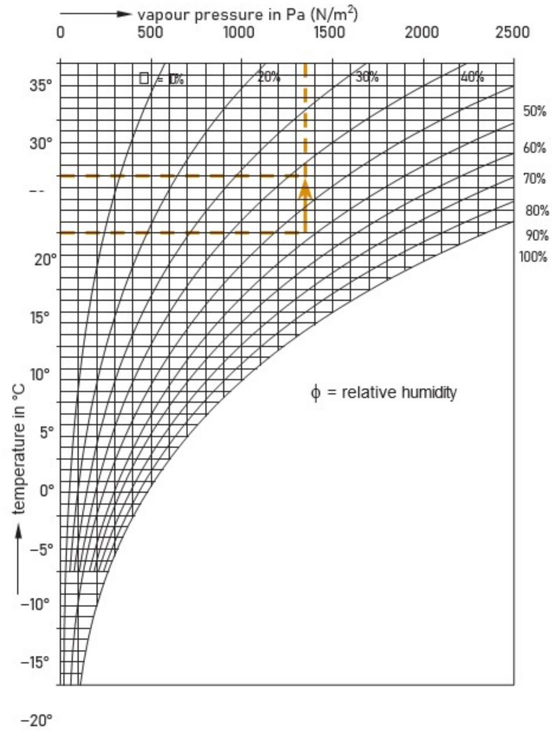


Figure 2.3 If the air heats up from 20 °C to 25 °C, relative humidity drops from ϕ = 58% to ϕ = 43%

Example figure 2.2

Suppose that the prevailing water vapour pressure is p = 1350 Pa. For an air temperature of 20 °C, the maximum vapour pressure p_{max} = 2340 Pa (see figure 2.1). The relative humidity is then:

$$\phi = \frac{1350}{2340} \cdot 100\% = 58\%$$

Example figure 2.3

Initial situation (figure 2.2):

Temperature equals θ = 20 °C

Maximum vapour pressure at 20 °C is p_{max} = 2340 Pa

Maximum vapour concentration is c_{max} = 17.28 g/m^3

Prevailing water vapour pressure is p = 1350 Pa

Prevailing water vapour concentration is c = 10 g/m^3

Relative humidity ϕ = 58%

If the air is heated to 25 °C (p_{max} = 3169 Pa), the relative humidity is:

$$\phi = \frac{1350}{3169} \cdot 100\% = 43\%$$

The ϕ = 100% line shows the relationship between the temperature (θ) and maximum vapour pressure (p_{max}). This figure can be used to demonstrate easily in graph form what happens if any of these parameters changes.

Because the temperature rises, the relative humidity drops. But something also happens to the water vapour concentration. The weight (mass) proportion between the water vapour and the other gases in the air remains the same, but because the air is getting warmer it expands. This brings about a change in the concentration (g/m^3) of the water vapour and the other gases in the air. After all, the same mass is now spread across more m^3.

For this reason, you must use water vapour pressure instead of the water vapour concentration in calculations where the temperature rises. In the example of figure 2.3, the relative humidity has dropped to ϕ = 43%. For 25 °C, c_{max} = 23.05 g/m^3. This means that the water vapour concentration has now become c = 0.43 · 23.05 = 9.9 g/m^3 instead of 10 g/m^3. It's only a small difference, but it is a difference.

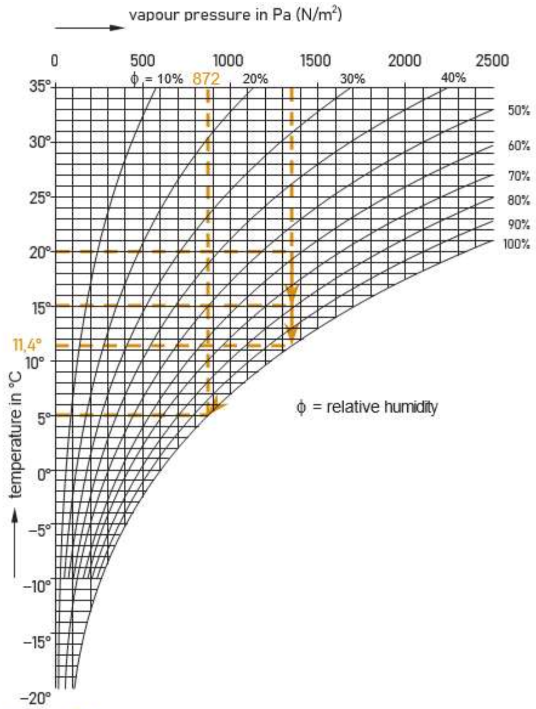


Figure 2.4 If the air cools by 5 °C, this causes the vapour in the air to condense

Example figure 2.4
Initial situation (figure 2.2): Temperature is θ = 20 °C
Maximum vapour pressure at 20 °C is p_{max} = 2340 Pa
Maximum water vapour concentration at 20 °C equals c_{max} = 17.28 g/m^3
Prevailing water vapour concentration equals p = 1350 Pa
Prevailing water vapour concentration equals c = 10 g/m^3
Relative humidity ϕ = 58%

If the air is cooled to 15 °C (p_{max} = 1706 Pa), the water vapour pressure remains the same, but the relative humidity becomes:

$$\phi = \frac{1350}{1706} \cdot 100\% = 79\%$$

If it cools down any further, the prevailing water vapour pressure (p = 1350 Pa) will at some point become equal to the maximum water vapour pressure (p_{max}). This occurs at θ = 11.4 °C.

The relative humidity then equals ϕ = 100%.
The dew point temperature of air at 20 °C and ϕ = 58% is therefore θ_d = 11.4 °C.

The air is saturated with water vapour. If it cools down any further, to 5 °C for example, the redundant water vapour will start to condense. The relative humidity remains at ϕ = 100%. The vapour pressure in this case becomes 872 Pa. The maximum water vapour concentration equals c_{max} = 6.83 g/m^3.
A total of approximately 10 – 6.83 = 3.17 g/m^3 of vapour is therefore condensed.

Note: Bear in mind the changing of the concentration when the temperature changes, as described above.

Formulas for the density of air at different temperatures are provided in section 6.3 about stack effect (or chimney effect) and of course in a variety of reference books. In order to avoid the issue of concentrations changing with temperatures the air treatment technology works with the humidity level of air expressed in kg water vapour per kg of dry air.

Condensation

If the amount of vapour is greater than can be held by the air ($p > p_{max}$), then condensation will occur. Some of the water will then change from vapour (gas) into a liquid (water). This can happen if the air is cooled or if vapour is added to the air. The temperature at which air starts to condensate is known as the dew point temperature.

Even if water vapour is added to the air, as in the case of boiling water, at some point condensation can take place. See figure 2.5.

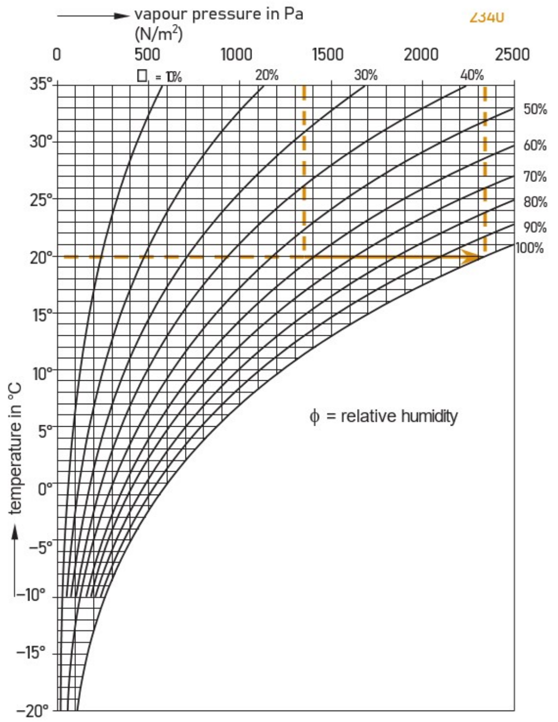


Figure 2.5 Addition of vapour also leads to condensation

> Example figure 2.5
> Initial situation (figure 2.2): Temperature equals $\theta = 20$ °C
> Maximum vapour pressure at 20 °C equals $p_{max} = 2340$ Pa
> Maximum water vapour concentration at 20 °C equals $c_{max} = 17.28$ g/m³
> Prevailing water vapour pressure equals $p = 1350$ Pa
> Prevailing water vapour concentration equals $c = 10$ g/m³
> Relative humidity $\phi = 58\%$
>
> If you supply moisture to air of 20 °C and $p = 1350$ Pa ($c = 10$ g/m³), the vapour pressure will change. If more than 7.28 g/m³ is supplied, condensation will take place (the maximum water vapour concentration at 20 °C is after all 17.28 g/m³ (see figure 2.1).

Condensation can occur on dust particles in the air. This causes mist, as in figure 2.6. Condensation moisture will also form on surfaces whose temperature is lower than the dew point temperature of the air (see figure 2.7).

Figure 2.6 If the temperature of the air suddenly drops to below the dew point temperature, the vapour in the air will condense, causing mist to occur.

Figure 2.7 If the temperature of the window is lower than the dew point temperature of the air on the inside, then condensation will occur.

2.2 Relative humidity in buildings

Moisture in enclosed spaces

Because of the production of vapour through human activity, the absolute humidity indoors (c in kg/m³) is almost always greater than outdoors. The situation regarding relative humidity is different. In the winter, the relative humidity where the outside air temperature is –10 °C, is an average of ϕ = around 80%. What will happen if the air at –10 °C and ϕ = 80% comes in and is heated to 20 °C?

At –10 °C, the maximum vapour pressure is p_{max} = 260 Pa. The prevailing vapour pressure at ϕ = 80% is therefore:

$$p = 0.8 \cdot 260 = 208 \text{ [Pa]}$$

This vapour pressure does not change when the air is heated up. As long as the total pressure of the mixture does not change, the partial pressures of the General Gas Law and Dalton's Law remain the same. What does change is the maximum vapour pressure. At 20 °C, this is: p_{max} = 2340 Pa. This means that the relative humidity of the air is now (see also the table in figure 2.1 and figure 2.8):

$$\phi = \frac{208}{2340} \cdot 100\% = 9\%$$

However, ϕ will never be this low indoors, as there is always a certain level of vapour production.

Conversely, the relative humidity indoors in the summer (for example in a cellar) can be markedly higher than outside. Suppose the outdoor conditions are 28 °C, ϕ = 50%, p_e = 1891 Pa. Because of the sturdy walls and floor (see section 1.4), the air temperature in the cellar may be only 20 °C. Here, p_{max} = 2340 Pa, so that the relative humidity in the cellar, when ventilated with outside air, will be:

$$\phi = \frac{1891}{2340} \cdot 100\% = 81\%$$

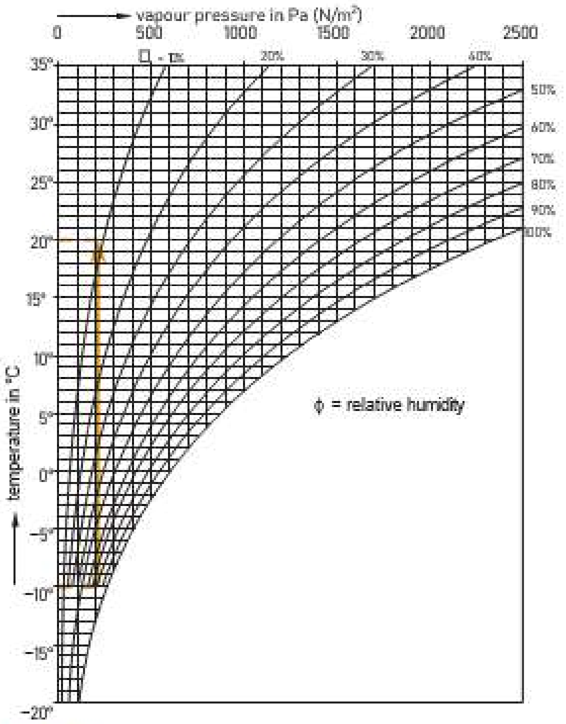


Figure 2.8 Outside air contains little vapour in the winter. This leads to a low level of relative humidity.

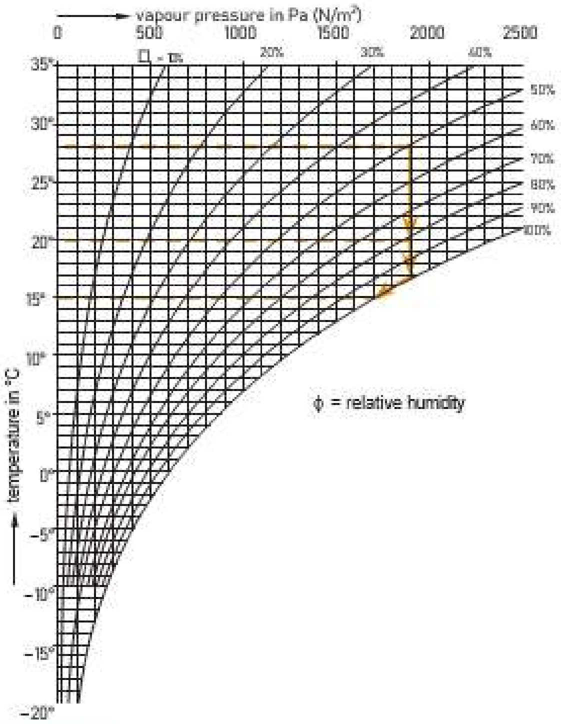


Figure 2.9 Outside air in the summer contains a lot of vapour. This can cause the relative humidity of a cool cellar to be high, which can lead to condensation.

Because of the mass of walls and floors and possibly also the 'cold' ground water touching the walls and floors, the surface temperature of the walls and floor can be even lower, for example 15 °C. Here, p_{max} = 1706 Pa. This means that condensation will occur on the walls – one reason to make sure that they too are properly insulated. Ventilation can actually cause cellars to become damper during the summer, not dryer (see figure 2.9).

Influence of ventilation on relative humidity

The influence of ventilation on the increase and the vapour density of the indoor air, and thereby on the relative humidity, can be calculated as follows:

$$\Delta c = \frac{P}{n \cdot V} \text{ [g/m}^3\text{]}$$

The meaning of the symbols is:

- Δc the increase of the vapour density in the indoor air in g/m³
- P the vapour production in g/h
- n the ventilation rate in h^{-1}
- V the volume of the space in m³

The term $n \cdot V$ stands for the amount of air with which the space is ventilated: the amount of ventilation that enters and leaves per hour. The factor n is the number of times that the air is refreshed per hour (the ventilation rate), and V is the volume of the space. We can illustrate this, using the example of a house or office and a school classroom.

Example house or office

When working without exerting themselves, people produce around 70 grammes of vapour an hour. This, of course, varies strongly depending on the person and activity. For the moisture balance to be stable, 70 g/h of water vapour will have to be disposed. Per person approx. 30 m³/h ventilation air is supplied and exhausted. This means that for every m³ of ventilation air, the amount of vapour being removed is:

$$\Delta c = \frac{P}{n \cdot V} = \frac{70}{30} = 2.3 \text{ [g/m}^3\text{]}$$

The absolute level of vapour in the air being removed (that is, the air in the relevant space) should therefore be 2.3 g/m³ greater than that of the air being supplied. Assuming a winter situation, with an outside air temperature of –10 °C, ϕ = 80%, p = 208 Pa and an indoor air temperature of 20 °C, you can use the formula in section 2.1 to calculate that this will lead to the following increase in vapour pressure:

$$\Delta p = \Delta c \cdot R \cdot T = \frac{2.3}{1000} \cdot 462 \cdot 293 = 311 \text{ Pa}$$

This causes the indoor vapour pressure to rise to:

$$p_i = p + \Delta p = 208 + 311 = 519 \text{ Pa}$$

Which leads to a relative humidity of:

$$\phi = \frac{519}{2340} \cdot 100\% = 22\%$$

It should be pointed out that this is still very low. Sometimes steps will therefore be taken (in office buildings for example) to humidify the air (up to ϕ = 35%) or to reclaim the moisture from the air. Where the outside temperature is a little higher (θ_e > 0 °C) however, the relative humidity will quickly rise to above 35% without any assistance.

Example classroom

A 150-m^3 school classroom is ventilated with outside air. The ventilation rate is 4 h^{-1}. That means that the air in the classroom is replaced four times every hour with fresh outside air. The total level of ventilation is:

$$n \cdot V = 150 \cdot 4 = 600 \text{ m}^3/\text{h}$$

If the 24-hour average outdoor temperature in the coldest months is θ_e = 2 to 3 °C, the moisture in the outdoor air will lead to an indoor vapour density of c = approx. 5 g/m³. For an inside air temperature of 20 °C, the relative humidity would be approximately 29%.

In the classroom there are 24 pupils and a teacher, who each give off around 70 grammes of vapour per hour. In total, then, about 1750 g/h (= 25 · 70 g/h) of vapour is released into the room.

On the basis of the starting points given in the example, this gives us:

$$\Delta c = \frac{1750}{4 \cdot 150} = 2.9 \text{ [g/m}^3\text{]}$$

Together with the increase, calculated above, in vapour concentration, the indoor concentration will be:

$$c_i = 5 + 2.9 = 7.9 \text{ g/m}^3$$

With the help of the formulas referred to previously, this can be used to work out that the relative humidity indoors will now be around 46%. If too little ventilation is provided, then the relative humidity will of course rise. The influence of the rate of ventilation on the relative humidity is given in figure 2.10.

Ventilating to a level that is greater than what people need in terms of hygienic fresh air is not necessary: this point is located in the flat part of the curve (figure 2.10); more ventilation does not produce any significant reduction in relative humidity levels. However, where ventilation is low, the relative humidity rises to an ever-increasing degree. No account is taken here of the fact at a given point condensation occurs on cold surfaces (windows), so that the absolute humidity in the room, and therefore the relative humidity, will rise less sharply.

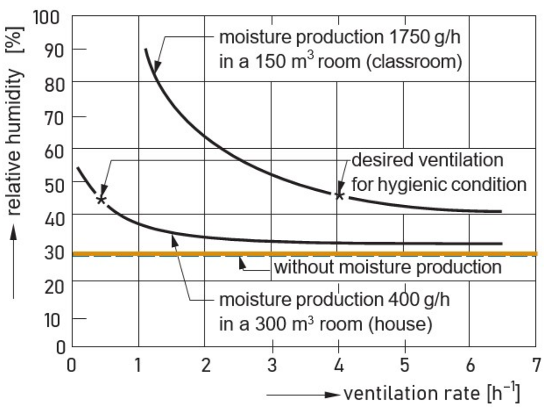


Figure 2.10 Relative humidity ϕ depending on the rate of ventilation in a room/space, temperature θ_i = 20 °C

Figure 2.10 also shows that no problems will arise in a house if there is no abnormal production of moisture (damp crawl spaces, damp walls, etc.), as long as the ventilation rate does not fall much below 0.5 h^{-1} (across the house as a whole). It will of course be necessary to provide more ventilation at peak hours (cooking) at the location where the moisture is being produced (in the kitchen). The presence of materials (plaster) that can temporary accumulate the moisture is very useful in such a situation (see below).

The removal of vapour through the outside walls (vapour diffusion) does not have any serious effect on the moisture balance. In average circumstances, only 0.1 g/(m²·h) disappears through a normal cavity wall. For a house with a large proportion of outside- facing walls (100 m²) this is in the order of 10 g/h, with an average moisture production of 400 g/h. The advice that cavities should not be insulated because the wall would be prevented from breathing is therefore irrelevant.

As well as moisture production, it is therefore ventilation and, by association, the moisture content of the outside air and the inside temperature that determine the relative humidity indoors. The moisture level of the in-flow air can be regulated in buildings with an air conditioning installation (humidifying in winter, dehumidifying in the summer), so that the relative humidity can also be kept under control. However, this does consume a good deal of energy.

Absorption of moisture and hygroscopic moisture content

Most materials contain a small amount of moisture, and this is quite natural. This is called hygroscopic moisture. The amount depends on the relative humidity of the air in which the material is located. We refer to the amount of moisture that is associated with the material, for a particular relative humidity, as the moisture content equilibrium. The moisture content in materials can be expressed in mass percentages or volume percentages. When calculating the mass percentage, we divide the mass of the amount of moisture present by the total mass and multiply the result by 100%. When calculating the volume percentage, the volume of the amount of moisture is divided by the total volume and multiplied by 100%. Both percentages are used. In figure 2.11 the moisture content is expressed in mass percentage and in figure 2.12 volume percentage is used.

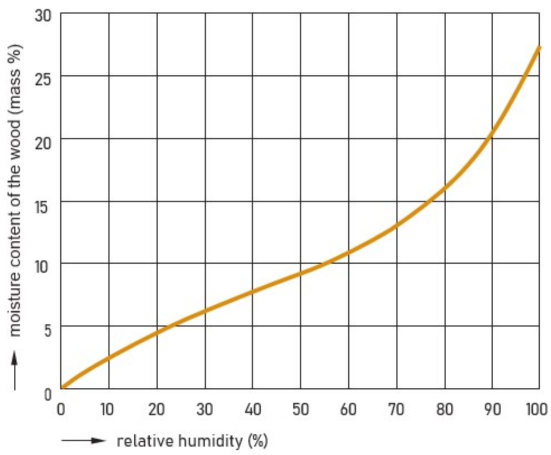


Figure 2.11 Hygroscopic moisture content of wood in relation to humidity

By absorbing and giving of moisture, wood expands or contracts respectively. This natural movement of wood should be duly taken into account when installing a floor for example. If the wood is laid too tightly, the wood will not be able to expand which will result in a bulging floor.

In figure 2.12, the hygroscopic moisture content of a number of materials is provided in volume percentage for various relative humidity levels. For brick, no values are listed, because brick is not hygroscopic. This means that the hygroscopic moisture content is insignificantly small. Insulation materials such as mineral wool and polystyrene are also not hygroscopic, so that the insulating characteristics of the material are guaranteed.

Materials	ϕ = 40%	ϕ = 65%	ϕ = 95%
Gravel concrete	2	3	7
Wood	6	10	18
Brickwork etc.	-	-	-
Sand-lime brick	2	4	10
Plaster coating	1	2	4
Wood-wool cement	1	3	6
Mineral wool	< 0.1	< 0.1	< 0.1
Polystyrene	0	0	< 0.2

Figure 2.12 Hygroscopic moisture content of various materials in percentage of volume

There are certain benefits to be had in, for example, kitchens with varying humidity levels, from the difference in the hygroscopic moisture content. As ϕ rises, the plaster on the walls will absorb more water vapour. When, at a later time, the relative humidity drops, the plaster will give of this moisture again to the inside air. This can be beneficial in kitchens and bathrooms.

Example

Suppose that the surface of a wall in a kitchen is 40 m², and that there is a plaster coating with a thickness of 5 mm that plays a role in the exchange of moisture. If ϕ increases from 40% to 65%, the hygroscopic moisture content of the plaster will rise by 1 volume percentage point. This means that the plaster can absorb 2 litres of water:

$$\frac{1}{100} \cdot 40 \cdot 0.005 = 0.002 \text{ m}^3$$

And that is precisely the amount of water that is released during cooking. This absorption and release of moisture has a stabilising effect on the humidity level. In a kitchen where there is plenty of plaster, as in the previous example, the relative humidity will not get anywhere near as high as in a space which is tiled. In the latter case, condensation is much more likely to occur on the windows (and sometimes the walls). If salt is present in the material, for example as a result of rising moisture, the hygroscopic moisture content may rise sharply.

Because joints and gaps are now more thoroughly sealed, and because ventilation installations have been improved and are used more selectively, average levels of ventilation and infiltration have decreased. As a result, indoor air humidity levels have risen. In some cases, where no effective ventilation installations are present, and where attempts at closing gaps have not been carried out properly, the lack of ventilation has caused humidity to increase so much that it has led to all kinds of surface condensation problems (for example on thermal bridges), and mould. See figure 2.10 about the influence of ventilation on relative humidity.

2.3 Surface condensation

Surface condensation was discussed in section 2.1. There are various reasons why surface condensation should be prevented:

- Damp patches encourage dirt.
- Damp patches can lead to mould, among other things.
- The part of the construction in question may crack during sharp frosts.
- Condensation on windows makes it difficult to look through them.

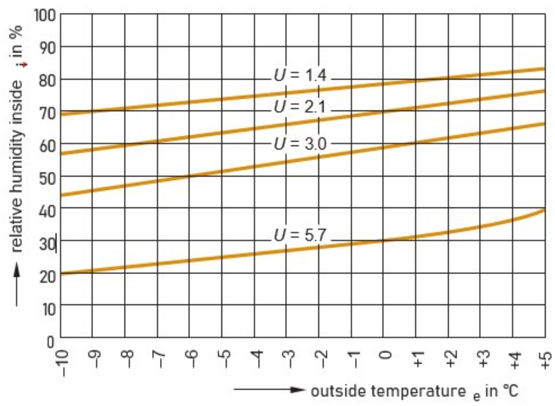


Figure 2.13 Outside temperature at which condensation can be expected for a given relative indoor humidity, for various types of glass (θ_i = 20 °C)

Although it is by no means ideal, surface condensation can occasionally be permitted on windows and aluminium frames. One reason for this is that in houses and offices without any air humidification, the levels of air humidity in the winter are so low that condensation only occurs when the outside temperature is very low. Moreover, glass and aluminium are not affected by moisture. More care needs to be taken with wooden frames, however. It goes without saying that steps should be taken to ensure that moisture from condensation can be effectively removed without damage being caused to other parts of the construction. Condensation on the windows also serves as a warning that ventilation levels are insufficient. This is the reason why in renovation projects, some small higher level windows sometimes have just a single pane of glass. In buildings with air humidification, the level of air humidification may need to be reduced when outside temperatures are low. Figure 2.13 shows, for various types of glass, what level of condensation might be expected with what level of relative humidity with an indoor temperature of 20 °C, depending on the outside temperature.

Cold glass surfaces not only lead to condensation, but can also cause problems that affect the comfort of users. With surfaces that are too big and temperatures that are low, a radiator will be needed to provide radiative heat compensation (see section 1.1).

Surface temperature and mould problems

Low surface temperatures can cause mould problems for dense construction elements, while wood can also be affected by fungus. In fact, surface condensation is not actually a prerequisite for this, as long as moisture levels in the subsoil are high enough (hygroscopic moist). In addition, mould can also actively absorb water from the air. Mould is not only an aesthetic problem (black marks on the walls); there is also a health issue. Their spores can cause allergic reactions. Around one million people in the Netherlands have a form of asthma or a chronic non- specific respiratory disease; 10 to 20% of cases are caused by mould, which incidentally occurs in many more places than just walls and other building constructions. The relative humidity on the surface at which mould is able to develop depends on the type of mould. For some varieties, it has to be greater than ϕ = 90%, while there are others for which ϕ = 70% is sufficient. The relative humidity on the surface can be calculated by dividing the vapour pressure of the air by the maximum vapour pressure for the temperature of the wall surface. The surface temperature of a wall can be easily calculated with the formulas from section 1.3:

$$\Delta\ \theta_m = \frac{R_m}{R_T} \cdot (\theta_i - \theta_e)\ [°C]$$

For calculating the surface temperature this results in:

$$\theta_{si} = \theta - \frac{R_{si}}{R_T} \cdot (\theta_i - \theta_e)\ [°C]$$

The meaning of the symbols is:

θ_{si} the temperature of the inside surface in °C

R_{si} the transfer resistance on the inside surface in m²·K/W

R_T the heat resistance air on air of the construction in m²·K/W

θ_i the indoor temperature in °C

θ_e the outdoor temperature in °C

In the figure 2.14 graphs, the temperature of the inside surface can be read for various levels of heat resistance of the construction (R_c), where the inside temperature is 22 °C, and the outside temperature is 0 °C or −10 °C.

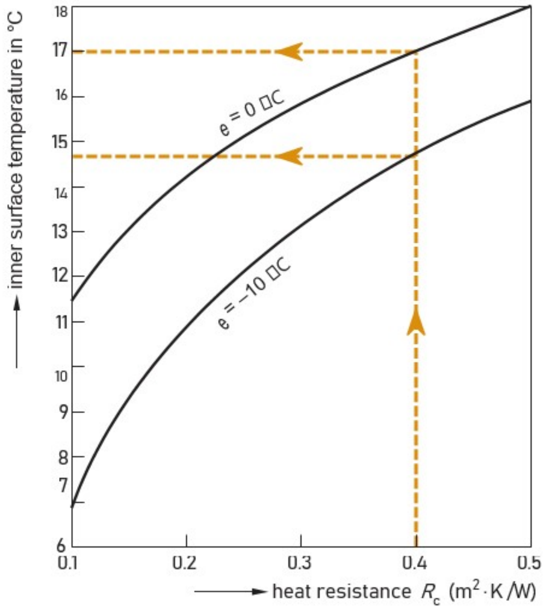


Figure 2.14 Determining the surface temperature of a construction (inside), where the outside temperature is θ_e = −10 °C or 0 °C, and the inside temperature is θ_i = 22 °C

Example

What is the temperature of the inside surface where the roof is made of 120-mm aerated concrete?

We will assume an indoor temperature of θ_i = 22 °C. The heat conduction coefficient of aerated concrete is λ = approx. 0.30 W/(m·K). If the effect of the roof covering is ignored, we arrive at the following heat resistance:

$$R_c = \frac{d}{\lambda} = \frac{0.12}{0.30} = 0.40\ \ m^2{\cdot}K/W$$

In figure 2.14 we then find a surface temperature of almost 15 °C when θ_e = −10 °C, because:

$$\theta_{io} = 22 - \frac{0.13}{0.4+0.17} \cdot 32 = 14.7\ °C$$

And when θ_e = 0 °C, the surface temperature is 17 °C:

$$\theta_{io} = 22 - \frac{0.13}{0.4+0.17} \cdot 22 = 17.0\ °C$$

The graph in figure 2.15 shows at what level of indoor air humidity condensation occurs for a particular surface temperature. Here, too, the indoor air temperature is assumed to be 22 °C.

For a roof of aerated concrete as in our example, it follows from figure 2.15 that with an outside temperature of −10 °C (the temperature of the inside of the roof is then almost 15 °C) and a relative humidity of 63% (= 1673/2645) or greater, condensation will occur on the inside surface. If the outside temperature is 0 °C (when the temperature of the inside of the roof is 17 °C), condensation will occur when the relative humidity is 73% (= 1938/2645) or greater.

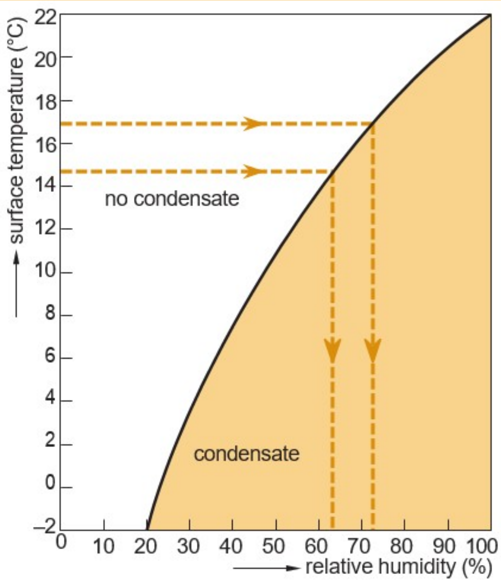


Figure 2.15 Determining the occurrence of condensation with an indoor air temperature of θ_i = 22 °C

Temperature factor

The Dutch Buildings Decree includes a range of requirements for the purpose of preventing surface condensation and mould, with the help of the so-called temperature factor. This is defined as follows:

$$f = \frac{\theta_{io} - \theta_e}{\theta_i - \theta_e}$$

The meaning of the symbols is:

f the temperature factor

θ_{io} the surface temperature of the inside of the construction

θ_i the inside temperature

θ_e the outside temperature

The temperature factor amounts to an indirect requirement of what the surface temperature of constructions should be. For homes, the temperature factor should be at least 0.65, and for offices 0.5. This means that when the outside temperature is 0 °C and the inside temperature is 20 °C; the temperature of the surface on the inside should not be less than 13 °C in homes and 10 °C in offices. This is easy to work out from the formula. Whether this always actually happens in practice is another matter. In reality, there is always a dynamic progression in temperature and humidity. Also the transfer resistance figures can vary with time. As it is difficult to represent this dynamic behaviour in a single calculation method, calculation models are used for making assessments of constructions, with fixed values for transfer resistance, and outdoor and indoor temperatures. For plane constructions the calculation can be carried out easily enough by hand. However, for thermal bridges – and that is what this problem is essentially about – computer models are needed.

When assessing a construction with the temperature factor, different surface resistances must be used than is usually the case with heat calculations. This is because the critical points in relation to the surface temperature are often the corners of a room where the convection is less than with a plane surface.

Roughly the following transfer resistances apply:

towards outside air:

R_{se} = 0.04 m²·K/W

towards inside air:

R_{si} = 0.13 m²·K/W for glazing between inside air and outside air;

R_{si} = 0.25 m²·K/W for all inside surfaces more than 1.5 m above floor level;

R_{si} = 0.50 m²·K/W for all inside surfaces lower than 1.5 m above floor level.

2.4 Vapour diffusion

Moisture transport through constructions

Moisture can be transported through a construction in different ways. If water is present in a construction it can run downwards, due to gravity (rainwater). A second type of transport takes place due to the influence of capillary forces. In narrow channels, water will move as a result of the attraction (adhesion) between the water and the walls of the channel. This occurs when ground moisture is absorbed, rising damp, but also in the case of transport in a horizontal direction (rain penetration). Differences in air pressure (wind pressure) can also cause water to be forced through porous constructions. A number of these transport mechanisms will be dealt with in Chapter 3. The last type of moisture transport is that of vapour (diffusion) through a construction, and is caused by a difference in vapour density on either side of the construction. This section deals with diffusion in greater detail.

Vapour diffusion resistance

The transport of vapour through a construction encounters a certain degree of resistance depending on the type and density of the material. Moisture flow, the difference in vapour pressure and vapour resistance are related as follows:

$g = \frac{\Delta p}{R_d} \cdot 1000$ [g//(m²·s)]

The meaning of the symbols is:

- g — the vapour transport in g/(m²·s)
- Δp — the difference in vapour pressure between the inside and outside ($\Delta p = (p_i - p_e)$ in P
- R_d — vapour diffusion resistance in m/s

The factor of 1000 is added in order to obtain a result in g/(m²·s) instead of in kg/(m²·s).

Diffusion resistance figure

The vapour density of various materials is expressed using the vapour diffusion resistance figure (μ). This indicates how many times greater the diffusion resistance is of a layer of material than of a layer of air of the same thickness. As a formula, the definition is as follows:

$$\mu = \frac{\text{vapour diffusion resistance of a layer of material}}{\text{ditto, for a layer of air of identical thickness}}$$

Vapour diffusion resistance of a layer

In discussions on the vapour diffusion resistance of a layer of material, it is not just the μ value that is important, but also the thickness of the material itself. The thicker the layer, the greater the resistance. However, as the μ value does not give an absolute value for the characteristics of the material, but is just a figure as it relates to a layer of air of the same thickness, it should as it were be multiplied by the diffusion resistance of air.

For normal building circumstances, the following calculation can be used:

$$R_d = 5.3 \cdot 10^9 \cdot \mu \cdot d \text{ [m/s]}$$

The meaning of the symbols is:

- R_d — the vapour diffusion resistance of the layer of material in m/s
- μ — the diffusion resistance figure
- d — the thickness of the layer of material in m

The product $\mu \cdot$ d is also referred to as the relative vapour resistance. This $\mu \cdot$ d value is sufficient for comparing levels of vapour resistance.

Vapour diffusion resistance of a construction

The table in figure 2.16 shows the ? value of several materials and the usual thickness (d) in which they are applied and the resulting product $\mu \cdot$ d (the so-called $\mu \cdot$ d value).

Material	μ	d [m]	$\mu \cdot$ d [m]
Mineral wool	2	0.05	0.1
Brickwork (red)	9	0.11	1.0
Concrete	100	0.15	15.0
Roofing material	10.000	0.002	20.0
Polyethylene foil	34.000	0.0003	10.2
Aluminium foil	100.000	0.0002	20.0

Figure 2.16 Vapour diffusion resistance of a number of materials

The total vapour diffusion resistance of a layered construction can be found by adding up the resistances of the individual layers:

$$(\mu \cdot \text{d})_{tot} = \mu_1 \cdot d_1 + \mu_2 \cdot d_2 + \mu_3 \cdot d_3 + \ldots \text{ [m]}$$

In fact, the vapour diffusion resistances (air on construction, and construction on air) should be added to this. However, with regard to the resistance of the construction, they are negligible.

Vapour pressure profile in a construction

The profile of the vapour pressure in a construction can be calculated or determined from a graph in the same way as the temperature profile in a construction. The total amount of vapour that diffuses through the construction (if there is no interstitial condensation) is determined by the formula shown above. The flow of vapour is of course the same in every layer of the construction. As a formula, this is expressed as follows:

$$g = \frac{\Delta p}{5.3 \cdot 10^9 \cdot (\mu \cdot d)_{tot}} = \frac{\Delta p_n}{5.3 \cdot 10^9 \cdot (\mu_n \cdot d_n)}$$

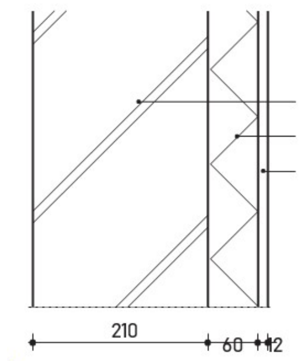
The meaning of the symbols is as follows:

g the vapour flow in kg/(m²·s)
Δp the difference in vapour pressure throughout the construction ($p_i - p_e$)
$(\mu \cdot d)_{tot}$ the sum of the $\mu \cdot$ d values for every layer of the construction
$\mu_n \cdot d_n$ the diffusion resistance of the n'th layer
Δp_n the difference in vapour pressure over the n'th layer

To calculate the vapour pressure difference across the layer in question, the formula becomes:

$$\Delta p_n = \Delta p \cdot \frac{\mu_n \cdot d_n}{(\mu \cdot d)_{tot}}$$

It can clearly be seen here that the $5.3 \cdot 10^9$ value is omitted and that we can only use the $\mu \cdot$ d values, as this concerns the relationship between the levels of vapour resistance of the different layers. Figure 2.17 gives an example of the calculation of the progression of the vapour density in a construction.



Construction layer	d [m]	μ	$\mu_n \cdot d_n$ [m]	Δp_n	p_n [Pa]
Outside air					208
R_{se}	–	–	–	–	208
Brickwork	0.210	13.5	2.84	232	440
Insulation material	0.06	100	6.00	490	930
Gypsum cardboard	0.012	6	0.07	6	936
R_{si}	–	–	–	–	
Inside air					936
					Δp = 728
		$(\mu \cdot d)_{tot}$ = 8.91			

Figure 2.17 Calculation of the progression of vapour density in a construction ($\Delta p = p_i - p_e$ = 936 – 208 = 728 Pa)

As is the case with the temperature profile in a construction, the vapour pressure in a construction can also be determined from a graph (see figure 2.18). The $\mu \cdot$ d value of the various layers is shown on the horizontal axis, and the vapour pressure on the vertical axis. The progression will then be a straight line between the inside vapour pressure (p_i) and the outside vapour pressure (p_e). The vapour pressure at any random location (p) in the construction can now be read.

The calculation of the vapour pressure profile can of course also be shown on the scale drawing of the wall construction, as in figure 2.19.

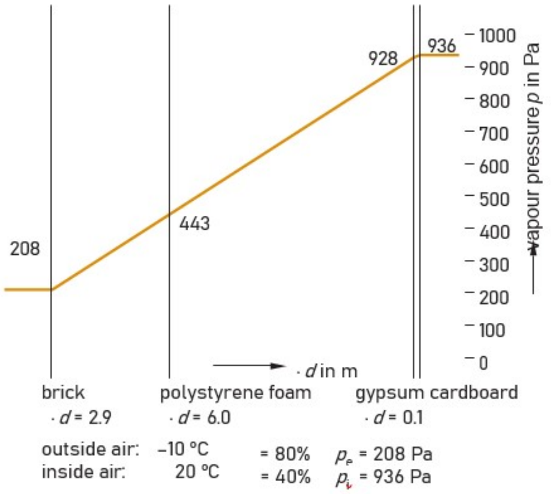


Figure 2.18 Graphic calculation of progression of vapour concentration in a wall construction

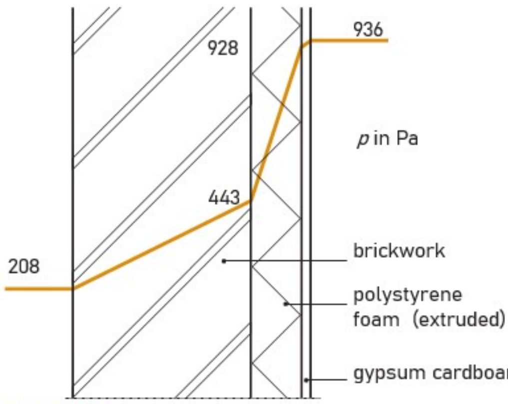


Figure 2.19 Progression of the vapour density in a wall construction

2.5 Interstitial condensation

So far we have looked at the vapour pressure profile in a construction without considering the temperature profile and the possibility that condensation may occur. In what follows, we will also look at the temperature profile in the construction.

The maximum vapour pressure profile in the construction (p_{max}) can be determined from the temperature profile – after all, there is a maximum level of vapour pressure for every temperature. In reality, the vapour pressure can never exceed the maximum vapour pressure. If the calculated values are higher, then condensation will occur in the construction. Interstitial condensation should be prevented or limited because:

- the construction may start to rot;
- there is a chance of damage caused by freezing;
- too much moisture reduces heat resistance.

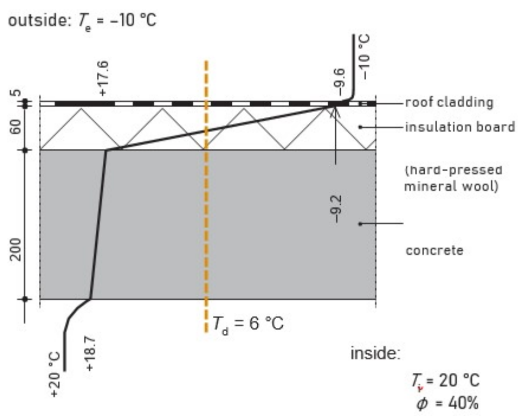


Figure 2.20 Determining the location of the dew point in a construction

An initial and simple way of checking is to find out where the dew point of the indoor air is located in the construction – an insulated concrete roof, for example. The inside air temperature and the relative humidity in figure 2.20 are 20 °C and 40% respectively. Condensation will occur at a dew point temperature of 6 °C (2340 · 0.40 = 936 Pa). If the 6 °C line is shown in the construction, we can see that the dew point is located in the layer of insulation. No vapour will condense before that point.

Condensation will therefore occur towards the underside of the roof cladding. If no or only very little moisture can reach that part of the construction, then that is fine. This is the case with a 100% damp-proof insulation material such as foam glass. With other insulation materials, a vapour-retardant layer under the insulation is generally necessary. For that reason, vapour-retardant layers are added to many insulation materials at the point of manufacture. Often, the concrete layer can be considered sufficiently vapour retardant. It all depends on the prevailing climate conditions inside the building. If it appears from calculations that the dew point is under the insulation layer or the vapour-retardant layer, then a thicker layer of insulation should be used.

Glaser Method

The following steps are necessary to determine whether condensation will occur in a construction and what the actual profile of the vapour pressure will be:

1. Determine the temperature profile in the construction.
2. Determine the maximum vapour pressure for the temperature given (see figure 2.2 or the vapour pressure table in the book of tables).
3. Determine the vapour pressure p_{calc} that has been calculated.
4. Calculate the amount of condensation.

As an example we first elaborate steps 1 to 3.

Example

We will calculate figure 2.20 as an example. The following vapour pressures are important:

- θ_i = 20 °C: ϕ_i = 40%, so that p_i = 0.4 · 2340 = 936 Pa;
- θ_e = –10 °C: ϕ_e = 80%, so that p_e = 0.8 · 260 = 208 Pa.

The table in figure 2.21 shows the calculations for the whole construction. All relevant details relating to the temperature profile and the vapour pressure should be entered into the table.

Using column p_{max} and column p_{calc}, it is possible to see whether interstitial condensation will occur. If $p_{calc} > p_{max}$, it will. From the calculation it appears that the vapour pressure (p_{calc}) at the dividing line between the insulation and the roof covering is greater than the maximum vapour pressure (p_{max}).

Condensation will therefore occur. $\theta_{condens}$ = –9.2 °C, so $p_{condens}$ = 276 Pa. These calculations will make it possible at a later stage to determine the amount of condensation moisture that will remain in the construction.

It is also possible to determine graphically whether interstitial condensation will occur in the roof construction. As in figure 2.18, plot the $\mu \cdot d$ values of the various layers as done in figure 2.22.

With an outside air temperature of –10 °C and a relative humidity of ϕ = 80%, p_e = 0.80 · 260 = 208 Pa (see figure 2.2 and the table in figure 2.1). When the indoor air temperature is 20 °C and ϕ = 40%, p_i = 0.40 · 2340 = 936 Pa.

By plotting these values in the chart, the vapour pressures in the various layers of the construction can be determined graphically. The maximum vapour pressures determined from the temperature profile are then entered onto the chart. It appears that the calculated vapour pressure exceeds the maximum vapour pressure. This should not happen – condensation will occur. It is also simple to work out

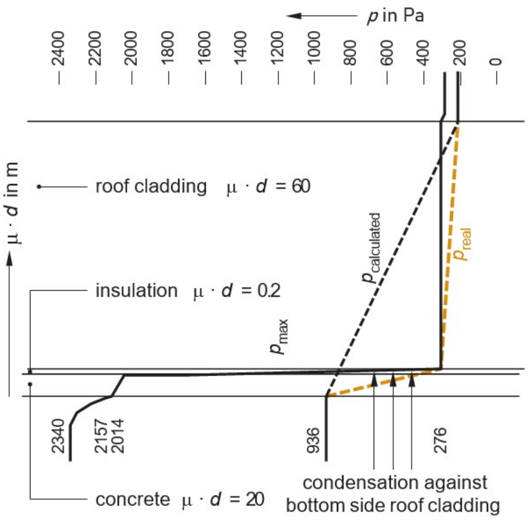


Figure 2.22 Determining the interstitial condensation in a roof construction, using a graph.

Construction layer	d [m]	λ [W/(m·K)]	R [m²·K/W]	$\Delta\theta$ [°C]	θ [°C]	p_{max} [Pa]	μ	$\mu \cdot d$ [m]	Δp_n [Pa]	p_{calc} [Pa]
Outside air					-10	260				208
R_{se}			0.04	0.4	-9.6	269	-	-	-	208
Roof cladding	0.006	0.2	0.03	0.3	-9.2	276	10.000	60	545	753
Insulation	0.08	0.03	2.67	26.9	17.6	2014	2	0.2	2	755
Concrete	0.2	1.9	0.11	1.1	18.7	2157	100	20	181	936
R_{si}			0.13	1.3			-	-	-	
Inside air					20	2340				936
Total			2.98	30				80.2	728	

Figure 2.21 Calculation of a construction in terms of physical parameters

where the condensation will occur using a graph: from the indoor and outdoor vapour pressure values, draw a tangent to the p_{max} line. Condensation will occur at the point of contact. In this example, the condensation will begin at the dividing line between the insulation and the roof cladding.

Figure 2.23 is a scale reproduction of the whole construction.

To evaluate the quality of the construction with regard to moisture, the Glaser Method continues with calculating the amount of penetrating moisture.

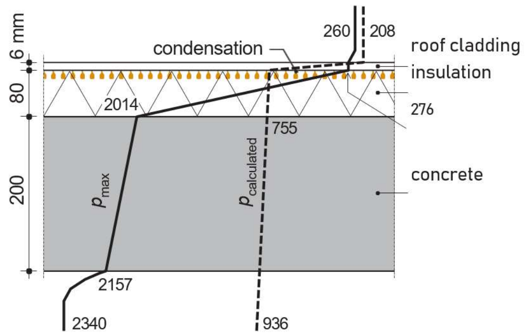


Figure 2.23 Interstitial condensation in a roof construction

Amount of condensation

Using the above information, it can be calculated how much condensation will remain in a construction during a winter period. For the winter Glaser takes a period of 60 days (that is, 60 ? 24 ? 3600 seconds) with an outside air temperature of –10 °C. The amount of condensation can be found by subtracting the incoming and outgoing flow of moisture from each other. The outgoing moisture flow is obviously so slight as to be negligible, as it would need to take place through the roof covering which is particularly vapour-proof. The amount of condensation remaining in the winter period can be calculated with the following formula:

$$g = 60 \cdot 24 \cdot 3600 \cdot \left(\frac{\Delta p_{in}}{R_d \cdot \sum \mu \cdot d_{in}} - \frac{\Delta p_{out}}{R_d \cdot \sum \mu \cdot d_{out}}\right) \cdot 1000 \text{ [g/m}^2\text{]}$$

The factor 1000 is added for the purpose of converting from kilograms to grams.

In our example, the incoming moisture flow is:

$$\frac{(936 - 276) \cdot 1000}{5.3 \cdot 10^{-6} \cdot (20 + 0.2)} = 6.2 \cdot 10^{-6} \text{ g/(m}^2\text{·s)}$$

And the outgoing moisture flow is:

$$\frac{(276 - 208) \cdot 1000}{5.3 \cdot 10^{-6} \cdot 60} = 0.2 \cdot 10^{-6} \text{ g/(m}^2\text{·s)}$$

So $g = 60 \cdot 24 \cdot 3600 \cdot (6.2 \cdot 10^{-6} \cdot 0.2 \cdot 10^{-6}) = 31.1$ g/m² for a period of 60 days

As has already been mentioned, it is not necessary to prevent every type of indoor condensation. However, the amount of moisture remaining in the construction as a result of indoor condensation during the winter period should not exceed a certain maximum. Also, moisture that enters during the winter must be allowed to disappear in the summer. The amount of moisture that can be present in a roof at the end of the winter period is generally 0.5 kg/m². In the case of wood or materials that contain wood, such as chipboard or plywood, it is 0.1 to 0.2 kg/m². For further details, see the table in figure 2.24. If the amount of condensation is greater than the level stated in the guidelines, the construction should either be modified, or extra vapour- retardant layers should be applied.

Material	Maximum amount [g/m²]
stony, frost-resistant with a vapour-retardant layer on the exterior (e.g. glazed tiles)	$50 \cdot \psi_c \cdot d$
stony, not frost-resistant	$300 \cdot \psi_c \cdot d$
organic materials	$30 \cdot \psi_c \cdot d$
organic materials, not frost-resistant bonded	50
non-moisture absorbent materials with possibility of leaking inside	100
insulation materials	500

The meaning of the symbols is:

ψ_c = critical moisture content [vol.%] ρ_m = similar density [kg/m³]

ψ_o = porosity [vol.%] ρ_m = similar density [kg/m³]

Figure 2.24 Guidelines for maximum permissible amounts of condensation when using certain materials

The amount of interstitial condensation in the insulation of a concrete roof, as seen in the above example, should therefore be less than 500 g/m² per winter. That is the case here because the insulation layer can store this amount without damage. If the roof is not made out of concrete, but of a layer of wooden beams with roof sheeting, the situation is markedly different. The vapour resistance of the wooden roof sheeting is at least 15-25 times less than that of 200 mm of concrete, while the heat resistance is more or less the same.

That means that during the winter around 1000 g/m² of moisture would come in through the roof, which is too much. A construction of this kind would need a vapour-retardant layer between the roof sheeting and the layer of insulation with a $\mu \cdot d$ value of around 5 m. Some 100 g/m² moisture would then enter during each winter. The calculations are made for conditions that are more severe than the normal Dutch winter, but this ensures a degree of safety. It also means that detrimental effects on the amount of condensation, such as those resulting from night radiation, are overcome. In cases of doubt, more accurate calculations can be made by using the average monthly temperatures (see book of tables, table 1) and perhaps by including the positive effect of solar radiation. The outcomes of the calculations in the instances that have been examined here are so clear that any further calculations would be pointless.

It should be noted that the relative values of calculations of this type should not be forgotten. This is especially true of the conditions that have been selected (inside and outside): to what degree do they actually correspond to reality? The same could be asked of the material characteristics taken from the tables.

2.6 Climate categories and condensation

To simplify the basis on which calculations are made, a number of climate categories have been defined. The starting points here are the activities taking place in the room or space in question and the type of installations fitted in the building. The table in figure 2.25 has an overview of the different climate categories.

Requirements can be imposed for different constructions, depending on the climate category, in relation to the value of the vapour-retardant layer, and in the case of ventilated constructions, to the size of the ventilation openings. It is also a requirement that any moisture that penetrates constructions in winter should be removed or have disappeared in the summer – this applies to climate categories I, II and III, for which standard Dutch climatic conditions are assumed. In the case of climate category IV, a year-on-year accumulation of moisture will take place, with all the consequences that that entails. Here it is necessary to apply layers that are so vapour retardant, that the permitted amounts of indoor condensation are not exceeded for 20 to 50 years. Formulas have been devised, in which all the constants and characteristics of indoor and outdoor climate have been included, for the purpose of testing constructions.

Climate category	Production of moisture	Type of building or construction	Vapour pressure p_i [Pa]	Average temperature	Average relative humidity
I	Buildings with little or no moisture production	areas for storing dry goods, garages, barns, churches, moderately used sport halls and gymnasia	$1030 \leq p_i < 1080$	18 °C	50 – 52%
II	Buildings with limited moisture production and good ventilation	offices, shops (without air humidification in the winter)	$1080 \leq p_i < 1320$	20 °C	46 – 56%
III	Intensely used buildings and spaces with moderate vapour production	houses, schools, homes for the elderly, nursing homes, buildings used for leisure purposes and buildings with a low level of air humidification	$1320 \leq p_i < 1430$	22 °C	50 – 54%
IV	Buildings with high vapour production or air humidification	humid industrial spaces, launderettes, swimming pools, bathing facilities, dairy factories, printing works, textile factories	$p_i \leq 1430$	24 °C	> 48%

Figure 2.25 Climate categories

For the different climate categories, the amount of condensing moisture in the winter can be calculated using the following formulas:

- for climate category I: g = $\frac{100}{\sum \mu \cdot d}$ [g/m²]
- for climate category II: g = $\frac{600}{\sum \mu \cdot d}$ [g/m²]
- for climate category III: g = $\frac{1000}{\sum \mu \cdot d}$ [g/m²]

The meaning of the symbols is:

g the amount of condensing moisture during the winter in g/m²

$\sum \mu \cdot d$ the sum of the $\mu \cdot d$ values from the interior surface to the location where the condensation is occurring

For a roof, then, it is generally the $\sum \mu \cdot d$ of the roof, without the roof covering. The formulas have in principle been devised for roof constructions. As a rule, condensation occurs against the underside of the roof cladding. A precondition for using the formulas is therefore that the location where the condensation occurs should not be too far away from the outside surface, at least as far as heat resistance is concerned. As has already been mentioned, it can be assumed that in the climate of the Netherlands that any condensation that has accumulated in winter will evaporate in summer. This means that for climate categories I, II and III, a simple test using the formulas on the above maximum permissible amounts of condensation is sufficient.

In the case of climate category IV, a year-by- year increase in the roof moisture content should be assumed. It would be better to look for a construction in which no condensation occurs at all in such circumstances, otherwise it will be necessary to apply vapour-retardant layers in such a way as to ensure that at the end of the projected lifetime of the construction, the amount of moisture is still below the maximum permitted level.

2.7 Position of insulation and vapour-retardant layers

The position of the vapour-retardant layer is very important. As an example, we shall look at a homogeneous construction with a given heat resistance, as in figure 2.26. In the original version (figure 2.26-1), there is no chance of condensation occurring on the inside. The actual vapour pressure profile remains below the maximum vapour pressure at every location.

If the exterior is made vapour retardant (figure 2.26-2), then the following picture arises. The p_{max} profile remains the same, as the temperature profile does not change. What does change is the $p_{calculated}$. Now, interstitial condensation will occur just behind the vapour-retardant layer. By placing a vapour-retardant layer on the inside (figure 2.26-3) there is no problem. The maximum vapour pressure is always greater than the vapour pressure that has been calculated. From the example it appears that a vapour-retardant layer should always be applied on the warm side of the construction.

Using the same example, we now look at the location for a layer of insulation (see figure 2.27). The vapour diffusion resistance of the insulation is negligible when compared to the rest of the construction. Applying the insulation layer changes the temperature profile in the construction and therefore the maximum vapour pressure profile.

Where there is insulation on the interior, it appears that the calculated level of vapour pressure is greater than the maximum, particularly on the dividing line between the insulation and stone (figure 2.27-1). This results in interstitial condensation, which problem can be resolved with a good vapour- retardant layer on the inside (figure 2.27-2). Applying insulation on the outside of the wall will also prevent interstitial condensation (figure 2.27-3) providing the roofing material is not vapour retardant (as in figure 2.23).

The examples in figures 2.26 and 2.27 show that warm side (the interior) of a construction is the proper location for a vapour-retardant layer. The insulation layer should preferably be placed on the exterior. This also has benefits because of heat accumulation (section 1.4) and the occurrence of thermal stress (see section 1.6).

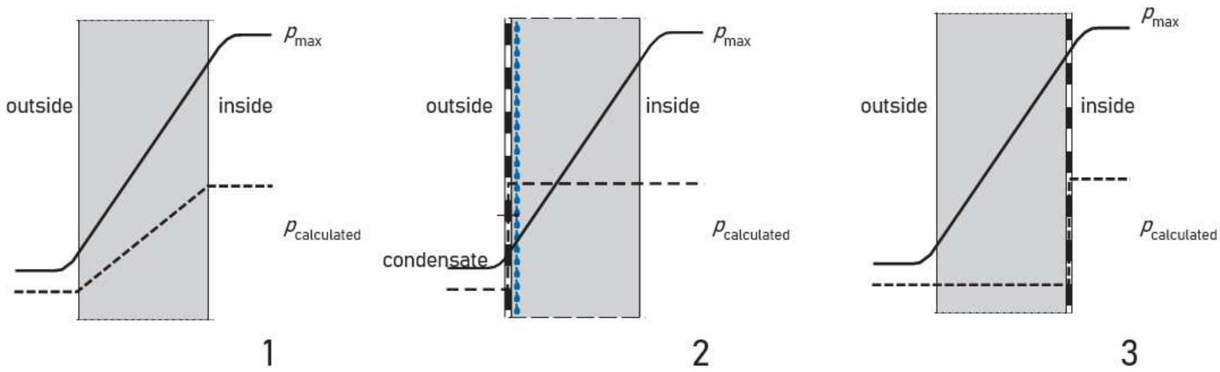


Figure 2.26 Influence of location of vapour-retardant layer on interstitial condensation

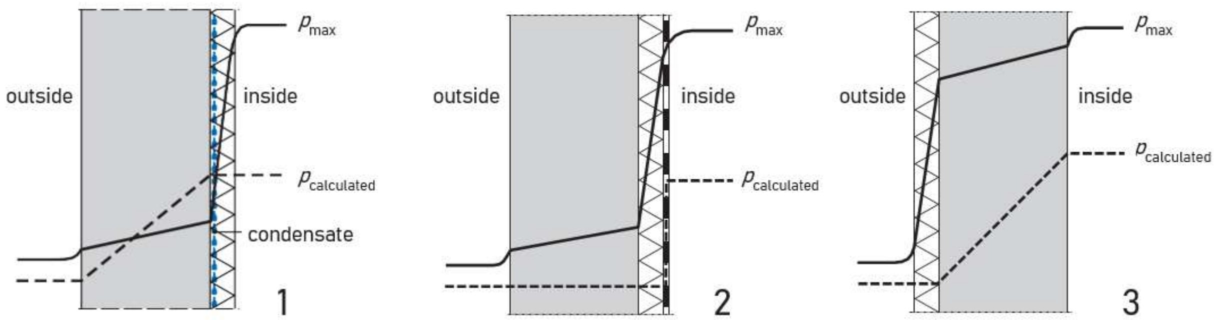


Figure 2.27 Influence of the position of the insulation on interstitial condensation

Placing a vapour-retardant layer on the inside imposes great demands on the design and use of the construction. The vapour-retardant layer has to be continuous, without any breaks. Joints and gaps should be properly covered and openings and ducts and so on should in principle be avoided. It should also be remembered that when the construction is being used, nothing should be hung on the walls if the vapour-retardant layer has been placed on the inside, as this may impair it.

In the case of roof construction, the roof covering usually forms a watertight layer, but which is actually on the wrong side (comparable with figure 2.26-2). Attempts are made at compensating this by applying a vapour-retardant layer under the insulation, such as foil between the roof sheeting and the insulation layer, or a vapour-retardant base, such as concrete. This does not prevent interstitial condensation, but at least limits the amount of vapour that condenses.

2.8 Other forms of moisture transport

Until now, we have focused primarily on the consequences of vapour diffusion through the construction. However, there are other types of moisture: building moisture, domestic moisture, rain, ground moisture. The terms relate to the origin of the moisture.

Building moisture

This is defined by moisture (water) that remains in the construction after the building work has been completed. Examples include roof insulation sheets that got wet, but also any concrete. Of the water that is present in concrete mortar, only a small proportion is needed for the chemical hardening process.

The rest is actually added to make the mortar easier to apply. For that reason, the percentage volume of moisture in concrete is around 15 to 20. In a 150-mm slab, this represents about 30 litres of water per square metre. The building moisture present in the construction will, over time, be gradually drained. This leads to higher than average levels of relative humidity in the house, and the chance of surface condensation and the formation of mould is therefore also greater. This aspect should be carefully borne in mind when moving into a house that has only recently been built. It is important to heat and ventilate it properly during the first few months.

Domestic moisture

Domestic moisture refers to the production of vapour caused by the activities in a house and the vapour given off by people. To illustrate this, here is the vapour production of an average family:

- cooking: 2 kg each time
- washing up: 0.5 kg each time
- taking a bath/shower: 0.5 kg each time
- plants: 1 to 2 kg every 24 hours
- 4 people: 5 kg every 24 hours
- In total, this is around 10 kg of vapour every 24 hours.

Rain

Water that enters walls as rainfall has to be able to evaporate from them. Nor should any damp patches be allowed to occur. A feature of the pattern followed by areas of damp is the decrease in moisture levels the further they enter the construction to the inside.

With brick walls it is often the case that it is not so much the bricks itself that are the cause of rain entering the building, but the joints. It appears in practice that the joints are seldom filled properly – this applies particularly to the head joints. The joint filler that is applied retrospectively is not watertight, which means damp patches are inevitable. If the wall in question is a half-brick or one-brick wall, this could lead to considerable problems. In the case of a cavity wall, any water that has entered will be able to run down the inside face of the outer wall and drain off through the open head joints. For this to happen, though, the construction of the cavity will have to have been ‘clean’: that is, there should be no moisture bridges as a result of excess mortar or any other leftover materials. In reality, it seems that damp patches resulting from this kind of contamination occur less frequently due to the increasingly common practice of entirely filling cavities.

Ground moisture, rising damp

Capillary forces play a role with this type of moisture: tiny channels draw the water upwards through the buildings through adhesion (attraction between water and the channel walls). This is the reason that the lower part of the wall is often built with a harder type of stone (clinkers), a so-called damp-proof course. In older buildings, this is not always present. If the foundations are located beneath the ground water level, or if there is any open water present, the moisture can be sucked upwards through the capillaries in the material to way above the ‘moisture level’. A feature of the pattern followed by rising damp is the increase in moisture content towards the middle of the construction. The height reached by rising damp is determined by the degree to which the moisture can evaporate in and outwards. In practice, rising damp problems are often cured by the application of a water and vapour- retardant layer on the inside of the construction. However, this is counterproductive. The moisture cannot evaporate as easily, so the rising damp moves higher. The result is often that the damp patches appear above the water and vapour-retardant layer.

A symptom of rising damp is that salts may be drawn out of the ground, and find their way into the capillaries. The moisture will evaporate, but the salts will remain behind in the construction. Salts are hygroscopic, which means they attract moisture, and this can result in permanent damp patches being visible on the wall. The presence and crystallisation of salt can also cause plasterwork to fall from the wall. Rising damp can be prevented by using a water-repellent layer. This can be done by adding foil or lead flashing to a horizontal joint across the full breadth of the joint above the moisture level. The foil or lead flashing repels the water and the capillary effect is disrupted. This is a fairly expensive solution. Another option is to inject the stone above the moisture level. A layer of sealant is introduced into the pores of the stone and this, too, serves to rupture the capillary function of the brickwork. In addition to combating rising damp, attention should also be paid to the salts remaining behind in the plasterwork. This will have to be removed and replaced by a salt-resistant finishing layer that can breathe.

3 Heat and moisture transport in practice

A.C. van der Linden; A. Zeegers

Using descriptions of prototypes of constructions and practical examples, this chapter gives an overview of the most important aspects of heat and moisture transport in various real-life constructions.

Chapter 1 dealt with the heat transport through constructions including thermal bridges and addressed the heat accumulating quality of the construction. Chapter 2 described the relationship between heat transport and moisture transport. With this knowledge you should be able to make a basic design. While making the design, you will notice that particularly at the site of connections, conflicts often arise between what is necessary for on the one hand the construction (e.g. connection details, suspensions) and on the other the building physics aspects. For new houses still to be built, you can often easily adjust the details on the drawing table, but once the building is erected you have to try to create the best result with what exists in practice. The minimum requirements in respect of the thermal insulation, energy efficiency and moisture prevention for both new developments as well as existing buildings are laid down in rules and regulations.

3.1 Outer walls

Facades can be solid (homogenous) or implemented with a cavity.

In regards to heat transport, the location of the insulation is of little influence, except where the (linear) thermal bridges are. Where the accumulative quality of the construction is concerned, the location of the insulation is essential.

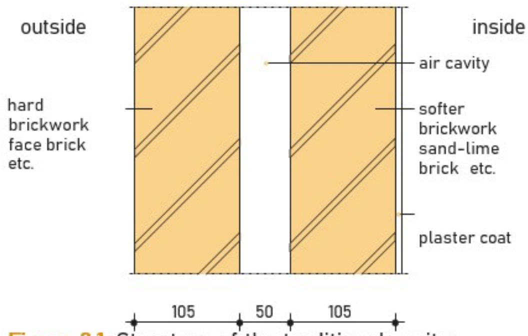


Figure 3.1 Structure of the traditional cavity

Homogeneous walls

Homogeneous walls include single concrete walls, single-brick walls, and one-and-a-half- brick walls, and so on. A single-brick wall does not, of course, have a high level of heat resistance. To meet the necessary requirements, it will have to be insulated. The solutions for new buildings are virtually the same as those for buildings undergoing renovation, and are dealt with here together.

Moisture balance

As far as the internal moisture balance is concerned, these walls do not cause any problems. However, the low heat resistance of walls of this kind can lead to surface condensation, and with old brickwork, damp patches can also appear due to rain. It is possible to treat the walls on the outside with a water repellent, although it should not be vapour-proof, as otherwise a significant level of interstitial condensation would occur, caused by vapour diffusing from the inside to the outside. There are water-repellent agents in existence which are not vapour-proof, but one of their drawbacks is that they require more intensive maintenance as they have to be reapplied on a regular basis. The effect of damp patches can sometimes be eliminated by the methods for insulating homogeneous walls, described below.

Light concrete homogeneous walls

Homogeneous walls made of light concrete (λ = 0.45 to 0.65 W/(m·K) have a reasonable level of heat resistance if they are thick enough. The water balance does not present any problems, as the vapour can diffuse outwards unhindered. The concrete should be frost-resistant, though, as a layer may become saturated with water due to rain on the outside.

Outside insulation

In case of outside insulation, the insulating material is placed (either glued or mechanically installed) on the outside layer (homogenous wall or cavity wall) and finished. The look of the facade therefore changes significantly. In The Netherlands planning permission must be obtained for this with licensing authorities. When the facade of, for example, a listed building is concerned, outer wall insulation is not an option.

Figure 3.3 Outside insulation of a facade

Benefits of outside insulation are:

- The insulation thickness is in principle unlimited.
- Thermal bridges can usually be prevented.
- The heat accumulating quality of the underlying construction is utilised.
- Thermal tensions in the underlying construction are prevented.
- The likelihood of interstitial condensation is extremely small, if the outside is vapour retardant, a cavity space is required.

Points of attention for outside insulation are:

- Moisture: it should be prevented that moisture gets behind the insulation sheets. Attention for a proper air and water proofing is important, especially at the location of connections.
- Crack formation: when gluing insulation sheets, the base layer should be sufficiently flat to prevent tensions between layers and crack formation in the finishing layer.
- Pollution: when applying plaster layers, pollution should be considered. Make sure end caps are placed at window frames and ensure sufficient overhang at weatherings and eaves to minimise pollution of the plasterwork. Water should be prevented from splashing as well.

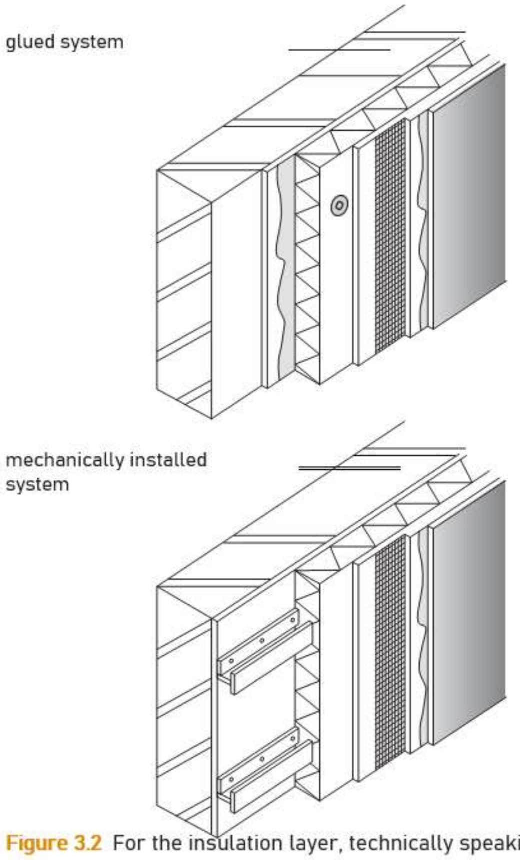


Figure 3.2 For the insulation layer, technically speaking both mineral wool as well as plastic foam can be used. The finishing takes place with plasterwork, with or without adding synthetic resin, including glass fibre or wire netting reinforcements. The various solutions of course have their own environmental quality.

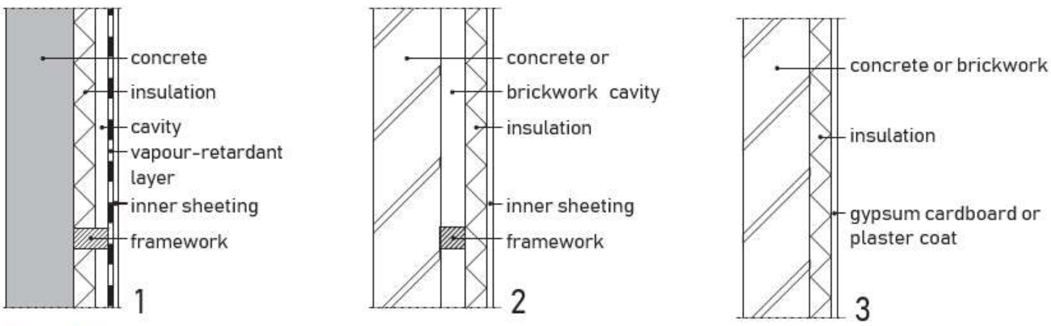


Figure 3.4 Options for inside insulating of walls

Inside insulation of outer walls

Although insulation at the outside is preferred for homogenous walls, this is not always possible. In such event, the only option is to insulate the wall at the inside.

There are three distinct methods for this:

- insulation on the wall, timber framed sheeting, figure 3.4-1;
- insulation on timber frame, figure 3.4-2;
- insulation glued to the wall, figure 3.4-3.

The advantage of inside insulation is that the outside look of the facade does not change. The disadvantages of inside insulation are:

- The thickness of the insulation package is at the expense of the living space.
- Implementing the insulation package and any vapour-retardant layer must take place with the utmost care.
- The effect of thermal bridges can worsen by applying insulation at the inside of a wall.
- The heat accumulating quality of the wall is no longer utilised.
- When attaching installations to the wall the vapour-retardant layer must not be broken.

The construction in figure 3.4-1 can be applied with climate categories I, II and III. However, in the case of the climate category III, a vapour- retardant $\mu \cdot d = 5$ m layer is needed. This construction is not suitable for walls where rain seepage occurs. Every kind of insulation available can be used here. The construction in figure 3.4-2 can be applied with climate categories I and II. Plastic foam can be considered for use as insulation material. The construction in figure 3.4-3 can be applied with climate categories I, II and III. This method of insulation can also be used in cavity walls. Sheets of plastic foam can be used as insulation material. A commonly used option is sheets consisting of a layer of plastic foam (polystyrene, polyurethane) on a sheet of gypsum cardboard. They can be attached directly to the wall using a plastic-based mortar, and the gypsum cardboard then serves either as the finish itself, or as the bearer of a layer of plaster. In the case of walls which are not entirely free of moisture seepage, only sheets made of water-resistant plastic foam (such as extruded polystyrene foam) or foam glass may be used.

When insulating the interior with plastic foam, the consequences of fire should be thoroughly examined. Many types of foam emit toxic fumes when they are heated. The amount of smoke given off may also be so great as to seriously hinder the efforts of rescuers and fire-fighters. Material of this nature should therefore be finished with gypsum cardboard, with the joins properly covered, or a layer of plaster.

Insulation on the interior removes the heat accumulation effect of the wall. This is not so serious if the inside walls and floors are of sufficient mass and are not overlaid with heavy carpets or wall coverings or panelling with good insulation qualities. However, cold bridges may be created at the points where floors and roofs meet with the walls (see figure 3.5) with condensation occurring due to the low surface temperatures (see section 1.5).

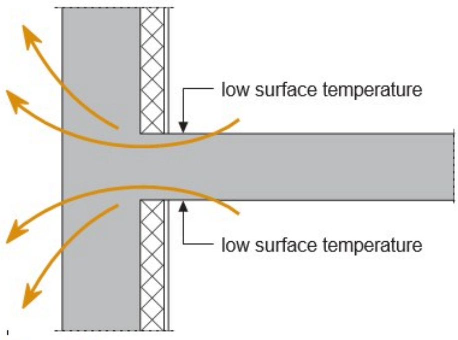


Figure 3.5 Cold bridges, created retrospectively, or aggravated due to insulating the indoor side of the wall

Cavity walls

In the Netherlands the cavity wall is still most used for outer wall constructions.
The traditional cavity (see figure 3.1) has various functions:

- to prevent damp caused by rain;
- to dispose of water that has penetrated the outer face of the wall;
- to increase heat resistance.

To comply with the requirements set out in the regulations with regard to heat resistance, cavity walls must be insulated. Insulating cavity walls serves to increase the heat resistance of the construction. This leads to a reduction in energy loss and to an improvement in levels of comfort (higher surface temperature of the interior of the construction).

Simply filling the air cavity with insulation material is not an option for new developments, at least not for traditional cavity widths of 50 mm. To meet the current requirements for thermal insulation, an insulation layer of 120-150 mm is necessary. Significantly wider cavities are therefore required.

Outer wall skin

With normal cavity walls it is not necessary to ventilate the cavity. It is not important to dry the outer wall face. From a construction point of view, brickwork is the best at coping with moisture (it is frost-resistant) and a wet outer wall dries out mostly through evaporation at the outside surface – 95% – and only 5% through cavity ventilation. This is not the case if the outer wall face is vapour retardant (for example if the brickwork is glazed, or if it is made of prefab concrete). No evaporation through the outer wall is possible in these circumstances, and a cavity is then needed to dispose of vapour that has diffused from the inside to the outside. Without any cavity ventilation, there will be condensation on and in the outer wall face which can cause, among other things, glazed surfaces to break when frozen. An outside sheet consisting of porous material (for example lightweight concrete) can for example have such high rain penetration, that an insulation layer in the cavity wall becomes unacceptably wet. Moisture penetration of the inner sheet is also possible. It is therefore necessary to drain away water in the cavity.

Inner wall skin

Inner cavity wall skins of facing brickwork, whether it is porous or not, should preferably be given a layer of mortar to make the construction draught-proof. The layer is not necessary if draught-proof insulation material is used, such as plastic foam, or mineral wool sheets with draught-proof paper. However, the latter should be fitted with great care. In every case, a layer of mortar on the inner cavity wall provides the most reliable solution, although it is very labour-intensive.

Cavity wall insulation during construction

In the case of new buildings, the insulation of the exterior walls should feature in the design phase. Numerous detailed designs have been developed for different building systems in order to obtain as optimal an insulation value for the exterior walls as possible (see figure 3.6). Cavity wall insulation is limited by the possible (construction) width of the cavity.

Insulation materials to be applied include mineral wool and plastice foam sheets (expanded or extruded polystyrene, PUR, PF, PIR).

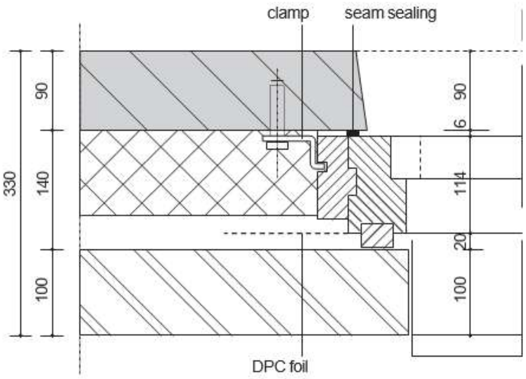


Figure 3.6 Modern cavity wall detail

Rigid plastic foam sheets

When using plastic foam, the cavity should only ever be partly filled, as an air cavity (20 to 30 mm) is required in order to prevent damp patches from occurring. If it were to be filled in completely, the joins between the sheets would start to function as moisture bridges. The sheets can be glued against the inside face of the wall, or be pressed against it by diaphragm clamps positioned over the cavity ties. There is no need to ventilate the cavity. However, a number of head joints should remain open in order to allow water that has entered through the outside face of the wall to run out.

Mineral wool

If mineral wool sheets are being used for insulation, the cavity wall can be completely filled. The fibrous edges of the sheets ensure a firm mutual grip, which prevents any moisture transport through the seams. Even though they are porous, the sheets themselves do not transport any water, because the material is water repellent and because there are no actual channels. In rain tests it appears that the moisture does not penetrate beyond a depth of 5 mm.

It is also possible to use mineral wool for partial insulation of cavities, although measures should be taken to ensure that the sheets are properly secured against the inside of the cavity wall. Such measures cost money, and often it is actually less expensive to use thicker sheets and simply fill the cavity entirely. Filling the cavity to completion eliminates the danger of damp patches arising due to pieces of mortar that have fallen. The insulation value is also greater.

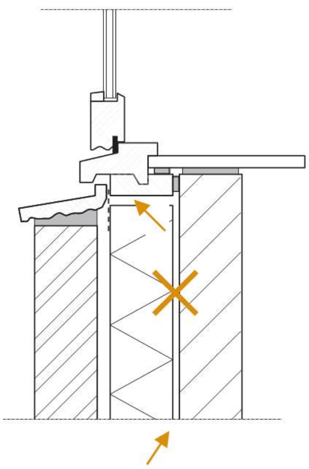


Figure 3.7 Unwanted air cavity

For partially insulated cavities, no unwanted air cavities may be created between the insulation material and the inner sheet (see figure 3.7).
This is because the insulation value will otherwise strongly deteriorate. Unwanted air cavities can be caused by:

- inaccurate attachment and installation of insulation material (see figure 3.8);
- mortar snots on the inner sheet or other additions in the cavity causing the insulation to not be completely pushed against the inner sheet;
- incorrect dimensioning of the inner sheet (for example protruding parts).

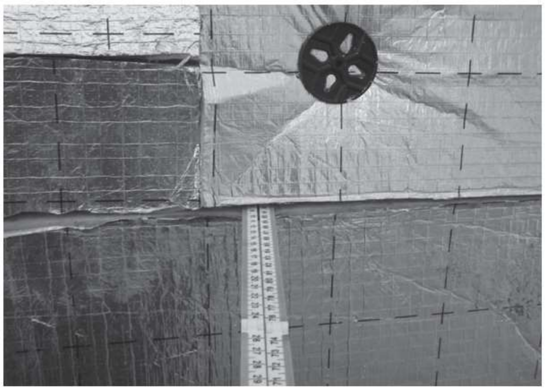


Figure 3.8 Inaccurate attachment and installation of the insulation material

Cavity wall insulated retrospectively

In existing projects, which often have cavity walls which are not insulated, it is necessary to improvise. There are no objections to completely filling cavity walls, so it is possible to retrospectively insulate cavity walls by injecting them with insulation material. Exceptions are vapour-retardant or very porous outer sheets. In these cases, the same things apply for retrospective insulation as for insulation during construction.

For retrospective insulation of cavity walls, the following applies:

- the cavity must be of sufficient width (≥ 50 mm);
- the wall and the pointing should be in good condition;
- the cavity should not be contaminated (for example by plaster remains or even fallen bricks, the presence of which could cause a thermal bridge between the outer and inner wall faces);
- any moisture-related problems should be resolved first.

There are a variety of materials with which the cavity can be filled afterwards: plastic foams (UF foam, polyurethane foam), mineral materials (rock wool and glass wool flakes and suchlike) and granular materials (polystyrene or perlite granules). All these cases concern the complete filling of cavities.

These materials all have a number of characteristics in common:

- insulating;
- vapour-proof;
- shrink-proof, crack and collapse resistant;
- vapour permeable;
- flame retardant.

Plastic foam

This method of insulation involves the insertion of a foam substance into the cavity through holes drilled through a joint in the outer wall. This foam is usually polyurethane foam. Besides for filling wall cavities, UF foam is mainly used for repairing unsuccessful cavity fillings. One of the most critical aspects of all products is the composition of the foam. The proportions of the components, the prevailing temperature, water hardness, the care with which the equipment is cleaned and so on – all have a significant influence on the quality of the end product.

Figure 3.9 Retrospective insulation

As UF foam, also polyurethane is foamed before it is brought into the cavity. Before long it shapes itself into a solid foam which adheres well to both cavity sheets. Because of its reasonable elasticity, it does not show any cracks due to shrinkage while still being partially closed celled, you can still use this material for porous outer cavity sheets. For all materials it is essential to properly apply the implementation guidelines.

Mineral wool flakes

This material can also be blown through small holes in the wall. One advantage is that wool flakes are pre-manufactured, which ensures a high level of quality control. It is the presence of motionless air that enables the material to be effective. The reduction in insulation value during rainfall is only slight and does not last very long.

Pellet-shaped materials

One possibility is to use compound polystyrene foam pellets. The pellets are inserted into the wall in a similar way to that described above, together with a water-based binding agent that to a degree helps the pellets adhere to each other so that they do not start to bulge or sag, and so that the insulation does not 'flow' from the cavity during any subsequent building renovations. Siliconised perlite pellets are another possible option. Perlite is a ground volcanic stone that has been expanded in special ovens into pellets of up to 4 mm. The pellets to be used for filling cavities are sprayed with a silicon layer to make them water repellent. Like the mineral flakes, the pellets are blown into the cavity. However, fewer openings are needed than is the case with mineral wool flakes, because the smaller dimensions of the pellets enable them to flow more easily into the cavity. On the other hand, their size also means that great care has to be taken in closing all gaps and cracks (between window frames and the walls, open head joints, etc.), as otherwise all the perlite will subsequently disappear. Nor is it possible (without special techniques) to insulate an individual house if it is physically adjoined to other residences, where the cavity passes from one to another. Perlite however is not frequently used.

Heat transmission coefficient of cavity insulation

Taking account of the fact that the parts of the cavity may not be completely filled, and that the insulation value may decrease during heavy rain, the following heat conduction coefficients can be used for the purpose of calculating efficiency levels:

- urea formaldehyde foam, λ = 0.050 W/ (m·K);
- mineral wool flakes, λ = 0.045 W/(m·K);
- compound polystyrene foam pellets, λ = 0.045 W/(m·K);
- polyurethane foam, λ = 0.040 W/(m·K);
- siliconised perlite, λ = 0.050 W/(m·K).

Note: these are save average values. Specific products may insulate better.

Other cavity constructions

Stony materials

The above sections deal with traditional cavity walls, actually consisting of two brick walls. Nowadays, the interior wall is often made of concrete (cast concrete, prefab). Provided the exterior wall is of a stony material, for example brickwork, walls of this type can be treated in exactly the same way as traditional cavity walls, with the same restrictions for highly porous or strongly vapour-retardant outer wall faces.

Light materials

Where the outer wall face is highly vapour retardant (plastic panelling, steel plates, etc.), the cavity must be ventilated. If the exterior is covered with wood, it is not always necessary to provide ventilation to the cavity as long as the interior wall face is waterproof ($\mu \cdot d$ = 5 m for climate category II, $\mu \cdot d$ = 25 m for climate category III). It goes without saying that the wooden coating must not be given any kind of waterproof finish (such as paint). A small level of ventilation through the joins is sometimes present in exteriors partly covered with wood. Light wall coverings are often very suitable for slightly ventilating cavities. The result is always a construction that is safe.

Sandwich panels

Outer walls (breastwork, or parapet) can also be built as sandwich panels. The outermost layers usually consist of waterproof or strongly vapour-retardant materials such as aluminium, concrete, plastic, fibre-reinforced concrete, etc.

Aluminium box constructions

Figure 3.10 shows two examples of aluminium box constructions. The way by which a solution is found for the edge connection is very important. In figure 3.10-1, the edge (continuous aluminium) forms a significant thermal bridge that sharply reduces the insulation value while strongly increasing the likelihood that surface condensation will occur along the edges. Present-day sandwich constructions are built according the principle shown in figure 3.10-2, where the two aluminium plates are thermally kept apart by a plastic profile. Polyurethane foam is often used as insulation material in these panels. Interstitial condensation is not a problem with aluminium sandwich panels, as the aluminium plate can be considered entirely vapour-proof.

Concrete sandwich panels

This type of panel is very common. Here too, finding a solution for the edges is a problem. This is because the sides may not be joined directly with each other. The innermost panel has a more or less constant temperature, while the outermost is exposed to solar radiation and the winter cold, causing large changes to occur in the difference in length between the inside and outside. Manufacturers have found various ways of tackling this. When the atmosphere is very moist (climate category IV), there is a possibility of highly undesirable interstitial condensation occurring, but otherwise these panels can be used without any problems. It is not generally possible to give the heat resistance level, as the way in which the solution to the edges is carried out can have a great effect on heat transport (cold bridge).

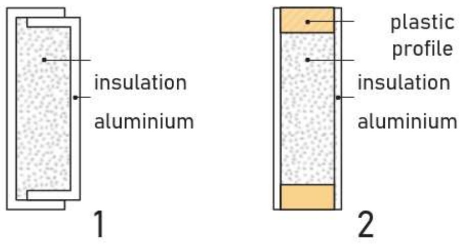


Figure 3.10 Aluminium box construction

Other panels

Plastic panels do not cause many problems either. The material is highly vapour retardant and the edge constructions do not create cold bridges.
In constructions with light sandwich panels, the delay in passing on heat is also short due to the minor heat accumulation. Because of the high insulation value of modern climate- dividing constructions, this is not a problem, as long as there is enough thermal mass in the inner room.

3.2 Floors, foundations and cellars

Foundations and floors above cavities

New buildings

Minimum requirements in relation to thermal insulation of floors are laid down in rules and regulations. Floors are laid on the foundations, potentially forming a thermal bridge. It is therefore not just important to look at the floor insulation, but also at the place where the floor and the walls meet the foundations. Extending the insulation layer in the cavity as far as the foundations and insulating the floor supports are important areas of focus in the details of the construction design. The corners also deserve special attention. See the detail provided in figure 3.11 as example. Figure 3.12 shows an example of floor insulation.

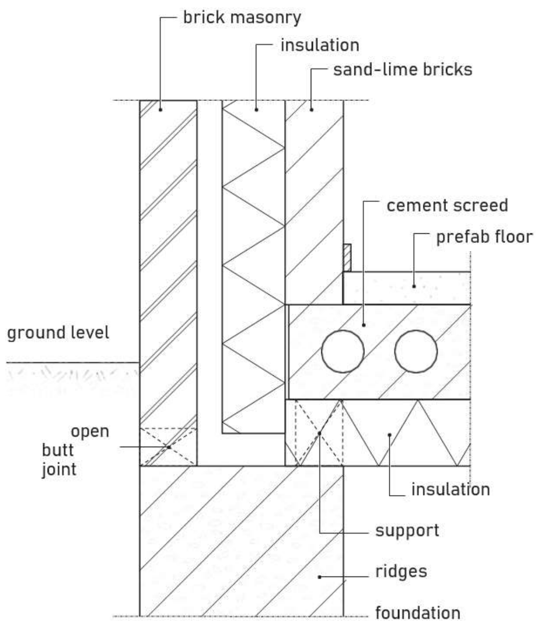


Figure 3.11 Continuing insulation layer in wall-floor foundation (detail)

Ground-level floors are subject to both air permeability and thermal requirements, intended to restrict the transport of moisture and harmful substances such as radon from cavities into homes. Particular attention should be paid to where the ground-level floor meets the walls and foundations, and to openings between cavities and the floors above, as well as to the support construction of floor hatches.

Figure 3.12 Floor insulation with EPS elements

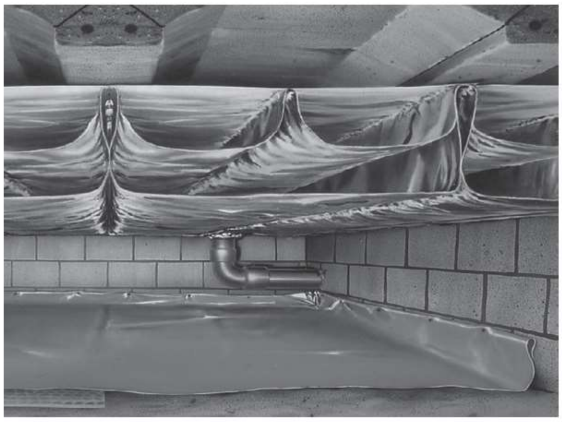


Figure 3.13 Example of retrospective insulation with plastic foil cushions with a preserved surface area of deposited aluminium and soil sealing with foil (both Tonzon)

Renovation

Older houses were often built at a time when no or only limited thermal and air permeability floor construction requirements existed. To improve the thermal requirements of a ground-level floor, to save energy for example, it will be necessary to insulate the floor (retrospective insulation), see figure 3.13.

It is not easy to calculate the effects of retrospective insulation on floors above cavities. Cavities are often lightly ventilated and the air is warmed up by the heat that penetrates through the floor. Increasing the insulation level of the floor means a reduction in heat transport, causing the temperature in the cavity to fall. A greater difference in temperature means more heat transport, leading to a vicious circle where the insulation does not completely have the desired effect. Nevertheless, it is certainly possible to achieve a saving of 6 to 8 m3 of gas for every m2 of floor. Therefore floor insulation is undoubtedly a good investment. There is now a range of different systems available on the market for insulating floors and foundations. As well as insulating the floor, it also advisable to cover the soil in order to restrict the passage of moisture and harmful substances to the space above. Covering the ground with insulation is also sometimes considered as floor insulation, but the effect of this very much depends on the degree of ventilation in the cavity. If it is only slightly ventilated, or not at all, insulating the ground also could be effective. The space between the floor and the ground can then be regarded as a cavity. If it is strongly ventilated, the ground insulation will be largely ineffective. It is therefore preferable to insulate the floor directly, or, in those cases where floor insulation is not possible, for example because the crawlspace is too small, to place insulation material direct to the ground which also limits water evaporating from the ground.

Floor insulation

If there is no crawlspace, installing floor insulation under the floor is ruled out. One could consider insulating the top of the floor, but this has major consequences (raising the floor, compressive strength of the floor, etc.).

Cellars

Cellars not in groundwater

Cellars that are not surrounded by groundwater do not always need to be insulated. The sandbags situated on the floor and walls represent a form of heat resistance between the cellar space and the outside air or more deeply located groundwater. The cellar walls are often insulated in any case, because the upper sections are just below or possibly even just above ground level, leaving them exposed to cold outdoor temperatures in the winter. The best option is to insulate them on the outside (to see how this should be done, please refer to the following section about cellars in groundwater). Insulation on the interior is also possible – this is done in the same way, in relation to vapour-retardant layers and so on, as insulating the interior of outer walls (see section 3.1). For this solution too, the cumulative effect will be undone.

Cellars in groundwater

The temperature of the groundwater in the Netherlands is almost constant, varying from around 7 to 13 °C, depending on whereabouts in the country it is. It always makes sense to insulate cellar walls. If there is a significant degree of groundwater flow (more than 0.1 m/day, as with sandy soil, or where there are differences in the level of the ground), the floor of the cellar should also preferably be insulated.

The only really proper way of insulating here is to use material on the exterior that does not absorb water and which will not rot or decay in any other way. Insulation on the interior requires a watertight layer to prevent vapour diffusion from the cellar space to the inside of the wall. However, this layer will inhibit the evaporation on the inside surface of the groundwater as it penetrates very slowly through the construction, leading to a build up of water behind the vapour-retardant layer.

A very good material for insulating the exterior of cellars is foam glass, although some extruded polystyrene foam sheets could also be considered. The sheets can be stuck onto the walls. They will sometimes need to be given a finish to prevent damage from machinery being used for putting extra soil into the ground. This can be done with glass fleece and bitumen-based coatings, for example (see figure 3.14).

When insulating the floor, the sheets can be laid directly on the subsoil (if it has been flattened), or on the concrete bed, as in figure 3.15 and 3.16. A layer of concrete tiles or a concrete bed should be laid on the sheets as supports for the reinforcements, in order to prevent damage by the reinforcements. No other steps need be taken for securing the sheets.

Figure 3.14 Insulation of a cellar wall with foam glass attached with a preparation of bitumen, and finished with bitumen and glass fleece

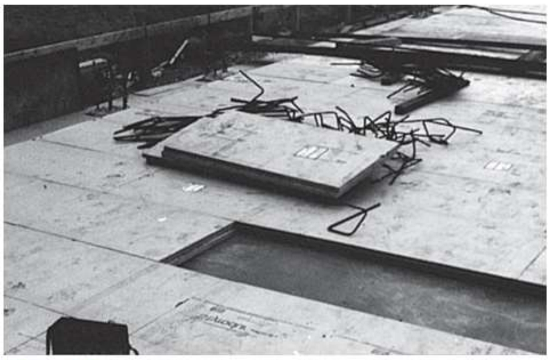


Figure 3.15 Insulation of a cellar floor with extruded polystyrene foam sheets. A layer of flowing concrete was first laid onto the sand.

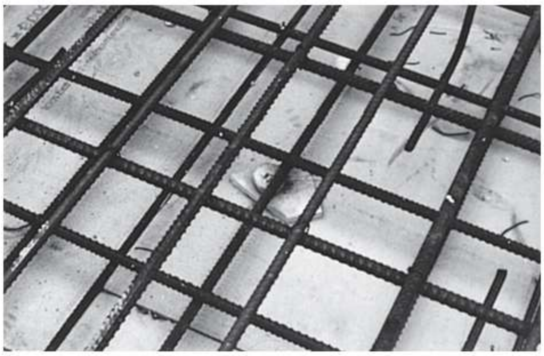


Figure 3.16 A piece of tile is laid under the support blocks of the reinforcements to prevent the insulation material from being squashed.

Floors above outside air

Floors above passageways or floors over spaces that are in direct contact with the outside air and which are not or hardly heated, must always be insulated, for two reasons. First, because otherwise too much energy would be lost (heat loss) and second, because the temperature of the interior surface would be too low (cold feet). The best option here is to apply insulation to the cold (exterior) side, thus creating an insulated and lowered ceiling that is windproof. Insulation sheets attached to the concrete (or even built in at the same time as the construction is put up) are a good solution.

3.3 Roofs

We make a distinction between sloping roofs, and those that are flat or just slightly sloping. The type of material also affects the way the construction functions. Whether insulation is carried out during the building stage or retrospectively makes little difference, so we make no distinction here either.

Uninsulated, sloping roofs

This type of roof is common on houses that were built before requirements were laid down with respect to the thermal insulation and air-tightness of homes.

Tiles, slates, and similar

A traditional roof is often made of a deck, affixed to purlins, with battens, laths, and roof tiles (see figure 3.17). Some roofs are covered with slates and other materials. No problems with regard to the internal water balance are to be expected in the depicted version. Ventilation occurs under the roof tiles, and indeed special ventilation tiles are often used. This means that vapour that has diffused through the roof deck is carried off immediately.

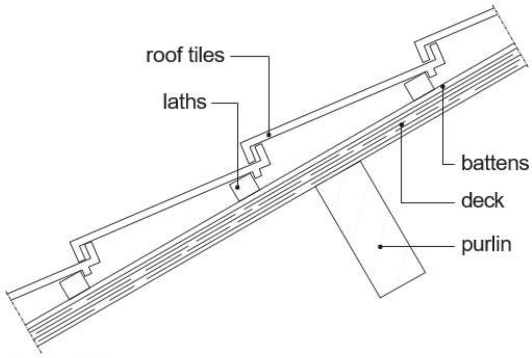


Figure 3.17 Uninsulated tiled roofs

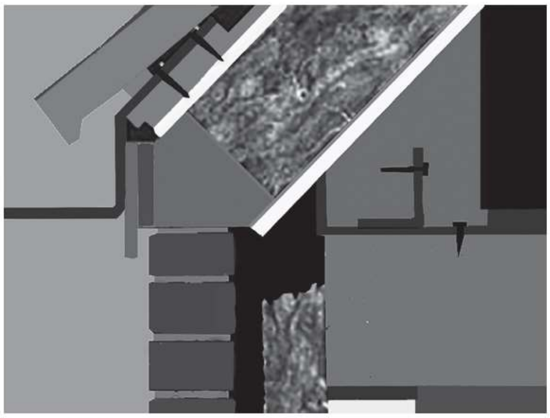


Figure 3.18 Insulation which does not continue where the outside wall meets the roof

However, the surface temperature of the roof deck can be so low in spaces with greater higher levels of moisture when outside temperatures are low, that condensation can occur on the wood. But as soon as the temperature rises again, this quickly evaporates, so there is no damage. Problems can arise, though, above spaces that are very damp. To prevent water that may have passed through the roof tiles from entering, a water- repellent vapour-permeable foil is stretched over the roof deck. It is very important that the foil is laid in relatively narrow overlapping strips, or to otherwise ensure that the foil is not vapour-proof, as this would cause condensation to occur under the foil. However, with good-quality tiles, a water- repellent layer of this kind is rarely needed. Instead of a normal roof sheating made of wooden parts or plywood, sometimes sheets of chipboard or other materials were used, which have a somewhat higher level of heat resistance.

The temperature of the inside surface will be higher in such cases, but the heat resistance will remain low. The same applies to materials of this kind as mentioned above in relation to a normal roof deck.

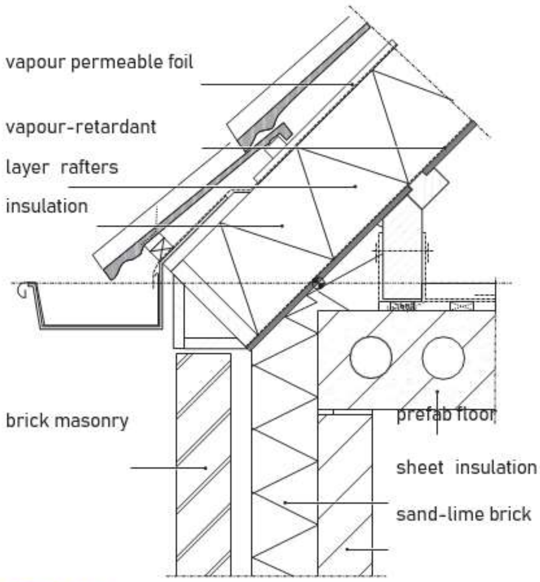


Figure 3.19 Roof detail with close-fitting insulation layer

Copper and similar

If the roof deck is covered with copper plating or another vapour-proof material, this will result in condensation occurring between the roof deck and the copper. If no measures are taken, the roof deck will be affected. A possible solution is to remove moisture (condensation) by ventilating the space under the roof deck (attic, lowered ceiling) with outside air. In this case, it is not advisable to apply a vapour-retardant layer under the roof deck to reduce vapour transport without ventilation. This is because the wood would be completely surrounded by vapour- retardant layers, and this would cause it to rot because moisture levels will become high.

Insulation of sloping roofs

The uninsulated roof as referred to above does not meet the requirements according to the regulations. Roofs of new buildings will always be insulated, for which various standard versions are available. For buildings undergoing renovation, insulating the roof should be considered from a thermal and energy point of view, especially if the space under the roof is regularly occupied (a bedroom, for example). In zinc roofs 'vapour de-pressurisation' takes place through the somewhat open French-fell seams.

Insulation on the roof deck

Insulation on the outside, as in figure 3.21-1, is the most preferable – the roof deck stays so warm that condensation on the inside is impossible. However, the insulation should not be covered with a vapour-retardant layer. Vapour diffusing outwards is removed under the roof tiles by ventilation. Sheets of mineral wool are very suitable as insulation material, but other materials could be considered as well. An important detail of the roof is the connection of the roof to the outside wall. Problems often arise here because the insulation is not continued. See figure 3.18 and 3.19.

There are also numerous products available on which a layer of insulation is applied by the manufacturer, on a supporting component of plywood, chipboard or flaxboard. Heat regulation and the water balance do not form a problem in this kind of component, but the plates must be connected in such a way as to make them sufficiently air tight. This applies to every other type of connection. Insulating a tiled roof retrospectively on the outside is much more awkward. There is hardly any room to place the insulation sheets under the existing tiles. If you wish to add insulation on the outside without affecting the roof tile construction, you may consider using compound polystyrene foam pellets (see figure 3.20). Together with a latex-based binding agent, the pellets are blown into the area between the tiles and the roof deck.
When the insulation has hardened, it forms a rigid sheet. You should make sure first that the tiles are thoroughly frost-proof. Because of the reduction in heat loss from the building (the home), the temperature of the tiles will be lower in winter than before the insulation was placed. This lower temperature and the elimination of the ventilation on the underside of the roof mean that the tiles will be wet for a longer period of time.

Figure 3.20 When insulating tiled roofs retrospectively, urea formaldehyde foam or compound polystyrene foam flakes are also used. A row of tiles is removed locally and the material is inserted under the tiles with a long lance.

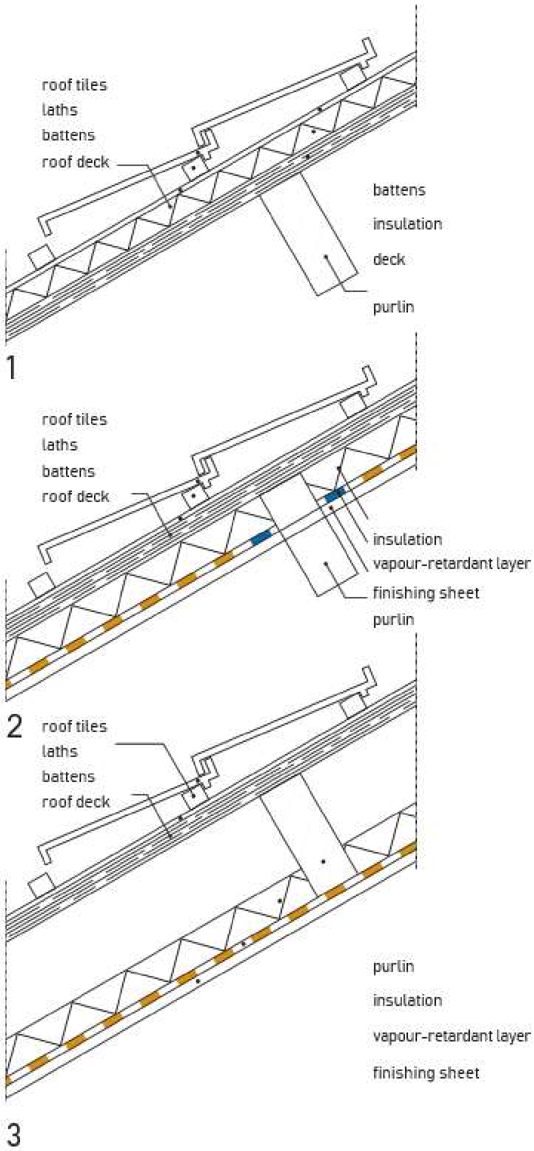


Figure 3.21 Possibilities for insulating tiled roofs

Insulation under the roof deck

If it is not possible to put any insulation on the roof deck, it can be placed underneath it. As it is now on the warm side of the construction, there is the risk that condensation will occur between the insulation and the roof deck. For that reason, a vapour-retardant layer will have to be placed on the warm side of the construction. It will also be necessary to ensure that the joins of the insulation, as well as the point where the insulation borders against other features of the construction, are made vapour-proof. The occupiers or users of the building should always be conscious of the fact that the vapour-retardant layer must not be penetrated (such as by hanging up paintings).

In principle, there are two options for placing insulation under the roof deck: insulation located immediately against the roof deck (see figure 3.21-2) and insulation under the purlins (see figure 3.21-3). In the case of the former, interstitial condensation may occur in the roof deck (between the roof deck and the insulation). Although the ventilation under the tiles provides the roof deck with plenty of opportunity to dry out, the quantity of diffusing vapour must nevertheless be restricted by placing a vapour-retardant layer between the finish and the insulation material. The join between the purlins and the insulation should also be vapour-proof, to prevent any moisture from entering the construction. Every type of insulation can be used here.

A good vapour-retardant layer is needed for insulation under the purlins, in order to prevent harmful condensation from forming on the underside of the roof deck which will get very cold in the winter. The advantage of this construction is that the vapour-retardant layer can be applied as one single entity because there are no interruptions by the purlins. Any of the usual types of insulation materials can be used successfully here. Besides being vapour retardant, this layer must also be airtight. No (moist) air must be allowed to penetrate the cavity from the space underneath the roof as described for flat roofs below.

Insulation under a tiled roof is very different from situations where insulation is placed under a flat roof, because the roof has a vapour-proof finish in the form of the roof covering (see below).

Insulated box-shaped components

There are also many prefab components where the supporting elements (often rafters) are covered on both sides with sheet material. Between this is insulation material, mineral wool or plastic foam. Components filled with loose cellulose fibre insulation (old paper) are now available as well. From an environmental point of view, this is very much worth considering.

In the case of components filled with plastic foam, the foam generally has sufficient vapour diffusion resistance to regulate the water balance. If the components are filled with mineral wool or loose cellulose fibres, a vapour-retardant layer will be required on the underside. What these components have in common is that they can be easily applied for providing excellent roof insulation at relatively low cost. Here, too, care should be taken that the sheets are properly joined up, and that the joints are vapour-proof, although in the case of many types of these components this has already been resolved.

Flat roofs

Cold roof

A cold roof is a construction where insulation is installed under the construction. Examples include roofs with lowered ceilings on which an insulation blanket has been laid. In constructions of this type, the inside surface of the roof deck can get particularly cold. If the vapour-retardant layer of the ceiling is pierced by lamps or similar objects, and if joints and gaps are not made properly vapour-proof, then the vapour-proof quality of the construction will be negligible compared to that of the roof covering, so that the air conditions in the cavity under the roof deck are almost identical to those in the room itself. For example, see the cold-roof construction in figure 3.22. A surface temperature of 2 °C on the underside of the roof deck means: p_{max} = 706 Pa. In other words, when the indoor air temperature is 20 °C (p_{max} = 2340 Pa), condensation will occur when the relative humidity is ϕ = 30%. Just a small amount of surface condensation is enough to cause rotting and mould growth.

When the outdoor temperature is –10 °C, the surface temperature on the underside of the roof deck is –7 °C (p_{max} = 337 Pa), so that condensation occurs with a relative humidity level of ϕ = 14%; moreover, the condensation freezes. When it suddenly thaws, water falls on the ceiling, where it causes stains and produces leak-like symptoms. To improve the situation, the amount of vapour being diffused to the cavity will first have to be reduced by applying a continuous vapour-retardant layer between the ceiling and the insulation. Particularly when the roof deck is made of wood and extends over a large surface area, it is important to remove by ventilation with outside air any moisture that has found its way to the ceiling. However, in the winter this ventilation air is not able to carry so much moisture. Sometimes, for every cubic metre of ventilation air only 1 gram of moisture can be removed. Good and unimpaired ventilation is therefore necessary, although difficult to achieve with roofs with large surfaces. Because the cavity ventilation can sometimes lead to the creation of an underpressure relative to the rooms below, the ceiling also has to be completely air tight. This is necessary to prevent moist air being sucked out of the room into the cavity. However this is very hard to achieve in practice, and that is the reason that this method of insulation can only really be used with roofs with small surface areas, where things can be monitored more easily. Examples include the conversion of a garage into a work space, or the insulation of the ceiling of a dormer window. In all other cases, outdoor insulation (warm roof, inverted roof, see below) is preferable. Many mistakes have been made with cold-roof constructions in the past, as for example in figure 3.23. One of the few properly executed cold-roof constructions is the concrete version (see figure 3.24). The vapour-proof and air-tightness features are assured thanks to the nature of the building. This type is most commonly found as a rooftop car-park.

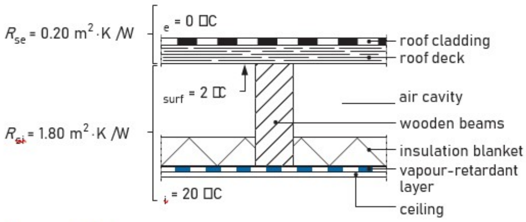


Figure 3.22 Example: cold roof

Figure 3.23 If the roof deck is damp for a long time, this can produce entire fungus cultures

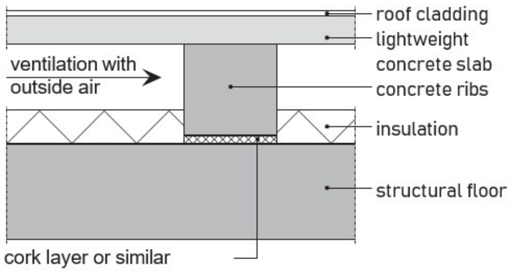


Figure 3.24 Example of properly executed cold roof (rooftop car park)

Warm roof

The principle of a warm roof is that the insulation layer is located entirely on the outside, so that the roof construction is completely on the warm side of the insulation. This type is used extensively for flat roofs.
Although the principle of a warm roof does not change, a distinction should be made in relation to the materials from which the roof sheets and the insulation layer are built. The roof covering that is placed on the layer of insulation is strongly vapour retardant. Depending on the moisture situation in the room below and the vapour-retardant qualities of the base on which the insulation is placed, the construction should be assessed to see if an extra vapour-retardant layer is needed.

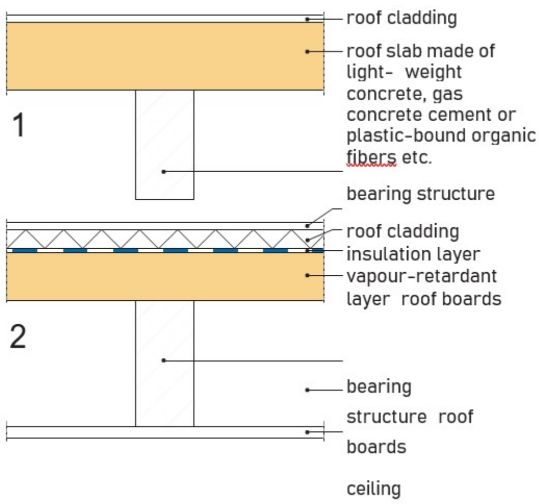


Figure 3.25 Roofs with ‘insulating’ roof sheets

‘Insulating’ roof sheets

A roof can be made up of sheets which themselves have heat resistant qualities, such as aerated concrete (see figure 3.25-1). This produces a very simple (and inexpensive) construction, but which does not provide sufficient insulation value for heated buildings according to current regulations.

From calculations, it appears that interstitial condensation is certain to occur under the roof covering. Additionally, the quantities of condensation moisture could be fairly high. Nevertheless, a construction of this kind is usually possible without any objection (although not for spaces with climate category IV), because gravity and capillary action cause the water that has accumulated under the skin of the roof to descend to the underlying surface, where it revaporises. The situation is more difficult if there is a ceiling, lowered or otherwise, present. It is generally assumed that with ceilings with a low level of heat resistance (plasterboard, plasterwork), having this construction does not pose any risks. In the case of ceilings with a high level of heat resistance (acoustic tiles made of mineral wool), the best solution is to apply an extra layer of insulation on the roofing sheets (on a vapour-retardant layer; see figure 3.25-2). The level of heat resistance should be such that no interstitial condensation can occur under the vapour-retardant layer. Often however, an extra layer of insulation will be needed in order to attain the desired level of heat resistance.

Concrete roof

With roofs of this type (concrete roof base), the layer of concrete can be considered sufficiently vapour-proof for climate categories I, II and III. For climate category IV, the required value of the sum of the $\mu \cdot d$ values of the construction without the roof covering should be calculated. A high level of diffusion resistance can be achieved by applying a vapour-retardant layer, or insulation material which itself is strongly vapour retardant (see figure 3.26). In the case of the latter, great care should be taken that the joins are properly closed.

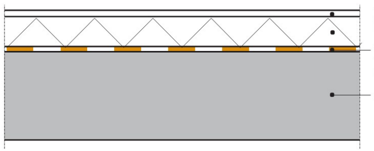


Figure 3.26 Warm roof, concrete

It should be possible to calculate whether or not interstitial condensation will occur under the vapour-retardant layer. In general, this will be the case if the dew point (the dew point temperature) of the inside air is above the vapour-retardant layer. If this is not so, then the insulation layer is too thin.

Wooden roof

A warm roof with a wooden deck (or wood- like sheet material), as in figure 3.27, cannot be used for the dampest interior climates. For climate category III, the vapour-retardant layer should have a $\mu \cdot d$ value of at least 5 m.

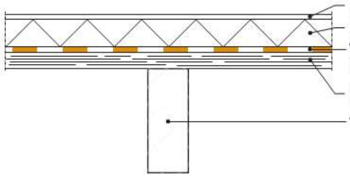


Figure 3.27 Warm roof, wood

Steel roof

If a roof is made of steel sheeting (see figure 3.28), the material itself can serve as a vapour-retardant layer. The joins between the sheets can be sealed. There should be no leaks caused by attaching the roof sheeting or insulation by mechanical means. If there is any doubt about this, or if the climatic conditions are very extreme, an extra vapour-retardant layer should be put on the roof sheeting, in order to ensure that the vapour diffusion resistance for roof constructions (without roof covering) is at a normal level. A completely vapour-proof insulation material can also be used, but that applies to all warm-roof constructions.

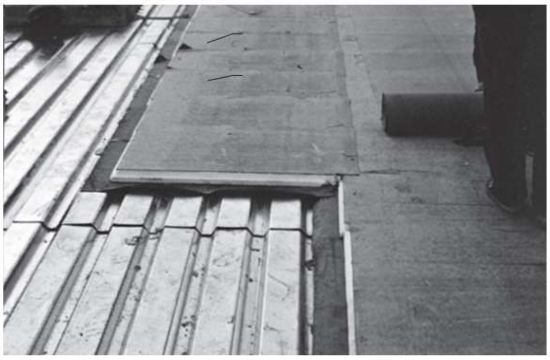


Figure 3.28 Steel roof with polystyrene foam insulation sheets with a laminated layer on either side. The roof covering is attached to the upper layer, while the lower layer functions as a vapour-retardant layer.

Lowered (acoustic) ceilings

The surface condensation on the underside of the roof, described in the cold roof section above, can also occur with insulated roofs. Many lowered acoustic ceilings have a very high level of heat resistance, so that the underside of the concrete sheet can often get very cold. Falling condensation droplets then cause stains on the ceiling and create the impression that there is a leak. This can be prevented by increasing the insulation on the top part of the roof and adapting it to the insulation of the cavity and the lowered ceiling (see figure 3.29).

Insulation materials

The type of insulation material used also has an influence on the physical response of the construction, and especially on the possibilities relating to the building's use. It is also important to pay attention to environmental aspects when deciding what kind of insulation material to use.

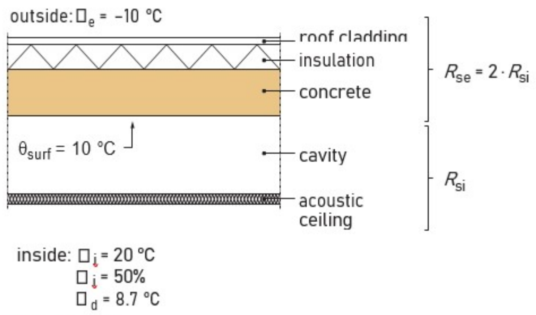


Figure 3.29 Influence of acoustic ceiling on condensation

Foam glass

Foam glass has the advantage that it is almost entirely vapour-proof, if the edges between the individual sheets are filled with bitumen while they are being attached. As the material is brittle, a good flat surface is a must. However, it is also very stiff, which means it has a favourable effect on the rigidity of the roof surface if it is affixed to a steel roof for example (which is perfectly feasible). Being vapour-proof, there is never any need for a vapour-retardant layer, so there is no doubt that it can be used, although fairly pricey. The slight expansion coefficient is favourable as regards the lifetime of the roof covering. This makes it quite possible to completely adhere the roof covering, although a locally adhered roof covering (a layer for spreading vapour pressure, see below) would also be better here.

Plastic foam sheets

Polystyrene and polyurethane foams with a closed-cell structure especially can have a fairly high level of vapour resistance, making a vapour-retardant layer unnecessary in some cases. Particularly with polystyrene foam, the high heat-expansion coefficient can cause problems with the roof covering (see also section 1.6), on which no adhesive should therefore be used at the location of the seam between sheets. Loose strips of roof covering can be laid over the seams for this purpose. This also applies to other materials if the sheet dimensions are bigger. Plastic foam sheets cannot buffer much moisture, so a good vapour-retardant layer is always necessary.

Porous materials

Expanded cork, perlite, mineral wool, compound organic fibres and similar materials are all porous and have a low level of vapour resistance. A vapour-retardant layer will therefore almost always be needed. Thanks to their greater porosity they can absorb more moisture before any harmful consequences occur (such as blistering on roofs).

Vapour-retardant layer

Polythene foil is obtainable in thicknesses starting from 0.02 mm. Theoretically, a very thin layer of foil would often be sufficient, but it is advisable not to use foils that are too thin (no less than 0.1 mm) as they are very fragile, making a good end-result very difficult to accomplish. In addition, very thin foils are statically charged, so they are difficult to handle. There is little difference in cost. Laying the foil is much more expensive than the material itself. The table in figure 3.30 shows the $\mu \cdot d$ values of a number of vapour- retardant layers.

Material	$\mu \cdot d$ [m]
Polyester foil (0.1mm)	1.5
Polystyrene foil (0.1mm)	4
Polythene foil (0.1mm)	6.5
Polythene foil (0.3mm)	10
Aluminium foil, laminated on both sides	25

Figure 3.30 $\mu \cdot d$ value of vapour-retardant layers

Insulation that becomes wet

All porous insulation materials must be prevented from becoming seriously wet during the construction phase. This is because the moisture would be trapped between two vapour-retardant layers (the skin of the roof and, for example, the concrete floor) so that it would require a long period of time for it to disappear through diffusion.

Inverted roof

We can state that this type of roof construction (see figure 3.31) fulfils every physical requirement: insulation on the exterior (laid separately, so not vapour-proof), a vapour- retardant layer on the warm side of the construction (roof covering under the insulation, figure 3.32). For that reason, there is no chance of interstitial condensation. Because the roof covering is beneath the insulation, it is not exposed to strong fluctuations in temperature, which can only benefit its lifetime. Here too, plastic foils laid not adhered can be used quite feasibly.

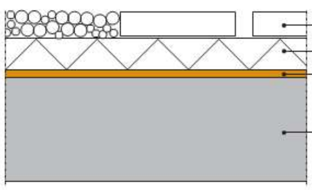


Figure 3.31 Inverted roof

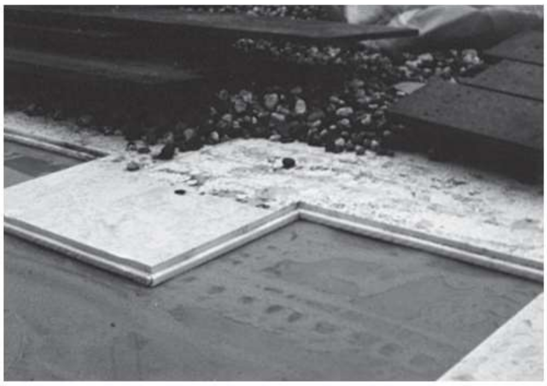


Figure 3.32 Inverted roof. The insulation sheets (extruded polystyrene foam) are simply laid onto on the roof covering, and covered with coarse gravel or tiles to protect them from sunlight (ultraviolet) and to prevent them being blown off.

As the roof covering and insulation are simply laid down without being attached to anything, they have to be weighted down with gravel or concrete tiles. This is also necessary to protect the insulation material from the influence of the sun's ultraviolet rays. Additionally, some rainwater may be able to run through the joins, especially as the sheets are not physically attached to each other. This results in a small reduction in the level of heat resistance, as the rainwater transports the heat. However, this need not be any greater than around 5% if the work is executed properly (sheets with grooves).

The fact that the insulation is laid outside puts extra demands on the material. At present, it is only extruded polystyrene foam – which has a negligible rate of water absorption, does not rot, and is not susceptible to mould – and specially treated sheets of high compression (approx. 200 kg/m3) mineral wool that can be considered. The mineral wool sheets only have to be ballasted at the edges and other critical points. Because of its own relatively heavy inherent weight and the equalisation of pressure that occurs between the top and bottom sides of the sheets, there is no danger of damage caused by wind suction. The same applies to the 'lightweight extruded polystyrene foam inverted-roof sheets', which are dealt with below.

Renovation, retrospective insulation

Inverted roofs are highly suitable for renovation or retrospective insulation. After the gravel or tiles being used as weights are removed, the old covering cleaned and, if necessary, a new layer applied, the insulation sheets can be laid out, followed (again) by the gravel or tiles. Roofs without a layer of ballast (roof covering with slate or a similar material worked in) can be changed into inverted roofs. This is because there are also 'lightweight inverted-roof sheets' on the market: extruded polystyrene foam sheets with a thin layer of special concrete on top, or the mineral wool sheets mentioned above. These products can be used if the support construction is not capable of bearing an extra layer of ballast.
The insulation layer will raise the level of the roof, incidentally, which may result in the need to alter cornices, roof ducts or the position of any doors that open onto the roof.

Vegetation roof

A notable form of the inverted roof is the vegetation roof, as in figure 3.33. It is becoming more and more commonplace for a layer of soil or other material to be laid on roofs, in which plants can be grown. It is usually sedum varieties that are used for this purpose.

In addition to the benefits mentioned previously, vegetation roofs also have the advantage of being effective in keeping out heat from the sun during the summer. Rainwater too is temporarily absorbed, which lessens the burden on drainage systems. And of course for people in nearby buildings, a vegetation roof is much more attractive to look at than one with just roofing material. The structure must of course be able to carry this additional load (including the rain water which will be stored).

Figure 3.33 Vegetation-covered roof

4 Lighting

A.C. van der Linden

For all functions of living and working, good lighting is essential. This does not just concern the amount of light required to 'perform the task of the eye', but also the level of visual comfort. It is especially important to prevent major differences in brightness in the field of vision. Furthermore, the lighting must be sufficiently divided or, rather, properly focussed if a certain object must be accentuated. This chapter deals with all basic variables and provides directions for dealing with daylight and artificial light.

4.1 Basic principles

Light as electromagnetic radiation

What we call light is, just as heat radiation, an electromagnetic wave. The difference lies in the wavelength. Radio waves on the one hand and roentgen and radioactive radiation on the other belong to the same physical phenomenon (see figure 4.1). The propagation velocity is the same for all these waves, namely 3 · 108 m/s, in other words 300,000 km/s. Within the electromagnetic radiation spectrum, it is only wavelengths between 0.38 and 0.78 µm (1 µm = 10^{-6} m) which are visible to the human eye. This is shown in figure 4.1. As the eye's sensitivity to each wavelength is not the same, measuring the amount of energy within the wavelength range of visible light will not do.

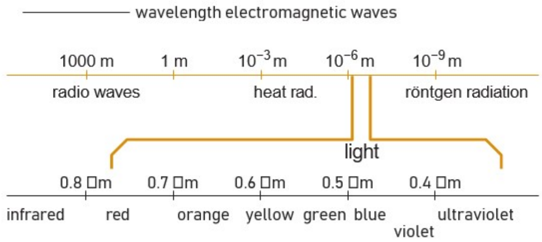


Figure 4.1 Wavelength of electromagnetic waves

Relative eye sensitivity is given in the table in figure 4.2 and figure 4.3, for the circumstances that you will face in the field of building physics. It appears that the eye is most sensitive to light with a wavelength of 0.555 µm (yellowish-green).

Wavelength [µm]	Eye sensitivity [%]	Colour impression
0.38	0.004	
		Violet
0.42	0.4	
		Blue
0.50	32	
		Green
0.555	100	
		Yellow
0.59	76	
		Orange
0.63	27	
		Red
0.78	0.001	

Figure 4.2 Colour impression and eye sensitivity, depending on the wavelength of the light

Luminous intensity and luminous flux

The units in which light is measured were originally laid down on the basis of comparisons of visual clarity, where light was allowed to fall on a particular surface for reference. The strength of light from a given light source was varied (by changing the distance or by filtering) until the same level of apparent clarity was achieved as at the point of the light source in question. The usual light source was a candle of a particular size and composition; the light from a standard candle had a luminous intensity of 1 candela, and created an illuminance of 1 lux on a surface at a distance of 1 m.

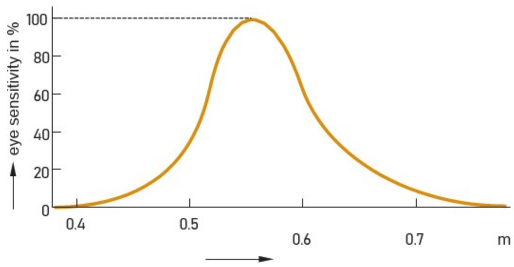


Figure 4.3 Relative spectral sensitivity of the human eye

It subsequently became the practice to measure light based on the energy generated by the light (the electromagnetic radiation). In addition to the luminous intensity (cd) and the illuminance (lux), the luminous flux (in lumen) is important. The luminous flux refers to the electromagnetic radiation that is perceived as light by the human eye. The starting point for measuring the various lighting units nowadays is the luminous intensity. The relationship between luminous intensity and luminous flux is defined as follows: 'The luminous intensity (in candela) is the luminous flux (in lumen) transmitted in a given direction per unit of solid angle (steradian).'

A solid angle ω is defined as the part of the surface area of a sphere (A) divided by the radius squared (R^2). This is illustrated in figure 4.4. The solid angle is expressed in steradians:

$$\omega = \frac{A}{R^2} \text{ [sr]}$$

The solid angle ω does not depend on the shape of the excision that is made on the surface area of the sphere. As the surface area of a sphere equals $4\pi \cdot R^2$, a solid angle that takes up the entire area is equal to 4π steradians.

From what is stated above, it would appear that the definition describing the relationship between luminous intensity and luminous flux assumes a point-shaped light source. In practice however, all light sources have finite dimensions. This does not form any problems as long as the beam from the 'imaginary' sphere created around the light source is many times greater than the dimensions of the light source. The relationship between the luminous intensity (I) and luminous flux (Φ) can of course also be written differently: 'The lumen is the luminous flux emitted at a strength of one candela by a light source, in a solid angle of one steradian.' The unit of luminous flux is therefore cd · sr. However, this has been given its own term, 'lumen'.

$$\Phi = I \cdot \omega \text{ [lumen]}$$

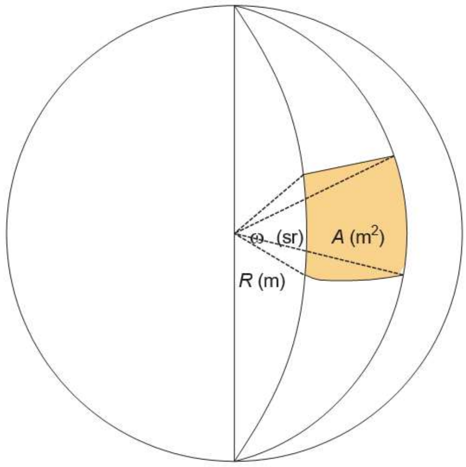


Figure 4.4 Solid angle ω cuts an area A of the surface from the sphere with radius R around the origin, and is expressed in steradians

If the luminous intensity of every direction of a light source is known, it should in principle be possible to determine the total luminous flux. If the luminous intensity is the same in every direction, the following applies to the luminous flux:

$$\Phi = 4\pi \cdot I \text{ [lumen]}$$

As already stated, the luminous intensity is used as the starting point for the definitions (SI basic unit). The candela is the amount of luminous intensity, perpendicular to the 1/600,000 square-metre surface of a black body, at the solidification temperature of platinum (2042 K), at a pressure of 101,325 Pa. Although the photometric units were originally associated with the above definition of the candela, present-day practice uses a definition based on an energy flow measured in watts, relative eye-sensitivity as shown in figure 4.3 and a 'photometric radiation equivalent' of 680 lumen/watt.

Illuminance

Illuminance E is the amount of captured luminous flux Φ per unit of surface area A:

$$E = \frac{\Phi}{A} \text{ [lumen/m}^2 \text{ or lux (lx)]}$$

In general, the illuminance – if the distance to the light source is great enough to regard it as a point source – will decrease by the square of the distance (see figure 4.5).

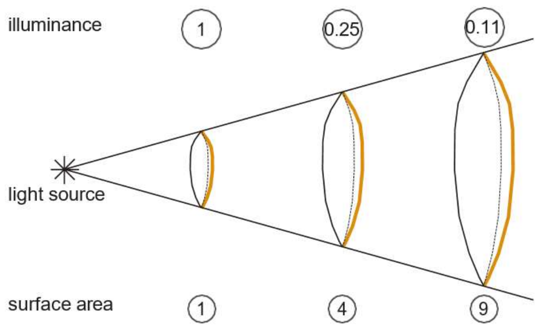


Figure 4.5 The luminous intensity decreases by the square of the distance, when the radiation from a point source (or one that can be regarded as such) is unhindered

At a distance of 1 m, the surface area of an imaginary sphere that is cut out by a solid angle of 1 sr, is 1 m^2 in size. With a luminous intensity of 1 cd (= 1 lm/sr), the illuminance at this point is 1 lm/m^2, or 1 lx. At a distance of 2 m, the same solid angle cuts out a surface area four times as large. The illuminance is then just 0.25 lx, because the same luminous flux passes over a surface area that is four times as large. The angle at which the light hits the surface is also important. If it falls at a non-perpendicular angle it is spread over a larger area. At distance R from a light source, the illuminance amounts to the following:

$$E = I \cdot \frac{\cos\theta}{R^2}$$

The meaning of the symbols is:

E the illuminance in lx (lm/m^2)

I the luminous intensity of the source in cd
R the distance to the point source in m
θ the angle of incidence

Clearly, a surface that stretches out, and which is lit by a pointed source, will have a different illuminance at different points, because both the distance from the light source and the angle at which the light hits the surface will vary. It should be noted, incidentally, that the luminous intensity is no indication of the brightness with which a particular surface is observed.

Luminance and brightness

The brightness of a particular surface is a subjective matter, determined by the physiological and psychological circumstances of the observer. The variable 'luminance' (*L*) was introduced in order to express the relationships governing brightness, etc. (see figure 4.6):

$$L(\theta) = \frac{I(\theta)}{A \cdot \cos\theta} \quad [cd/m2]$$

The meaning of the symbols is:
$A \cdot \cos\theta$ the 'apparent' surface of surface element *A*
I(θ) the luminous intensity as emitted by a surface element A in the direction of *θ*

An image forms on our retina on which the surface is in proportion not just to the distance with the illuminated surface, but more especially with the 'apparent' surface of element A:

$$A_{apparent} = A \cdot \cos\theta$$

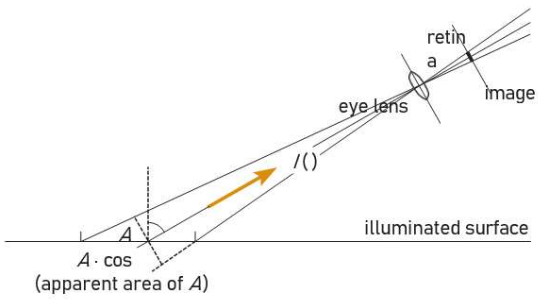


Figure 4.6 Luminance of an illuminated surface depends on luminous intensity *I(θ)*, surface element *A* and angle *θ*

The luminous flux that forms the image on the retina is in proportion with the illuminance emitted and the distance of the eye from surface element A. The number of lumen received per m^2 of retina does not depend on the size of the surface element A and its distance from the eye. After all, if the size of the surface element is halved, the luminous intensity that is emitted, in other words the luminous flux in lumen per steradian, is twice as small. Given that the image on the retina is also twice as small, the number of lumen received for each m^2 of retina remains the same. If the distance between the eye and the surface element is doubled, the illuminance that is emitted by the surface element will be four times less at the location of the eye. As the image on the retina is also four times smaller, the luminous flux (in lumen) that is picked up by the eye again remains the same per m^2 of retina. This all applies to the luminance defined above, but for practical purposes is just as relevant to the subjective aspect of brightness. The terms brightness and luminance are often mixed up. However, when quantifiable variables are under discussion, luminance should always be used.

Surfaces reflecting or radiating diffused light

A surface radiates diffused light, if the luminance on every point of the surface is the same in every direction. A surface can transmit light through heat (burning steel plate), through transmission (opal cover for a lighting fitting or ornament) or through reflection of incident light. In the case of reflection, the surface radiates diffused light regardless of the angle of incidence of the incident light. Surfaces on which this may occur, to a greater or lesser degree, include plasterwork, gypsum, and new concrete – in contrast to a mirror on which the angle of incidence of light is the same as the angle of reflection. Hybrids are also possible (see figure 4.7).

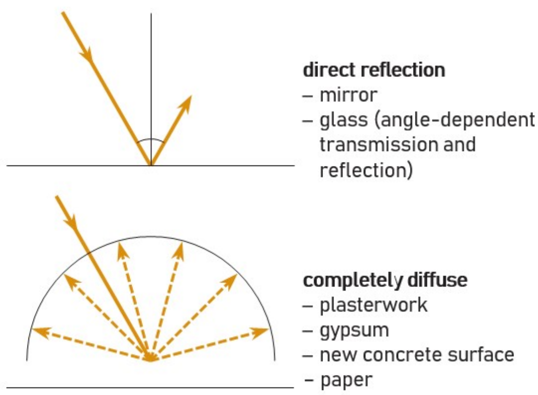


Figure 4.7 Targeted and diffused reflection of light

The luminance of surfaces reflecting diffused light can be easily calculated from the illuminance if the reflection coefficient of the surface is known.

$$L = \frac{r \cdot E}{\pi} \text{ [cd/m2]}$$

The meaning of the symbols is:
L the luminance in cd/m^2
r the reflection coefficient
E the illuminance in lx

This formula clearly illustrates that luminance and illuminance are totally different variables. As has already been explained, the illuminance is determined by incident light. The surface on which the light falls is totally irrelevant. The luminance of a surface – what we perceive – is on the one hand dependent on the illuminance of the surface and on the other, the characteristics of the surface, such as the reflection factor. Different surfaces have different luminances, even where the illuminance is the same. The table in figure 4.8 shows the reflection factor for a number of materials. It goes without saying that the reflection factor does not have to be the same for all wavelengths. If this were the case, then with incident white light the surface would become more and more grey with a lower and lower reflection factor, until black at r = 0.

Surface / colour	Reflection Factor			White plasterwork (new, dry)	0.70-0.80
	Light	Medium	Dark	White plasterwork (old)	0.30-0.60
White	0.80	0.70	-	Brick (new)	0.05-0.15
Grey	0.60	0.35	0.20	Brick (old)	0.10-0.30
Black	-	-	< 0.04	Concrete (new)	0.40-0.50
Yellow	0.70	0.50	0.30	Concrete (old)	0.05-0.15
Beige	0.65	0.45	0.25	Aluminium, high-reflection	0.80-0.85
Brown	0.40	0.20	0.07	Aluminium, matt	0.50-0.60
Red	0.35	0.20	0.10	Dark wood varieties (iroko, wengé)	0.10-0.30
Green	0.50	0.25	0.12	Light wood varieties (birch, light oak)	0.30-0.50
Blue	0.55	0.25	0.08	Writing paper	0.70-0.80

Figure 4.8 Numerical values of the diffuse visible light reflection coefficients of a number of surfaces of various materials

A surface only reflecting light of a certain wavelength will show just this colour when it is illuminated by white light. For instance when red light strikes a green surface this will show black because it reflects only green light.

Colour temperature

Colours and their associated wavelengths are given in figure 4.1. All colours together, as in sunlight, are perceived as being white. This also applies to the light given out by incandescent lamps, for example, although sunlight appears whiter than the light from lamps. This depends on the extent to which the various wavelengths are represented in the spectrum. Like the sun, incandescent lamps emit thermal radiation. As was explained in the chapter on heat radiation, all objects emit radiation. With low temperatures this is only heat radiation or infrared radiation, but when temperatures are higher, it also includes visible light and ultraviolet radiation. In the case of the temperature of the surface of the sun (on average, about 5750 K) the peak of the radiation is located in the middle of the field of visible light. As temperatures fall, the peak shifts to where there are longer wavelengths, the red area, and the light becomes more yellow in colour. With incandescent lamps (2700–2900 K), the peak of the radiation curve is actually outside the range of vision.

The radiant temperature is a measure for the ‘ambience’ of white light. Fluorescent lamps and LED lights do not emit thermal radiation and therefore often have a spectrum that is very different to that of an incandescent lamp. In principle three colours (red, green, blue) are enough to create white light. Modern LED lamps however use more colours. Nevertheless, a radiation temperature is used in order to be able to indicate the colour of the light. This is what is known as the added colour temperature. Descriptions of the light colours, with their associated temperatures, are as follows:

- 2500–2900 K: extra warm white
- 2900–3300 K: warm white
- 3300–5000 K: (neutral) white
- > 5000 K: cool white

The added colour temperature is determined by comparing the light from the lamp in question with the light from a black body. The temperature at which the light colour of the black body most closely corresponds to the light colour of the lamp in question is referred to as the 'added' colour temperature. However, the colour temperature gives no indication about the colour rendering of the light of the lamp in question. An object of a particular colour can only be seen, after all, in that colour if the colour is sufficiently represented in the light directed at it. Different fluorescent and LED lamps can have a different spectrum even with the same added colour temperature, and therefore have different colour rendering.

Colour rendering index and luminous efficacy

When deciding upon a light source, there are two areas that are important: the quality of the light and the level of energy consumption. The luminous efficacy provides information on the latter. This is calculated by dividing the total luminous flux by the amount of input energy. The luminous efficacy is therefore expressed in lumens per watt (lm/W). Apart from the efficacy of the light source, the features of the fitting and the location (colour of the walls, ceiling, etc.) are important factors in determining the eventual energy consumption for illuminating the building. This is covered below.

The colour rendering index R_a was introduced to properly describe colour rendering. The index shows to what degree the colours of a number of sample objects being lit by the light source under investigation correspond with the colours of the same objects under the light of a reference source, under strictly prescribed circumstances. For light sources with an added colour temperature of 5000 K, the reference light source is a black body radiator with a temperature that is the same as the added colour temperature of the light source being tested. Above 5000 K, a reference light source has to be used with a spectral energy distribution that corresponds with CIE (Commission Internationale de l'Eclairage) standard daylight D.

The general colour rendering index is determined from the degree of colour shift that occurs with eight sample colours. It can be supplemented with the colour shifts of another six sample colours – it may be possible for the individual colour rendering index to be given for one or more of the total of fourteen samples. If the colour rendering indices of two light sources correspond, but the added colour temperature does not, the colour rendering in itself may well differ. When comparing two light sources, it is therefore important always to consider both variables. The maximum value of the colour rendering index is $R_a = 100$. This is the case if there is no colour shift at all. The colour rendering index of incandescent lamps is usually fairly close to the maximum – they emit, after all, thermal radiation. Very high values can also be attained with fluorescent and LED lamps as well. Very high colour rendering ($R_a > 93$) is often at the expense of a certain amount of efficiency, for example because more fluorescent layers need to be introduced for fluorescent lights, which layers hinder each other's transparency.

There are therefore always three matters which determine the choice of lamp:

- the light output in lumen per watt;
- the (added) colour temperature in Kelvin;
- the colour rendering index including a picture of the light spectrum.

4.2 Artificial lighting

Required levels of illuminance

In international and Dutch standards recommendations relating to illuminance for a large number of spaces are given. The table in figure 4.9 gives a general indication for the level of lighting required for carrying out various tasks where good vision is important.

All kinds of illuminance levels can be found in the home. For reading with an extra lamp, values of 250–500 lx are not uncommon, while what is referred to as 'atmospheric lighting' will often not be any more than 50 lx. Values that generally suffice for performing certain tasks like reading, working with one's hands, and so on, can be worked out from the table in figure 4.9.

Calculating illuminance

The light output of every type of lamp is known. Figure 4.10 shows that the 'efficiency' of fluorescent lamps and led lamps especially is much higher than that of incandescent bulbs for example. The use of these lamps is therefore encouraged by the government and the use of incandescent lamps is discouraged. The table lists the light efficiency (luminous flux) in lumen per watt for the total lighting system plus any ballast. The values in the table provide a global indication of the light efficiency to be expected. There are considerable differences for each type and size of lamp and each product, which makes it important to request all the necessary information.

The life expectancy is expressed in burning hours. For certain types of lamps, life expectancy is often defined as the point at which the light output of a given group of lamps has fallen by 30%, either through deterioration or cessation of function. In the case of incandescent and compact fluorescent lamps with integrated electronic ballasts, it is usually the point when 50% of the lamps in the relevant group no longer work. The level of illuminance that is present in working areas is affected by many factors. First, the fitting in which the lamp is housed. The fitting has a certain luminous efficacy, but also distributes the light in various directions.

The shape of the room in which the fittings are located is therefore also an influencing factor, as of course are the colours (reflection characteristics) of the ceiling, walls and the floor. The features of the fitting and the room are summarised in what is called the luminous efficacy – see the table in figure 4.11. The table shows that fittings with almost identical fitting efficacies sometimes have very different luminous efficacies as a result of the way they distribute the light. It can also be seen that a high fitting efficacy does not necessarily lead to a high luminous efficacy. The luminous efficacy is greater in larger rooms than in smaller ones. If there is a lot of direct light (mirror optics), the influence of the reflections off the walls of the room is less than that of fittings that give off more diffused light. In general terms it can be said that the luminous efficacy shows the relationship between the average illuminance at the actual work location and the installed luminous flux in lumen per m2 of floor surface. To make lighting calculations, please refer to the relevant manuals.

Nature of the activities	Recommended average levels of illuminance
Orientation lighting	
observing large objects and movement of persons (storage areas, car parks)	50 lx
observing basic details and recognising persons (corridors, staircases)	100 lx
Lighting in the work place	
observing basic details (building site, smithy, warehouse)	200 lx
reading and writing, comparable details and contrasts (offices, classrooms)	400 lx
observing finer details and subtler contrasts (drawing office, detailed editing work)	800 lx
Special work lighting	
observing very fine details on a dark background (precision work, cadastral drawing work, close inspection work)	1600 lx
observing at the limits of visual scrutiny (microminiaturisation, operating theatres)	> 3200 lx

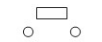
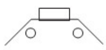
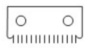
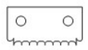
Figure 4.9 Recommended average levels of illuminance for general lighting in various spaces, ranked according to the nature of the activities being performed there

Type of lamp	System output [lm/W]	Life expectancy [burning hours]
Incandescent lamps	6-19	1000-3500
Halogen lamps	12-25	2000-3500
Fluorescent tubes	65-105	6000-12500
Compact fluorescent lamps	25-80	6000-10000
Led lamps	60-120	15000-25000

Super high-pressure sodium lamps	30-50	8000
High-pressure mercury lamps	32-57	7500
High-pressure sodium lamps	50-86	6000
Low-pressure sodium lamps	72-173	12000
Induction lamps	65-70	60000

The bottom four lamp types are not suitable for indoor lighting; they are intended for outdoor lighting purposes, such as for public spaces, etc. Here too, led lamps are applied increasingly more often.

Figure 4.10 Light output (luminous efficacy) and life expectancy of various types of lamp

Type of fitting			Efficacy of fitting	Luminous efficacy small room (h = 2.7m) shape index = 1* Low** reflection	High** reflection	large room (h = 2.7m) shape index = 3* Low** reflection	High** reflection
a		Beam	0.96	0.27	0.46	0.50	0.70
b		Trough	0.81	0.40	0.51	0.65	0.73
c		Laminated grid	0.59	0.34	0.41	0.49	0.55
d		Prism cover	0.57	0.34	0.40	0.48	0.53
e		Opal cover	0.54	0.24	0.32	0.39	0.46
f		Mirror optics	0.56	0.36	0.42	0.49	0.53

*shape index $k = \frac{l \cdot b}{h(l + b)}$ where: l = length of the room, b = width of the room, h = distance from the fitting to work location

** low reflection factors: ceiling –0.3; walls –0.1; floor –0.1

*** high reflection factors: ceiling –0.7; walls –0.5; floor –0.1

Figure 4.11 Standard values for the luminous efficacy for various types of fittings in different-shaped rooms with different reflection characteristics NB: Higher efficacies are obtainable with modern mirror-optic fittings than those shown in the table.

Differences in brightness

Too large differences in brightness can lead to problems (such as dazzling) when work is being performed, while if the differences are too small the surroundings will be dull, at least from a visual point of view. For that reason, it is recommended to keep the levels of luminance in the immediate vicinity of the working area in proportion. If the luminance ratio is greater than 10:1, the room will look unsettling, but if the ratio is less than 3:1, it will seem monotonous.

The luminance of the surface directly in the eye's vision and that of the immediate surrounding area, in other words of a piece of paper and of the desk on which the paper is lying for example, should preferably not differ by more than a factor of 3. Within the normal field of vision, the luminance ratio limit should be a factor of 10, although for areas located outside the direct field of vision, a factor of 20 should be the maximum (see also the table in figure 4.12). Proper light fittings ensure that dazzling is prevented by covering the lamp.

Luminance ratio	Subjective perception of contrast
1	None
3	Easily visible
10	Considerable
30	Too great
100	Much too great

Figure 4.12 Subjective perception of contrast (differences in brightness)

As an illustration, examples are given in figure 4.13 and 4.14 of dazzling caused by unprotected fluorescent lamps and the impossibility of distinguishing details due to too great differences in luminance. In the last case (a person in front of a window) the brightness of the window will have to be reduced (with blinds or curtains), or the person lit up by turning on the lights in the room.

Figure 4.13 Too great differences in brightness caused by unprotected fluorescent lamps

Figure 4.14 A person in front of a brightly lit window appears only as a silhouette

Colour and colour rendering

For a comfortable indoor environment it is important that the colour of the artificial lighting is appropriate to the luminous intensity. This is also the case with daylight. The greater the luminous intensity, the more preferable it is to opt for a higher colour temperature. In spaces without daylight with an illuminance of less than 500 lx, lamps with a low colour temperature (< 3300 K, warm white) are best. For illuminance levels of between 500 and 1000 lx, or for combinations of daylight and artificial light, lamps with a colour temperature of around 4000 K (white) are the most suitable. Light sources with a high colour temperature (> 5000 K, cool white) should only be used where there is a high level of illuminance. The suggested values for the colour temperature and colour rendering index in a number of situations are given in the table in figure 4.15.

Colour rendering indices can be qualified as follows:

- R_a = 90–100: good
- R_a = 80–90: sufficient
- R_a = 50–80: moderate
- R_a = < 50: poor

Heat development through light

In general only a very limited proportion of the electricity that is fed to a lamp is actually converted into light. The largest share is immediately released as heat (radiation and convection), such as with spot lamps. The light, too, is converted into heat after it has been absorbed by the objects and walls in the room. Fluorescent lamp ballasts also give off a limited amount of heat.

All the energy that is supplied eventually ends up as heat in the building. In large factories and office buildings this can be as much as around 15 (it used to be 25 to 35) watts per m^2 of the floor surface. Together with the heat emitted by office equipment and solar radiation this represents a heat burden that often has to be removed through mechanical ventilation. To prevent this, or at least to restrict it, and also with a view to making savings on the electrical energy that is used for the lighting itself, it makes sense to be as careful as possible about using lighting. Normal, low-energy lighting equipment has an installed capacity of approx. 10 W/m^2. It does not need to be any higher than this. With the help of 'workplace lighting' or more 'localised' general lighting it is possible (in specific cases) to go back to 6 to 8 W/m^2.
In buildings with a mechanical ventilation installation, the air is often sucked away through the lighting fittings, so that a significant proportion of the heat is removed directly from the room. This is also favourable for the luminous efficacy as it helps cool the lamp.

Examples of locations and activities	Recommended colour temperature [K]	Minimum desirable colour rendering index [R_a]
offices, shops, schools and sport halls with extended combination of daylight and artificial light	4000	80*
offices and shops where only a small amount of daylight is present; covered swimming pools	< 3300	80
houses, schools and meeting places in hospitality establishments and social and cultural locations	< 3300	80
areas where medical research is performed	4000	90
Industry:		
• Workshop in clothing factories	4000	80
• Assembly hall, lathe workshops	4000	50
• Foundries, rolling mills	-	-
assessing colour slides in the graphic industry	4500/5000	90
assessing colours in the textile, paint, foodstuffs and graphic industries	7400	90
locations where people move from one place to another, halls, staircases	< 3300 or 4000**	50 of 80**

* For school classrooms where drawing and painting are taught, a value of $R_a > 90$ is recommended.
** These values should be adapted to the other light sources in the building.

Figure 4.15 Suggested values for colour temperature and colour rendering index in sample situations

4.3 Daylighting

Availability of daylight

The amount of natural light available during normal working hours is rarely sufficient for the recommended illuminance levels mentioned in section 4.2. Outside illuminance levels vary during the course of the day, and can change even for a short period of time, as a result of cloud movements, thunder storms, etc. Research has shown during what percentage of the time at least a certain level of illuminance is present in an outdoor open space. This is shown in figure 4.16. Between 8.00 hrs and 16.00 hrs the illuminance outside, in an open space, is more than 6000 lx for 90% of the time.

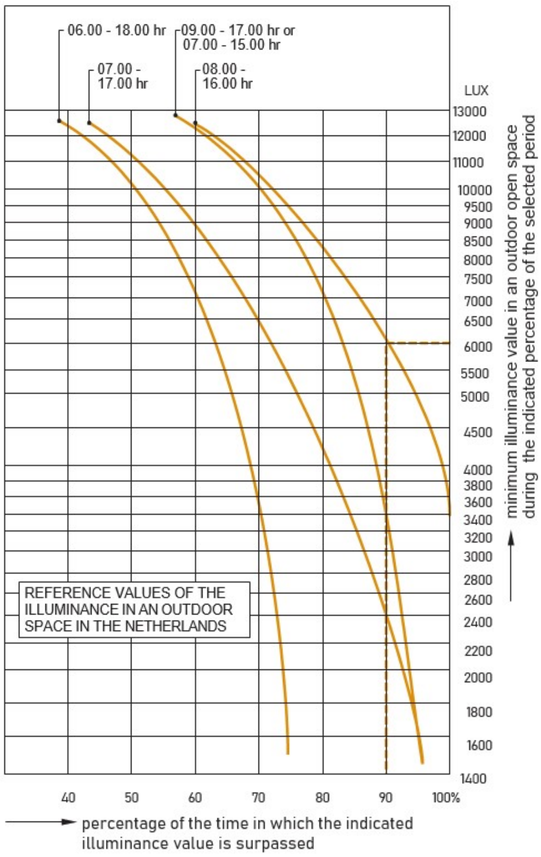


Figure 4.16 Illuminance in the free field outdoors

Daylight factor

For the purposes of lighting a space during daytime it can now be required that there be a minimum level of illuminance during a certain period of the day (during working hours, for example). Clearly though, it will not be possible to reach this minimum level with daylight throughout the whole year. During winter, with its short days, or when there is very thick cloud cover, artificial light will be needed. To determine the level of illuminance through daylight, the so-called daylight factor is used.

The daylight factor is defined as the relationship between the illuminance indoors and the illuminance outdoors in an open space, at the same time. If the former is 150 lx and the latter 5000 lx, the daylight factor would be as follows:

$$\frac{150}{5000} \cdot 100\% = 3\%$$

If the outdoor level rises to 10,000 lx, the illuminance inside rises to 300 lx. The daylight factor remains the same.

To achieve a given daylight factor various matters have to be taken into consideration, including the size of windows, the interception of light by protrusions from the building (canopies, for example) or indeed other buildings, the transparency of the glass and blinds if present, dirt on the windows, the reflection of light by the interior walls, floor and ceiling in the room (a white wall is a better reflector than a coloured one), and so on. It should also be borne in mind that the spatial distribution of daylight from the sky differs from one direction to another.

Example

An illuminance level of 300 lx is required in a workshop for 90% of the time between 8.00 hrs and 16.00 hrs. From the graph in figure 4.16, it can be seen that the outdoor illuminance is greater than 6000 lx for 90% of the time during that period. The daylight factor required in the workshop is then:

$$\frac{300}{6000} \cdot 100\% = 5\%$$

The calculations for determining the daylight factor assume a cloudy sky, as the strength of the sun is too changeable as a source of light. As far as the sky is concerned, the starting point is generally a distribution of luminance levels laid down by the CIE (Commission Internationale de l'Eclairage), based on research by Moon and Spencer, where the luminance in the zenith (perpendicular) is three times greater than that on the horizon. Various measurements have shown that, for the Netherlands, this distribution is a reliable approach for most cloud-cover situations. It is only when there are very heavy, low clouds that the distribution is more appropriate to a uniform sky: a luminance level that is the same over the whole sky.

Sky component

The most important aspect of the daylight factor is the sky component. This is the direct light from the sky reaching the point under consideration after it passes through the window opening. It is initially calculated without the reduction caused by glass or blinds (d_h^*). The sky component therefore primarily depends on the part of the sky that is seen through the window. It is converted into a measurable unit through a projection on a horizontal plane (see figure 4.17). This projection can be made with the help of a radial diagram. (You can find a radial diagram on www.klimapedia.nl together with other diagrams for personal use.) Entry variables for this are the angles from which the daylight opening in question are seen (see figure 4.18).

Eindhoven University of Technology has developed a diagram that can be used in combination with the radial diagram. This daylight diagram is divided up into a large number of sections, all of which contribute equal amounts (0.1%) to the illuminance on the horizontal plane. There are two versions of the diagram: one for a uniform sky, and one for a sky with a CIE luminance distribution.

A random window and skylight have been entered onto the radial diagram in figure 4.19. With the help of the daylight diagram for a uniform celestial sphere, the

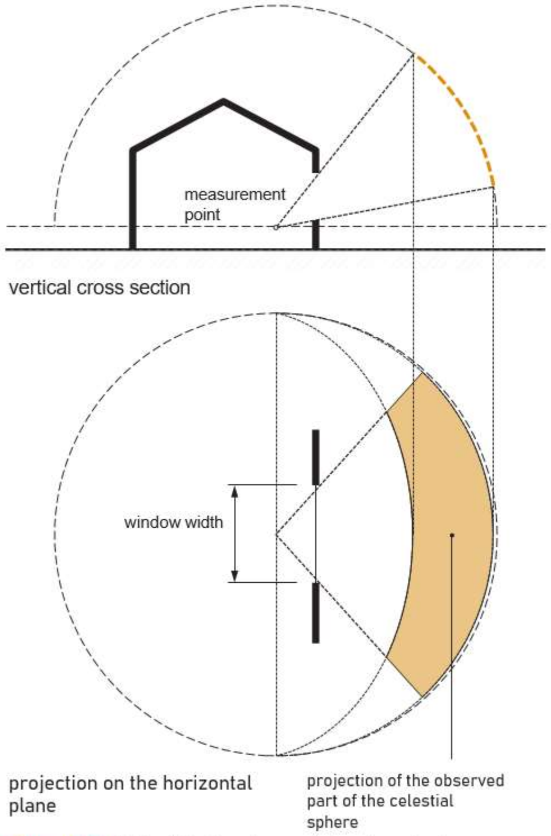


Figure 4.17 Principle for determining the sky factor

number of sections can be counted (including half sections as much as possible). Around 48 sections are counted for the window, and about 62 for the skylight. This means a sky component (without losses caused by glass) of d_h^* = 4.8% and d_h^* = 6.2% respectively.

If the diagram with the CIE distribution is used, the result is d_h^* = 3.9% and d_h^* = 7.1% respectively. It is a coincidence that the totals are identical. However, it is clear that in using this division of luminance, the contribution of the skylight is greater, and that of the window is smaller. There are of course a number of computer programs which let you determine the daylighting without using diagrams. A well-know program is 'Dialux' which can be downloaded free of charge. However, the diagrams provide good insight into the matters at play and remain useful for a quick judgement on the daylighting situation.

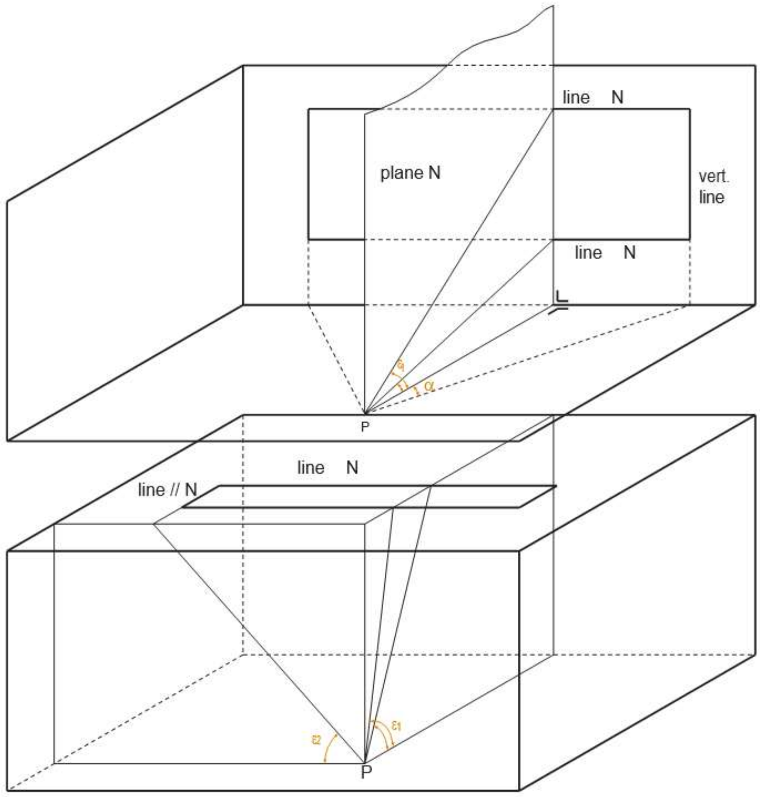


Figure 4.18 Calculating the azimuth (α) and elevation (ε) of the outer parameters of surface for projection in a radial diagram

External reflection component

To work out the external reflection component (d_e^*), it is in principle necessary to determine the luminance of all the surfaces that are capable of reflecting the daylight towards the light opening under consideration. The contribution made by these reflections to the indoor illuminance should then be calculated. This is a very time-consuming task and difficult to conduct to precision. For that reason, the following approach will suffice (and also because the contribution to the total daylight factor is usually fairly slight). It should be stated that the luminance of any obstacles that are visible through the light opening from the measuring point is about 15% of the luminance of the sky located behind these obstacles. This means, then, that the external reflection component can be determined, with the help of the diagrams, by working out the sky component of the part of the sky that is blocked from view by the obstacles, and multiplying the result by 0.15:

$$d_e^* = 0.15 \cdot d_h^*$$

Here, d_h^* is the sky component (without losses through the presence of glass) of the part of the sky that is not visible. If the surrounding buildings reflect very strongly (due to their light colour) a slightly higher 'reflection' value than 15% can be used. However, it is often worthwhile in such cases to take the trouble of making a more accurate calculation. A light floor finish can also make a contribution to the indoor illuminance, through reflection off the ceiling for example. Usually, though, this contribution is negligible.

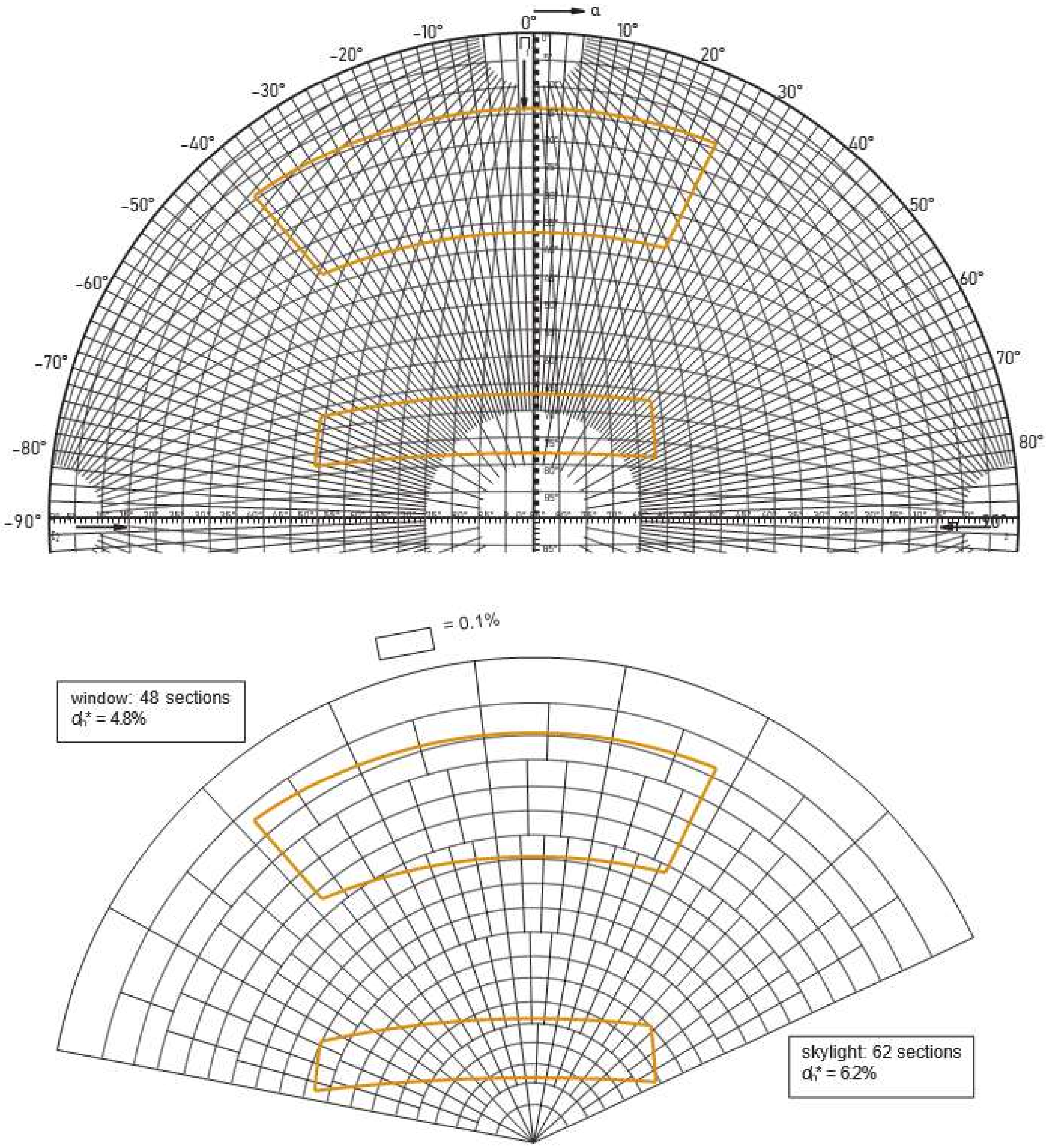


Figure 4.19 Window and skylight entered into the radial diagram and a diagram for calculating the sky component, where there is an even spread of luminance (uniform sky)

Losses in the light opening

Glass (or other material) and sun-blinds in the light opening will reflect and absorb part of the incoming light. The LTA factor (absolute light entry factor) indicates which part of the incoming light ultimately ends up in the room. For single and double glazing these are:

- LTA = 0.85 to 0.90, single glazing
- LTA = 0.70 to 0.80, double glazing
- LTA = 0.70-0.80 HR++ insulation glazing
- LTA < 0.70 solar control glass

A reduction factor c_k, to be used if there are any railings in front of the window, or if the window itself is partitioned, can be determined from the ratio between the nett glass surface area and the area including the railings, partitions, etc. If not enough is known about the frame, the following value can be used:

$$c_k = 0.85$$

Transparency can be reduced further by dirt, to a level 0.9 to 0.5 times the value of a clean surface:

$$c_v = 0.9 \text{ to } 0.5$$

Based on the above, the total level of loss in the light opening is denoted by factor c:

$$c = LTA \cdot c_k \cdot c_v$$

Internal reflection component

When light falls upon a surface in a room, the surface will, depending on its characteristics, in turn reflect some of the light, thereby contributing to the illumination of other surfaces (including working surfaces) in the room. The calculations involved here are complex. Luckily, there are computer programmes in existence for working out internal reflections, the resulting luminances of the various surfaces in the room and the level of illuminance of working surfaces. To gain an impression, without having to make any calculations, of the size of the internal reflection component (d_i), the table in figure 4.20 can be used. This gives the d_i components in percentages for various reflection factors for walls, floors and ceilings (see also the table in figure 4.8), based on an average situation for losses in the light opening and any possible obstacles, assuming the presence of single-glazing.

Glass area as proportion of floor area [%]	Refelction factor of walls			
	20%	40%	60%	80%
10	0.2	0.3	0.6	0.9
20	0.3	0.6	1.1	1.7
30	0.5	0.6	1.5	2.4
40	0.6	1.2	2.0	3.1

Figure 4.20 Internal reflection component, in percentages, of various wall-finish reflection factors

When other types of glass are used, whether with sun blinds or not, the figure from the table should be corrected using the actual LTA. The table applies where LTA = 0.9. For HR++ glazing the correcting-factor is for example: LTA_{dg}/LTA_{eg} = 0.75/0.9 = approx. 0.85. If the calculation appears to show that the contribution of di is a decisive element in the total daylight factor, then it is worthwhile to make an accurate measurement of the internal reflection component.

Determining the daylight factor

The daylight factor can be found by adding up the calculated components mentioned above:

$$d = d_h + d_e + d_i \text{ or}$$

$$d = (d_h^* + d_e^*) \cdot c + d_i^* \cdot \frac{LTA}{0.9}$$

The meaning of the symbols is:

d_h^* the sky component without losses caused by the presence of glass
d_e^* the external reflection component without losses caused by the presence of glass
c the reduction factor for losses in the light opening ($c = LTA \cdot c_k \cdot c_v$)
d_i^* the internal reflection component from the table in figure 4.8, including average losses in the daylight opening, with a light entry factor of LTA = 0.9

Daylight requirements for homes and other buildings

Dutch building legislation includes requirements for light entry for residences, in the form of an equivalent daylight surface area. This is defined in the standards indicated in the building regulations.

As is usual, legislation assures a certain minimum level of quality. Building design, however, involves more than simply applying the rules, and that is certainly the case as far as windows are concerned. As well as light entry, appearance is also very important. It should also be remembered that large glass surfaces, conservatories, atria and skylight domes cause a significant flow of heat into buildings whenever the sun shines on them. This leads to welcome energy savings during the winter, but in the summer it can cause the indoor temperature to rise to sometimes unacceptably high levels. However, this can be prevented if the building is designed properly (effective summer ventilation, sun-blinds, etc.). Incoming sunlight can also cause problems through large differences in brightness, particularly for people working with documents, on drawing tables, and so on. For that reason, some type of sun-blinds will often be necessary.

5 Thermal comfort

A.C. van der Linden

The quality of the indoor environment is about all the aspects that can influence certain sensory perceptions, or which can affect the way people function physiologically. All the factors that feature in the physical side of construction – heat, moisture, sound, light – have a role to play here. But there are also other matters, such as the purity of the indoor air, that are important. This involves the removal of combustible products (respiration), waste substances given off by machinery (copying machines) and pollution introduced into the air by building materials (formaldehyde, radon). Thermal comfort has a prominent position in this area.

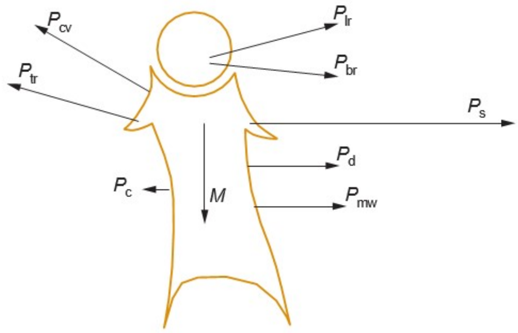
One of the things that designers of buildings aim at is a comfortable indoor climate for the people who will be working or living in them. To achieve this, a method is needed to work out from measurable, physical variables, how people assess their indoor climate. This will, of course, be affected by the circumstances in which people find themselves (sitting at a desk, or carrying out strenuous physical work) and the clothes they will be wearing. Most models that govern thermal comfort date from the 1970s and are based primarily on research in laboratories. A well-known model is that of Fanger. Since 2000, more information has been emerging about how the internal thermal climate is valued in real-life situations. Results from field studies conducted all over the world have been pooled and as a result, a direct link has been made between the outside temperature and the desired indoor situation. It appears, among other things, that some kind of psychological adaptation takes place. This means that someone's recent contact with outdoor conditions, and their expectations with regard to the indoor prevailing temperature both help form that person's judgement. When outdoor temperatures are higher, it seems that people accept without any problems higher indoor temperatures than would be suggested by Fanger's model for instance.

5.1 Fanger's thermal comfort model

There have been models developed by various researchers. One the best known is that of Fanger (1970). This model is given extensive coverage here because it gives a good insight into the areas relevant to thermal comfort. The model assumes an energy balance for people in a stationary situation, in which energy released by the body's metabolism is equal to energy given off to the environment (see figure 5.1).

The heat balance can, of course, be affected by changing the amount of clothing being worn (heat resistance). By adding comfort requirements with regard to skin temperature and perspiration to this energy balance, Fanger arrived at a comfort comparison, for which research was carried out using human guinea pigs. The scale that was used is shown in figure 5.2. The neutral point on this scale is defined by an air temperature of T_ℓ = 29 °C and an equal, uniform radiation temperature, a relative humidity level of ϕ = 30% and an air velocity of v = 0.1 m/s, for a naked person exposed to these conditions for one hour. In the same circumstances, the term 'very hot' would be used when $T_\ell = T_s$ = 45 °C, and 'very cold' when $T_\ell = T_s$ = 10 °C.

The comparisons made by Fanger – based on research with human guinea pigs in a laboratory – apply to the area between valuations from −2 to 2. His comparisons led to a 'Predicted Mean Vote' (PMV) which can be compared to the figures on the scale in figure 5.2. According to Fanger's comparisons, there are all kinds of factors that have no influence on how an interior climate is appreciated – these include age, gender, country of origin and race. If there are any differences, they are more likely to be the result of various individuals having, for example, different metabolisms (energy that is developed in the body) in the same circumstances. Outside the 'comfort range' (PMV > 2 or PMV < −2) studied by Fanger, there probably do exist large differences as referred to above. The limitations



M the energy released by the body's metabolism
P_{mw} the external mechanical work
P_d the energy removed through the skin by vapour diffusion
P_{tr} heat removed by evaporation of transpiration (evaporation heat)
P_{br} heat removed by respiration (tangible breath)
P_{lr} (latent) heat removed by respiration
P_{cv} convective heat exchange to air at the surface of the body (clothing)
P_s radiative heat exchange to surrounding walls at the surface of the body (clothing)
P_c conductive heat exchange (generally negligible)

Figure 5.1 Heat balance of a person in a room

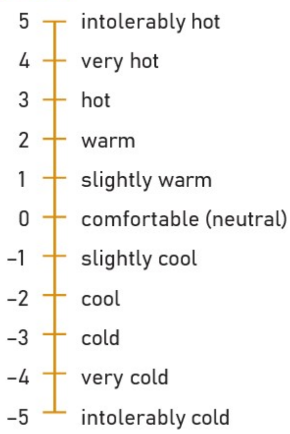


Figure 5.2 Scale for ascribing a numeric value for a given indoor climate valuation

of Fanger's model are that it only applies within the comfort range, and that it assumes a stationary situation. As a result, it is not possible to give a valuation for the climate during a brief stay in a room (up to half an hour) or for activities that last only a short time. Models have also been developed that take greater account of the dynamic character of processes, all the way to fully dynamic models in which the human body is divided into four layers. These models are used mostly for research purposes and are less suitable for practical applications. Fanger's model is the one which is still used in practice. It creates sufficient insight into comfort-related matters in normal situations where people can be found in the comfort range (homes, offices, schools, etc.). For this reason, it is dealt with in this book. An advantage of Fanger's model is that it is easy to use with a PC or a programmable pocket calculator. It should be pointed out, however, that knowledge of how people respond to any particular indoor climate is nowhere near complete. Fanger worked with fixed groups – mostly male students of between 20 and 30 years of age, who were, to a certain extent, 'trained'. In the Netherlands, more extensive research with subjects is being carried out at the University of Maastricht in particular.

5.2 Desired indoor temperature based on PMV

Although new practical application guidelines based on the 'adaptive thermal comfort limits' derived from field studies exist nowadays, we will first look at the level of desired indoor temperatures as suggested by Fanger's model on the one hand, because it is useful for obtaining an insight into people's responses to a particular indoor temperature, and on the other because the adaptive temperature limits apply strictly speaking only to office work.

Based on Fanger's observations, it is possible to make recommendations for the interior climate in a building, bearing in mind that individuals are capable – within limits – of adapting to indoor climates by changing the insulation value of their clothing (putting on or taking off a jumper, jacket, etc.). Assuming that a change of this type could be approx. 0.3 clo (see below) it can be calculated that, based on an average level of clothing insulation, a fluctuation in the indoor climate of PMV = –0.5 to PMV = +0.5 under normal circumstances is easily acceptable (see figure 5.3). From practical experience, it also appears that occasional (such as during extreme climate conditions outdoors) going out of this range to PMV = approx. 0.8 can be tolerated, at least temporarily.

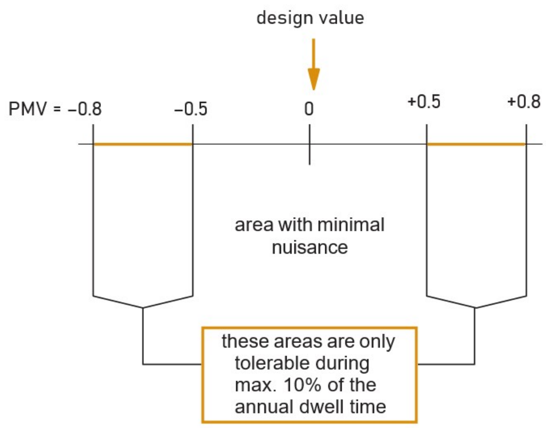


Figure 5.3 Scale for assessing the indoor climate in a building

From his experiments, Fanger was also able to show a link between PMV and the percentage of people that experience the indoor climate as warm or cool. In a neutral (in theory) situation (PMV = 0), around 5% of the human guinea pigs nevertheless experience the climate as warm or cool. Where PMV = 0.5 some 10% feel warm, while the figure is about 20% when PMV = 0.8. Similar percentages apply with negative PMVs with regard to the number of people experiencing the climate as cool. See figure 5.4 for the connection between the PPD (Predicted Percentage Dissatisfied) and the PMV.

Although the best way in principle of describing the indoor climate is to use a comfort index, such as the PMV, it is useful for practical purposes to 'translate' it into the desired indoor air temperature, where certain combinations of other influencing factors are present. The reason is that most installations work provisionally on the basis that the air temperature is the chief criterion. One of the variables that should be considered is that of metabolism. A five-tier classification has therefore been made for the most common levels of activity (see the table in figure 5.5).

The premise of the clothing resistance is also important. Clothing resistance (I_{clo}) is expressed in clo (1 clo = 0.155 m²·K/W). This unit came about because a business suit (threepiece) was chosen as a reference (see the table in figure 5.6).

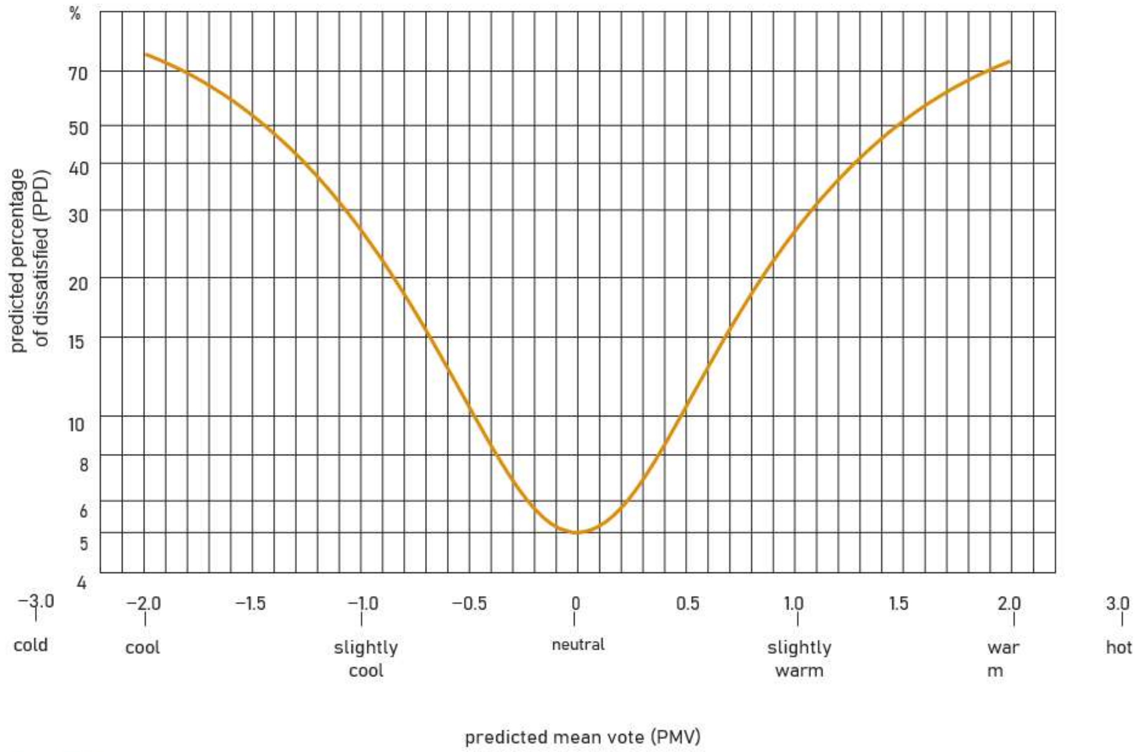


Figure 5.4 Connection between PPD and PMV

Category	Activity	Metabolism* [W]
I	Resting (lying)	85
II	Sitting calmly, reading	105
III	General office work, writing letters, drawing	130
IV	Typing, general laboratory work, teaching	160
V	Light assembly work, houseworking (ironing, washing up)	200

* This assumes a body surface area of 1.8 m^2

Figure 5.5 Classification of activities according to five levels of metabolism

Type of clothing	Value [clo]
None	0
Bikini	0.05
Shorts	0.1
Normal tropical clothing (shorts, open- necked shirt with short sleeves, light underwear)	0.3
Light summer clothing (light long trousers, short-sleeved shirt)	0.5
Summer suit	0.8
Normal suit (shirt and tie)	1.0
Heavy suit with waistcoat, thick underwear	1.5
Clothing suitable for polar regions	3.0-4.0

Figure 5.6 Approximate indication of the heat resistance of various types of clothing, expressed in clo (1 clo = 0.155 $m^2 \cdot K/W$)

Research has shown that women often wear clothes with a resistance of 0.1 to 0.2 clo lower than men in similar circumstances. In drawing up the starting points for achieving the desired indoor climate (homes, schools, offices), the following values can be used as averages for men and women:

- summer 0.4–1.0 clo, average 0.7 clo
- winter 0.6–1.2 clo, average 0.9 clo

The dispersion around the average should be seen as the adjustment in clothing that an individual can make in order to respond to the indoor climate that is present.
Working on the basis of these values, we give below the required indoor air temperatures with various PMVs, where the values of the other variables are fixed. We will then make recommendations for admissible values for air velocity and relative humidity.

Air temperature

The table in figure 5.7 shows what air temperature, depending on the radiation temperature, is appropriate to a PMV of 0, −0.5 and −0.8 respectively in a winter situation (I_{clo} = 0.9), for the five activity categories mentioned above. Similarly, it shows the air temperature that goes with a PMV of 0, 0.5 and 0.8 in a summer situation (I_{clo} = 0.7). An air velocity of v = 0.15 m/s and a relative air humidity of ϕ = 50% are also assumed. However, the effect of the relative humidity is relatively slight. It is possible to work out from these tables what temperature should be aimed for as the design temperature (PMV = 0) in a given situation, and what temperature limits should apply for 90% (preferably) of the time (−0.5 < PMV < 0.5). The temperatures beyond PMV = approx. 0.8 are limits that should only be crossed on an incidental basis. This would not be harmful, only less comfortable (see also figure 5.3). For a better assessment of what else can be done with clothing, a rough guideline is that a difference of 0.2 clo means a difference in temperature of around 1 °C.

The table in figure 5.8 shows separately how the summer situation would look if an air velocity of v = 0.4 m/s were the starting point (greater air movements as a result of the windows being opened). This appears to help the temperature rise by around 1 °C. However, it should be realised that by no means in all areas of the room can such an air velocity be achieved, and that in certain locations the prevailing air velocity will be much too great, leading to arguments about whether windows should be open or closed, if the room is shared by more than one person. These tables highlight the influence of the radiation temperature through the difference in air and radiation temperature. $T_\ell = T_s$ therefore applies to a room with a limited proportion of outside walls, or to an internal space with a lightweight building construction, or to a situation that has become reasonably stationary (continuous heating).

		Air temperature [°C] winter ($I_{clo,i}$ = 0.9)			summer ($I_{clo,i}$ = 0.7)		
	PMV=	-0.8	-0.5	0	0	+0.5	+0.8
Activity level I, M = 85 W							
	$T_s = T_\ell$	24	24	26	27	28	29
	$T_s = T_\ell - 2$	24	25	26	28	29	29
	$T_s = T_\ell - 4$	25	26	27	28	30	30
	$T_s = T_\ell + 2$	23	24	25	26	27	28
	$T_s = T_\ell + 4$	22	23	24	25	26	27
Activity level II, M = 105 W							
	$T_s = T_\ell$	21	22	24	25	27	28
	$T_s = T_\ell - 2$	22	23	25	26	28	29
	$T_s = T_\ell - 4$	23	24	26	27	29	29
	$T_s = T_\ell + 2$	20	22	23	24	26	27
	$T_s = T_\ell + 4$	20	21	22	24	25	26
Activity level III, M = 130 W							
	$T_s = T_\ell$	19	20	22	24	26	27
	$T_s = T_\ell - 2$	19	21	23	24	26	28
	$T_s = T_\ell - 4$	20	22	24	25	27	28
	$T_s = T_\ell + 2$	18	19	21	23	25	26
	$T_s = T_\ell + 4$	17	18	21	22	24	25
Activity level IV, M = 160 W							
	$T_s = T_\ell$	15	17	20	22	24	25
	$T_s = T_\ell - 2$	16	18	21	22	25	26

	$T_s = T_\ell - 4$	17	19	22	23	26	27
	$T_s = T_\ell + 2$	15	16	19	21	23	24
	$T_s = T_\ell + 4$	14	15	18	20	22	24
Activity level V, M = 200 W							
	$T_s = T_\ell$	11	14	17	19	22	23
	$T_s = T_\ell - 2$	12	14	18	20	22	24
	$T_s = T_\ell - 4$	13	15	18	20	23	25
	$T_s = T_\ell + 2$	11	13	16	18	21	23
	$T_s = T_\ell + 4$	10	12	15	17	20	22

Figure 5.7 Required air temperature for a particular PMV value (ϕ= 50%, v = 0.15 m/s)

	Air temperature [°C] during activity level								
	II, M = 105 W			III, M = 130 W			IV, M = 160 W		
PMV=	0	+0.5	+0.8	0	+0.5	+0.8	0	+0.5	+0.8
$T_s = T_\ell$	26	28	28	25	26	27	23	25	26
$T_s = T_\ell - 2$	27	28	29	25	27	28	24	26	27
$T_s = T_\ell - 4$	28	29	30	26	28	29	24	26	28
$T_s = T_\ell + 2$	26	27	28	24	26	27	22	24	26
$T_s = T_\ell + 4$	25	26	27	23	25	26	22	24	25

Figure 5.8 Required air temperature for the PMV value indicated, where different levels of activity are taking place (clothing resistance 0.7 clo, ϕ= 50%, v = 0.4 m/s)

Where $T_s = T_\ell - 2$ or $T_\ell - 4$, this means the radiation temperature lags behind the air temperature. This occurs near cold glass surfaces, or in sturdier buildings during the first part of the day, especially after weekends when the indoor temperature has been lower at night (because of energy efficiency considerations). In buildings with air heating systems especially, this will be felt very keenly. This situation can also occur during the summer when, by incoming solar radiation, the indoor air temperature rises quickly, for example through the convective heat emissions of furniture or internal sunblinds, while the radiant temperature lags behind. Naturally this does not apply to the location immediately behind the internal sunblinds. What happens there is as follows.

A difference of $T_s = T_\ell + 2$ or $T_\ell + 4$ occurs in spaces where one or more surfaces are clearly warmer than the air temperature. This applies, for example, in situations with radiant heating or with surfaces that have been strongly heated up by the sun during the summer. The situation also occurs in buildings where the inside air has been cooled mechanically. In the case of ceiling cooling (low radiant temperature), the situation is directly reversed. In this case, $T_s = T_\ell - 4$ and for a relative high inside air temperature (see figure 5.8) a comfortable situation can still be achieved.

Relative air humidity

The level of relative humidity hardly matters in terms of thermal comfort. An upper limit of ϕ = 70%, or a moisture content of x = 12 g/kg, is often maintained. There is no lower limit from a comfort point of view, although often it is set at ϕ = 30%, as below this level there is an increased chance of static electricity occurring which causes dust to move around leading to the irritation of the mucous membranes. It is therefore a good idea to consider these values for relative humidity from a general comfort point of view.

5.3 Adaptive thermal comfort

The indoor climate criteria discussed above are based on a static comfort model. However, the following points should be noted:

- The clothing resistance should be known. Apart from the inherent uncertainty of its
- value – even when knowing the specific clothing pieces – this is one of the variables that a person will actually use to optimise his own level of comfort with the climate, as opposed to this being a fixed, determining factor.
- The metabolism that goes with a particular activity can vary considerably.

- The model assumes steady-state situations. In other words, the effect of the dynamic character of thermal conditions is omitted.
- The static model works on the idea that only thermophysiological aspects determine thermal sensations. However, it is clear that nonthermal factors also play a role: in particular the degree to which persons can themselves influence their surroundings, but also their expectations with regard to the thermal indoor climate are important factors.

In principle, the first two points can be dealt with by varying the input variables for clothing resistance and metabolism when using the static models. However, this seldom happens. The third point is, as expected, of only limited importance, because the situation under

consideration (office work) is more or less stationary. The most important point is the fourth. Research by Brager and De Dear in particular has provided much insight into how users of buildings valuate the indoor climate in the actual (practice) situation. When account is taken of adjustments to clothing resistance levels at various outside temperatures, the same 'comfort temperatures' using Fanger's static model are obtained for buildings with a centrally controlled indoor temperature and in which the windows cannot be opened, as with the adaptive model, which was drawn up on the basis of information gathered through field research. This is shown in a graph in figure 5.9.

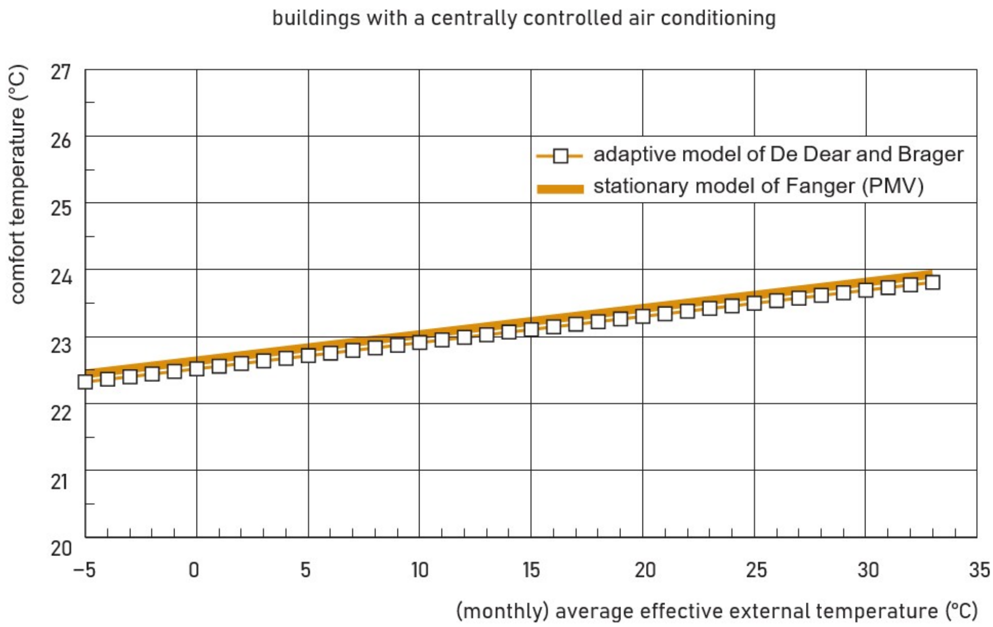


Figure 5.9 Comfort temperature in relation to average outdoor temperature in closed buildings with a centrally controlled climate installation

For buildings in which the windows can be opened and where the occupants can influence the indoor climate themselves, it appears that the 'comfort temperature', as stated by the building's users, is not the same as the 'neutral thermal situation', as defined by the PMV model. In the case of low outdoor temperatures, the comfort temperature is lower than that of PMV model, and higher when outdoor temperatures themselves are higher (see figure 5.10).

It turns out that in practice the comfort temperature in naturally ventilated buildings moves much more markedly in line with the outdoor temperature than might be explained using the static PMV model. If account is taken of changes to clothing resistance and of air velocity in the room when the temperature is higher, this explains only half the difference. The other half appears to be related primarily to the psychological ability to adjust to an indoor climate that follows outdoor conditions much more closely, than in a climate- controlled building. The conclusion is that the recent thermal history experienced by a person has an important role to play, along with the expectations that a user has in relation to his surroundings. The comfort temperature in the adaptive model is related to the 'average outdoor temperature'. For the summer situation in the Netherlands – where the average daytime temperature over a period of several days is never higher than 23–25 °C – this means that differences that stray from the values obtained from the PMV model are limited to around 1 °C (see figure 5.10). Combined with the fact that until 2005 calculations using a comfort temperature that followed the outdoor temperature had hardly ever been used in practice, the new insights nevertheless represent a significant practical improvement. This applies especially to the upper limit to the indoor temperature. Higher outdoor temperatures provide greater leeway, while when they are lower the standard values become stricter in relation to the 'old' standard value of 25 °C. This latter factor has consequences for buildings with sealed facades and centrally controlled air conditioning. It also explains the dissatisfaction among users in some of these buildings.

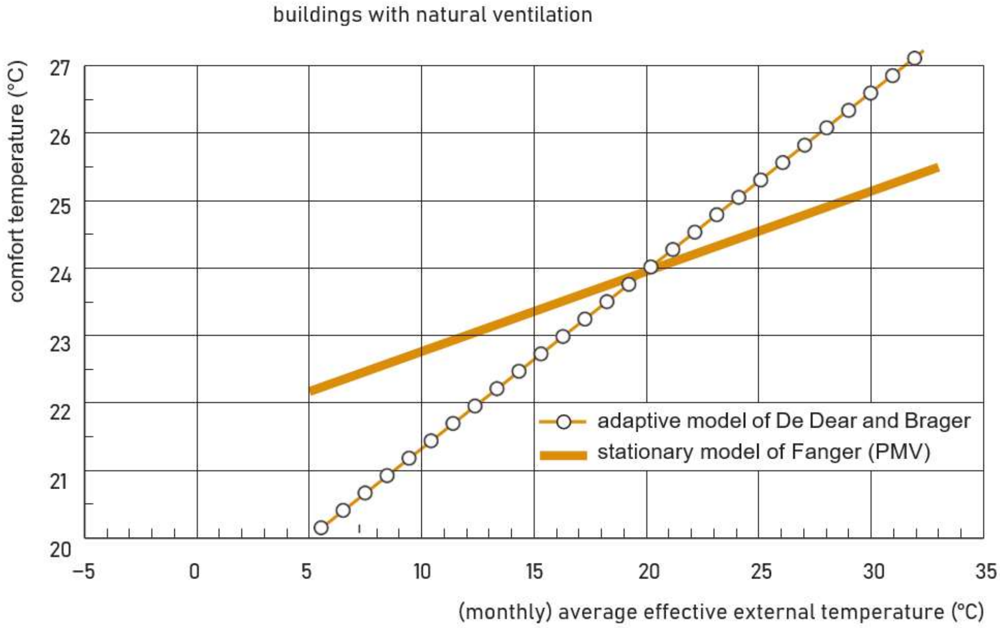


Figure 5.10 Comfort temperature in relation to average outdoor temperature in naturally ventilated buildings, where there are opportunities for individuals to influence the indoor climate

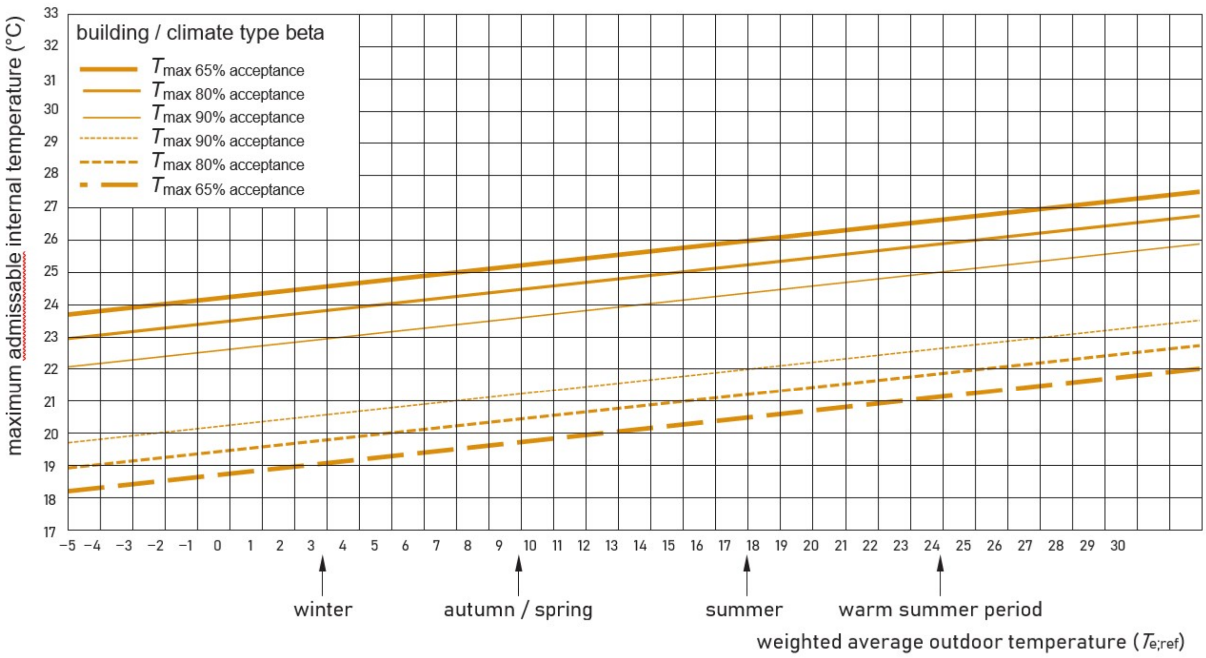


Figure 5.11 Maximum admissible operational indoor temperature given a certain level of acceptance, depending on the outdoor temperature $T_{e;ref}$, for buildings with sealed facades and centrally controlled air conditioning. To give the full picture, the lower limits are also shown.

Indoor temperatures of 25 °C when outdoor temperatures are lower in spring and autumn are simply too high. In figure 5.11 and 5.12, an indication is given of what these insights mean for the assessment of certain indoor climate situations in offices. In the Netherlands, these standard values are further elaborated for practice situations in publications by ISSO and NEN.

A distinction is made in figure 5.11 and 5.12 between building and climate types – alpha and beta. Alpha is used for buildings in which the windows can be opened and where the users can influence the indoor thermal climate, while beta applies to buildings with sealed facades and centrally controlled air conditioning. As far as the maximum and minimum admissible indoor temperatures are concerned, the limits relate to the operational temperature, accepted as the mathematical average of the air temperature and the radiation temperature.

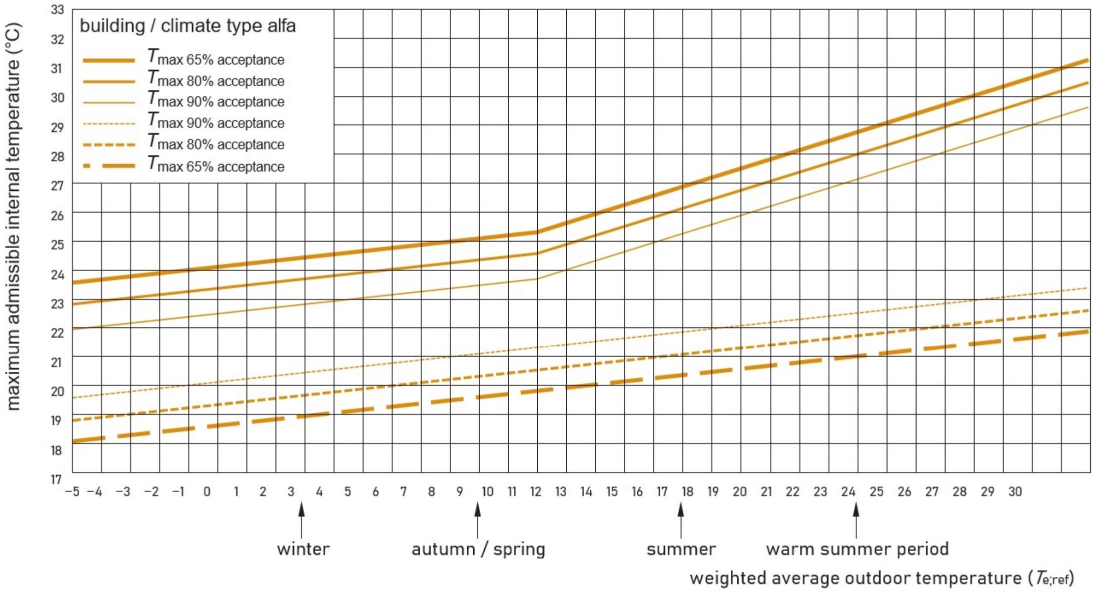


Figure 5.12 Maximum admissible operational indoor temperature given a certain level of acceptance, depending on the outdoor temperature $T_{e;ref}$, for buildings in which the windows can be opened, and where there are sufficient opportunities for individuals to influence the indoor thermal climate. To give the full picture, the lower limits are also shown.

A good approximation of the reference outdoor temperature, $T_{e;ref}$ is worked out from the average of the maximum and minimum outside air temperatures of the day in question and the three preceding days, according to the following formula:

$$Te;ref = \frac{T_{today} + 0.8 \cdot T_{yesterday} + 0.4 \cdot T_{bf.yesterday} + 0.2\, T_{bf.bf.yesterday}}{2.4}$$

During the season when heating is used (with average outdoor temperatures below 10 to 15 °C), there is effectively no such thing as an alpha building/climate. The effect of behavioural adaptation (such as clothing) does still play a role, but psychological adaptation no longer does so. For that reason, the same operational temperature is used for alpha buildings/climates as for beta types, when Te;ref is below 10–12 °C. This can be seen in the alpha building/climate graph in the lines to the left of the bend. To complete the picture, the lower limits for 65, 80 and 90% acceptance levels have been included in the graph, shown with dotted lines. For both alpha and beta types of building/climate, the lower limits for buildings with sealed facades are used. Where the lower limits are approached, it is assumed that the perception of the building's users, in both types, will be around the same, and that the windows will be closed. The figures apply to a general office setting and other comparable situations. Where there are unusual circumstances, the value limits can be modified according to metabolism and the clothing resistance in that particular situation. The starting point for a standard situation is an 80% level of acceptance of the limits. This can be raised to 90% for buildings where an extra high level of quality is sought. The limits for 65% acceptance can be used as a reference point for existing buildings (measurements in older buildings following complaints), or for temporary buildings – these limits should not in fact be exceeded. However, in all cases, it has to be accepted that occasional exceeding will occur in exceptionally hot periods, in order to prevent the need for installing extremely large climate services.

5.4 Local discomfort

In addition to the general indoor climate situation discussed above, it is necessary to take account of local discomfort. Uniform air and radiant temperatures are assumed in the standard situation, but the overall comfort experience can also be affected by too great a vertical temperature gradient (where the difference in temperature between the head and the feet is too great), or by an asymmetrical radiation exposure (cold window, temperature of radiant heating too high). A floor that is too cold, or air velocity that is too high, can also cause problems.

Vertical temperature gradient

If general levels of comfort are found in –0.5 < PMV < 0.5, or within the adaptive temperature limits, and there is no radiation asymmetry (see below) or draught, then a difference in air temperature of 3 °C between the head (1.1 m) and ankles (0.1 m) is acceptable. Where the other circumstances are not known, a temperature gradient of 1.5 °C is an acceptable rule of thumb.

Asymmetric thermal radiation

The asymmetry in the radiant temperature (due to a cold window, for example) should not be greater than 10 °C. Vertically (heated ceilings), the asymmetry should not exceed 5 °C. Asymmetry here refers to the difference in the radiant temperature that is received on one side of a room (the window, for example) from a hemisphere, and by the other side of a room from a hemisphere. This also applies vertically. It should be realised here that it is not just a question of the temperature of the window or ceiling, but of the average radiant temperature of all the surfaces visible within the range of a hemisphere.

Floor temperature

In places where people wearing normal footwear are present, the minimum recommended surface temperature is 19 °C, and the maximum is 28 °C. A lower temperature is found in many buildings at night in the interests of energy efficiency, which means that buildings have to be heated up again at the beginning of the day. If the floor remains too cold, this causes discomfort. The minimum temperature mentioned above should therefore be reached no later than 90 minutes after the start of the working day. It is especially important to remember this in the case of floors located above outdoor air. Such floors should be properly insulated and be covered on the top side with a material with a slight heat capacity (light finishing layer, carpet). The maximum temperature is important with buildings with floor heating, and this should be carefully borne in mind when designing floor heating systems.

Air velocity

Designers of mechanical ventilation installations, air-conditioning and air-heating systems should consider with care what air supply grids to use in order that the air velocities in the areas where people are present are not too high. The table in figure 5.13 shows the maximum admissible average air velocity with a given air temperature, for the various levels of activity.

Air temperature [°C]	maximum admissible air velocity v [m/s], for activity level			
	I-II	*III*	*IV*	*V*
20	0.15	0.15	0.20	0.20
22	0.15	0.20	0.20	0.20
24	0.20	0.20	0.20	0.30
26	0.30	0.30	0.30	0.40
28	0.30	0.40	0.40	0.40

Figure 5.13 Maximum indoor admissible air velocities with various air temperatures for the different levels of activity shown in figure 5.5, and where $T_\ell = T_s$

The air velocity should not be allowed to fluctuate too much either. All this information applies not only to air currents caused by climate installations, but can also be used for assessing problems arising naturally, such as draughts or cold downdraughts. However, more sophisticated assessment methods for air velocity (draughts) are starting to appear. The fluctuation in air velocity also appears to be very important.

6 Ventilation and infiltration

A.C. van der Linden

Ventilation with fresh outside air is necessary for good air quality inside a building, and for controlling the indoor environment during the summer. At the same time, it is important to distinguish basic ventilation from summer ventilation. Unmanaged ventilation with outside air through (opening) joints (infiltration) is undesirable as it causes draughts and unnecessary energy consumption. For that reason, this chapter also covers the air permeability of the building shell.

The stack effect, or chimney effect, plays an important part in the driving forces for natural ventilation.

Basic ventilation is the minimum necessary for having good-quality air in a building. Because air quality has a direct influence on health, the Buildings Decree contains requirements with regard to basic ventilation. Summer ventilation is the extra ventilation that is needed for the removal of excess heat from a building during the summer months. Insufficient summer ventilation leads to unpleasantly high temperatures in buildings without air conditioning. High indoor temperatures in summer (heat waves) also result in a higher mortality rate in the elderly and sick in particular. It is therefore very important to have proper summer ventilation and to make use of the building mass and mechanical cooling if necessary. Ventilation can either occur naturally or be provided mechanically. In both cases it is important that the ventilation installations are designed with deliberation, and above all that they properly meet the needs relating to the types of ventilation mentioned above – basic ventilation and summer ventilation.

Ventilation is sometimes confused with infiltration. Infiltration is the exchange of air between the inside and outside through (opening) joints in the shell of the building. It can lead to draughts, prevent air from being properly divided through the building and cause energy to be wasted. Infiltration is considered undesirable as it actually amounts to the unregulated exchange of air. The degree of infiltration is determined by the air permeability level of the outer wall, the floor at ground level, and the roof. As restricting infiltration – and therefore the air permeability of the shell of the building is so important, this chapter deals with the air permeability of the shells of buildings, in addition to basic and summer ventilation.

6.1 Basic ventilation

Ventilation is needed for various reasons. People and animals exhale carbon dioxide and give off moisture, both of which are the product of burning off nourishment (metabolism) for which oxygen is required. The primary function of ventilation is therefore to extract the carbon dioxide and moisture, and ensure the supply of oxygen. In addition, it can also remove odours given off by people or materials (such as furniture, floor covering, etc.), but also hazardous substances (gases, vapours), radon (radioactive gas), micro-organisms and dust. In all areas where people or animals live or work, ventilation that deals with any of these aspects is a necessity. As previously mentioned, ventilation of this kind is known as basic ventilation. The requirements as set down in ventilation regulations, usually deal with this basic ventilation.

A person needs around 100 litres of oxygen per hour. A cubic metre of air contains more than 200 litres of oxygen, so a modest level of ventilation is all that is required to prevent the oxygen content from falling too low. Odorants can be measured directly within increasing ease and can therefore be directly used as a criterion for indoor air quality. However, since the production of odorants and (other) waste products broadly match the CO_2 production and since the latter can be measured much more easily, the level of CO_2 is usually used as a criterion for the indoor air quality (freshness). The concentration of CO_2 has to become very high indeed before CO_2 levels will start to form a real problem. At a carbon dioxide level of approximately 0.12% (1200 ppm), the air is as a rule not yet experienced as being stuffy. Based on this hygienic limit, the required ventilation level results in 25 to 30 m^3/h per person. These values are the minimum required ventilation levels for a long-term stay in a room. Judging the 'freshness' of the air, however, is still a subjective matter. Fanger developed a method based on which a sound decision can be made in respect of the air purity without directly measuring the CO_2 level or the odorants. In order to measure air quality, this method uses the human nose via specially trained smell panels. As unit for the source strength of the pollution, the Olf unit (one standard person) was introduced. The air quality based on smell is expressed in Decipol (dp). An advantage of this method is that not only odorants produced by people are considered, but also odorants coming from the furniture. Disadvantages of this method are the complex way in which air quality is determined and the impracticability of the results for the (automatic) control of ventilation installations.

In the regulations, distinctions are usually made between rooms and areas where people gather. The minimum ventilation level is made dependent on the occupancy (number of people per m^2 of surface area) and the activities taking place in a building. When laying down the requirements in advance in regulations, there is no information on the actual number of people that will be present. Not only will these details vary over time, they will also simply not be known at the time the building application is made. In principle, the applicants themselves can indicate the relevant function or functions of the building involved (education, shop, etc.). The function can be used as a basis to work out the intensity or intensities of use that might be expected. A low intensity of use will mean limited requirements being made in relation to the ventilation flow and also brings benefits when it comes to working out the dimensions of the necessary equipment. It goes without saying that opting for a low intensity of use will mean limitations to the uses to which a building may be put. For example, if planning permission is granted for a building with a sports function on the basis of its having a relatively low intensity of use, there may be problems in obtaining an occupancy permit for holding, say, a fleamarket there.

Ventilation systems

As far as basic ventilation is concerned, the building legislation places obligations not only on the amount of ventilation, but also on the systems that are needed to provide it.
Imposing requirements on the way ventilation systems are made rules out as much as possible the need for their being switched off – as a result of a draught, for example. It is

important that every room has a facility for the provision of fresh air and for the extraction of indoor air, and of course the capacity of both facilities should correspond with the required ventilation flows. For premises where people live, the supply of fresh air has to come directly from outside or from a different area where other people are present, or from a corridor or staircase that forms part of the same building, with a minimum of 50% of the required capacity coming directly from outdoors.
Where a building has other functions, the supply of fresh air to where people are located has to come entirely from outside. Stale or polluted air in the toilet, bathroom and kitchen must always be directly extracted. It remains debatable as to what constitutes 'directly from outside'. Does it include ventilation air that has originated in a conservatory, or which has passed hundreds of metres through a ventilation duct? Supplying air from a conservatory is not allowed if it is a place where people sit or pass through.
Supplying air through ventilation ducts is always permitted, although research has shown that this can have a disadvantuous effect on air quality.

Natural and mechanical ventilation

Ventilation can take place naturally or be provided mechanically. Both systems have benefits and drawbacks. Completely natural ventilation (where natural air is supplied by natural means) or the natural supply of ventilation air in combination with mechanical extraction of it has a number of advantages over supplying and removing air mechanically:

- Many people prefer natural ventilation.
- There is a reduced chance of complaints related to the installation.
- The investment and running costs of the system are relatively low.

So although natural ventilation has a number of benefits, it is conceivable that there are a number of situations where it may not be possible, or even desirable. These might include locations with a high noise level, or buildings where there is a high degree of pollution in the surrounding area.

Natural ventilation also does not allow for easy realisation of heat recovery from exhaust air, while this is certainly desirable from energy saving perspectives. However, this too can be resolved, for example by installing a heat exchanger in the exhaust opening. An example of this is a heat pump boiler, which uses the exhaust air as a heat source. Another situation in which natural ventilation may not automatically be preferred is where the floor surface area per person is small, such as meeting rooms or school classrooms. Complaints about levels of comfort will inevitably occur in such places if only naturally ventilated air is present without any extra equipment. Rooms where more than three or four people work are also less suitable for natural ventilation. As every individual has their own definition of what is and is not comfortable, complaints are more likely as it is difficult to satisfy everyone. Manuals and practical guidelines issued by standardisation and building research organisations describe in which situations and with which systems you can meet the required ventilation levels.

Natural ventilation installations

Natural ventilation installations concern primarily those in the outer walls, such as grids and hopper windows. However, natural ventilation can also take place in part via vertical ventilation ducts. As far as the prevention of draughts is concerned, it may be assumed that no problems will occur if the underside of the grids or windows is at least 1.8 m above ground floor level. Furthermore in relation to the ease of operation it is necessary that the installation should be more or less steplessly variable. A choice between open and closed is not enough. This is often just a choice between draft or no ventilation. The provisions also need to be properly manageable. Ventilation grids and silencers should preferably be accessible from the inside so that they can be cleaned, and so that the sound-absorbing materials can be changed easily. See figure 6.1.

It may be sufficient for the underside of a ventilation grid however to be at least 1.8 m above the ground, but it cannot be guaranteed even at that height that no problems with draughts will occur in practice. When it comes to draughts, it is the area immediately behind the outer wall that is the most critical. The likelihood of draughts in winter is reduced if ventilation air is mixed with heated indoor air quickly, and this is one reason that radiators or other heating devices are often located beneath ventilation grids or windows. However, a radiator is by no means a guarantee for draught-free ventilation. It appears in practice that comfort-related problems can occur during periods of cold winter weather (–5 to –10 °C), and in spring and autumn when the heating is not on. The chances of draught-related problems can be kept to a minimum if account is taken of the following:

- ventilation grids or windows are placed
- immediately above a heating element;
- ventilation grids or windows are located as high as possible;
- the design of the building and systems is such that ventilation air and indoor air are encouraged to mix as much as possible.

Examples of the latter include horizontal sheeting (perhaps in the form of a ceiling) directly below or above the ventilation opening, or a perforated sheet immediately thereunder. Various research programmes in climate chambers show that extra facilities can help achieve positive results. Another means of cutting back the probability of draught-related complaints in the winter is, for example, to preheat the inflow air by allowing it to flow through a glass-covered area or heated passage.

Figure 6.1 Silencer where the sound absorbing material can be cleaned or replaced easily

Natural ventilation occurs as a result of differences in pressure around the building, caused by wind pressure for example, or differences between in and outdoor temperatures. The wind regularly reaches speeds of 10 m/s or more, but sometimes there is virtually no wind at all. The average wind speed in the Netherlands varies from 3.5 m/s in Limburg to 7 m/s on the North Sea coast. A natural ventilation system has to be able to provide the required level of air when the difference in temperature on the inside and outside is 10 °C, and the wind speed is 2 m/s. As far as the capacity of the installation is concerned, it is assumed that for a ventilation volume of 1 dm^3/s, an inlet of 12 cm^2 (nett) is required, and that an average air speed of around 0.85 m/s will occur. If the opening is fitted with a gauze (for insects or other reasons), the inlet should be twice as big because of dirt arising from insufficient maintenance. Less air will enter the inlet when there is no wind. However, with wind speeds of 20 m/s, the pressure on the outer wall will be so great that too much air will get in, and this is one of the most important reasons why ventilation openings should always be easily adjustable. With self-regulating ventilation grids, it is possible to keep levels of natural ventilation under control automatically, so residents do not have to operate the installation themselves all the time.

Mechanical ventilation installations

In the case of high buildings, or spaces where relatively large numbers of people are present, it is often necessary to install a mechanical system for the supply and extraction of ventilation air. The application of such a system also has a number of advantages:

- the possibility of extracting heat from the air that is removed and bringing it back into the building via the air inflow;
- the possibility of heating or cooling the ventilation air;

- the possibility of humidifying or dehumidifying the ventilation air.

Choice of systems for buildings with residential functions

A commonly used classification of ventilation systems is given in figure 6.2. It also indicates which systems meet requirements for high-rise and low-rise properties and which do not. Whether a building is high or low rise depends on the position of the highest floor in relation to the lowest. If the former is more than 13 m above the latter, the building in question has to be defined as high rise.

System	Category low-rise residental buildings	high-rise residental buildings
A completely natural ventilation	sufficient	(in)sufficient*
B mechanical supply and natural extraction	more than sufficient	(in)sufficient*
C natural supply and mechanical extraction	more than sufficient	sufficient
D mechanical supply and extraction	good	good

* Systems A and B are insufficient in high-rise buildings if combined ducts are used for natural extraction. Some air may flow back, resulting in air being transported from one home into another, which of course is to be avoided.

Figure 6.2 Ventilation systems rating according to Dutch standards

The systems in figure 6.2 are described as follows:

A natural ventilation, where:
- adjustable ventilation openings are present in the outer walls;
- vertical ventilation ducts are used at least in the kitchen, toilets, and bathrooms.

B mechanical supply and natural extraction, where:
- the supply air is brought to all rooms, etc. via a mechanical system;
- vertical ventilation ducts have to be present in at least the kitchen, toilets and bathrooms.

C natural supply and mechanical extraction, where:
- adjustable ventilation openings are present in the outer walls;
- air is extracted mechanically via a system of ducts from at least the kitchen, toilets and bathrooms.

D mechanical supply and extraction, where:
- the supply air is brought to all rooms, etc. via a mechanical system;
- air is extracted mechanically via a system of ducts from at least the kitchen, toilets and bathrooms.

Choice of systems for buildings with other functions

In deciding what kind of ventilation system to use for buildings with non-residential functions, it is possible in principle to use the classification for homes and residential buildings. The most important difference is that the air is not, or only to a limited degree, extracted via kitchens or bathrooms, but primarily via corridors and passageways. More than is the case with buildings with residential functions, it is also very rare for system B to be used in this type of building. If the truth be known, system B (mechanical supply of air and natural extraction) combines the disadvantages of natural and mechanical ventilation, but without any advantages.

If it is decided to use a natural supply together with natural or mechanical extraction, then there are basically three different systems:
- ventilation through one outer wall;
- ventilation through two opposite facing walls (cross ventilation);
- ventilation through outer wall and the roof.

The first system is based on supply and extraction via grids or windows in the same outer wall. The second system (see figure 6.3) is based on the supply of ventilation air through one of the outer walls and extraction through the opposite facing wall, a system generally known as cross ventilation. A disadvantage of this system is the possibility that dirt will be transferred from rooms on the windward side to rooms on the leeward side. In addition, if the ventilation grids in one of the facades are closed, this has a direct impact on the ventilation in the area next to the opposite facade.

The third and final system (see figure 6.4) is based on the supply through the outer wall and extraction through corridors and passageways, or the roof. The air can be extracted by both natural and mechanical means.

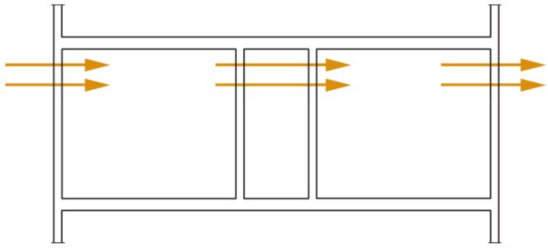


Figure 6.3 Ventilation through opposite facing walls (cross ventilation)

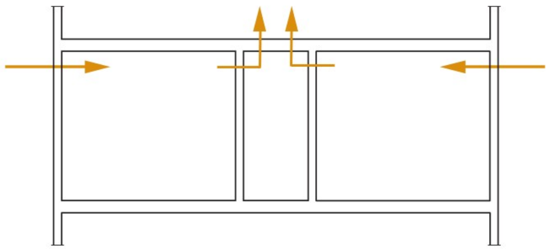


Figure 6.4 Ventilation through outer wall and roof

A disadvantage of the first system (supply and extraction through the same outer wall) is the limitations imposed on the user, such as keeping inside doors closed. Its functioning also strongly depends on the available differences in wind pressure along the facade. This means the system is of little practical use. A drawback to the second system (cross ventilation) is the increased likelihood of draughts, as more ventilation is needed for each linear metre. With wall and roof ventilation (the third system), the air can enter via both outer walls. This halves the level of ventilation for each linear metre of the walls in comparison with the second system, thus reducing the possibility of draughts. Apart from the effects on the level of comfort, this has positive consequences for facades exposed to traffic noise. In general then, the third system is the preferred option. Another important advantage of ventilation through the facades and roof as opposed to cross ventilation is that the system is easier to manage. It is also possible with this system to extract the air mechanically, either wholly or partly. This means the benefits of having ventilation air supplied naturally are maintained, while the frequently-heard objections, such as those of unreliability, are allayed. Regardless of which system is chosen, it is essential that the parts of a ventilation system work together as an integrated entity.

6.2 Summer ventilation

As stated in the introduction, summer ventilation (also known as purge ventilation) is needed for extracting heat during the summer months. The purpose of summer ventilation is to control the indoor temperature in buildings without any mechanical cooling. A condition for ventilation to be effective is that the outdoor temperature is lower than that indoors. There is a clear distinction between daytime and nighttime hours as far as summer ventilation is concerned. During daytime, excess heat should be extracted by ventilation as much as possible. If the mass of the building is sufficient, some of the excess heat can be stored in it, so this can be extracted through ventilation at night.

Daytime

The amount of summer ventilation required depends on how much heat is produced in a building, and on a number of features of the building. The heat produced in a building by people, machines, and so on, is known as the internal heat load. The internal heat load is dependent among other things on the floor surface area per person, and the organisation. In office buildings, the internal heat load will rarely be greater than 30 W/m² of floor surface. Statements of Requirements often quote a level of 35 to 40 W/m². By using energy-efficient equipment and lighting, and by applying a certain degree of synchronicity, the internal heat load can often be reduced to 25 to 30 W/m². The features of the building that can help determine the amount of ventilation that is required are primarily the dimensions of the windows and the quality of the sun-blinds, both of which directly influence the amount of summer heat that can enter.

With factory and office buildings in particular, the maximum allowable ventilation flow is limited in the summer months. In the daytime, the flow is restricted due to the levels of thermal comfort experienced by the users, and by the practical consideration of not having large quantities of paper blowing all over the place. The maximum ventilation in these circumstances is about five times the amount of air in the room per hour.

Appliances

Summer ventilation appliances generally consists of windows that can be opened. Regardless of the system used for basic ventilation, opening windows will cause mostly cross ventilation. A window (that can be opened) of about 0.5 m² should be assumed for both outer walls for the purpose of summer ventilation. Note that it should be possible to open the windows completely. If a 0.5 m² window can only be opened 0.1 m, the ventilation surface is then not 0.5 m², but only 0.05 m².

Nighttime

In addition to summer ventilation in the daytime, night ventilation is very important when it comes to temperature control in the summer. In buildings with a reasonable mass, the daytime indoor climate is controlled by virtue of the fact that some of the heat is stored by the building mass, which then has to be removed after working hours. The effect of night ventilation will obviously be greater, the higher the mass of the building, and therefore the more heat that can be stored in the daytime. In buildings with not so much mass or buildings where the mass is shielded by a lowered ceiling, for example, there is less possibility for heat to be stored. This can lead to a considerable increase in the daytime temperature.

Appliances

In general, the appliances that are used for basic ventilation are the same as used for night ventilation. Depending on whether or not extraction takes place mechanically (in part or otherwise), the level of ventilation will amount to between once or twice the air volume of the room per hour. Given that windows that can be opened have a greater capacity than ventilation grids, they should theoretically be preferable. In practice, of course, windows are closed at night to prevent break-ins, so ventilation grids are used, in spite of their lesser capacity.

6.3 Driving forces behind natural ventilation

As discussed above, natural ventilation is caused by two different forces: wind pressure and stack effect. The latter is also referred to as the chimney effect. We will not discuss these phenomena too deeply within the context of this book, but only address the essentials.

Wind pressure

From aerodynamics, we know that the speed pressure generated by flowing liquid or gas follows from:

$$p = ½ \cdot \rho \cdot v^2 \text{ [Pa]}$$

The meaning of the symbols is:

ρ the density of the flowing medium (for air this is approx. 1.25 kg/m^3)
v the rate of flow of the medium in m/s

Where the air speed around a building (wind) is concerned, the speed at the roof edge (v_r) is used for reference. The flow however is distributed around the building. The greatest pressure is created at the top on the windward side and just above that, on the flat roof, the strongest pull (negative pressure) is generated.

In addition, under pressure is created on the sides parallel to the wind direction. This is determined and represented for a great number of situations. Figure 6.5 and 6.6 give an idea of what this looks like. The numbers in these figures concern the so-called wind pressure coefficient (cp). De value for the speed pressure calculated using the above formula must be multiplied with this cp value in order to find the pressure on the facade or roof at the relevant location.

$$p = c_p \cdot ½ \cdot \rho \cdot v_r^2 \text{ [Pa]}$$

The meaning of the symbols is:
c_p the wind pressure coefficient
v_r the wind speed at the location of the roof edge (reference)

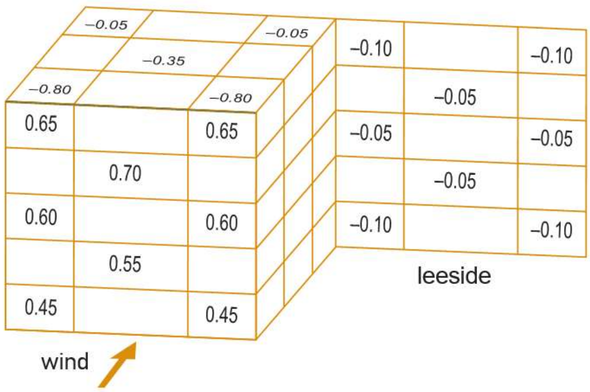


Figure 6.5 Wind pressure coefficient c_p on the windward side and leeside for a medium rise building

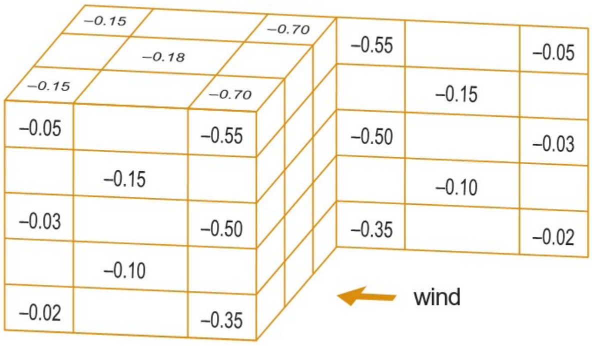


Figure 6.6 Wind pressure coefficient c_p for wind parallel to the facade

The difference in wind pressure between the various places on the building shell produces the driving force for ventilation. The total available pressure difference between windward side and leeside for wind perpendicular to one of the facades follows from:

$$\Delta p = (c_{p,windward} - c_{p,lee}) \cdot ½ \cdot \rho \cdot v_r^2 \text{ [Pa]}$$

In the formula $c_{p,windward} - c_{p,lee}$ is the difference of the wind pressure coefficient between two opposite facades of the building.

In figure 6.5, for a wind speed of 4 m/s for the pressure difference on the top floor of the building, it follows that:

$$\Delta p = 0.65 - (-0{,}10) \cdot ½ \cdot 1.25 \cdot 4^2 = 7.5 \text{ Pa}$$

For a wind speed of 2 m/s: 1.875 Pa.
For a wind speed of 8 m/s: 30 Pa.

For the ground floor of the building, the available pressure difference at a wind speed of 4 m/s is equal to:

$$\Delta p = 0.45 - (-0{,}10) \cdot ½ \cdot 1.25 \cdot 4^2 = 5.5 \text{ Pa}$$

Naturally, other values for the wind pressure coefficients apply for situations where the wind is parallel to the facade (see figure 6.6) or is at a certain angle. Effectively, this means that calculations need to be made for all possible situations.

The distribution of the wind speed above ground level varies according to the surroundings (open terrain, scattered buildings, city, etc.). Manuals list so-called ‘wind speed profiles’ for this distribution. Based on the wind speed measured by meteorological services at the standard height of 10 m above ground level, the wind speed at a specific height can be determined. For the average wind speed at a height of 10 m in the Netherlands, a value of 4 to 5 m/s can be used. This can be your starting point when calculating the ventilation level for calculations concerning the general energy loss through ventilation. Ventilation levels must also meet requirements at lower wind speeds. A speed of 2 m/s usually serves as a basis for this. The flow of ventilation that arises at a certain pressure difference depends on the size and shape of the flow-through openings. These determine for example the level of contraction and dispersion. At the edges of the opening, extra resistance occurs as the air there is slightly blocked causing turbulence.

The flow characteristics of the opening are described by flow coefficient C_d. For the average window a value applies of C_d = approx. 0.8. Several manuals list the values of C_d for a variety of situations.

The flow volume can now be determined with:

$$\Phi = C_d \cdot A_e \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} \text{ [m3/s]}$$

A_e is the equivalent flow-through opening (in case of a single window this is the nett inlet in m^2). In the situation where the air flow runs through two openings, one of the windward side and one on the leeside, there is of course higher flow resistance. The openings then have to be slightly larger in order to realise the same flow volume. In relatively large openings and turbulent flow, you can compensate for this with the following formula:

$$\frac{1}{A_e^2} = \frac{1}{A_{window}^2} + \frac{1}{A_{lee}^2} \text{ [m}^{-2}\text{]}$$

For two equal openings, the required window opening can be found through:

$$A_{window} = \sqrt{2 \cdot A_e}$$

For a random number of openings on the route of the air flow – cracks under doors, etc. – the equivalent flow-through opening can be determined in a similar way. For each opening you have to determine whether the flow is laminar or turbulent. For an opening such as a window (a normal square whole of reasonable dimensions), the flow can be considered to be turbulent. For air flow through a small crack (a duct, etc.), laminar flow may be at play and different formulas will apply.

For the basic ventilation via continuous, adjustable hopper windows, self-regulating or otherwise adjustable ventilation grids and suchlike, similar calculations can in principle be made. However, ventilation grids do not have a simple square opening, which is why the true air passage can in reality only be determined through measurements. The catalogues of grid manufacturers lists the flow volume which can pass through a specific grid at a certain pressure difference. Naturally, this also applies to self-regulating grids which make proper well-regulated natural ventilation possible, especially when sufficient pressure difference is guaranteed due to mechanical extraction.

The above clearly shows that it is not easy to determine for which situation (wind direction, wind speed, etc.) you must make ventilation calculations. Besides, natural ventilation does not occur only through wind pressure: the stack effect also plays a role (see below). This means that ventilation is also possible when it is practically windless. As all of this requires a great deal of knowledge and because regulatory bodies seek

Example

Assume a situation with a through lounge or living room/kitchen combination at the top floor of an apartment building for which summer ventilation must be realised through the windows of the facades opposite. Assume the apartment building is similar in terms of its location, shape and dimensions to the building in figure 6.5. For the pressure difference between the front and rear aspect a value of Δp = 1.875 Pa was found at a wind speed of 2 m/s at roof level.

Assume 600 m^3/h ventilated air is required (ventilation rate n = 4 – 5). What should the dimensions of the hopper windows be?
For the calculation, the required flow volume is expressed in m^3/s, or ϕ = 600/3600 = 0.167 m^3/s. Entering this into the formula above results in:

$$\Phi = C_d \cdot A_e \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} = 0.8 \cdot A_e \cdot \sqrt{\frac{2 \cdot 1.875}{1.25}} = 0.167 \text{ m}^3/\text{s}$$

This results in a required equivalent flow-through opening Ae = 0.120 m^2. For two equal-sized windows, the required opening results from:

$$\frac{1}{A_e^2} = \frac{2}{A_{window}^2} \text{ [m}^{-2}\text{]}$$

So that

$$A_{window} = \sqrt{2} \cdot A_e = \sqrt{2} \cdot 0.120 = 0.170 \text{ m}^2$$

This means that if the hopper windows have a height of 1.20 m, they need to be opened to at least 0.170/120 = 14 cm in order to deliver the required level of ventilation.

unambiguity, building regulations and standards provide simplified methods with predetermined general solutions for a great number of situations.

A rule of thumb for determining the flow volume for summer ventilation is that, in cross ventilation for example, an air speed of 0.4 m/s is assumed in the opening. For the window from the example calculation which is 14 cm ajar you can calculate the ventilation level as follows: $\phi = A_{window} \cdot v_{window} = 0.170 \cdot 0.4 = 0.068\ m^3/s$ or $0.068 \cdot 3600 = 245\ m^3/h$. This is not even close to the level of 600 m^3/h we wanted to achieve. Rules of thumb: always err on the 'safe' side. If you use this rule of thumb to determine the required window opening, it should be possible to open the window by 35 cm.

Stack effect

Because air has different densities (ρ) at different temperatures, a pressure difference arises between the inside and outside of a building. The total height of a residential home easily reaches 7 m from ground level to the roof. For a situation where the air inside the house is warmer and therefore lighter than the outside air, the heavy outside air will force the light air to rise.

The density of air at 273 K (0 °C) and a barometric pressure of 100,325 Pa is $\rho = 1.293\ kg/m^3$. For other temperatures, the density can be calculated with:

$$\rho = \frac{1.293 \cdot 273}{T} \text{ [kg/m}^3\text{]}$$

ρ is the air density at a temperature of T in Kelvin.

Figure 6.7 represents a drawing of the cross section of a home. The difference in height between two window openings or ventilation grids is h m.

With the above formula for air density, the pressure difference expressed as the difference in weight of two columns of air with height h and temperatures Ti and Te can easily be determined from:

$$\Delta p = \frac{1.293 \cdot 273 \cdot (T_i - T_e) \cdot g \cdot h}{T_i \cdot T_e} \text{ [Pa]}$$

The meaning of the symbols is:

Δp the pressure difference between inside and outside across h in m
T_i the inside temperature in K
T_e the outside temperature in K
g the acceleration of gravity (9.81 m/s^2)
h the difference in height between the two openings under examination

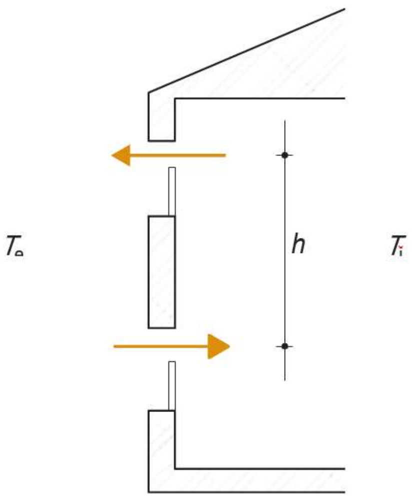


Figure 6.7 Stack effect principles

Assume the values in the example of figure 6.7 are as follows: h = 3 m, T_i = 295 K (22 °C) and T_e = 278 K (5 °C). The pressure difference is:

$$\Delta p = \frac{1.293 \cdot 273 \cdot (295-278) \cdot 9.81 \cdot 3}{295 \cdot 278} = 2.15 \text{ Pa}$$

For a conservatory or atrium in an office building with a height of 35 m, the pressure difference becomes Δp = 25 Pa for the same temperatures. This driving force was also used in vertical ventilation ducts until mechanical home ventilation (extraction) came in use as a standard way to increase ventilation. A chimney is in fact a vertical duct where a large pressure difference is created because the high temperature of the flue gas duct. This is why this mechanism is also called 'chimney' effect.

Natural ventilation makes use of both mechanisms: wind pressure and stack effect. Often a hybrid system is designed to compensate for the – usually short-lived – periods when the system does not perform sufficiently due to calm winds or because the difference between indoor and outdoor temperatures is not large enough. This means that a mechanical system takes over the ventilation tasks in those periods that the natural forces fail to do their work.
You must also realise with stack effects that when the temperature difference is the other way round – when it is warmer outside than inside (which is often the case during the summer) –, the pressure difference and subsequently the ventilation flow also work the other way round.

Figure 6.8 Experimental setup of a solar chimney (research by dr. B. Bronsema)

A solar chimney also makes use of the stack effect. A solar chimney can be designed in many ways. The basic idea is that the air in a vertical shaft is heated by the sun causing an extra large stack effect. Glass is installed in the shaft on the sunny side so that extra heat from the sun can enter which is then trapped in the black rear wall. See figure 6.8 for an example of an experimental setup. The hot air can be used to heat the building, but the stack effect can also be used as 'motor' for air transport.

The design of a solar chimney is, by the way, a complex matter and it will be possible to realise additional energy savings only in combination with other provisions (integral design) and by making calculations.

6.4 Air permeability through the building shell

A few decades ago, buildings with closed windows were ventilated through (opening) joints in the building shell. A disadvantage of this type of ventilation (infiltration) is that the ventilation flow cannot be controlled. With high winds, the total ventilation flow is often many times greater than the required minimum. This results in energy being lost unnecessarily, as well as causing nuisance through draughts. To prevent draughts and the unnecessary loss of energy, requirements relating to air permeability are given in the building legislation and standards. Manuals and practical guidelines list what is required for specification with attention to the 'airtightness' of (opening) joints.

Requirements

Requirements exist for the air permeability of buildings in the shape of a maximum permissible flow volume for a given pressure difference. The volume of air flow through the totality of external dividing constructions (the $q_{V;10}$ value) of an area where people are present, toilets, or bathrooms, may for instance not exceed 0.2 m³/s at a difference in pressure of 10 Pa and a nett volume of no more than 500 m³. In the case of buildings with a greater nett volume, the air permeability is based on a volume of 500 m³. Roughly translated, this means that the air permeability for every 500 m³ of the volume of a building may not exceed 200 dm³/s (200 liters a second), where the difference in pressure between the inside and outside is 10 Pa. This level has been chosen as it represents the average pressure difference, over the period of a year, that is present at the various openings. Modern buildings in particular, including office buildings, with their high-quality curtain walls, easily meet this requirement.

Determination method

Because measurements that are taken when the air pressure is a slight 10 Pa are easily disrupted by natural differences in pressure (wind, thermal draughts), the air permeability should be measured using six different air pressure levels between 15 and 100 Pa.

Figure 6.9 gives a representation of a measurements system. As can be seen in the figure, a home is pressurized using a ventilator, for the purpose of taking the measurement. To create the supply opening for the ventilator, the front door is removed and replaced by a 'dummy' door, in which a round opening is made. A ventilator is then used to blow air into the home.

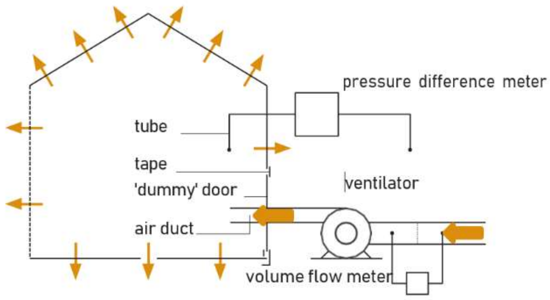


Figure 6.9 Basic sketch of measuring system for air permeability of a home

The measurement involves establishing and noting not only the volume flow rate that is needed to maintain a certain difference in pressure, but also the difference between the outside and inside pressure levels (see figure 6.10). The flow volume for the pressure difference reference (10 Pa) can be determined from these details. Figure 6.11 illustrates the notation of the measurement details on double logarithmic paper. From this graph, indicating the relationship between flow volume and pressure difference, the flow volume at 10 Pa can then be read.

Example

Δp in Pa	q_V in dm³/s
15	740
20	840
27	1080
34	1200
40	1320
50	1530

Figure 6.10 Example of results of air permeability measurements in a house

It can be seen from the graph in figure 6.11 that the volume flow rate at 10 Pa is equivalent to:

$q_{V;10}$ = 580 dm³/s

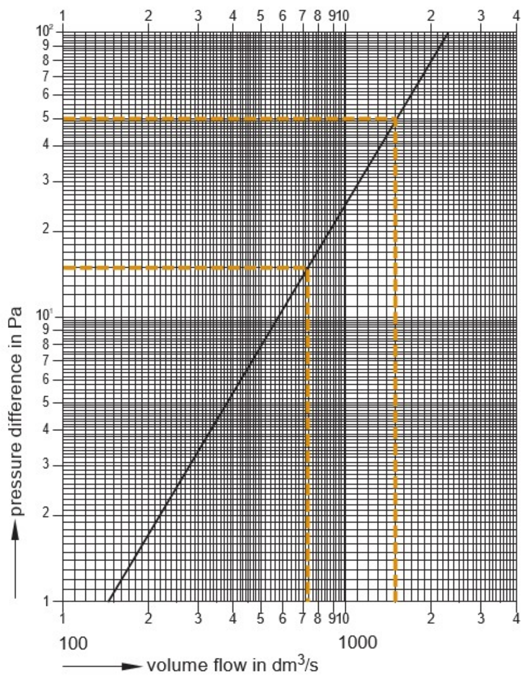


Figure 6.11 Representation on double logarithmic paper of the results shown in figure 6.10

Example calculation of air permeability coefficient

The air flow through an opening can be described in general terms using the following comparison:

$$q_V = C \cdot \Delta p^{\frac{1}{n}} \text{ [dm}^3\text{/s]}$$

The meaning of the symbols is:

q_V the volume flow rate in dm^3/s

C the air permeability coefficient in $dm^3/(s \cdot Pa^{\frac{1}{n}})$

Δp the difference in pressure at the opening

n the flow exponent

Quantity C is in fact the volume flow rate through the opening when the difference in pressure is 1 Pa. Note: this is a completely different quantity than the C_d from paragraph 6.3. This C is not dimensionless!

Exponent n can be determined from the series of measurements, as follows:

$$n = \frac{\log p_2 - \log p_1}{\log q_2 - \log q_1}$$

The meaning of the symbols is:

n the flow exponent

p the difference in pressure for a given measurement

q the volume flow rate of the same measurement

When the first and last measure from the example are taken (see the graph), the exponent is as follows:

$$n = \frac{\log 50 - \log 15}{\log 1530 - \log 740} = 1.66$$

The value of the air permeability coefficient C can then be found by completing the formula for the volume flow rate for one of the measurements that is more or less on the line of the graph:

$$q_V = C \cdot \Delta p^{\frac{1}{n}} \quad \text{or} \quad C = \frac{q_V}{\Delta p^{\frac{1}{n}}}$$

Therefore:

$$C = \frac{1530}{50^{\frac{1}{1.66}}} = 145 \text{ dm}^3/(s \cdot Pa^{\frac{1}{n}})$$

The value for C can of course also be deduced from the graph in figure 6.11. The value for the volume flow rate at 10 Pa follows directly from the formula given previously:

$$q_{V;10} = C \cdot \Delta p^{\frac{1}{n}} = 145 \cdot 10^{\frac{1}{1.66}} = 580 \text{ dm}^3/s$$

Another quantity that can be determined from the measurements is the 'equivalent surface' (A_e). This is the size of a fictitious opening that lets in as much air at 1 Pa as the total openings in the shell of the building. The equivalent surface therefore represents the total surface area of the shell of the building that 'leaks'. The equivalent surface can be calculated using the following formula:

$$A_e = \frac{C \cdot \sqrt{\rho}}{10^3 \cdot 2^{\frac{1}{n}}} \text{ [m2]}$$

The meaning of the symbols is:

A_e the equivalent surface in m^2

C the air permeability coefficient in $dm^3/(s \cdot Pa^{\frac{1}{n}})$
ρ the density of the air (approx. 1.25 kg/m^3)
n the flow exponent (2 for turbulent flow, 1 for laminar flow)

In the example, with n = 1.66 A_e is:

$$A_e = \frac{145 \cdot \sqrt{1.25}}{1000 \cdot 2^{\frac{1}{1.66}}} = 0.11 \text{ m}^2$$

Note that the value for total air permeability of the shell of the building is not a direct measure for the quantity of air that enters the house through infiltration in realistic circumstances. In determining the air permeability of the shell of a building, it is always assumed that the air pressure on the outer walls is at a constant 10 Pa. In reality, air pressure around the house is distributed differently as a result of wind direction and strength, surrounding buildings, the difference between the indoor and outdoor temperatures, etc. In practice, the way in which the leaks are distributed over the shell of the building affects air permeability. In publications concerning air-tight buildings, calculation methods for determining the air permeability of a building in advance are given, based on the exterior surface area of the shell of the building, and the joints in metres.

Buildings larger than 3000 m³

The method described before cannot be used for buildings with a volume in excess of 3000 m³. Buildings of this size are too large for achieving enough pressure difference with the usual equipment. One method that does make it possible to gain an impression of the air permeability of the shell of a building with a volume greater than 3000 m³ focuses on the air permeability of a so-called representative section of the outer wall. The method assumes that the air permeability of the roof and the ground level floor in larger office buildings and factories is generally adequate. It is accepted that air leaks are found predominantly in the outer walls and at the point where the outer walls meet both the roof and the floors. For test purposes, an airtight box is placed around 1 to 2 m away from the inside of the outer wall. The box is built up of sheet material on the spot and pressed up – air-tight – against the surrounding construction (see figure 6.12).

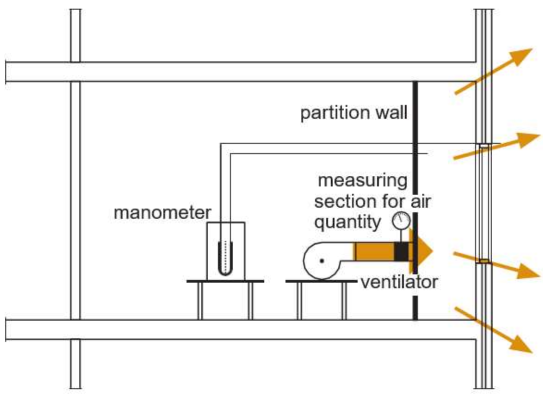


Figure 6.12 Principle of the measuring system

Air permeability of the outer wall elements

The building legislation only contains requirements with regard to the air permeability of the building as a whole. The requirements themselves are not very severe and mainly intended as minimum limits. To achieve a good indoor climate in an energy efficient building, strict requirements on, for example, the permeability of outer wall elements and windows are desirable. For evaluating windows and facade elements which are produced in a factory, separate guidelines exist. Demands are made on an air permeability test in a test cabinet. No more than 2.5 $dm^3/(s \cdot m)$ of air can be allowed to pass through cracks at test pressures as given for the Dutch situation in figure 6.13.

Height* in m	Test pressure in Pa	
	Inland	Coast**
15	75	300
40	150	300
100	300	450

* Height of the top of the topmost outer wall element above ground level which is assumed to be flat.
** The coastal area includes the IJsselmeer region and a 2.5-km zone inland from the North Sea.

Figure 6.13 Test pressures for determining the air permeability of outer wall fillings

The connections between the fixed elements and between the glass and the rabbets are considered 'closed' if no more than 0.14 $dm^3/(s \cdot m)$ of air can pass, based on the test pressures in the table in figure 6.13. In addition to the requirements mentioned above, outer wall fillings should be constructed in such a way that the air that is admitted is distributed as equably as possible. Localized concentrated leaks are permissible as long as their air permeability does not exceed 0.5 dm^3/s per 100 mm.

Basic principle of airtightness

The basic principle for making the shell of a building properly airtight is to have a double sealing system. A double sealing system consists of a moisture barrier and an air seal. It is essential that the water barrier is positioned on the outside and the air seal on the inside. A simple overlap on the connections between the various elements is sufficient for the outermost seal (the moisture barrier). Because the cavity between the two seals is directly exposed to the outside air, there is no difference in air pressure on the seal (moisture barrier). This means that rainwater that flows down on the outside of the seal is not drawn inside. However, rainwater that is driven into the cavity by strong winds may flow down the inside face of the outer wall. The airtightness in a double sealing system is provided by the innermost seal. As this seal has to be continuous, some difference in air pressure does generally occur along it.
However, this is not a problem as there is no downwardly running rainwater present at this location. Examples of an outer wall surface with a double seal system include the brick wall of a cavity or a tiled roof with a deck. In both cases, there is a moisture barrier on the outside which is generally so open that little or no difference in pressure exists between the cavity and the outside air. Where there is a single seal, it has to fulfill the function of both moisture barrier and air seal. As a result, there is a risk that any difference in pressure over the outer wall will draw rainwater inwards wherever there are any ruptures on the seal.

Detailing building components

One of the most important aspects in constructing a building that complies with the requirements relating to air permeability is the detailing. Although insufficient airtightness of an outer wall may be caused by areas of porosity in the wall, it is usually the direct result of inattention to design details. Firstly, it is important when working on the details to think three-dimensionally. A specific detail that may appear to be airtight when viewed from a vertical or horizontal cross-section, may turn out not to be so from a three-dimensional perspective. This can be clearly seen in the example in figure 6.14. The joins where the steel roof sheets meet the outer wall are, on closer inspection, anything but airtight. Secondly, it is important not only that the air seal is positioned on the inside of the shell of the building, but also that it is continuous. In fact, every detail on the inside should be constructed in such a way that it should be possible to draw an uninterrupted line, symbolizing the air seal. Anywhere that two (or more) materials border each other should have a permanent (mostly flexible) seal. This continuous line is shown in the example in figure 6.15. The air seal in the innermost cavity wall has been achieved by putting a layer of plaster (not a layer of mortar) on the cavity side. This makes the entire innermost cavity wall air-tight.

The transition from the innermost cavity wall to the window sill and from the window sill to the window frame has been achieved using a flexible sealant. Although this is generally used for this purpose, sealing band is preferred from an environmental point of view. However, the use of sealing band does require different detailing techniques to those needed when sealant is applied.

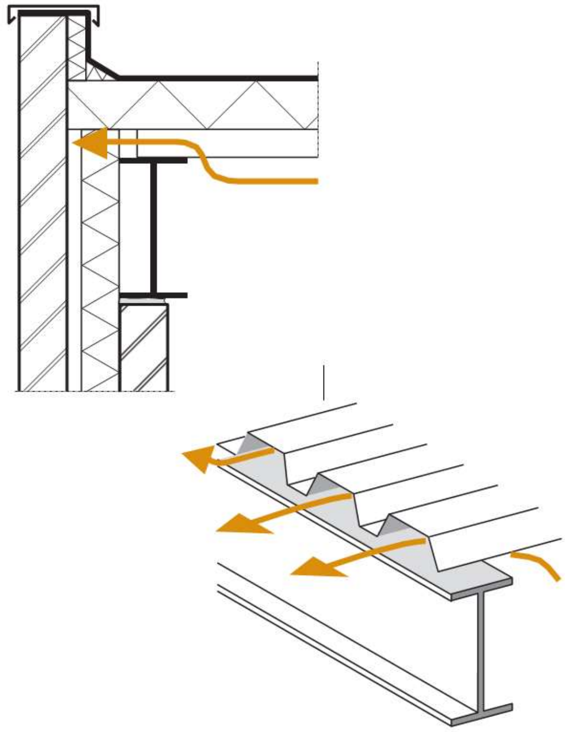


Figure 6.14 Example of air leak at join locations

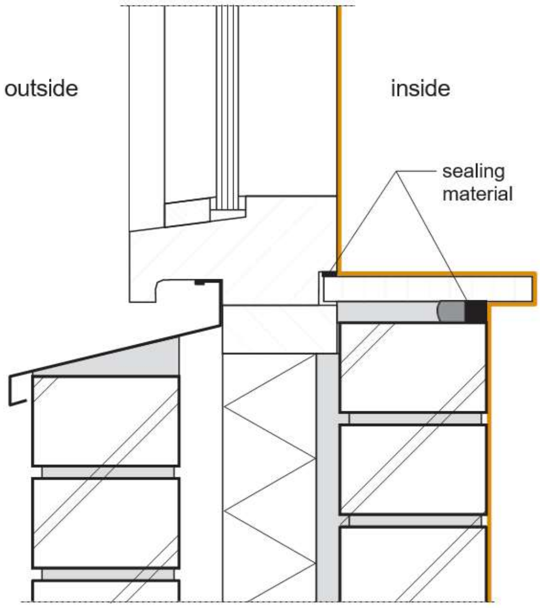


Figure 6.15 Example of 'continuity check' of the air seal on the inside of the shell of the building

7 Solar gain and solar control

A.C. van der Linden

The strength of the solar radiation that falls on the outer wall of a building can be as much as 900 $W/(m^2$, depending on the time of year and its orientation. If the radiation is able to enter the building, it will heat it up considerably. During the winter, spring and autumn this can be pleasant, and the radiation may help save energy. In the summer, however, it can lead to unwanted increases in temperature.

There are various factors that determine the amount of solar gain: the orientation of the outer wall, shade from protruding parts of the building (canopies, etc.) or indeed from other buildings themselves, characteristics of the glass, sunscreens, etc. All of this determines the possibilities to realise energy savings with solar heat. This chapter covers the basic principles of solar gain, and there is also a section on preventing overheating. Allowing too much sun into a room can cause problems in the summer, and sometimes in the spring and autumn, as the indoor temperature can reach a high level. Solar radiation can also lead to large differences in levels of brightness, with the associated problems of dazzle. On the other hand, the admission of sun into a room can be particularly pleasant. The sun's rays provide agreeable heat and brightness, drive out the gloom and heighten contact with the outside world. In other words, there are advantages, disadvantages, and conflicting interests, all of which mean that the totality of measures needs careful consideration.

7.1 Amount of sunlight received

Recommendations and guidelines

The building legislation has no requirements relating to sunlight shining into buildings. For houses especially however, it is important that a minimum level of sunlight gets in. This can be determined by using the amount of sunlight received by a 'norm point' as given in already long existing guidelines. This 'norm point' is located in the middle of the window sill on the inside of the outer wall. If the 'norm point' is exposed to the sun for at least three hours on 20 January (and 22 November) between 9.00 and 15.00 hrs, then it can be qualified as 'good', while any point subject to at least two hours' exposure on 19 February (and 23 October) could be described as 'moderate'. In the case of factories, working areas, offices and so on, users have to have the choice of being protected from exposure to direct sunlight. Rules governing this are given in working conditions guidelines. There are no further generally accepted detailed guidelines on this subject, so the personal vision of the individual designer is decisive.

Influence of orientation

Figure 7.1 shows how the intensity of the solar radiation progresses during the day, for four different orientations. As well as direct solar radiation, there is also so-called diffused radiation (sunlight that is dispersed by the atmosphere) and radiation reflected off the ground. In figure 7.1, the direct and total radiation (that is, direct + diffused + reflected) is given. This graph applies to the month of July. It can clearly be seen that the intensity on the western and eastern outer wall is greater than that on their southern counterpart. This is because the sun is much higher in the middle of the day when it shines on the southern outer wall, than at the beginning or end of the day, when it is directed at the eastern and western sides (see figure 7.2).

The intensity perpendicular to the direction of the solar radiation is more or less the same in both cases. Calculated per square metre of the surface area of the outer wall (the vertical surface) however, the intensity of the solar radiation is relatively low when the sun is high in the sky. Things are different in the month of September, when the position of the sun is much lower, even for the south-facing outer wall, which therefore receives a greater radiation intensity than during the summer months. See figure 7.3. In these circumstances, the western side will get less radiation as the position of the sun is relatively very low and the intensity of the radiation strongly reduced by the atmosphere.

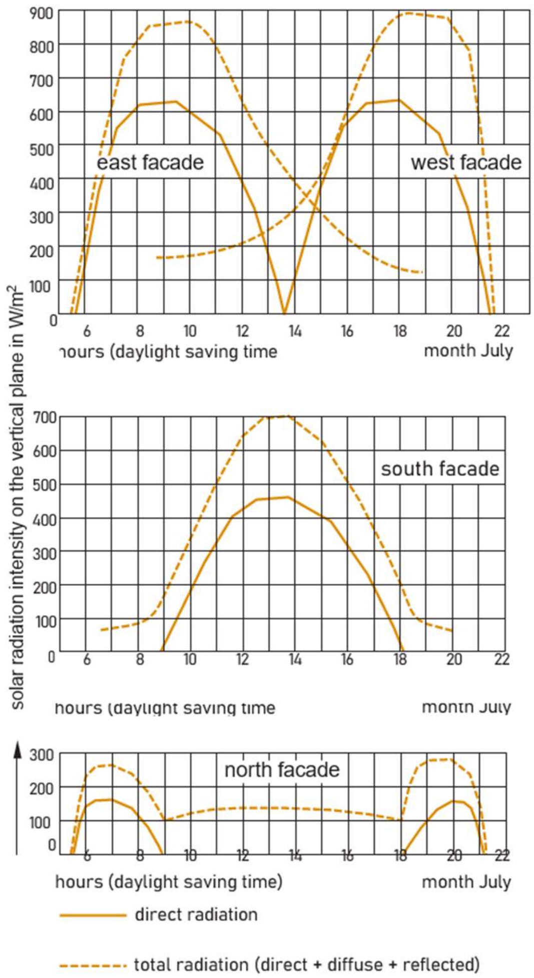


Figure 7.1 Daily progress of the intensity of solar radiation during July, for four orientations

Western or southwestern facing orientations provide most of the problems when it comes to overheating. Solar radiation is high in the afternoon, precisely when the outside temperature is also at its peak.

It should be pointed out that daylight saving time has a favourable effect on the situation in offices. The indoor temperature reaches its maximum at the end of the working day, slightly later than the outdoor temperature. This means that sunscreens have to be kept closed outside office hours in order to prevent the building from heating up. If the sunscreens are outside, they more or less have to be operated automatically, because they have to be raised when the wind is strong to prevent their being damaged. The same applies to east and south facing walls, where the sunscreens should be left down before the working day begins, to prevent employees walking into a room that has already been considerably heated up.

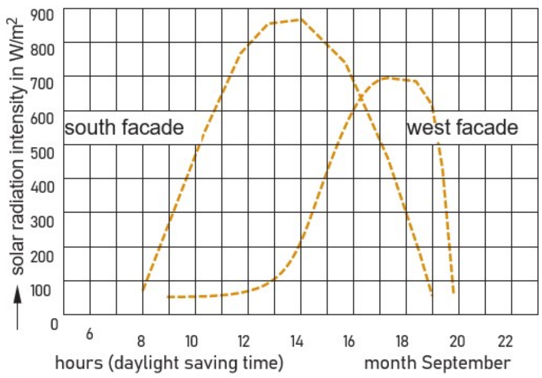


Figure 7.3 Daily progress of the intensity of solar radiation during September, for two orientations

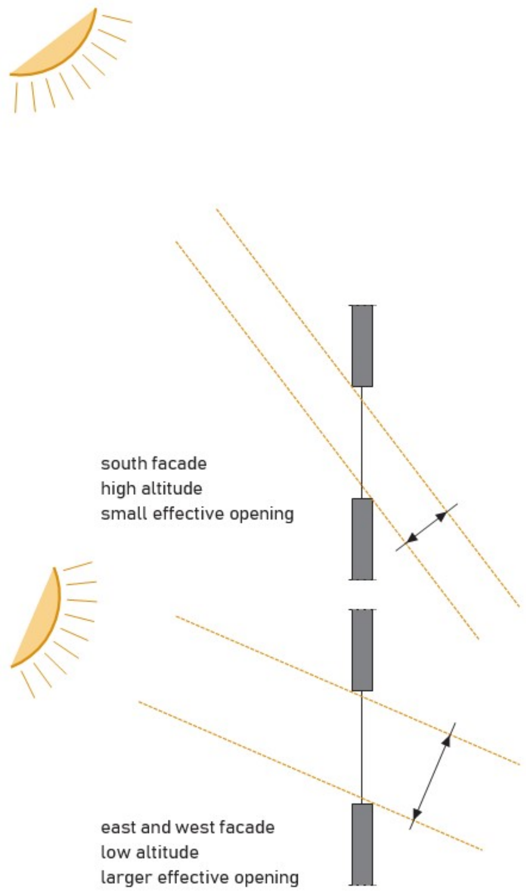


Figure 7.2 Influence of the height of the sun on the solar radiation intensity reaching the outer wall

Shadow

It is clear that in determining the solar load on an outer wall, the shadows cast by other buildings or objects such as trees play a role. If part of a building is hardly ever exposed to the sun because of the shadow of an adjacent building, then of course there is no need for any kind of sunscreen.

The design of an outer wall is also an important factor with sunlight. If the windows are deeply recessed, part of the glass will be in the shade for long periods of time (see figure 7.4), but where the glass is near the surface of the wall, a greater proportion of it will be exposed to the sun.

Canopies and horizontal screens can also function as sunscreens. The effect of the former is only very slight on western and eastern-facing outer walls because of the low position of the sun.

A canopy is suitable for southern-facing outer walls, as the sun rises high in the sky during the summer months. Outer walls facing towards the north-east or north-west can be shielded with vertical screens, for example, because the sun is always at an angle to such walls, rather than facing them directly (see figure 7.5).

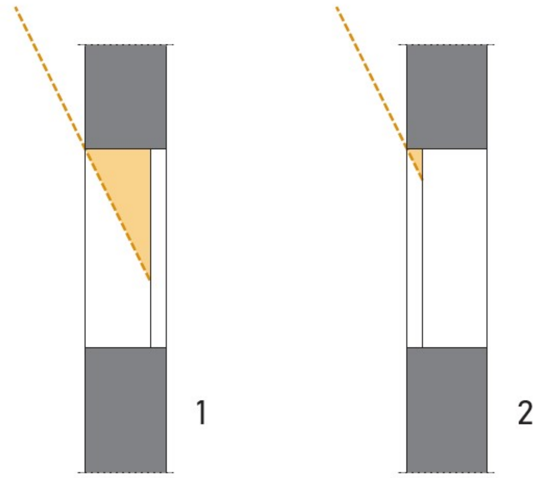


Figure 7.4 Influence of position of window on solar energy entering the building

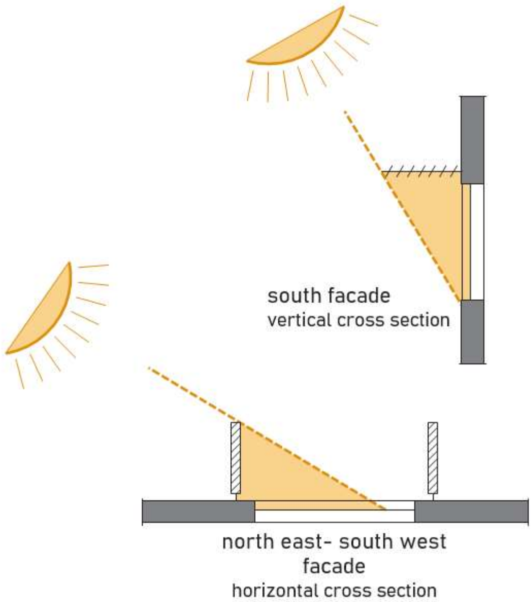


Figure 7.5 Canopies and screens as sunscreens

Greenhouse effect

Figure 7.6 shows how solar energy is distributed over the various wavelengths of light. A very large part of the sun's energy reaches the earth in the form of visible light, with another part as infrared (heat) radiation, and a small proportion as ultraviolet (UV).

Insulation glazing (HR^{++}) without sun-repelling features allows around 60% of solar radiation through. Depending on the angle of incidence, it is partly reflected, and partly absorbed, so that the glass heats up (see figure 7.7). This results in the interior becoming also warmer due to convection heat being given off by the glass.

Walls, floors and objects reached by radiation after it has passed through glass will be heated up as a result. Their higher temperatures will cause them to radiate heat to the other walls and items in the room. The wavelength of this radiation amounts to around 10 μm. However, these wavelengths hardly penetrate glass, which means the heat becomes trapped in the room. This is known as the greenhouse effect.

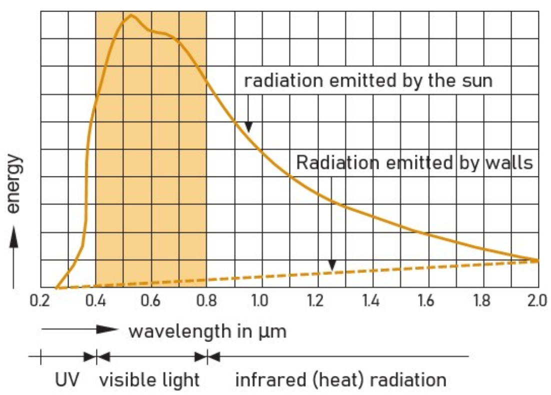


Figure 7.6 Distribution of solar energy over various wavelengths

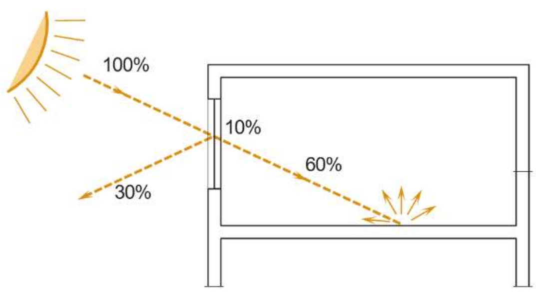


Figure 7.7 Greenhouse effect

7.2 Sunscreens

To keep the sun out of a building to a sufficient degree, some kind of sunscreen or shield is generally necessary. The most common types are external blinds, and reflective windows. The solar transmission quality of a construction is represented by the so-called solar transmission factor (*g*) and the convection factor (CF).

The *g* factor indicates the proportion of the solar energy that ends up inside the room. If it is 0.45, this means that 45% of the solar energy ultimately finds it way into the room, while 55% remains outside. The energy that enters as radiation influences the air temperature of the room at a very slow rate. The walls and objects in the room are heated up first before they give off the heat to the air, by convection.
The proportion of the energy that enters as convection heat affects the air temperature directly however. For that reason, the convection factor (CF) is at least as important as the g factor. The convection factor indicates which part of the incoming solar energy is convective. A CF of 0.30 means that, of the total incoming solar heat, 30% is instantly given off into the air by convection. A high convection factor is unfavourable as this quickly leads to a rise in temperature and consequently raises the capacity needed for any cooling system that may be present.

Figure 7.8 shows diagrammatically what energy flows occur with a window system as a result of solar radiation. The meaning of the symbols is:

q_{ze} the totality of solar energy directed at the building
q_r radiation that is reflected
q_d radiation that is admitted
q_a radiation that is absorbed
q_{ce} heat that is given off outside through convection
q_{se} heat radiation that is given off outside
q_{ci} heat that is given off inside through convection
q_{si} heat radiation that is given off inside

The *g* factor and CF can also be written as formulas:
qd + qci + qsi qze
qci
qd + qci + qsi

A disadvantage of sunscreens is that they also keep daylight out. Another unit of measurement that merits attention in this context is the light transmission factor (LTA). If this is low, it may mean that artificial lighting is required during the day, which consumes extra energy. It also results in extra heat being brought into the room and therefore a greater need for cooling, something that sunscreens are intended to prevent. In other words, it is important to find an optimum situation between keeping out the sun and allowing in sufficient daylight.

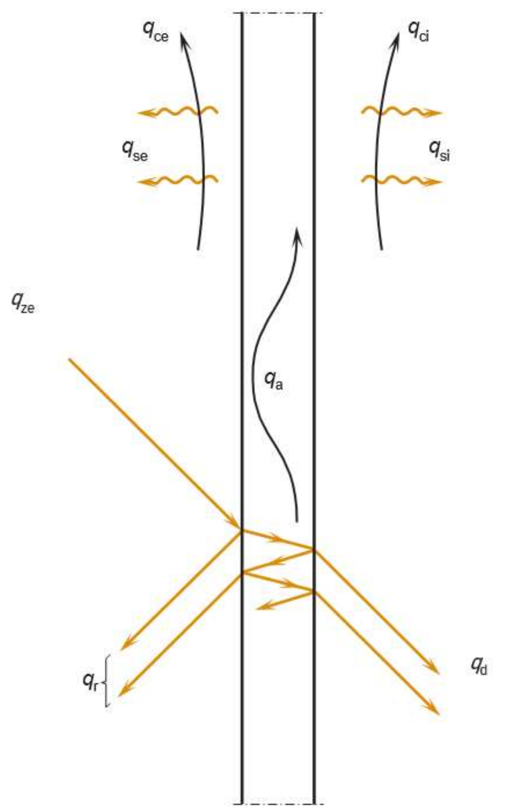


Figure 7.8 Energy flows that occur with a window system as a result of solar radiation

External sunscreens

To prevent the exclusion of solar energy in the winter, adjustable external sunscreens are generally preferred. This means it is possible to use the screens only when necessary, as a means of preventing either overheating or the need to use a cooling system. External sunscreens reflect a significant proportion of the sun's rays before they reach the glass. Another proportion, again significant in size, is absorbed by the screens, but rereleased through convection (air movements, wind) into the outside air. The solar heat that gets in consists mostly of directly admitted radiation. Solar transmission factors of up to around 0.15 can be achieved with effective external sunscreens, and an extra advantage of external sunscreens is that the CF is often no greater than 0.1. This means that just 0.15 · 0.1 = 1.5 % of the solar heat that lands on the sunscreens is eventually released into the room by convection (see figure 7.9).

As already mentioned, adjustable external sunscreens are preferred. Commonly used systems include vertical blinds, screens that can be rolled up, and canopy blinds. The disadvantages of adjustable external sun- screens are that they have to be constantly maintained and the fact that they are ineffective where there are strong air movements. In addition, where a significant proportion of a building is made up of glass, external screens may not be sufficient, quite apart from the aesthetic objections that they give rise to when present in large numbers. It is partly for this reason that in recent years attempts have been made with many new buildings to use other kinds of solar exclusion, at least to a degree. Examples include perforated metal panels, or panels with etched glass, placed parallel to the outer wall, but at some distance. The drawbacks to this type of sun exclusion are the permanent reduction of the amount of daylight that gets in, and the diminishing of the view from the inside.

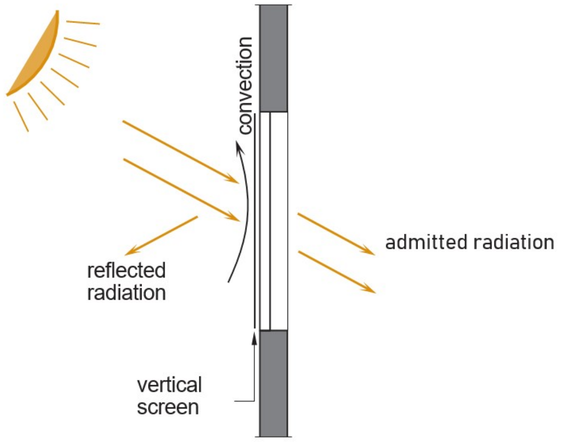


Figure 7.9 External sunscreens (the most important energy flows)

Figure 7.10 The ventilation through open windows or ventilation grids can be seriously hindered by external sunscreens

Another downside to external sunscreens is that the flow of air through open windows or ventilation grids is often seriously hindered, and the heat that has been captured by the sun excluders is then ventilated into the building anyway. There are various options for preventing this problem. One is to place separate panels that can be opened, for summer ventilation. As these panels do not have any glass, no sunscreens are needed for them.

Solar control glazing

There are two main types of solar control glazing: absorbing glass and reflecting glass. Figure 7.11 highlights how these types of glass work (only the most important arrows are drawn).

An extra component, usually metal oxides, is added to absorbing glass to make window panes capable of absorbing a significantly large proportion of the sun's radiation. As a result, the windows become relatively very warm. Most of this heat is released to the outside air through convection (air flows, wind), with a small amount to the inside air through radiation and convection. Absorbing windows are often dark in colour, resulting in a low level of light permeability. Another disadvantage of absorbing glass is its gloomy appearance. In the case of reflecting glass, the solar radiation is largely reflected, with a small portion being absorbed. The solar heat that does manage to enter consists mostly of directly admitted radiation. The reflective layers are usually made of a layer of metal produced by vapour deposition, metal oxide or a coating. This layer is very fragile and is therefore attached to the inside of the outer window. A drawback of reflective glass is its mirror-like character. This effect also occurs to a limited degree with high-efficiency glazing. The development of solar control glazing has seen huge strides in the last ten years. Nowadays there are very good spectrally selective types of glass available; they hold back most of the heat-producing part of the sun's radiation, while allowing the light- producing section to pass. Glass with a g value of 0.35 or less, and an LTA of 0.6 or more, is now available. Any further

improvement to the features of solar control glazing will not be easy with current technology, given the partial overlap that exists between the heat-producing and light-producing part of the spectrum.
The sun-resistant features of the open areas of the outer wall could be improved by combining solar control glazing with external sun blinds, but this option is not exercised very often, as any such improvement would only be modest in relation to the relatively large investment that would be required.

Internal sunscreens

Internal sunscreens merit a particular mention. As far as their sun-resistant capacities are concerned, they perform considerably worse than their external counterparts. Some of the sun's radiation is reflected back outside through the glass, but a significant proportion is absorbed by the excluders, causing them to become much warmer (see figure 7.12). The rise in temperature causes the screens to emit heat by convection, but because of their position, this occurs into the inside air.
In addition to convection heat, the internal sunscreens also give off heat radiation. As has already been explained this heat radiation cannot, because of its wavelength, pass through the glass to the outside, leaving it trapped inside the room. Internal sunscreens will never achieve better results than a g factor of 0.40 in combination with relatively high CF levels. Besides Venetian blinds also fabrics (curtains) with a reflective layer of aluminium are used, the CF levels of which are often lower than those of Venetian blinds, for example. Due to the limited results that can be achieved through the use of internal sunscreens, they should really only be applied where it is not possible to have external screens or solar control glazing, for example with restoration projects. The Venetian blinds that are used on the inside of many buildings are often referred to as sunscreens, but are generally only intended to regulate the incoming light, a function for which they are highly suitable.

Overview of sun transmission characteristics

Figure 7.13 shows the g factor and the LTA for various solar control constructions, and which part is given off as convection heat by the solar control system (CF). The table in figure 7.14 gives these specific values for sunscreens and different types of high- efficiency glazing.

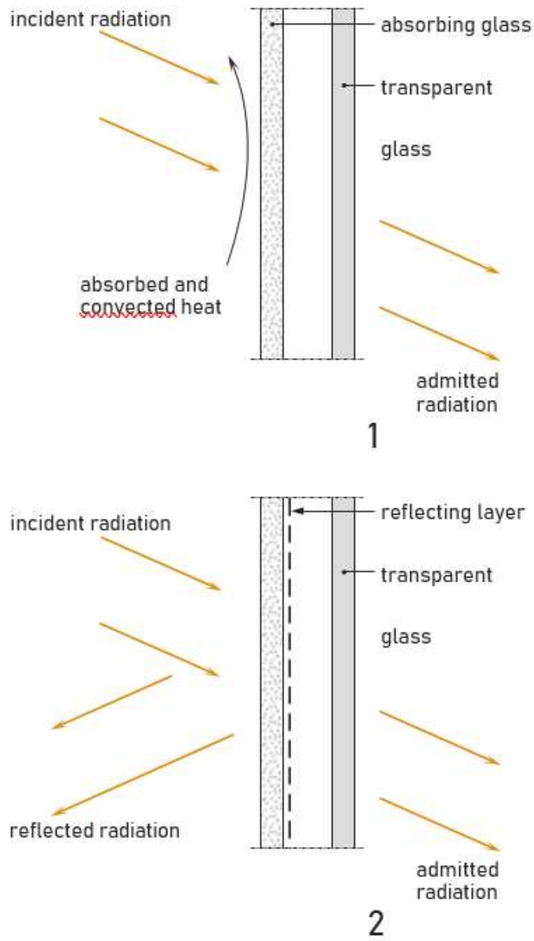


Figure 7.11 Sun resistant glass (the most important energy flows)

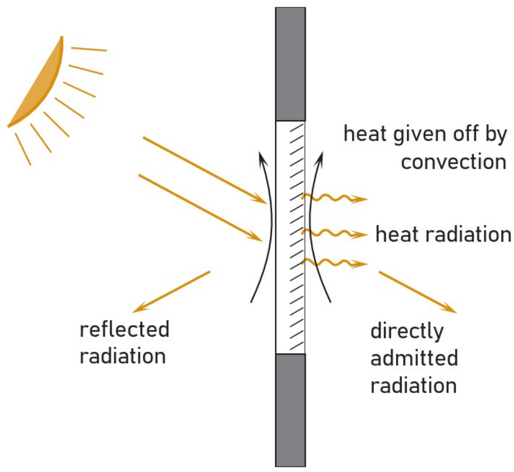


Figure 7.12 Effects of internal sunscreens

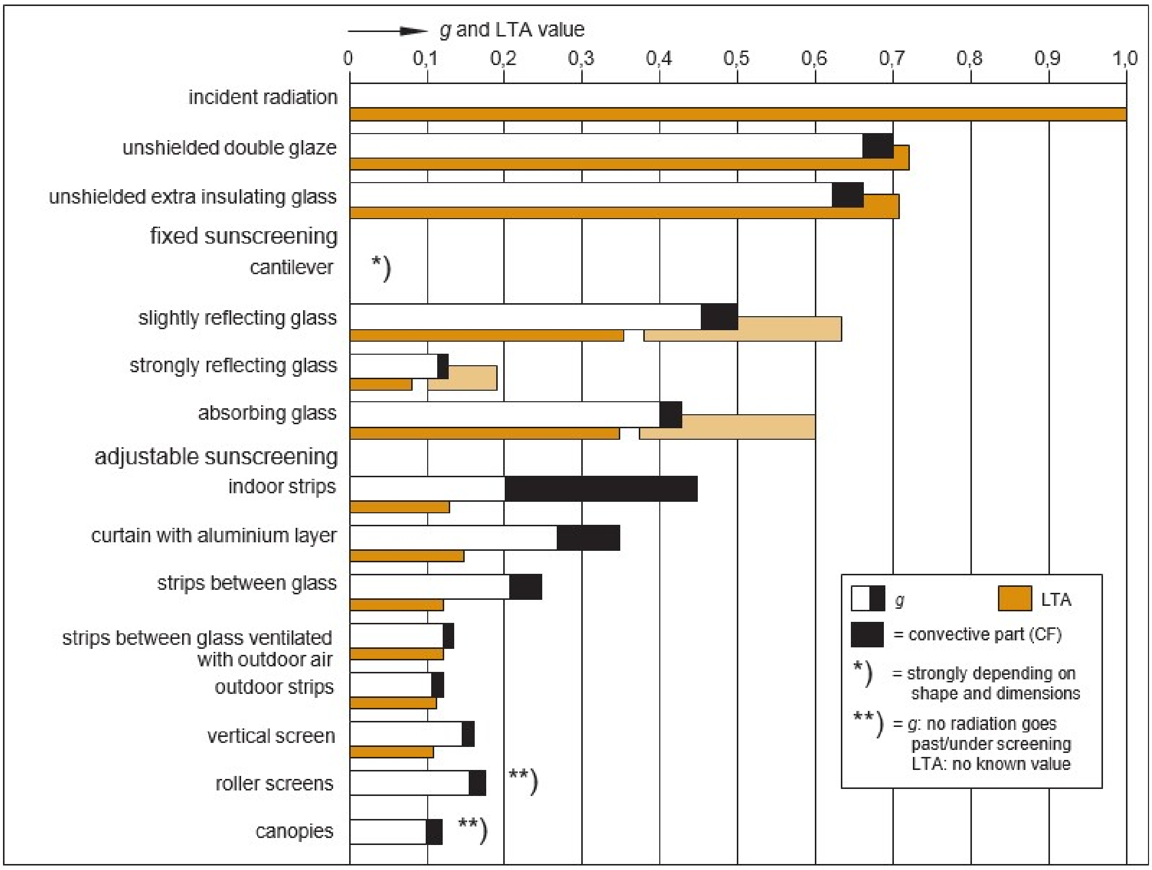


Figure 7.13 Standard values for sun transmission characteristics of several window systems (source: SBR/ISSO publication 213, *Ontwerpen van energie-efficiënte kantoorgebouwen* (Designing energy-efficient office buildings). The values shown should be regarded as an indication – certain products may have characteristics that significantly deviate from them. The angle of incidence of the solar radiation is often important as well, as is the position of the blinds in the form of strips. In this case, both the angle of incidence of the sun and the position of the blinds are assumed to be 45° (that is, perpendicular to the solar radiation).

Window system	g	CF	LTA
High-efficiency glass, unprotected	0.60	0.04	0.70
High-efficiency glass, Venetian blinds (light colour)	0.47	0.55	0.12
High-efficiency glass, outdoor blinds	0.12	0.05	0.10
High-efficiency glass, screens			
Light	0.20	0.10	0.15
Heavy	0.13	0.15	0.05
High-efficiency glass, roller screens (not connected)	0.15	0.15	0.14
High-efficiency, canopy screens	0.11	0.18	0.05

The values given in the table should be regarded as standard values certain products may have characteristics that significantly deviate from them. Additionally, with many constructions (glass surfaces), the angle of incidence of direct solar radiation affects the reflection onto the outer surface. This table is based on an angle of incidence of 45°. In the case of sun blinds, the level of solar control depends strongly on the angle of the blinds. The table assumes an angle of 45°, in other words perpendicular to the sun's radiation.

Figure 7.14 Standard values for the *g*, LTA and CF, for combinations of solar control systems and high-efficiency glass.

8 Energy and energy performance

ir. I.M. Kuijpers-van Gaalen MBA

Approximately 40% of the total yearly energy consumption in the Netherlands is used in buildings. The building practice has a great need for predicting and calculating the various elements of energy use of buildings. This makes sense, because besides the environmental need to reduce energy use, energy costs money.

Using less energy will result in money-saving. This means that when a company or consumer is considering the purchase of a new boiler or lighting, they should also consider the energy use of this device. The financial investment in such a device, after all, goes beyond the initial investment: the energy itself also has to be paid each year. And the aggregate costs of this over the years could be even higher than the purchase price.

8.1 Energy use

It is very difficult to predict energy use in practice. Buildings are dynamic and people do not always behave as expected. Before we go into the way in which energy use can be predicted, it is important to make a distinction between the various items of energy use existing in a building.
The main distinction is between building- related energy use and non-building-related energy use. These two main groups can then be further divided.

- Building-related energy use: the energy which can be attributed directly to the building itself. This includes:
  - energy use for climatising the building (heating, ventilation, cooling, humidification);
  - energy use for lighting the building (lighting and emergency lighting);
  - other building-related energy uses (tap water and auxiliary energy, for example for pumps).
- Non-building-related energy use: the energy which cannot be directly attributed to the building itself. For example:
  - office equipment (servers, computers, printers, coffeemakers, TVs, fridges, washing machines);
  - process energy, the energy use which belongs to processes. In most office buildings, schools and homes, this share is very small or zero, but in for example an industrial building or a swimming pool, the share of process energy is often significant.

Non-building-related energy use

Here, we mainly focus on the building-related energy use, because this is the area of attention of the building physicist. We will briefly provide a guideline for calculating the energy use of processes and of equipment, such as servers and computers. Predicting the energy use of industrial processes is very complex and varied and falls outside the scope of this book.

In order to map out the energy use of machinery, the following data need to be collected:

- P_{full} = full load capacity of the machine in watt;
- P_{part} = partial load capacity of the machine in watt*;
- $P_{stand\text{-}by}$ = the stand-by capacity of the machine in watt;
- t_{full} = the number of hours per year the machine operates on full load;
- t_{part} = the number of hours per year the machine operates on partial load;
- $t_{stand\text{-}by}$ = the number of hours per year the machine is in stand-by mode.

* Partial load = the power required to have the machine operate on 'half power'. In many cases, if a machine can be only turned 'on' (full load) or 'off' (= 0 or stand-by), you do not need this value.

The energy use of the equipment (in kWh) is calculated by using the following formula:

$$E_{equipment} = \frac{P_{full} \cdot t_{full} + P_{part} \cdot t_{part} + P_{stand\text{-}by} \cdot t_{stand\text{-}by}}{1000} \quad [\text{kWh}]$$

In order to calculate the total non-building- related energy use, you make an estimation for all machines in the way shown above and you find the aggregate:

$$E_{non\text{-}building\text{-}related} = \sum_{i=0}^{n} E_{equipment,i} \quad [\text{kWh}]$$

Clearly, the difficulty lies in estimating the number of hours per year a machine operates or is in stand-by mode. In general, you will notice you tend to overestimate this. Equipment is turned off more often than you might think. For example, due to holidays, illness, bank holidays and appointments elsewhere.

Building-related energy use

In order to predict the building-related energy use of a building, a model will have to be made which includes all parameters that influence building-related energy use. These are constructional data, climate data, installation data and the data concerning the actual usage of a building. This type of calculations can generally not be performed by hand. A variety of software packages have been introduced for this purpose.

These software packages can be divided into static models and dynamic models.

The static models are simple models which could be performed by hand, albeit with some effort and help of Excel. A static model assumes many parameters to have fixed values (static). This makes the calculation simpler and it will therefore take less time to perform it. The level of accuracy, however, will also be lower. A static calculation makes use of a simplified outside climate: for each month, a fixed average outside temperature is used. Based on the average outside temperature, the energy use for heating or cooling is calculated. The building parameters, as well as the use are often represented by a fixed value in a static model (for example an average yearly efficiency), while in practice these values may fluctuate.

In dynamic models, it is attempted to simulate the actual use of the building as much as possible. This means the input will be extremely detailed. It is possible to indicate how the building is used, how many people are present and what the climate settings are on an hourly basis. The outside climate, including the sun load, is available in the model on an hourly basis. In the dynamic model, it is calculated from hour to hour what the expected inside temperatures and energy uses will be. The model also takes account of what happened in the building in the preceding period. If, for example, it has been warm for a couple of days, the building will be heated up. It will then take more energy to cool down the building, since the structure itself is also heated up (thermal mass). The dynamic model takes account of these effects.

Still, a dynamic calculation is not always better than a static calculation. If certain input parameters are unknown when performing the dynamic calculation, and the person performing the calculation 'takes a guess', the quality of the static calculation could be higher. And if the input for the dynamic calculation is the same as for the static calculation, there will be little difference between the static and dynamic calculation. Dynamic calculations are only of any use if sufficiently detailed information is available about the building and the use of the building.

Comparing measured energy uses

Once a building is in use, it is interesting to see how the energy use develops over the years.
Does it increase or drop? And is it possible to see whether a given energy-saving measure actually results in a reduction in energy use?

Simply comparing the energy uses of two years with each other will result in incorrect analyses. One year may after all be colder than the other and this has an impact on energy use for heating. It is therefore desirable to correct the actual energy uses for heating for climate influences to be sure of an objective comparison. You can do this by utilising a 'degree day correction'.

The point of departure is: if the average outside temperature is higher than the average inside temperature, the boiler does not need to be turned on. If the outside temperature is lower, the boiler needs to go on and degree days need to be counted. There are degree days when, during an entire day, the average temperature is lower than the heating threshold of 18 °C (the reference temperature generally used in the Netherlands above which heating is not necessary). Above the threshold of 18 °C, there are no degree days.

The term degree days is confusing, because it does not refer to days. A degree day is a measure for the amount

Figure 8.1 Energy meter in a home. Both the gas and electricity use can be read at distance.

of energy required to heat a building. A degree day is calculated as follows: reference temperature of the heating threshold (18 °C) – the average temperature of that day. Every day it is registered how many degree days there are that day. If the average temperature on a given day is 11 °C, that day has (18 – 11 =) seven degree days. If a day has the average temperature of 20 °C, the number of degree days is zero (you can't have negative degree days).

We also have the term weighted degree days. For weighted degree days, account is taken of the fact that buildings are also heated by sunlight and that the boiler needs to deliver less energy. Depending on the season, the number of degree days is multiplied with a weight factor. The weight factors are:

- 0.8 in the months of April to September;
- 1.1 in the months of November to February;
- 1.0 in the months of March and October;

We generally use weighted degree days when comparing energy use over a number of years, so that the influence of sunlight is included. To determine the total number of weighted degree days over a time period, the (weighted) degree days of the separate days are added.

Example
In 2013, 1000 m^3 was used on heating in a home. The number of weighted degree days in 2013 is 3094 (De Bilt). Gas use in 2014 was 800 m^3. The number of weighted degree days in 2014 is 2418. Gas use dropped significantly, but is this due to the climate or because actually less gas was used?

By calculating the gas use per degree day for each year, we can clarify this.
2013: 1000 m^3/3094 degree days = 0.323 m^3/degree day
2014: 800 m^3/2418 degree days = 0.331 m^3/degree day

When we work out the energy use of 2014 to reference year 2013, we find a use of 0.331 m^3/degree day = 1024 m^3. In other words: in comparison to the reference year, use in both years is practically the same. The drop in gas use is caused by the fact that 2014 was a milder year than 2013.

Counting up degree days is not something you have to do yourself. There are a number of websites available which let you determine the number of degree days in a given period. The basic details are collected by the KNMI (Royal Dutch Meteorological Institute) and tables of degree days can be found on their website.

Note: the degree date correction is only performed for the gas use for heating. Gas use for tap water must first be subtracted from gas use for heating, because the gas use for tap water does not depend on the climate. This same calculation can of course also be performed for buildings with district heating or electric heating (heat pumps), but then the calculation must be done with GJ or kWh instead of m^3 gas.

8.2 Energy savings and financial analyses

The nice thing about calculating energy is that you can also work out energy savings and financial savings. In practice, this is often done to make investment assessments. The question is: will we make back the investments we put in during the lifetime of the device or the building?

There are various ways to make these calculations. We will illustrate the two most common methods: the simple payback time and the net present value method.

Usually, this type of financial analyses is done in order to make a choice. This means that the additional investment of the one option is scrutinised in relation to the other. This additional investment must be paid back within a certain period through the lower energy costs. In order to be able to make a calculation, we do not only need the (additional) investment costs, we also need to know the costs of energy, interest and maintenance to include them in the calculation.

Simple payback time

The calculation of the simple payback time SPT is, as the name suggests, simple. This calculation looks only at the additional investment of a given choice and it is calculated in how many years this additional investment will be recovered. The method does not take into account any costs of interest, maintenance, etc.

In general, entrepreneurs want to recover their investments in the short term. A payback time of five to seven years is still acceptable. If it takes longer than that, entrepreneurs often think the risk to high as they cannot see into the future that far ahead. For a private or
non-profit organisation this turning point can be a little further into the future, since they are in a more stable market.

Example

An entrepreneur is considering changing the
lighting of his premises. He has the choice between placing traditional fluorescent lighting or led lighting. He does not like the additional investment of led lighting, but he has also heard led is more economical. To get a first idea of the numbers he quickly finds out the simple payback time with the formula:

$$SPT = \frac{\text{additional investment}}{\text{yearly savings on energy costs}}$$

The additional investment amounts to € 10,000 and he saves 18,500 kWh per year on the more economical led lights. Based on his energy price for electricity (€ 0.15/kWh) he calculates that the investment is recovered in 10,000/(18,500 · 0.15) = 3.6 years.

The lighting has a much longer lifespan than 3.6 years. He therefore decides to purchase the led lights, as he will after all start making money on them after 3.6 years.

Net present value

The calculation of the net present value is somewhat more complicated. In this calculation more components are included than in the simple payback time, and account can be taken of variable costs per year. The net present value method looks at all future cash flows (such as interest, maintenance costs and energy costs) which are associated with the investment currently under consideration.
These future cash flows are expressed in their present value.

In order to work out the net present value (NPV) you need the following details:

- the initial investment (INV_0);
- the yearly cash flow, consisting of costs and profits for energy, maintenance, energy, etcetera;
- the discount rate (r), or the interest of the loan to finance the investment with;
- the time period (t) you want to calculate the NPV over.

The formula for calculating the NPV is:

$$NPV = \sum_{t=1}^{n} \frac{\text{yearly cash flow}}{(1+r)^t} - INV_0$$

The first term in the formula calculates the yearly cash flow back to the value in the first year (at the start of the project). So you calculate the first term for every year separately, whereby the cash flow can vary for each year. For year 1, you calculate the term with t = 1, for year 2 with t = 2, etc. The initial investment (INV0) has already been found for the current value, so this does not have to be worked out again, which is why it is outside the aggregate sum.

For investments in energy conservation, there is often a choice between two options which have to be compared. The NPV will then have to be calculated for both situations and the option with the highest NPV can be selected. An alternative is to look at the additional investments and the savings (so just the difference between the two options needs to be regarded), so that only one calculation has to be performed. In that case, you will have to test whether the NPV is larger than zero, because then the additional investments can be compensated by the savings. This is elaborated in the calculation example below.

Example

Let us again consider the situation of the entrepreneur who has the choice to install either led lighting or fluorescent lighting. The additional investment for led lighting amounts to € 10,000. The yearly energy saving is € 2,775 and he estimates maintenance will cost him € 1,000 less on a yearly basis. He uses a discount rate of 7%.

year	additional investment (INV_0)	yearly savings on energy costs	yearly savings on maintenance costs	total yearly savings	total yearly savings made current with savings $(1 + r)_t$
0	€ 10,000				
1		€ 2,775	€ 1,000	€ 3,775	€ 3,528
2		€ 2,775	€ 1,000	€ 3,775	€ 3,297
3		€ 2,775	€ 1,000	€ 3,775	€ 3,082
4		€ 2,775	€ 1,000	€ 3,775	€ 2,880
5		€ 2,775	€ 1,000	€ 3,775	€ 2,692
6		€ 2,775	€ 1,000	€ 3,775	€ 2,515
7		€ 2,775	€ 1,000	€ 3,775	€ 2,351
sum of the present value of the savings					€ 20,345
additional investment					€ 10,000
net present value					€ 10,345

Figure 8.2 Calculation example of the net present value of a led light project

The net present value is clearly positive. So also from a financial point of view it is better to invest in led lighting than in fluorescent lighting.

8.3 European energy performance legislation

Reducing energy use is one of the main objectives of the European Union (EU). Because 40% of our energy is used in buildings, the EU has introduced legislation to make sure that buildings will start using less energy.

An important part of this legislation is the Energy Performance of Buildings Directive (EPBD, directive 2002/91/EG). This directive was first published in 2002 and forces allEU countries to improve their building regulations and to introduce energy certificate regulations for buildings. The directive was amended in 2010 and refined into the EPBD Recast (directive 2010/31/EG).

The main points from the EPBD 2002 directive:

- There must be a calculation method which can work out the integrated energy performance of a building. The directive establishes which requirements this method must observe. For this purpose, the NEN 7120 standard was formulated in the Dutch Buildings Decree. This standard meets the requirements in the EPBD directive.
- Minimum requirements must be set for the energy performance of new buildings. This is implemented in the Netherlands by setting requirements of the energy coefficient (EPC) of new buildings.
- For existing large buildings which have to undergo drastic renovations, minimum requirements must be set to their energy capacity in order to encourage reduced energy use in these buildings. In the Netherlands, this is laid down in the Building Decree.
- When selling or letting a home or building, an energy label must be available, so that the new occupant or owner can form a picture of what the possibilities of making savings are.

- Boilers and air-conditioning systems in buildings must be regularly tested in order to prevent these systems from functioning below their optimum level.

In the Netherlands, the requirements from the 2002 EPBD directive have been translated into laws and legislation. This legislation is accommodated in the Building Decree, the Energy Performance of Buildings Decree (BEG) and the Buildings Energy Performance Regulation (REG).

The EU published a revision of the EPBD Directive in 2010. This revised directive is designed to force countries to take steps in the further reduction of energy use in buildings.
The EPBD Recast includes the following requirements which must be laid down in the legislation of all EU member states:

- New buildings must be 'nearly zero energy' as of 2021. The government must play a leading role in this and as of 2018 only 'nearly zero energy' buildings may be bought, rented or built by the government.
- More stringent requirements must be laid down regarding insulation (R_c) of the building shell for drastic renovations and the replacement of insulation materials.
- Member states must introduce sanctions for non-observance of the directive. Fines, for example, for not having an energy label.

Legislation in the Netherlands

Several laws and regulations exist in the Netherlands which have to ensure that the country meets the obligations from the EPBD Recast. It is laid down in the Building Decree that new buildings and buildings which are to be drastically renovated are properly insulated. This is established by placing demands on the R_c values of facades, floors and roofs and the U values of windows and doors. It has also been established that the buildings as a whole must be energy efficient. This means they have to meet the energy performance requirements (EPC requirements) which are laid down for each designated use. In section 8.4, we will explain the structure of an EPC calculation and which aspects play a part. Section 8.5 will briefly deal with the energy label for existing buildings.

In 2021, the legislation in the Netherlands will also have to be revised, so that here too we will meet the requirements for 'nearly zero energy building'. In section 8.6 we will briefly discuss what this means.

8.4 Energy performance of new buildings: the EPC calculation

The energy performance of new buildings is regulated in the Building Decree. The Building Decree includes energy performance requirements and a basic requirement of opaque parts (R_c) and transparent parts for new buildings (U value). New homes, residential buildings and utility buildings must meet the energy performance requirements from the Buildings Decree. Per designated use there is a single energy performance requirement (EPC value), which must not be exceeded. The energy performance of a building is calculated using NEN 7120. The energy performance is expressed in the Energy performance coefficient (EPC). The basic principle is this: the lower the EPC value, the more energy efficient the building is.

The energy performance is an integrated energy efficiency requirement. This is intended to achieve that buildings have a minimum energy efficiency at an architectonic and installation level. How exactly this is realised and which measures are taken, is at the discretion of the parties in the construction process. Higher energy use due to a 'poor boiler' with low generation efficiency, for instance, can be compensated by additional insulation in the facade. In order to ensure that the building as a good basic insulation quality, limits have been set in the Buildings Decree to the minimum requirements of the insulation of walls, roofs and floors. This is also referred to as 'safety net requirements'.

Basically, the energy performance requirements say that the total energy use of a building as a whole may not exceed the allowed maximum. The Building Decree lists the energy performance requirements for various designated uses. When the level of the EPC requirement per designated use was determined, account was also taken of the fact that some designated uses require more energy than others. A hospital for example will require more energy than an office, because a hospital is open 24 hours a day and usually is somewhat warmer.

An EPC calculation is formulated before the building is actually built. The ultimate use of the building is not yet known at that time. In order to work on the EPC anyway and to keep the requirements equal for all users, the energy performance standard assumes a 'standard occupancy behaviour'. Because of this standard occupancy behaviour, the energy use calculated by means of the energy performance standard does not represent the true energy use of the building! After all, the true energy use strongly depends on the behaviour of the users. The energy performance calculation is a so-called static calculation (see section 8.2).

Although the energy use should be calculated according to the energy performance standard, the standard by itself is not a design tool for determining the required performance of ventilators and/or cooling units for example.

The NEN 7120 standard should not hinder innovation. This is why an appeal can be made to the principle of equivalence in the Buildings Decree for energy-saving measures which have not yet been included in the standard.

Upon lodging the application for a construction permit, it must be shown that the EPC requirements are met. This means that in an early phase of the design process, besides choices concerning the actual construction, choices for climate installation and lighting must also have been made.

Elements of the EPC calculation

The calculation of the EPC looks at the building- related energy items. The non-building-related energy use is therefore left out of the equation. As mentioned above, the building-related energy use based on the energy use of standard occupancy behaviour is calculated. The EPC calculation is therefore a standardised calculation for the (assumed) energy use of a building. In the EPC calculation, the energy use is converted into the primary energy use.

The calculation takes account of the various energy items. These items are assigned a letter in the energy performance standard. The letters for energy items originate from a European standard and are used in all EU countries. When you come in contact with a French standard, you will find the same assignments of letters (derived from English terms):

- heating (H);
- humidification (hum);
- cooling (C) or summer comfort (SC);
- dehumidification (dhum);
- warm tap water (W);
- ventilators (V);
- lighting (L);
- auxiliary energy (aux) for the various energy items, this mainly refers to pumps;
- self-generated energy, such as the results of solar cells or CHP (deduction item).

EP_{tot}/EP_{admin} and EPC

Basically, the total typical primary energy use of a building in an EPC calculation (EP_{tot}) is worked out by finding the sum total of all calculated primary energy uses of all the items listed above. This total primary energy use is then compared to the energy budget (EP_{admin}) which depends on the size, shape and designated use of the building. The energy budget includes the EPC requirement of the designated use.

When a building has multiple designated uses, it is tested whether EP_{tot} / EP_{admin} is equal to or smaller than 1 for the purpose of the building permit. If a building only has one designated use, for example a home, EP_{tot} / EP_{admin}, is usually not used, but EPC is instead calculated by means of:

$$EPC_{Building} = EPC_{Building\ Decree} \cdot \frac{EP_{tot}}{EP_{admin}}$$

This is basically the same, but causes some confusion in practice. Therefore, make sure you know whether people are talking about the EPC or the EP_{tot} / EP_{admin}. The term EP_{tot} / EP_{admin} is popularly termed the Q/Q. This term is from the predecessor of the NEN 7120 (the NEN 2916).

Example
A home has an EP_{tot} / EP_{admin} of 0.85. The EPC requirement for homes is 0.40. The EPC of this home is 0.40 · 0.85 = 0.34. The EPC therefore meets the requirements because the EPC is smaller than 0.40. This was already obvious from EP_{tot} / EP_{admin} , because it is smaller than 1.

From energy needs via energy use to primary energy

To be able to calculate EP_{tot}, a similar calculation is performed for each energy item, with the primary energy ultimately being calculated from energy needs. We here describe the basic design of the calculation, so you can get a clear idea of the calculation method.

The calculation for each energy item is divided into three steps each time.

1. First the energy need is calculated.
2. Then it is decided how much energy must be supplied to the building to cover this energy need.
3. Finally, the amount of energy supplied is converted into primary energy. Primary energy is the amount of energy derived from fossil fuels. In this calculation, all energy losses which occur, from extraction of the oil or gas to the delivery to a building are included. Especially when generating electricity, much energy loss occurs, since the efficiency of power station is not very high (approx. 40%).

We will explain this system based on the calculations for heat. For other energy items a similar method applies. Figure 8.3 shows this principle in the form of a diagram

Energy need

The energy need for heating is determined by performing a transmission calculation. This calculation takes account of the shape, the size, the thermal insulation, thermic mass, internal heat load and the amount of sunlight that enters the building. Account is also taken of the amount of ventilation air which must be heated and of course with the outside climate. In brief, you could say that the energy need of a building is the sum total of the amount of heat you need in each room during on year in order to keep the room at the desired temperature.

Supplied energy

The next step is to determine how much supplied energy ('on the meter') is required to supply this heat to the building. This concerns the various losses which occur before the gas is converted into heat at room level:

- In the building itself, energy losses occur between the central heating boiler and the rooms. We call this distribution and delivery losses. Consider for example energy losses through (poorly) insulated heating pipes running under the floor. The boiler will have to generate more energy than just the energy need. The energy lost in transit from the central heating boiler to the rooms will also have to be supplied by the boiler.
- In addition, the efficiency of the central heating boiler itself plays a part. Inside the boiler, (small) energy losses occur via the chimney due to the combustion of gas.

Primary energy

The final step is calculating the amount of primary energy that is needed to supply the required amount of energy to the building. A number of losses may occur:

- Transport losses. These are the losses between the building and the location where the energy is generated. For gas, these losses are zero, but for district heating these losses do indeed occur. Consider for instance the heat losses of the transport pipes located in a residential area and the electricity use of the pumps necessary to pump the district heating water from the central plant to the buildings.
- Conversion losses. These too are limited: the gas extracted from the ground can be used in buildings without any major conversions. This is different for electricity. Electricity is produced

inside a power station by burning gas or coal for example. Much energy is lost during this process and this is set off in the conversion of energy use into primary energy.

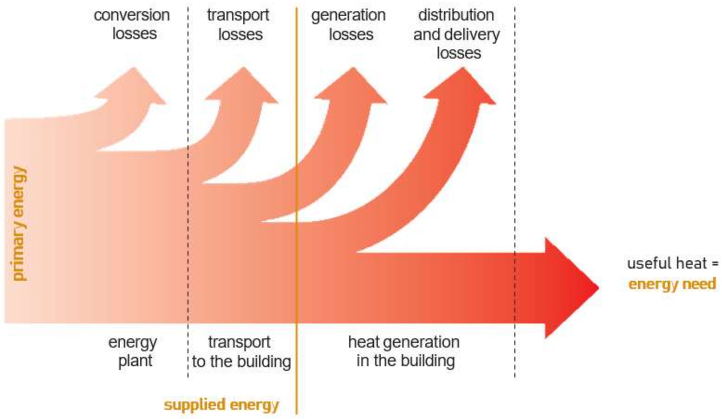


Figure 8.3 Schematic representation of calculating the primary energy use from the energy need.

For calculating energy use into primary energy use, you can use the following rule of thumb:

- 1 m^3 natural gas (on the meter) = 35.17 $MJ_{primary\ energy}$ (the combustion value of gas)
- 1 kWh electricity (on the meter) = 3.6 $MJ_{on\ the\ meter}/0.40$ = 9.0 $MJ_{primary\ energy}$

The central (average) generation efficiency of electricity in the Netherlands is approx. 40%. If all 'bioenergy' is included (burning of biomass or use of biogas), this efficiency is approx. 47%. By deploying sustainable energy, the efficiency will increase in the future. For all energy items included in the EPC calculation, the above calculation is usually performed, whereby a calculation is performed which works out the primary energy use based on the energy need and the supplied energy.

Figure 8.4 A solar boiler on the roof of a home sustainably generates warm tap water (partly)

A special item is the energy generated on the own grounds. Consider for instance solar boilers (see figure 8.4), PV cells and the electricity produced by combined heat and power. This energy is immediately set off as a deduction item (because of PV the amount of electricity to be supplied to a building becomes lower).

Performing an EPC calculation

An EPC calculation cannot be done manually as the calculation is too complex for this.
There are a number of computer programs available, which can help you to perform these calculations. The way this is done is described below.

Schematizing the building

You start by making a diagram of the building. The complete geometry of the building must be entered into the software. The building must be divided into different fields with designated uses. The structural and installation parameters are then assigned to these fields. Basically, the calculation is divided into many small calculations which are added together by the end of the calculation.

Structural input parameters

Subsequently, the structural input parameters have to be entered. This means that the following details have to be available:

- R_c value, U value, g value of the outer walls, roof and floor, including the surface areas of the different parts;
- orientation and level of shading of the windows and facade elements;
- thermal mass of the building;
- infiltration characteristics of the building (such as the type of facade).

In order to properly enter the structural input parameters, consultation with the architect will need to take place.

Installation input parameters

For the installation characteristics, many details concerning installation need to be entered.
The list below is not exhaustive, but does provide you with an idea about the details you have to collect.

- Heating:
  - type, efficiency and capacity of the central heating boiler;
  - supply temperature of the heating system;
  - presence of (un)insulated pipes and ducts;
  - auxiliary energy of the central heating boiler;
  - presence of any (additional) circulation pumps.
- Cooling units (if present):
  - type, efficiency and capacity of the cooling installation;
  - supply temperature of the cooling system;
  - auxiliary energy for cooling.
- Warm tap water (W);
  - type of tap water appliance;
  - pipe lengths of the tap water appliance to the bathroom/kitchen;
  - diameter of the pipes;
  - presence of a shower heat recovery system (including efficiency).
- Ventilation:
  - type of ventilation system (natural ventilation, balanced ventilation, etc.);
  - flow rate of the ventilation system;
  - efficiency of heat recovery;
  - ventilator capacity.
- Humidification system (if present):
  - type of humidification.
- Solar boilers (if present):
  - surface areas and orientation of the solar panels;
  - type of solar boiler;
  - auxiliary energy for the solar boiler system.
- PV system (if present):
  - surface areas and orientation of the PV system;
  - watt peak capacity of the PV system.
- Lighting (input only required for utility buildings – for residential buildings fixed values apply which cannot be adjusted):
  - installed power for lighting;
  - type of lighting control.

In order to properly enter the installation input parameters, consultation with the installation consultant or contractor will need to take place.

Final result verification

When all details have been collected and entered, it needs to be verified whether EP_{tot} / EP_{admin} meets statutory requirements. If it doesn't, additional measures will have to be taken in consultation with the architect and the installation consultant. The building physicist can advise in this since he has knowledge of both installations and structural solutions.

8.5 Energy efficiency of existing buildings: the energy label

It is established in the EPBD that existing buildings need to be provided with an energy label when the building changes owner or tenant. An existing building's energy label is calculated in a similar way as the energy performance of a new building. The calculation of the energy label is therefore also a static calculation based on a standardised occupancy behaviour of the users of the building.

The energy label of a building can vary from an A-label to a G-label. A G-label means that there are many possible ways of implementing energy-saving measures in a building. In a building with an A-label, most energy-saving measures have already been implemented.

8.6 Nearly zero energy buildings

As of 2021, all new buildings will be 'nearly zero energy'. The first question on your mind will probably be: 'what is nearly zero energy'? During the period 2015 – 2020, all EU countries will define the exact meaning of nearly zero energy buildings in their country. The EU has recorded in the EPBD Recast which preconditions these buildings must meet.

A nearly zero energy building must meet three separate requirements:

- A maximum energy need requirement per m^2. Only the energy needs for heating, cooling and lighting are considered.
- A maximum primary energy use requirement per m^2. Only the total primary energy use is considered here, so including all energy items and energy generation.
- A minimum requirement concerning the share of renewable energy. This will encourage that part of the energy use in a building is covered by the renewable sources (such as wind, solar and geothermal energy).

For the Netherlands, the arrival of nearly zero energy buildings means that at that point we must say goodbye to the EPC as indicator for the performance of a building. For construction, this means that a new way of designing energy efficient buildings will develop. It is possible in EPC to compensate poor insulation of the shell with a great heating system: as long as the total EPC remains below a certain value. This is no longer possible for these buildings: all three requirements must be met. It will become increasingly important to limit the energy need (first requirement). This will result in new concepts and design solutions in buildings which will show many similarities with the solutions used in passive building.

8.7 Passive building

The EPC calculation method was introduced in the Netherlands in 1995. A result of this introduction is that the market parties started designing buildings which score well in the EPC method. This mostly means that rather many installations are present in those buildings, and less attention is given to applying high-quality insulation materials or sun-oriented building. We also refer to this as 'active building': the installations ensure the building is energy efficient.

The opposite of active building is passive building. Passive building is popular in countries surrounding the Netherlands, and also in the Netherlands some passive buildings have been realised.

Passive building is characterised by the following (fixed) principles:

- A passive building is very well insulated. This means R_c values of 8-10 $m^2 \cdot K/W$ and the application of triple glazing. The first step is to reduce heat loss.
- A passive building has sufficient thermal mass which can be used to store heat and stabilise the temperature in the building.
- Passive buildings have a balanced ventilation system with heat recovery possibilities.
- A passive building has a southern orientation with large windows facing south and smaller windows facing north. During the winter, the sun is low and therefore heats the building with free solar heat. In the summer, the sun is high in the sky. This high sun can be easily kept out by

making use of overhangs and sun blinds. This way, a passive building profits from the sun in the winter, and can easily keep out the sun in the summer.

- A passive building also has internal zoning. This means that rooms where heat is desirable are located on the south. These are living rooms, nurseries and suchlike. Rooms which produce heat, or which do not require heat face north. These are kitchens, stairwells, storage areas, garages and suchlike.

Passively built homes are often additionally provided with a solar boiler and or solar cells for generating sustainable energy.

9 Sustainable construction

ir. I.M. Kuijpers-van Gaalen MBA

Sustainable construction means that homes, buildings and other structures are developed and used with respect for people and the environment. Sustainable construction does not just concern energy-saving in homes and buildings, but also includes:

- the use of sustainable materials with take account of the environment and the health of residents and users;
- a healthy indoor environment due to good ventilation which prevents moist, mould and accumulation of hazardous substances.
- sustainable demolition, where materials can be used again (reuse and recycling);
- responsible use of water;
- respect for the environment;
- prevent raw materials for construction from being depleted.

Sustainable construction is therefore a very broad term.

There is a number of models and systems with which you can 'measure' the sustainability of a building. In this chapter, we will briefly address the two main models used in the Netherlands: BREEAM-NL and GPR. It is beyond the scope of this book to discuss the models in great details; for this, we refer you to the internet site of the models in question. Besides BREEAM-NL and GPR, the American model LEED is also used in construction projects on occasion. LEED can be compared with BREEAM-NL, although its main focus is on the American market. For more information on LEED, we refer you to the website of the US Green Building Council, the party which develops LEED.

9.1 BREEAM-NL

BREEAM-NL is a method with which the sustainability of new buildings, existing buildings, areas and demolition projects can be assessed in its entirety. BREEAM-NL is derived from the international BREEAM model developed in England by BRE. In the Netherlands, BREEAM-NL is managed and developed by the Dutch Green Building Council.

BREEAM-NL has three different quality marks:

- BREEAM-NL New building and Renovation;
- BREEAM-NL In Use;
- BREEAM-NL Demolition and Dismantling;
- BREEAM-NL Area.

BREEAM-NL New buildings and Renovation

With BREEAM-NL New buildings and Renovation, new developments and large-scale renovations can be assessed on sustainability performance. BREEAM-NL New buildings and Renovation can be used for offices, retail, schools, industrial buildings, homes, meeting and accommodation facilities, and data centres.
Buildings are assessed on nine different sustainability items. The items are indicated by a three-letter code, derived from the English term of the sustainability item.

- Management (MAN). This theme includes aspects such as the lay-out of a sustainable construction site, notification of neighbours and ensuring correct completion of the building.
- Health (HEA). Daylighting, view, high- quality lighting, air quality, thermal comfort and acoustics are items included in this theme.
- Energy (ENE). For example, energy-efficient designs, installing additional meters, implementing renewable energy and using energy-efficient appliances are covered in this theme.
- Transport (TRA). In this theme, public transport and basic facilities, transport plans, and pedestrian and cyclist safety play a role.
- Water (WAT). This is not just limited to the use of water, but, for instance, also the reuse of (rain)water.
- Materials (MAT). This theme pays attention to the origins and environmental impact of the construction materials.
- Waste (WST). This category does not just assess limitation and separate collection of waste during construction, but also during the operational phase.
- Land use and ecology (LE). Reuse of land and respect for the plants and animals present at the construction site form part of this category.
- Pollution (POL). Within this theme group, various aspects of pollution are dealt with, such as light pollution, pollution due to refrigerant leakages and noise pollution.

The nine sustainability themes are subdivided into credits. For each credit a certain number of points can be scored if it is shown that the requirements of this credit have been met.

In order to determine the final score of a project, first the separate scores of each sustainability theme are determined in relation to the maximum score. In the final score, each category has its own weighting factor: management 12%, health 15%, energy 19%, transport 8%, water 6%, materials 12.5%, waste 7.5%, land use & ecology 10% and pollution 10%. This leads to a final score expressed in stars in combination with an English mark ranging from pass to outstanding.

Stars		Score
★	Pass	≥ 30%
★★	Good	≥ 45%
★★★	Very good	≥ 55%
★★★★	Excellent	≥ 70%
★★★★★	Outstanding	≥ 85%

Figure 9.1 BREEAM stars and scores

BREEAM-NL In Use

Sustainability is more than just erecting a sustainable building. As soon as the building is completed, it will start being used, and then it will be important to pay attention to a sustainable and conscious use of the building. In order to clarify this, BREEAM-NL In Use was developed. This allows the sustainability performance of an existing building to be monitored. As with BREEAM-NL New buildings and Renovation, assessments are made on nine sustainability categories: management, health, energy, transport, water, materials, waste, land use & ecology and pollution. These credits are, of course, adapted for existing structures. BREEAM-NL In Use also makes a distinction between three elements:

- asset: the sustainable performance of the building;
- management: the level of sustainability at which the building is managed;
- use: the sustainable use of the building.

As is the case with New buildings and Renovation, the final score of an In-Use assessment is also expressed in stars and an English mark ranging from pass to outstanding.

BREEAM-NL Demolition and Dismantling

In order to encourage parties to contribute to the circular economy, BREEAM-NL Demolition and Dismantling was developed. Demolition projects are assessed on eight different sustainability categories: management, health, materials, energy, transport, water, land use & ecology and pollution. For BREEAM-NL Demolition and Dismantling too, the final score is expressed in a number of stars and a mark ranging from pass to outstanding.

BREEAM-NL Area

The BREEAM-NL Area assess not just the sustainability performance of a single building, but of an entire area. Area developments are assessed on six sustainability categories: area management, synergy, sources, spatial development, wellbeing & prosperity and area climate. For BREEAM-NL Area too, the final score is expressed in a number of stars and a mark ranging from pass to outstanding.

9.2 GPR

In comparison to BREEAM-NL, GPR is a more accessible model with which to map out the sustainability of buildings and urban development areas. The GPR has a high level of freedom and flexibility; the model is les rigid than BREEAM. GPR is an originally Dutch model, which was developed by W/E consultants commissioned by the Tilburg Municipality. The abbreviation GPR refers to Gemeentelijke Praktijk Richtlijn: Municipal Practice Guideline.

The GPR currently distinguishes different modules:

- GPR buildings;
- GPR urban development.

In addition, a number of associated modules are available which will not be discussed here. For these, we refer you to the GPR website.

GPR Buildings

The name says it all: GPR Buildings lets you measure the sustainability of buildings. Not just new developments and large-scale renovations, but also existing structures can be assessed with GPR. GPR Buildings can be used for homes, offices, schools, places of business, accommodation facilities, meeting facilities, shops and healthcare-related real estate. In addition, there are so-called GPR Specials for railway station buildings, sports buildings and swimming pools.

GPR Buildings assess buildings on five themes: energy, environment, health, quality of use and future value.

- Energy. In this theme, the philosophy of the trias energetica is leading. The results for
- energy performance calculations play an important role in this theme. A number of additional criteria have also been included which are not covered by the energy performance calculations.
- Environment. The environmental impact of (construction) materials and the assessment
- whether renovation is more sustainable than new development is considered in this theme. In this theme, attention is also given to limiting water use in buildings.
- Health. The objective of this theme is realising healthy buildings to live and work in.
- Consider for example limiting noise pollution, sufficient fresh air, comfortable ventilation and sufficient daylight.
- Quality of use. In this theme, it is encouraged that designers think about the
- quality of use of buildings. The aim is to make buildings appropriate, accessible, functional, of good technical quality and in a safe living environment. GPR Buildings offers insight into the extent to which a building or design meets the requirements of the target population.
- Future value. Empty buildings and unattractive residential neighbourhoods are a social and financial problem. They have not been realised futureproof at the time they were built. For construction or renovation of buildings, it must be taken into account that the function and amenity value of the area may change in the future. A high score on this theme, a building can be adapted to changing user requirements or law and legislation without great expenditure or wasting of materials.

In general, GPR uses menu selections (for the themes health, quality of use, and future value) and the results of calculations which have to be made anyway in the context of building permits (such as the EPC calculation). A score is determined for each theme (from 0 to 10). No overall score is determined as is the case for BREEAM. It is possible that a building scores 9 for energy and 7.5 for future value in GPR.

GPR Urban Development

Not just the sustainability of a single building is assessed with GPR Urban Development, but that of an entire area. Area developments are assessed on five sustainability categories: energy, space and supply; wellbeing and health; practical value and future value. For GPR Urban Development, too, a score of 0 to 10 per theme is given.

10 Acoustics

A.C. van der Linden; A. Zeegers

In this chapter, the basic principles in relation to sound come up for discussion: what is sound, how do people experience sound, how does sound absorption work. We also discuss how the sound situation in spaces can be evaluated and how to deal with this in the design.

10.1 Basic terms

Sound is energy that is produced by a source in the form of vibrations (variations in pressure), which moves through a medium (such as air) as sound waves and is received by a detector (such as the ear):

The energy produced or generated by the source is called acoustic power. This is expressed in watt (W). The energy at a random place inside the medium is called the sound intensity and is expressed in W/m2. The energy perceived by an observer is called the sound pressure, which is expressed in pascal (Pa).

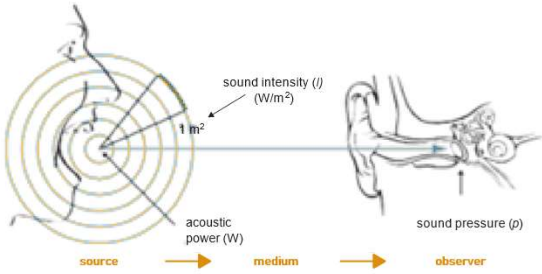


Figure 10.1 Sound production and perception

Sound source

If a source is made to vibrate (the vocal chords for instance) then the adjacent medium (air for instance) will also start to vibrate. Acoustic power is primarily used to describe the noise production from machines and appliances.
Acoustic power is also used in calculating sound propagation through air duct systems.

Sound waves

The sound source will make the adjoining medium (for instance air) vibrate. These vibrations are called sound waves. If you move the end of a piece of rope up and down then a wave will propagate through the rope as shown in figure 10.2. The direction of movement in the rope is perpendicular to the propagation direction of the wave. This is known as a transverse wave motion. The wave propagates, the particles of the rope remain in place and move around a point of equilibrium.

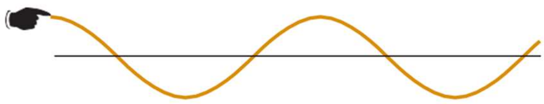


Figure 10.2 Propagation of a transverse wave

It is somewhat different for a sound wave. Here the direction of movement of the particles is the same as the direction of propagation. This is known as a longitudinal wave motion. This can be illustrated using a number of spherical balls that are suspended on wires in a frame (see figure 10.3). If you allow the left hand ball to fall onto the row of stationary balls, then a longitudinal wave propagates through the row of balls and the right hand ball is flung out.

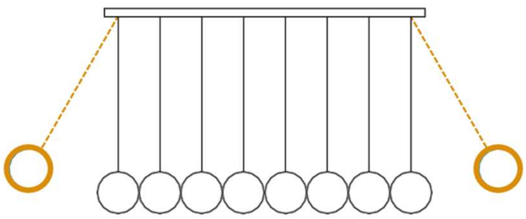


Figure 10.3 Propagation of a longitudinal wave

In a sound wave in air there are rarefactions and compressions (negative and positive sound pressures): the air particles vibrate around an equilibrium position (see figure 10.4). The air particles remain in their locations, the wave propagates. Longitudinal sound waves arise also when driving a pile in the ground. When this pile receives a blow, a shockwave is produced which travels to the end of the pile.

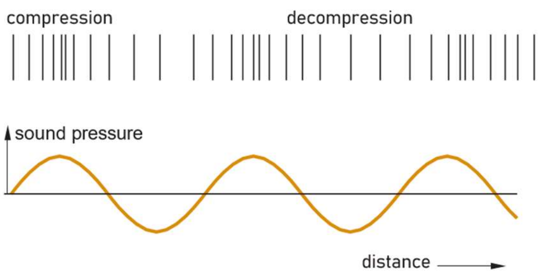


Figure 10.4 Propagation of a sound wave through the air

A number of characteristic values can be derived in relation to wave motions, specifically, the frequency (f), the wavelength (λ) and the propagation speed (c).

Frequency, wavelength and propagation

The sound wave (λ) in a longitudinal wave is the distance between two compressions (or two rarefactions). In general, the wave length is the distance between two points which are in an identical state (they are in phase). The number of vibrations per second is the frequency (*f*), which is expressed in Hertz (Hz).

Different tones have different frequencies. This way low tones have a low frequency (therefore a small number of vibrations per second or a 'long wavelength') and high tones have a high frequency (therefore a large number of vibrations per second or a short wavelength). A pure tone consists of a sound whose sound pressure changes in time in the shape of a sine wave (see figure 10.5). Pure tones are rare. The tone produced by a musical instrument is also built up of a base tone and various harmonics (see figure 10.6). The composite sound then displays an image similar to that shown in figure 10.7-1. Most sounds occurring in the environment are build up of many different tones causing the progression of the sound pressure to become very jagged with time (see figure 10.7-2).

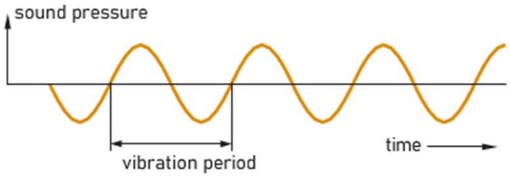


Figure 10.5 The progress of a sound wave as a function of time for a pure tone

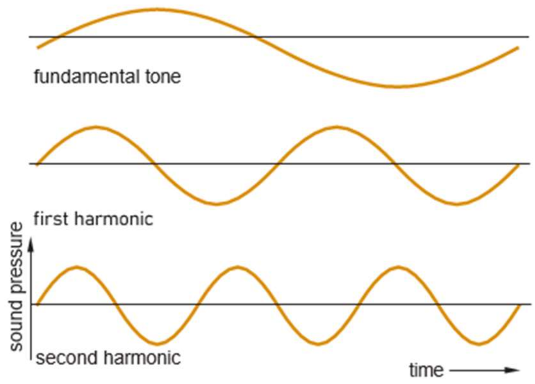


Figure 10.6 Base tone and harmonics

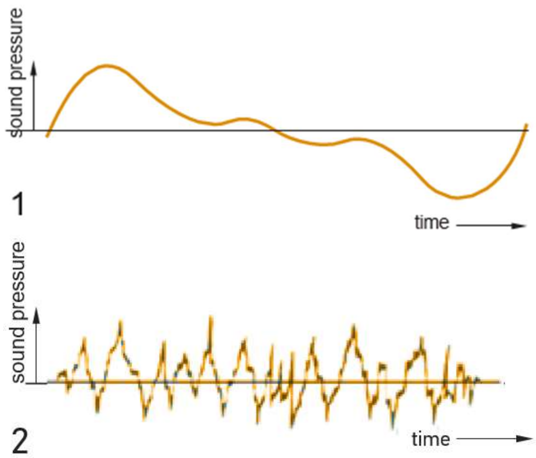


Figure 10.7 Composite sounds

The propagation speed (*c*) of longitudinal waves is the same for all frequencies and depends on the medium and the temperature of the medium. However, the temperature differences in structures are relatively small in practice so that a single propagation speed can be used for calculations. The propagation speed in air is approximately 340 m/s (20 °C).

The following propagation speeds apply for other media:

- $c_{aluminium}$ = 5100 m/s
- c_{steel} = 4900 m/s
- $c_{concrete}$ = 4000 m/s
- $c_{masonry}$ = 2000 m/s
- c_{water} = 1450 m/s

The following relationship exists between the propagation speed, the frequency and the wavelength:

$$c = f \cdot \lambda \text{ [m/s]}$$

The meaning of the symbols is:

c the propagation speed of the sound in m/s
f the frequency in Hz
λ the wavelength in m

The wavelength of a specific frequency (in air) can therefore be calculated as follows:

$$\lambda = \frac{c}{f} = \frac{340}{f} \text{ [m]}$$

This is shown for a number of frequencies in the table in figure 10.8.

f [Hz]	λ [m]
63	5.40
125	2.72
250	1.36
500	0.68
1000	0.34
2000	0.17
4000	0.09
8000	0.04

Figure 10.8 Frequencies and wavelengths

Sound spectrum

When we want to know how the sound energy is distributed across the frequency range we generally use an internationally standardised system of octave bands. An octave band gets its name from the fact that the upper threshold frequency is twice as high as the lower threshold frequency. The upper threshold frequency forms the octave of the lower threshold frequency. Octave bands are designated by their mid frequency.

In addition to octave bands, one-third octave bands are also frequently used (particularly in Germany). These are 1/3 octave bands. Figure 10.9 shows the frequency range with the octave bands of a keyboard and the register of a number of musical instruments and singing voices.

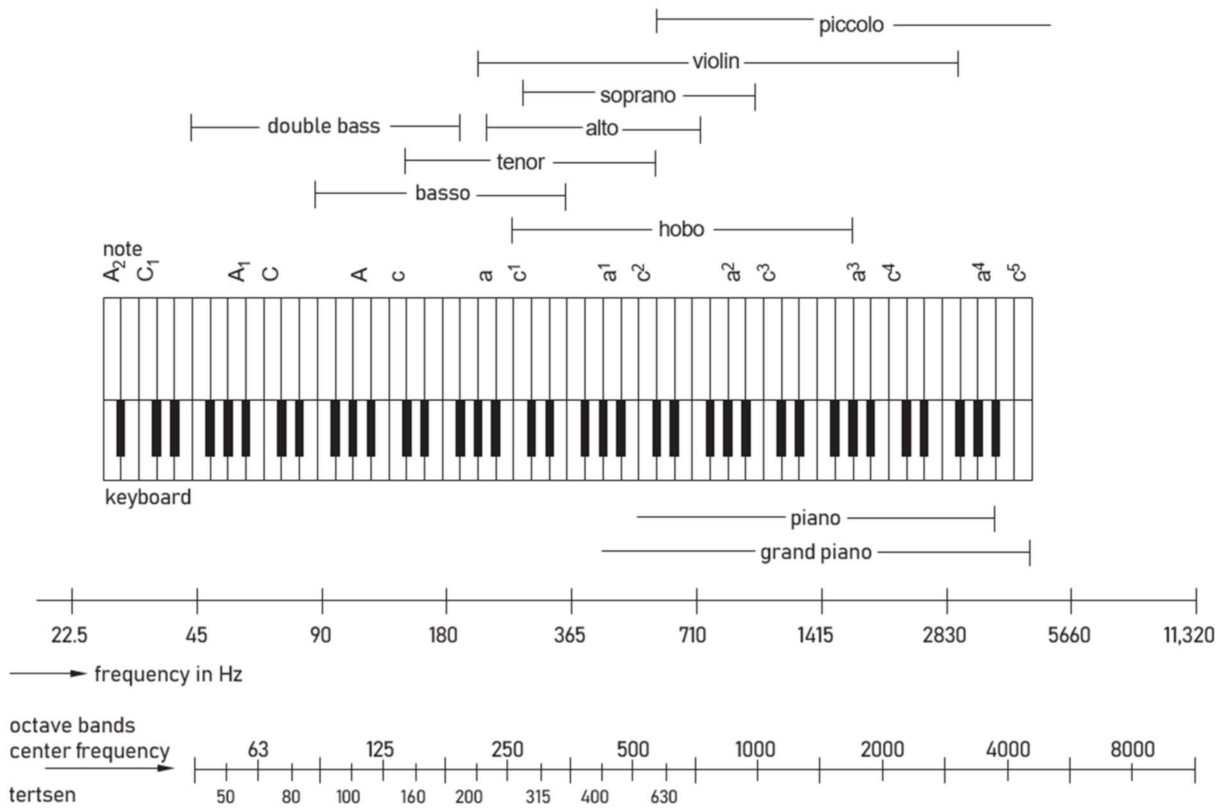


Figure 10.9 Arrangement of the frequency range into octave bands and thirds

Sound propagation

The energy produced by the sound source, will spread through the medium and arrive at the observer. Here we can make a distinction between sound propagation in the free field (unhindered sound expansion is possible) and sound expansion in a closed room (no unhindered sound propagation is possible). In the free field sound waves can, therefore, expand 'unhindered'. In that case we mean progressing waves. In a closed room the sound waves will not be able to expand unhindered because of the limited space: they will quickly reflect from the wall. In this case the sound waves can propagate through the room in a random fashion. We then talk about a diffuse sound field. In other words:

- The conditions for a progressing wave are roughly met by a sound that comes from a specific direction, as is often the case outdoors (industrial noise etc.).
- There is a diffuse sound field when the sound waves run in all directions, such as is roughly the case inside a room.

This distinction is very important. We will use this for deriving relationships in the course of this and subsequent chapters.

Sound intensity in the free field

Sound propagation in the free field depends on the characteristics of the source. Here a distinction can be made between:

- a point source (a loudspeaker for example),
- line source (for example a busy motorway with a continuous flow of cars).

In sound propagation from a point source the energy will expand spherically (equal energy in all directions). In sound expansion from a line source the energy will expand cylindrically. When the sound intensity (the energy per square metre) at a specific point has to be determined this is relatively simple. It is equal to the energy produced by the source divided by the area over which the energy has been spread. The amount of energy that is determined using this method is known as the sound intensity (*I*).

The following applies for a point source:

$$I = \frac{W}{\left(\frac{4\pi r^2}{Q}\right)} \ [\mathrm{W/m^2}]$$

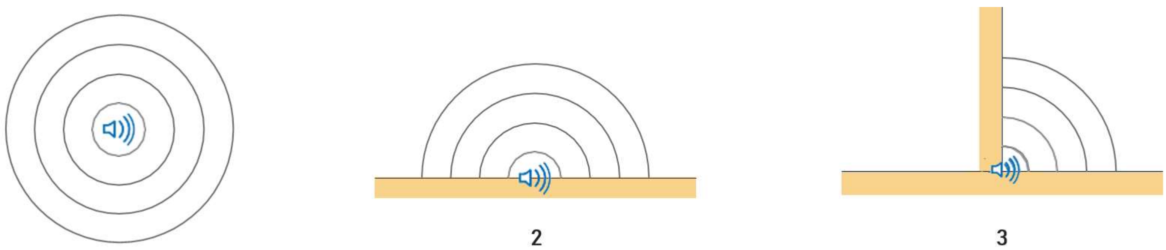
The following applies for a line source:

$$I = \frac{W}{\left(\frac{2\pi r}{Q}\right)} \ [\mathrm{W/m^2}]$$

The meaning of the symbols is:

I	the intensity in watts per m^2
W	the acoustic power of the source in W
r	the radius of the sphere or cylinder in m
Q	the direction factor

Q is the direction factor of the source. If the source is transmitting an equal amount of energy in all directions, the direction factor is Q = 1, a source that is free in space for example (see figure 10.10). If the same source is placed on a hard surface, then the same amount of energy will spread over a hemisphere ($2\pi r^2$). This leads to a direction factor Q = 2. The intensity is therefore twice as great. If, however, the



1
free field
Equal amount of sound propagation in all directions, in a sphere ($4\pi r^2$), $Q = 1$

2
free field
Reflection via a hard surface. Energy distributed in a hemisphere ($2\pi r^2$), $Q = 2$

3
free field
Reflection via the bottom and a wall. Energy distributed in a quarter of a sphere (πr^2), $Q = 4$

Figure 10.10 Direction factor *Q*

source is placed on a soft (absorbent) surface, then the direction factor Q is equal to 1. Approximately half the quantity of energy will immediately be absorbed by the soft surface.

Sound intensity in a closed room

In a closed room the sound waves will hit the surrounding structure. Part of the sound wave is reflected by the structure, but part of it is also absorbed by the structure (particularly if the structure comprises acoustically 'soft' material). We can use the difference between an empty house and a furnished house as an example. In an empty house with a lot of concrete everything sounds much louder than when the same house has been furnished (with carpeting, curtains and furniture for example). The difference in sound intensity is caused by the absorption of the sound waves by the acoustically 'soft' materials.
The amount of sound absorption is expressed in m^2 sabin (square metres open window). Section 10.3 discusses this subject in detail. For sound propagation in a closed room, a diffuse field, it holds that the relationship between the acoustic power and the sound intensity depends on the quantity of absorbing material in the room:

$$I = \frac{W}{A} \text{ [W/m2]}$$

The meaning of the symbols is:
I the intensity in W/m^2
W the acoustic power of the source in W
A the total sound absorption in a room in m^2 open window (see section 10.3)

Sound pressure

As a result of vibrations, pressure variations (under pressure and over pressure) are created in relation to the barometric air pressure (B = 100,000 Pa of 105 Pa). The human ear can detect these vibrations and from the sound pressure (p) it can determine the strength-impression of the sound from the rapid changes in pressure at a specific method of averaging. This (quadratic) average is known as the effective sound pressure. When effective sound pressure is mentioned in this chapter it is indicated by p_{eff}.

$$p_{eff} = \sqrt{p^2} \text{ [Pa]}$$

The sound pressure is very small in relation to barometric pressure. A radio playing loudly for example creates an effective sound pressure of p_{eff} = 0.2 Pa. This is 500,000 times smaller than barometric pressure.

Relationship between sound pressure and sound intensity

Just as there is a relationship between acoustic power and the sound intensity there is also a relationship between sound pressure and sound intensity. For a progressing wave this is:

$$I = \frac{p_{eff}^2}{\rho \cdot c} \text{ [W/m}^2\text{] (free field)}$$

And for a diffuse field it is:

$$I = \frac{p_{eff}^2}{4 \cdot \rho \cdot c} \text{ [W/m2] (closed room)}$$

The meaning of the symbols is:
p_{eff} the effective sound pressure in Pa
ρ the density of the air in kg/m^3
c the propagation speed of the sound in m/s

Under average conditions the expression $\rho \cdot c$ has a numerical value of approximately 400 $kg/(m^2 \cdot s)$.

Limits of hearing

When a sound is too soft, the ear can no longer detect it. There is therefore a limit of hearing. This is at a sound pressure of p = approx. $2 \cdot 10^{-5}$ (0.00002) Pa. This is $5 \cdot 10^9$ times smaller than barometric pressure.

There is also an upper limit of hearing where the sound pressure is so great that the ear is damaged. This 'pain threshold' is at p = approx. 200 Pa. This is still 500 times smaller than barometric pressure. Even below the pain threshold there is, however, a risk of damage to hearing depending on the length of time that someone is exposed to the sound pressure. Consider the noise from pneumatic picks, compressors and suchlike.

Type of sound	Sound pressure (p_{eff}) [Pa]	$\frac{p_{eff}}{p_0}$	$\frac{p^2_{eff}}{p^2_0}$	L_p [Pa]
Limit of hearing	$2 \cdot 10^{-5}$	1	1	0
Rustling leaves	$2 \cdot 10^{-3}$	10	10^2	20
Whispering at 1m distance	$2 \cdot 10^{-3}$	100	10^4	40
Conversation at 1m distance	$2 \cdot 10^{-2}$	1000	10^6	60
Loud radio	$2 \cdot 10^{-1}$	10.000	10^8	80
Nearby car horn	2	100.000	10^{10}	100
Jet engine	20	1.000.000	10^{12}	120
Pain threshold*	200	10.000.000	10^{14}	140

* The sound pressure level at which a 'feeling of pain' occurs, differs widely from individual to individual however.

Figure 10.11 Examples of sound pressures and sound levels

Sound pressure level

The human ear therefore has a 'measurement range' for sound pressure from $2 \cdot 10^{-5}$ to 200 Pa. These extremes differ a factor of 10^7. Because it is difficult to work with figures that are so widely spread, sound pressure cannot be directly used as a dimension of the sound intensity. A logarithmic relationship has therefore been introduced: the sound pressure level (L_p). For this, p_{eff} is compared to a fixed comparison pressure (p_0), that matches the lower limit of hearing:

$$p_0 = 2 \cdot 10^{-5} \text{ Pa} = 0.00002 \text{ Pa}$$

Because the square of the effective sound pressure is a measure of the intensity of the sound, the following expression is used to determine the sound pressure level (L_p):

$$\frac{p^2_{eff}}{p^2_0}$$

The sound pressure level is the logarithm of this relationship multiplied by 10:

$$L_p = 10 \log \left(\frac{p^2_{eff}}{p^2_0}\right) \text{ [dB]}$$

The factor 10 has been introduced to obtain an agreeable scale distribution. Now the scale runs from 0 to 140 dB (decibels) (see the example sound pressure levels in the table in figure 10.11). Without the factor 10, the scale would run from 0 to 14 (bel).

A logarithmic scale is used for sound pressure for reasons of usability. This also means that the intensity of the acoustic power can be expressed logarithmically.

Power: $L_W = 10 \log\left(\frac{W}{W_0}\right)$ [dB]

Intensity: $L_I = 10 \log\left(\frac{I}{I_0}\right)$ [dB]

Sound pressure: $L_p = 10 \log\left(\frac{p^2_{eff}}{p^2_0}\right)$ [dB]

The meaning of the symbols is:
L_W the acoustic power level in dB
W the acoustic power in W

W_0 the reference power (10^{-12} W)
L_I the sound intensity level in dB I the sound intensity in W/m^2
I_0 the reference intensity (10^{-12} W/m^2)
L_p the sound pressure level in dB
p_{eff} the effective sound pressure in Pa
p_0 the reference sound pressure ($2 \cdot 10^{-5}$ Pa)

As already mentioned, the value of the reference level for sound pressure has not been chosen at random but it is based on the limit of hearing. The reference level for the sound intensity and the sound power can then also be derived as follows:

$$I_0 = W_0 = \frac{p_0^2}{\rho \cdot c} = 10^{-12}\ [\mathrm{W/m^2}]$$

Because the acoustic power, the sound intensity and the sound pressure are logarithmic functions, the calculation rules in respect of the logarithm apply. These rules are shown below for the sake of completeness:

$g^x = y \Leftrightarrow x = {}^g\log y$
$\log(ab) = \log a + \log b$
$\log(\frac{a}{b}) = \log a \cdot \log b$
$\log(a^b) = b \cdot \log a$
$10 \log 2 = 3$
$10 \log 3 = 4.7$
$10 \log 4 = 6$

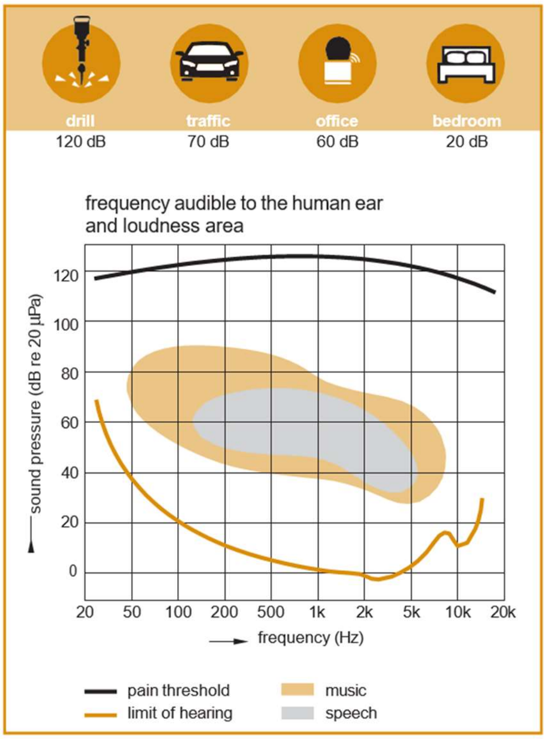


Figure 10.12 Range of human hearing

Adding sound pressure levels

Because of their logarithmic scale, sound levels cannot be added just like that (see the calculation rules for this). You must first add the values for $\frac{p_{eff}^2}{p_0^2}$ together and then find the logarithm again. This is how when you add two sound pressure levels of 60 dB together, the total is only 63 dB:

$$\frac{p_{eff}^2}{p_0^2} = 10^6 \rightarrow \frac{p_{eff}^2}{p_0^2} + \frac{p_{eff}^2}{p_0^2} = 2 \cdot 10^6 \rightarrow 10 \log (2 \cdot 10^6) = 10 \log 10^6 + 10 \log 2 = 63 \text{ dB}$$

The following applies in the same way: 40 dB + 40 dB = 43 dB.

When two unequal sound pressure levels are added together, then the final result is a minimum of 0 to a maximum of 3 dB more than the highest value of the two (60 dB + 60 dB = 63 dB, 60 dB + 50 dB = 60.4 dB).

The following can be used as a rule of thumb:

- When added together two equal (independent) sound pressure levels give an increase of 3 dB (10 log 2).
- When two (independent) sound pressure levels differ by more than 10 dB you can ignore the smallest value and the total sound pressure level is equal to the highest value.

Adding together two sound pressure levels can be done using the graph in figure 10.13. On the horizontal axis you take the difference between the two sound pressure levels ($L_{p1} - L_{p2}$) and on the vertical axis you find the highest level (L_{p1}) for the value to be added (C). See the table in figure 10.14 also.

When a number of sound pressure levels have to be added, this can be done two by two. See the example in figure 10.15.

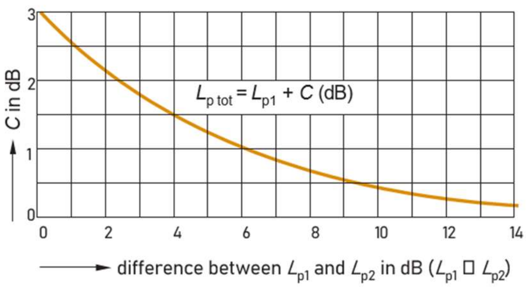


Figure 10.13 Adding sound pressure levels

$L_{p1} - L_{p2}$	C	L_{p1}	L_{p2}	$L_{p1} + C$	$L_{p;tot}$
0	3.0	60	60	60 + 3.0	= 63.0
0.5	2.8	60	59.5	60 + 2.8	= 62.8
1	2.5	60	59	60 + 2.5	= 62.5
2	2.1	60	58	60 + 2.1	= 62.1
3	1.8	60	57	60 + 1.8	= 61.8
4	1.5	60	56	60 + 1.5	= 61.5
5	1.2	60	55	60 + 1.2	= 61.2
7	0.8	60	53	60 + 0.8	= 60.8
10	0.4	60	50	60 + 0.4	= 60.4
20	0.04	60	40	60 + 0.04	= 60.0
30	0.004	60	30	60 + 0.004	= 60.0

Figure 10.14 Example of adding sound pressure levels

Adding sound pressure levels can be expressed in the following formula:

$$L_{p;tot} = 10 \log \left(10^{\frac{L_{p1}}{10}} + 10^{\frac{L_{p2}}{10}} + 10^{\frac{L_{p3}}{10}} + \ldots\right) \text{ [dB]}$$

The meaning of the symbols is:

$L_{p;tot}$ the resulting sound pressure level
L_{p1} the sound pressure level of sound 1
L_{p2} the sound pressure level of sound 2
... etc.

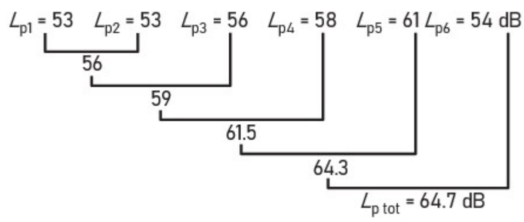


Figure 10.15 Example of adding sound pressure levels

The example in figure 10.15 can therefore be calculated as follows:

$$L_{p;tot} = 10 \log \left(10^{\frac{53}{10}} + 10^{\frac{53}{10}} + 10^{\frac{56}{10}} + 10^{\frac{58}{10}} + 10^{\frac{61}{10}} + 10^{\frac{54}{10}}\right) = 64.7 \text{ [dB]}$$

Relationship between acoustic power, sound intensity and sound pressure

As we have seen, earlier mutual relationships can be shown between acoustic power, sound intensity and sound pressure. These relationships can also be converted into logarithms. In doing so we must always make a distinction in the conditions under which the sound can propagate: the free field or the diffuse sound field.

Free field

For the sake of simplicity we assume a point source. The relationship can easily be worked out for other sources. The formulas discussed earlier apply for the sound intensity of decaying waves (i.e.: at a long distance from the source).

$$I = \frac{W}{\left(\frac{4\pi r^2}{Q}\right)} \text{ [W/m}^2\text{]}$$

$$I = \frac{p^2_{eff}}{\rho \cdot c} \text{ [W/m}^2\text{]}$$

$$I_0 = \frac{p^2_0}{\rho \cdot c} = 10^{-12} \text{ [W/m}^2\text{]}$$

$$L_I = 10 \log \left(\frac{I}{I_0}\right) \text{ [W/m}^2\text{]}$$

The relationship between the sound intensity level and the acoustic power level now follows with:

$$L_I = 10 \log \frac{\frac{W}{\left(\frac{4\pi r^2}{Q}\right)}}{10^{-12}} \rightarrow L_I = L_W + 10 \log \left(\frac{Q}{4\pi r^2}\right)$$

And the relationship between the sound intensity level and the sound pressure level is then:

$$L_I = 10 \log \frac{\left(\frac{p^2_{eff}}{\rho \cdot c}\right)}{\left(\frac{p^2_0}{\rho \cdot c}\right)} = 10 \log \left(\frac{p^2_{eff}}{p^2_0}\right) \rightarrow L_I = L_p$$

Using the relationships derived above we can now determine the relationship between the sound pressure level and the acoustic power level as follows:

$$L_p = L_W + 10 \log \left(\frac{Q}{4\pi r^2}\right) \text{ [dB]}$$

Or:

$$L_p = L_W - 10 \log \left(\frac{4\pi r^2}{Q}\right) \text{ [dB]}$$

If the distance from the source doubles (2r) then we can derive from the formulas above that the sound pressure level decreases by 10 log 4 = 6 dB.

Diffuse sound field

In a diffuse sound field equally strongly decaying waves arrive from every direction. This assumption applies particularly to closed rooms that are not too big. This assumption will not however apply to large rooms or rooms with a strongly segmented floor plan. We will derive the relationships between the sound intensity, the sound pressure level and the acoustic power level in the same way as for the free field. The formulas discussed earlier apply for sound intensity in a diffuse field:

$$I = \frac{W}{A} \text{ [W/m}^2\text{]}$$

$$I = \frac{p^2_{eff}}{4 \cdot \rho \cdot c} \text{ [W/m}^2\text{]}$$

$$I_0 = \frac{p^2_0}{\rho \cdot c} = 10^{-12} \text{ [W/m}^2\text{]}$$

$$L_I = 10 \log \left(\frac{I}{I_0}\right) \text{ [W/m}^2\text{]}$$

The relationship between the sound intensity level and the acoustic power level is determined as follows:

$$L_I = 10 \log \frac{\left(\frac{W}{A}\right)}{10^{-12}} \rightarrow L_I = L_W - 10 \log A \text{ [dB]}$$

And the relationship between the sound intensity level and the sound pressure level follows from:

$$L_I = 10 \log \frac{\left(\frac{p_{eff}^2}{4 \cdot \rho \cdot c}\right)}{\left(\frac{p_0^2}{\rho \cdot c}\right)} = 10 \log \left(\frac{p_{eff}^2}{p_0^2}\right) - 10 \log 4 \text{ ->}$$

$$L_I = L_P - 10 \log 4 \text{ [dB]}$$

Using the relationships derived above we now determine the relationship between the sound pressure level and the acoustic power level as follows:

$$L_p = L_I + 10 \log 4$$

$$L_i = L_w - 10 \log A \text{ ->}$$

$$L_p = L_W + (10 \log 4 - 10 \log A)$$

or

$$L_p = L_W + 10 \log \left(\frac{4}{A}\right) \text{ [dB]}$$

Note: this is a greatly simplified derivation, which, however, provides sufficient insight for practical purposes. For the complete derivation, the last term is 10 log $\frac{4 \cdot (1 - a_{gem})}{A}$ · a_{gem} is the average absorption coefficient of all surrounding walls. Only in rooms with extremely absorbent finishings will this make an important difference.

10.2 Evaluating sound

The sensitivity of the ear

The human ear is not equally sensitive to all tones. In this way a tone of 1000 Hz and 30 dB will be evaluated as being equally as loud as a lower tone of 63 Hz and 56 dB. Isophones have been determined using tests. These are lines of equal loudness (see figure 10.16).

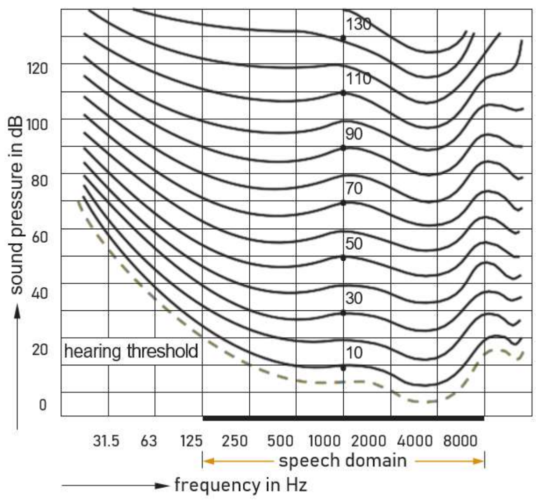


Figure 10.16 Isophones (lines of equal loudness)

Measuring a sound spectrum

An electronic measuring instrument can be used to determine the sound pressure level. This type of measuring instrument consists of a microphone that converts the sound pressure (vibrations) into an electronic signal. This signal is amplified and the effective value is determined using a network of electronics and compared to the comparison value. The result (in dB) is made visible using a pointer on a scale or using a display (figures).

Figure 10.17 Sound meter

When we want to determine the spectrum of a sound (the distribution of the sound energy across the frequency range) then an electronic filter is included in the sound level meter. This type of filter allows only part of the frequency range to pass through. Normally a so-called octave filter is used, which works with the standardised octave bands mentioned in section 10.1. When the filter has been set to an octave band of 500 Hz for example, then only frequencies between 355 Hz and 710 Hz are allowed to pass through and be measured. In this way the sound pressure level can be determined in every octave band. From the octave band levels we can eventually determine the final sound pressure level (across the entire frequency range) by adding them logarithmically (see section 10.1). For a more accurate analysis a different filter can be used to split every octave band into three for example. Even smaller frequency bands are also possible.

Weighted sound level

When you want to evaluate a sound spectrum, you have to consider the sensitivity of the human ear to each octave band. A sound level A has been introduced to be able to make a single measurement suffice. A measuring instrument with a filter that mimics the sensitivity of the human ear is used for this. The entire frequency range can then be determined in a single (weighted) measurement. For a sound level L_A measured in this fashion, the used unit is often dB(A). In international standards however, L_A is expressed in dB. The attenuation or amplification that the A-filter produces is shown for each frequency in the table in figure 10.18.

Frequency [Hz]	A-weighting [dB]
63	-26.1
125	-16.1
250	-8.6
500	-3.2
1000	0.0
2000	1.2
4000	1.0
8000	-1.0

Figure 10.18 Attenuation or amplification in accordance with the A-weighting

The total sound level of an octave spectrum in dB is found by adding together (algebraically) the corrections shown against the octave values in figure 10.18 and then totalling the octave values logarithmically (see section 10.1). Figure 10.19 shows a couple of examples of spectra.

Line I is the spectrum (the sound production) for traffic noise. Line II is the spectrum (the sound production) of a jet plane landing. Line III is the spectrum (the sound production) of a jet plane taking off.

When you compare spectrum II and III to each other, you might at first sight conclude that a jet plane taking off causes more noise than a jet plane landing. However, as you can see from the example below, this is an incorrect conclusion. When taking the auditory sensitivity of the human ear into account, reducing the low frequencies in the measurements, the total sound level of both jet planes is equal, namely 90 dB. See also figure 10.20.

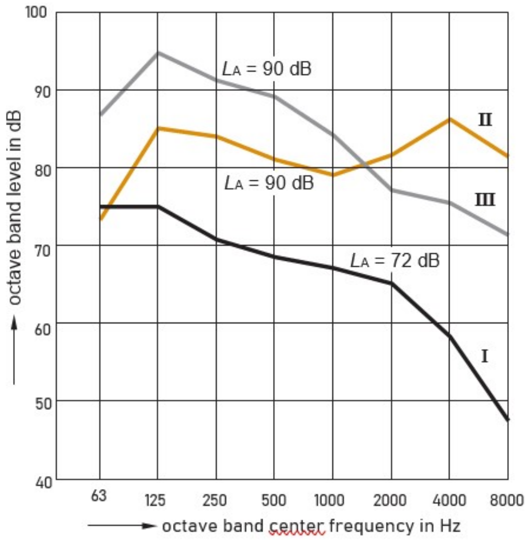


Figure 10.19 Example of a number of sound spectra

The sound level L_A in dB does not provide information about the shape of the spectrum. When it comes to taking measures such as improving the sound insulation of a facade, the shape of the spectrum is, however, important. In this way the sound insulation of all structures (including glass therefore) is the smallest for low frequencies (see section 11.1). The sound of spectrum III will therefore cause more problems than the sound of spectrum II, despite the fact that both represent a sound level of L_A = 90 dB. Luckily the shape of the spectrum is known for many types of sounds so that it usually suffices to determine L_A in dB when taking measurements.

Centre frequency [Hz]	L_p [dB] source II	Source III	A measurement [dB]	L_p [dB] source II	Source III
63	73	87	-26.1	46.8	60.8
125	85	95	-16.1	68.9	78.9
250	84	91	-8.6	75.4	82.4
500	81	89	-3.2	77.8	85.8
1000	79	84	0.0	79.0	84.0
2000	82	78	1.2	83.2	79.2
4000	86	75	1.0	87.0	76.0
8000	81	72	-1.0	80.0	71.0
Resulting sound pressure L_A [dB]				90.0	90.0

Figure 10.20 Calculation example

Evaluating a sound with a widely varying strength

A simple measurement cannot suffice when evaluating a sound where the sound pressure level varies widely with time, such as next to a motorway. Here it is necessary to record the course of the sound pressure levels over a longer period, so that some kind of average can be determined. The so-called equivalent sound pressure level (L_{eq}) is used most frequently. This is the level of a sound of constant strength which, taken over a specific time, represents an acoustic energy equivalent to the sound that varies widely in strength over the same period. The equivalent sound pressure level can be calculated as follows:

$$L_{eq} = 10 \log \left(\frac{1}{T} \cdot \int \frac{p_t^2}{p_0^2} \cdot dt\right) \text{ [dB]}$$

The meaning of the symbols is:

L_{eq} the equivalent sound pressure level in dB
T the exposure time in s
p_t the effective sound pressure in Pa during the exposure time
p_0 the reference sound pressure in Pa

Example

The sound pressure level is measured for 1 hour in a factory building. The meter is read 100 times during this hour.

Number of reading	Sound pressure level [dB]
30	75
20	80
20	85
20	90
10	95

The equivalent sound pressure level can now be calculated as follows:

$$L_{eq} = 10 \log \left(\frac{30}{100} \cdot 10^{7.5} + \frac{20}{100} \cdot 10^{8.0} + \frac{20}{100} \cdot 10^{8.5} + \frac{20}{100} \cdot 10^{9.5} + \frac{10}{100} \cdot 10^{9.5} \right) = 88 \text{ dB}$$

It is also possible to determine the sound pressure level that is exceeded during a specific percentage of the time. In this way L_{10} represents the sound pressure level that is being exceeded during 10% of the time. L_5 and L_{10} form a measure for the 'recognisable sound peaks', L_{90} and L_{95} form a standard for the 'background noise'.

Permissible sound levels

The permissible sound levels in relation to indoor noise depends on the nature of the activities that take place inside the room. In this way the requirements for indoor noise in a bedroom will be more stringent than in a living room, etc. There is also a difference if a sound is at a continuous strength (traffic, factories) or if it displays significant peaks (aircraft, trains). This is why regulations set requirements to facade sound proofing, distinguishing between traffic noise, industrial noise and air traffic noise.

10.3 Sound absorption

When sound strikes a structure, part of it is reflected, part is allowed to pass through and part remains inside the structure (see figure 10.21). The amount of sound that is allowed through is generally small in proportion. In a normal half brick wall this is only approximately 1/10,000th part of the sound energy striking the wall and even with a simple hardboard door this is still only approximately a 1/100th part.

The sound that is permitted to pass through is ignored in absorption problems so that the following applies for the coefficient of absorption and reflection:

$$a + r = 1 \text{ or } a = 1 - r$$

The meaning of the symbols is:

a the absorption coefficient (the absorbed sound)

r the reflection coefficient (the reflected sound)

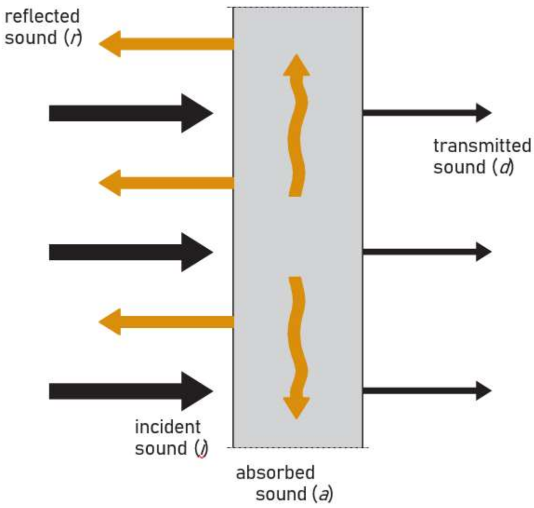


Figure 10.21 Sound energy striking and allowed to pass through, absorbed and reflected

So, what is not reflected is absorbed, and vice versa. The harder the structure, the more sound is reflected. Porous surfaces can absorb more sound. Structures that absorb efficiently can achieve an absorption coefficient of a = 0.7–0.9 across the frequency range from 500-2000 Hz (see the book of tables).

Reflection of sound waves from a wall

On reflection of a wave movement from a wall, a standing sound wave will occur of which the antinodes (maximum amplitude) and the nodes (no amplitude) occur at fixed distances from the wall. This can be demonstrated by Melde's experiment (see figure 10.22).

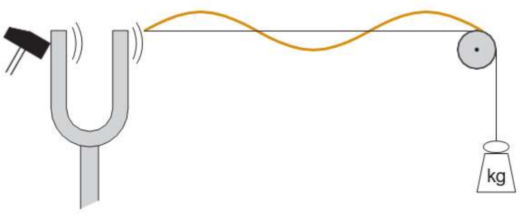


Figure 10.22 Melde's Experiment

One end of a wire is connected to a tuning fork and the other end is attached to a weight (fixed end). The tuning fork is made to vibrate. The outgoing wave is reflected from the far end (interference). It can now be seen that at mutually identical distances there are points that remain fully at rest (nodes) and that different parts of the wire vibrate with unequal amplitudes. The points with the greatest amplitude fall in the middle between two nodes. The points are known as antinodes. The speed of the parts is at its maximum at a distance of $\frac{1}{4}\lambda$ from the weight (which is comparable with a wall). The antinodes are at a large distance from the wall particularly for the low and middle frequencies (with a relatively high λ value) (see the table in figure 10.23). This has consequences for the effectiveness of the sound insulation applied to the wall.

f [Hz]	λ [m]	$\frac{1}{4}\lambda$ [m]
63	5.40	1.35
125	2.72	0.68
250	1.36	0.34
500	0.68	0.17
1000	0.34	0.09
2000	0.17	0.04
4000	0.09	0.02
8000	0.04	0.01

Figure 10.23 Frequencies, wavelength and $\frac{1}{4}$ wavelength (distance to first antinode).

Sound absorption capacities

Absorption of sound is, in fact, nothing more than the conversion of vibrations into heat. In principle, sound absorption can be achieved in two ways:

- by friction with air movement in porous materials.
- by means of resonance.

Friction

When a sound wave penetrates a porous material there is friction between the coming and going air particles in the pores of the material. This friction causes the sound energy (movement) to be converted into heat. The sound is absorbed by the material. In order to ensure that the sound can penetrate the material it must be as porous as possible. Too much noise must not be reflected at the passage from air to material. This is indicated using the airflow resistance of the material. Absorbing material must have a low airflow resistance so that the passage from the air to the material is such that not too much sound is reflected. On the other hand, the airflow resistance must not be too low, otherwise there will not be sufficient friction and absorption will be inadequate. The thickness of the material is also important. As shown the particle speed is at its maximum at $\frac{1}{4}\lambda$ from the wall. This is where the majority of the energy is.

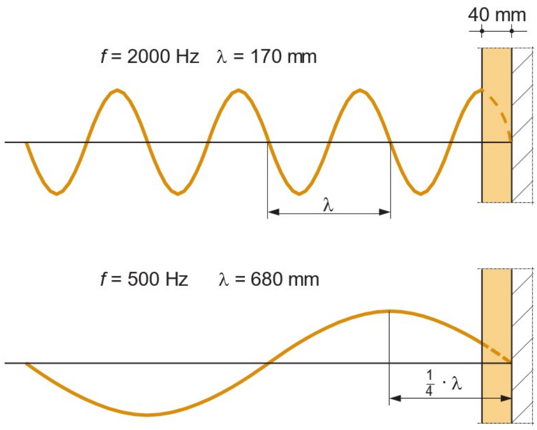


Figure 10.24 Influence of wavelength and layer thickness (porous material) on sound absorption.

f = 500 Hz λ = 680 mm

Figure 10.25 Apparent increases in the layer thickness produces better sound absorption.

Absorption material that is fitted to a wall must therefore have a thickness of one quarter wavelength ($\frac{1}{4}$ λ) of the sound to be absorbed in order to absorb effectively (see figure 10.24). This will not be a problem for the high frequency area. In the low frequency area, a stack of absorption material offering enough absorption will be too thick.

This is, however, not necessary. By applying the material at a certain distance from the wall you can ensure that it is exactly at the place where the particle speed is greatest (see figure 10.25).

The effect described above is used productively in suspended ceilings for example. It is also the reason why wall cladding is often fitted on framing. See the book of tables for the absorbing properties of the various structures. The frequency range at which absorbing materials are most effective is between 500 and 2000 Hz.

Absorbing materials are often very soft and delicate (mineral wool and suchlike) and must be protected against mechanical damage.

This can be done with a perforated sheet of metal, hardboard, plaster, etc.

In order that the absorbent qualities are not affected, the percentage of perforations must, however, be greater than approximately 20% and the intermediate distance between the openings must not be greater than 20 mm, otherwise the perforated surface acts as a wall. It is also possible to use wooden laths between which a space is kept open. The laths must, however, be kept as small as possible. In addition, the material could be covered with a porous fabric or membrane, or with a very thin plastic foil.

It is clear that painting the surface of absorbent materials could make them so closed that the airflow resistance is increased and that sound waves are no longer able to penetrate the material. This must be duly taken into account when considering the choice of material. Rough-fibred materials can sometimes be painted using a roller which should not block the pores and only colours the outer surface. You must, therefore, select materials that do not, or do not easily become dirty, or which can easily be cleaned.

Resonance

All objects have a frequency at which they spontaneously start to vibrate (their natural frequency). When an object is struck by a vibration that is equal to this natural frequency, the object will spontaneously start to vibrate. Example: if two identical tuning forks are set up some distance from each other and one tuning fork is struck, then the vibrations are taken up by the second tuning fork (check this by stopping the arms of the first tuning fork, the second continues to emit sound). This phenomenon is known as resonance. To prevent resonance in a structure then, for example, soldiers have to break step to march across an unstable bridge. If they didn't, it would be possible for the construction is 'triggered' at its frequency of oscillations and will start to vibrate spontaneously, causing an instable construction to collapse.

The way in which the previously mentioned perforated panels work is based on the resonance principle. The air in the holes forms a kind of mass that can vibrate on the air layer that lies behind it, acting as a kind of spring. This type of mass-spring system has a natural frequency (or resonance frequency).
The mass-spring resonance of these structures lies in the frequency range from approximately 300-1500 Hz (see figure 10.26). In that case, however, the percentage of perforations must not be too high (5 to 10%). The absorption (by the porous material) of higher frequencies is, perhaps, lost by this degree of perforation, but in return there is a gain in absorption in the lower and middle frequencies.

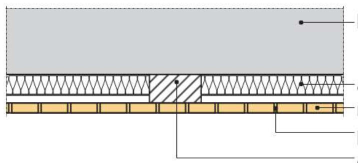


Figure 10.26 Perforated panels: good absorption in a frequency range from approx. 300-1500 Hz

Sheet material such as plywood, chipboard, metal etc., can also have a sound absorbing effect when they are fitted at a certain distance from the wall. The sheet forms a mass-spring system with the underlying air layer (see figure 10.27). The natural frequencies of these structures fall in the range from approximately 50-500 Hz. In addition, all kinds of bending waves occur in the sheet with specific natural frequencies.

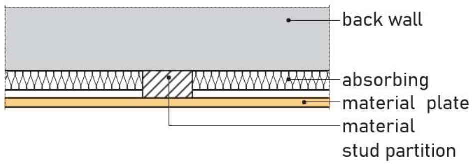


Figure 10.27 Un-perforated panels: absorption in a frequency range from approx. 50-500 Hz

When the sheet is struck by sound waves at its natural frequency, then it easily starts to vibrate. This vibration is converted into heat in the sheet's fixing points. The absorption takes place in a limited frequency range, but it does have a high absorption coefficient. Filling the cavity with an absorbent material (mineral wool) reduces the absorption coefficient to a = 0.25 to 0.50, but the range across which absorption takes place is much wider. Absorption by this type of sheets is always at lower frequencies (50-500 Hz).

Combination

The now antiquated bored or sawn-in softboard tiles or combination tiles of hardboard and softboard or other fibre materials form a kind of absorption material that combines the properties of the two aforementioned types. The fibre material (board) is, in fact, not porous enough to be used as it is as an insulation material. The resonance in the holes or grooves gives rise to good absorption in the middle frequencies range. In addition, the sheet acts as an un-perforated panel, which means that the lower tones are absorbed a little more. This type of sheet can safely be painted (with a roller) because the outside surface does not contribute to sound absorption behaviour. The absorption occurs in the holes or grooves in the underlying material.

Absorption characteristics

The absorption characteristics of the various materials can be summarised as follows:

Porous material:

- Absorbs well in the 500-2000 Hz frequency range.
- Preferably place the absorbing material at $\frac{1}{4}$ wavelength from the wall.
- Preferably use material with a low flow resistance.
- Protect using a perforated sheet with a degree of perforation >20% and intermediate opening distances < 20 mm.
- Do not paint due to blockage of the pores.

Perforated panel:

- Absorbs well in the 300-1500 Hz frequency range.
- The desired degree of perforation is 5-10%.
- When using absorption material in the cavity, the absorption coefficient is lower but the range across which absorption takes place is wider.
- Can be painted.

Un-perforated panel:

- Absorbs well in the 50-500 Hz frequency range.
- When using absorption material in the cavity, the absorption coefficient is lower, but the range across which absorption takes place is wider.
- Can be painted.

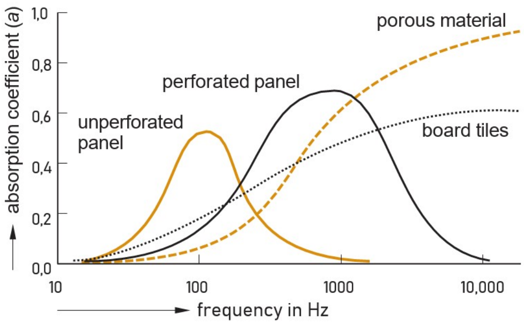


Figure 10.28 Absorption characteristics

Figure 10.28 shows how the absorption behaviour of the previously described materials looks. In addition, it can be clearly seen that a good absorption across the entire frequency range can only be achieved by a combination of different materials. Remember again that the absorption coefficient of a material is different for every frequency.

Amount of sound absorption in a room

In a room that has just been delivered (and is therefore empty), voices sound much louder and the noise level is higher than in a furnished dwelling. If you want to lower the noise level in a 'hard' room with a large amount of stony walls and ceiling and/or a large amount of glass, then you need to fit the previously discussed sound absorbing coverings to the ceiling and walls. Textiles such as heavy curtains and deep-pile carpets and upholstered furniture can contribute to this.

The amount of sound absorption in the room influences the reverberation time. This reverberation time is discussed in section 10.4.

The unit used for sound absorption is the 'square meter open window' (m^2 sabin). This is based on the fact that, seen from the point of view of a room, all sound energy falling on an open window disappears to the outside. This comes down to the same as all sound energy that falls upon it being absorbed. The total sound absorption in a room (A) is found by multiplying the surface area of all surrounding walls (S) by the absorption coefficient (a) associated with the material:

$$A = a_1 \cdot S_1 + a_2 \cdot S_2 + a_3 \cdot S_3 + \dots \ [m^2 \text{ sabin}]$$

The meaning of the symbols is:

A	the total amount of absorption in m^2 sabin
$a_1, a_2, a_3, \dots$	the absorption coefficient of the materials
$S_1, S_2, S_3, \dots$	the surface areas of the structures in m^2

People and objects (furniture etc.) in the room also contribute to the absorption of sound. The furnishings must therefore be taken into account when determining the total absorption. If a dense cupboard is placed in front of an absorbing wall, the part of the wall that is shielded by the cupboard will not contribute to the total sound absorption. Concert halls always have well-upholstered chairs. If the chairs are not occupied, they will contribute to the total sound absorption. If the chairs are occupied, the absorbing surface area is shielded by the people sitting on the chairs. These people in turn will absorb sound through their clothing.

Functional absorbers

Functional absorbers, also known as baffles, can be used for reducing the sound pressure level in larger rooms and halls. In their most simple form – for industrial use – these consist, for example, of thick sheets of mineral wool with a width of approximately 0.5 m coated in thin plastic foil which are suspended in vertical strips below the ceiling (see figure 10.29). It is preferable that the baffles are included as a separate element in the calculation of the total absorption. An absorption coefficient of approximately $a = 1.6$ can be achieved if the absorption by the baffles is assigned to the ceiling – calculated on a square metre ceiling surface area. This would make the reflection factor negative and that is physically incorrect.

Figure 10.29 Functional absorbers (baffles)

The advantage of baffles below the ceiling is that the ceiling or roof does not become thermally insulated. This means that there will be no increased risk of condensation. This is as opposed to sealed acoustic ceilings: these cannot just be applied below the roof structure without considering the damp engineering consequences.

10.4 Acoustics of the room

Reverberation time

The reverberation time (T) is one of the most significant acoustic properties of a room. In rooms for which high standards are set in connection with speech or music, there are also matters such as the diffusivity of the room and the correct use of reflections from walls or specially applied panels.

The reverberation time is defined as the time that expires before the sound level has decayed by 60 dB after the sound source has been switched off (see figure 10.30).

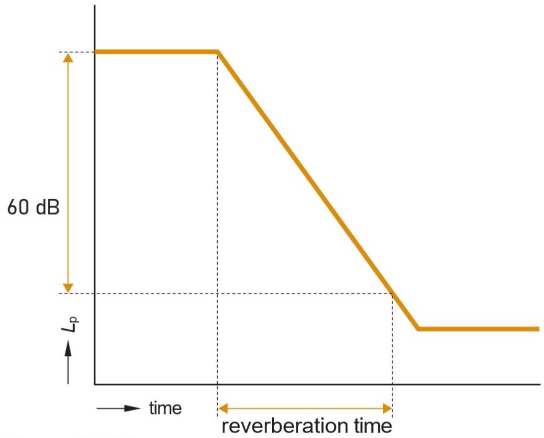


Figure 10.30 Reverberation time

The reverberation time depends on the absorption in the room. The more sound absorption that is present the shorter the reverberation time. The reverberation time can be calculated using Sabine's formula:

$$T = \frac{1}{6} \cdot \frac{V}{A} \text{ [s]}$$

where $A = a_1 \cdot S_1 + a_2 \cdot S_2 + \ldots$

The meaning of the symbols is:

T the reverberation time in s
V the volume of the room in m^3
A the sound absorption present in m^2 sabin

Figure 10.32 shows an example of the calculation of the reverberation time. The activities that take place in a room determine which reverberation time is best for that room. The table in figure 10.33 shows examples for guide values. The size of the room (hall) also plays a role in determining the required reverberation time for the room, as does the diffusivity of the room. In principle, the reverberation time should be the same across the entire frequency range. In general, a longer reverberation time is allowed for the lower frequencies and a somewhat shorter time for the higher frequencies (see the table in figure 10.34).

Example calculation of reverberation time

As an example we calculate the absorption and from that the reverberation time for a room with a linoleum floor covering. The walls comprise plastered masonry and glass and the ceiling is 25 mm woodwool cement sheet on a 30 mm cavity. See figure 10.31 and the table in figure 10.32. The absorption coefficients of the materials used can be found in the book of tables.

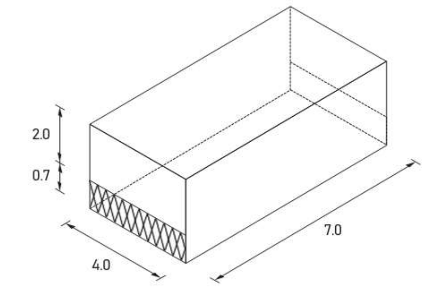


Figure 10.31 Room dimensions

The volume of the room is:

$$V = 4.0 \cdot 7.0 \cdot 2.7 = 75.6 \text{ m}^3$$

Because the absorption coefficient (*a*) of the materials depends on the frequency, the reverberation time (*T*) of the room is also a function of the frequency.

		Frequency [Hz] 125		250		500		1000		2000		4000	
Surface	S [m^2]	a	$a \cdot S$	a	$a \cdot S$	a	$a \cdot S$	a	$a \cdot S$	a	$a \cdot S$	a	$a \cdot S$
Ceiling	28.0	0.25	7.0	0.29	8.1	0.79	22.1	0.76	21.3	0.74	20.7	0.93	26.0
Floor	28.0	0.02	0.6	0.02	0.6	0.03	0.8	0.03	0.8	0.04	1.1	0.04	1.1
Plasterwork	43.4	0.01	0.4	0.01	0.4	0.02	0.9	0.02	0.9	0.02	0.9	0.04	1.7
Glass	16.0	0.10	1.6	0.04	0.6	0.03	0.5	0.02	0.3	0.02	0.3	0.02	0.3
A [m^2 sabin]			9.6		9.7		24.3		23.3		23.0		29.1
$T = \frac{1}{6} \cdot \frac{V}{A} = \frac{1}{6} \cdot \frac{75.6}{A}$			1.3		1.3		0.5		0.5		0.5		0.4

Figure 10.32 Calculation of reverberation time

Room	T [s]
Well-furnished room	Approx. 0.5
Office room	0.5–0.7
Open-plan office	0.7–0.9
School classroom	0.6–0.8
Music room	0.8–1.2
Theatre	0.9–1.3
Chamber music room	1.2–1.5
Opera	1.2–1.6
Concert hall	1.7–2.3
Church (organ music)	1.5–2.5

Figure 10.33 Guide values for the reverberation time in various rooms

	Frequency range [Hz] 125	250	500	1000	2000	4000
Deviation Relat. to 500 Hz	1.4	1.15	1.0	0.9	0.9	0.9

Figure 10.34 Permitted deviations from 500 Hz

Measuring the reverberation time

When measuring the reverberation time a high sound pressure level is created in a room using a noise source (a starting pistol was used in the past). The decay of the sound pressure level is directly determined using an integrated soundmeter (see figure 10.17). However, a level recorder can also be used for this. A paper runs inside this at a set speed. The pen moves vertically on the paper with the sound pressure level. Figure 10.35 shows the sound pressure level during a specific time for three frequencies.
As can be seem from this figure it is generally not possible to measure the full 60 dB decay.

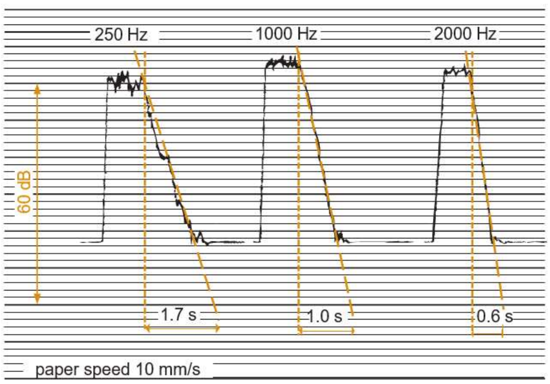


Figure 10.35 Example of determining reverberation time

You would then have to start more than 60 dB above the background noise level. Because the decay curve is straight at the start, the reverberation time can be determined by extrapolation. The reverberation time associated with the three curves is given in the figure.

Sound pressure level in a room

Both direct and reflected sound will be detected in a room. As discussed earlier, for the direct sound the formula is:

$$L_p = L_W + 10 \log \left(\frac{Q}{4\pi r^2}\right) \text{ [dB]}$$

And for the diffuse sound:

$$L_p = L_W + 10 \log \left(\frac{4}{A}\right) \text{ [dB]}$$

The resulting sound pressure level is derived from:

$$L_p = L_W + 10 \log \left(\frac{Q}{4\pi r^2} + \frac{4}{A}\right) \text{ [dB]}$$

The meaning of the symbols is:

L_p the sound pressure level in dB
L_W the acoustic power level in dB
i the distance to the source in m
Q the direction factor
i the total sound absorption in the room in m^2 sabin

Close to the source the direct sound field will dominate and at a large distance from the source the diffuse sound field will dominate. At a certain distance in the room the direct sound will be equal to the indirect sound. This distance is known as the reverberation radius and is calculated as follows:

$$\frac{Q}{4\pi r^2} = \frac{4}{A} \rightarrow r^2 = \frac{Q \cdot A}{16\pi}$$

$$r_{\text{reverberation}} = \sqrt{\frac{Q \cdot A}{16\pi}} \text{ [m]}$$

If the distance to the source is much smaller than $r_{\text{reverberation}}$, then the direct sound field dominates and the formula for the direct sound field as derived in section 10.1 can be used for calculations:

$$L_p = L_W - 10 \log \left(\frac{4\pi r^2}{Q}\right) \text{ [dB]}$$

If the distance to the source is much greater than rreverberation then the indirect, diffuse sound field dominates. The formula for the diffuse sound field as derived in section 10.1 applies for this too.

$$L_p = L_W + 10 \log \left(\frac{4}{A}\right) \text{ [dB]}$$

In the area around the radius of reverberation we have to take account of both the direct and the diffuse sound field. The radius of reverberation is of great significance if measures for improving the acoustics are required. If the direct field is dominant there is little sense in taking measures for total absorption – measures must be taken in relation to the source. If the diffuse sound field dominates then it is exactly those measures for total absorption that are required.

Diffusivity of a room, reflections

We understand diffusivity to mean the degree to which the sound is distributed regularly (equal strength) across the room. The sound reaches the listener from all directions instead of a few angles. This is almost never a problem in smaller rooms. Diffusivity can cause problems in bigger rooms however. In these types of rooms a great deal of attention has to be paid to the path of the sound and the possible occurrence of useful and unwanted reflections. It is in larger rooms in particular where the diffusivity is not self-evident that a distinction will have to be made between the sound that reaches the listener directly (direct sound) and sound that arrives at the listener via reflections (indirect sound). Sound arriving at the listener via reflections will have to follow a longer path (and therefore be en-route longer) than sound that arrives at the listener directly. For speech, if the path time difference is not more than 50 ms (17 m) the indirect sound (the reflection) is heard as a useful contribution to the direct sound. A longer path time difference of approximately 80 ms (27 m) applies for music. Specially installed panels (sound reflectors, see figure 10.36) can be used in a room where the sound from a specific location (podium, stage, etc.) has to reach the entire room. Such useful reflections promote the effective transmission of sound in the hall. In order to avoid indirect sound arriving with the listener with too long a delay in relation to the direct sound and being heard as an echo, parts of the ceiling concerned and the rear wall are clad with sound absorbing material.

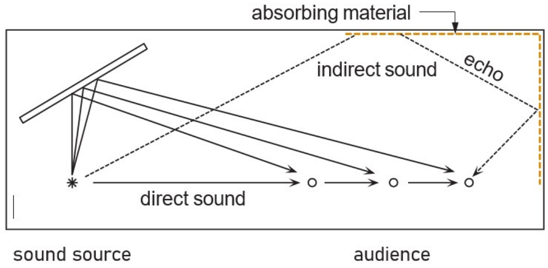


Figure 10.36 Supporting the direct sound with useful reflections and preventing echoes by applying absorbing material.

It is often different in smaller rooms (conferences rooms, classrooms etc.). All those present have to be able to hear each other. In this case it makes sense not to fit sound absorption to the ceiling, but to the walls and the floor. The ceiling is then built as a hard structure and serves as a reflector (see figure 10.37).

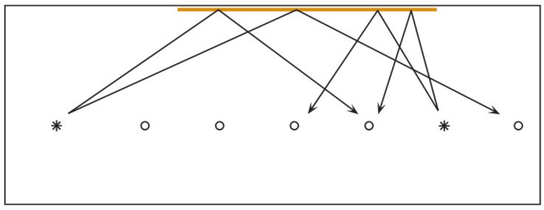


Figure 10.37 Reflective ceiling (conference room)

The shape of rooms also plays an essential role in speech intelligibility. In this way rectangular rooms contribute less to useful reflection. They can also lead to problems in relation to unwanted echoes. If two parallel walls are good reflectors and are more than 7 m from each other then flutter echoes can occur (consider a sports hall for example). The sound can be reflected back and forth between these walls a number of times. There are two possible solutions in this case. One solution is to clad one (or both) of the walls in absorbing material. The other is to build the walls so that they are not parallel to each other and give them a relief. That is why one or more of the walls or the ceiling is often fitted with sloping surfaces or other irregularities, such as in figure 10.38.

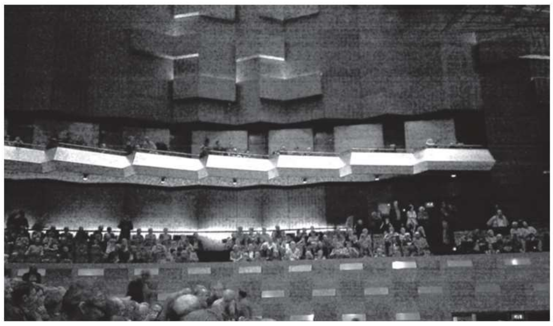


Figure 10.38 Surfaces in relief and large objects (balconies) for diffusion of the sound.

If these irregularities are to have an effect on the diffusion of the sound then the dimensions must be of the same order of magnitude as the wavelength of the sound (see section 10.1). Good speech intelligibility is achieved in rooms where the walls are so formed as to deliver a good contribution to the useful reflections. In addition to avoiding two parallel reflective walls in connection with flutter echoes, round hall shapes should also be avoided. Reflections of sound on a round (arched) wall will lead to a focussing of the sound at a single point.

Lowering the sound pressure level using extra absorption

When a great deal of noise is being produced in a room (workshop, reproduction department, etc.) you can try to lower the sound pressure level (diffuse sound) by fitting extra absorption. This will reduce the term 10 log($\frac{4}{A}$) (see above) and make it stronger negative. The sound pressure level (L_p) will therefore decrease. Doubling the amount of absorption doubles the amount of sound absorbed (see figure 10.39). This means a reduction of the sound pressure level by 3 dB. If we want to lower the sound pressure level by 6 dB we have to quadruple the amount of sound absorption. A reasonable reduction in level will only be achieved in very 'bare', reverberating rooms. In rooms where more absorption already exists (suspended ceilings and suchlike) there is usually no space left for two or four times as much absorbing material.

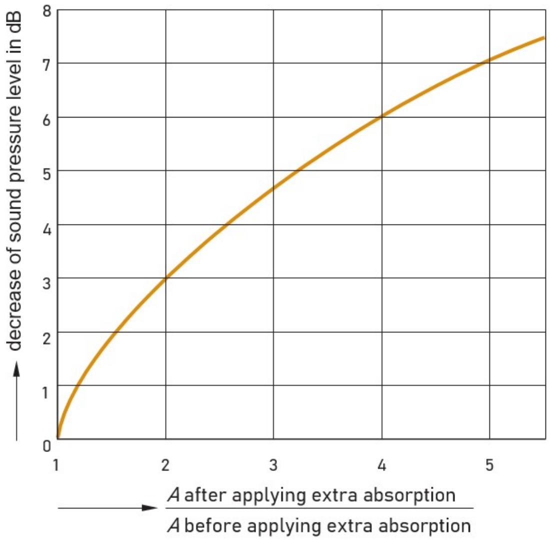


Figure 10.39 Reduction in the sound pressure level by the application of additional sound absorption in a room

11 Sound insulation and sound proofing

A.C. van der Linden; A. Zeegers

This chapter discusses sound insulation and sound proofing between rooms and between the inside and outside of rooms (facade sound proofing). We explain how sound insulation can be calculated and how this can be measured in practice and in the laboratory.

11.1 Sound insulation between rooms

In sound insulation we differentiate between airborne sound insulation and impact sound insulation. The former relates to insulation against sound waves generated in the air (speech for example). The latter relates to the degree to which vibrations caused by walking or slamming of doors propagate in structures and are retransmitted into the air, for example (see figure 11.1).

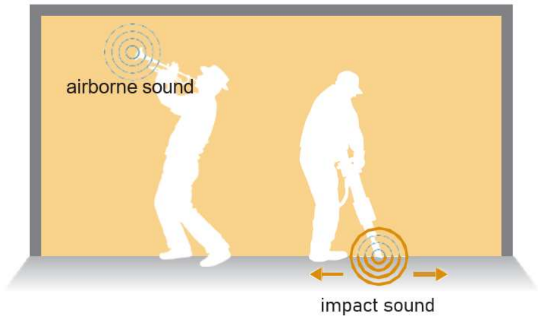


Figure 11.1 Airborne sound causes a structure to vibrate which causes it to emit sound on the other side.
A structure can also be caused to vibrate mechanically and

Airborne sound insulation

When we consider the airborne sound insulation between two rooms there are three significant transmission routes (all three of which are determinative for the sound insulation that is finally realised):
1 direct sound emission from the partition wall
2 the partition wall causes the adjacent structures to vibrate
3 transmission via the sidewalls.

The latter two routes are known as flanking sound. All of this is illustrated in figure 11.2. First we will consider direct transmission.

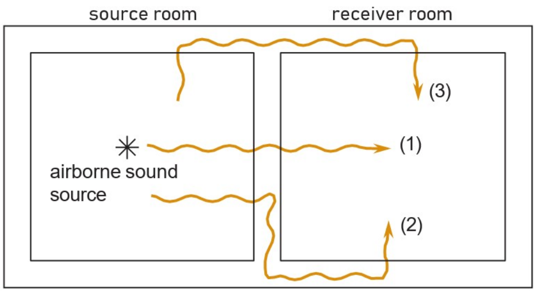


Figure 11.2 Direct and flanking sound transmission

In the previous chapter we discussed sound absorption being important for sound management in the room concerned. Sound insulation is of great importance where nuisance arises from sound outside (traffic noise, for example) or from a neighbouring dwelling (radio, TV and suchlike) or a room in the same building (sound produced in a reproduction room causing nuisance to the occupants of an office room for example). The sound insulation of an element is determined by the part of the sound that passes through. The part of the sound allowed to pass through is that part which is not reflected or absorbed (see figure 10.21 also). The following applies:

$$r + a + d = 1$$

The meaning of the symbols is:
r the reflected part of the sound energy
a the absorbed part
d the part allowed to pass through

Sound insulation is defined as the relationship between the sound striking the structure and the sound allowed to pass through. This relationship is expressed in dB. This means that the logarithm of the relationship has to be evaluated:

$$R = 10 \log(\frac{1}{d}) \text{ [dB]}$$

The meaning of the symbols is:
R the airborne sound insulation in dB
d the part of the sound striking the structure that is allowed to pass through

The part that is allowed to pass through a normal hardboard door amounts to approximately d = 0.01 (see figure 11.3-1). This means that the sound insulation (R) is equal to:

$$R = 10 \log(\frac{1}{0.01}) = 20 \text{ [dB]}$$

Likewise, in a half brick wall d = 0.0001 (see figure 11.3-2), thus:

$$R = 10 \log(\frac{1}{0.0001}) = 40 \text{ [dB]}$$

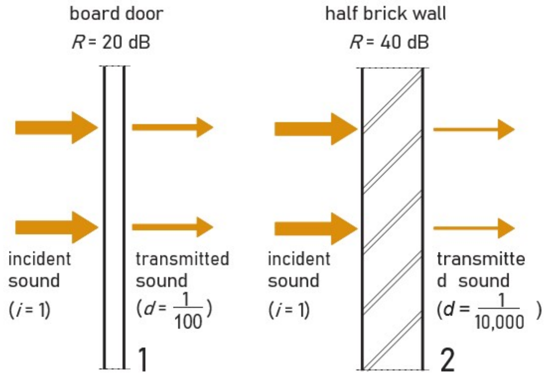


Figure 11.3 Airborne sound insulation

The insulation mechanism can broadly be described as follows. The impacting sound energy causes the wall to vibrate. On the other side of the wall the air is caused to vibrate. The sound pressure, which consists of rapid changes in pressure, forms a force to the wall. This force can be calculated with the following formula:

$$F = m \cdot a \text{ (force = mass} \cdot \text{acceleration)}$$

The force on the wall (in the transmitting room) imparts a specific acceleration to the wall (mass). A heavy wall receives a smaller acceleration and it is therefore harder to cause it to vibrate. This smaller vibration in the wall causes a smaller sound pressure in the receiving room (the other side of the wall). Something similar applies to the number of vibrations per second (the frequency) of the impacting sound. A high frequency (many small vibrations per second) will be less easily taken up by the (generally more rigid) wall and cause a smaller sound pressure in the receiving room.

In summary:
larger mass -> better sound insulation
higher frequency -> better sound insulation

Mass law

It is possible to theoretically derive what the sound insulation should be for homogeneous structures (a single layer of concrete, stone, wood, etc.). This depends on the mass of the structure and the frequency of the sound. The values found in practice are different to those predicted by the theoretical mass law due to all kinds of peripheral effects. Such a 'practical mass law' has come about experimentally where the sound insulation can be calculated:

$$R = 17.5 \log m + 17.5 \log (\frac{f}{500}) + 3 \text{ [dB]}$$

The meaning of the symbols is:
R the sound insulation of the structure in dB
m the mass of the structure in kg/m^2
f the frequency in Hz

This practical mass law is shown in the graph in figure 11.4. The graph shown is for sound insulation at a frequency of 500 Hz. Sound insulation at other frequencies can be found by adding approximately 5 dB to the R_{500} value found for each doubling of the frequency. Approximately 5 dB per octave has to be substracted for lower frequencies.

The heavier the structure the better the sound insulation. But in masses below 100 kg/m² in particular the value according to the graph in figure 11.4 is only a very general guide value. Special effects such as coincidence often occur which significantly affect the sound insulation.

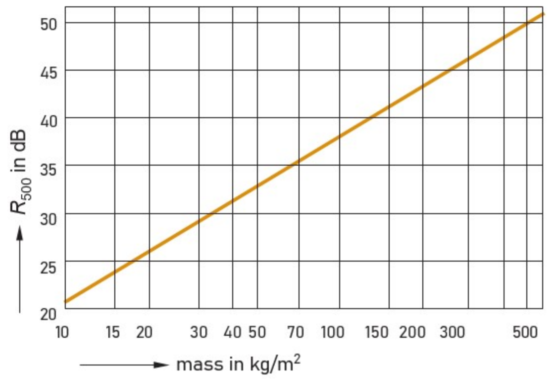


Figure 11.4 Practical mass law for sound insulation at 500 Hz

Coincidence

When a sound wave strikes a wall at an angle, a bending wave is generated in that wall by the under and over pressures (rarefactions and compressions) of the sound wave in the air (see figure 11.5). When the frequency of this wave motion matches the natural frequency of the wall (the frequency at which the wall vibrates very easily) then the sound energy is allowed to pass through very easily. This is known as coincidence (falling together). Coincidence causes a deviation from the mass law as can be seen from the general insulation graph in figure 11.6.

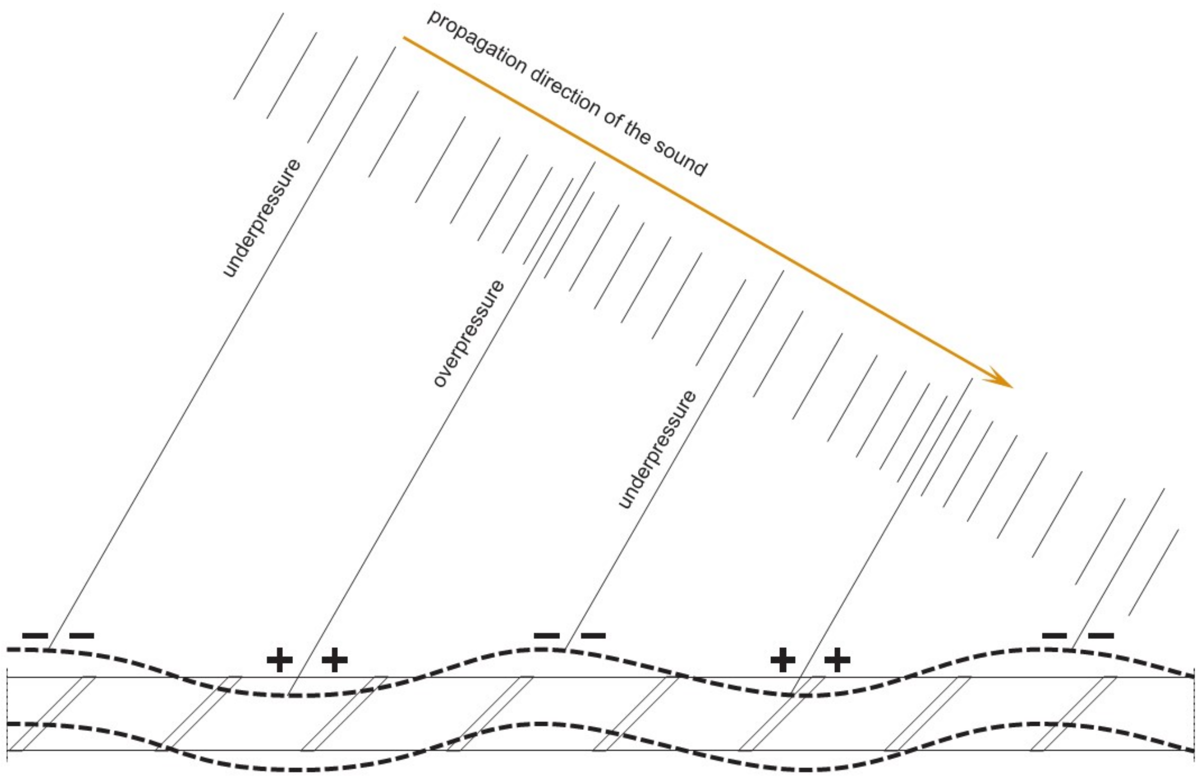


Figure 11.5 Generation of a forced bending wave in a sheet-like structure by an impacting sound

This so-called coincidence frequency depends on the rigidity of the wall and therefore the thickness and type of material. The threshold frequency for coincidence (f_g) is found using the following formula:

$$f_{g;coincidence} = \frac{f_g \cdot d}{d} \text{ [Hz]}$$

The meaning of the symbols is:
$f_g \cdot d$ a material dependent constant in Hz·mm
d the thickness of the structure in mm

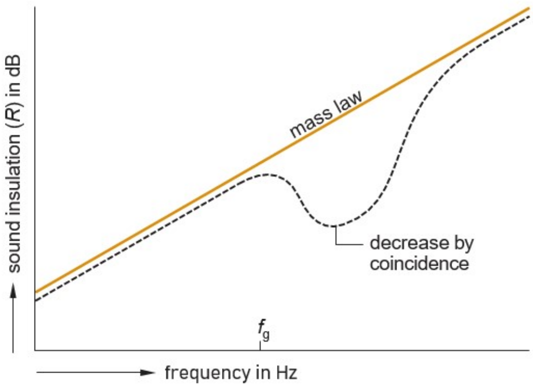


Figure 11.6 Effect of coincidence on sound insulation

The table in figure 11.7 shows the constant $f_g \cdot d$ for various materials, with the coincidence frequency for two commonly used thicknesses of the material as an example. Here the material-dependent constant is expressed in Hz·mm. In order to determine the coincidence frequency the constant has to be divided by the thickness in millimetres. When choosing a partitioning structure, it is important to know what the frequency range is of the sound which is to be insulated by the partitioning structure. For an effective sound insulation, the coincidence frequency of the partitioning structure must be outside the frequency area of the sound which the structure should block.

Material	$f_g \cdot d$	Example d [mm]	f_g [Hz]	Example d [mm]	f_g [Hz]
Aluminium	12,500	2	6250	5	2500
Steel	12,800	1	12,800	3	4267
Glass	12,800	4	3200	8	1600
Concrete	17,300	120	144	200	87
Aerocrete	38,000	80	475	200	190
Lime-sand brick	21,400	105	204	210	102
Porous brick	26,100	50	520	90	289
Lightweight concrete	32,000	80	400	200	160
Plaster	35,500	50	710	70	507
Plasterboard	35,500	9	3944	15	2367
Wood	25,000	12	2083	22	1136
Chipboard	25,000	8	3125	18	1389
Lead	51,200	0.5	102,400	2	25,600

Figure 11.7 Threshold frequency for coincidence in various materials

In general, the coincidence frequency of a partitioning structure should not be in the frequency range of 300 to 3000 Hz (this range includes the human voice). From figure 11.7, it can be derived that for heavy walls the influence of the coincidence is less noticeable. The coincidence frequency of a concrete wall for example is around the 100-150 Hz. Furthermore the table in figure 11.7 clearly shows that, for instance, 50-90 mm porous brick and 50-70 mm plaster have a very unfavourable insulating behaviour because the range in which the coincidence frequency falls (300-700 Hz) is exactly the range in which the human voice falls. Increasing the thickness of the material (for example, the glass in a partition wall from 4 mm, f_g = 3200 Hz to 8 mm, f_g = 1600 Hz) does not always have to produce better sound insulation by moving the threshold frequency.

The practical mass law does not take account of coincidence and can therefore only be used as a general guideline value. The plateau method has been developed to predict the behaviour of simple walls in a better way. This method does take the effects of coincidence into account. The method is somewhat more laborious but approximates reality more closely than the practical mass law.

Plateau method

If we want to predict the sound insulation more accurately we have to take the effect of coincidence into account. To this end, we introduce the plateau method. This method can be used to predict the airborne sound insulation of single structures.
In this method the sound insulation is split into three (see figure 11.8):

I the range before the area of influence around the coincidence frequency
II the range around the coincidence frequency
III the range after the area of influence around the coincidence frequency

Effectively, you need to determine only the start and end frequencies (f_l and f_g) of the coincidence area (the plateau) and the level of insulation when determining the sound insulation. The rest will follow automatically.

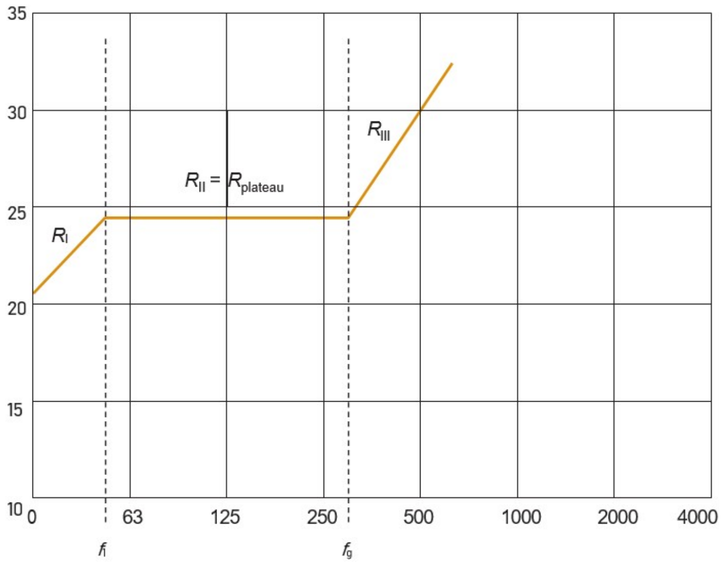


Figure 11.8 Plateau method

The range around the coincidence frequency (II) is known as the plateau. This range is marked by the frequencies f_l and the previously discussed frequency f_g where:

$$f_l = 1.57 \cdot f_g \cdot \eta^{\frac{1}{2}} \text{ [Hz]}$$

The meaning of the symbols is:

f_l the lower threshold frequency of the plateau (the start point of the plateau) in Hz
f_g the upper threshold frequency of the plateau (the end point of the plateau) in Hz
η the loss factor (see figure 11.9)

$$f_g = \frac{f_g \cdot d}{d} \text{ [Hz]}$$

The meaning of the symbols is:

$f_g \cdot d$ the material-dependent constant in Hz·mm (see figure 11.7)
d the thickness of the structure in mm

The sound insulation between two frequencies is determined by the following formula:

$$R_{plateau} = 20 \log(m \cdot f_g) + 10 \log \eta - 44 \text{ [dB]}$$

The meaning of the symbols is:

m the mass in kg/m²
f_g the threshold frequency in Hz
η the loss factor

Material	η values
Steel	$1 \cdot 10^{-4}$ to $2 \cdot 10^{-4}$
Glass	$4 \cdot 10^{-3}$
Concrete	$7 \cdot 10^{-3}$
Aerocrete	10^{-2}
Lime-sand brick	10^{-2}
Porous brick	10^{-2}
Plasterboard	$3 \cdot 10^{-2}$
Wood	10^{-2}
Lead	$2 \cdot 10^{-2}$

Figure 11.9 η values of various materials

For area I, there is a decrease of 6 dB per octave starting at frequency f_l. For area III, an increase applies of 7.5 dB per octave.

The heavier the structure the less the influence of the coincidence-effect will be. In the calculation used we should therefore obtain a negative performance. If the mass is greater than 70 kg/m^2 then we can increase the plateau. The permitted increase is:

$$\Delta R = 20 \log(\frac{m}{70}) \text{ [dB]}$$

The meaning of the symbols is:
ΔR the increase in sound insulation (plateau increase) in dB
m the mass in kg/m^2

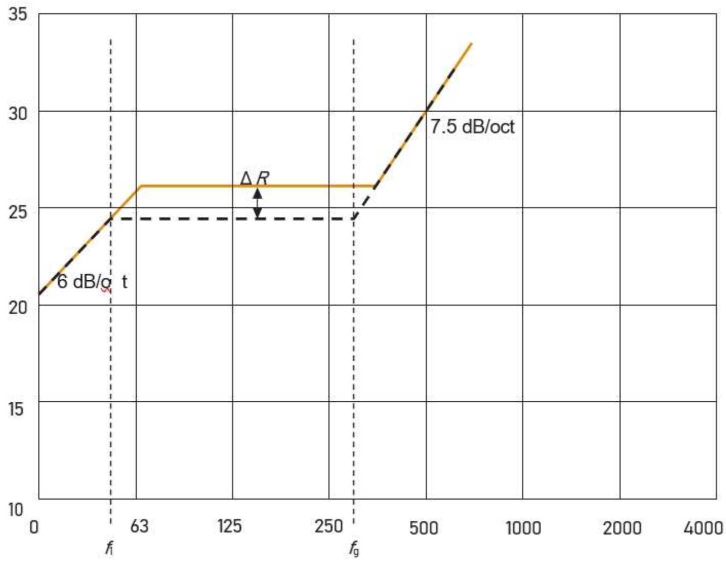


Figure 11.10 Plateau method for masses greater than 70 kg/m^2

The following working method should be used to sketch the new situation (see figure 11.10):
1 Draw the original situation (i.e. without plateau increase, see the dotted line).
2 Draw the new plateau in the graph (a horizontal line).
3 Extend the line for the frequency range f1 until it reaches the new plateau.
4 Extend the line for the plateau until it touches the line for the frequency range after f_g.

The frequencies f_l and f_g will therefore move.

Example (see also figure 11.11)
The following is given for cellular concrete (aerocrete):
ρ = 650 kg/m^3
d = 0.14 m
η = 10–2
$f_g \cdot d$ = 38,000 Hz·mm

Calculation:

$m = \rho \cdot d = 650 \cdot 0.14 = 91$ kg/m^2,

so take a plateau increase into account!

$$f_g = \frac{f_g \cdot d}{d} = \frac{38{,}000}{140} = 271 \text{ Hz}$$

$$f_l = 1.57 \cdot f_g \cdot \eta^{\frac{1}{2}} = 1.57 \cdot 271 \cdot (10^{-2})^{\frac{1}{2}} = 43 \text{ Hz}$$

Therefore:

$$R_{plateau} = 20 \log(91 \cdot 271) + 10 \log 10^{-2} - 44 = 24 \text{ dB}$$

The plateau increase is:

$$\Delta R = 20 \log(\frac{m}{70}) = 20 \log(\frac{91}{70}) = 2.3 \text{ dB}$$

Therefore, the new plateau lies at 24 + 2.3 = 26.3 dB

After the threshold frequency the sound insulation will increase by 7.5 dB per octave (doubling of the frequency). For frequency f_l the sound insulation will decrease by 6 dB per octave.

Structure built up from a number of layers

Constructing a wall (or other structure) in two parts with air in between (cavity structure) can achieve a large degree of sound insulation for a relatively low mass because of the lack of direct transmission of vibration from one leaf to the other. In the best case (total disconnection of the cavity leaves, cavity width 100 mm or more, sufficient absorption in the cavity etc.) the insulation values of both cavity leaves can be added together. This does not apply, however, for cavity walls of normal dimensions. There are also a number of other special effects.

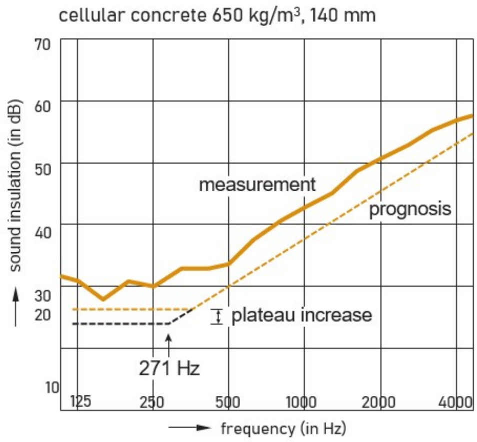


Figure 11.11 Comparison between calculation with plateau method and measured sound insulation

Mass-spring resonance

The two cavity leaves (masses) can vibrate on the intervening air layer (spring). As mentioned earlier all mass-spring systems have a natural (resonance) frequency at which the system can very easily be caused to vibrate. This significantly reduces the insulation value, at one frequency theoretically to zero. When sound strikes the wall perpendicular this resonance frequency (f_0) can be found using the following formula:

$$f_0 = 60\sqrt{\frac{m_1 + m_2}{m_1 \cdot m_2} \cdot \frac{1}{b}}\ \text{[Hz]}$$

The meaning of the symbols is:

f_0 the resonance frequency of perpendicular impacting sound in Hz
m_1 the mass of the first cavity leaf in kg/m^2
m_2 the mass of the second cavity leaf in kg/m^2
b the width of the cavity in m

The sound insulation associated with the resonance frequency can be calculated as follows:

$$R_0 = 20 \log \left(\frac{m_1}{2 \cdot m_2} + \frac{m_2}{2 \cdot m_1}\right)\ \text{[dB]}$$

If the walls are of the same mass theoretically the sound insulation will reduce to R = 0 dB.

The resonance frequency for a number of structures is shown in the table in figure 11.12. For the sake of ease we assume two equally thick cavity leaves here. Because of this resonance-effect, the insulation effect of a double-glazed window is sometimes worse than a single glazed window when the intention is to stop traffic noise. The traffic noise is exactly at its maximum in frequencies from 100-200 Hz. The fact that this window is still seen as an improvement mostly comes from the improved sealing along the joints and gaps. Good insulation requires a mass-spring resonance of f_0 < 80 Hz.

Cavity resonances

Cavity resonances are caused by standing waves in the cavity. The frequency depends on the width of the cavity (see the formulas in figure 11.13). In this way the lowest cavity resonance frequency is found for a cavity with a width of 12 mm (cavity width = half wavelength):

$$\frac{1}{2}\lambda = 0.012 \text{ m} \Leftrightarrow \lambda = 2 \cdot 0.012 = 0.024 \text{ m}$$

$$f = \frac{c}{\lambda} = \frac{340}{0.024} = 14{,}000 \text{ Hz}$$

For a cavity with a width of 120 mm this is f_{sp} = 1400 Hz.

	$m_1 = m_2$ [kg/m²]	b [m]	f_0 [Hz]
Plasterboard (12mm)	14	0.080	80
Glass (6mm)	15	0.012	200
Glass (6mm)	15	0.100	69
Porous brick (70mm)	85	0.030	53

Figure 11.12 Resonance frequencies

The formula above can be rewritten so that there is a relationship between the frequency, the resonance and the width of the cavity. The first cavity resonance is:

$$\frac{1}{2}\lambda = b \leftrightarrow \lambda = 2 \cdot b > f_{sp} = \frac{340}{2 \cdot b} = \frac{170}{b}$$

The second cavity resonance is:

$$\lambda = b > f_{sp} = \frac{340}{b} = \frac{2 \cdot 170}{b}$$

The third cavity resonance is:

$$1\frac{1}{2}\lambda = b \leftrightarrow \lambda = \frac{2}{3} \cdot b > f_{sp} = \frac{340}{(\frac{2}{3} \cdot b)} = \frac{3 \cdot 170}{b}$$

The fourth cavity resonance is:

$$2\lambda = b \leftrightarrow \lambda = \frac{1}{2} b > f_{sp} = \frac{340}{(\frac{1}{2} \cdot b)} = \frac{4 \cdot 170}{b}$$

And so on.

Sound insulation is quite minimal at a resonance frequency. For cavity resonances a similar threshold can be drawn as for coincidence. Cavity resonances should not, in fact, occur below 3000 Hz. In order to still use the useful effect of wide cavities the resonations have to be suppressed by introducing absorbing material into the cavity. In closed structures this can be in the form of sheets of mineral wool, in glass structures it can be in the form of edge absorption (in the clear space of the cavity). This will also suppress the mass-spring resonance.

The diagram in figure 11.14 gives a general view of the sound insulation of a cavity structure. Below the mass-spring resonance frequency a double wall has approximately the same insulation value as a single wall with the same mass as the composite wall. Insulation is quite minimal at a resonance frequency. Far above this the sound insulation is roughly the same as the sum of the insulation values of both individual cavity leaves. In the intervening area the air layer acts somewhat like a link between both cavity leaves, but there is still a considerable gain in relation to a single structure.

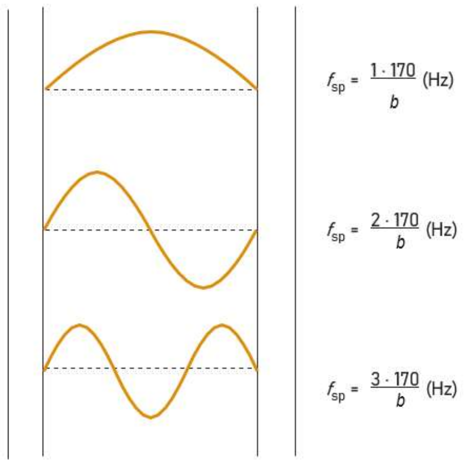


Figure 11.13 Cavity resonances (standing waves in the cavity)

Composite walls

A wall structure is often built up from parts with different sound insulation, for example, a door (R = 20 dB) in a half brick wall (R = 40 dB). What is the average insulation of the wall with the door?

The insulation difference of 20 dB between the wall and the door means that for every m^2 a hundred times more sound energy passes through the door than through the rest of the wall (10 log 100 = 20). But in addition to the insulation values of the composite parts the relationship of the area is also significant. The average insulation can be calculated using the following equation:

$$R_{res} = -10 \log \left(\frac{S_1}{S_{tot}} \cdot 10^{\frac{-R_1}{10}} + \frac{S_2}{S_{tot}} \cdot 10^{\frac{-R_2}{10}} + \dots \right) \text{ [dB]}$$

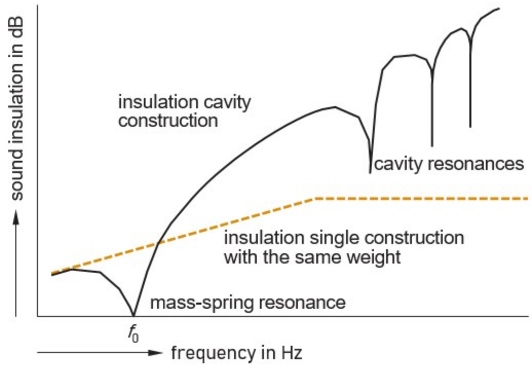


Figure 11.14 General insulation curve of a cavity structure

The meaning of the symbols is:

R_{res} the resultant sound insulation of the structure in dB

S_1 , S_2 the area of element 1 and element 2 respectively in m^2

S_{tot} the total area of the structure in m^2

R_1 , R_2 the sound insulation of element 1 and element 2 respectively in dB

In addition to the calculation a quick estimate of the reduction in insulation as a result of a part with less insulation can also be made using figure 11.15.

The meaning of the symbols in the graph is:

ΔR the value to be substracted from R_1

R_1 the insulation of the best insulating part in dB

R_2 the insulation of the worst insulating part in dB

S_2 the area of the worst insulating part in m^2

S_{total} the total area of the wall in m^2

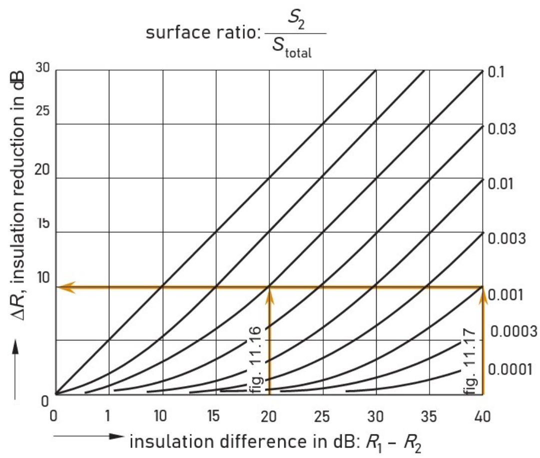


Figure 11.15 Insulation reduction in a wall as a result of a part having less insulation

The following applies for the example in figure 11.16:

- total area of wall + door = 17.8 m^2
- area of door = 1.6 m^2
- area of wall = 16.2 m^2

$$R_{res} = -10 \log\left(\frac{1.6}{17.8} \cdot 10^{\frac{-20}{10}} + \frac{16.2}{17.8} \cdot 10^{\frac{-40}{10}} \right) = 30 \text{ dB}$$

The same value can also be derived from figure 11.15:

- the insulation difference between the wall and the door is 20 dB
- the area relationship between the door and the wall is $\frac{1.6}{16.2} = 0.1$.

These two values can be used to derive that the insulation reduction because of the door will amount to approximately 10 dB.

In principle this calculation must be performed for each octave band. Both constituent parts can have a very different insulation spectrum.

An example of a wall where a gap of approximately 2.5 mm (R_{gap} = 0 dB, see figure 11.17) has been left in the join with the ceiling can be examined in the same way. In this case:

- total area of wall + door = 17.755 m^2
- area of gap = 0.017 m^2
- area of wall = 17.738 m^2

$$R_{res} = -10\log\left(\frac{0.017}{17.755}\cdot 10^{\frac{-0}{10}} + \frac{17.738}{17.755}\cdot 10^{\frac{-40}{10}}\right) = 30\text{ dB}$$

The same value can also be derived from figure 11.15.

These two values can be used to derive that the insulation reduction because of the gap will amount to approximately 10 dB. The influence of a gap will be much greater in a wall with an even higher insulation value. See figure 11.18 for a practical example.

There are also other effects that occur with gaps and cracks that are not discussed here.

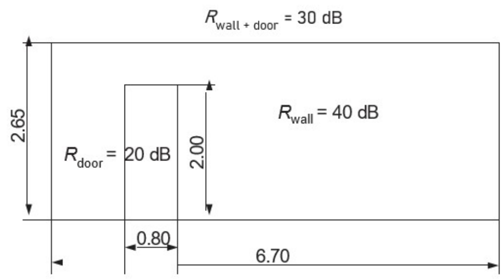


Figure 11.16 Wall built from parts having different sound insulation

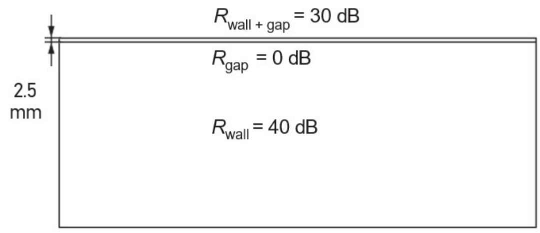


Figure 11.17 Sound insulation of wall with a gap at the joint

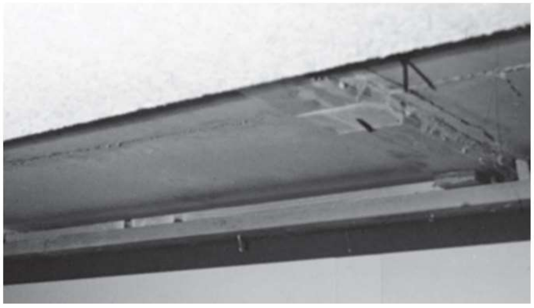


Figure 11.18 The sound insulation expected in this situation is not achieved due to the poor sealing of a wooden rail against the concrete ceiling. After sealing with mastic the sound insulation is a good 6 dB better.

Flanking sound transmission

Earlier we discussed direct sound transmission. Sound propagation also occurs via the flanking structure however (see figure 11.2). This can occur in two ways:

- Sound waves that cause the partition wall to vibrate propagate through the structure so that the sidewalls, floor and ceiling of the receiving room also start to vibrate and start to transmit sound (2 in figure 11.2).
- Vibrations (sound waves) that are generated in a sidewall of the transmitting room propagate through the structure and are transmitted in the receiving room (3 in figure 11.2).

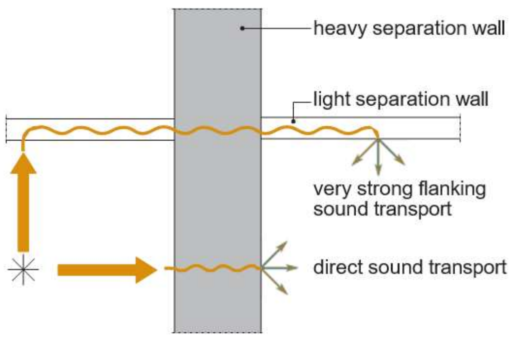


Figure 11.19 Flanking sound transmission in joints with light walls

This phenomenon is known as flanking sound transmission. The anticipated sound reduction by a partition wall can be significantly affected by this type of effect. Particularly the light partition walls of gypsum blocks, aerocrete, light concrete stone, light brick etc. used in house building can very significantly reduce the sound reduction of a massive wall which, itself, has sufficient sound insulation (see figure 11.19). The light walls have to be disconnected from the massive wall to prevent this. This can be done by including an elastic layer (cellular rubber, cork and suchlike) in the joint. In doing so care must be taken that sound leaks do not occur between the rooms that are separated by the light walls. In addition, the effect on very massive walls shown in figure 11.19 is less strong because of the larger transmission damping.

Another example of flanking sound transmission is a light facade (a wooden lower front, for example) that runs in front of a concrete floor as shown in the cross section in figure 11.20. In the transmitting room (bottom) the lower front is caused to vibrate. Via the struts the vibration propagates to the room situated above where it is transmitted in the form of sound. Disconnecting the lower front will lead to improved insulation. With inaccurate sealing this type of structure also easily leads to sound leaks.

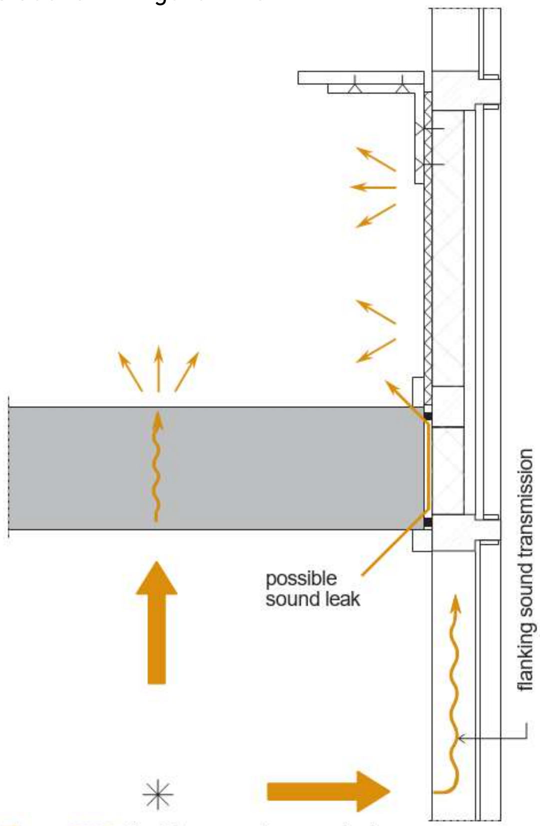


Figure 11.20 Flanking sound transmission and sound leaks in continuous facade lower fronts

As a rule of thumb the sound insulation of the wall will be reduced by approximately 5 dB as a result of flanking sound transmission. There is the possibility of calculating the flanking but that is a step too far within the current scope.

Impact sound insulation

The matter of insulation against airborne sound has been discussed above. That is to say: the insulation for sound vibrations that are generated by one or more sound sources (loudspeaker, voice, etc.) and are present in the air. The vibrations that this generates in the structure are propagated by the structure and can be retransmitted as airborne sound by the floors and walls elsewhere in the building. It is, however, also possible to generate sound by directly impacting the building structure (walking, vibrations from operating machinery, slamming a door, sliding a chair etc.). Water pipes fitted in or on the wall can also generate such vibrations in the building structure. The same applies here too; more massive structures are less easily caused to vibrate than less massive structures. A concrete floor of a reasonable thickness ($m \geq 400$ kg/m^2) usually provides sufficient insulation against the sound of footsteps. With more stringent requirements or in light structures, thick carpets, floating covering floors or suspended ceilings have to be used. Machinery must be fixed using the appropriate vibration dampers and fixing means with rubber sleeves and suchlike must be selected for pipes.

11.2 Measuring airborne sound insulation in a laboratory

Section 11.1 showed how the sound insulation of a structure can be roughly calculated. As a guide this can suffice for a first indication, but in the end we want to know what the ‘actual’ sound insulation will be. To do this we need more precise values. The sound insulation of materials and structures can be measured more accurately in laboratories. In the laboratory, special testing rooms are used to determine the sound insulation of a structure (see figure 11.21). Two rooms are built next to each other in such a way (separate foundations etc.) that no flanking sound transmission is possible. Therefore only the sound insulation of the element is measured.

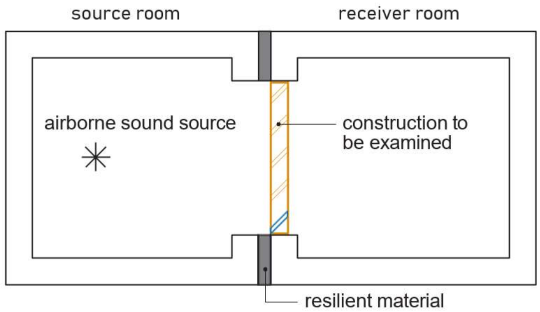


Figure 11.21 Acoustic testing rooms

In one room (the transmitting room) a sound source (loudspeakers) is used to generate airborne sound. The sound pressure level is then measured in both rooms. The measured level in the receiving room (the amount of sound allowed to pass through) is, however, dependent on the area of the partitioning structure and the presence of absorbing material in the receiving room. In order to determine the absorption present, the reverberation time in the receiving room is measured. With the help of formula $A_o = 1/6\ (V/T)$, the absorption value in the receiving room can be determined.

The formula below can now be used to calculate the sound insulation of the structure:

$$R = L_z - L_o + 10 \log \left(\frac{S_z}{A_0}\right) \quad [\text{dB}]$$

The meaning of the symbols is:

L_z the sound pressure level in the transmitting room in dB
L_o the sound pressure level in the receiving room in dB
S_z the area of the partitioning structure at the transmitting side in m^2
A_o the absorption in the receiving room in m^2 sabin

Laboratories usually measure sound insulation in 1/3 octave bands. For use in practice these measurements are 'translated' to octave bands by the following formula:

$$R_{octave} = -10 \log \frac{1}{3} \sum_1^3 10^{\frac{-R_{\frac{1}{3}oct,i}}{10}} \quad [\text{dB}]$$

Example
Using the formulas from section 10.1, the example below will explain how the formula above relating to sound insulation was derived.

The formula for calculating sound insulation (section 11.1) is:

$$R = 10 \log \left(\frac{1}{d}\right) [\text{dB}]$$

The meaning of the symbols is:

R the sound insulation of the structure in dB
d the part of the sound striking the structure that is allowed to pass through

This formula can also be written as:

$$R = 10 \log \left(\frac{W_{in}}{W_{af}}\right) [\text{dB}]$$

The meaning of the symbols is:

R the sound insulation of the structure in dB
W_{in} the impacting acoustic power in W
W_{af} the acoustic power delivered in W

A diffuse sound field will dominate in the transmitting room. Section 10.1 gives the relationships in connection with the diffuse sound field. This is what we are using now. The acoustic power striking the wall is:

$$W_{in} = I_z \cdot S_z = \left(\frac{p^2_{eff,z}}{4 \cdot \rho \cdot c}\right) \cdot S_z \ [\text{W}]$$

The meaning of the symbols is:

W_{in} the impacting acoustic power in W
I_z the intensity in the transmitting room in W/m^2
S_z the area of the wall in the transmitting room in m^2
$p_{eff;z}$ the effective sound pressure in the transmitting room in Pa

Part of this acoustic power radiates from the receiving room and there results in a certain sound intensity. Transmitted sound power and sound intensity in the receiving room relate to each other as follows:

$$W_{af} = I_o \cdot A_o = \left(\frac{p^2_{eff,o}}{4 \cdot \rho \cdot c}\right) \cdot A_o \text{ [W]}$$

The meaning of the symbols is:

W_{af} the acoustic power delivered in W
A_o the absorption in the receiving room in m^2 sabin
I_o the intensity in the receiving room in W/m^2
$p_{eff;o}$ the effective sound pressure in the receiving room in Pa

The sound insulation is that part of the impacting sound that is finally allowed to pass through the structure:

$$\frac{1}{d} = \frac{W_{in}}{W_{af}} = \frac{I_z \cdot S_z}{I_o \cdot A_o} = \frac{\left(\frac{p^2_{eff,z}}{4 \cdot \rho \cdot c}\right) \cdot S_z}{\left(\frac{p^2_{eff,o}}{4 \cdot \rho \cdot c}\right) \cdot A_o}$$

Because the term $4 \cdot \rho \cdot c$ appears in both the numerator and the denominator they cancel each other out. This leads to:

$$\frac{1}{d} = \frac{p^2_{eff,z} \cdot S_z}{p^2_{eff,o} \cdot A_o}$$

The sound insulation is now:

$$R = 10 \log \left(\frac{1}{d}\right) = 10 \log \left(\frac{p^2_{eff,z} \cdot S_z}{p^2_{eff,o} \cdot A_o}\right) = 10 \log (p^2_{eff,z} \cdot S_z) - 10 \log (p^2_{eff,o} \cdot A_o) = 10 \log (p^2_{eff,z}) + 10 \log (S_z) - 10 \log (p^2_{eff,o}) - 10 \log (A_o) \text{ [dB]}$$

If we divide all the expressions by the square of the reference sound pressure (p^2_o) the formula then becomes:

$$R = 10 \log \left(\frac{p^2_{eff,z}}{p^2_o}\right) + 10 \log \left(\frac{S_z}{p^2_o}\right) - 10 \log \left(\frac{p^2_{eff,o}}{p^2_o}\right) - 10 \log \left(\frac{A_o}{p^2_o}\right) = L_z - L_o + 10 \log \left(\frac{S_z}{A_0}\right) \text{ [dB]}$$

In principle the indices for the absorption and the area of the partitioning structure are omitted causing the formula to become:

$$R = L_z - L_o + 10 \log \left(\frac{S}{A}\right) \text{ [dB]}$$

The meaning of the symbols is:

R the sound insulation of the structure in dB
L_z the sound pressure level in the transmitting room in dB
L_o the sound pressure level in the receiving room in dB
S the area of the wall in the transmitting room in m^2
A the absorption in the receiving room in m^2 sabin

The sound insulation is a property of the structure to be investigated, the same value must always be found regardless of the rooms between which it forms the partition. The correction term 10 log($\frac{S}{A}$) makes the sound insulation independent of the room.

Correction term 10 log (S/A)

$\frac{S_z}{A_0} = \frac{1}{4}$ -> correction term = -6 dB

$\frac{S_z}{A_0} = \frac{1}{2}$ -> correction term = -3 dB

$\frac{S_z}{A_0} = 1$ -> correction term = 0 dB

$\frac{S_z}{A_0} = 2$ -> correction term = 3 dB

$\frac{S_z}{A_0} = 4$-> correction term = 6 dB

Example
When the wall becomes twice as big, twice as much sound energy is allowed to pass through to the receiving room, which causes a sound pressure level 3 dB (10 log 2) higher to be measured there. When there is twice as much sound absorption in the receiving room a sound level 3 dB lower will be measured. In the first case, without the correction expression a sound insulation would be measured that is 3 dB too low, and in the second case it would be 3 dB too high.

11.3 Sound insulation in practice

In practice, not the sound insulation of an element is important, but rather the difference in level of sound pressure between rooms, or between inside and outside. In other words: how much do I notice of the sound from another room (either airborne noise or impact sound), or from outside. The sound insulation of an element is important, but other aspects also play an important role, such as flanking sound propagation, sound leaks, dimensions of the room, etc. Besides these aspects, the properties of the sound source are also important. Measurements are taken with a sound generator and amplifier.
In practice, the sound which is to be reduced will deviate from the sound used to determine the sound insulation. Two conversion values are determined for airborne noise, with which the effect of the reference spectrum of the source sound and the A-weighting can be set off (see figure 11.22).

Such a standard spectrum has also been formulated for impact sound (see figure 11.23).

Determining the airborne sound level difference between two rooms happens in separate steps:

1 Determining normalised sound level difference. Per octave band (mid frequencies 125, 250, 500, 1000 and 2000 Hz) the normalised sound level difference is determined. This is done through measurements.
2 Correction for the standard spectrum. The normalised sound level difference is 'weighted' in relation to the appropriate standard spectrum and the results per octave band are added up. The results for the weighted unit are rounded to the nearest integer. If the unrounded number ends in .5, it should be rounded up.
3 Room correction. From the building practice, there is a need for flexible and variable lay-out. This means that, basically, the building is delivered as a shell and the user can choose the lay-out. Because an undivided room must also meet requirements, the weighted values must be corrected for the room factor.

The same approach applies to impact sound, provided that in this case no room corrections take place.

standard reference spectrum airborne noise	octave band mid frequencies (in Hz)				
	125 i = 1	250 i = 2	500 i = 3	1000 i = 4	2000 i = 5
K_i values neighbour noise spectrum (speech, music, TV, playing children)	–21	–14	–8	–5	–4
K_i values road traffic noise	-14	-10	-6	-5	-7

Figure 11.22 Airborne noise

standard impact sound weighing spectrum	octave band mid frequency (in Hz)				
	125 i = 1	250 i = 2	500 i = 3	1000 i = 4	2000 i = 5
H_i	–15	–15	–15	–15	–15

Figure 11.23 Impact sound

Normalised airborne sound level difference D_{nT}: calculation method

In section 11.1, we examined the transmission paths significant for the airborne noise insulation of a partitioning wall. We will repeat them here:

1 direct sound emission from the partition wall;
2 the partition wall causes the adjacent structures to vibrate;
3 transmission via the sidewalls.

If you want to determine exactly what the impact of flanking is, you have to include the surface area, the mass, the type of joints between the different structures in your calculation. However, this is beyond the scope of this book. For the preliminary calculations it suffices to work with a guideline. In practice, the sound insulation as a consequence of flanking is set to approximately 5 dB below the laboratory values. In this section we are going to work out what the normalised airborne sound level difference (D_{nT}) is based on the sound-insulation value (R value). We can do this based on previously introduced formulas:

$$R = L_z - L_o + 10 \log \left(\frac{S_z}{A_0}\right) \rightarrow L_z - L_o = R - 10 \log \left(\frac{S_z}{A_0}\right) \rightarrow L_z - L_o = R + 10 \log \left(\frac{A_0}{S_z}\right)$$

$$D_{nT} = L_z - L_o + 10 \log \left(\frac{T}{T_0}\right) \rightarrow D_{nT} = R + 10 \log \left(\frac{A_0}{S_z}\right) + 10 \log \left(\frac{T}{T_0}\right) = R + 10 \log \left(\frac{A_0 \cdot T}{S_z \cdot T_0}\right)$$

$$T = \frac{V}{6 \cdot A_0} \rightarrow A_0 = \frac{V}{6 \cdot T}$$

$$D_{nT} = R + 10 \log \frac{V \cdot T}{6 \cdot S_z \cdot T \cdot T_0} = R + 10 \log \frac{V}{6 \cdot S_z \cdot T_0}$$

The reference reverberation time is 0.5 s. This changes the formula into:

$$D_{nT} = R + 10 \log \frac{V}{3 \cdot S_z} \text{ [dB]}$$

Airborne sound level difference between rooms: measurement method

Airborne sound comes from a source that causes the air to vibrate. These vibrations will cause the adjacent structure to vibrate. The structure will then cause the air in the adjacent room to vibrate (source -> air -> structure -> air).

When taking measurements, you effectively want to find out what the difference is between the sound levels in de sound source room and the sound receiving room (what can I hear from my neighbours). For measuring the normalised sound pressure difference, a sound source is placed in a room and the difference in sound pressure level per octave band between the sound source room and the sound receiving room is measured. Because often measurements are taken in an unfurnished room, the reverberation time is longer than in a furnished room, resulting in a higher sound level. In order to get an impression what the sound insulation will be in practice, the measured reverberation time will have to be corrected to the reference reverberation time (T_0); the reverberation time you can expect in practice in a furnished space. For classrooms (primary and secondary, higher or university education) the reverberation time amounts to 0.8 s. For other rooms, such as homes and offices, the reverberation time amounts to 0.5 s. The formula for this is:

$$D_{nT,i} = L_z - L_o + 10 \log \left(\frac{T_i}{T_0}\right) \text{ [dB]}$$

The meaning of the symbols is:

$D_{nT,i}$ the normalised airborne sound level difference in dB in octave band i

L_z the sound pressure level in the transmitting room in dB
L_o the sound pressure level in the receiving room in dB
T_i the average reverberation time in the receiving room in s
T_0 the reference reverberation time in s

If the reverberation time in the room is equal to the reference reverberation time (0.5 s) then the correction factor is 0. The table in figure 11.24 shows the magnitude of the correction term for a number of reverberation times.

T [s]	Correction term [dB]	*T* [s]	Correction term [dB]
0.20	-4.0	0.8	2.1
0.25	-3.0	0.9	2.6
0.30	-2.1	1.0	3.0
0.35	-1.5	1.2	3.8
0.40	-1.0	1.4	4.5
0.45	-0.5	1.6	5.1
0.50	0.0	1.8	5.6
0.60	0.8	2.0	6.0
0.70	1.5	2.5	7.0

Figure 11.24 Magnitude of the correction term 10 log T/T_0 (T_0 = 0.5 s) for determining normalised airborne sound level difference (D_{nT})

Weighted airborne sound level difference

In order to compare structures with each other, it would be preferable to express the sound level difference of a structure in one number. For this purpose, the DnT,A value is introduced. In order to calculate this value, the following formula is used:

$$D_{nT,A} = -10 \log \sum_{i=5}^{5} 10^{\frac{K_i - D_{nT,i}}{10}} \text{ [dB]}$$

The meaning of the symsbols is:
$D_{nT,A}$ weighted airborne sound level difference (dB)
$D_{nT,i}$ normalised airborne sound level difference per octave band (dB)
K_i reference spectrum of the source sound and the A-weighting (dB), see figure 11.22

See the example in figure 11.25.

Example
Determining the A-weighted normalised airborne sound pressure level difference
In this example, the calculation of an airborne noise measurement between two rooms is given.

	Octave band mid frequencies (in Hz) 125, i = 1	250, i = 2	500, i = 3	1000, i = 4	2000, i = 5
standard reference spectrum neighbour noise K_i [dB]	-21	-14	-8	-5	-4
normalised air pressure level difference $D_{nT,i}$ [dB]	38.3	44.5	50.2	53.8	57.4
$K_i - D_{nT,i}$	-59.3	-58.5	-58.2	-58.8	-61.4

$$D_{nT,A} = -10 \log \sum_{i=1}^{5} 10^{\frac{K_i - D_{nT,i}}{10}} = -10 \log (10^{\frac{-59.3}{10}} + 10^{\frac{-58.5}{10}} + 10^{\frac{-58.2}{10}} + 10^{\frac{-58.8}{10}} + 10^{\frac{-61.4}{10}})$$
$$= 52.1 \text{ dB, rounded up to 52 dB}$$

Figure 11.25

Typical airborne sound level difference

The $D_{nT,A}$ value is derived from the D_{nT} value and is a unit dependent on room type and use. This space-dependent unit has to be transferred into room-independent unit. To this end the typical airborne sound level difference ($D_{nT,A,k}$) is introduced. The formula for deriving the $D_{nT,A,k}$ value for offices spaces is as follows:

$$D_{nT,A,k} = D_{nT,A} - 10 \log \left(\frac{0.16 \cdot V}{T_0 \cdot S_r}\right) \text{ [dB]}$$

The meaning of the symbols is:

$D_{nT,A,k}$ typical airborne sound level difference in dB

$D_{nT,A}$ weighted airborne sound level difference per octave band in dB

V volume of the receiving room in m^3

T_0 the reference reverberation time in s

S_r surface area of the communal partition structure between transmission and receiving structure in m^2

If there is no communal part of the partitioning structure between transmission and receiving room, or if the surface area between transmission and receiving room (S_r) is smaller than (0.16 · V)/(2.5 · T_0), then, for the calculation of the typical airborne sound level difference, the surface area between transmission and receiving room (S_r) must be set equal to (0.16 · V)/(2.5 · T_0) with a minimum of 7 m^2.

Impact sound transmission between rooms

For measuring the impact sound insulation, a standard impact sound generator is used (tapping machine). This device has a number of steel or brass hammers weighing 500 grams in total, which make a free fall from a height of 40 mm for a total of ten times a second and strike the floor (see figure 11.26). This way, vibrations are generated in the floor which propagate through the building structure and are then transmitted into other rooms in the shape of airborne sound.

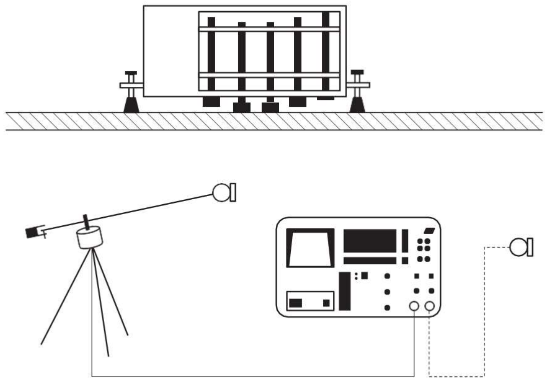


Figure 11.26 Impact sound insulation measurement

In the receiving room the impact sound level is measured (L_i) in the five octave bands mentioned above. This receiving room may be situated under the impacted floor, but it could also be a room adjacent to the one where the tapping machine is set up. The measured impact sound level (L_i) is again normalised for the reverberation time of T_0 = 0.5 s (except for classrooms). This results in the following formula:

$$L_{nT,i} = L_i - 10 \log \left(\frac{T_i}{T_0}\right) \qquad \text{[dB]}$$

The meaning of the symbols is:

$L_{nT,i}$ the normalised impact sound level in dB

L_i the sound pressure level in dB measured in the receiving room

T_i average reverberation time in the receiving room determined in octave band i in s

T_0 the reference reverberation time (= 0.5 s, except for class rooms)

The formula shows that the higher $L_{nT,i}$, the worse the sound insulation!

Weighted contact sound insulation level

When we compare the impact sound level of a variety of structures, we again want to compare them to each other in one number. For this purpose, the $L_{nT,A}$ value is introduced. The weighted impact sound level LnT,A is found by adding up the Hi weighted normalised impact sound level values ($L_{nT,A}$) as measured with the tapping machine. The formula for this is:

$$L_{nT,A} = - 10 \log \sum_{i=1}^{7} 10^{\frac{L_{I,i} - H_i}{10}} \text{ [dB]}$$

The weighted impact sound insulation level relates to the protection of a room against impact sounds which can arise from a floor, stairs or another surface meant for walking on. All this does not apply only to rooms on top of each other, but also to rooms next to each other.

Contrary to the weighted airborne sound level difference, no correction is applied for the room in determining the weighted impact sound level. The weighted impact sound level appears to a large extent to be independent of the lay-out variants. From the viewpoint of the variable layout, the $L_{nT,A}$ value appears to be a suitable unit already so it does not need to be adjusted.

Example

Determining the A-weighted normalised impact sound pressure level

In this example, an impact sound measurement between two rooms is performed.

	Octave band mid frequencies (in Hz)				
	125	250	500	1000	2000
	$i = 1$	$i = 2$	$i = 3$	$i = 4$	$i = 5$
normalised impact sound pressure level $L_{nT,i}$	60.3	61.7	63.1	63.5	59.2
weighing values standard impact sound spectrum H_i (see figure 11.23)	-15	-15	-15	-15	-15
$L_{nT,i} + H_i$	45.3	46.7	48.1	48.5	44.2

$$L_{nT,A} = -10 \log \sum_{i=1}^{5} 10^{\frac{L_{nT,i} - H_i}{10}} = -10 \log (10^{\frac{-45.3}{10}} + 10^{\frac{-46.7}{10}} + 10^{\frac{-48.1}{10}} + 10^{\frac{-48.5}{10}} + 10^{\frac{-44.2}{10}})$$

$= 53.8$ dB, rounded up to 54 dB

Figure 11.27

Legislation on sound insulation

Legislation sets requirements on homes in terms of the typical airborne sound level difference ($D_{nT,A,k}$) and the weighted impact sound level ($L_{nT,A}$).

These are the minimum requirements. Especially when there is a big difference in the daily lives of the various residents, nuisance may still occur even when the requirements are met. Consider for example nuisance because of radio, television, playing musical instruments, practising loud hobbies and walking on hard shoes (e.g.) on a hard floor finish (tiles, stone, parquet) without taking special precautions.

In general, there is no legislation regarding sound insulation between rooms inside one and the same office building, because they strongly depend on the type of work that is carried out. The Central Government Real Estate Agency does however make room-dependent $D_{nT,A}$ en $L_{nT,A}$ demands on office spaces. The level of demands is based on the level of privacy to be realised (see figure 11.28).
As supplement to the desired insulation value, the table of figure 11.29 provides recommendations for the maximum equivalent background noise level as a result of outside noise ($L_{A,eq}$) and as a result of technical installations ($L_{i,A}$). This latter numerical value also needs to be used as guideline for the devices present in the rooms for the same categories of rooms as in figure 11.28.

11.4 Installation noise

Installations in buildings produce noise; think for example of air handling units, lifts, etc. To what extent users of the building are affected by this noise depends on many factors and cannot be easily determined in advance. Measuring the installation noise is often the only option.

The way the typical A-weighted installation sound level ($L_{I,A,k}$) is determined does not differ greatly from the way the typical A-weighted airborne sound level difference is measured. Here too there are three steps for determining the typical A-weighted installation sound level:

1 For each octave, determine the installation sound pressure level in the receiving room ($L_{I,i}$). The octave bands with mid frequencies of 63, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz must be used for the installation sound pressure level.

2 Determine the A-weighted installation sound level ($L_{I,A}$) with the following formula:

$$L_{I,A} = 10 \log \sum_{i=1}^{7} 10^{\frac{L_{I,i} - W_i}{L_{I,i}}} \text{ [dB]}$$

In the case of installation noise, there is no spectrum. For this reason, only the A-weighting (W) is used as derivation value (figure 10.18).

3 Determine the typical A-weighted installation sound level ($L_{I,A,k}$) for a room with the formula:

$$L_{I,A,k} = L_{I,A} + 5 \log \left(\frac{V}{V_0}\right) \quad \text{[dB]}$$

The meaning of the symbols is:

$L_{I,A,k}$ typical A-weighted installation sound level in dB
$L_{I,A}$ A-weighted installation sound level
V volume of the receiving room
V_0 25 m^3 reference volume of the receiving room

11.5 Sound insulation and sound proofing of facades

A-weighted sound proofing (GA): measurement method

Sound proofing of the facade is effectively the difference between the indoor and outdoor level, normalised for the reverberation time.

$$G_A = L_{bu} - L_{bi} + 10 \log\left(\frac{T}{T_0}\right) \text{ [dB]}$$ The meaning of the symbols is:

G_A sound proofing of the facade in dB
L_{bu} the outdoor sound pressure level in dB
L_{bi} the sound pressure level in the receiving room in dB
T the reverberation time in the room in s
T_0 the reference reverberation time in s

For measurements of sound proofing of the outside partitioning structure, you have to determine the indoor and outdoor level difference and the reverberation time per octave band (mid frequencies 125, 250, 500, 1000, 2000 Hz). The room has to be corrected for the reverberation time to the reference reverberation time T_0 (= 0.5 s, except for classrooms). Sound proofing of the facade is measured by using a sound source aimed at the facade with an angle of 45°. The incoming sound level is derived from sound level measurements taken 2 metres in front of the facade.

Performance level Acoustic guidelines matrix					
	Enclosed spaces Category 1	Category 2	Category 3	Open spaces Category 4	Category 5
Air born sound pressure level difference minimum requirement $D_{nT,A}$ in dB					
To rooms	45	52	39	NA	NA
To traffic areas	33	33	27	NA	NA
To rooms via wall with door		33	33	NA	NA
To bathrooms	48	48	48	48	48
To other rooms	45	42	33	33	33
Maximum impact sound pressure level $L_{nT,A}$ in dB including floor finish					
To rooms	57	57	57	57	57
To traffic areas	67	67	67	67	67
To rental or user partition	48	48	48	48	48
Example situation for enclosed spaces					
Category 1	high level of speech privacy e.g. meeting centre				
Category 2	increased level of speech privacy in office location e.g. consulting rooms				
Category 3	private work space/concentration area (1-4 people)				

Example situation for open spaces	
Category 4	open, grouped work space (4-6 people)
Category 5	open meeting area, call centre

Figure 11.28 Performance requirements for airborne and impact sound insulation (source: Handboek Bouwfysische kwaliteit gebouwen)

Type of background noise	Enclosed spaces			Open spaces	
	Category 1	Category 2	Category 3	Category 4	Category 5
sound pressure level as a result of outdoor sound (industrial railway, road and air traffic sound) ($L_{A,eq}$ in dB)	< 35	< 40	< 40	< 40	< 45
installation sound pressure level ($L_{I,A}$ in dB)	< 35	< 35	< 35	< 40	< 40

Figure 11.29 Recommended values for background noise level in dB in offices (source: Handboek Bouwfysische kwaliteit gebouwen)

The formula for this is:

$$D_{2m,nT} = L_{bu} - L_{bi} + 10 \log(\frac{T}{T_0}) \text{ [dB]}$$

The meaning of the symbols is:

$D_{2m,nT}$ sound proofing of the facade in dB
L_{bu} the outdoor sound pressure level in dB
L_{bi} the sound pressure level in the receiving room in dB
T the reverberation time in the room in s
T_0 the reference reverberation time in s

Because reflections against the facade occur, the measured sound level will be higher than the actual incoming sound level. This has to be corrected for with derivation term C_r. For a level facade C_r = 3 dB. Basically, you measure the sound twice, assuming that virtually everything is reflected. For facades with balconies and suchlike, you will find values between 1 and 3 dB. Instructions regarding measurements and calculation provide the values depending on the facade structure. As a result of the position of the building in relation to the source, it is possible that the sound level on the facade is not the same for all areas of the facade. This could for example be a building parallel to a traffic route. The facades at right angles to the road effectively see half of the length of the total road. This means that the sound level at that spot is 3 dB less. This is accounted for with the derivation value C_L. Here too, instructions provide values for all possible situations. The partial facade sound proofing (G_i) can now be determined per octave band with the following formula:

$$G_i = 10 \log 10^{\frac{-D_{2m,nT,i} - C_r + C_L}{10}} \text{ [dB]}$$

The meaning of the symbols is:

G_i partial sound proofing of an external partitioning structure for octave band i (sound level derivation term) in dB
$D_{2m,nT,i}$ normalised facade sound level difference between a room and outdoor space for octave band in dB
C_r derivation term for the influence of reflections and geometrical factors in dB (3 dB for flat facades)
C_L derivation term for variations in sound levels due to screening and reflection (sound level derivation term) in dB

A standard spectrum is also defined for traffic noise which takes into account the typical sound production of the source and the auditory sensitivity of the observer. In order to determine the A-weighted facade sound proofing (G_A) per octave band, the partial sound proofing is subtracted from the standard airborne noise reference spectrum and the aggregate logarithmic sum of the results is determined.

$$G_A = -10 \log \sum 10^{\frac{K_i - G_i}{10}}$$

The meaning of the symbols is:
G_A A-weighted sound proofing of an external partitioning structure in dB
G_i partial sound proofing of an external partitioning structure for octave band in dB
K_i reference spectrum of the source sound and the A-weighting in dB (see figure 11.22)

As a result of the wish for variable lay-out, the GA must finally be defined as a value which is lay-out independent. The following formula applies:

$$G_{A,k} = G_A - 10 \log \left(\frac{0.16 \cdot V}{T_0 \cdot S_{r,u}}\right) \text{ [dB]}$$

The meaning of the symbols is:
$G_{A,k}$ A-weighted typical sound proofing of an external partitioning structure in dB
G_A A-weighted sound proofing of an external partitioning structure in dB
V volume of the room in m^3
T_0 the reference reverberation time in s
$S_{r,u}$ surface area of the external partitioning structure between outside area and the receiving room in m^2

Typical sound proofing of external partitioning structures

A facade generally consists of multiple elements, such as a cavity wall, windows, ventilation provisions, etc. The acoustic quality of the total façade depends among other things on the quality of the individual elements, the surface area of the element in relation to the total facade and the way in which the elements are attached. In order to estimate the typical facade sound proofing in practice and to determine whether the regulations are met, calculations need to be performed. In general, a computer program will do the work, but for simple situations (when, for example, there is only a single facade surface) the calculation can also be performed manually.

The typical sound proofing of the external partitioning structure can be determined in three steps:

- Determine for each octave band with mid frequencies of 125, 250, 500, 1000, 2000, and 4000 Hz the sound insulation of the composite facade (R_i). This does not say anything about the sound proofing of the structure, but only about the quality of the facade (comparable to the sound insulation R of a partitioning structure between rooms).
- Determine the A-weighted facade sound proofing (G_A) for the reference spectrum.
- Determine the typical sound proofing of the external partitioning structure ($G_{A,k}$).

Sound insulation of composite facade

First we have to calculate or determine the sound insulation value of the external partitioning structure per octave band.

Each part of a certain material has its own specific sound insulating characteristics. An enormous number of materials have been measured in laboratories and we can look up the sound insulation of many materials, per octave band, in books of tables. The values that are determined in laboratories depend on the situation in which they will eventually be placed.

If the facade comprises more than one element we first determine the total sound insulation of the facade using the following formula (see section 11.1 also):

$$R_{A;i} = -10 \log \left(\sum_{j=1}^{n} \frac{1}{S_{tot}} \left(S_j \cdot 10^{\frac{-R_{j;A;i}}{10}} + 10 \cdot 10^{\frac{-D_{n;e;i}}{10}}\right) + K\right)$$

The meaning of the symbols is:
$R_{A;i}$ the sound insulation value of the facade in dB
$\sum$ the sum of n facade elements
S_j the area of facade element j in m^2
S_{tot} the total facade area, seen from inside the sound-sensitive room in m^2
$R_{j;A;i}$ the A-weighted sound insulation value of the facade element j in dB

$D_{n;e;i}$ the A-weighted normalised sound level difference of a ventilation provision, normalised to 10 m^2 sabin, in dB
K the gap term

Ventilation provisions such as ventilation grids and cantilever windows are often little more than an opening in the facade. The sound insulation of such provisions is therefore not as high and that will dramatically limit the sound insulation of the facade. Ventilation provisions that provide better sound insulation will have to be used in order to still be able to ventilate naturally under higher sound loads. Sound attenuators have been developed for this purpose. Put simply, a sound attenuator is a box containing sound absorbing material. The air, and therefore the sound also, is conducted across the sound-absorbing material. This dampens a large proportion of the sound before the ventilation air enters the room (see figure 11.30). Because the air is conducted across the absorbing material, which increases the air flow resistance, the net flow through opening cannot be determined as simply as for cantilever windows. The amount of air that can be introduced into the room through the sound attenuator is determined in laboratories in accordance with standard norms and expressed in a (fictional) net flow through opening for the ventilation provision. As can be seen from the formula for sound insulation, no area for the sound attenuator is taken into consideration in the calculation. All sound transmission via the sound attenuator is assigned the fictional flow through opening in measurements in the laboratory. This means that the closed part of the box does not have to be included as a separate component in the calculation of the facade sound proofing. The entire gross box area must be included in determining the total facade area S. The ventilation capacity of a ventilation provision is expressed in dm^3/s. This is the ventilation capacity per m^1 of sound attenuator. In order to meet ventilation requirements we have to determine the total linear metres of sound attenuator needed. The longer the box the lower the sound insulation. The contribution from the sound attenuator is determined as follows:

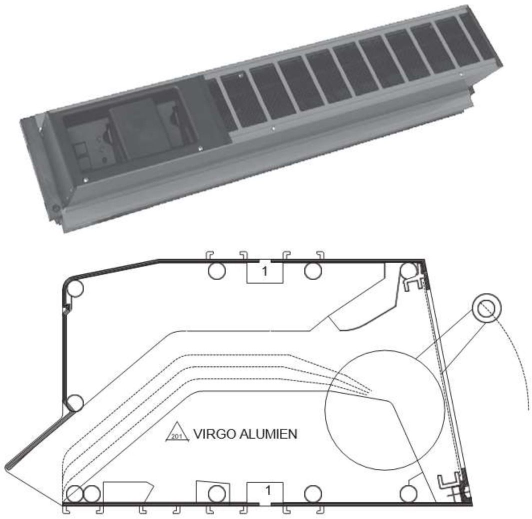


Figure 11.30 Alusta Vigro type sound attenuator
Source: www.alusta.nl

$$D_{n;e} = D_{n;e;lab} - 10\log\left(\frac{Q_{vent}}{C}\right) \text{ [dB]}$$

The meaning of the symbols is:
$D_{n;e}$ the A-weighted normalised sound level difference normalised to 10 m^2 sabin, in dB
$D_{n;e;lab}$ the A-weighted normalised sound level difference normalised to 10 m^2 sabin, as measured in the laboratory, in dB
Q_{vent} the required ventilation capacity in dm^3/s
C the pass-through measured in the laboratory in dm^3/s per m^1

The presence of joints and gaps influences the sound insulation of the facade. In calculations it is assumed that the total length of the gaps is related to the area of the facade and does not have to be measured separately. The value of the gap term depends on the manner in which the gap and joint sealing has been handled. The total sound insulation required must be taken into consideration in the choice of joint and gap sealant. If the sound proofing of the facade can be realised using a gap term of 10^{-4}, then there is no sense in using a much better gap sealant as this will only have a marginal effect. The table in figure 11.31 shows various gap terms.

Sound proofing of a partitioning structure

The sound insulation R_i relates to the structure but tells us nothing about the final sound proofing of the facade. The room that lies behind, the structure of the facade and the effect of values measured in the laboratory versus reality, are not included in the calculation. Therefore, the sound insulation of the facade has to be converted into the sound proofing of the partitioning structure (G_i) using the following formula:

$$G_i = R_i + 10 \log \left(\frac{V}{6 \cdot T \cdot S}\right) - 3 + C_g \text{ [dB]}$$

The meaning of the symbols is:

G_i the partial sound proofing of the partitioning structure for octave band i in dB
R_i the sound insulation of the composite facade based on the laboratory insulation of the constituent parts, in dB
V the volume of the room in m^3
T_0 the reference reverberation time in s
S the area of the external partitioning structure in m^2
–3 a constant term that can be used to calculate the difference between the sound striking in practice (point source/ line source) and in the laboratory
C_g the facade structure correction term in dB

Situtation	Gap term K	R_a in dB
Existing dwellings		
Facades		
• without provisions	$3 \cdot 10^{-3}$	25
• single gap sealing	$1 \cdot 10^{-3}$	30
• double gap sealing and inproved joint sealing	$3 \cdot 10^{-4}$	35
• special double gap sealing *	$3 \cdot 10^{-5}$	45
Roofs		
• with gaps in roof boarding	$1 \cdot 10^{-3}$	30
• with gap-tight roof boarding	$1 \cdot 10^{-4}$	40
New build dwellings		
Facades		
• single gap sealing and good joint sealing	$3 \cdot 10^{-4}$	35
• double gap sealing and good joint sealing	$1 \cdot 10^{-4}$	40
• special double gap sealing*	$1 \cdot 10^{-5}$	50
Roofs		
• with single scale roof elements < 30 kg/m2	$3 \cdot 10^{-5}$	45
• other roof structures	$3 \cdot 10^{-6}$	55
* – remaining good joint sealing – two or three-point clamp fixing – draught mouldings welded in the corners – sound attenuator connection, carefully sealed		

Figure 11.31 Gap term values

The facade sound proofing is a room- dependent variable. By adding the term 10 log $\left(\frac{V}{6 \cdot T \cdot S}\right)$ the influence of the room that lies behind is included in the total facade sound proofing. Because room-independent variables – in connection with variable layout – are used in legislation, this term will be subtracted later when calculating the typical sound proofing. The sound insulation values (R_i values) are based on laboratory measurements (diffuse sound field). In practice, there is a direct sound field outside. This means that the insulation values differ from the laboratory values. Research has proven that this causes a reduction in the sound insulation of 3 dB. The construction of the facade also has an influence on the sound level just in front of the facade. Some facade structures can shield the striking sound to a certain degree. This means a reduction of the sound levels immediately in front of the facade. This could be a balcony/ loggia with a closed parapet (glass) and possibly an additional sound absorbing ceiling. If you plan things carefully, this could reduce the sound pressure level by values of up to 3 dB. The term used for correcting the façade structure is shown by C_g. Calculation instructions provide values for C_g for all possible situations. Subsequently, the normalised A-weighted sound proofing (G_A) and the typical facade sound proofing ($G_{A;k}$) are determined with the formulas as given above.

Performing calculations with one-number values

Manufacturers often mention the R_A value along with the sound-insulation values. The R_A value is a single-number value for the sound insulation of the element for which the spectrum of road traffic has already been set off. If we are dealing with railway or aircraft traffic noise we can assume the same value but have to make a correction of 3 dB for railway traffic and of 2 dB for air traffic.

> Example
> Imagine that a facade has to have a sound proofing of 30 dB. For railway traffic the facade only needs a sound proofing of 27 dB, calculated with the standard spectrum for road traffic and 28 dB for air traffic.

Performing calculations with one-number values does not differ much from the calculation method discussed earlier. The advantage of this method is that it is faster, since we don't have to make calculations for all octave bands separately. Below, it is briefly explained which steps ultimately lead to the normalised A-weighted sound proofing. First, the RA value of the total facade is calculated by finding the aggregate of all elements:

$$R_A = -10 \log \left[\sum_{j=1}^{n} \frac{S_j}{S} \cdot 10^{-\frac{R_{A,j}}{10}} + \frac{10}{S} \cdot 10^{-\frac{D_{ne;A}}{10}} + K \right]$$

The meaning of the symbols is:

$R_{A,j}$ the weighted (laboratory) sound insulation of facade element j in dB
S_j the surface area of facade element j in m^2
$D_{ne,A}$ laboratory value of a weighted sound level difference normalised at 10 m^2 of a sound-insulated ventilation provision in dB
K the gap term [–]

Because adjustment of the road traffic reference spectrum has already been applied to the sound insulation, the normalised A-weighted sound proofing can now be immediately determined with the formula:

$$G_A = R_A + 10 \log \left(\frac{V}{6 \cdot T_0 \cdot S} \right) - 3 + C_g \ \text{[dB]}$$

The meaning of the symbols is:

R_A the (laboratory) sound insulation of the facade surface in dB for the relevant standard reference spectrum; without any further specification this concerns outside noise
V volume of the room in m^3
S the surface area of the facade in m^2
C_g the facade structure correction term in dB

The conversion of G_A into $G_{A,k}$ takes place as described above.

Situations may arise where it is useful or necessary to start from the actual spectrum. If elements are used in the facade elements that provide good sound insulation in exactly the high frequencies for example, or if the spectrum differs from the standard spectrum. Calculation based on the R_A value can then return sound insulation values that are incorrect.

Requirements for typical sound proofing of facades in legislation

The typical sound proofing that must be achieved depends on the sound load on the facade from industry, road or railway traffic, and the use of the room. Threshold values are given for the sound level that has to be achieved in an accommodation area (that which, as an occupant, you eventually hear from outside). The typical sound proofing of an external partitioning structure forming the partition between an accommodation area and outside is the difference between the sound pressure level outside (determined in accordance with the Noise Abatement Act) and the inside level prescribed by the Building Decree, with a minimum of 20 dB. The threshold value of the interior level for a dwelling function, with the exception of a dwelling function of a caravan, is 35 dB. A threshold value of 40 dB applies for offices. For accommodation rooms a typical sound proofing applies that is 2 dB lower than the typical facade sound proofing of an accommodation area in which the accommodation room lies.

We speak of Kosten units (Ke) in relation to air traffic noise. The Ke is the average sound load from aircraft considered over a full year. The number of flights, the type of aircraft and a night correction have been incorporated into this unit. Lines of equal Cost unit can be drawn around airports based on these calculations. Based on this a check can be made of the sound proofing that has to be met.

Example

We give an example of the calculation method using the R_A value and the R_i value. Given:

- A flat facade of a new build dwelling (3.6 · 3.0 m) comprising a cavity wall and 35% double glazing (glass thickness 4 mm, cavity width 6 mm).
- The facade structure correction is 0.
- The gap sealing is double.
- The joint sealing is good.
- The volume of the room lying behind is 52 m^3.

octave band [Hz]	125	250	500	1000	2000	R_A [dB]
stony cavity wall + mineral wool	33	37	41	46	52	41.6
double glazing (4–6–4)	22	23	24	32	34	26.9
road traffic noise spectrum	-14	-10	-6	-5	-7	

Further details:
The gap term is $K = 10^{-4}$ (see figure 11.31).
The area of the facade is 3.6 · 3 = 10.8 m^2.
The area of the glass, including the frame is 3.6 ? 3 ? 0.35 = 3.78 m^2.
The area of the cavity wall is 3.6 · 3 · 0.65 = 7.02 m2.

Calculation using the average of the R_A value gives:

$$R_A = -10 \log \left(\sum_{j=1}^{n} \frac{1}{S_{tot}} \left(S_j \cdot 10^{-\frac{R_{j;A}}{10}} + 10 \cdot 10^{-\frac{D_{n;j;A}}{10}}\right) + K_{tr}\right)$$

$$= -10 \log \left(\frac{3.78}{10.8} \cdot 10^{-2.69} + \frac{7.02}{10.8}\, 10^{-4.16} + 10^{-4}\right) = 30.7 \text{ dB}$$

As there are no ventilation provisions, the term $10 \cdot 10^{-\frac{D_{n;j;A}}{10}}$ is omitted.

$$G_A = R_A + 10 \log \left(\frac{V}{6 \cdot T_0 \cdot S}\right) - 3 + C_g$$

$$= 30.7 + 10 \log \left(\frac{52}{6 \cdot 0.5 \cdot 10.8}\right) - 3 + 0 = 29.8 \text{ dB}$$

It is a flat facade, therefore the facade correction equals 0. In addition, it is a dwelling, so we have to take a reverberation time of 0.5 s into account.

$$G_{A;k} = G_A - 10 \log \left(\frac{V}{6 \cdot T_0 \cdot S}\right)$$

$$= 29.8 - 10 \log \left(\frac{52}{6 \cdot 0.5 \cdot 10.8}\right) = 27.7 \text{ dB}$$

We perform the same calculation once again, but this time based on the spectrum. The formulas required are:

$$R_i = -10 \log \left(\sum_{j=1}^{n} \frac{1}{S_{tot}} \left(S_j \cdot 10^{-\frac{R_{i;j}}{10}} + 10 \cdot 10^{-\frac{D_{n;i;j}}{10}}\right) + K_{tr}\right) \text{ [dB]}$$

$$G_i = R_i + 10 \log \left(\frac{V}{6 \cdot T_0 \cdot S}\right) - 3 + C_g \text{ [dB]}$$

$$G_A = -10 \log \sum 10^{-\frac{G_i - K_{tr}}{10}} \text{ [dB]}$$

$$G_{A;k} = G_A - 10 \log \left(\frac{V}{6 \cdot T_0 \cdot S}\right) \text{ [dB]}$$

From the table and formulas it follows that:

G_A = 29.8 dB

$G_{A;k}$ = 27.7 dB

Both calculations arrive at the same value (naturally).

Other details are:

octave band [Hz]	125	250	500	1000	2000
stony cavity wall + mineral wool	33	37	41	46	52
double glazing (4–6–4)	22	23	24	32	34
gap term	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}
R_i	25.8	27	28.1	34.7	36.1
G_i	24.9	26.1	27.2	33.8	35.2
road traffic noise spectrum K_{tr}	-14	-10	-6	-5	-7
G_i - K_{tr}	38.9	36.1	33.2	38.8	42.2

Converting sound insulation units from other units

In the context of the standardisation of European regulations, the methods of determining airborne noise and impact sound have changed drastically over the last years. Suppliers have adapted their products as much as possible to the new regulations, but in older literature the original terms are still mentioned. In order to be able to use them, a number of different unambiguous relationships between the old and new units are provided below:

$D_{nT,A}$ ≈ I_u + 51 dB

$D_{nT,A,k}$ ≈ I_{uk} + 52 dB

$L_{nT,A}$ ≈ 59 – I_{co} dB

R_w ≈ I_u + 54 dB [practice value]

R'_w ≈ I_u + 59 dB [laboratory value]

$D_{g,Atr}$ ≈ G_A + 3 dB

$L_{I,A}$ ≈ L_A for furnished rooms

≈ L_A – 5 for unfurnished rooms and other rooms

$L_{n,A}$ ≈ $L_{n,w}$ + C_I ≈ 59 – $I_{co,lab}$

R_A ≈ R_W + C ≈ $I_{u;lab}$ + 51 dB

$R_{A;tr}$ ≈ R_W + C_{tr} ≈ R_A (road traffic)

R_A ≈ R_W + C ≈ R_{Ar} (railway traffic)

12 Applied sound insulation

A.C. van der Linden; A. Zeegers

During the design process the architect or advisor will need design tools on the basis of which estimates can be made of the sound insulation to be achieved for the structure, without having to perform 'complicated' calculations. This chapter describes a number of rules of thumb that can be used to make a quick estimate. A number of things must always be checked or measured later in the design process.

12.1 Desired sound insulation

Before a designer starts designing and selecting the right materials, he or she must first determine which requirements have been set for the room, the facade and the interior walls. Regulations pose demands to the sound insulation between rooms in homes. It is very well possible that you want to realise a sound insulation between rooms which do not have specific regulatory requirements, e.g. between office rooms. In order to set proper requirements, it is important to determine the goal to be realised with the requirements, which could be:

- prevent the noise produced in the room from becoming a nuisance to other rooms;
- prevent outside noise (from adjoining rooms or from outside) from becoming a nuisance in the room itself;
- prevent information shared inside the room from being overheard in other rooms;
- ensure that everybody in the room can hear each other properly.

Speech privacy refers to the extent to which a conversation taking place inside a room is intelligible or audible in an adjoining room or in the vicinity. For office spaces, speech privacy is very important. For setting sound insulation requirements based on speech privacy, it must be clear:

- to what extent sound may be heard in other rooms
- what the voice volume is that is generally used (normal, raised or loud)
- to what extent the conversation is allowed to be overheard (clearly intelligible, intelligible with difficulty, audible but not intelligible, inaudible)
- what the background noise level is inside the room, e.g. due to sound installations, equipment inside or outside the room
- what the dimensions of the room are
- what the absorption capacity of the room is

In order to make a fair estimation of what the sound insulation should be, a simple determination method has been formulated.

The determination method takes into account the speech level, the extent of the nuisance, the background noise level and the desired level of privacy. The formula is:

$$D = S + P + 11 - 10\log(\frac{A}{4}) - N - X \text{ [dB]}$$

The meaning of the symbols is:

D the sound level reduction present (or desired) between rooms ($L_z - L_o$) in dB

A the amount of absorption in the room where the conversation takes place in m^2 sabin

N the background level in the room to be protected in dB

X the extent of the nuisance, specified as:

- satisfied (no nuisance) = 0
- nuisance = 6
- serious nuisance = 12

S the speech level at 1 m distance from the speaker, specified as:

- normal = 60 dB
- raised = 66 dB
- loud = 72 dB

P an addition for the desired level of privacy, specified as:

- normal privacy = 9 dB
- confidential = 15 dB

Example
The sound insulation for a room (surface area 12 m^2, reverberation time 0.5 s) is determined
Points of departure are:

- increased privacy: P = 15 dB;
- no nuisance: X = 0;
- background level: N = 30 dB;
- normal speech level: S = 60 dB;
- sound absorption; A = 16 m^2 sabin.

$$D = 60 + 15 + 11 - 10 \log\left(\frac{16}{4}\right) - 35 - 0 \approx 45 \text{ dB}$$

Note: this is a rule of thumb which can be used at the start of the design process. On further specification, advanced determination methods must be used.

Various diagrams can be found in the literature, based on which speech privacy can be determined (see figure 12.1). From this figure, it can be determined that for a room of 20 m^2 with a reverberation time of 0.5 s for the points of departure mentioned in the example (where increased privacy refers to inaudibility), an A-weighted normalised typical airborne sound level difference of approx. 47 dB is required. Figure 12.1 clearly shows that the A-weighted normalised typical airborne sound level difference between two rooms can be lower if the background noise level in the receiving room increases. The background noise 'drowns out' the sound of the adjoining room as it were. In smaller rooms, a background noise level of 35-40 dB is acceptable. A level higher than 40 dB will be experienced as a nuisance. For a background noise lever lower than 35 dB, the A-weighted normalised typical airborne sound level difference becomes so high that standard solutions will not suffice.

This is different in open-plan offices. Users produce a sound level of 40-45 dB. A background noise level of 40 dB will then be acceptable. A lower background noise level is not desirable, because conversations between people can then easily be overheard by others. The rule of thumb is that a conversation is not intelligible if the sound level of the conversation is 10 dB lower than the background noise level.

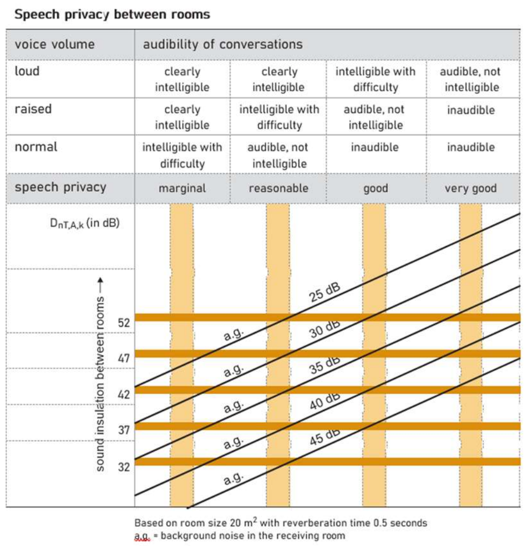


Figure 12.1 Relationship between audibility of conversations, sound insulation between rooms and background noise level (source: *Handboek Bouwfysische kwaliteit gebouwen*)

12.2 Construction of the walls

In construction of the walls we discuss, for a number of structures, how they perform in practice and the errors that must be avoided during construction. Practice shows that as a consequence of connections, cracks, crevices and flanking noise, the sound insulation will at least be 5 dB lower than the values as measured in a laboratory. Bear this in mind when selecting walls.

Rules of thumb for single walls

Rules of thumb can be given for various types of walls which can be used during the design process to make a quick estimate in relation to the sound insulation of a wall. A number of frequently used rules of thumb are given below. However, do not forget that in practice the insulation can be lower than calculated as a result of flanking transmission and the construction of joints. Section 11.1 discusses the practical mass law:

$$R = 17.5 \log m + 17.5 \log \left(\frac{f}{500}\right) + 3 \text{ [dB]}$$

The meaning of the symbols is:
R the sound insulation of the structure in dB
m the mass of the structure in kg/m^2
f the frequency in Hz

The abovementioned formula does not take the coincidence frequency into account. In order to make a correct estimate this is determined using the following formula:

$$f_{g;coincidence} = \frac{f_g \cdot d}{d} \text{ [Hz]}$$

The meaning of the symbols is:
f_g the coincidence frequency in Hz
$f_g \cdot d$ a material dependent constant in Hz·mm (see figure 11.7)
d the thickness of the structure in mm

The coincidence frequency must not fall in the speech range and therefore not be lower than 3000 Hz.

For a more accurate estimate of the sound insulation of a single structure it is better to use the plateau method (see section 11.1).

The following applies for converting the R value to the D_{nT} value:

$$D_{nT,A} = R_A + 10 \log \left(\frac{V}{6 \cdot T_0 \cdot S}\right) \text{ [dB]}$$

$$D_{nT,A,k} = D_{nT,A} - 10 \log \left(\frac{0.16 \cdot V}{T_0 \cdot S_r}\right) \text{ [dB]}$$

$D_{nT,A}$ value of stony walls with m = 60–160 kg/m2

The following applies for gypsum blocks and cellular concrete:

$$D_{nT,A,k} = 25.4 \log m - 69 + 10 \log\left(\frac{V}{3 \cdot S}\right) - 51$$

The following applies for stone and lightweight concrete:

$$D_{nT,A,k} = 12.7 \log m - 41 + 10 \log\left(\frac{V}{3 \cdot S}\right) - 51$$

The meaning of the symbols is:
m the mass of the (single) wall in kg
V the volume of the room in m^3
S the area of the partitioning structure in m^2

Stony walls with $D_{nT,A} \geq 41$ dB

A number of internal wall types are listed below, which, with good construction and attention to detail, can provide airborne sound insulation of $D_{nT,A} \geq 41$ dB.

- Half stone masonry (brick), plastered on one or two sides, possibly in neatwork, but then very carefully laid (shoved joints) and pointed. Cracked or damaged bricks must not be used.
- Porous brick masonry, 90 mm thick, plastered on one or two sides. Because this structure is on the limit of the insulation requirement, small shortcomings in the joints can lead to insufficient insulation. Neatwork is not possible.

- Porous brick masonry, twice 70 or 90 mm with a mortar joint between. This mortar joint should guarantee the air tightness of the wall so that the outsides can be constructed in neatwork.
- Light concrete stone. Because of the high porosity of these stones it is not possible to realise neatwork in a half stone wall. These walls, which must have a mass m > 150 kg/m², should be plastered on one or two sides. They can also be made airtight by treating them on one or two sides with a thick latex paint (see figure 12.2). Double walls with a mortar joint in the middle must also be used for neatwork in concrete stone.
- Building blocks (concrete, sand-lime brick, etc.) with a minimum mass of m = 150 kg/m² plastered on one or two sides or treated with latex paint. Neatwork is not possible as, due to the large dimensions of the blocks, it is not possible to guarantee that all joints are sealed sufficiently with mortar during laying.

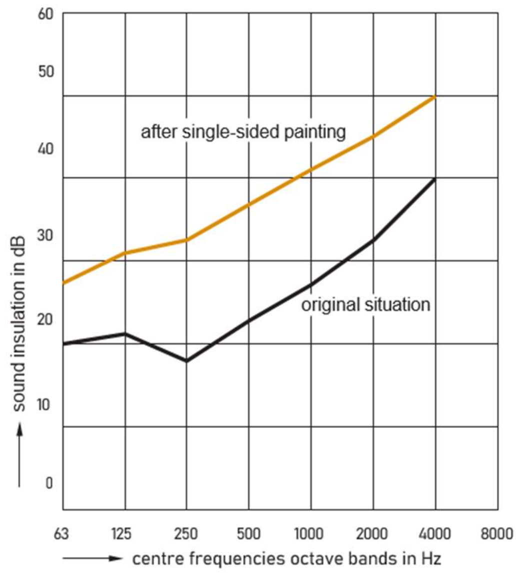


Figure 12.2 Example of improvement of the airborne sound insulation of a porous concrete stone wall using a single sided paint treatment

Double walls with a mortar joint in between must actually function as a single mass. Therefore, mortar must be used in such a way that a very strong bond is achieved. Both cavity leaves must be erected simultaneously. The use of anchors (or better yet: continuous reinforcement strips) is a necessity. When both halves of the wall disassembly by shrink a cavity structure is created with a very narrow cavity, which could have a very unfavourable (mass-spring) resonance frequency. Walls that are plastered or carefully jointed must also receive this treatment above a suspended ceiling, as otherwise there is a risk of circulating noise (see section 12.4).

Stony walls with $D_{nT,A} \geq 51$ dB

A structure meeting $D_{nT,A} \geq 51$ dB can be, amongst other things, a monolith wall of concrete or stone, with a minimum mass of m = 400 kg/m². Neatwork is not possible (see figure 12.3-1).

Rules of thumb for double structures with cavity

The sound insulation of this type of wall is difficult to predict because of various aspects such as mass-spring resonance and cavity resonations. With cavity structures it is important to know the frequency at which resonation occurs. This resonance frequency can be calculated using the following formula (see section 11.1 also):

$$f_0 = 60 \sqrt{\frac{m_1 + m_2}{m_1 \cdot m_2} \cdot \frac{1}{b}} \text{ [Hz]}$$

The meaning of the symbols is:

f_0 the resonance frequency in Hz
m_1, m_2 the mass of cavity leaf 1 and cavity leaf 2 respectively in kg/m²
b the cavity width in m

If the resonance frequency is higher than 80 Hz, then it is necessary to suppress this by, for instance, inserting mineral wool in the cavity.

Stony cavity walls with $D_{nT,A} \geq 51$ dB

Stony cavity walls that meet this requirement can be:

- A cavity wall of porous stone, light concrete stone, etc. with leaves of unequal thickness, plastered (rendered) on the inside or outside to achieve good airtightness, and where the cavity is filled with mineral wool.
- A cavity structure of brick masonry or massive concrete stone, where at least one cavity leaf is rendered on the inside to realise good airtightness. Sometimes the mistake is made of building-in wall sockets opposite each other on either side of the wall (for electricity, radio and television or telephone for example) which causes a sound leak (see figure 12.3-2). In addition, in existing situations sealing the openings in the boxes (cable feed-in) and other joints with sealant is useful.

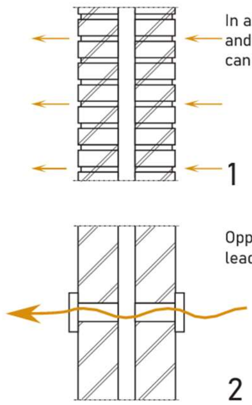


Figure 12.3 Sound leaks in cavity walls

The previously mentioned flanking sound transmission can seriously reduce the sound insulation at joints between light partition walls and the massive wall.

Stony cavity walls with $D_{nT,A} \geq 55$ dB

The unanchored cavity wall provides good opportunities for achieving very good results ($D_{nT,A} \geq$ 55 dB). The cavity leaves should both have good airtightness and the cavity must continue through to the foundation in order to avoid flanking sound transmission. In any event, the floors must not continue through. In order to avoid mortar bridges and suchlike, the cavity widths in masonry cavity walls must, preferably, be at least 50 mm.

Naturally care must be taken at the joints (such as with the facade) to avoid circulation noise and flanking sound transmission. The details can be implemented analogous with the principle given in figure 12.17-2. In joints with the roof too we must be aware of flanking sound transmission and sound leaks. Roof girders must not continue through and the ceiling must be constructed well sealed (see figure 12.4).

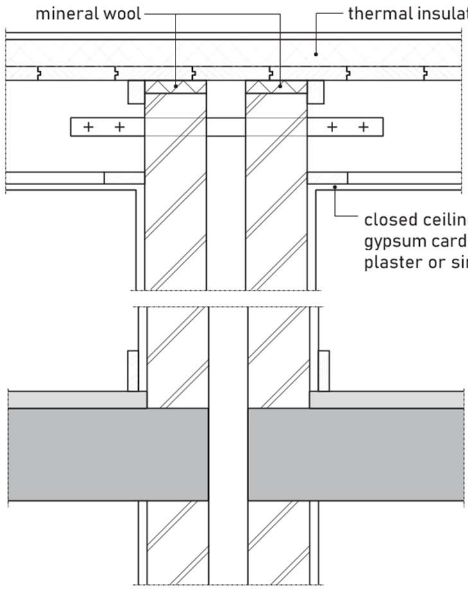


Figure 12.4 Unanchored cavity wall

Light walls

Light walls only provide reasonable insulation when they have been constructed with a cavity. These walls derive their sound insulation not from mass but from the properties of cavity structures (see section 11.1). This relates to plasterboard walls with wooden or metal framing. In order to achieve a good result, the cavity leaves must not have any (rigid) joints between them to prevent the direct transmission of vibrations from the one cavity leaf to the other.

Construction

The plasterboard wall is constructed as follows (see figures 12.5 and 12.6 also):

- one or more plasterboards
- a cavity structure, whether or not filled with absorbent material, and framing (separated or otherwise) made from wood or metal
- one or more plasterboards.

The quality of the wall is derived from its flexible character. If the flexible character is affected, the acoustic quality of the wall diminishes significantly. This must be continuously taken into account when selecting or designing a wall.

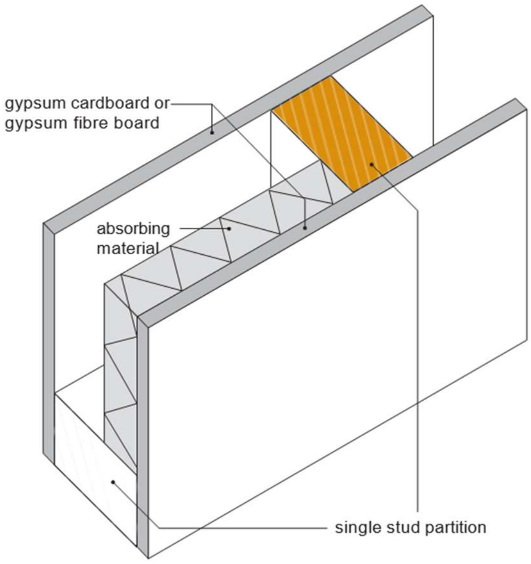


Figure 12.5 Construction of single framing

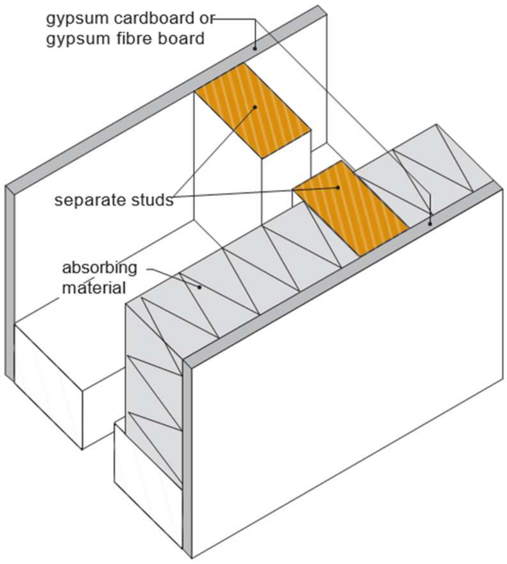


Figure 12.6 Construction of separated framing

Mass

Very good sound insulation can be achieved using plasterboard walls while the mass of the wall remains limited. In principle, increasing the mass often leads to better sound insulation (mass law). The sound insulation of plasterboard walls is, however, based on the fact that they are flexible and not so much on their mass (which is too low for this). If the mass of the plasterboards were to be increased the flexible character would be affected and there would be less sound insulation.

If more boards are fitted one on top of the other without there being rigid connections between them (so the flexible character is retained) then better sound insulation can be achieved.

Framing

The more framing that is used the more the rigid the structure becomes. And if the structure becomes more rigid, the sound insulation become worse. If the boards are fixed rigidly to the framing, the flexibility of the structure is affected and the sound insulation is reduced. When separated framing and flexible fixing of the boards to the framing are used this would, in principle, create the ideal situation.
Transmission can then only occur through the air cavity.

Cavity

The resonance frequency depends on the width of the cavity and the mass of the structure (see section 11.1). Wider cavities are preferred over narrow cavities. As a result of the sound absorbent cavity filling (such as mineral wool) the sound in the cavity will be dampened and the mass-spring resonance will be reduced, increasing the sound insulation.

Joints

The aspects mentioned up to now are determinative for the quality of the plasterboard wall in general. Apart from the wall itself we must, however, also consider the joints between the wall and the surrounding structure. The good sound insulation properties of a wall can be totally destroyed as a result of incorrect or careless connections.
There are three ways in which Sound leaks can occur at joints (see figure 12.7):

- between side connections, the covering floor and the subfloor and the edge profile (a)

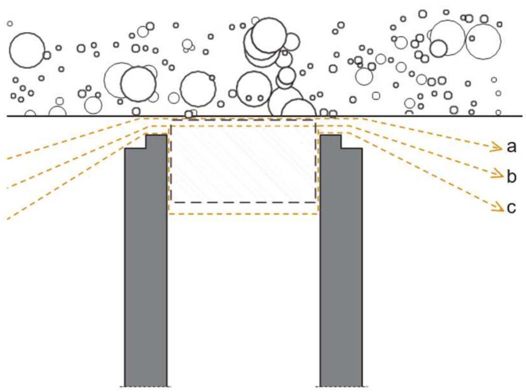


Figure 12.7 Possible sound leaks at connections between an insulating wall and the surrounding structure

- between the plasterboards and the edge profile (b)
- via the edge profile itself (c).

In addition to the wall itself and the method of connection to the surrounding structure there are also countless aspects that have to be taken into account:
- preventing connections of disconnected framing
- breaking the plasterboard at expansion joints
- the detailing of feed-throughs
- the building-in of technical services such as wall sockets
- the fixing of the various facilities to a wall

Airborne sound insulation

Empirical formulas have been arrived in relation to the airborne sound insulation of plasterboard walls based on laboratory research. The standard deviation is approximately 2-2.5 dB. The $D_{nT,A,lab}$ should be approximately 5 dB better than the practical value. This must be properly taken into account.

The following applies for cavity walls on single, wooden framing:

$$D_{nT,A,lab} = v + b + 1{,}5 \log m'' + 60 \cdot s - 39 - 51 \text{ [dB]}$$

The meaning of the symbols is:

v the cavity filling:
- 0 = unfilled cavity
- +3 = cavity filled with mineral wool

b the fixing of the plasterboards to the framing:
- 0 = normal (rigid) fixing
- +6 = flexible fixing

s the cavity width in m:
- between 0.03 and 0.08 m

m'' the total mass of the cavity leaves in kg/m^2:
- between 18 and 50 kg/m^2

The following applies for cavity walls on single, metal framing:

$$D_{nT,A,lab} = v + 30 \log m'' + 150 \cdot s - 61 - 51 \text{ [dB]}$$

The meaning of the symbols is:

v the cavity filling:
- 0 = unfilled cavity
- +5 = cavity filled with mineral wool (1.5 kg/m^2)

s the cavity width in m:
- between 0.04 and 0.075 m
- for a cavity between 0.075 and 0.1 m a maximum of s = 0.075 m

m'' the total mass of the cavity leaves in kg/m^2:
- between 10 and 70 kg/m^2
- maximum of 15 kg/m^2 per board

The following applies for cavity walls with separated framing:

$$D_{nT,A,lab} = v + 20 \log m'' + 30 \cdot s - 32 - 51 \text{ [dB]}$$

The meaning of the symbols is:

v the cavity filling:
- 0 = unfilled cavity and/or $m'' > 30$ kg/m^2
- +3 = cavity filled with mineral wool (3 kg/m^2) provided $m'' < 30$ kg/m^2

s the cavity width in m:

- between 0.07 and 0.2 m

m" the total mass of the cavity leaves in kg/m^2:

- between 10 and 70 kg/m^2
- maximum of 15 kg/m^2 per board

Cavity walls built in-situ

When cavity walls are built in-situ it is easiest to work with separated framing (see figure 12.9). It is important that the flexible character of the wall is affected as little as possible so that there is no negative effect on the acoustic quality.

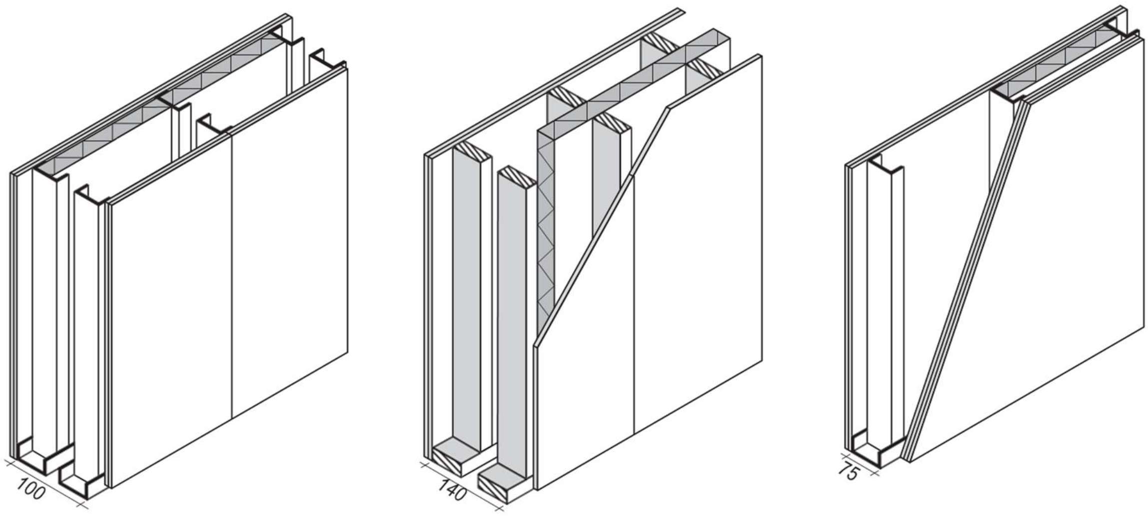


Figure 12.8 Solutions for plasterboard walls $D_{nT,A,k}$ = 52

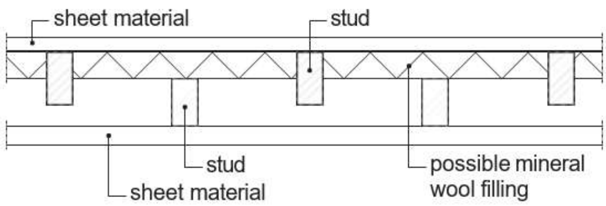


Figure 12.9 Light wall with separated framing

Plasterboard sheets of various thicknesses can be used for cladding. The cavity can be filled with mineral wool to suppress resonations. Polystyrene foam or other 'closed cell' materials are not suitable as they are not porous and therefore do not have any sound absorbing capacity. With this type of structure sound insulation indices of $D_{nT,A} \geq 36$ dB can be achieved in any event. Even better values are possible with careful construction and larger sheet thicknesses (or more layers not connected to each other or not rigidly connected to each other). In doing so the joints between the insulation boards must also be well sealed.

Figure 12.10 Noise reduction wall consisting of metal profiles with springy underlay and finished with plasterboard attached free from the wall

Industrially produced walls

It is going to far to discuss every type of system wall here. The principle is the same as discussed above. When choosing a wall you must not begin only with the value for average insulation between 100 and 3200 Hz that is (often) specified by the manufacturer. It is best to request test reports with the insulation at various frequencies so that the A-weighted sound level difference can be calculated from them. In addition, it must be understood that the measurement data generally represents laboratory values. Because of flanking sound transmission and incorrectly constructed connections values approximately 5 dB lower are easily found in practice. It is generally the case that the walls themselves provide sufficient options for good sound reduction from room to room. The final result succeeds or fails with the design and construction of the connection details.

Noise reduction walls

It is possible to place an extra wall in front of a stony wall. Herewith you can provide better sound insulation for existing walls or limit the transmission of impact sound. The extra walls can consist of boards on framing (see figure 12.10). The usual materials can be used for this (plasterboard, plastered wood wool cement, etc.). Wood or metal profiles are often used for the framework. Noise reduction walls can also be glued against the back wall. Acoustic elements (sheeting and insulation) are attached against the underlying wall with glue dots. Naturally the best results are achieved if the framing is kept free from the wall, of if elastic material is used to fix it to the wall instead of rigid material. Filling the cavity with mineral wool avoids the occurrence of troublesome resonations.

Values as high as $D_{nT,A}$ = 54 dB can be achieved by placing a flexible wall in front of a monolith wall (masonry, concrete) with a mass of $m \geq 200$ kg/m². See figure 12.11 for the improvements of the airborne noise insulation attainable in many situations.

Existing wall Construction	Weight	Noise reduction wall construction	Improvement airborne noise insulation
Cavity wall	400	• metal framework • 40 mm mineral wool • 12.5 mm plasterboard	+1
	400	• metal framework • 40 mm mineral wool • 2 x 12.5 mm plasterboard	+2
Sand-lime brick 265 mm	500	• metal framework • 40 mm mineral wool • 12.5 mm plasterboard	+3
	500	• metal framework • 40 mm mineral wool • 2 x 12.5 mm plasterboard	+3
Half-brick masonry	200	• metal framework • 40 mm mineral wool • 12.5 mm plasterboard	+5
	200	• metal framework • 40 mm mineral wool • 2 x 12.5 mm plasterboard	+6
Concrete 180 mm	400	• 50 mm mineral wool (glued) • 10 mm plasterboard	+6
Gypsum blocks 70 mm	65	• 30 mm mineral wool (glued) • 10 mm plasterboard	+8
	65	• metal framework • 40 mm mineral wool • 12.5 mm plasterboard	+10
	60	• metal framework • 40 mm mineral wool • 2 x 12.5 mm plasterboard	+14

Figure 12.11 Improvement of the airborne noise insulation by applying a detached noise reduction wall in relation to the airborne noise insulation of the existing wall (source: SBR info sheet 388)

12.3 Floor construction

The acoustic quality of floors is an important point for attention, particularly if residential buildings are involved. Impact sound in particular (walking across the floor) can be an enormous source of nuisance and often leads to rows with the neighbours. In addition to the quality of the floor, the floor finish also plays a significant role. Floor covering will have a dampening effect. Hard floor finishes on the other hand (such a parquet, natural stone, etc.) do not provide a positive contribution.

Impact sound insulation of floors

It can be argued that a massive floor starts to vibrate less easily and therefore provides better impact sound insulation (lower $L_{nT,A}$) than a light floor. Floors with a mass of m ≥ 400 kg/m2 (approx. 160 mm of concrete) are needed with requirements of $L_{nT,A} \geq 59$ dB. A number of figures are shown in the table in figure 12.12 as a guide.

	$L_{nT,A}$ [dB]
wooden floor frame with wooden floor and ceiling	approx. 71
bare concrete floor, m = 300 kg/m^2	approx. 63
bare concrete floor, m = 410 kg/m^2	approx. 59
bare concrete floor, m = 490 kg/m^2	approx. 57
bare concrete floor, m = 525 kg/m^2	approx. 55

Figure 12.12 Impact sound insulation of a number of floor types

Roughly the total weight per m^2 (including ribs) can be used for beam-and-slab or caisson slab floors. A covering floor can also provide some improvement. An improvement of 5-8 dB is possible with screed covering floors with cork or wooden fibre as added material. The improvement from floor covering is limited and only thick and special types provide a noticeable improvement. Thin floor coverings (linoleum, PVC, needle punch carpet, etc.) only provide a slight improvement (0–5 dB) for walking sounds. For sound as a result of moving chairs and suchlike, needle punch carpet, for example, can provide a significant improvement. Floor coverings such as cork linoleum, carpet or plastic on a thick backing (foam rubber, waffle backing etc.) can provide an improvement to approximately 15 dB. Thick, deep pile carpets with underlay can provide even greater improvement as can a floating covering floor (approx. 25 dB).

Airborne sound insulation of floors

Heavy floors

In general, few problems occur with the floors that are normally used (concrete). A concrete floor with a mass of m ≥ 400 kg/m^2 usually achieves an $D_{nT,A} \geq 51$ dB. When a higher $D_{nT,A}$ is required, a suspended ceiling can be used which, when well-constructed (see later), has the same effect as a flexible extra wall. However, this effect can only be expected if there is no flanking sound transmission.

Light, stony floors

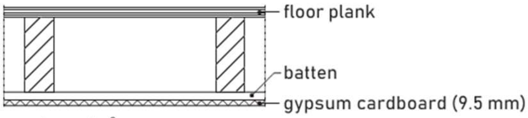
Lights floors (m = 200 to 300 kg/m^2) can comprise thin concrete slabs, light concrete, hollow concrete elements and brick, etc. Suspended ceilings must be used with these where high requirements are set ($D_{nT,A} \geq 51$ dB). This is not necessary for use within a single dwelling ($D_{nT,A} \geq 36$ dB). Flanking sound transmission does not exist, or does not exist to a serious degree, if the connecting walls have approximately the same mass (m in kg/m^2) as the floor, or if they have a greater mass, or if the walls are kept free from the floors.

Wooden floor structures

A number of examples of wooden floors are given in figure 12.13 as a guide.

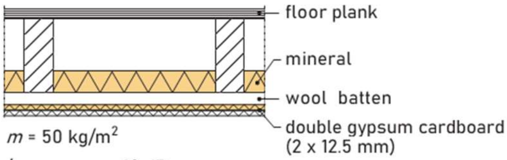
Although adding mass to a floor structure is, in principle, correct from an acoustic perspective, it is often not possible in connection with the permitted load on the beams. In existing situations, it would appear that installing a relatively heavy, free-hanging suspended ceiling is the most attractive solution. If the joints in the floor are well sealed (hardboard sheets, edges sealed etc.) and if sufficient absorbent material is fitted in the cavity, then it may be possible to achieve values a few decibels higher than those mentioned here. Suspended ceilings are dealt with in greater detail later. A wooden floor is also not attractive from the impact sound insulation perspective. Both aspects of sound insulation mean that a wooden floor cannot meet the requirements for a dwelling partitioning floor ($D_{nT,A} \geq 51$ dB). A free-hanging suspended ceiling is, in fact, a requirement even for rooms within a dwelling.

Much lower values than those indicated here can be found in practice due to the gaps between the parts of the floor and in the connections between the floor and the walls. Another solution for improving the sound insulation of a wooden floor is the use of a stony, floating covering floor (cast floor). Floating covering floors are discussed later on.



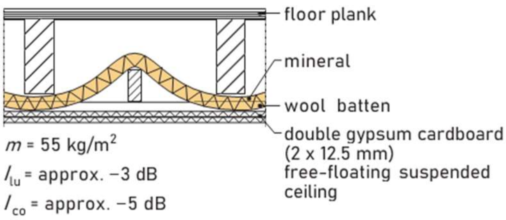
m = 35 kg/m^2
I_{lu} = approx. −15 dB
I_{co} = approx. −20 dB
$D_{nT,A}$ = approx. 36 dB
$L_{nT,A}$ = approx. 79 dB

1



m = 50 kg/m^2
I_{lu} = approx. −12 dB
I_{co} = approx. −13 dB
$D_{nT,A}$ = approx. 39 dB
$L_{nT,A}$ = approx. 72 dB

2



m = 55 kg/m^2
I_{lu} = approx. −3 dB
I_{co} = approx. −5 dB
$D_{nT,A}$ = approx. 48 dB
$L_{nT,A}$ = approx. 64 dB

3

Suspended ceilings

With the aforementioned suspended ceilings we can expect the following improvements for the various construction types (the figures apply in the absence of flanking sound transmission and other leaks):

- Porous boards (wood wool cement, mineral wool, etc.) can provide an improvement of 3-5 dB.
- System ceilings with somewhat thicker panels that fit closely into the suspension structure provide an improvement of 3-8 dB.
- Closed ceilings, suspended, not fitted to the floor or with an elastic fitting to the floor and with a sufficiently high mass ($m \geq 5$ to 10 kg/m^2) provide an improvement of 10 to 15 dB with a reasonable cavity height (≥ 0.2 m).

With a narrow cavity (plasterboard on a cavity of 30 to 50 mm) resonations can occur that actually decrease the sound insulation at some frequencies (see section 11.1).

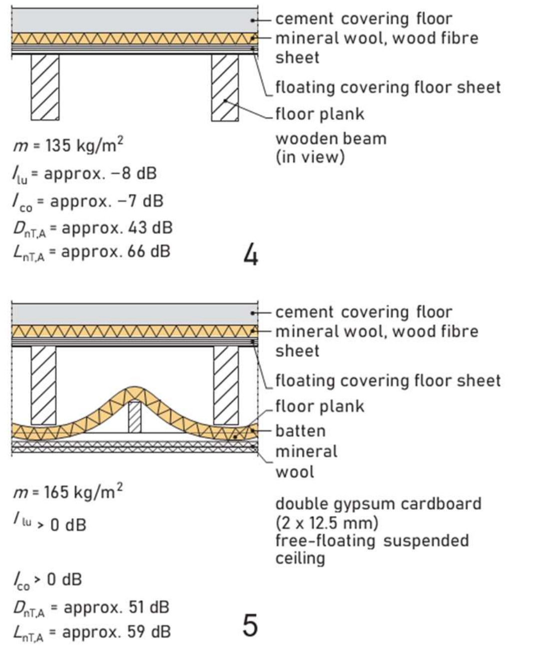


Figure 12.13 Guide to sound insulating properties of wooden floors. Naturally the sealing of the joints and gaps and any flanking sound transmission have a significant effect on the final result. As a reference the (older) I_{lu} and I_{co} values are also given.

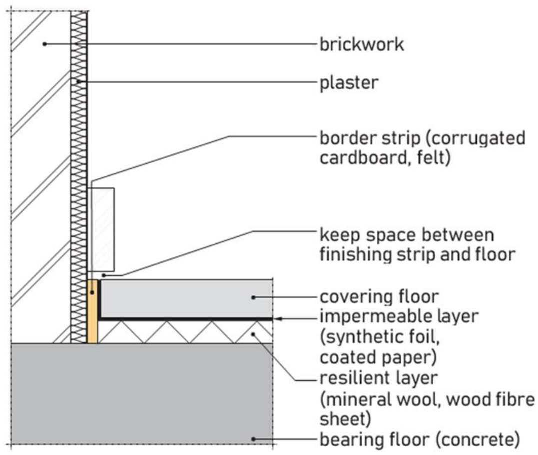


Figure 12.14 Floating covering floor

Floating covering floors

A floating covering floor is kept fully free (using elastic materials) of all surrounding structures (see figure 12.14). Three different systems can be distinguished:

- wet systems with cement or calcium sulphate bonded (anhydrite) covering floors (most used)
- dry (light) systems made from wood or (fibre-reinforced) plasterboard with insulation on the underside
- the constructional floating floor comprising a profiled metal sheet with a covering floor of fine concrete.

The light (dry) systems generally provide less insulation ($L_{nT,A}$ = 52-54 dB) than the heavy (wet) systems ($L_{nT,A}$ = 45-49 dB). The rigidity of the elastic layer is a very significant factor. The lighter the supporting floor, the softer the elastic layer has to be. In addition, the insulation must again be so rigid that it can accept the loads without overly large deformations occurring.

Sheets of the following are suitable as materials: mineral wool in a special, fairly dense pressing, elasticised polystyrene foam, specially intended for acoustic floating floors, foam, specially intended for floating covering floors, soft flake foam, cork, etc. Other organic materials can also be used. The thickness of the insulation material must be 15 to 25 mm in a compressed state. Smaller thicknesses only have a marginal effect or no effect.

The waterproof layer is of great importance in preventing cement water penetrating the elastic layer. This could lead to the formation of sound bridges. Their influence is shown in the table in figure 12.15.

	Improvement [dB]
floating covering floor	approx. 25
with one sound bridge	approx. 15
with ten sound bridges	5–10

Figure 12.15 The effect of sound bridges in floating covering floors

The conditions for a good floating covering floor are:

- The base must be smooth. If this is not the case the substructure must still be evened out.
- The floating covering floor, including floor finish, should be kept fully free of the rising structure (walls and facades). Sound bridges at the connection to a wall may influence the improvement in the frequency range from approximately 1000 Hz. For this reason, a thinner (more rigid) elastic layer can suffice (corrugated cardboard, polystyrene foam sheet 2 to 3 mm thick, etc.). There will be a small decrease in the insulation over time because of aging of the elastic layer.

In practice, however, this does not appear to amount to more than 3 to 4 dB, if, at least, good material is used and the elastic layer is not trodden 'mushy' during construction.
- The plinths must be kept free from the floating covering floor, including finishing.

12.4 Circulation noise

In addition to the flanking sound transmission that was described in section 11.1 there is also the so-called circulation noise. Here we must consider:
- sound via other rooms
- sound via connecting details
- sound via a suspended ceiling
- sound via coves, unit housings and suchlike
- sound via air ducts.

The latter two types of circulation travel via installations. These are dealt with in the following section.

Sound via other rooms
The sketch in figure 12.16 shows how sound can still reach the adjacent room via roundabout routes.

A good partitioning wall between two office rooms is of little use if there is any serious degree of circulation noise. Two doors that are close to each other in the corridor wall can undo good sound insulation if they are not provided with reasonable gap sealing (thresholds are often not used). The same applies for ventilation provisions that are close to each other or windows that can be opened in the facade (particularly in the direction of rotation drawn). Because of this, it is often possible to hold a conversation from one room to another without raising the voice.

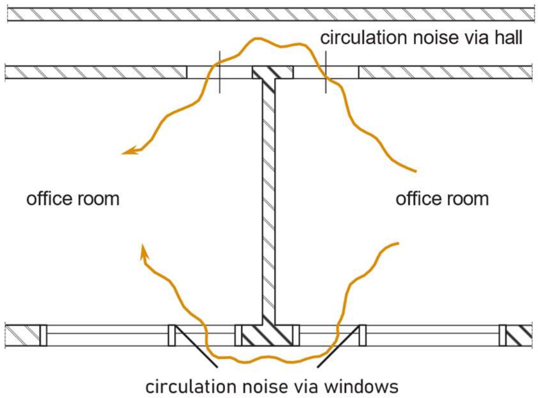


Figure 12.16 Circulation noise via windows and doors

Sound via connection details
Connection details often lead to all kinds of sound leaks. A common shortcoming is found in the connection between a common wall and a facade, such as shown in figure 12.17. Adding mineral wool and sound air sealing of the connection between the frame and the wall can significantly improve the sound insulation (see figure 12.17-2).

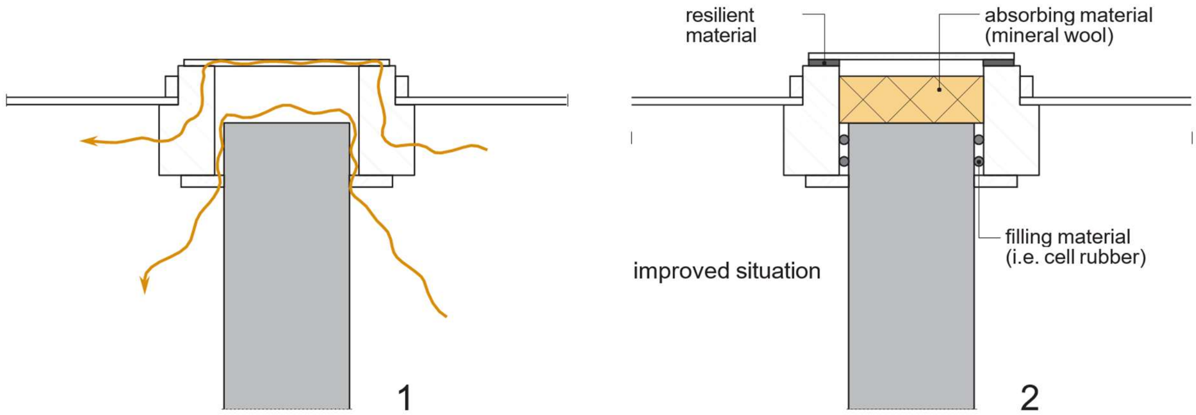


Figure 12.17 Sound leaks and flanking sound transmission at the joint of facade ends to the common wall

Another example is the connection of a light partitioning wall to a concrete beam, as in figure 12.18. A good connection between wall and ceiling is created using a strip of multi-ply. The sound that penetrates the very porous wood wool cement sheet will however, find an easy route to the other room via the remaining gap.

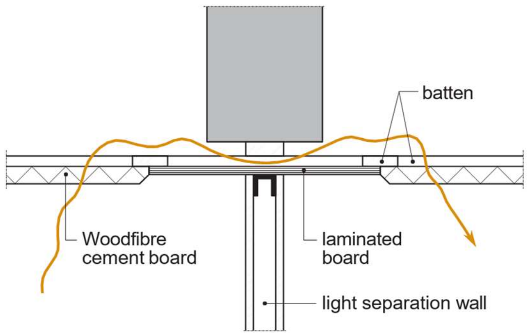


Figure 12.18 Circulation noise at the connection between a light partitioning wall and a ceiling and concrete beam

Sound via a suspended ceiling

Figure 12.19-1 shows how sound can enter the other room via the space above a suspended ceiling Sometimes it is desirable to connect movable partitioning walls to a suspended ceiling, in connection with flexibility within the building. In the first instance direct gaps (route A) must be avoided when doing this.

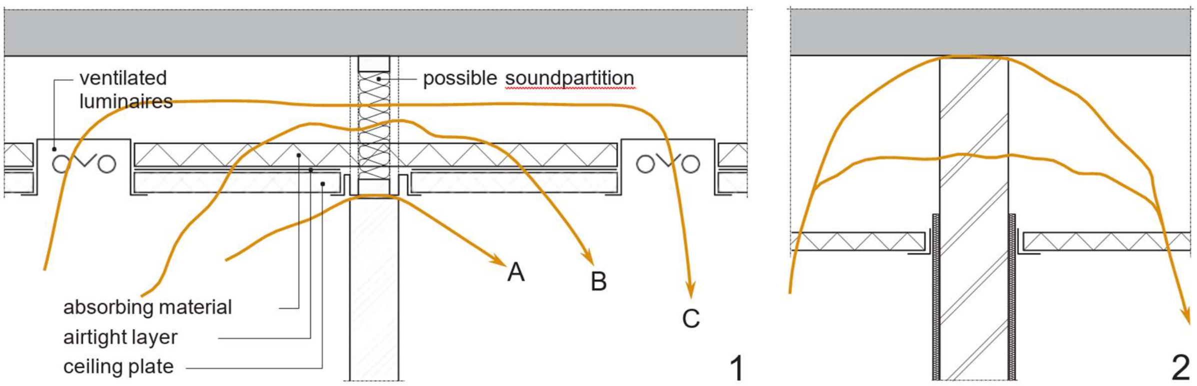


Figure 12.19 Circulation noise above a suspended ceiling

Keeping circulation noise via route B within limits is not so simple. Only very massive ceiling panels that have good connections to the supporting profiles will be able to achieve reasonable sound insulation. In doing so the cavity must not be higher than approximately 0.3 m. In addition, a large amount of absorbent material has to be fitted in the cavity. Furthermore, an airtight layer, which can be combined with a ceiling panel or with the absorbent material, is required. It is still, however, difficult to meet a requirement of $D_{nT,A} \geq 37$ dB as has been set for office rooms. Sound via route C can be avoided by fitting light fittings with sound damping shades or by connecting them directly (via acoustic damping hoses) to an air duct. The best method is still to continue the wall through to the bottom of the structural floor or by placing a sound baffle or a 'silencer' between the ceiling and the bottom of the structural ceiling These additions are certainly necessary if requirements of $D_{nT,A} \geq 41$ dB are set.

Problems can also occur with stony partitioning walls, as can be seen from figure 12.19-2. When the plaster layer above the ceiling is not continued through there is a significant risk of a porous wall. Often the backing up against the structural floor is not properly airtight. Significant sound leaks can then occur in a ceiling that is not soundproof (mineral fibre tiles or suchlike).

12.5 Construction of installations

Sound via coves, unit housings and suchlike

A familiar sound leak is the leak from one room to another via continuous coves, cable ducts, unit housings and suchlike (see figure 12.20). This type of though-channel must be sealed in every partitioning wall with a baffle. In the case of a cable channel, it is sometimes possible to fill a piece with mineral wool along a length of approximately 0.5 m.

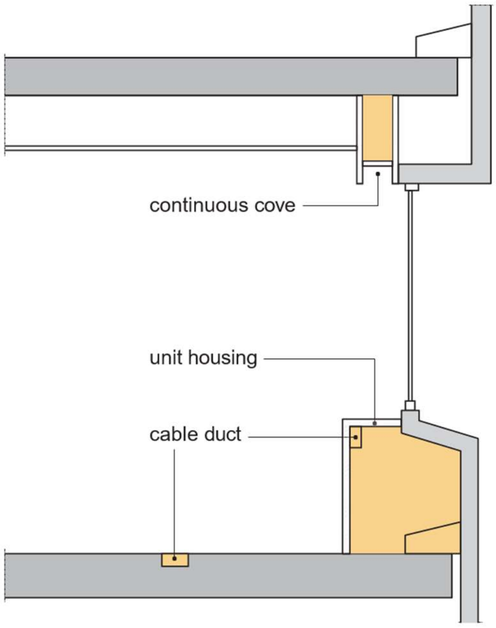


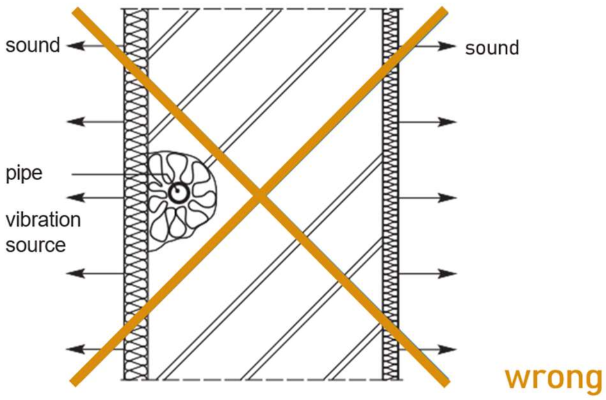
Figure 12.20 Circulation sound via through-coves, unit housings and suchlike

Sound via air ducts

When a room is connected to an air duct sound transmission to the adjacent room can occur via this duct. Often the grids have to be connected to the duct using acoustically dampened hoses or sound absorbers have to be included in the system.

Pipes and sanitary fittings

Water carrying pipes and sanitary fittings must be connected to the walls and floor in such a way that the noise nuisance from vibrations transmitted directly to the structure is avoided. 'Cutting' pipes into the walls of sound sensitive rooms is therefore not a good solution (see figure 12.21-1). It is best to use acoustically dampened fixing materials for fixing pipes, as in figure 12.21-2. Nothing should be fitted to the walls of sound sensitive rooms (such as a toilet next to an office room). In addition, it is important to pay attention to the sound production when selecting fittings. There are many 'low-noise' fittings.



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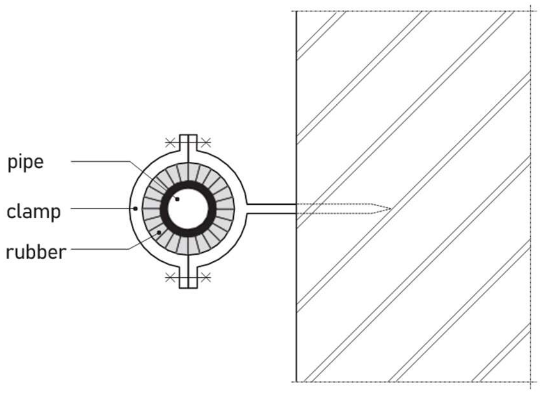

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Figure 12.21 Transmission of sound by a pipe fitted into a wall (1) and a pipe fitted to a wall using a proper acoustic fitting (2)

Feeding-through pipes

Pipe feed-throughs through floors and walls often cause sound leaks (airborne sound) and the transmission of impact sound. The pipe must not be in contact with the floor and leaks must not occur (see figure 12.22-1).

Naturally loose rosettes hardly form a seal at all. The opening between the pipe and the pipe sleeve can be sealed by including cast in situ feed-through casings to which a covering rosette can be screwed (see figure 12.22-2). It is also possible to ensure a permanent seal using sealant and mineral wool (see figure 12.22-3). Additionally, a seal by injecting plastic foam is a good option (see figure 12.23). Other solutions are also possible, all kinds of special feed-through casings can be obtained from the trade.

Machines

Most machines are fitted with appropriate vibration dampers in the factory to prevent impact sound. Details about the sound production must be requested in order to determine the airborne sound insulation requirements that have to be set for the surrounding walls of the rooms in which these machines are set up.

The examples quoted above are certainly not exhaustive. We have only tried to show that good sound insulation requires continuous attention to detail both in the design and in the implementation.

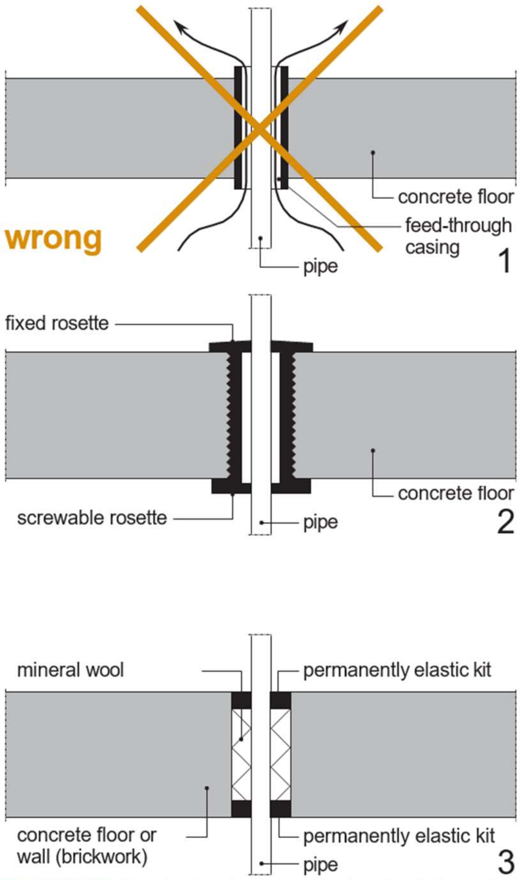


Figure 12.22 One bad and two good pipe feed-throughs

Figure 12.23 Pipe feed-throughs can often cause sound leaks. In this case the feed-throughs have been sealed using (injectable) plastic foam.

13 Fire safety

R.H.P. van Herpen; A.C. van der Linden;
T.A.J. Selten

In order to be able to construct fireproof buildings and to use buildings safely, first it has to be determined what 'safe' is.

Constructing buildings 'even more safe' is not always achievable. Limiting factors can be the costs involved, but also the ease of use, flexibility and durability. What, then, is sufficiently safe and which measures must be taken to ensure this? Which ones are worth considering and which go 'too far'? After all, fire hazards are always present in buildings, leaving aside unused and therefore empty bunkers. The trick is to curtail these hazards sufficiently.

This chapter deals with how fire safety is regulated in the Netherlands, what fire means exactly and what the points of departure are for protecting people, offering means of escape and preventing fire damage.

In the Netherlands, building owners are the ultimate party responsible for the safety situation in the building. They therefore also have a duty of care for fire safety. Building regulations of course provide for basic requirements for fire safety, but designers and consultants have to work out the exact performance requirements and the ideas in respect of fire safety for each individual case.

The rules and regulations address the limitation of risk of casualties with regard to the users of the building, emergency and medical workers, and bystanders and the limitation of damage to the environment. Damage control to buildings or inventory is a matter for the owner and users of the building.

Fire safety is of such complexity that prescribing individual measures is not sufficient. The aim of this chapter is to provide a first introduction to fire safety. In practice, fire safety construction has developed into Fire Safety Engineering. Here, use is made of physics models of how a fire develops and models for simulating escape routes for people in a building. There is, after all, no standard fire and no standard response of people and structures to a fire. Based on the results of these studies, i.e. the risk analyses, the evaluating authorities can decide whether the proposed provisions meet the functional requirements laid down in the rules and regulations. For further information regarding Fire Safety Engineering, visit www.klimapedia.nl.

13.1 Fire safety in rules and regulations

Rules and regulations differ from one country to another and also develop in time. At a European level a general framework is available and several directions and standards exist for testing separate materials and structures for fire resistance.

Limiting fire spreading

In the Netherlands, a building is divided into fire compartments no larger than 1000 m^2 floor area. This should limit the speed with which fire can spread. Resistance against fire penetration and fire spreading from one compartment to the next must therefore take at least 60 minutes. If a sprinkler installation is present which is activated automatically in case of fire, it is not necessary to divide a building into compartments in order to remain in control of the fire. For existing buildings, and in particular in case of their renovation or adaptation, explicitly specified (limited) exceeding of the compartment size is allowed.

Safe use of the building and possibilities of escape

In order to make it possible to make use of a building in a fire safe way, attention must also be paid to fire safety installations (fire and smoke detectors), accessibility of the building by emergency services and of course to the lay-out of the building. This includes special precautions such as for the storage of hazardous materials. Providing safe escape routes is also of major importance. The escape routes must be properly accessible and it must be made impossible to become locked in. This means that there must always be two possibilities of escape. Additionally, the escape route must offer plenty of resistance against fire in the surrounding area and must be sufficiently smoke free. Rules and regulations specify minimum requirements for these matters and sometimes even certain solutions.

13.2 How a fire originates

Combustion is oxidation of a material at high temperatures, releasing heat. This is called an exothermic reaction. Combustion requires:

- the presence of fuel;
- sufficient supply of air for the required oxygen;
- fuel at combustion temperature;
- environmental conditions which keep the fire going as a progressive chain reaction.

If one of these conditions is missing, the fire will die: these are the principles on which fire prevention and firefighting are based.

Fuels can be divided into the following categories:
- solids (for example wood, fabric, carpet, asphalt, synthetic materials);
- liquids (for example oil, petroleum, methylated spirits, alcohol);
- gases (for example natural gas, mine gas, carbon monoxide);
- aerosols or dust particles (for example sawdust, soot).

The products created by combustion are:
- heat (flames);
- combustion gases (CO_2, CO, H_2O, SO_2, etc.);
- smoke in the event of incomplete combustion (soot, aerosols).

Smoke hinders vision and can be dangerous, because you will no longer be able to find your way around. Combustion gases (including smoke) are suffocating and generally hot. Any carbon monoxide present will bind with red blood cells and hinder oxygen uptake.

In the course of the fire the following phases can be distinguished:
- the smouldering phase (before the fire turns in to actual open flames);
- the creation of the fire (at time t = 0);
- the development phase of the fire until the moment of flash-over at the location of the fire;
- the completely developed fire created after the flash-over;
- the dying down phase which occurs after time has elapsed as a result of fuel deficiency or active withdrawing of fire capacity (extinguishing).

The first phase is called a fuel-controlled fire. There is no shortage of oxygen and with enough fuel, the fire will spread in all directions with equal speed. At the top of the entire space, a hot zone develops which heats the space in its entirety. The temperature in the room increases until all combustible materials in the room catch fire spontaneously, regardless of the distance to the seat of fire. This phenomenon is called flash-over. This causes the local fire to change into a compartment fire with all available combustible fuel taking part. From this moment on, the fire capacity is determined by the amount of oxygen which can gain access to the compartment via windows, doors or other openings. There is usually not enough air supply to let the fire burn unrestrainedly. Due to lack of oxygen, there is no complete combustion causing partially burned, combustible gases to be produced. When these partially burned gases are released from the compartment they will catch fire because of the oxygen present outside the compartment and the released gases are so hot that they contain enough energy for spontaneous combustion. This combustion phenomenon creates a conflagrant fire. When the fuel runs out, the dying down phase sets in. In the dying down phase the fire capacity reduces to zero and this is what determines the entire duration of the fire. The fire compartment has of course not yet cooled down to the starting phase (environment temperature). Depending on the structural features of the fire compartment, this will take some considerable cooling down time. Figure 13.1 shows the course of the temperature during the entire fire.

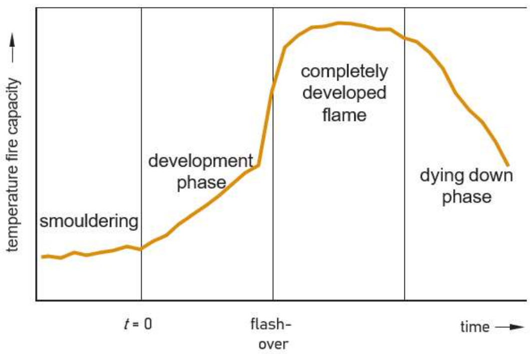


Figure 13.1 Example of a fire process in the case of fire in a room

13.3 Fire penetration, fire spread and strength of buildings during fire

Fire always seeks a way outside and in doing so, tends to move sideways and upwards. Another feature is that it is able to spread itself by moving through small openings.

The term WBD (*Weerstand tegen BrandDoorslag,* Resistance to Fire Penetration) refers to the level of fire spread resistance of a partition between two adjacent rooms (see figure 13.2). The term WBO (*Weerstand tegen BrandOverslag*, Resistance to Fire Spread) refers to the level of resistance against fire spreading via the outside air. In general, this concerns the spread of fire as a result of flames breaking out.

The WBDBO (*Weerstand tegen BrandDoorslag and BrandOverslag*, Resistance to Fire Penetration and Fire Spread) is the total resistance against the spread of fire between two rooms, via both the partition constructions in the building and the outside air. If a wall has a WBDBO of 60 minutes, this means that the wall (the partition construction) is able to resist fire for 60 minutes. The WBDBO of materials and constructions can be determined in a laboratory fire experiment. To be able to create clearly defined parameters when determining fire-resistant qualities, the so-called standard fire curve is used (standardised fire). It is not only the time needed for the flames to penetrate the partition (the flame density) that is looked at during the test, but for example also the temperature of the partition construction during a fire. With walls that are subject to a WBDBO requirement, extra attention should be paid to holes and openings for air channels, electricity and data cables, pipes and so on. These openings can affect the WBDBO and should all be fitted with fire-resistant elements. For air channels this should be a fire flap, and in the case of holes used for cables and so on, some sort of fire-resistant material should be considered. Without taking these measures there would be no point in having a fire- resistant wall, as a fire will always seek the route of least resistance in order to spread. Considering that the temperature of the centre of a fire can get as high as around 1100 °C, it hardly needs stating that the relevant fittings must be properly designed and installed. As far as the actual work is concerned, it is sensible to have the supplier issue a completion certificate, which can be used subsequently to show that the conditions have been met. Whenever fire doors are fitted, the supplier must always issue a completion certificate. The WBDBO between two rooms can be calculated. Figure 13.3 has a diagram showing the routes and components that need to be borne in mind when calculating the WBDBO between room A and C.

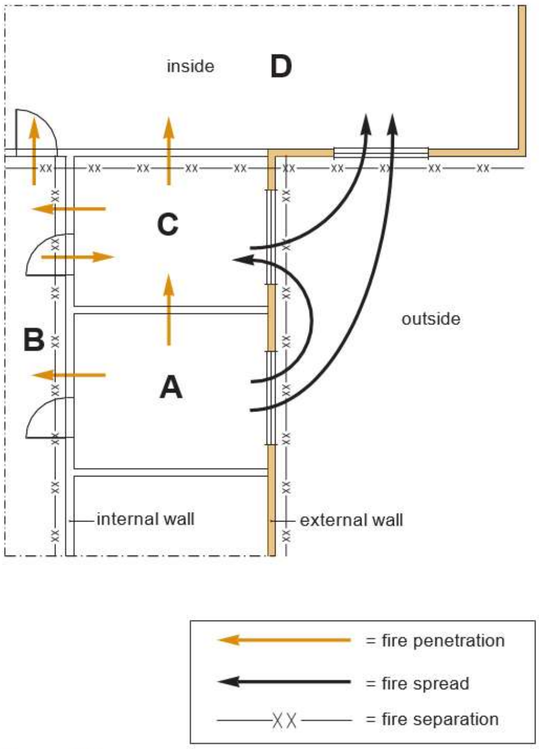


Figure 13.2 Fire penetration and fire spread

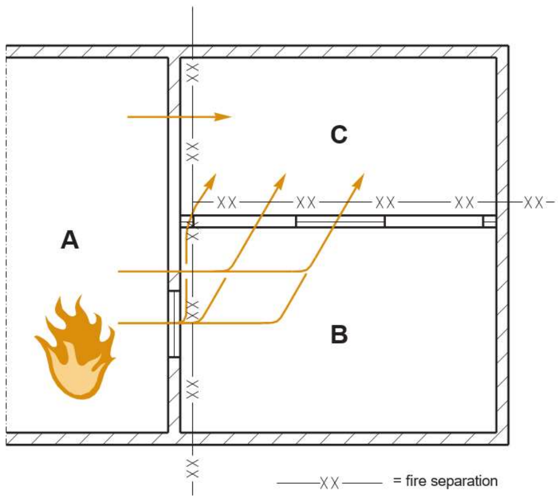


Figure 13.3 Influences in determining the WBDBO

Risk of fire spreading

The greater the distance from the fire, the smaller the risk that it will spread. It can be compared to a campfire situation. The level of radiation reduces, the further the distance from the fire. The limit to the intensity of the heat radiation that is used for determining the risk of fire spreading is 15 kW/(m². As an illustration, the level of total heat radiation in direct sun (UV, visible light and infrared) on a hot summer's day is about 0.8 kW/(m².

Based on the general rules of thumb, the following distances can be taken (see figure 13.4):

- Within a total in-between distance of 5 m, flame contact will occur and fire-resistant measures are necessary.
- Within a total in-between distance of between 5 and 15 m the fire spread risk has to be calculated based on methods given in standards. Software programs are available for this.
- If the total distance is greater than 15 m, then there is in principle no risk of fire spreading.

Mirror symmetry

The legal regulations include a method for defining, at the design stage, the risk of fire spreading in cases where no information is available about any other constructions on adjacent plots of land. This method is known as mirror symmetry and assumes that a mirror image of the same design of building is present on the boundary of the neighbouring plot of land. If, for example, a building is erected along the outer edge of its plot of land, it should have a total WBDBO of 60 minutes. However, according to the mirror symmetry method, this total can be divided over both future buildings that may be put up on either side of the boundary, in which case a WBDBO of 30 minutes will suffice. By building say, 7.5 m from the edge of the site boundary (and therefore 15 m from a mirror symmetry point of view), the chance of fire spreading through radiation is virtually impossible and no extra measures will be necessary.

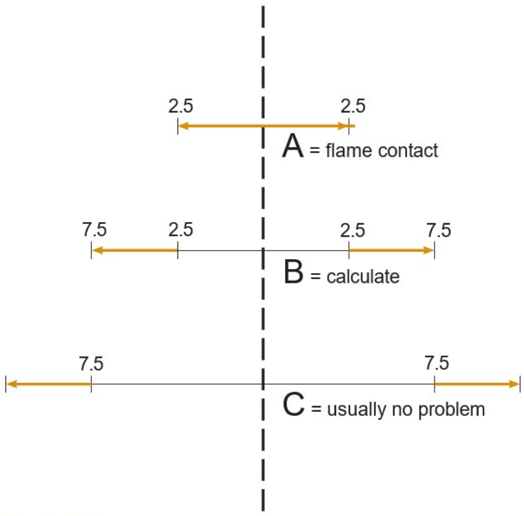


Figure 13.4 Influence of the total in-between distance on the risk of fire spreading

Strength of buildings during fire

A building has to be able to remain standing for a period of time when it catches fire, as any collapse would represent an additional danger to any people still present, and to fire fighters.

The requirements with regard to the strength of a building during fire are aimed at the main load-bearing structure. This comprises structural components that, when they give way, can cause the building (or part of it) to suffer a progressive collapse (see figure 13.5). An example of a progressive collapse is that of the Twin Towers in New York. Because the main load-bearing structure was weakened, both buildings collapsed. The requirements set for the capacity of the load-bearing construction in the event of fire depend on the height of the building. The strength of a high rise residential building will have to be such that an entire floor can burn down, while the load-bearing construction remains intact. The duration that the load- bearing construction must remain intact during a fire varies from 30 to 120 minutes. Of equal relevance to the requirements relating to the main load-bearing construction is the permanent fire load of the building. This is the amount of heat

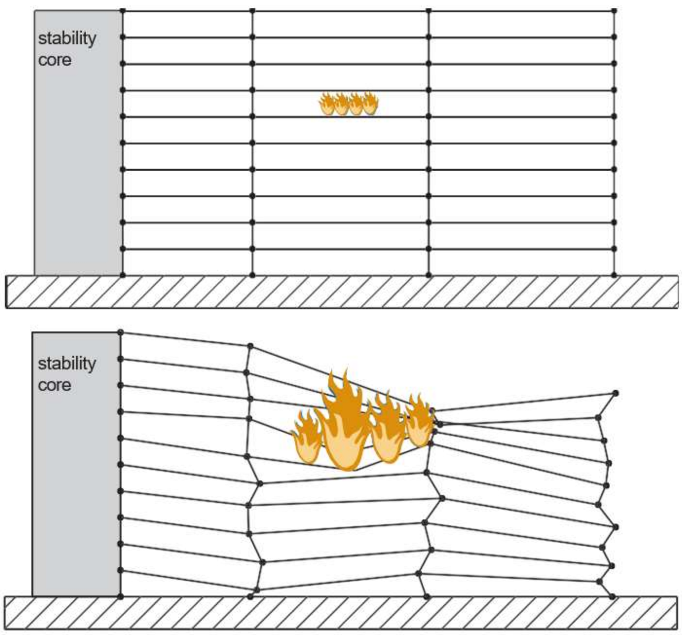


Figure 13.5 Progressive collapse of the main load-bearing construction

that is released for every m² of floor surface when the materials that were used in the construction of the building, burn. Some requirements for buildings that contribute little to the permanent fire load may be reduced. The limit is a permanent fire load of 500 MJ/m^2. If this is exceeded, then a reduction of the requirements is not permitted. The fire load is often expressed in kg/m^2 pine equivalent. In this case, 1 kg/m^2 is equal to 19 MJ/m^2. A fire load of 500 MJ/m^2 as an example equals 25 kg pine wood per m^2. A permanent fire load of less than 500 MJ/m^2 corresponds with a construction primarily made of concrete, stone and steel. As soon as wood or other flammable material is used in wall units or load-bearing elements, the limit of 500 MJ/m^2 is quickly exceeded. Another area of attention here is the fire load of the roof covering.

13.4 Fire compartmentalisation and escape routes

The first aspect to be looked at when it comes to fire safety is that of fire compartmentalisation. Apart from the odd exception, a fire compartment may not be any larger than 1000 m². This means that on premises where two buildings are situated with a surface area of 400 m², no separate fire compartmentalisation is necessary, as the maximum of 1000 m² would not be exceeded. The WBDBO between fire compartments should be 60 minutes, though it may be possible to reduce this if the building is no higher than two storeys. If that is the case, the WBDBO can be lowered to 30 minutes. When designating the fire compartments, it is important they do not include any smoke and fireproof escape routes. In addition, only self-closing doors may be installed in internal, fire-resistant partitions. The use of doors held open by electronic magnets is allowed as long as the power to the magnet is cut by the fire alarm when activated, causing the door to close automatically.

Fire sub-compartments

A next step on from fire compartmentalisation is that of fire sub-compartmentalisation. This is a sub-division within a fire compartment and is used in buildings where people sleep, but who are not able to bring themselves to safety, or who are dependent on others for doing so. The extra level of protection that this sub- division produces is intended to strictly limit the opportunities a fire has of spreading, in relation to how the building is used. Containing the fire even more rigorously means there are more possibilities for people to escape or for putting the fire out.

Escape possibilities and smoke compartmentalisation

The second aspect concerns the evacuation of people from a threatened area to a safe location. It is well known that most casualties in a fire are caused by suffocation due to the expulsion of oxygen by smoke. For that reason, criteria have been drawn up to judge whether a person is able to escape in time from an environment threatened by smoke. The general rule of thumb is that people can hold their breath for 30 seconds and cover a distance of 30 m, walking at a speed of 1 m per second, to the exit of a so-called smoke compartment, from which point they should be able to escape via a smoke and fireproof emergency exit route.

A smoke compartment is always situated in a fire compartment. A fire compartment can contain one smoke compartment, but also two or more. The boundary of a smoke compartment must be smoke resistant. The smoke resistance of a construction is 1.5 times its fire resistance, so that a WBDBO of 20 minutes is equivalent to a smoke resistance level of 30 minutes. Smoke compartmentalisation for public buildings can be done on the basis of general regulations. The maximum allowed length of the escape route depends on the occupancy factor of the building. In most cases, 30 m per partitioned room applies. For areas that are not sub-divided (such as an open-plan office), this value should be divided by a factor of 1.5. The maximum length of the emergency escape route would then be 20 m. For open-plan offices and other rooms that are not sub-divided, it is easy to establish whether the requirements are being met by ‘drawing’ a circle with a 20-metre radius from the access point to a smoke compartment. This will make clear quite quickly if the basic structure creates any bottlenecks. In applying this method, it should be borne in mind that people will have to walk round construction features, and that mezzanines are not accessible. Design bottlenecks tend to occur where there are corridors that do not lead anywhere, or when there is only one escape route available. Additional legal requirements apply in such a situation. By working on the basis that a building has two escape routes as standard, it is much easier to comply with safety requirements. For the construction of houses it is important to ensure that the room that is furthest from an emergency escape door is located no more than 15 m away. Also, the rooms through which the escape route passes must have fire alarms connected to the mains.

Escape routes

An escape route must be safe enough for people to be able to escape by. The escape route runs from the point at which it is accessed from the smoke compartment to when it reaches a public highway. In principle, it should be possible to escape in two directions, or there should be two separate escape routes available from any smoke compartment. If this is not the case, then the rules allow for exceptions – with corresponding restrictions – whereby use can be made of escape routes that coincide. Should there be just one stairwell that will be used by more than 25 people, then it must be smoke and fireproof. This also applies to stairwells higher than 8 m. A feature of a smoke and fireproof stairwell is that it should have a WBDBO of 60 minutes in relation to the rooms in the building. Separate rules apply to doors. A door can open in three directions: in the same direction as the escape route, against the flow of those escaping, or sideways (as a sliding door). No more than 25 people may be situated behind a door that opens against the flow of people escaping. If there are more people than this, there is a danger that the door cannot be opened because of the sheer numbers pushing forward in their panic to escape. A sliding door that is used on a daily basis can be considered as a door that opens in the same direction as the escape route, as the people present will be familiar with the door. Escape route doors that are only used in emergencies may not be sliding doors.

13.5 Measures for limiting and fighting fire

In this section we will discuss the measures which relate to limiting the development of a fire and fighting already developed fires. The latter mainly concerns the accessibility of the seat of the fire for the fire brigade and the possibilities of firefighting.

Restricting the fire and smoke

Depending on their specific location, structural components should be such that they do not help the fire spread in any significant way. The degree by which materials enable fire to spread is divided into five categories. Category 1 materials are those that make a very minor contribution to the spread of fire, while those in category 5 contribute very strongly. There are also requirements relating to smoke. Clearly, materials used in the construction of smoke-proof or smoke and fireproof escape routes are subject to more stringent requirements than the materials used in rooms, offices, etc. The requirements also make a distinction between structural components on the exterior and interior of the building. In the case of the former, extra requirements apply with regard to the fire spread category from a height of 13 m upwards, as the average fire engine hose will not reach beyond this height (see also figure 13.6).

Because of the risk of vandalism, the first 2.5 m of the outer walls of buildings with a floor (where people live or work) higher than 5 m must be constructed with material from category 1 (i.e. those that hardly contribute to the spread of fire). This prevents high buildings from catching fire on the outside as a result of the actions of arsonists.

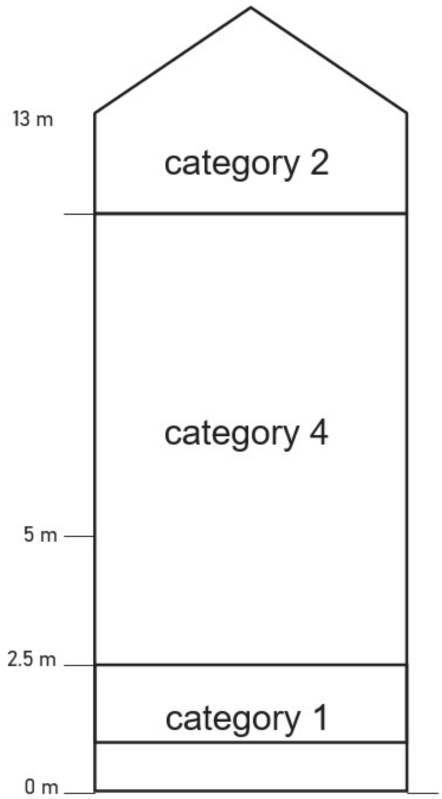


Figure 13.6 Fire-spreading category requirements of outdoor construction materials

Naturally, fire safety installations play an important role in the safe use of a building. This applies especially to fire detection and fire alarm installations, which have to ensure a timely alarm and start of the firefighting. It is remarkable that no requirements are included in the rules and regulations for active fire control installations (such as a sprinkler system) and active smoke detection. The reason for this is that active fire and smoke control installations are generally not necessary. Rules and regulations assume passive (structural) solutions for controlling fire and smoke. Only in the event of large fire and/or smoke compartments, active fire and smoke control installations can be applied as equivalent safety measures. The rules and regulations do, however, ask for regular inspection of the provisions.

It is also of great importance that it is clear to everyone what type of building they are dealing with and where certain provisions are located in the building. This is not just important for evaluating the safety situation in advance, but also for emergency services. This concerns the following general matters:

- the size of the plot, the construction and the locations;
- specification of the gross volume and the gross surface area of the building;
- the purpose of the building (designated uses) and the corresponding surface area;
- the designated use of each room (populated areas, populated rooms, functional area, functional room, control room, etc.);
- number of people for each room and the escape route;
- drawings (maps, facades, cross-sections and details) along with dimensions.

With regard to fire safety the following must additionally be indicated:

- accessibility of the building, the location of water for fire extinguishing and location for fire trucks (for large plots);
- the combustion properties of used materials;
- the (sub)compartmentalisation (including the WBDBO: 20, 30 or 60 minutes);
- the fire resistance of the construction;
- the direction in which the movable construction parts rotate (in relation to the escape route);
- drawings and/or calculations of specific measures and constructions in the building.

With regard to installation components the following must be specified:

- the location of dry risers and connection points;
- the location of fire hose reels;
- the location of fire brigade lifts;
- the escape route signs;
- the emergency lighting.

Dealing with fire

When a fire is starting it is important that action can be taken quickly. If fire hose reels have been installed, people who are on the spot will be able to combat a fire in its early stages. To ensure that fire fighters can perform their tasks properly, requirements are in place for the design of buildings higher than 20 m:

- In order to be able to quickly tackle a fire that is high up, the fire service has to have a fire lift at their disposal. Additionally, the walking distance from the lift and an escape stairwell to a smoke compartment or smoke sub-compartment should be limited in order to enable the fire fighters to do their work quickly.
- In order that no time is lost pulling fire hoses up to great heights, so-called dry risers must be installed. These are pipes that run vertically from the ground floor to the higher floors which can be used by fire fighters for pumping water upwards. They can then attach their hoses to the pipes.

Register

Building Physics
tables and formulas

See also www.klimapedia.nl.

Climate data

Outdoor climate
(Adapted from data of KNMI in De Bilt)

Table 1 mentions the monthly averages in De Bilt for:

- temperature ($\overline{T}_e$)
- vapour pressure ($\overline{P}_e$)

Table 1
Monthly averages in De Bilt of temperature and vapour pressure

month	$\overline{T}_e$ °C	$\overline{P}_e$ (Pa)
january	3.1	650
february	2.3	650
march	6.2	720
april	9.7	855
may	13.1	1095
june	15.6	1316
july	17.9	1525
august	17.5	1575
september	14.5	1375
oktober	10.7	1095
november	6.7	860
december	3.7	715

See also www.knmi.nl.

Indoor climate
For various climate classes, the average vapour pressure during winter months ($\overline{p}_{iw}$) and the corresponding relative humidity at 20 °C (φ_{iw}) can be indicated.
This division in climate classes is done according to SBR publication no. 51.

I $\overline{p}_{iw}$ = 700 Pa; φ_{iw} = 30% (if heated): buildings with negligible moisture production, such as sheds, garages and store rooms

II $\overline{p}_{iw}$ = 935 Pa; φ_{iw} = 40%: buildings with minor moisture production, such as dwellings, offices and shops (all without humidification)

III $\overline{p}_{iw}$ = 1170 Pa; φ_{iw} = 50%: buildings with higher moisture production, such as schools and retirement homes, and buildings with minor humidification

IV $\overline{p}_{iw}$ = 1400 Pa or above; φ_{iw} = 60% or above: buildings with major moisture production, such as laundries, swimming pools and dairy plants, and buildings with major humidification, such as printing houses and texile mills

Heat and moisture

Global approximation of interstitial condensation in the winter period

$$m = \frac{100}{\Sigma\mu \cdot d} \text{ [g/m}^2\text{] for climate class I}$$

$$m = \frac{600}{\Sigma\mu \cdot d} \text{ [g/m}^2\text{] for climate class II}$$

$$m = \frac{1000}{\Sigma\mu \cdot d} \text{ [g/m}^2\text{] for climate class III}$$

The meaning of the symbols is:

m amount of condensing moisture during winter in g/m^2

$\Sigma\mu \cdot d$ the sum of the $\mu \cdot d$ values from the inner surface to the surface of condensing

Heat transfer through radiation between two parallel surfaces

$$q_s = \frac{\varepsilon_1 \cdot \varepsilon_2}{\varepsilon_1 - \varepsilon_1 \cdot \varepsilon_2 + \varepsilon_2} \cdot 56.7 \cdot 10^{-9} \cdot \left(T_1^4 - T_2^4\right) \text{ [W/m}^2\text{]}$$

The meaning of the symbols is:

q_s the net radiation transfer in W/m^2

ε_1, ε_2 the emission coefficient of surface 1 and 2 respectively

T_1, T_2 the temperature in Kelvin of surface 1 and 2 respectively

Heat transfer through radiation with formula below

$$q_s = \varepsilon \cdot 56.7 \cdot 10^{-9} \cdot T^4 = \varepsilon \cdot q_{sz} \text{ [W/m}^2\text{]}$$

The meaning of the symbols is:

q_s the heat flow density of the emitted radiation in W/m^2

ε the emission coefficient of the material's surface

T the absolute temperature in Kelvin

q_{sz} the heat radiation of the 'black body'

$56.7 \cdot 10^{-9}$ the Stefan-Boltzmann constant

Accumulated heat

$Q = \rho \cdot c \cdot d \cdot \Delta T$ [J/m²]

The meaning of the symbols is:

Q the amount of heat accumulated in the construction layer per m²
ρ the density of the material in kg/m³
c the specific heat in J/(kg·K)
d the thickness of the layer in m
ΔT the rise in temperature of the layer in K

Table 2
Hygroscopic moisture content of various materials

material	φ = 40%	φ = 65%	φ = 95%
gravel concrete	2	3	7
wood	6	10	18
brick etc.	–	–	–
lime	2	4	10
plaster	1	2	4
wood wool cement	2	3	6

Table 3
Heat radiation emission/absorption coefficient for some material surfaces

material surface	ε
glossy polished metals	0.02–0.07
galvanised steel	0.20–0.30
aluminium, regular smooth	0.07–0.09
aluminium, anodised	0.40–0.50
aluminium lacquer	0.35–0.40
regular lacquer, any colour	0.90–0.95
brick, concrete, roofing felt, wood and almost all other building materials	0.90–0.95

Table 4
Expansion of various materials

material	linear expansion coefficient α (m/(m·K))
brick	$5 \cdot 10^{-6}$ (0,000 005)
concrete	$10 \cdot 10^{-6}$
steel	$12 \cdot 10^{-6}$
aluminium	$23 \cdot 10^{-6}$
polystyrene foam	$70 \cdot 10^{-6}$
polyurethane foam (coated plate)	$27 \cdot 10^{-6}$
foam glass	$9 \cdot 10^{-6}$

Table 5
Heat resistance (R_m) of some often-applied construction layers, finishes and coatings

layer	R_m (m²·K/W)
flexible roofing, either weighted with gravel or not	0.04
roofing with tiles, including the layer of air between the tiles and the decking	0.06
plaster on an inner surface	0.02

Table 6
Vapour barriers

name	*d* (10^{-3} m)	*μ* (10^3)	*μ · d* (m)
blown bitumen	–	70–120	1
asphalt felt 330–37	–	–	20
bituminised glass fleece	–	–	20–180
sanded asphalt felt 500–56	2.6	–	50
tar felt 280–40/45	–	–	14
single-sided bituminated paper	0.1	–	0.7
flintkote (bitumen mix)	–	0.75	–
polyester film	0.1	13	1.3
polystyrene film	0.1	42	4.2
polyvinylchloride film	0.1	10–100	1–10
polyethylene film	0.1	50–100	5–10
bitumen with aluminium foil lining	–	–	100–∞
aluminium foil 0.06 mm, coated single-sided with plastic	–	–	100
aluminium foil 0.08 mm, coated doube-sided with plastic	–	–	160

Some of the data in this table was made available by ‘Vedidak’.

Table 7
Standard values for sunscreen data, light entry and *U* values for various window systems

window system	*ZTA*	*CF*	*LTA*	*U* (W/(m^2·K))
single glazing (6 mm), unshielded	0.80	0.01	0.84	5.7
single glazing, indoor blinds (colour)	0.45	0.5	0.15	5.4
single glazing, outdoor blinds	0.15	0.05	0.12	4.9
double glazing, unshielded	0.7	0.04	0.74	3.2
double glazing, indoor blinds (light colour)	0.47	0.55	0.12	3.1
double glazing, indoor textile with deposited metal layer				
– light	0.5	0.3	0.3	3.0
– heavy	0.3	0.5	0.05	2.9
double glazing, outdoor blinds	0.12	0.05	0.1	2.8
double glazing, vertically strained cloth				
– light	0.2	0.1	0.15	2.8
– heavy	0.13	0.15	0.05	2.8
double glazing, roller screens (not continuous)	0.15	0.15	0.14	2.8
double glazing, canopy	0.11	0.18	0.05	2.8
reflecting double glazing				
– light	0.45	0.02	0.65	*
– heavy	0.25	0.05	0.35	*
absorbing double glazing				
– light	0.45	0.06	0.35	3.2
– heavy	0.25	0.1	0.1	3.2
double glazing with spectrally selective coating and adapted cavity	0.65	0.05	0.55	1.6
filling (heat insulation)	0.57	0.07	0.5	2.2
triple glazing				

* If a window’s reflection is realised by a deposited metal layer at the inside of the outer pane, the heat transfer in the cavity will also be reduced and the *U* value might drop to 1.8 – 2.0 W/(m^2·K) and even to 1.4 W/(m^2·K) if another cavity filling than air is applied.

Note:
The values in the table should be considered standard values. Specific products can have strongly differing properties. Furthermore, in many structures (glass surfaces), the angle of incidence of direct solar radiation is of influence on the reflection of the outer surface. In this table an angle of 45° is assumed. With blinds, the screening is also dependent on the position/angle of the blinds. In this table an angle of 45° is assumed, so perpendicular to the solar radiation.

Table 8
Maximal vapour concentration and vapour pressure dependent on temperature

c_{max}		saturated vapour pressure p_s in N/m^2									
g/m^3	temp. °C	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
39.56	+ 35	5627	5657	5688	5720	5752	5784	5816	5848	5880	5912
37.54	34	5323	5352	5381	5412	5443	5472	5503	5533	5564	5595
35.62	33	5033	5061	5090	5118	5146	5176	5205	5234	5264	5293
33.77	32	4757	4785	4812	4838	4866	4893	4921	4949	4977	5005
32.02	31	4496	4521	4546	4573	4598	4625	4650	4677	4704	4730
30.34	30	4245	4270	4294	4319	4344	4369	4393	4418	4443	4469
28.73	29	4007	4031	4054	4078	4102	4125	4149	4173	4197	4221
27.21	28	3782	3803	3826	3848	3871	3893	3915	3939	3962	3984
25.75	27	3567	3588	3610	3630	3651	3674	3695	3716	3738	3760
24.36	26	3363	3383	3403	3423	3443	3463	3484	3504	3530	3546
23.05	25	3169	3188	3207	3226	3246	3264	3284	3303	3323	3343
21.78	24	2985	3003	3022	3040	3058	3076	3095	3114	3132	3151
20.55	23	2811	2828	2844	2861	2879	2896	2915	2932	2949	2967
19.43	22	2645	2661	2677	2693	2710	2727	2744	2760	2778	2793
18.35	21	2488	2504	2518	2535	2549	2565	2581	2597	2613	2629
17.28	20	2340	2353	2368	2382	2397	2412	2428	2442	2457	2473
16.30	19	2198	2212	2225	2240	2253	2268	2281	2296	2310	2325
15.37	18	2065	2077	2090	2104	2117	2130	2144	2157	2170	2184
14.47	17	1938	1950	1962	1978	1988	2001	2014	2026	2034	2052
13.65	16	1818	1830	1842	1854	1866	1878	1890	1902	1914	1926
12.85	15	1706	1717	1728	1739	1750	1761	1773	1784	1796	1808
12.07	14	1599	1609	1619	1630	1641	1651	1662	1673	1684	1696
11.35	13	1498	1507	1518	1527	1538	1547	1558	1569	1578	1589
10.65	12	1403	1413	1422	1431	1441	1450	1459	1469	1478	1489
10.01	11	1313	1321	1331	1339	1349	1358	1366	1375	1385	1394
9.40	10	1229	1237	1245	1253	1262	1270	1278	1287	1295	1305
8.82	9	1148	1156	1164	1172	1179	1187	1195	1203	1212	1220
8.27	8	1072	1080	1087	1095	1103	1110	1118	1126	1132	1140
7.76	7	1002	1008	1016	1023	1030	1036	1044	1051	1059	1066
7.28	6	935	942	948	955	962	968	975	982	988	995
6.83	5	872	879	884	891	898	903	910	916	923	928
6.40	4	814	819	826	831	836	843	848	855	860	867
5.99	3	758	763	768	775	780	786	791	796	802	808
5.59	2	706	711	716	722	727	732	736	742	747	752
5.21	1	657	661	667	671	676	681	685	691	696	701
4.84	+ 0	611	615	620	624	628	633	637	643	647	652
4.84	– 0	611	605	600	596	591	587	581	576	572	567
4.48	– 1	563	557	553	548	544	539	535	531	525	521
4.14	– 2	517	513	508	504	500	496	492	488	484	480
3.82	– 3	476	472	468	464	460	456	452	448	444	440
3.53	– 4	437	433	429	425	423	419	415	412	408	404
3.26	– 5	401	397	395	391	388	384	381	377	375	371
3.01	– 6	368	365	361	359	356	352	349	347	344	340
2.77	– 7	337	335	332	329	327	323	320	317	315	312
2.55	– 8	309	307	304	301	299	296	293	291	288	285
2.34	– 9	283	281	279	276	273	271	269	267	264	261
2.15	– 10	260	257	255	252	251	248	245	244	241	240
1.98	– 11	237	235	233	231	229	227	225	223	221	219
1.82	– 12	217	215	213	211	209	207	205	204	201	200
1.67	– 13	199	196	195	193	191	189	188	185	184	183
1.53	– 14	181	179	177	176	175	173	171	169	168	167
1.41	– 15	165	164	163	160	159	157	156	155	153	152
1.29	– 16	151	149	148	147	145	144	143	141	140	139
1.18	– 17	137	136	135	133	132	131	129	128	127	125
1.08	– 18	124	124	123	121	120	119	117	116	116	115
0.99	– 19	113	112	111	111	109	108	107	105	105	104
0.90	– 20	103	101	101	100	98.7	98.7	97.4	96.0	94.7	94.7

Table 9

Density ρ, heat conduction coefficient λ, specific heat c and vapour diffusion resistance figure μ of building materials

Material type	ρ	λ (W/(m·K))		c	μ
	(kg/m³)	I*	II*	(J/(kg·K))	–
Metals					
lead	12250	35	35	130	∞
copper	9000	370	370	390	∞
iron	7900	72	72	530	∞
steel	7800	41–52	41–52	480–530	∞
zinc	7200	110	110	390	∞
aluminium	2800	200	200	880	∞
Stone					
basalt	3000	35	35		–
granite	3000	35	35		–
limestone	2750	23	29		–
freestone	2750	23	29	840	–
marble	2750	2.3	2.9		–
sandstone	2000–2300	2–4	4–6		15
tuff	1100–1500	0.35–0.50	0.5–0.7		5–10
Bricks					
clinkers (facade)	2100	0.8	1.3		31
clinkers 'Hardgrauw'	1700–1900	0.65–0.70	1.0–1.2		9–14
	1700	0.65	1.0		9
clinkers 'Rood/Boerengrauw'	1500	0.55	0.85	840	8
	1300	0.45	0.75		75
light weight brick	1000	0.3			–
sand-lime	2000	1.0	1.5		25
Gravel concrete					
compacted, reinforced	2500	1.9	2.3		37–200
compacted, not reinforced	2400	1.7	2.2		31–200
not compacted, reinforced	2300	1.4	1.9	840	27–200
not compacted, not reinforced	2200	1.3	1.7		23–200
Lightweight concrete					
	1900	0.95	1.4		130
	1600	0.70	1.2		80
	1300	0.45	0.8		75
general indication	1000	0.35	0.5	840	65
	700	0.23			55
	500	0.17			45
	300	0.12			35
	200	0.08			28
pumice concrete	700–1000	0.23–0.35		840	6
	1000–1400	0.35–0.50			6.5–12
concrete with expanded clay and such as	500–1000	0.18–0.35		840	5–6.5
aggregate	1000–1800	0.35–0.85			6.5–12
	220	0.07			4.5–5.5
polystyrene concrete	400	0.11			16–20
	650	0.20			–
	1300	0.50	1.2		7.5–9
cellular concrete	1000	0.35	0.7		5.5–7.5
	700	0.23		840	4.5–7.5
	400	0.17			3–7.5
cement-based cellular concrete					
lime-based cellular concrete	400–750	0.17–0.26			3.7–6.5
	1900	0.70	1.0		14
blast furnace slag-based concrete	1600	0.45	0.7	840	10
	1300	0.30	0.45		8
	1000	0.23	0.35		6.5
Other anorganic materials					
asbestos cement	1600–1900	0.35–0.70	0.95–1.2		37–150
gypsum board	800–1400	0.23–0.46	(–)–0.65		6
glass (mirrored or plain)	2500	0.8	0.8		∞
glass ceramics	2500	1.4	1.4	840	–
foam glass	120–150	0.05–0.06			∞
mineral aggregate for concrete	50–800	0.04–0.23			–
mineral wool	35–250	0.041			1.1–1.8

Table 9 (continuation)

Density ρ, heat conduction coefficient λ, specific heat c and vapour diffusion resistance figure μ of building materials

Material type	ρ	λ (W/(m·K))		c	μ
	(kg/m^3)	I*	II*	(J/(kg·K))	–
Plasters					
cement plaster	1900	0.93	1.5		15–41
lime plaster	1600	0.70	0.8	840	9–41
gypsum plaster	1300	0.52	0.8		7–10
Tiles					
hard-baked tiles	2000	1.2	1.3	840	28
floor tiles	1700	0.8	1.1		23
Organic materials, bound or other (excluding wood products and plastics)					
expanded cork	100–200	0.041–0.046		1760	4.5–29
expanded impregnated cork	100–200	0.041–0.046		1760	9–46
linoleum	1200	0.17		1470	1800
rubber	1200–1500	0.17–0.29		1470	900
expanded ebonite	100	0.35		1470	450–900
cane fiber board	250–350	0.08–0.09		2100	3
straw fiber board	200–400	0.08–0.12		2100	3
flaxboard bound with resin	300–700	0.08–0.17		1880	7–46
flaxboard bound with cement	330–700	0.08–0.12		1470	3.5–7
Wood products					
hardwood	800	0.17[1])	0.23[1])		–
pine	550	0.14[1])	0.17[1])	1880	–
plywood	700	0.17	0.23		–
hardboard	1000	0.29		1680	46–75
softboard	250–300	0.08		2100	–
	450	0.10			–
chipboard	600	0.15		1880	–
	1000	0.29			–
woodchip cement plate					
wood wool cement plate	350–700	0.09–0.21		1470	3.7–10
wood wool magnesite plate	400–500	0.10–0.12			3.7–10
Hard plastics					
polyester board (reinforced with glass fiber)	1200				
polyethene	920–950				
polymethacrylate	1200	0.2		1470	9000
polypropylene	900				
polyvinylchloride	1400				
abs polymers	1100				
Plastic foams					
expanded polystyrene foam	15–30	0.035			23–150
extruded polystyrene foam	30–40	0.027			150–300
urea resin foam	8–20	0.054[2])		1470	1.5–3
polyurethane foam	30–60	0.021–0.026			23–185
phenolic resin foam (hard)	25–200	0.035			3.7
polyvinylchloride foam	25–50	0.035			92–260

Note: when two values of ρ and λ are given, λ can be linearly interpolated for intermediate values of ρ.

1 perpendicular to the fibers

2 when applied as cavity filing

3 when aging due to disappearing of freon filling, can rise to 0.035 W/(m·K)

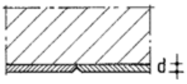
– Little is known yet about the μ value of wood products. The μ value also depends strongly on the moisture content.

* Column I concerns circumstances where the vapour is mainly determined by the indoor climate. Column II refers to circumstances where a higher vapour value is to be expected.

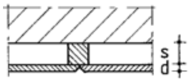
Tables acoustics

Table 10

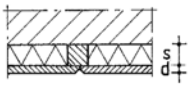
Acoustics absorption coefficients (from: *Bouwfysisch Tabellarium*, TU Delft)



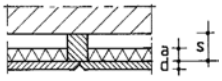
A = material directly on hard surface



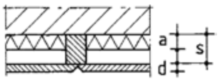
B = material on battens, air cavity



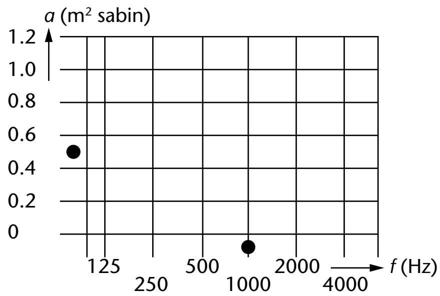
C = material on battens, cavity filled completely with acoustic material



D = material on battens, cavity filled partially with acoustic material



E = material on battens, cavity filled partially with acoustic material



Reference characteristic

Table 10 (continuation)

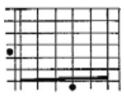
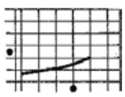
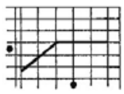
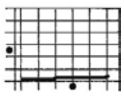
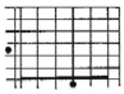
Nr.	Material (measurements in mm)	Type	Absorption coefficients α (m^2 sabin) at center frequencies						Characteristics
			125	250	500	1000	2000	4000	
	Stony materials								
1	gravel concrete, ca. 500 kg/m^2		0.01	0.01	0.02	0.02	0.03	0.04	
2	aerated concrete, 70 kg/m^2		0.14	0.19	0.24	0.32	0.41	–	
3	pumice concrete		0.15	0.40	0.60	0.60	0.60	0.60	
4	brick masonry		0.02	0.03	0.03	0. 04	0.05	0.07	
	Plaster								
5	lime plaster, directly on stony surface	A	0.01	0.01	0.02	0.02	0.02	0.04	 

Table 10 (continuation)

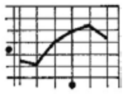
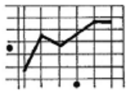
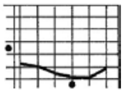
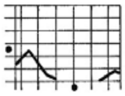
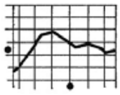
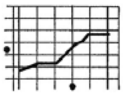
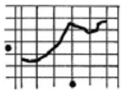
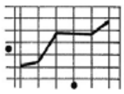
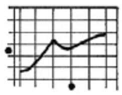
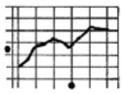
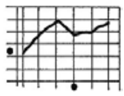
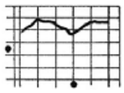
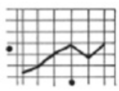
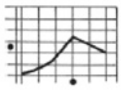
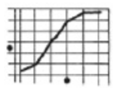
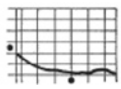
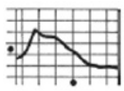
Nr.	Material (measurements in mm)	Type	Absorption coefficients α (m^2 sabin) at center frequencies						Characteristics
			125	250	500	1000	2000	4000	
6	acoustic plaster, applied in several layers	A	0.15	0.20	0.20	0.60	0.60	0.50	
7	sprayed asbestos	A	0.29	0.24	0.65	0.79	0.88	0.65	
	Acoustic materials								
8	softboard (unpainted), $d = 19$; $s = 23$	B	0.13	0.72	0.59	0.76	0.90	0.92	
9	half hardboard (unpainted), $d = 6.2$; $s = 50$	B	0.24	0.20	0.09	0.04	0.04	0.12	
10	chipboard, 5,0 kg/m^2, $d = 8$; $s = 30$	B	0.25	0.22	0.04	0.00	0.03	0.08	
11	lightweight chipboard, 6.4 kg/m^2, $d = 19$; $s = 50$	B	0.16	0.58	0.75	0.53	0.54	0.42	
12	wood wool cement board, acoustic, $d = 25$	A	0.15	0.23	0.23	0.51	0.73	0.75	
13	wood wool cement board, acoustic, $d = 25$; $s = 10$	B	0.30	0.26	0.51	0.91	0.79	0.95	
14	wood wool cement board, acoustic, $d = 25$; $s = 30$	B	0.25	0.29	0.79	0.76	0.74	0.93	
15	wood wool cement board, acoustic, $d = 25$; $s = 50$	B	0.11	0.33	0.67	0.53	0.64	0.80	
16	wood wool cement board, acoustic, $d = 25$; $s = 80$	B	0.23	0.55	0.64	0.57	0.81	0.80	
17	wood wool cement board, acoustic, $d = 25$; $s = 30$, $a = 30$	C	0.43	0.80	1.00	0.79	0.80	0.98	
18	wood wool cement board, acoustic, $d = 25$; $s = 80$, $a = 30$	D	0.76	1.00	0.90	0.73	0.94	0.95	
19	cork board, acoustic, painted, $d = 20$; $s = 25$	B	0.08	0.15	0.44	0.54	0.38	0.60	
20	polystyrene foam board, $d = 10$; $s = 4$	B	0.05	0.11	0.31	0.73	0.58	0.47	
21	wood pulp, whitewashed, $d = 22$	A	0.07	0.20	0.60	1.00	1.13	1.13	
	Perforated board								
22	gypsum board, not perforated, $d = 9,5$; $s = 100$; $a = 30$	D	0.28	0.14	0.09	0.06	0.05	0.10	
23	gypsum board, perforated 6%, $d = 9,5$; $s = 100$; $a = 30$, holes ∅8, ∅15, ∅20	D	0.39	0.81	0.68	0.44	0.25	0.20	

Table 10 (continuation)

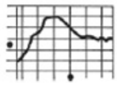
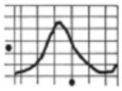
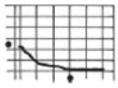
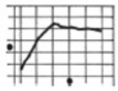
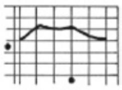
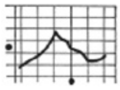
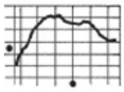
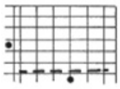
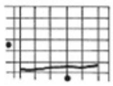
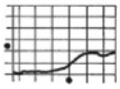
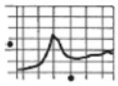
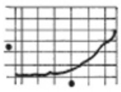
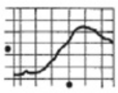
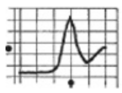
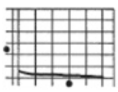
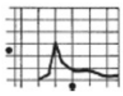
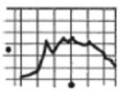
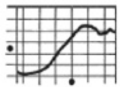
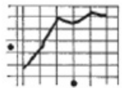
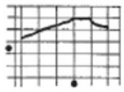
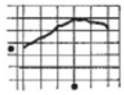
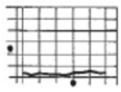
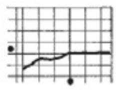
Nr.	Material (measurements in mm)	Type	Absorption coefficients α (m^2 sabin) at center frequencies						Characteristics
			125	250	500	1000	2000	4000	
24	gypsum board, perforated 19.6%, *d* = 9,5; *s* = 100; *a* = 30, holes ∅15	D	0.30	0.69	1.01	0.81	0.66	0.62	
25	gypsum board, cutting slots, *d* = 9.5; *s* = 30; *a* = 20, slots 2.3	D	0.10	0.26	0.92	0.55	0.20	0.10	
26	asbestos cement board, not perforated, *d* = 4; *s* = 50	B	0.43	0.15	0.10	0.05	0.04	0.02	
27	asbestos cement board, perforated 16%, *d* = 4; *s* = 50	C	0.13	0.65	0.90	0.82	0.82	0.77	
	Panelling								
28	wooden slats, wide 50, interspace 25 mm, *d* = 12; *s* = 200; *a* = 25	E	0.60	0.85	0.80	0.82	0.70	0.62	
29	wooden slats, wide 45, interspace 16 mm, mineral wool on bitumen paper in cavity, *d* = 25; *s* = 50; *a* = 20	E	0.19	0.36	0.73	0.50	0.25	0.31	
30	aluminium strips, wide 50, interspace 12.5 mm, *d* = 0,3; *s* = 176; *a* = 20	D	–	0.89	1.00	0.88	0.88	0.61	
	Flooring								
31	linoleum, glued to surface	A	0.02	–	0.30	–	0.04	–	
32	parquetry, glued to surface	A	0.04	0.04	0.06	0.12	0.10	15.00	
33	carpet, 1.87 kg/m^2, *d* = 4.5	A	0.00	0.02	0.04	0.15	0.36	0.32	
34	carpet, 1.87 kg/m^2, with underlay (8 mm felt), *d* = 4.5	A	0.05	0.13	0.60	0.24	0.28	0.32	
35	carpet, 1.98 kg/m^2, *d* = 5.3	A	0.00	0.03	0.05	0.11	0.31	0.58	
36	carpet, 1.98 kg/m^2, with underlay (8 mm felt), *d* = 5.3	A	0.04	0.10	0.31	0.70	0.93	0.74	
37	coconut flooring, loose on surface, 2 kg/m^2, *d* = 10	A	0.03	0.03	0.07	1.13	0.28	0.55	
	Miscellaneous								
38	glass		0.10	0.04	0.03	0.02	0.02	0.02	
39	plastic film, tightly strained, PVC 0.2 kg/m^2, *d* = 0.2; *s* = 20	B	0.00	0.00	0.64	0.17	0.12	0.04	
40	plastic film, folded 3:1, PVC 0.2 kg/m^2, *d* = 0.2, *s* = 20	B	0.00	0.13	0.51	0.66	0.59	0.30	

Table 10 (continuation)

Nr.	Material (measurements in mm)	Type	Absorption coefficients α (m^2 sabin) at center frequencies						Characteristics
			125	250	500	1000	2000	4000	
41	curtain, cotton, tightly strained, 0.2 kg/m^2, s = 50, ca. 0.4 kg/m^2	B	0.04	0.09	0.37	0.68	0.89	0.72	
42	curtain, cotton, folded 3:1 s = 50, ca. 0.4 kg/m^2	B	0.15	0.45	0.96	0.97	1.06	1.02	
43	a single seated person		0.15	0.30	0.45	0.45	0.45	0.45	
44	a single person in a space with much reverb (e.g. church)		0.65	0.75	0.85	0.95	0.95	0.80	
45	audience (including orchestra) per m^2		0.52	0.68	0.85	0.97	0.93	0.85	
46	wooden chair (unoccupied)		0.02	0.02	0.02	0.04	0.04	0.03	
47	lined chair (unoccupied)		0.15	0.30	0.30	0.40	0.40	0.40	

Note:
The table above presents only general values derived from literature. More complete data with more accurate values with product description etc. can be found in reports of suppliers and at www.klimapedia.nl.

Table 11
Coincidence threshold frequency for various materials

material	$f_g \cdot d$	example d (mm)	example f_g (Hz)	example d (mm)	example f_g (Hz)
aluminium	12 500	2	6 250	5	2 500
steel	12 800	1	12 800	3	4 267
glass	12 800	4	3 200	8	1 600
concrete	17 300	120	144	200	87
glass concrete	38 000	80	475	200	190
sand-lime	21 400	105	204	210	102
poriso	26 000	50	520	90	289
lightweight concrete	32 000	80	400	200	160
gypsum	35 500	50	710	70	507
drywall	35 500	9	3 944	15	2367
wood	25 000	12	2 083	22	1136
chipboard	25 000	8	3 125	18	1389
lead	51 200	0.5	102 400	2	25 600

Table 12
Standard values for reverberation times in various spaces

furnished room	T = ca. 0,5 s
office room	T = 0,5–0,7 s
open-space office	T = 0,7–0,9 s
classroom	T = 0,6–0,8 s
music room	T = 0,8–1,2 s
theatre	T = 0,9–1,3 s
chamber music room	T = 1,2–1,5 s
opera hall	T = 1,2–1,6 s
concert hall	T = 1,7–2,3 s
church (organ music)	T = 1,5–2,5 s

Table 13
Attenuation or strengthening according to the A-weighting

frequency in Hz	A-weighting in dB
63	–26.1
125	–16.1
250	–8.6
500	–3.2
1000	0.0
2000	1.2
4000	1.0
8000	–1.0

Figure 1 Adding sound pressure levels

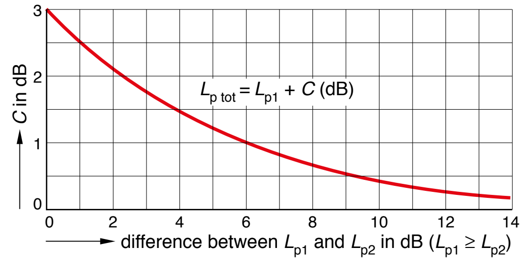


Figure 2 Insulation reduction of a wall as a result of a part having less insulation

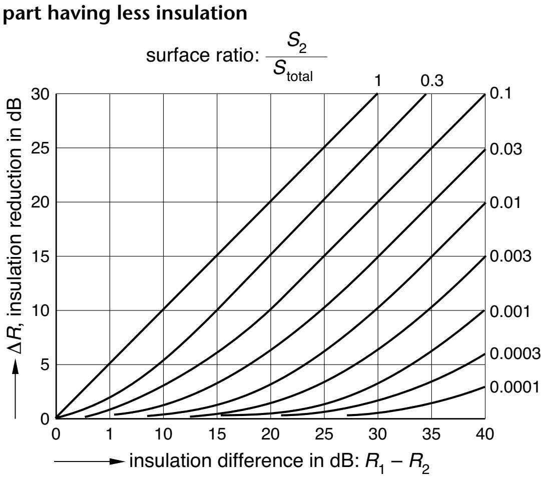


Table 14

Recommended values for background noise in dB in offices

Type of background noise	Enclosed spaces			Open spaces	
	Category 1	Category 2	Category 3	Category 4	Category 5
sound level as a result of outdoor sound (industrial, railway, road and air traffic sound) ($L_{A,eq}$ in dB)	< 35	< 40	< 40	< 40	< 45
installation sound pressure level ($L_{i,A}$ in dB)	< 35	< 35	< 35	< 40	< 40

Table 15

Performance requirements for airborne and impact sound insulation

	Enclosed spaces			Open spaces	
	Category 1	Category 2	Category 3	Category 4	Category 5
Air born sound pressure level difference minimum requirement $D_{nT,A}$ in dB					
to rooms	45	52	39	NA	NA
to traffic areas	33	33	27	NA	NA
to rooms via wall with door	33	33	NA	NA	
to bathrooms	48	48	48	48	48
to other rooms	45	42	33	33	33
Maximum impact sound pressure level $L_{nT,A}$ in dB including floor finish					
to rooms	57	57	57	57	57
to traffic areas	67	67	67	67	67
to rental or user partition	48	48	48	48	48
Example situations for enclosed spaces					
category 1	high level of speech privacy e.g. meeting centre				
category 2	increased level of speech privacy in office location e.g. consulting rooms				
category 3	private work space/concentration area (1-4 people)				
Example situations for open spaces					
category 4	open, grouped work space (4-6 people)				
category 5	open meeting area, call centre				

Formulas sound

Sound pressure level

$$L_p = 10 \log \frac{p_{eff}^2}{p_0^2}$$

The meaning of the symbols is:

- L_p the sound pressure level in dB
- p_{eff} the effective sound pressure
- p_0 the reference sound pressure ($2 \cdot 10^{-5}$ Pa)

Sound intensity

$$I = \frac{p^2}{4 \cdot \rho \cdot c} \text{ for a diffuse sound field}$$

$$I = \frac{p^2}{\rho \cdot c} \text{ for a plane wave}$$

The meaning of the symbols is:

- I the sound intensity in W/m^2 (energy)
- p the sound pressure in Pa
- ρ the density of the air in km/m^3
- c the speed of sound in m/s
- $\rho \cdot c$ for average conditions, numerical value ca. 400

Sound power level

$$L_w = 10 \log \frac{W}{W_0} \text{ [dB]}$$

The meaning of the symbols is:
L_w the sound power level in dB
W the sound power in watt
W_0 the reference power (10^{-12} W)

Adding sound pressure levels

$$L_{p;tot} = 10 \log\left(10^{\frac{L_{p1}}{10}} + 10^{\frac{L_{p2}}{10}} + 10^{\frac{L_{p3}}{10}} + \ldots\right) \text{ [dB]}$$

The meaning of the symbols is:
L_{p1} the sound pressure level of sound 1
L_{p2} the sound pressure level of sound 2
$L_{p;tot}$ the resulting sound pressure level in dB

Wavelength and frequency

$$c = f \cdot \lambda \text{ [m/s]}$$

The meaning of the symbols is:
c the propagation speed of the sound in m/s
f the frequency in Hz
λ the wavelength in m

Mass-spring resonance in cavity constructions

$$f_0 = 60 \sqrt{\frac{m_1 + m_2}{m_1 \cdot m_2} \cdot \frac{1}{b}} \text{ [Hz]}$$

The meaning of the symbols is:
f_0 the resonance frequency of perpendicular impacting sound in Hz
m_1 the mass of the first cavity leaf in kg/m^2
m_2 the mass of the second cavity leaf
b the width of the cavity in m

Sound insulation of a construction

$$R = L_z - L_o + 10 \log \frac{S}{A} \text{ [dB]}$$

The meaning of the symbols is:
L_z the sound pressure level in the send room in dB
L_o the sound pressure level in the receiver room in dB
S the area of the wall
A the absorption in the receiver room

Standardised airborne sound level reduction

$$D_{nT} = L_z - L_o + 10 \log \frac{T}{T_0} \text{ [dB]}$$

The meaning of the symbols is:
D_{nT} the standardised airborne sound insulation in dB
L_z the sound pressure level in the send room in dB
L_o the sound pressure level in the receiver room in dB
T the measured reverberation time in the receiver room
T_0 the standardised reverberation time (= 0.5 s)

Typical airborne sound level difference $D_{nT,A,k}$

$$D_{nT,A,k} = D_{nT,A} - 10 \log\left(\frac{0.16 \cdot V}{T_0 \cdot S_r}\right) \text{ [dB]}$$

The meaning of the symbols is:
$D_{nT,A,k}$ typical airborne sound level difference in dB
$D_{nT,A}$ weighted airborne sound level difference per octave band in dB
V volume of the receiving room in m^3
T_0 the reference reverberation time in s
S_r surface area of the communal partition structure between transmission and receiving structure in m^2

Lighting

Figure 3
Illuminance in the free field outdoors

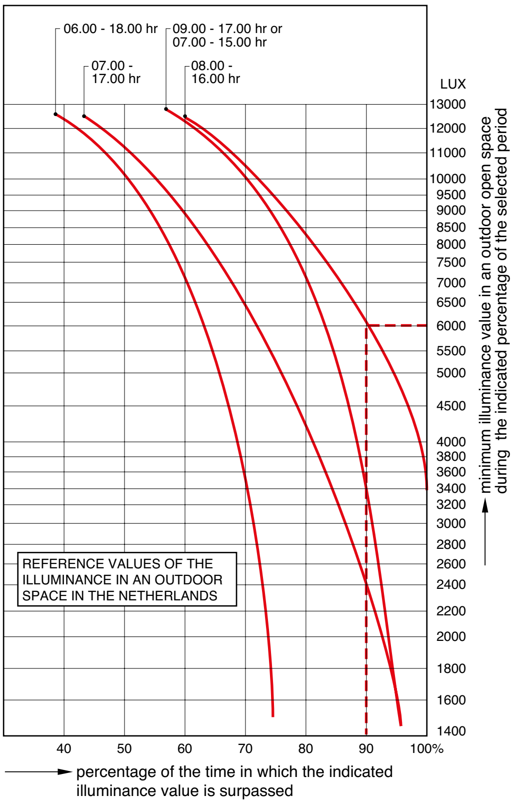


Table 16
Internal reflection component in % for various reflection factors of wall finish in the room. Reflection factor ceiling approx. 70%, floors approx. 20%.

glass area related to floor area in %	reflection factor of walls			
	20%	40%	60%	80%
10	0.2	0.3	0.6	0.9
20	0.3	0.6	1.1	1.7
30	0.5	0.9	1.5	2.4
40	0.6	1.2	2.0	3.1

Building Physics
Questions and Answers

Building Physics Questions and answers

Questions composed by F.A.J. Keizer, lecturer Building physics at MTS Hengelo (Netherlands) based on the book Building Physics, 5th edition 2000. Also questions have been used that were made by N. Zwaan, lecturer Building Physics at MTS Leiden. The Q&A has been translated by J.M. Schaap, BSc and checked by Ir. E.R. van den Ham and Ir. H.R. Schipper, all from the Delft University of Technology.

The English version of the book (1st edition) is equal to the 7th edition of the Dutch version.

When making use of tables and formulas for building physics one should use average values.

Preface

1. What do we mean with the term comfort?
2. What do we mean by passive solar energy?
3. Why should a building be ventilated effectively?
4. In which regulations or documents the requirements and guidelines regarding building physics have been established?

1. Heat, heat transport, thermal insulation

1. What do we mean by the heat flow density q?
2. What three types of heat transfer do you know? Give an example of each.
3. The heat transfer flow is dependent of what?
4. What are common heat transfer coefficients through flow?
5. The temperature on the outer surface of a wall is -1 °C at an outdoor air temperature of -3 °C. Calculate the heat flux density as a result of convection of this construction, at average wind speed.
6. Having an inner wall with an interior surface temperature of 18 °C, the indoor air temperature is 13 °C. Using two different heat transfer coefficients a = 2.1 and 2.5, calculate the heat flux, q, through the wall.
7. At which temperature an object does not emit any heat?
8. How do we experience a cold glass surface and how do you explain this?
9. Which emission coefficient applies to most building materials?
10. A brick wall has a temperature of 22 °C. Calculate the heat flow density, q_s, of the radiation emitted by an emission factor ε = 0.9.
11. The heat flux of radiation emitted by a wall is q_s = 375 W/m2 at an emission factor ε = 0.9. Calculate the wall temperature.
12. A radiator has a heat flux density as a result of radiation of q_s = 800 W/m^2 at a temperature T = 75 °C. Calculate the emission factor ε of the radiator surface.
13. What relationship do the emission- and absorption coefficient usually have?
14. Explain 'freezing' of a car windshield at an air temperature that is above zero.
15. A normal painted radiator having a surface temperature of T = 65 °C radiates heat to a glass window having a temperature of T = 5 °C. Calculate the net radiation transfer q_s.
16. A normal painted radiator with a surface temperature T = 70 °C, radiates heat to a brick parapet with a surface temperature of T = 19 °C. Calculate the net radiation transfer q_s.
17. Given data as in question 16, but now a radiation screen is placed in front of the parapet consisting of aluminium foil, emission factor ε = 0.08. The surface temperature of the radiation shield is T = 19 °C. Calculate the net radiation transfer q_s and give your opinion about the difference between question 16 and 17.
18. The inner side of a plywood parapet of a wooden window frame has a temperature of T = 17 °C. In front of this window, a normal painted radiator is situated with a surface temperature of T = 65 °C. Calculate the net radiation transfer q_s.
19. Given data as in question 18 but now the parapet of plywood has been painted with an aluminium coating. Calculate the net radiation transfer q_s and give your opinion about the

difference between question 18 and 19.

20. What we mean by the thermal conductivity λ of a material and what is its unit?
21. What do we mean by the thermal resistance R of a layer of material and what is its unit?
22. Give the relationship between the thermal resistance R and the heat flow density q. What do you notice?
23. What do we mean by the thermal resistance R_c of a structure?
24. What types of heat transfer take place in a cavity construction? Of each type, give the positive or negative contribution to the value of R_{sp}.
25. Give three R_{sp} -values that we use in practice for horizontal and vertical cavity constructions.
26. What do we mean by heat resistances r_e and r_i, on what do they depend and which values are commonly used for inside and outside?
27. What do we mean by the thermal resistance R_l of a structure? (Note: mind the different subscript as compared to Q23)
28. A wall construction from outside to inside has the following layers: 105 mm brickwork (hard gray), 60 mm cavity, 105 mm brickwork (farmer gray) and 10 mm of cement plaster. T_e = -10 °C. and T_i = 20°C. Calculate R_c, R_l, U, q and the temperature line of this construction.
29. Calculate R_c, R_l, U, q and the temperature line for the same wall structure as in question 28, but the cavity is now completely filled with mineral wool. T_e = -10 °C. and T_i = 20°C.
30. A roof has the following buildup from outside to inside: 6 mm bituminous glass fleece, μ-value = 10000, λ = 0.17 W/m^{2}K, 200 mm compacted concrete and and 25 mm cement-wood-fibreboard. T_e = -10 °C. and T_i = 20°C. Calculate R_c, R_l, U, q and the temperature line of this construction.
31. Calculate R_c, R_l, U, q and the temperature line of the same roof construction as in question 30, but now with 50 mm extruded polystryrene foam (XPS) (30-50 kg/m^3) under the roof covering. T_e = -10 °C. and T_i = 20°C.
32. A 2-point supported ground floor of reinforced concrete (2300 kg/m^3) and a thickness of 130 mm is finished with a 30 mm cement screed layer (λ = 0.93 W/m^{2}K). Calculate, R_c, R_l, U, q and sign the temperature line of this construction, non-insulated, and also for the situation in which40 mm of expanded polystyrene foam (EPS, 15-30 kg/m^3) is arranged on the bottom side of of the floor. T_e = 14°C. and T_i = 19°C.
33. Given a wooden roof structure, layered from the outside to the inside: 5 mm bituminized glass fiber (λ = 0.17 W/m^{2}K, μ = 10 000), 20 mm chipboard (μ = 60.5), a beam 20 mm thick and 12 mm plasterboard. T_e = -10°C. and T_i = 22°C. Calculate R_c, R_l, U, q and the temperature line of this construction.
34. Calculate R_c, R_l, U, q and the temperature line of the same roof structure as in question 33, but now with a 40 mm layer of mineral wool under the roofing. T_e = -10°C. and T_i = 22°C.
35. A tiled roof structure consists of (outside to inside) 40 mm tiles + air layer (μ = 1), 40 mm extruded polystyrene foam (15-30 kg/m^3), 20 mm chipboard (μ = 70), purlins + girders 200 mm thick and 12 mm plasterboard. . T_e = -10°C. and T_i = 20°C Calculate R_c, R_l, U, q and the temperature line of this construction.
36. What do we mean by the U-value of a structure and what do we use it for?
37. What factors do substantially determine the thermal resistance of single glass? What is the influence of the thickness of the glass in this?
38. Compare the insulation of double glazing with that of an un-insulated cavity wall construction and give your opinion about this.
39. What determines whether the surface of a doubleglazing unit will condensate?
40. What do we mean by heat accumulation of a building and what impact does this have on the interior climate?
41. By what is the accumulating capacity of a building determined and what impact does this have on the central heating equipment and comfort?
42. A wall of compacted concrete, 200 mm thick, is heated from 12 °C to 18 °C. Calculate the accumulated heat in this wall.
43. What do we mean with a cold bridge in building constructions and what problems can occur as

a result?

44. What problems can be caused by temperature stresses in constructions? Give some examples.
45. An aluminium roof trim must be made in lengths up to 3 m on a roof length of 57 meters. Calculate with a temperature gradient of 83 °C. Calculate the total expansion and the necessary width of the expansion joints of the roof trim.
46. What benefits do we obtain by establishing a loose roofing on a roof? What is this a disadvantage?
47. When can you say that a ventilated cavity ventilates strongly?
48. How do you calculate the average U-value of a structural element, composed of parts each with different U-value?
49. What are weighing factors and what are they for? Describe each application situation. Write down the formula of each situation.
50. What do you know about stony and metal roofs and cantilevered construction parts with regard to the calculation of the average U-value?
51. What is the minimum requirements of the R_c-value for roof, floor and wall constructions in housing in the Dutch regulations?

2. Moisture, Moisture transport, condensation

1. In what way we have to deal with soil moisture and which provision should not be missing in this context?
2. What is determining the maximum amount of water vapour in air?
3. What do we mean by the relative humidity ϕ of air?
4. What is the result when the concentration of water vapour or vapour pressure due to the cooling air becomes greater than the maximum water vapour concentration or the maximum vapour pressure?
5. How can condensation on the inside surface of windows occur while the relative humidity of the indoor air is not 100%?
6. The maximum water vapour concentration in air is $c_{max} = 15.37\ gr/m^3$ at a temperature of T = 18 °C. Calculate the maximum vapour pressure p_{max} of this air.
7. The maximum vapour pressure of air of 12 °C is $p_{max} = 1403\ Pa$. Calculate the maximum water vapour concentration c_{max} of this air.
8. What consequences can the relative humidity have for the ventilation of a basement in the summer?
9. What do we mean with the term ventilation rate n?
10. In a classroom of 170 m^3 are 30 students and one teacher. Per person 60 grams of water vapour per hour are released. The ventilation rate is $n = 4h^{-1}$. Calculate the increase in the water vapour concentration Δc in the classroom.
11. Use the information of question 10 and calculate with a ventilation rate of $n = 3$ and $n = 5\ h^{-1}$ the vapour concentration c.
12. What should be the minimum ventilation rate for a house to prevent moisture problems?
13. Mention factors that determine the relative humidity in a building.
14. What do we mean by the hygroscopic moisture content of the materials and what effect on the humidity does it have?
15. What are climate categories, what are they used for, and how are they determined?
16. Why should surface condensation be avoided?
17. What is meant by the temperature factor f and for what is it used?
18. Calculate the temperature factor f at an outside temperature T_e = -5 °C, an indoor temperature T_i = 22 °C and an inner surface of T_{io} = 15 °C.
19. Calculate the temperature factor f at an outside temperature T_e = -10 °C, an indoor temperature T_i = 22 °C and an inner surface of T_{io} = 13 °C.
20. Calculate the temperature factor f at an outside temperature T_e = -8 °C, an indoor temperature T_i = 20 °C and an inner surface of T_{io} = 17 °C.
21. What do we mean with the vapour diffusion resistance R_d?

22. What do we mean with the vapour diffusion resistance figure μ?
23. What formula can we use for normal building practice?
24. In what way can we find the total vapour diffusion resistance of a layered structure?
25. What do you know about the location of an insulating layer in a structure? What is the impact on the interior?
26. What do you know about the location of a vapour barrier in a construction?
27. What are the problems that may occur when applying vapour barriers?
28. How much moisture can be accepted to be present in building materials during a period of frost? Is this a similar value for all materials?
29. How long does a period of frost last, when used in calculations?
30. Use the information of question 28 of Chapter 1 in order to calculate μ_{total}, the maximum and present vapor pressure lines and the occurring internal condensation. Assume $\phi_e = 85\%$ and $\phi_i = 45\%$.
31. Use the information of question 29 of Chapter 1 in order to calculate μ_{total}, the maximum and present vapour pressure lines and occurring internal condensation. Again assume $\phi_e = 85\%$ and $\phi_i = 45\%$.
32. Use the information of question 33 of Chapter 1 in order to calculate μ_{total}, the maximum and the present vapor pressure lines and occurring internal condensation. Now assume $\phi_e = 85\%$ and $\phi_i = 50\%$.
33. Use the information of question 34 of Chapter 1 in order to calculate μ_{total}, the maximum and present vapor pressure lines and occurring internal condensation. Assume $\phi_e = 85\%$ and $\phi_i = 50\%$.
34. Use the information of question 35 of Chapter 1 in order to calculate μ_{total}, the maximum and present vapor pressure lines and occurring internal condensation. Assume $\phi_e = 75\%$ and $\phi_i = 45\%$.

3. Heat and Moisture transport in practice

1. What do you know about the insulation of floors above crawl spaces and what methods do you know?
2. Why should we apply a sealing foil especially with wooden ground floors?
3. What do you know about insulating of basements? What materials are commonly used?
4. How do you insulate the walls and floor of a basement?
5. How should a basement be ventilated and what are possible dangers?
6. How can you prevent cold bridges? Give some situations used in practice.
7. What functions does the traditional cavity wall have?
8. How does the drying process of a wet outer leaf take place, and when is this not possible?
9. Which requirements should be made when installing plastic foam sheets as cavity wall insulation? What are the dangers?
10. Which requirements should be made when applying mineral wool boards for insulation in a cavity? Is a partial cavity filling is necessary and why?
11. When is it essential to apply an air cavity in front of an insulation layer?
12. What do you know about the current application of reflective foils? Can you still use this as a cavity insulation nowadays? What are the dangers of this application in a cavity wall?
13. In what ways can we isolate existing cavity wall constructions?
14. What are the dangers of afterwards isolating with UF foam insulation system?
15. How do you assess a post-insulation of a cavity wall insulation with mineral wool flakes and what is the quality of this method?
16. What do you know about post- insulation of a cavity wall insulation with compound polystyrene pellets?
17. How do you assess a post-insulation of a cavity wall with polyurethane foam and what is the quality of this method?
18. What criteria should we apply in assessing post-insulation?
19. What are sandwich panels and how they are generally built up? What is important for the edge

finishing and why?
20. What means should be used to make old walls water-repellant?
21. Which hazards occur during the insulation of a wall on the inside, or on the warm side of the structure?
22. Name two materials that can be used to insulate on the inside of a wall without any problem.
23. What do you know about the fire behaviour of insulation materials?
24. What do you know of aerated concrete walls as insulation wall?
25. How should we insulate a sloping roof using copper or zinc as external finishing? What do you know about vapour transport?
26. What problems can arise with insulation on the tiled roof deck and why?.
27. What are the dangers of putting insulation under a roof deck? When is a vapour barrier necessary?
28. What is a cold roof and what is a warm roof? Give for each construction the pros and cons.
29. What are the pros and cons of a steel roof? Which insulation materials can you apply best and why?
30. What do you know of cellular glass as insulation material? What are the pros and cons of this material?
31. What do you know about plastic foam panels for insulation? What are the pros and cons of this material?
32. What do you know about the loose-fill insulation materials and where can they be applied?
33. What do you know about the application of polyethylene foils? Where can we apply those?
34. What must we always avoid when using porous insulation materials in construction and what dangers can occur?
35. How can blisters occur on a roof and what could be the reason of this?
36. What is the function of a vapour pressure distribution layer on a flat roof and how we can achieve this in practice?
37. What do we mean with an inverted roof, what are the advantages of such a roof compared to the warm roof and cold roof?
38. What are the pros and cons of a loose roofing?
39. What are the benefits of a green roof?

4. Lighting

1. What is light?
2. How big is the propagation speed of light?
3. What causes different types of electromagnetic radiation?
4. Give an overview of the various electromagnetic waves and give the portion with the visible waves and the corresponding colours.
5. Define the illuminance E in (lux).
6. Define the flux ϕ in lumen (lm).
7. Define the intensity I in candela (cd).
8. Define the luminance L in cd/m^2.
9. By whom and under what title is the illuminance indicated?
10. Which of the values listed in the table is used with regard to artificial lighting in practice?
11. What average illuminance is used for a detailed editing room, a normal classroom and a reading chair at home?
12. What average illuminance is used for 'mood lighting'?
13. Is only natural light in a school situation enough?
14. What is denoted by the colour rendering index of a light source?
15. Which factors influence the illuminance on a work surface?
16. Does a fitting efficacy always result in a high lighting efficacy? What factors play a role?
17. What problems can occur with excessive brightness differences?
18. What problem can occur with too small brightness differences?
19. What do we mean by the shape index k of a room? What do we use it for?

20. What illuminances are recommended for areas without daylight and in a combination of daylight and artificial light?
21. How should we deal with the generated heat by artificial lighting and how can we avoid or eliminate it?
22. During what percentage of the time can we expect an illuminance of *E = 4600 lux* between 06.00 and 18.00 in an open space?
23. Define the daylight factor.
24. Calculate the daylight factor as within an illuminance of *E = 250 lux* measured and outside *E = 5000 lux*.
25. In a classroom, an illuminance of E = 500 lux is required for 90% of the time between 09:00 and 17:00. Calculate the daylight factor.
26. Which 'structural' factors play a role in achieving a required daylight factor?
27. Which, for instance atmospheric, further aspects should be taken into account?
28. Define the sky component at a certain point.
29. Where do we find the so-called dot diagram (stippendiagram)?
30. What are sizes of the points that are used?
31. Which ease of use does the scale 1:40 yield corresponding to a distance of 2 m from the glass?
32. In what way is the method of using the ratio and the angle more correct?
33. Does it make sense for the sky component to havewindows going down to the floor?
34. With which numbers does the sky component need to be multiplied at an angle of 15°, resp. 30° and 45° (with respect to the fact that the sky luminance is not distributed equally)?
35. Which values are used for the absolute light entry factor of single and double glazing?
36. How big can you expect the reduction factor regarding to pollution to be?
37. Which formula do we need now in order to calculate the sky component?
38. Why are external reflections usually neglected?
39. For what reason ceilings and walls are made in a light colour?
40. What disadvantages are inherent with the use of large glass areas and skylights?
41. What does this usually mean for buildings with air conditioning?
42. Which limitation will be needed and which facilities should be made?

5. Thermal comfort

1. What do we mean by indoor environment?
2. What do we mean by the thermal comfort of a building?
3. What do we mean by local discomfort? What factors can affect this?
4. What do we mean by the PMV and what is the purpose of the PMV?
5. What are the requirements related to the vertical temperature gradient regarding the thermal comfort in a room?
6. What do we mean by asymmetric thermal radiation?
7. Which floor temperature is recommended in areas where people with normal footwear stay?
8. What problems can occur with the air speed of mechanical ventilation regarding the thermal comfort?
9. What values can we use for the relative humidity regarding the thermal comfort?

6. Ventilation and infiltration

1. Why do we need ventilation a good indoor environment?
2. What we mean by basic ventilation? Which document states the necessary requirements in the Netherlands?
3. What is the need for ventilation in the different rooms in a house?
4. What types of ventilation systems do you know? What are the pros and cons of these systems?
5. What is the difference between ventilation and infiltration?
6. What is the advantage of a CO_2 measurement? What is the maximum CO_2 content in a room to still be considered a 'fresh' space?
7. What are the basic requirements for basic ventilation of new homes and residential buildings in

the Dutch situation?

8. How is the ventilation rate determined?
9. What is a ‘silencer’ and what is its purpose? Make a sketch of the cross section.
10. Mention some structural measures to prevent drafts problems.
11. What is cross ventilation? Make this clear with sketch.
12. Mention the benefits of ventilation via façade and roof over cross ventilation.
13. What do we mean by the air permeability of façade elements?
14. Give some façade detailing to which we must pay attention the air permeability.

7. Solar penetration and sunscreens

1. What amount of solar radiation can be expected on a facade? Which factors determine this?
2. What disadvantages are there if much sun is received by a room?
3. What does it mean that on February 19th and October 23rd the qualification 'moderate' is achieved? Where is the standard point?
4. What applies to solar penetration related to factories, workshops and auxiliary offices?
5. Mention the daylight saving times at which global solar radiation in July reaches its maximum intensity respectively for north, east, south and the north façade, due to the direct radiation.
6. What is the maximum intensity of the total radiation on the south facade and what time and at which place?
7. What do we mean by diffuse radiation?
8. Why is the intensity on a south façade in July smaller than on the east and west facade?
9. What does this means with regard to effective window openings, and how does this go in September?
10. Which orientations give the most problems? Explain why.
11. What are the consequences related to the introduction of the daylight saving time?
12. Why is the automatic control of outdoor blinds a necessity?
13. What factors play a role when determining the solar heat load on the façade?
14. What facades are and which are definitely not suitable for the use in canopies?
15. On which facades do vertical screens make sense? Explain why.
16. Give a sketch showing the relative influence of placement of a window in the façade area at different heights of the sun.
17. What do we mean by the greenhouse effect in buildings?
18. What can we do to cope with the greenhouse effect?
19. Give a sketch show how solar radiation is transmitted, reflected or absorbed by normal single glass.
20. Sketch the graph of the distribution of solar energy over the different wavelengths.
21. Which wavelength (global) is transmitted very poorly through glass? What is the result of this?
22. Does this also apply to double glazing?
23. Using which values the quality of a sun shading system is indicated?
24. What means $SF = 0.45$?
25. How does an indoor sun shading system emit heat? What side effect acts here?
26. What happens to the directly transmitted radiation?
27. What does a convection factor $\beta = 0.50$ mean?
28. Is a high convection factor favourable or unfavourable?
29. Using an indoor sun shading, what is the maximum SF?
30. Why is the absorption of heat by an external sun protection in contrast to internal protection is not a problem?
31. What is responsible for the small amount of solar heat that still enters?
32. Which solar factor can be achieved with external solar shading and what is a quite normal value?
33. In what form can external blinds be designed?
34. Which main types of solar control glass are there? What is their global operation principle and in what situations are they applied?

35. In what way we can greatly increase the absorption of double glazing? What consequences does this have for a window?
36. Which disadvantage has an absorbing single glazing?

8. Buildings and climate installations

1. What types of climate systems are found in homes and residential buildings?
2. What are single, double and triple radiators?
3. What is the difference between a radiator and a convector?
4. Mention some criteria determining the choice for either radiators or convectors in a building.
5. In modern buildings floor- or wall heating is more or less self controlling. What is the explanation of this phenomenon.
6. What do we mean by a low- temperature heating and for which purposes are these systems particularly suitable? What is a disadvantage and what are the advantages of this system?
7. What do we mean by air-heating? What requirements must this system meet and what are the advantages and disadvantages of this type of heating?
8. What do we mean by wall- and floor- heating? What are the pros and cons of these systems compared with hot water and air-heating?
9. What is a major advantage of floor- heating for indoor climate?
10. What do we mean by 'weather dependent' controlling of the heating system for large buildings? What is the disadvantage of this type of control if used in a well-insulated building?
11. What do you know about radiant heating in the ceiling? Where do we apply this system, and what are the benefits?
12. How can we recover heat from the ventilation?
13. What we mean by the four-pipe induction system? What are the pros and cons?
14. In what ways can we cool a building?
15. What is the difference between 'real cooling' and 'peak cooling' in a building? What should one think of in real cooling?

9. Energy consumption, energy saving, setting energy performance standards

1. Which gain and loss items occur in the energy balance of a home?
2. The energetic equivalent of 1 kWh electricity equals approximately 0,1 m^3 natural gas. Why is the value given in Figure 9.2 none the less 0,25 m^3?
3. How long is a standard heating season?
4. At what point does a calculation of the energy consumption for offices differ from homes?
5. What danger can occur at the northern hemisphere with too much glass oriented to the south?
6. What factors affect the calculation of heat loss through ventilation?
7. What conclusion can we draw from the gross heat loss through windows with insulated shutters, cavity walls and heat loss through ventilation?
8. What do various devices contribute to heat gain in domestic use and how can energy be lost through a number of devices?
9. What do you know about the efficiency of heating installations?
10. Which day periods apply to offices and why does it differ from the day periods for homes?
11. Which indicative saving formulas do you know and what's the point of using them?
12. Sum up some influences of a building and the installation parameters that affect the savings.
13. When do saving formulas not apply?
14. What factors determine the final efficiency of energy-saving measures?.
15. What factors may affect the use of a thicker layer of insulation unfavourably?
16. How is the energy efficiency regulated by in the Dutch Building Decree? What is the reason?
17. Which buildings must meet the energy performance requirements?
18. Describe briefly the effect of the EP requirements on a building.
19. How does the building function relate to the EP requirements?
20. When must one demonstrate that the building complies with the EP requirement?
21. What R_c-value should a residential area in a new building and renovation have?
22. What are integral energy saving measures? Sum up a few.
23. What is the first step for creating an energy performance calculation?

24. Make a roadmap for calculating the EP coefficient for a home (single-zone model).
25. What do you conclude from the EP formula using the terms usable floor space and surface area loss?
26. What do we mean by the total energy $Q_{pres;tot}$?
27. What do we mean by energy use for heating?
28. What do we mean by the heat demand?
29. What do we mean by heat loss through ventilation and infiltration?
30. Mention some important energy saving measures for public buildings.
31. Make a roadmap for EP calculation of a public building.

NOTE: The questions and answers were originally made on the basis of the 5th (Dutch) edition. Starting with the 6th edition the setup of the Acoustics chapters 10 and 11 has changed. Therefore the numbers of the questions continue going from chapter 10 to 11 in this "Questions and Answers" and start again at 1 half way chapter 11.

10. Acoustics

1. What is sound and how does it move?
2. What do we call the movement of sound?
3. How can we describe the propagation of a sound wave in air?
4. Explains this with a drawing.
5. What is the barometric pressure, relative to which pressure fluctuations occur?
6. Why do we use a logarithmic calculation to indicate a sound level instead of the effective sound pressure level as it is?
7. What is the sound pressure created by a radio playing loudly?
8. How do we call the lower limit of sound perception and what is the sound pressure at this threshold? Do the same for the upper limit.
9. When already can hearing loss occur?
10. Why do we use logarithms to calculate the sound pressure level L_p?
11. Why do we use squares for of the effective sound pressure and the fixed comparison pressure?
12. With what value would the sound pressure level L_p increase if we would add the levels of two, equally directed, equal-level, in-phase noise sources?
13. And what if it concerns not equally directed, but oppositely directed noise?
14. What is this increase in practice?
15. What is the effect of adding a sound pressure level L_p that is more than 10 dB less than the first one?
16. What is the formula for sound sources when adding both up?
17. Simplify the formula regarding the sound intensity I in a room.
18. According to which formula, can we calculate the sound power level L_w of an air duct system?
19. Draw a representation graph of a pure tone and indicate the vibration. Do this also for the most common sound in society.
20. What is the propagation velocity of sound waves in air applicable for all frequencies, with which we work in the building sector?
21. Calculate the wavelength λ for a frequency of $f = 1000$ Hz.
22. Calculate the lower and upper limit frequency of the octave band of 63 Hz.
23. Calculate the middle frequency of the octave band with a lower limit frequency 180 Hz and 355 Hz as the upper limit.
24. At what frequency is our hearing consistent with the sound pressure level meter?
25. Which middle frequencies limit the speech area?
26. What is meant by a sound spectrum?

27. Which frequencies are let through by a 63 Hz octave filter ?
28. In what way we can determine the overall sound pressure level over the entire frequency range?
29. For what purpose do we turn the sound meter in the A- weighting filter?
30. Determine with the table in figure 10.14 the strengthening respectively. the weakening for an A-weighting at f = 4000 Hz and f = 125 Hz.
31. So, in which case is the shape of the spectrum (with linear, unfiltered values measured) important?
32. What can be said about the sound insulation of constructions?
33. In what way should car traffic noise be measured?
34. What do we mean by the equivalent sound pressure level L_{eq}?
35. And what is meant by total sound level L_A? Explain the difference.
36. What do the terms L_{10} and L_{90} mean?
37. Explain with examples how in daily life noise hindrance may occur.
38. Which noise levels may be considered allowable for homes respectively offices, in accordance with the Dutch Noise Abatement Act in areas along traffic routes?
39. What are the requirements with respect to the sound proofing of the façade?
40. Are these values absolute?
41. Are there requirements regarding industrial noise and noise from airplanes?
42. Where are the requirements for interior noise stated?
43. Which rules apply with respect to the measurement of noise levels?
44. Sketch what happens with sound when it hits a wall.
45. What part of the sound intensity I in W/m^2 is passed by a half-brickwall respectively a board door?
46. So, what do we use as a practical rule with regard to absorption and reflection?
47. Explain the concept of absorption of porous materials.
48. Which requirement is imposed on the air flow resistance of an absorbing material?
49. Which conditions have to be met with regard to the thickness of an absorption material? Draw a "good" situation. Explain this situation.
50. To improve the acoustics of a room one uses absorbent material, thickness 20 mm, applied against the walls using timber lats. The frequency the sound source produces the most disturbing is f = 2000 Hz. The lats should be mounted with 10 mm of felt (vilt). Give a clear outline of the construction with data.
51. What should approximately be the distance between the suspended ceiling and the underside of a concrete floor at f = 250 Hz?
52. For whatever reasons must we handle careful with most of the absorbent materials?
53. Mention some structural features that may be affected.
54. Can we simply paint these materials?
55. Describe how perforated panels work. At what frequency are they functional?
56. As in the previous question but now for non-perforated panels.
57. In what way can we reduce the noise level in acoustically hard areas? What materials can we use?
58. On what is the concept of 'square meters open window' (or m^2 sabin) or perfect absorbent material?
59. How can we find the total sound absorption A ?
60. How can we find the average sound intensity I?
61. And from which the sound pressure level L_p (in the reverberant field)?
62. What effect can we notice in the immediate proximity of a sound source?
63. If we want to reduce the noise level with additional absorption in a room with 7 dB what action should we take and what restrictions should we take? Use Figure 10.32.
64. Indicate with a drawing in which way by means of functional absorbers, per m^2 of a ceiling surface of absorption coefficient $a = 1.6$ can be achieved.

65. How is the concept of reverberation time T defined? Of which terms is it depending?
66. What is the formula of Sabine?
67. Which is the best reverberation time in a particular area?
68. Which values apply to a living room and for a classroom?
69. A room 8 m long, 5 m wide and 2.6 m high has the following finishes: parquet floor glued to the subfloor, ceiling battens 85 mm wide, 25 mm spacing. A long wall of brick masonry without finishing layer. The two short walls masonry of lime cement with plaster. A long wall 17,8 m^2 with a glass curtain wall a = 0.01 and the rest of this wall are cotton curtains, pleated 3:1. In the room are 14 seats, all unoccupied. Calculate the reverberation time of the room at the frequencies f = 250 Hz and f = 500 Hz.
70. Calculate the reverberation time of the same room as in question 71 at the frequencies f = 250 Hz and f = 500 Hz, but now on the floor: carpet 1.87 kg/m^2 with a layer 4.5 mm thick. All seats now are occupied.
71. How is the reverberation time for lower and higher frequencies adjusted?
72. What do we mean with diffusivity of a space?
73. What is the difference between a diffuse sound field and a direct sound field?
74. What applies to large venues with respect to the placement of the walls?
75. In what way should there be between direct sound and reflected (indirect) sound?
76. Give a sketch what measures can be taken in a large hall. Explain your sketch.
77. As in the previous problem, but now in a small room. Explain again your sketch.
78. In which case does echo occur?
79. What do we mean by the occurring of flutter echoes in sports halls?

11. Sound insulation

80. How is sound insulation distinguished? Explains this.
81. How is the sound insulation defined and displayed in a formula?
82. Which aspects determine the isolation of a homogeneous wall?
83. Under which reservation should the mass law be applied in practice?
84. Determine with this law, the insulation of a wall of 70 kg/m^2 at a frequency of f = 1000 Hz.
85. Similarly, for a wall of 500 kg/m^2, at f = 250 Hz.
86. Explain rule ‘larger mass leads to higher sound insulation’.
87. Similarly, the rule ‘higher frequency leads to increased sound insulation’.
88. Which formula is valid for the coincidence?
89. What do you notice about the frequently used construction system 70 mm thick plaster walls?
90. What is the influence of the weight on these walls?
91. What benefit can structures, composed of several layers, have, compared to homogeneous walls?
92. Describe such an ideal construction also in relation to the practical applicability.
93. What is meant by a mass-spring resonance regarding a cavity construction?
94. Which formula is used to find the resonance frequency f_0 in case of sound inciding perpendicularly?
95. Calculate the resonance frequency f_0 of double glazing 4 - 20 - 6 mm (m_{glass} = 2500 kg/m^3).
96. Similarly of 4 - 80 - 6 mm double glazing.
97. What can you say about both outcomes? (Question 97 and 98)
98. Is double glazing in all cases an improvement when it comes to insulation against traffic noise? Which requirement applies?
99. In what way is cavity resonance f_{sp} created? Explain with a sketch.
100. What is the impact on the sound insulation?
101. How can we describe an unwanted area in the resonant frequencies?
102. In what way can we suppress cavity resonances in closed structures or in glass constructions?

103. Explain chart 11.13 regarding the overall insulation curve of a cavity construction.
104. What details are important regarding the sound insulation *R* of a wall in which a door is mounted?
105. What does a difference of 20 dB isolation between wall and door mean?
106. What effect has a door of 1.6 m^2 and sound insulation *R* = 20 dB on a wall of 17 m^2, and *R* = 40 dB?
107. Calculate the situation of figure 11.15 when the wall is 10 meters long.
108. What effect does a gap have of 0.017 m^2 with *R* = 0 dB sound insulation in a wall of 17 m^2 with *R* = 40 dB?
109. Is the influence of such a gap on a wall with an even higher insulation value greater or less?
110. Determine from Figure 11.16 the insulation reduction for the case that for the wall the insulation were *R* = 60 dB.
111. What is the insulation for the combination wall + door as the wall insulation *R* = 50 dB would apply?
112. Give a sketch again how flanking sound transfer can take place.
113. What is the difference between the sound insulation of a wall between two rooms and the overall sound reduction between the two areas?
114. Give a sketch and show how lightweight stony partition walls perpendicularly placed to a wall with sufficient insulation can greatly reduce the insulation of that wall.
115. Give with a clear drawing of how all this can be improved (think of sound leakage).
116. Give a sketch to show how curtain walls passing the floors can negatively affect the flanking sound transmission and lead to sound leakage from floor to floor.
117. Give possible improvements.
118. In what ways can impact sound occur?
119. From what thickness is the insulation of a concrete floor is usually sufficient to prevent impact sounds caused by walking?

Sound insulation continued

1. What do we mean by the source room and receiving room when measuring the airborne sound insulation of a partition wall?
2. What do we mean by the correction term 10 log (S/A) and why do we use it?
3. What do we mean by the normalized airborne sound insulation D_{nT}?
4. Why isn't there made a correction for sound absorption in the source room?
5. How do we measure the reverberation time? Sketch a test setup.
6. What do we mean by the airborne sound insulation-index I_{lu}?
7. What do we mean by the typical (karakteristieke) airborne sound insulation-index $I_{lu;k}$?
8. What requirements should be made for a separating wall between dwellings?
9. What are the boundary conditions for the calculation of $I_{lu;k}$?
10. How should you interpret the requirements of the Building Decree?
11. At a noise measurement of a separating wall between dwellings, the following results:

Frequency *f*	125	250	500	1000	2000	*Hz*
Transmission L_z	88.	87.2	87.6	85.2	83.3	*dB*
Receiving L_o	61.6	53.4	42.7	35.6	30.2	*dB*
Reverberation time *T*	0.9	0.9	1	0.8	0.8	*s*

Calculate the insulation-index I_{lu} for airborne sound of this wall.

12. At a noise measurement of a separating wall between dwellings, the following results:

Frequency *f*	125	250	500	1000	2000	*Hz*
Transmission L_z	83.2	85.4	84.7	83.7	82.2	*dB*
Receiving L_o	56.3	52.6	46.5	38.4	30.7	*dB*
Reverberation time *T*	0.8	0.7	0.8	0.8	0.7	*s*

Calculate the insulation-index I_{lu} for airborne sound of this wall.

13. How can we measure impact sound insulation?
14. What requirements must we make regarding impact sound insulation against noise from other dwellings?
15. With an impact sound insulation measurement the following results:

Frequency f	125	250	500	1000	2000	Hz
Sound Pressure level L_{co}	63.4	65.5	69.3	71.1	69	dB
Reverberation time T	0.9	1	1	0.9	0.8	s

Calculate the insulation index I_{co} for impact sound.

16. With an impact sound insulation measurement the following results:

Frequency f	125	250	500	1000	2000	Hz
Sound Pressure level L_{co}	67.3	69.4	73.6	75.8	69.5	dB
Reverberation time T	0.9	1	1.1	1	0.8	s

Calculate the insulation index I_{co} for impact sound.

17. How is the sound insulation of a façade measured? Which parts must we also measure and from which measuring position?
18. How do we correct the reflection of the façade ? This correction is always the same?
19. What problem arises when a car passes by?
20. Why does the Building Decree use a corrected value of the sound proofing value G_A?
21. What is the formula for the sound insulation G_A of the façade in dB, to be calculated in octave band i?
22. Which octave bands are relevant, as well as with indoor sound insulation?
23. Why are calculations in the total sound insulation of a known spectrum in dB(A) needed?
24. In what way can the weighted octave values be deducted from the outer level in dB (A)?
25. Does the standard spectrum apply in absolute terms for traffic noise?
26. What is the correction in case of railway noise and aircraft noise?
27. Why should gap term K be used and which construction requirement is taken as a starting point for this?
28. What problem arises in sound proofing of older buildings?
29. How can a control measurement of the sound insulation of the facade be carried out?
30. At what distance from the façade do we measure the sound pressure level inside and how on the inside?
31. In what way can we obtain an indication?
32. What is the formula for the normalized level difference per octave band?
33. How is the sound insulation of the façade G_i determined?
34. How can you then calculated, using the standard spectrum, the sound insulation G_A in dB (A)?
35. What does the correction of 3 dB reflection term regarding façade measurement remind you of?
36. When is the correction 0 dB? Mention some examples.
37. Which requirements apply to the Building Decree for a façade sound insulation $G_{A;k}$?
38. For which structures is the gap term R_A = 30 dB (A)?
39. For which types of sound applies this?
40. What applies always as the minimum requirement on noise insulation of facades?
41. What value should this be taken as a house façade has a noise load of 55 dB (A)?
42. May one always built inside a noise zone?
43. In which case can't one build buildings holding noise-sensitive areas at all?
44. Where deviate the requirements for aircraft sound compared to others?

12. Applied sound insulation

1. What is flanking sound transmission and how does this occur in practice?

2. What can we do against this flanking sound transmission?
3. What should be considered when looking for the right place for doors and windows in walls of offices etc. during the design?
4. What provision should therefore be made into door frames?
5. Give a sketch again how sound leakage at the connection of a building wall may occur at a façade.
6. Give a sketch again how flanking sound transmission can occur when connecting ceilings to lightweight partitioning walls.
7. What requirement to ceiling and the method of application should be made?
8. In what way can you make a provision for lighting fittings?
9. Sketch the method how a sound insulation $I_{lu} \geq -10$ dB can achieved.
10. What provision should be applied in a cove and unit housing when connecting to a partition?
11. How can this be done with a cable ducts?
12. How can sound transmission through air ducts be prevented?
13. In what way can a half-brick masonry wall achieve an airborne sound insulation $I_{lu} \geq -10$ dB?
14. How can 90 mm thick poriso-masonry and twice 70 or 90 mm poriso masonry airborne sound insulation $I_{lu} \geq -10$ dB be achieved?
15. How can a sound insulation $I_{lu} \geq -10$ dB be achieved using aerated concrete blocks?
16. What should be checked if making a construction of double walls with a mortar joint between the walls?
17. What problem arises when both halves wall shrink loose?
18. How can an air insulation $I_{lu} \geq 0$ dB be realized with a monolithic wall of concrete or stone?
19. How can a sound insulation $I_{lu} \geq 0$ dB with a cavity wall of porisosteen, aerated concrete blocks or similar material be achieved?
20. How can a sound insulation $I_{lu} \geq 0$ dB with a cavity construction of brick or heavy concrete block be achieved?
21. How can a sound insulation $I_{lu} \geq 0$ dB with a unanchored cavity wall be achieved?
22. Based on what principle can a reasonable sound insulation be achieved with lightweight walls and partition walls?
23. How can an airborne sound insulation $I_{lu} \geq 15$ dB with an in situ light wall be achieved?
24. Why dopolystyrene and other "closed cell" materials not help against noise if used to fill a cavity?
25. What causes are responsible for an approximately 5 dB lower value in practice than in theory?
26. For what purpose are facing walls used in existing situations?
27. Describe the layout when studs are applied.
28. What improvement in sound insulation can be reached when placing a thin flexible wall for a monolithic wall of masonry or concrete with a mass $m \geq 200$kg/m^3?
29. With which heavy floor construction can an air insulation $I_{lu} \geq 0\ dB$ usually be achieved?
30. How will flanking sound transmission not be annoying?
31. Is a wooden floor suitable as separating floor?
32. Which defects make a free hanging ceiling inside a house actually necessary?
33. What problem can occur with too narrow a cavity?
34. What can regarding the impact sound insulation of floors be stated?
35. What advantage can be gain with a screed that is equipped with a light aggregate, such as cork or wood?
36. What is the impact of a typical carpet and linoleum?
37. In which case can, for example, needle felt already give a big improvement?
38. Which floor coverings may give an improvement in the sound insulation up to about 15 dB?
39. Which floor coverings may give an improvement in the sound insulation of 25 dB?
40. How does the floor covering material be helpful to meet the requirements of the NEN 1070?
41. What can be therefore be the case in situations with higher requirements or lighter structures?
42. What is a floating covering floor and what is essential?

43. What is the relationship between the stiffness of the resilient layer and the weight of the floor?
44. How can sound bridges occur and how can they be prevented?
45. How can vibration noise reduction in machine set-ups be taken care off?
46. What can generally be said about fixing water pipes, sewers, sanitary appliances and central heating pipes?
47. What does all this mean for the slashing of pipes in walls of noise sensitive areas?.
48. Which requirement is therefore made to the fastening means for pipes? Sketch an attachment point.
49. To which walls may nothing at all be attached?
50. To what for devices should be sought?
51. Which two problems are only difficulty to solve at penetrations of ducts and cables? What kind of requirement is needed?
52. Sketch a good solution with a bushing with screw rosettes. Also a solution with sealant and mineral wool respectively polyurethane foam.

Appendix units

1. What are the basic units of the SI system? Specify the units.
2. How much is K = 23 °C, and how much °C is 330 K?
3. A motor produces for 15 minutes a power output of 1250 Watts. Calculate the energy consumption of this engine.
4. The energy consumption of an engine was 2 kWh at a power of
5. 5000 Watts. Calculate the time that the engine was operating.
6. A heater consume 4 kWh for 50 minutes. Calculate the net power of the element.
7. How many joules is 15 kWh?

Answers of the questions of the book Building Physics

1. Heat, heat transport, thermal insulation

5. 40 W/m^2
6. 10.5 and 12.5 W/m^2
10. 393 W/m^2
11. 291.6 K
12. 0.95
15. 350 W/m^2
16. 326 W/m^2
17. 30.1 W/m^2
18. 296 W/m^2
19. 125 W/m^2
28. R_c = 0.47 m^2K/W; R = 0.64 m^2K/W; U = 1.57 W/m^2K, q = 47.09 W/m^2
    Temp. line = -10, -8, 12, -3.63, 4.38, 13.37, 13.88, 20 °C
    Max. vapour pressure line = 258, 305, 451, 835, 1533, 1584, 2336 Pa
    Occ. vapour pressure line = 219, 219, 640, 661, 954, 1051, 1051 Pa
    p_i = 1051 Pa; p_e = 219 Pa; vapor pressure = 832 Pa
    Diffusion resistance = 1.2 + 0.1 + 0.8 + 0.3 = 2.4 m
    Condensation in this construction = 309.8 g/m^2 in 60 days.
29. R_c = 1.76 m^2K/W; R = 1.93 m^2K/W; U = 0.52 W/m^2K, q = 15.54 W/m^2
    Temp. line = -10, -9.39,-7.90, 14.85, 17.87, 17.98, 20°C
    Max. vapour pressure line = 258, 273, 311, 1687, 2038, 2059, 2336 Pa
    Occ. vapour pressure line = 219, 219, 635, 666, 955, 1051, 1051 Pa
    p_i = 1051 Pa; p_e = 219 Pa; vapor pressure = 832 Pa
    Diffusion resistance = 1.2 + 0.1 + 0.8 + 0.3 + 2.4m
    Condensation in this construction = 524.1 g/m^2 in 60 days
30. R_c = 0.31 m^2K/W; R = 0.48m^2K/W; U = 2.10 W/m^2K, q = 62.86 W/m^2
    Temp. line = -10, -7.49,-5.27, 1.35, 11.83, 20°C
    Max. vapour pressure line = 258, 323, 391, 673, 1385, 2336 Pa
    Occ. vapour pressure line = 206, 206, 894, 1166, 1168, 1168 Pa
    p_i = 1168 Pa; p_e = 206 Pa; vapor pressure = 962 Pa
    Diffusion resistance = 60 + 23.7 + 0.2 = 83.9 m
    Condensation in this construction = 28.8 g/m2 in 60 days
31. R_c = 2.16 m^2K/W; R = 2.33m^2K/W U = 0.43 W/m^2K,q = 12.88 W/m^2
    Temp. line = -10, -9.48,-9.03, 14.82, 16.18, 18.33, 20 °C
    Max. vapour pressure line = 258, 270, 281, 1684, 1837, 2104, 2336 Pa
    Occ. vapour pressure line = 206, 206, 813, 927, 1166, 1168, 1168 Pa
    p_i = 1168 Pa; p_e = 206 Pa; vapor pressure = 962 Pa
    Diffusion resistance = 60 + 11.3 + 23.7 + 0.2 = 95.1 m
    Condensation in this construction = 23.5 g/m2 in 60 days
32. R_c = 0.13 m^2K/W; R_l = 0.39m^2K/W U = 2.60 W/m^2K, q = 12.98 W/m^2
    Temp. line = 14, 15.7, 16.9, 17.3, 19 °C
    R_c = 1.27 m^2K/W; R_l = 1.53 m^2K/W U = 0.65 W/m^2K, q = 3.27 W/m^2
    Temp. line = 14, 14.4, 18.2, 18.5, 18.6, 19 °C
33. R_c = 0.35 m^2K/W; R = 0.52 m^2K/W U = 1.93 W/m^2K, q = 61.89 W/m^2
    Temp. line = -10, -7.52, -5.70, 2.55, 11.83, 13.95, 22 °C
    Max. vapour pressure line = 258, 322, 377, 734, 1386, 1592, 2641 Pa
    Temp. line = -10, -7.52,-5.70,
    Occ. vapour pressure line = 219, 219, 1289, 1315, 1321, 1321, Pa
    p_i = 1321 Pa; p_e = 219 Pa; vapor pressure = 1101 Pa
    Diffusion resistance = 50 + 1.2 + 0.2 + 0.1 = 51.5 m
    Condensation in this construction = 619.6 g/m2 in 60 days
34. R_c = 1.32 m^2K/W; R = 1.49m^2K/W U = 0.67 W/m^2K, q = 21.44 W/m^2

Temp. line = -10, -9.14,-8.51, 12.40, 15.26, 18.48, 19.21, 22 °C
Max. vapour pressure line = 258, 279, 295, 1439, 1732, 2125, 2225, 2641 Pa
Occ. vapour pressure line = 219, 219, 1288, 1289, 1315, 1319, 1321, 1321 Pa
p_i = 1321 Pa; p_e = 219 Pa; vapor pressure = 1101 Pa
Diffusion resistance = 50 + 0.1 + 0.2 + 0.2 = 51.5 m
Condensation in this construction = 649.0 g/m^2 in 60 days

35. R_c = 1.86 m2K/W; R = 2.60 m2K/W U = 0.49 W/m2K,q = 14.78 W/m2 Temp. line = -10, -9.41,-8.52, 13.38, 17.57, 18.08, 20 °C
Max. vapour pressure line = 258, 272, 294, 1534, 1743, 2007, 2336 Pa
Occ. vapour pressure line = 194, 194, 917, 1029, 1045, 1051, 1051 Pa
p_i = 1051 Pa; p_e = 194 Pa; vapor pressure = 832 Pa
Diffusion resistance = 0 + 9.0 + 1.4 + 0.1 = 10.7 m
Condensation in this construction = 78.3 g/m^2 in 60 days

42. 252 000 J/m^2

45. Total expansion = 109 mm. At 18 joints 6 mm and at 20 joints a clearance of 5 mm

2. Moisture, moisture transport, condensation

6. 2066.3 N/m^2
7. 10.65 gr/m^3
10. 2.73 gr/m^3
11. 3.88 gr/m^3 and 2.33 gr/m^3
18. 0.74
19. 0.72
20. 0.89
30. See question 28 Chapter 1.
31. See question 29 Chapter 1.
32. See question 33 Chapter 1.
33. See question 34 Chapter 1.
34. See question 35 Chapter 1.

4. Lighting

24. 5%
25. 14.7%

10. Acoustics

21. 0.34m
22. 45 and 90 Hz
71. V = 104 m^3
    Abs. 250 Hz = 38.0 m^2 o. w.;T = 0.46 s
    Abs. 500 Hz = 38.6 m2o. w. ; T = 0.45 s
72. V = 104 m3
    Abs. 250 Hz = 48.8 m2 o. w.;T = 0.38 s
    Abs. 500 Hz = 66.5 m2o. w. ; T = 0.26 s

11. Sound insulation

95. 173.2 Hz
96. 86.5 Hz
106. 61.5 Hz
107. 37 Hz

Sound insulation (continued)

11.

Frequency	125	250	500	1000	2000	Hz
$10\log\left(\frac{T}{T_0}\right)$	2.6	2.6	3.0	2.0	2.0	s
standardized value	29.3	36.4	47.9	51.6	55.1	dB
insulation difference	-4.7	-6.6	-2.2	-1.4	1.1	dB

$A = -3\ dB$ $B = -4\ dB$ $C = -3\ dB$

The insulation index L_{lu} for airborne sound = $-4\ dB$

12.

Frequency	125	250	500	1000	2000	Hz
$10\log\left(\frac{T}{T_0}\right)$	2.0	1.5	2.0	2.0	1.5	s
standardized value	29.3	36.4	47.9	51.6	55.1	dB
insulation difference	-5.1	-8.7	-9.1	-5.7	-1.0	dB

$A = -6\ dB$ $B = -7\ dB$ $C = -6\ dB$

The insulation-index L_{lu} for airborne sound = $-8\ dB$

15.

Frequency	125	250	500	1000	2000	Hz
$10\log\left(\frac{T}{T_0}\right)$	2.6	3.0	3.0	2.6	2.0	s
insulation difference	9.2	3.5	-0.3	-2.5	3.0	dB

$A = 3\ dB$ $B = 1\ dB$ $C = 2\ dB$

The insulation-index L_{co} for airborne sound = $1dB$

16.

Frequency	125	250	500	1000	2000	Hz
$10\log\left(\frac{T}{T_0}\right)$	2.6	3.0	3.4	3.0	2.0	s
insulation difference	5.3	-0.4	-4.2	-6.8	2.5	dB

$A = 1\ dB$ $B = 3\ dB$ $C = -3\ dB$

The insulation-index L_{co} for airborne sound = $-3dB$

Appendix units

3. 1 125 000 Ws = 1 125 000 J = 0.312 kWh
4. 1440 s = 24 min
5. 4800 W