Building Physics

1. Heat and moisture transfer - thermal insulation

ir. A. Zeegers, Government Real Estate Agency, The Hague
ir. A.C. van der Linden, AaCee Building & Environment, Delft

Klimapedia, August 2022

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.

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.

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).

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/(m². If a wall has a surface area of 15 m², 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

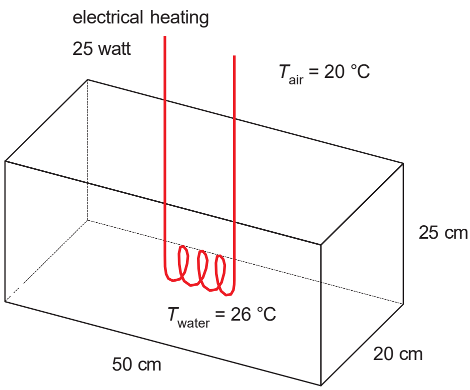


Figure 1.1 Example of heat flow

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:

$$q_c = \alpha_c \cdot (T_1 - T_2) \; [\mathrm{W/m^2}]$$

The meaning of the symbols is:

q_c	the heat flow density in $\mathrm{W/m^2}$
α_c	the heat transfer coefficient in $\mathrm{W/(m^2 \cdot K)}$
$T_1 - T_2$	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 α_c are:

- indoors: α_c = 2 to 2.5 $\mathrm{W/(m^2 \cdot K)}$;
- outdoors: average wind α_c = 19 to

20 $\mathrm{W/(m^2 \cdot K)}$, strong wind α_c = 100 $\mathrm{W/(m^2 \cdot K)}$.

Heat transport through radiation

Heat transport through radiation is part of the electromagnetic spectrum.

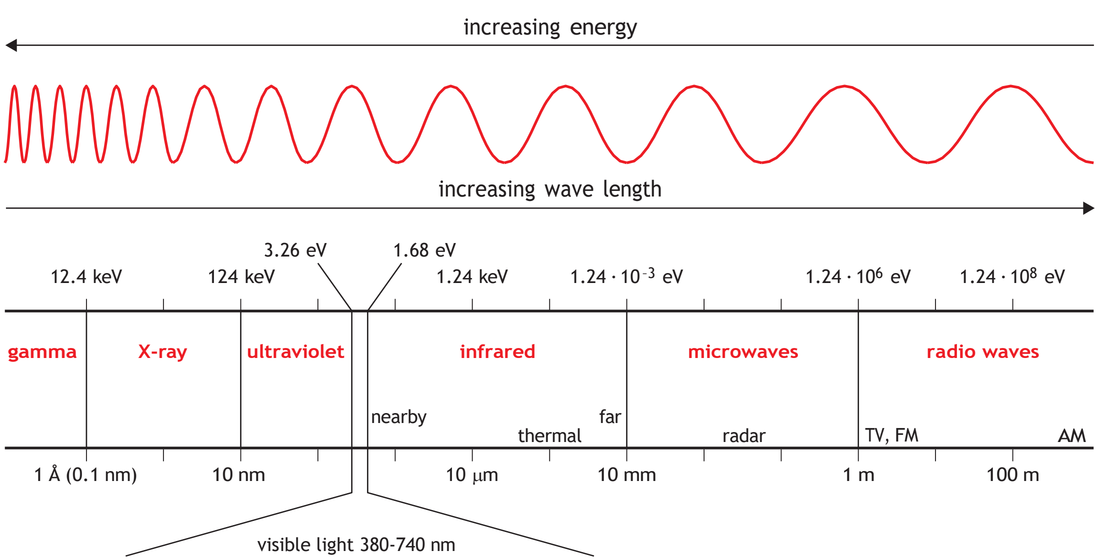


Figure 1.2 Electromagnetic radiation

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.

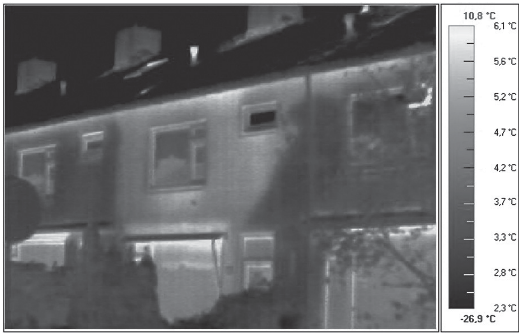


Figure 1.3 Temperature portrayed by an infrared camera

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:

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

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

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.

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

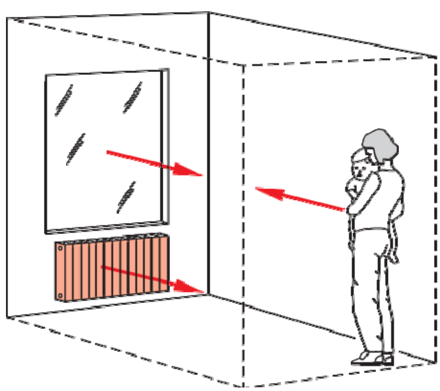


Figure 1.4 Emissions of radiation from person, glass and radiator

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.

radiation	trans-mission	reflection	absorption
sunlight	86%	9%	5%
heat radiation	0%	10%	90%

Figure 1.5 Transmission, reflection and absorption normal glass

Figure 1.6 White paint preventing overheating

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:

$$q_s = \frac{\epsilon_1 \cdot \epsilon_2}{\epsilon_1 - \epsilon_1 \cdot \epsilon_2 + \epsilon_2} \cdot 56.7 \cdot 10^{-9} \cdot (T_1^4 - T_2^4)$$

[W/m²]

The meaning of the symbols is:

q_s the net radiation transfer in W/m²
ϵ_1, ϵ_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.

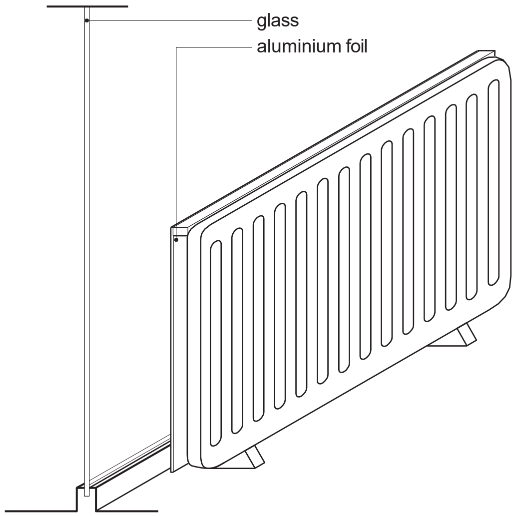


Figure 1.7 Heat shield behind radiator

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

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

The meaning of the symbols is:

q_s heat transfer through radiation in W/m²
α_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 α_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/(m·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.

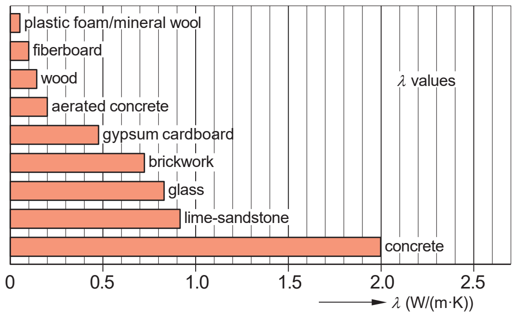


Figure 1.8 Comparison of the heat conduction coefficients of several different materials

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/λ by the thickness (*d*).

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

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

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

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

material	heat conduction coefficient λ [W/(m·K)]	thickness d [m]	heat resistance $R_m = \frac{d}{\lambda}$ [m²·K/W]
concrete	2.0	0.18	$\frac{0.18}{2.0} = 0.09$
chipboard	0.2	0.018	$\frac{0.018}{0.2} = 0.09$
insulation material	0.04	0.10	$\frac{0.10}{0.04} = 2.50$

Figure 1.9 Examples of heat resistance levels

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.

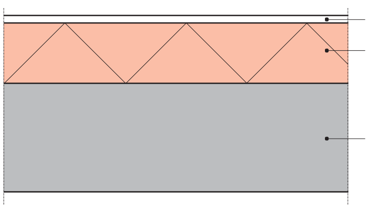


Figure 1.10 Multi-layered construction

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:

$$R_c = R_{m1} + R_{m2} + R_{m3} + \dots$$

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 [m²·K/W]
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 ($R = 1/\alpha$).

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 m²·K/W
R_{se} = 0.04 m²·K/W

These values are based on the following assumptions for convection and radiation transfer of heat: $\alpha_{csi} = 2$ W/(m²·K); $\alpha_{ssi} = 5.7$ W/(m²·K); $\alpha_{cse} = 20$ W/(m²·K); $\alpha_{sse} = 5$ W/(m²·K). With $R_s = 1/(\alpha_c + \alpha_s)$ [m²·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 [m²·K/W]
R_{si} heat transfer resistance at the inside surface [m²·K/W]
R_c heat resistance of a (construction) part [m²·K/W]
R_{se} heat transfer resistance at the outside surface [m²·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 or crawlspace	0.17	0.17
	floor 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 constructions	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).

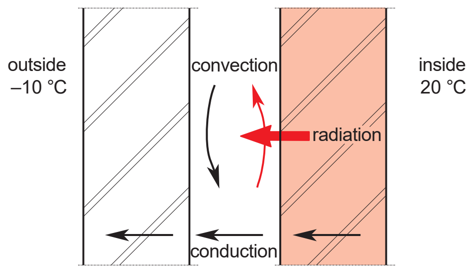


Figure 1.13 Heat transfer in cavity constructions

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:

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

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

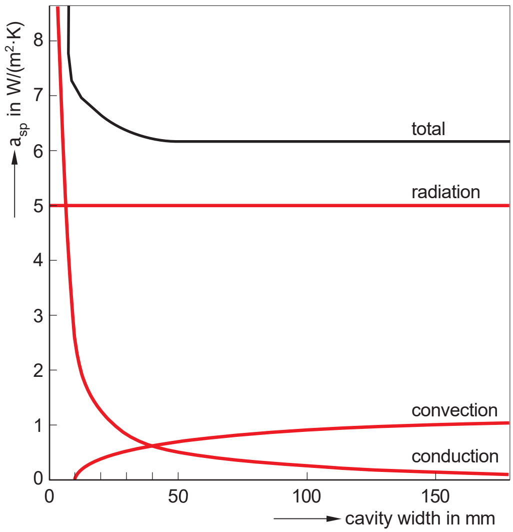


Figure 1.14 Heat transport through vertical air cavities through conduction, radiation and convection, depending on width of cavity: approximate indication of transfer coefficient α_{sp}

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.

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:

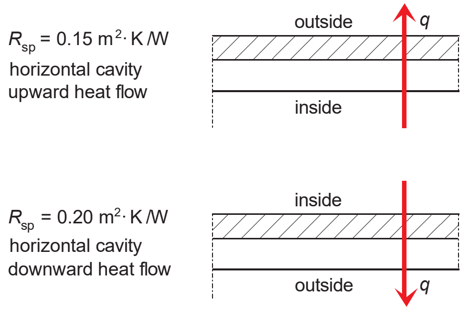


Figure 1.15 Heat resistance of horizontal cavity

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

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:

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

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·K/W and R_{se} = 0.04 m^2·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).

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

	R_c [m²·K/W]	R_T [m²·K/W]	U_T [W/(m²·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

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:

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

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:

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

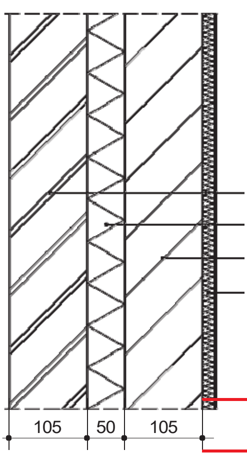
The meaning of the symbols is:

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



construction layer	d [m]	λ [W/(m·K)]	$R_{m;i}$ [m²·K/W]	$\Delta T_{m;i}$	T [°C]
outside air					−10
R_{se}			0.04	0.73	−9.3
brickwork	0.105	1.2	0.09	1.60	−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

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).

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.

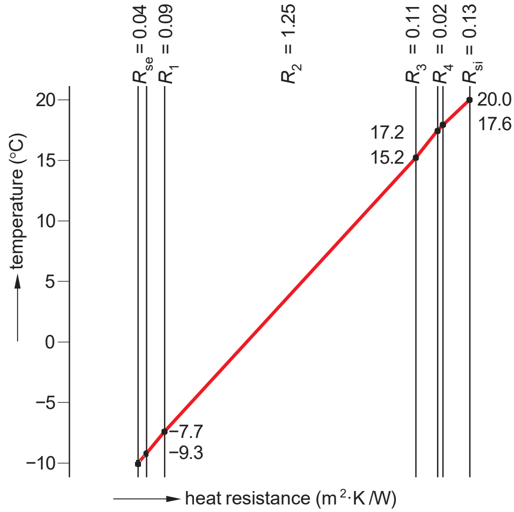


Figure 1.20 Determining the temperature progression using graphs

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.

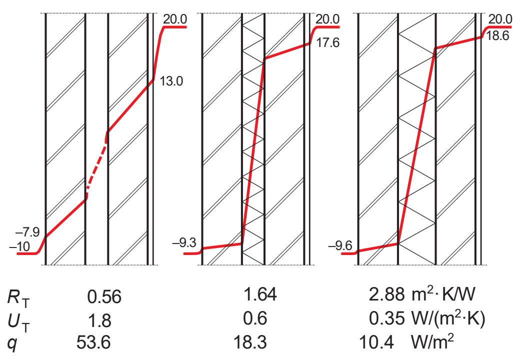


Figure 1.21 Temperature progression, heat resistance, heat transmission coefficient and heat loss (heat flow density) at 30 °C for several cavities

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.

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).

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

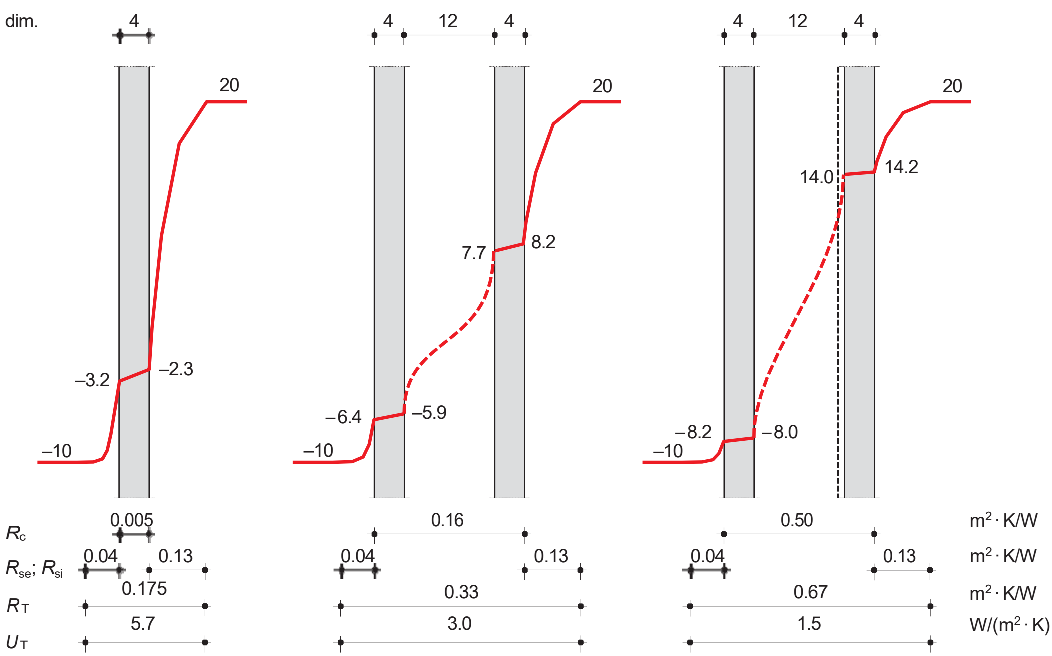


Figure 1.22 Temperature progression in single-glazing, double-glazing and high-efficiency glass

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.

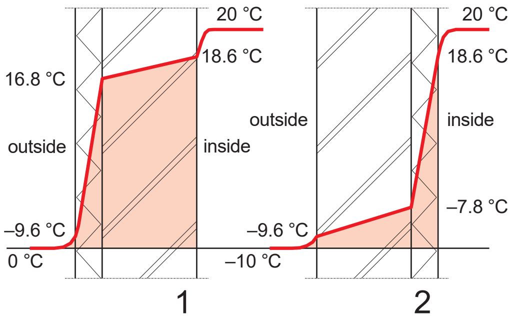


Figure 1.23 Insulation on the inside and outside of the wall, influence on heat accumulation

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:

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

The meaning of the symbols is:

- Q the amount of heat that is accumulated in the construction layer per m^2
- ρ the density of the material in kg/m^3
- 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/m² is being 'supplied'.

	d [m]	*ρ* [kg/m³]	*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:

$$\frac{-9.6 + 16.8}{2} = 3.6\ ^\circ\mathrm{C}$$

And for the brickwork:

$$\frac{16.8 + 18.6}{2} = 17.7\ ^\circ\mathrm{C}$$

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:

$$Q_{acc} = 0.1 \cdot 200 \cdot 840 \cdot 13.6 = 228 \cdot 10^3\ \mathrm{J/m^2}$$

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

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

This means the total accumulation is:

$$Q_{acc;tot} = 228 \cdot 10^3 + 9284 \cdot 10^3$$

$$= 9512 \cdot 10^3\ \mathrm{J/m^2}$$

The time needed to heat up the construction is therefore:

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

or 10.6 hours

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

$$\frac{-9.6 - 7.8}{2} = -8.7\ ^\circ\mathrm{C}$$

And for the insulation material:

$$\frac{-7.8 + 18.6}{2} = 5.4\ ^\circ\mathrm{C}$$

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:

$$Q_{acc} = 0.21 \cdot 1900 \cdot 840 \cdot 1.3$$

$$= 436 \cdot 10^3\ \mathrm{J/m^2}$$

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

$$Q_{acc} = 0.1 \cdot 200 \cdot 840 \cdot 15.4$$

$$= 259 \cdot 10^3\ \mathrm{J/m^2}$$

The total accumulation is therefore:

$$Q_{acc;tot} = 436 \cdot 10^3 + 259 \cdot 10^3$$

$$= 695 \cdot 10^3\ \mathrm{J/m^2}$$

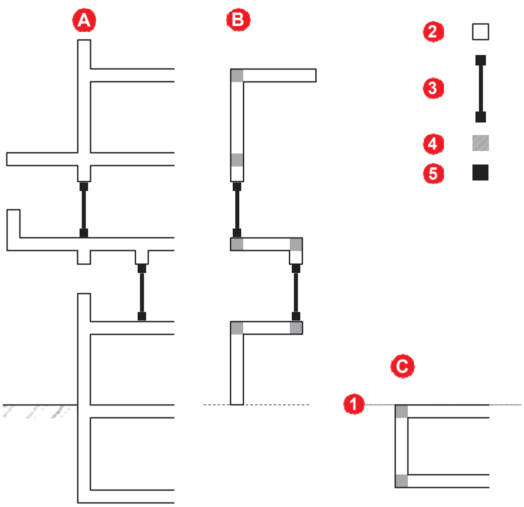
The length of time needed to heat up the construction is now:

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

or 0.8 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.



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)

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.

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:

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

The meaning of the symbols is:

$A_{T;i}$ the projected surfaces of the level element *i* of the outside partition construction [m^2]

$U_{C;i}$ the heat transmission coefficient of the level element *i* of the outside partition construction [W/(m^2·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/(m·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).

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.

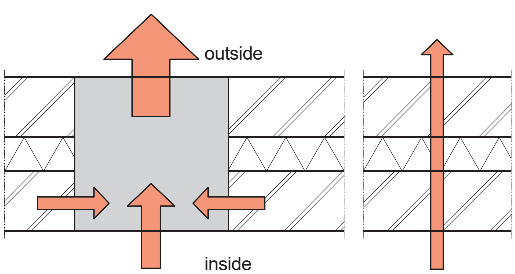


Figure 1.25 Extra heat loss at thermal bridge through indirect supply of heat

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

- depth of the construction: 1 m[1]
- brickwork: $\lambda = 1.0$ W/(m·K)
- insulation: $\lambda = 0.04$ 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

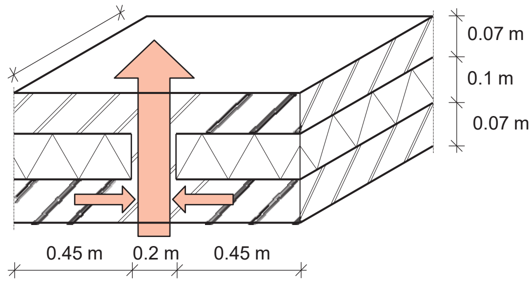


Figure 1.26 Thermal bridge

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.

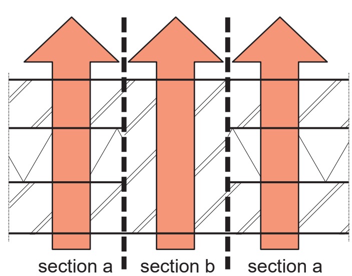


Figure 1.27 Heat flows R' value

The construction is divided into sections, perpendicular to the ground surface. Each section has the same profile, and each is made up of one ore 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:

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

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:

$$R' = \frac{A_{con}}{A_a U_a + A_b U_b} = \frac{0.9 + 0.2}{0.9 \cdot 0.36 + 0.2 \cdot 2.44}$$

$$= 1.37 \text{ m}^2\cdot\text{K/W}$$

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).

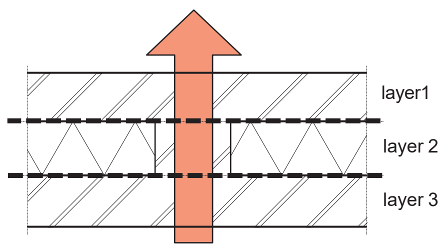


Figure 1.28 Determining the R'' value

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:

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

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:

$$\lambda_1'' = 1 \text{ W/(m·K)}$$

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

$$\lambda_3'' = 1 \text{ W/(m·K)}$$

The minimum heat resistance of the construction is then:

$$R'' = \frac{0.07}{1} + \frac{0.1}{0.21} + \frac{0.07}{1} = 0.62 \text{ m}^2\text{·K/W}$$

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.

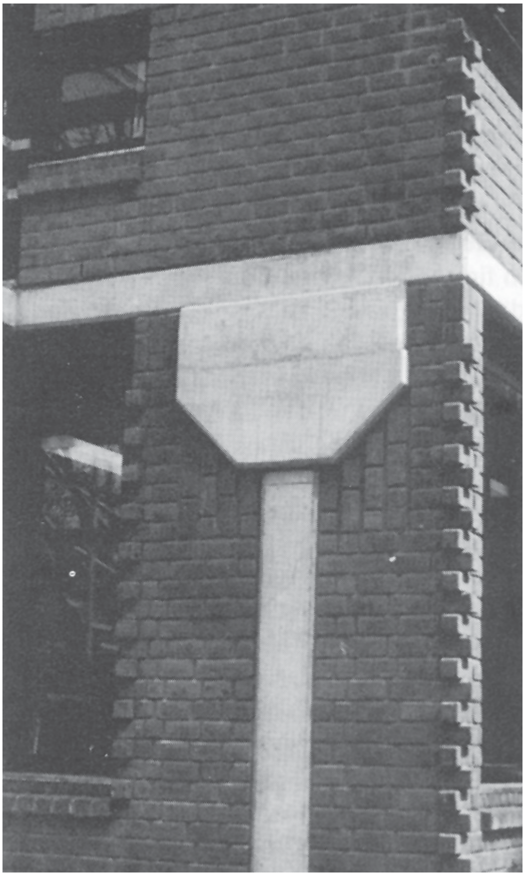


Figure 1.30 Concrete column and floor edge forming a thermal bridge

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.

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).

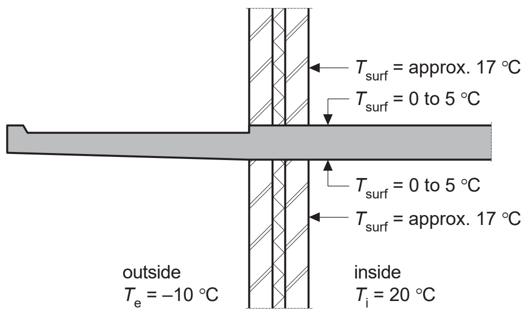


Figure 1.32 Concrete cantilever

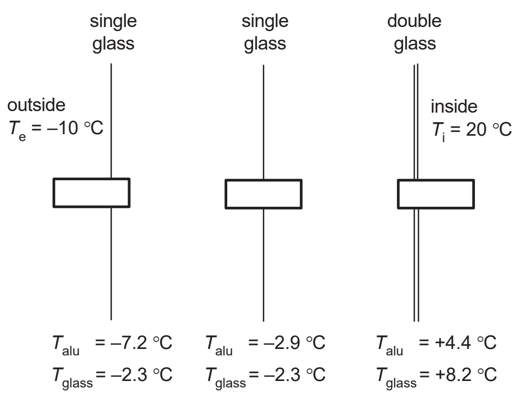


Figure 1.33 Influence on surface temperature of presence of aluminium hollow cross-section

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.

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 α. 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.

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

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

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.

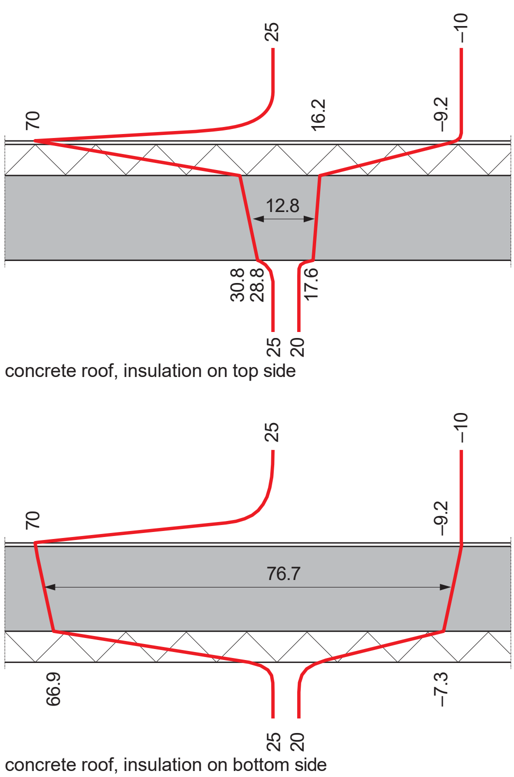


Figure 1.35 Insulated concrete roof temperature distribution

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.

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/m^3). 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/m^2 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 m^3
R the specific gas constant (for vapour: $R = 462$ J/(kg·K))
T the absolute temperature in K
c the concentration in kg/m^3

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 p_{max} 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 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.

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.

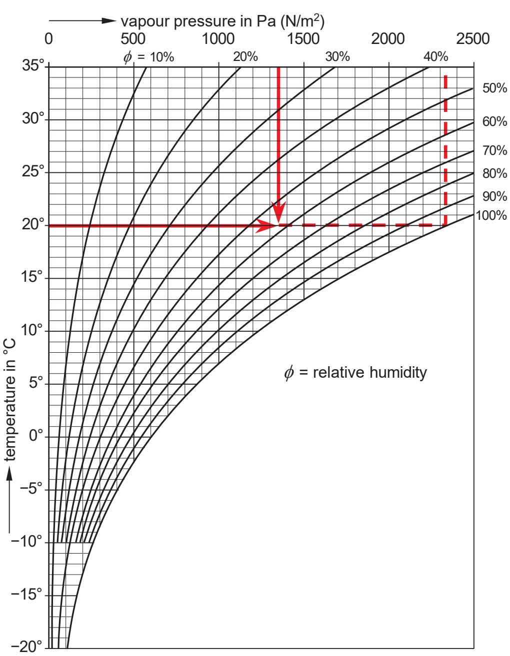


Figure 2.2 Vapour pressure p = 1350 Pa, relative humidity ϕ = 58%

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:

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

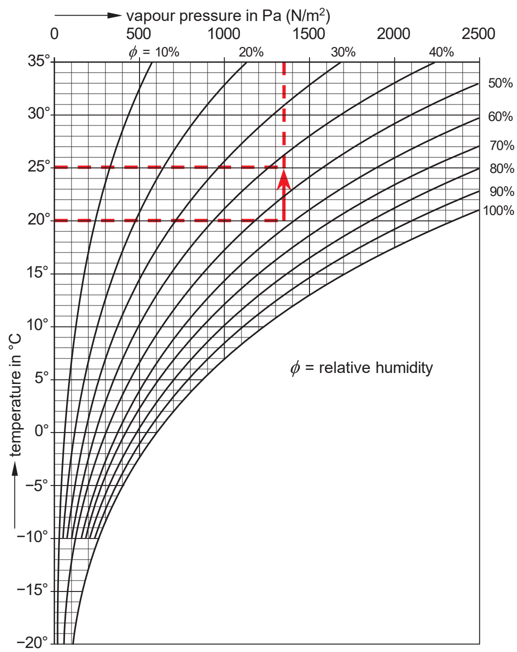


Figure 2.3 If the air heats up from 20 °C to 25 °C, relative humidity drops from ϕ = 58% to ϕ = 43%

Example figure 2.3

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:

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

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 $c = 0.43 \cdot 23.05 = 9.9$ g/m^3 instead of 10 g/m^3. It's only a small difference, but it is a difference.
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.

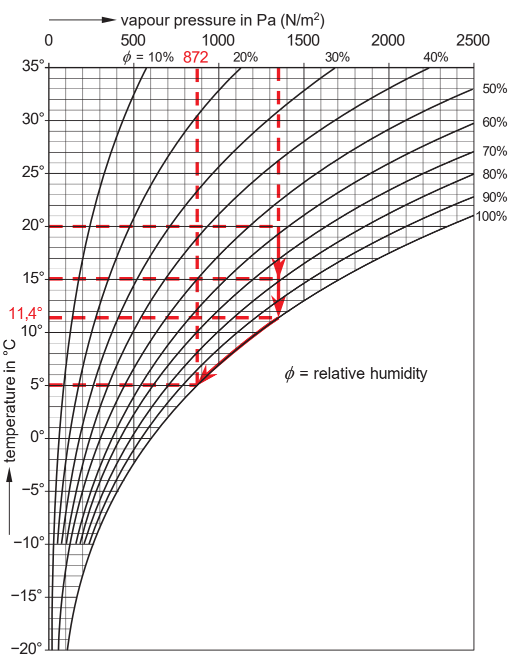


Figure 2.4 If the air cools by 5 °C, this causes the vapour in the air to condense

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.

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.

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.

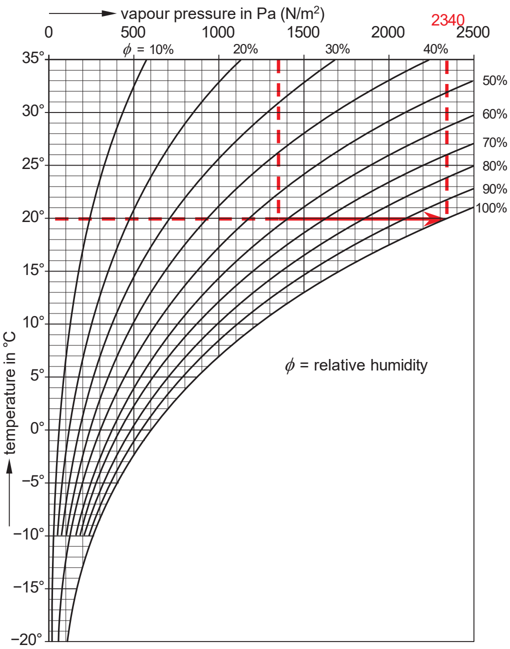


Figure 2.5 Addition of vapour also leads to condensation

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/m^3
Prevailing water vapour pressure equals $p = 1350$ Pa
Prevailing water vapour concentration equals $c = 10$ g/m^3
Relative humidity $\phi = 58\%$

If you supply moisture to air of 20 °C and $p = 1350$ Pa ($c = 10$ g/m^3), the vapour pressure will change. If more than 7.28 g/m^3 is supplied, condensation will take place (the maximum water vapour concentration at 20 °C is after all 17.28 g/m^3 (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.

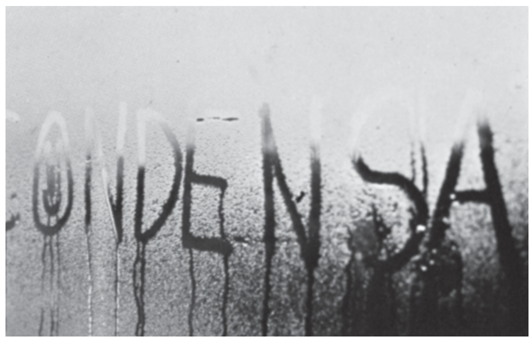


Figure 2.7 If the temperature of the window is lower than the dew point temperature of the air on the inside, then condensation will occur.

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/m^3) 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 $\phi = 80\%$ 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:

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

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).

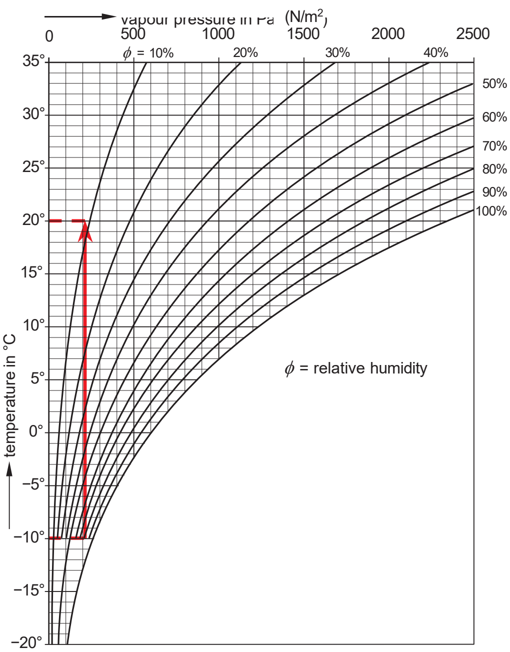


Figure 2.8 Outside air contains little vapour in the winter. This leads to a low level of relative humidity.

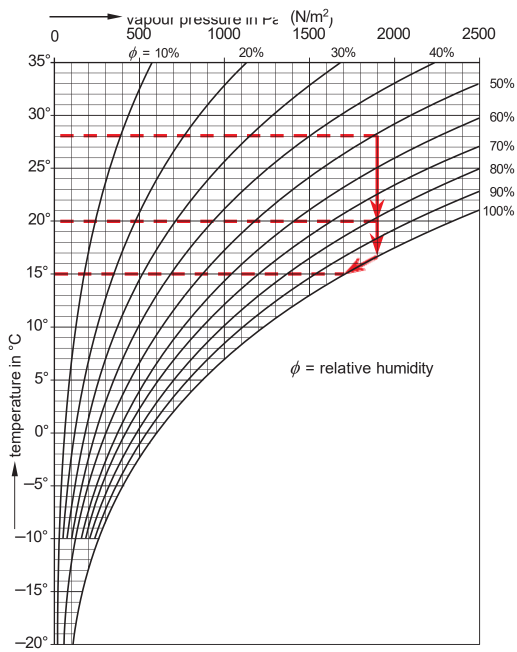


Figure 2.9 Outside air in the summer contains a lot of vapour. This can cause the relative humidity of a cool cellar to be high, which can lead to condensation.

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-m³ 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:

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

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.

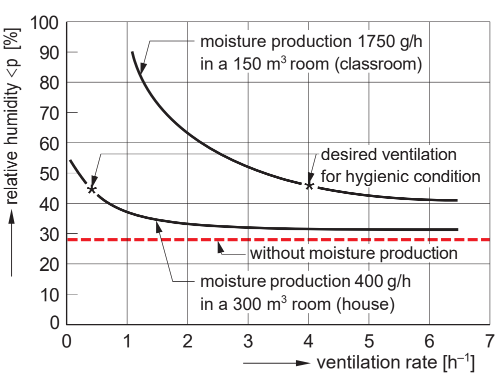


Figure 2.10 Relative humidity ϕ depending on the rate of ventilation in a room/space, temperature $\theta_i = 20$ °C

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/($m^2 \cdot h$) disappears through a normal cavity wall. For a house with a large proportion of outside-facing walls (100 m^2) 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.

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.

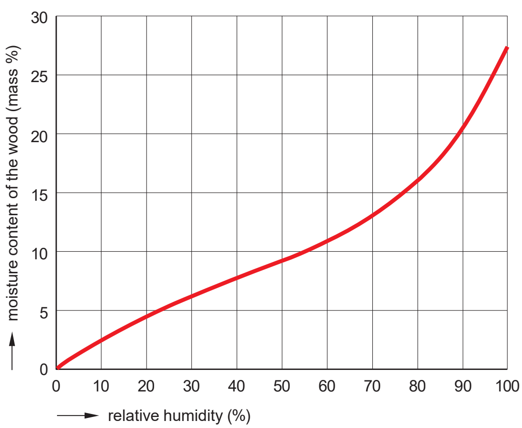


Figure 2.11 Hygroscopic moisture content of wood in relation to humidity

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 m^2, 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.

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.

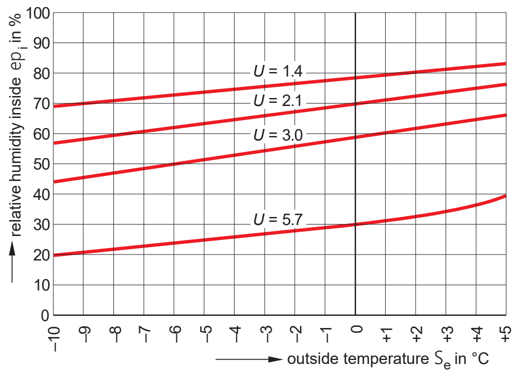


Figure 2.13 Outside temperature at which condensation can be expected for a given relative indoor humidity, for various types of glass (θ_i = 20 °C)

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:

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

For calculating the surface temperature this results in:

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

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.

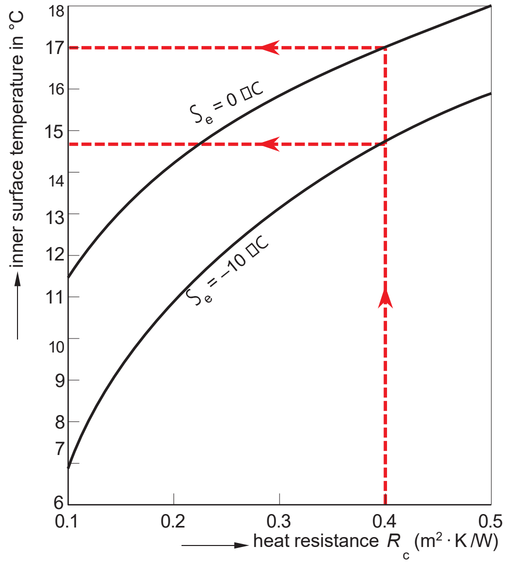


Figure 2.14 Determining the surface temperature of a construction (inside), where the outside temperature is θ_e = -10 °C or 0 °C, and the inside temperature is θ_i = 22 °C

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:

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

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

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

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.

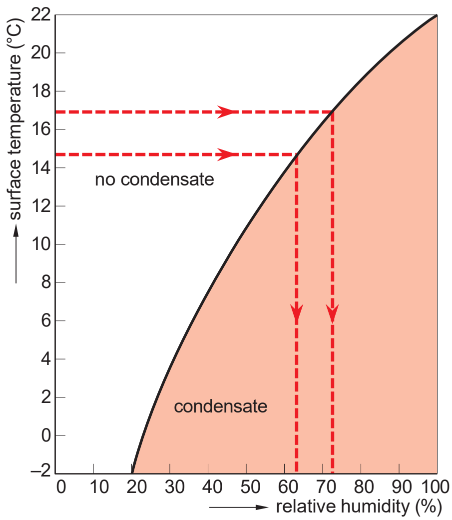


Figure 2.15 Determining the occurrence of condensation with an indoor air temperature of θ_i = 22 °C

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.

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 $m^2 \cdot K/W$

towards inside air:

R_{si} = 0.13 $m^2 \cdot K/W$ for glazing between inside air and outside air;

R_{si} = 0.25 $m^2 \cdot K/W$ for all inside surfaces more than 1.5 m above floor level;

R_{si} = 0.50 $m^2 \cdot K/W$ 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:

$$g = \frac{\Delta p}{R_d} \cdot 1000 \; [\mathrm{g/(m^2 \cdot s)}]$$

The meaning of the symbols is:

g the vapour transport in $\mathrm{g/(m^2 \cdot s)}$
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 $\mathrm{g/(m^2 \cdot s)}$ instead of in $\mathrm{kg/(m^2 \cdot s)}$.

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:

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

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 μ 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:

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

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:

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

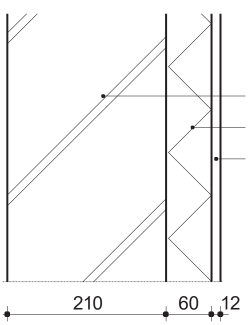
The meaning of the symbols is as follows:

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 [Pa]	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
					$\Delta p = 728$
			$(\mu \cdot d)_{tot} = 8.91$		

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 μ · *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.

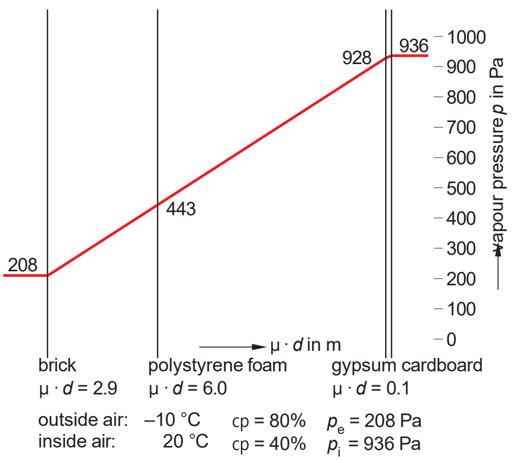


Figure 2.18 Graphic calculation of progression of vapour concentration in a wall construction

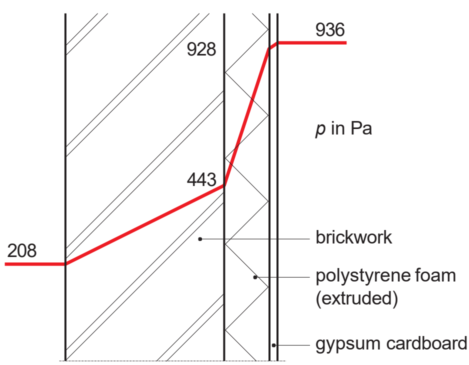


Figure 2.19 Progression of the vapour density in a wall construction

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.

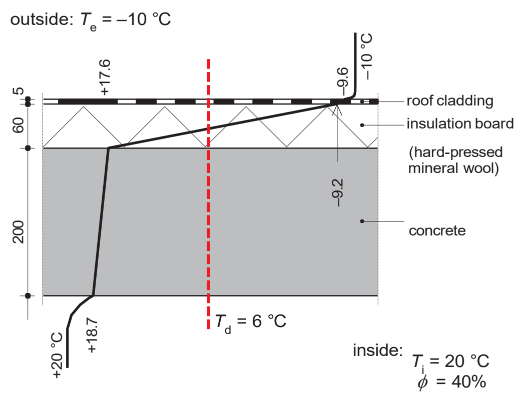


Figure 2.20 Determining the location of the dew point in a construction

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:

- $\theta_i = 20\ ^\circ C$: $\phi_i = 40\%$, so that $p_i = 0.4 \cdot 2340 = 936$ Pa;
- $\theta_e = -10\ ^\circ C$: $\phi_e = 80\%$, so that $p_e = 0.8 \cdot 260 = 208$ 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.
$\theta_{condens} = -9.2\ ^\circ C$, 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.

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			10,000	60	545	
					−9.2	276				753
insulation	0.08	0.03	2.67	26.9			2	0.2	2	
					17.6	2014				755
concrete	0.2	1.9	0.11	1.1			100	20	181	
					18.7	2157				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

It is also possible to determine graphically whether interstitial condensation will occur in the roof construction. As in figure 2.18, plot the μ · *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.

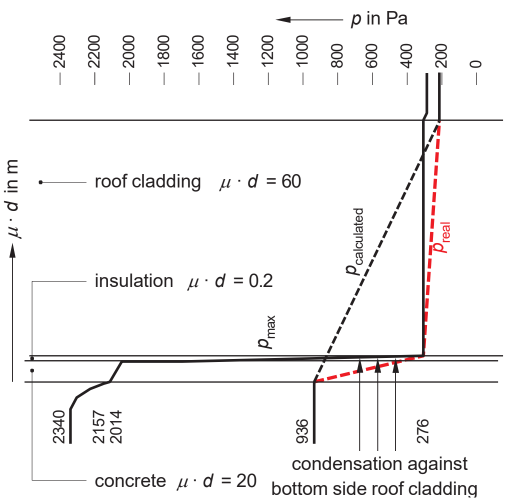


Figure 2.22 Determining the interstitial condensation in a roof construction, using a graph.

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 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.

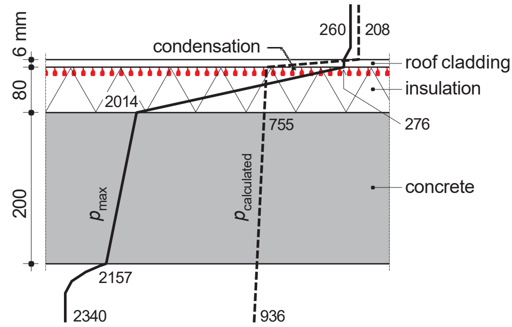


Figure 2.23 Interstitial condensation in a roof construction

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

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:

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

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

In our example, the incoming moisture flow is:

$$\frac{(936 - 276) \cdot 1000}{5.3 \cdot 10^9 \cdot (20 + 0.2)} = 6.2 \cdot 10^{-6}\ \mathrm{g/(m^2{\cdot}s)}$$

And the outgoing moisture flow is:

$$\frac{(276 - 208) \cdot 1000}{5.3 \cdot 10^9 \cdot 60} = 0.2 \cdot 10^{-6}\ \mathrm{g/(m^2{\cdot}s)}$$

So $g = 60 \cdot 24 \cdot 3600 \cdot (6.2 \cdot 10^{-6} - 0.2 \cdot 10^{-6})$

$= 31.1\ \mathrm{g/m^2}$ 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.

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.

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	$300 \cdot \psi_o \cdot d$
organic materials	$30 \cdot \rho_m \cdot d$
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.%]
ψ_o = porosity [vol.%]
ρ_m = similar density [kg/m³]
d = thickness [m]

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

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: $g = \frac{100}{\Sigma \mu \cdot d}$ [g/m^2]
- for climate category II: $g = \frac{600}{\Sigma \mu \cdot d}$ [g/m^2]
- for climate category III: $g = \frac{1000}{\Sigma \mu \cdot d}$ [g/m^2]

The meaning of the symbols is:

g the amount of condensing moisture during the winter in g/m^2

$\Sigma\mu \cdot d$ 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 $\Sigma\mu \cdot d$ 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).

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.

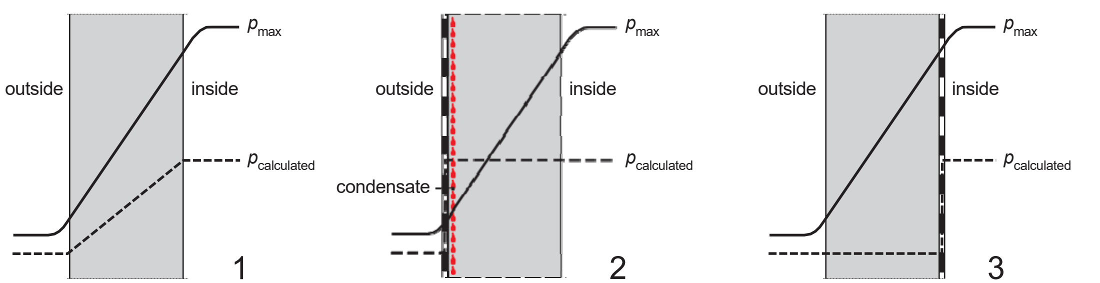


Figure 2.26 Influence of location of vapour-retardant layer on interstitial condensation

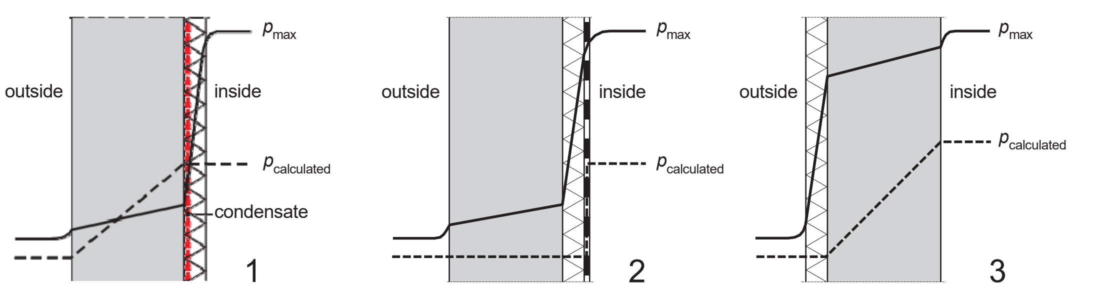


Figure 2.27 Influence of the position of the insulation on interstitial condensation

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.

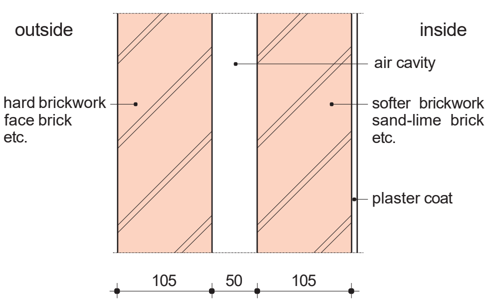


Figure 3.1 Structure of the traditional cavity

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.

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.

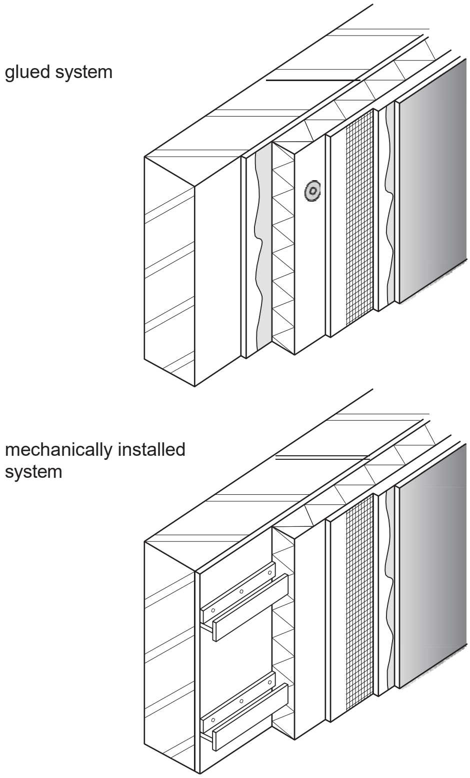


Figure 3.2 For the insulation layer, technically speaking both mineral wool as well as plastic foam can be used. The finishing takes place with plasterwork, with or without adding synthetic resin, including glass fibre or wire netting reinforcements. The various solutions of course have their own environmental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

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.

Figure 3.3 Outside insulation of a facade

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.

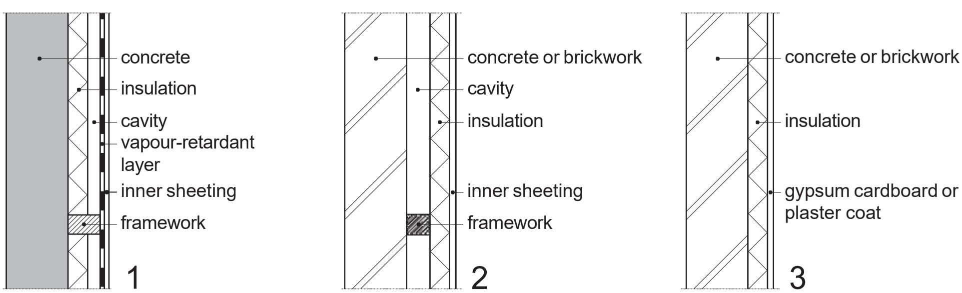


Figure 3.4 Options for inside insulating of walls

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).

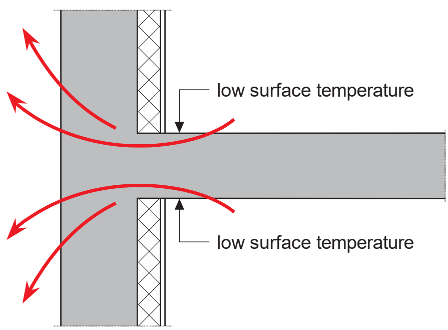


Figure 3.5 Cold bridges, created retrospectively, or aggravated due to insulating the indoor side of the wall

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.

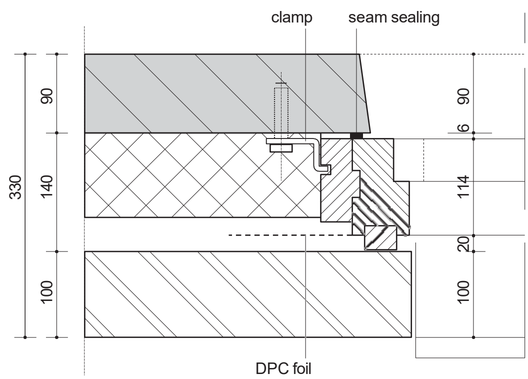


Figure 3.6 Modern cavity wall detail

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

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.

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).

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.

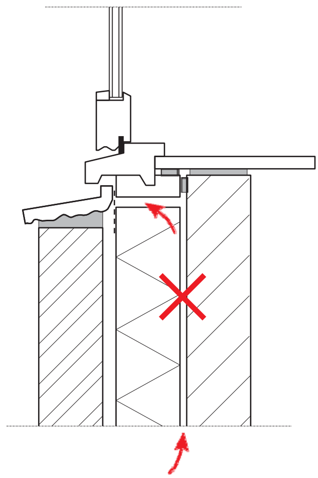


Figure 3.7 Unwanted air cavity

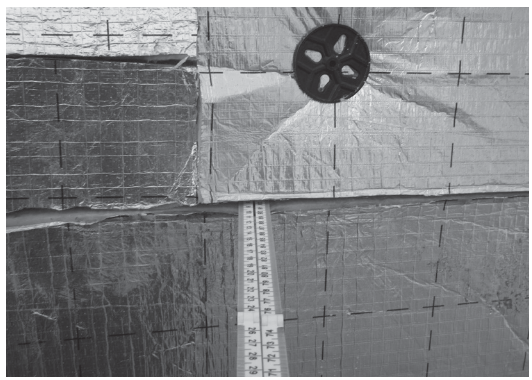


Figure 3.8 Inaccurate attachment and installation of the insulation material

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.

Figure 3.9 Retrospective insulation

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.

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 (μ · *d* = 5 m for climate category II, μ · *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.

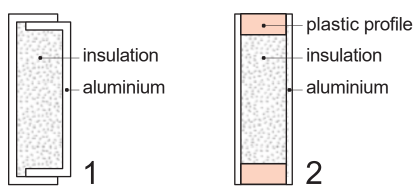


Figure 3.10 Aluminium box construction

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).

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.

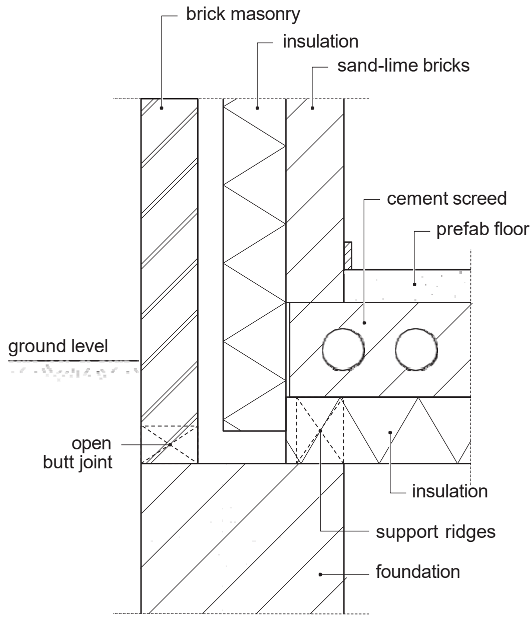


Figure 3.11 Continuing insulation layer in wall-floor foundation (detail)

Figure 3.12 Floor insulation with EPS elements

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.

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.

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.

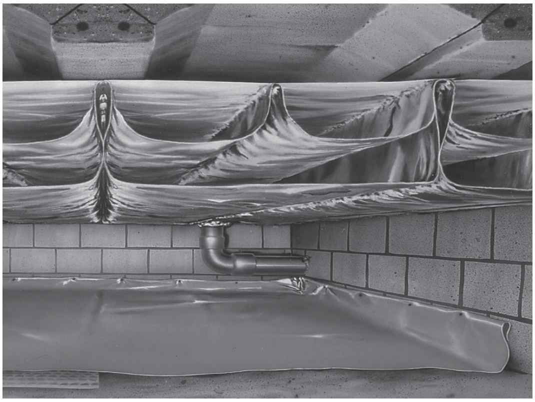


Figure 3.13 Example of retrospective insulation with plastic foil cushions with a preserved surface area of deposited aluminium and soil sealing with foil (both Tonzon)

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 m^3 of gas for every m^2 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 evapourating 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

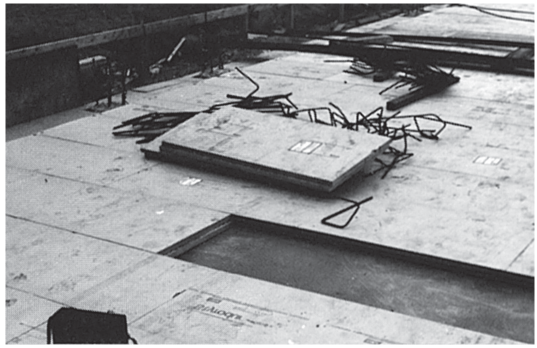


Figure 3.15 Insulation of a cellar floor with extruded polystyrene foam sheets. A layer of flowing concrete was first laid onto the sand.

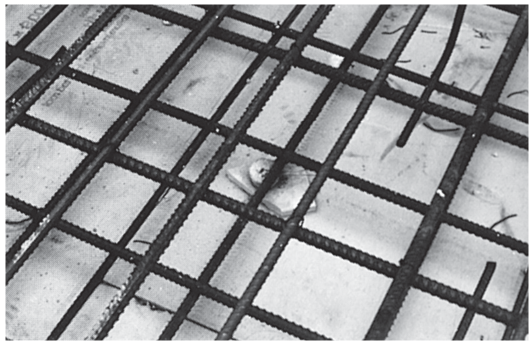


Figure 3.16 A piece of tile is laid under the support blocks of the reinforcements to prevent the insulation material from being squashed.

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.

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.

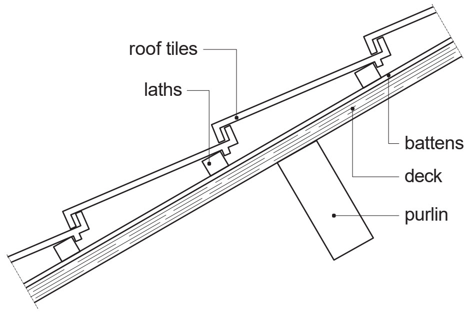


Figure 3.17 Uninsulated tiled roofs

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.

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.

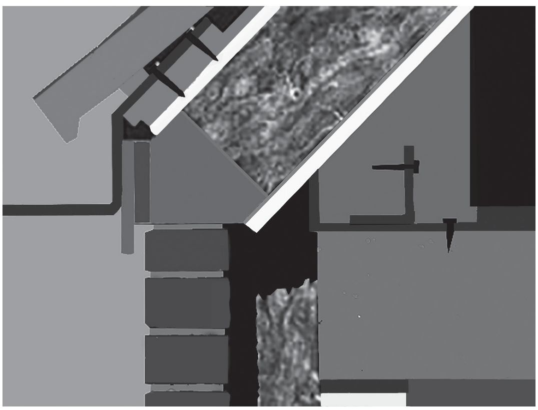


Figure 3.18 Insulation which does not continue where the outside wall meets the roof

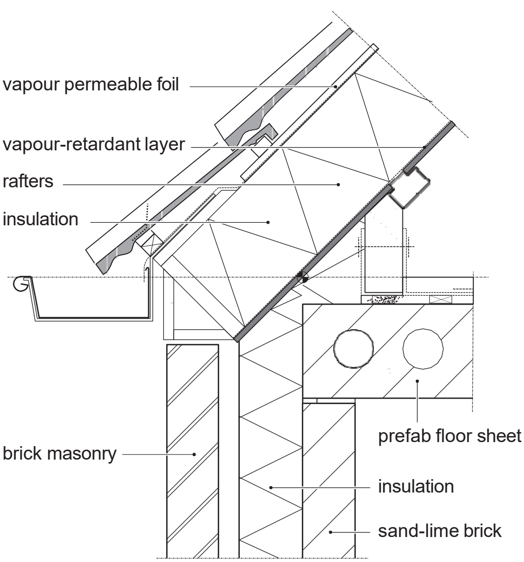


Figure 3.19 Roof detail with close-fitting insulation layer

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.

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.

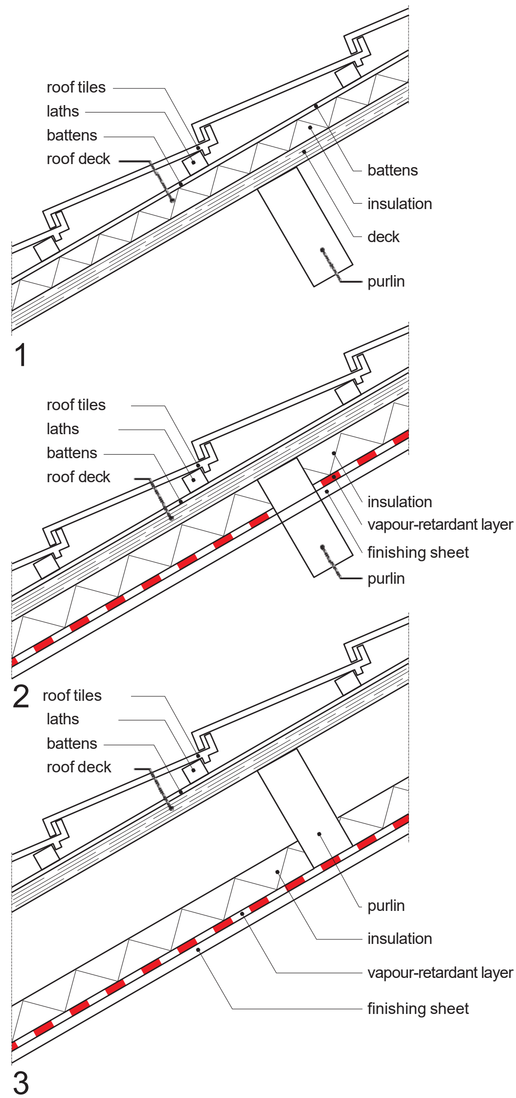


Figure 3.21 Possibilities for insulating tiled roofs

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

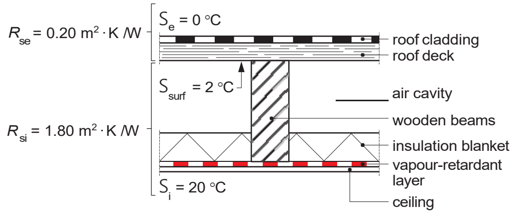


Figure 3.22 Example: cold roof

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.

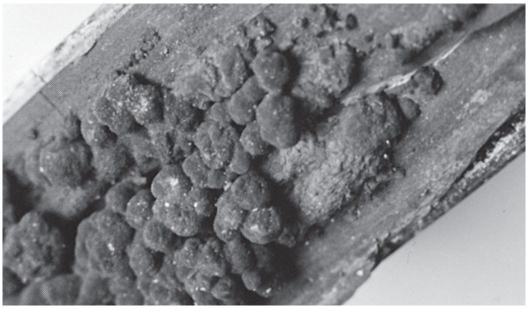


Figure 3.23 If the roof deck is damp for a long time, this can produce entire fungus cultures

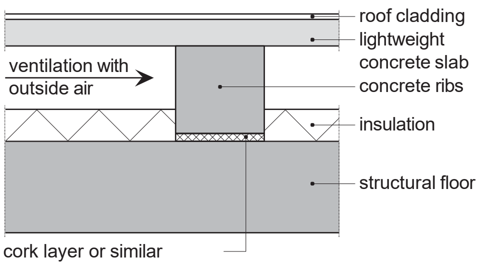


Figure 3.24 Example of properly executed cold roof (rooftop car park)

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.

'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.

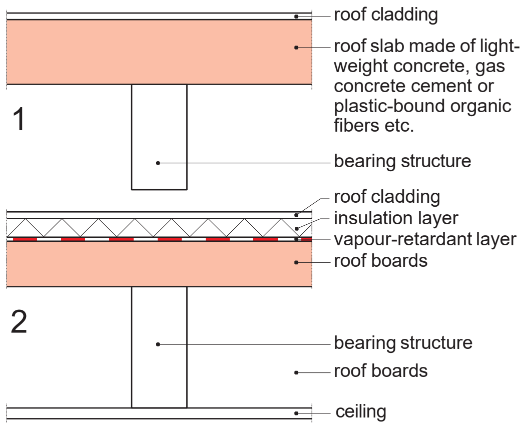


Figure 3.25 Roofs with 'insulating' roof sheets

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.

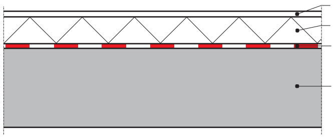


Figure 3.26 Warm roof, concrete

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.

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.

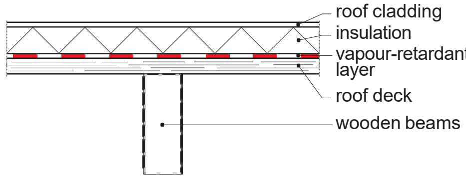


Figure 3.27 Warm roof, wood

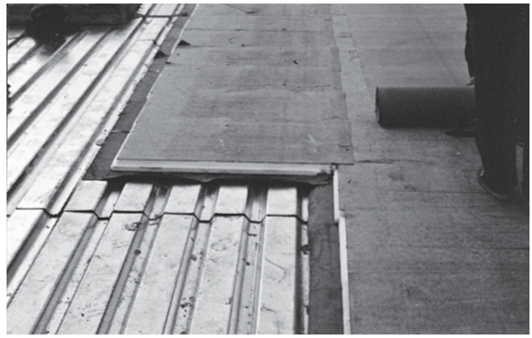


Figure 3.28 Steel roof with polystyrene foam insulation sheets with a laminated layer on either side. The roof covering is attached to the upper layer, while the lower layer functions as a vapour-retardant layer.

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).

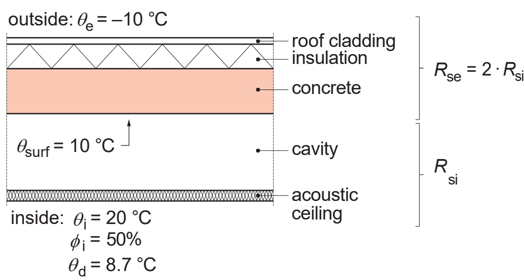


Figure 3.29 Influence of acoustic ceiling on condensation

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.

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]
bitumised paper (on one side) (0.1 mm)	0.7
polyester foil (0.1 mm)	1.5
polystyrene foil (0.1 mm)	4
polythene foil (0.1 mm)	6.5
polythene foil (0.3 mm)	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.

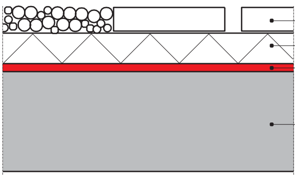


Figure 3.31 Inverted roof

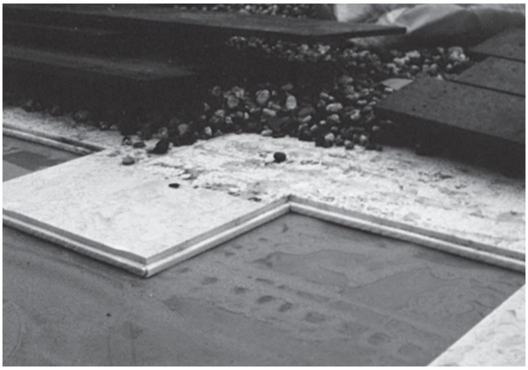


Figure 3.32 Inverted roof. The insulation sheets (extruded polystyrene foam) are simply laid onto on the roof covering, and covered with coarse gravel or tiles to protect them from sunlight (ultraviolet) and to prevent them being blown off.

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.

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/m^3) 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