Building Physics

3 Thermal Comfort - Ventilation - Solar Control

ir. A.C. van der Linden, AaCee Building & Environment, Delft

Klimapedia, August 2022

5

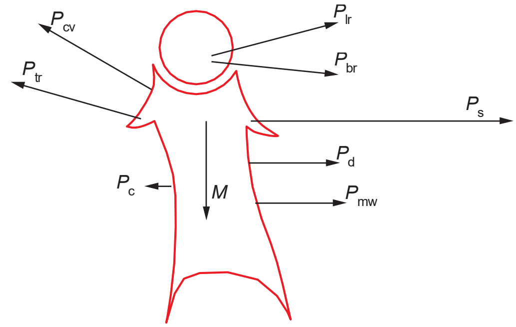
Thermal comfort

A.C. van der Linden

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

One of the things that designers of buildings aim at is a comfortable indoor climate for the people who will be working or living in them. To achieve this, a method is needed to work out from measurable, physical variables, how people assess their indoor climate. This will, of course, be affected by the circumstances in which people find themselves (sitting at a desk, or carrying out strenuous physical work) and the clothes they will be wearing. Most models that govern thermal comfort date from the 1970s and are based primarily on research in laboratories. A well-known model is that of Fanger.

Since 2000, more information has been emerging about how the internal thermal climate is valued in reallife situations. Results from field studies conducted all over the world have been pooled and as a result, a direct link has been made between the outside temperature and the desired indoor situation. It appears, among other things, that some kind of psychological adaptation takes place. This means that someone's recent contact with outdoor conditions, and their expectations with regard to the indoor prevailing temperature both help form that person's judgement. When outdoor temperatures are higher, it seems that people accept without any problems higher indoor temperatures than would be suggested by Fanger's model for instance.



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

Figure 5.1 Heat balance of a person in a room

5.1 Fanger's thermal comfort model

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

The heat balance can, of course, be affected by changing the amount of clothing being worn (heat resistance). By adding comfort requirements with regard to skin temperature and perspiration to this energy balance, Fanger arrived at a comfort comparison, for which research was carried out using human guinea pigs. The scale that was used is shown in figure 5.2.

The neutral point on this scale is defined by an air temperature of T_ℓ = 29 °C and an equal, uniform radiation temperature, a relative humidity level of ϕ = 30% and an air velocity of v = 0.1 m/s, for a naked person exposed to these conditions for one hour. In the same circumstances, the term 'very hot' would be used when $T_\ell = T_s$ = 45 °C, and 'very cold' when $T_\ell = T_s$ = 10 °C.

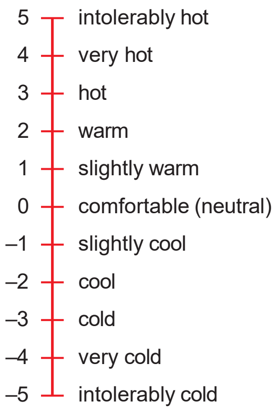


Figure 5.2 Scale for ascribing a numeric value for a given indoor climate valuation

The comparisons made by Fanger - based on research with human guinea pigs in a laboratory - apply to the area between valuations from -2 to 2. His comparisons led to a 'Predicted Mean Vote' (PMV) which can be compared to the figures on the scale in figure 5.2.
According to Fanger's comparisons, there are all kinds of factors that have no influence on how an interior climate is appreciated - these include age, gender, country of origin and race. If there are any differences, they are more likely to be the result of various individuals having, for example, different metabolisms (energy that is developed in the body) in the same circumstances. Outside the 'comfort range' (PMV > 2 or PMV < -2) studied by Fanger, there probably do exist large differences as referred to above.
The limitations of Fanger's model are that it only applies within the comfort range, and that it assumes a stationary situation. As a result, it is not possible to give a valuation for the climate during a brief stay in a room (up to half an hour) or for activities that last only a short time.
Models have also been developed that take greater account of the dynamic character of processes, all the way to fully dynamic models in which the human body is divided into four layers. These models are used mostly for research purposes and are less suitable for practical applications. Fanger's model is the one which is still used in practice. It creates sufficient insight into comfort-related matters in normal situations where people can be found in the comfort range (homes, offices, schools, etc.). For this reason, it is dealt with in this book.
An advantage of Fanger's model is that it is easy to use with a PC or a programmable pocket calculator. It should be pointed out, however, that knowledge of how people respond to any particular indoor climate is nowhere near complete. Fanger worked with fixed groups - mostly male students of between 20 and 30 years of age, who were, to a certain extent, 'trained'. In the Netherlands, more extensive research with subjects is being carried out at the University of Maastricht in particular.

5.2 Desired indoor temperature based on PMV

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

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

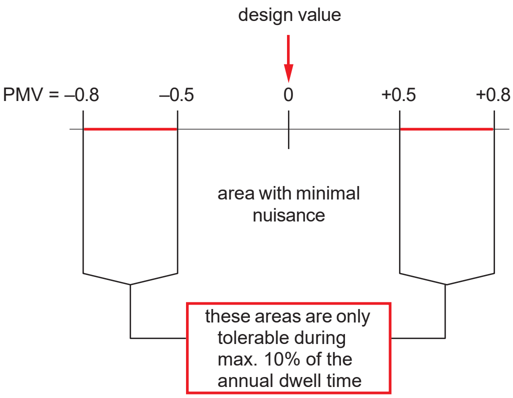


Figure 5.3 Scale for assessing the indoor climate in a building

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

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

The premise of the clothing resistance is also important. Clothing resistance (I_{clo}) is expressed in clo (1 clo = 0.155 $m^2 \cdot K/W$). This unit came about because a business suit (threepiece) was chosen as a reference (see the table in figure 5.6).

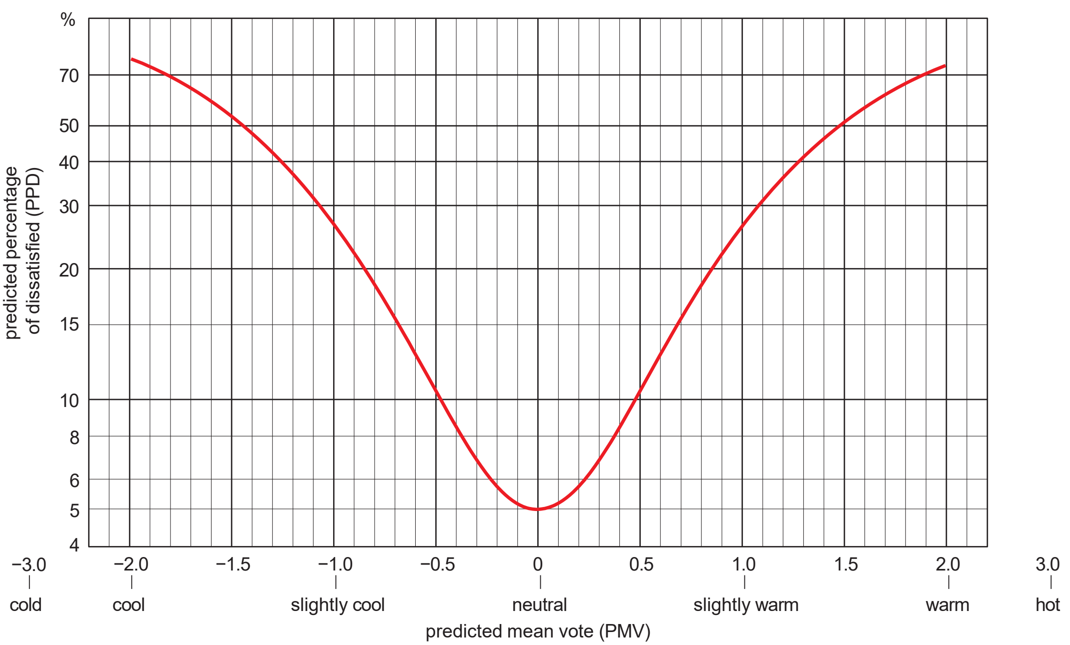


Figure 5.4 Connection between PPD and PMV

category	activity	metabolism* [W]
I	resting (lying)	85
II	sitting calmly, reading	105
III	general office work, writing letters, drawing	130
IV	typing, general laboratory work, teaching	160
V	light assembly work, houseworking (ironing, washing up)	200

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

Figure 5.5 Classification of activities according to five levels of metabolism

type of clothing	value [clo]
none	0
bikini	0.05
shorts	0.1
normal tropical clothing (shorts, open-necked shirt with short sleeves, light underwear)	0.3
light summer clothing (light long trousers, short-sleeved shirt)	0.5
summer suit	0.8
normal suit (shirt and tie)	1.0
heavy suit with waistcoat, thick underwear	1.5
clothing suitable for polar regions	3.0-4.0

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

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

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

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

Air temperature

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

The table in figure 5.8 shows separately how the summer situation would look if an air velocity of v = 0.4 m/s were the starting point (greater air movements as a result of the windows being opened). This appears to help the temperature rise by around 1 °C. However, it should be realised that by no means in all areas of the room can such an air velocity be achieved, and that in certain locations the prevailing air velocity will be much too great,

	air temperature [°C]					
	winter ($I_{clo.i}$ = 0.9)			summer ($I_{clo.i}$ = 0.7)		
PMV =	-0.8	-0.5	0	0	+0.5	+0.8
activity level I, *M* = 85 W						
$T_s = T_\ell$	24	24	26	27	28	29
$T_s = T_\ell - 2$	24	25	26	28	29	29
$T_s = T_\ell - 4$	25	26	27	28	30	30
$T_s = T_\ell + 2$	23	24	25	26	27	28
$T_s = T_\ell + 4$	22	23	24	25	26	27
activity level II, *M* = 105 W						
$T_s = T_\ell$	21	22	24	25	27	28
$T_s = T_\ell - 2$	22	23	25	26	28	29
$T_s = T_\ell - 4$	23	24	26	27	29	29
$T_s = T_\ell + 2$	20	22	23	24	26	27
$T_s = T_\ell + 4$	20	21	22	24	25	26
activity level III, *M* = 130 W						
$T_s = T_\ell$	19	20	22	24	26	27
$T_s = T_\ell - 2$	19	21	23	24	26	28
$T_s = T_\ell - 4$	20	22	24	25	27	28
$T_s = T_\ell + 2$	18	19	21	23	25	26
$T_s = T_\ell + 4$	17	18	21	22	24	25
activity level IV, *M* = 160 W						
$T_s = T_\ell$	15	17	20	22	24	25
$T_s = T_\ell - 2$	16	18	21	22	25	26
$T_s = T_\ell - 4$	17	19	22	23	26	27
$T_s = T_\ell + 2$	15	16	19	21	23	24
$T_s = T_\ell + 4$	14	15	18	20	22	24
activity level V, *M* = 200 W						
$T_s = T_\ell$	11	14	17	19	22	23
$T_s = T_\ell - 2$	12	14	18	20	22	24
$T_s = T_\ell - 4$	13	15	18	20	23	25
$T_s = T_\ell + 2$	11	13	16	18	21	23
$T_s = T_\ell + 4$	10	12	15	17	20	22

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

leading to arguments about whether windows should be open or closed, if the room is shared by more than one person.
These tables highlight the influence of the radiation temperature through the difference in air and radiation temperature. $T_\ell = T_s$ therefore applies to a room with a limited proportion of outside walls, or to an internal space with a lightweight building construction, or to a situation that has become reasonably stationary (continuous heating).

Where $T_s = T_\ell - 2$ or $T_\ell - 4$, this means the radiation temperature lags behind the air

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

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

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

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

Relative air humidity

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

5.3 Adaptive thermal comfort

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

- The clothing resistance should be known. Apart from the inherent uncertainty of its value – even when knowing the specific clothing pieces – this is one of the variables that a person will actually use to optimise his own level of comfort with the climate, as opposed to this being a fixed, determining factor.
- The metabolism that goes with a particular activity can vary considerably.
- The model assumes steady-state situations. In other words, the effect of the dynamic character of thermal conditions is omitted.
- The static model works on the idea that only thermophysiological aspects determine thermal sensations. However, it is clear that nonthermal factors also play a role: in particular the degree to which persons can themselves influence their surroundings,

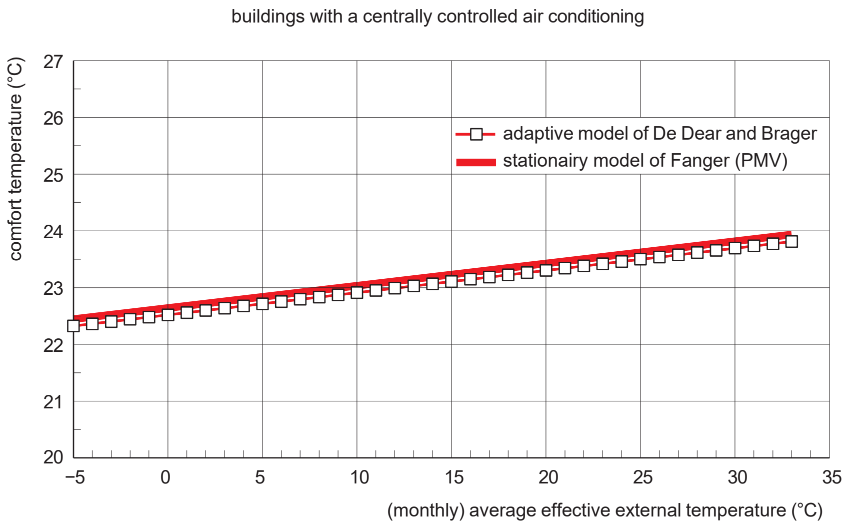


Figure 5.9 Comfort temperature in relation to average outdoor temperature in closed buildings with a centrally controlled climate installation

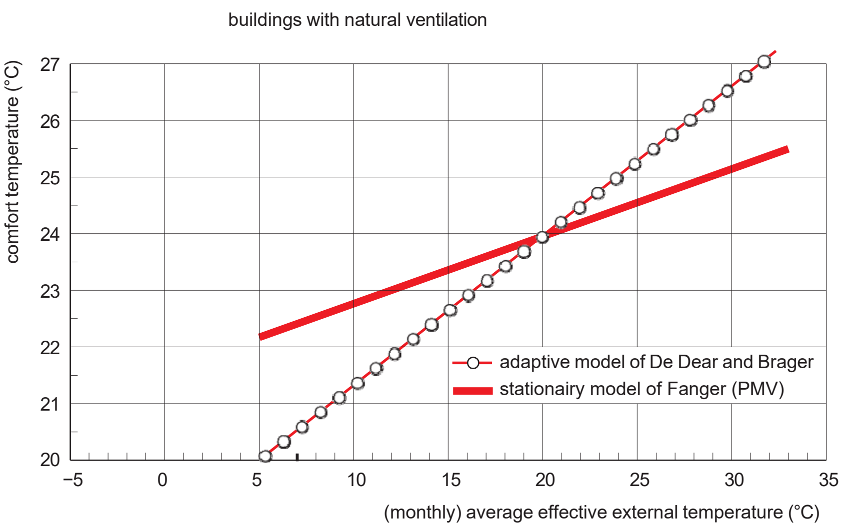


Figure 5.10 Comfort temperature in relation to average outdoor temperature in naturally ventilated buildings, where there are opportunities for individuals to influence the indoor climate

but also their expectations with regard to the thermal indoor climate are important factors.

In principle, the first two points can be dealt with by varying the input variables for clothing resistance and metabolism when using the static models. However, this seldom happens. The third point is, as expected, of only limited importance, because the situation under consideration (office work) is more or less stationary. The most important point is the fourth. Research by Brager and De Dear in particular has provided much insight into how users of buildings valuate the indoor climate in the actual (practice) situation.
When account is taken of adjustments to clothing resistance levels at various outside temperatures, the same ‘comfort temperatures’ using Fanger’s static model are

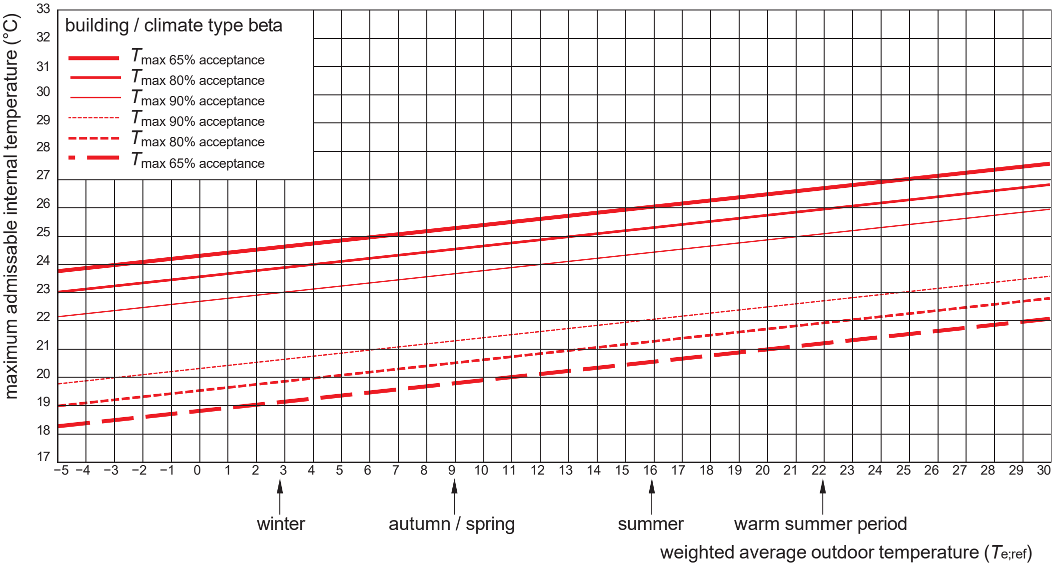


Figure 5.11 Maximum admissible operational indoor temperature given a certain level of acceptance, depending on the outdoor temperature $T_{e;ref}$, for buildings with sealed facades and centrally controlled air conditioning. To give the full picture, the lower limits are also shown.

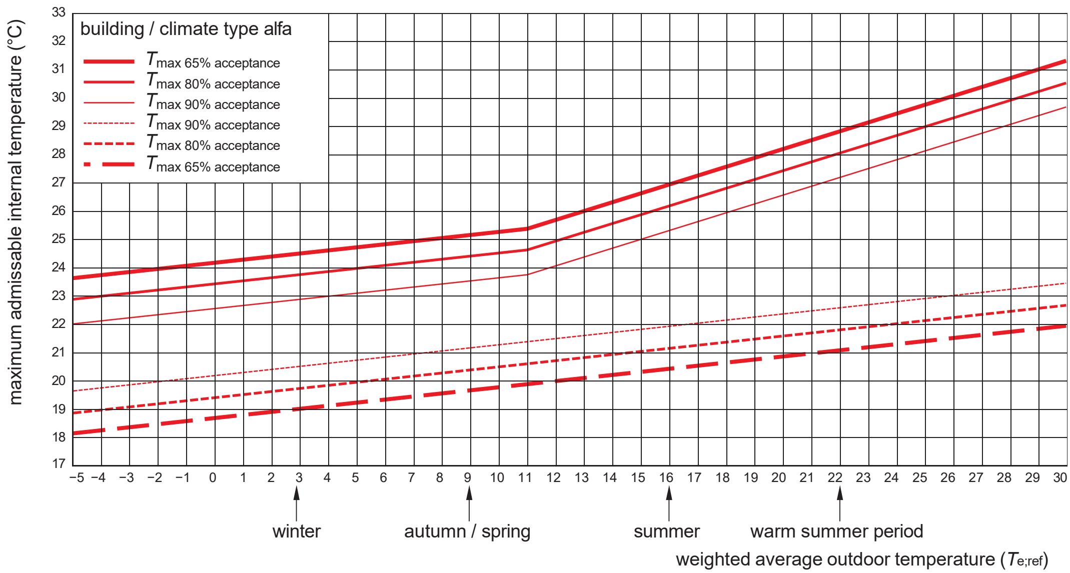


Figure 5.12 Maximum admissible operational indoor temperature given a certain level of acceptance, depending on the outdoor temperature $T_{e;ref}$, for buildings in which the windows can be opened, and where there are sufficient opportunities for individuals to influence the indoor thermal climate.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

obtained for buildings with a centrally controlled indoor temperature and in which the windows cannot be opened, as with the adaptive model, which was drawn up on the basis of information gathered through field research. This is shown in a graph in figure 5.9.

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

It turns out that in practice the comfort temperature in naturally ventilated buildings moves much more markedly in line with the outdoor temperature than might be explained using the static PMV model. If account is taken of changes to clothing resistance and of air velocity in the room when the temperature is higher, this explains only half the difference. The other half appears to be related primarily to the psychological ability to adjust to an indoor climate that follows outdoor conditions much more closely, than in a climate-controlled building. The conclusion is that the recent thermal history experienced by a person has an important role to play, along with the expectations that a user has in relation to his surroundings.
The comfort temperature in the adaptive model is related to the ‘average outdoor temperature’. For the summer situation in the Netherlands – where the average daytime temperature over a period of several days is never higher than 23–25 ºC – this means that differences that stray from the values obtained from the PMV model are limited to around 1 ºC (see figure 5.10). Combined with the fact that until 2005 calculations using a comfort temperature that followed the outdoor temperature had hardly ever been used in practice, the new insights nevertheless represent a significant practical improvement.
This applies especially to the upper limit to the indoor temperature. Higher outdoor temperatures provide greater leeway, while when they are lower the standard values become stricter in relation to the ‘old’ standard value of 25 °C. This latter factor has consequences for buildings with sealed facades and centrally controlled air conditioning. It also explains the dissatisfaction among users in some of these buildings.
Indoor temperatures of 25 °C when outdoor temperatures are lower in spring and autumn are simply too high. In figure 5.11 and 5.12, an indication is given of what these insights mean for the assessment of certain indoor climate situations in offices. In the Netherlands, these standard values are further elaborated for practice situations in publications by ISSO and NEN.

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

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

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

During the season when heating is used (with average outdoor temperatures below 10 to 15 ºC), there is effectively no such thing as an alpha building/climate. The effect of behavioural adaptation (such as clothing) does still play a role, but psychological adaptation no longer does so. For that reason, the same operational temperature is used for alpha buildings/climates as for beta types, when $T_{e;ref}$ is below 10–12 °C. This can be seen in the alpha building/climate graph in the lines to the left of the bend.
To complete the picture, the lower limits for 65, 80 and 90% acceptance levels have been included in the graph, shown with dotted lines. For both alpha and beta types of building/climate, the lower limits for buildings

with sealed facades are used. Where the lower limits are approached, it is assumed that the perception of the building's users, in both types, will be around the same, and that the windows will be closed.
The figures apply to a general office setting and other comparable situations. Where there are unusual circumstances, the value limits can be modified according to metabolism and the clothing resistance in that particular situation. The starting point for a standard situation is an 80% level of acceptance of the limits. This can be raised to 90% for buildings where an extra high level of quality is sought. The limits for 65% acceptance can be used as a reference point for existing buildings (measurements in older buildings following complaints), or for temporary buildings – these limits should not in fact be exceeded. However, in all cases, it has to be accepted that occasional exceeding will occur in exceptionally hot periods, in order to prevent the need for installing extremely large climate services.

5.4 Local discomfort

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

Vertical temperature gradient

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

Asymmetric thermal radiation

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

Floor temperature

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

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

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

Air velocity

Designers of mechanical ventilation installations, air-conditioning and air-heating systems should consider with care what air supply grids to use in order that the air velocities in the areas where people are present are not too high. The table in figure 5.13 shows the maximum admissible average air velocity with a given air temperature, for the various levels of activity. The air velocity should not be allowed to fluctuate too much either. All this information applies not only to air currents caused by climate installations, but can also be used for assessing problems arising naturally, such as draughts or cold downdraughts. However, more sophisticated assessment methods for air velocity (draughts) are starting to appear. The fluctuation in air velocity also appears to be very important.

6

Ventilation and infiltration

A.C. van der Linden

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

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

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

6.1 Basic ventilation

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

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

quality based on smell is expressed in Decipol (dp). An advantage of this method is that not only odorants produced by people are considered, but also odorants coming from the furniture. Disadvantages of this method are the complex way in which air quality is determined and the impracticability of the results for the (automatic) control of ventilation installations.

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

Ventilation systems

As far as basic ventilation is concerned, the building legislation places obligations not only on the amount of ventilation, but also on the systems that are needed to provide it. Imposing requirements on the way ventilation systems are made rules out as much as possible the need for their being switched off – as a result of a draught, for example. It is important that every room has a facility for the provision of fresh air and for the extraction of indoor air, and of course the capacity of both facilities should correspond with the required ventilation flows. For premises where people live, the supply of fresh air has to come directly from outside or from a different area where other people are present, or from a corridor or staircase that forms part of the same building, with a minimum of 50% of the required capacity coming directly from outdoors. Where a building has other functions, the supply of fresh air to where people are located has to come entirely from outside. Stale or polluted air in the toilet, bathroom and kitchen must always be directly extracted. It remains debatable as to what constitutes ‘directly from outside’. Does it include ventilation air that has originated in a conservatory, or which has passed hundreds of metres through a ventilation duct? Supplying air from a conservatory is not allowed if it is a place where people sit or pass through. Supplying air through ventilation ducts is always permitted, although research has shown that this can have a disadvantuous effect on air quality.

Natural and mechanical ventilation

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

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

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

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

Natural ventilation installations

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

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

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

Examples of the latter include horizontal sheeting (perhaps in the form of a ceiling) directly below or above the ventilation opening, or a perforated sheet immediately thereunder. Various research programmes in climate chambers show that extra facilities can

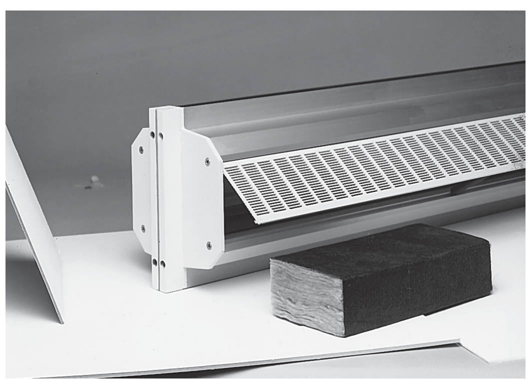


Figure 6.1 Silencer where the sound absorbing material can be cleaned or replaced easily

help achieve positive results. Another means of cutting back the probability of draught-related complaints in the winter is, for example, to preheat the inflow air by allowing it to flow through a glass-covered area or heated passage.

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

Mechanical ventilation installations

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

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

Choice of systems for buildings with residential functions

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

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

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

Figure 6.2 Ventilation systems rating according to Dutch standards

The systems in figure 6.2 are described as follows:

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

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

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

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

Choice of systems for buildings with other functions

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

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

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

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

A disadvantage of the first system (supply and extraction through the same outer wall) is the limitations imposed on the user, such as keeping inside doors closed. Its functioning also strongly depends on the available differences in wind pressure along the facade. This means the system is of little practical use. A drawback to the second system (cross ventilation) is the increased likelihood of draughts, as more ventilation is needed for each linear metre. With wall and roof ventilation (the third system), the air can enter via both outer walls. This halves the level of ventilation for each linear metre of the walls in comparison with the second system, thus reducing the possibility of draughts. Apart from the effects on the level of comfort, this has positive consequences for facades exposed

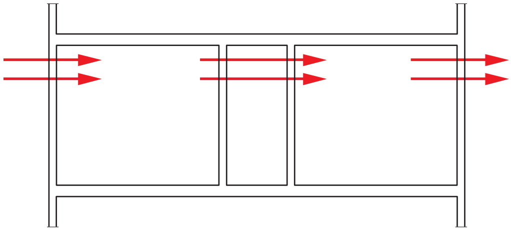


Figure 6.3 Ventilation through opposite facing walls (cross ventilation)

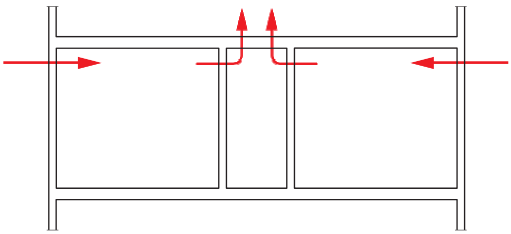


Figure 6.4 Ventilation through outer wall and roof

to traffic noise. In general then, the third system is the preferred option. Another important advantage of ventilation through the facades and roof as opposed to cross ventilation is that the system is easier to manage. It is also possible with this system to extract the air mechanically, either wholly or partly. This means the benefits of having ventilation air supplied naturally are maintained, while the frequently-heard objections, such as those of unreliability, are allayed. Regardless of which system is chosen, it is essential that the parts of a ventilation system work together as an integrated entity.

6.2 Summer ventilation

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

Daytime

The amount of summer ventilation required depends on how much heat is produced in a building, and on a number of features of the building. The heat produced in a building by people, machines, and so on, is known as the internal heat load. The internal heat load is dependent among other things on the floor surface area per person, and the organisation. In office buildings, the internal heat load will rarely be greater than 30 W/m^2 of floor surface. Statements of Requirements often quote a level of 35 to 40 W/m^2. By using energy-efficient equipment and lighting, and by applying a certain degree of synchronicity, the internal heat load can often be reduced to 25 to 30 W/m^2. The features of the building that can help determine the amount of ventilation that is required are primarily the dimensions of the windows and the quality of the sun-blinds, both of which directly influence the amount of summer heat that can enter. With factory and office buildings in particular, the maximum allowable ventilation flow is limited in the summer months. In the daytime, the flow is restricted due to the levels of thermal comfort experienced by the users, and by the practical consideration of not having large quantities of paper blowing all over the place. The maximum ventilation in these circumstances is about five times the amount of air in the room per hour.

Appliances

Summer ventilation appliances generally consists of windows that can be opened. Regardless of the system used for basic ventilation, opening windows will cause mostly cross ventilation. A window (that can be opened) of about 0.5 m^2 should be assumed for both outer walls for the purpose of summer ventilation. Note that it should be possible to open the windows completely. If a

0.5 m² window can only be opened 0.1 m, the ventilation surface is then not 0.5 m², but only 0.05 m².

Nighttime

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

Appliances

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

6.3 Driving forces behind natural ventilation

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

Wind pressure

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

$$p = \tfrac{1}{2} \cdot \rho \cdot v^2 \text{ [Pa]}$$

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

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

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

$$p = c_p \cdot \tfrac{1}{2} \cdot \rho \cdot v_r^2 \text{ [Pa]}$$

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

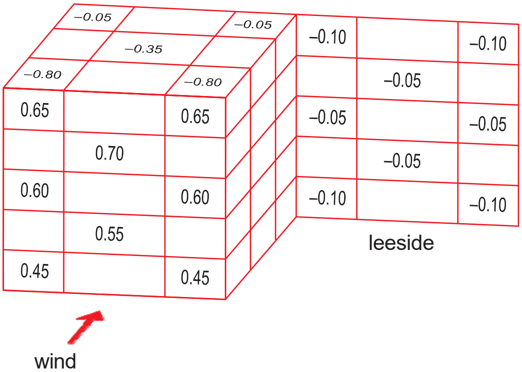


Figure 6.5 Wind pressure coefficient c_p on the windward side and leeside for a medium rise building

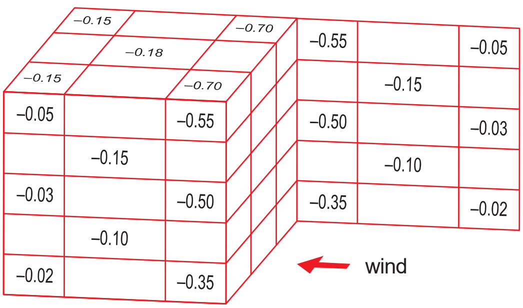


Figure 6.6 Wind pressure coefficient c_p for wind parallel to the facade

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

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

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

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

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

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

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

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

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

The distribution of the wind speed above ground level varies according to the surroundings (open terrain, scattered buildings, city, etc.). Manuals list so-called ‘wind speed profiles’ for this distribution. Based on the wind speed measured by meteorological services at the standard height of 10 m above ground level, the wind speed at a specific height can be determined.
For the average wind speed at a height of 10 m in the Netherlands, a value of 4 to 5 m/s can be used. This can be your starting point when calculating the ventilation level for calculations concerning the general energy loss through ventilation. Ventilation levels must also meet requirements at lower wind speeds. A speed of 2 m/s usually serves as a basis for this. The flow of ventilation that arises at a certain pressure difference depends on the size and shape of the flow-through openings. These determine for example the level of contraction and dispersion. At the edges of the opening, extra resistance occurs as the air there is slightly blocked causing turbulence. The flow characteristics of the opening are described by flow coefficient C_d. For the average window a value applies of C_d = approx. 0.8. Several manuals list the values of C_d for a variety of situations.

The flow volume can now be determined with:

$$\phi = C_d \cdot A_e \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} \; [m^3/s]$$

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

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

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

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

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

Example

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

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

$$\phi = C_d \cdot A_e \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} = 0.8 \cdot A_e \cdot \sqrt{\frac{2 \cdot 1.875}{1.25}}$$

$$= 0.167 \; m^3/s$$

This results in a required equivalent flow-through opening A_e = 0.120 m^2.
For two equal-sized windows, the required opening results from:

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

so that

$$A_{window} = \sqrt{2} \cdot A_e = \sqrt{2} \cdot 0.120 = 0.170 \; m^2$$

This means that if the hopper windows have a height of 1.20 m, they need to be opened to at least 0.170/120 = 14 cm in order to deliver the required level of ventilation.

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

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

A rule of thumb for determining the flow volume for summer ventilation is that, in cross ventilation for example, an air speed of 0.4 m/s is assumed in the opening. For the window from the example calculation which is 14 cm ajar you can calculate the ventilation level as follows: $\phi = A_{window} \cdot v_{window} = 0.170 \cdot 0.4 = 0.068$ m³/s or $0.068 \cdot 3600 = 245$ m³/h.
This is not even close to the level of 600 m³/h we wanted to achieve. Rules of thumb: always err on the 'safe' side. If you use this rule of thumb to determine the required window opening, it should be possible to open the window by 35 cm.

Stack effect

Because air has different densities (ρ) at different temperatures, a pressure difference arises between the inside and outside of a building. The total height of a residential home easily reaches 7 m from ground level to the roof. For a situation where the air inside the house is warmer and therefore lighter than the outside air, the heavy outside air will force the light air to rise.
The density of air at 273 K (0 °C) and a barometric pressure of 100,325 Pa is $\rho = 1.293$ kg/m³. For other temperatures, the density can be calculated with:

$$\rho = \frac{1.293 \cdot 273}{T} \text{ [kg/m}^3\text{]}$$

ρ is the air density at a temperature of T in Kelvin.

Figure 6.7 represents a drawing of the cross section of a home. The difference in height between two window openings or ventilation grids is h m.

With the above formula for air density, the pressure difference expressed as the difference in weight of two columns of air with height h and temperatures T_i and T_e can easily be determined from:

$$\Delta p = \frac{1.293 \cdot 273 \cdot (T_i - T_e) \cdot g \cdot h}{T_i \cdot T_e} \text{ [Pa]}$$

The meaning of the symbols is:

- Δp the pressure difference between inside and outside across h in m
- T_i the inside temperature in K
- T_e the outside temperature in K
- g the acceleration of gravity (9.81 m/s²)
- h the difference in height between the two openings under examination

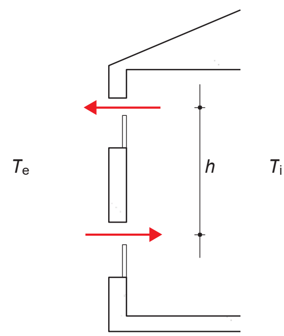


Figure 6.7 Stack effect principles

Assume the values in the example of figure 6.7 are as follows: $h = 3$ m, $T_i = 295$ K (22 °C) and $T_e = 278$ K (5 °C). The pressure difference is:

$$\Delta p = \frac{1.293 \cdot 273 \cdot (295 - 278) \cdot 9.81 \cdot 3}{295 \cdot 278}$$

$$= 2.15 \text{ Pa}$$

For a conservatory or atrium in an office building with a height of 35 m, the pressure difference becomes $\Delta p = 25$ Pa for the same temperatures.
This driving force was also used in vertical ventilation ducts until mechanical home ventilation (extraction) came in use as a standard way to increase ventilation. A chimney is in fact a vertical duct where a large pressure difference is created because the high temperature of the flue gas duct. This is why this mechanism is also called 'chimney' effect.

Natural ventilation makes use of both mechanisms: wind pressure and stack effect. Often a hybrid system is designed to compensate for the – usually short-lived – periods when the system does not perform sufficiently due to calm winds or because the difference between indoor and outdoor temperatures is not large enough. This means that a mechanical system takes over the ventilation tasks in those periods that the natural forces fail to do their work.

You must also realise with stack effects that when the temperature difference is the other way round – when it is warmer outside than inside (which is often the case during the summer) –, the pressure difference and subsequently the ventilation flow also work the other way round.

A solar chimney also makes use of the stack effect. A solar chimney can be designed in many ways. The basic idea is that the air in a vertical shaft is heated by the sun causing an extra large stack effect. Glass is installed in the shaft on the sunny side so that extra heat from the sun can enter which is then trapped in the black rear wall. See figure 6.8 for an example of an experimental setup.
The hot air can be used to heat the building, but the stack effect can also be used as 'motor' for air transport.

Figure 6.8 Experimental setup of a solar chimney (research by dr. B. Bronsema)

The design of a solar chimney is, by the way, a complex matter and it will be possible to realise additional energy savings only in combination with other provisions (integral design) and by making calculations.

6.4 Air permeability through the building shell

A few decades ago, buildings with closed windows were ventilated through (opening) joints in the building shell. A disadvantage of this type of ventilation (infiltration) is that the ventilation flow cannot be controlled. With high winds, the total ventilation flow is often many times greater than the required minimum. This results in energy being lost unnecessarily, as well as causing nuisance through draughts. To prevent draughts and the unnecessary loss of energy, requirements relating to air permeability are given in the building legislation and standards. Manuals and practical guidelines list what is required for specification with attention to the 'airtightness' of (opening) joints.

Requirements

Requirements exist for the air permeability of buildings in the shape of a maximum permissible flow volume for a given pressure difference. The volume of air flow through the totality of external dividing constructions (the $q_{V;10}$ value) of an area where people are present, toilets, or bathrooms, may for instance not exceed 0.2 m^3/s at a difference in pressure of 10 Pa and a nett volume of no more than 500 m^3. In the case of buildings with a greater nett volume, the air permeability is based on a volume of 500 m^3. Roughly translated, this means that the air permeability for every 500 m³ of the volume of a building may not exceed 200 dm³/s (200 liters a second), where the difference in pressure between the inside and outside is 10 Pa. This level has been chosen as it represents the average pressure difference, over the period of a year, that is present at the various openings. Modern buildings in particular, including office buildings, with their high-quality curtain walls, easily meet this requirement.

Determination method

Because measurements that are taken when the air pressure is a slight 10 Pa are easily disrupted by natural differences in pressure (wind, thermal draughts), the air permeability should be measured using six different air pressure levels between 15 and 100 Pa.

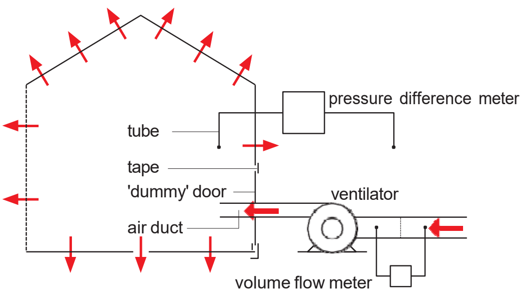


Figure 6.9 Basic sketch of measuring system for air permeability of a home

Figure 6.9 gives a representation of a measurements system. As can be seen in the figure, a home is pressurized using a ventilator, for the purpose of taking the measurement. To create the supply opening for the ventilator, the front door is removed and replaced by a 'dummy' door, in which a round opening is made. A ventilator is then used to blow air into the home.

The measurement involves establishing and noting not only the volume flow rate that is needed to maintain a certain difference in pressure, but also the difference between the outside and inside pressure levels (see figure 6.10). The flow volume for the pressure difference reference (10 Pa) can be determined from these details. Figure 6.11 illustrates the notation of the measurement details on double logarithmic paper. From this graph, indicating the relationship between flow volume and pressure difference, the flow volume at 10 Pa can then be read.

Example

Δp in Pa	q_V in dm³/s
15	740
20	840
27	1080
34	1200
40	1320
50	1530

Figure 6.10 Example of results of air permeability measurements in a house

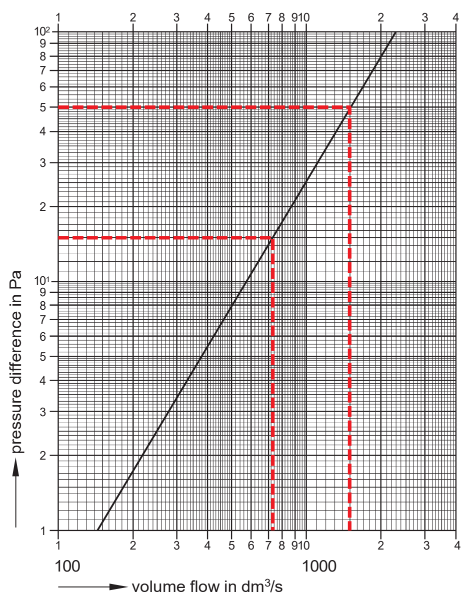


Figure 6.11 Representation on double logarithmic paper of the results shown in figure 6.10

It can be seen from the graph in figure 6.11 that the volume flow rate at 10 Pa is equivalent to:

$$q_{V;10} = 580 \text{ dm}^3/\text{s}$$

Example calculation of air permeability coefficient

The air flow through an opening can be described in general terms using the following comparison:

$$q_V = C \cdot \Delta p^{\frac{1}{n}} \ [dm^3/s]$$

The meaning of the symbols is:

q_V the volume flow rate in dm^3/s

C the air permeability coefficient in $dm^3/(s \cdot Pa^{\frac{1}{n}})$

Δp the difference in pressure at the opening

n the flow exponent

Quantity C is in fact the volume flow rate through the opening when the difference in pressure is 1 Pa.
Note: this is a completely different quantity than the C_d from paragraph 6.3. This C is not dimensionless!

Exponent n can be determined from the series of measurements, as follows:

$$n = \frac{\log p_2 - \log p_1}{\log q_2 - \log q_1}$$

The meaning of the symbols is:

n the flow exponent

p the difference in pressure for a given measurement

q the volume flow rate of the same measurement

When the first and last measure from the example are taken (see the graph), the exponent is as follows:

$$n = \frac{\log 50 - \log 15}{\log 1530 - \log 740} = 1.66$$

The value of the air permeability coefficient C can then be found by completing the formula for the volume flow rate for one of the measurements that is more or less on the line of the graph:

$$q_V = C \cdot \Delta p^{\frac{1}{n}} \quad \text{or} \quad C = \frac{q_V}{\Delta p^{\frac{1}{n}}}$$

Therefore:

$$C = \frac{1530}{50^{\frac{1}{1.66}}} = 145 \ dm^3/(s \cdot Pa^{\frac{1}{n}})$$

The value for C can of course also be deduced from the graph in figure 6.11. The value for the volume flow rate at 10 Pa follows directly from the formula given previously:

$$q_{V;10} = C \cdot \Delta p^{\frac{1}{n}} = 145 \cdot 10^{\frac{1}{1.66}} = 580 \ dm^3/s$$

Another quantity that can be determined from the measurements is the 'equivalent surface' (A_e). This is the size of a fictitious opening that lets in as much air at 1 Pa as the total openings in the shell of the building. The equivalent surface therefore represents the total surface area of the shell of the building that 'leaks'. The equivalent surface can be calculated using the following formula:

$$A_e = \frac{C \cdot \sqrt{\rho}}{10^3 \cdot 2^{\frac{1}{n}}} \ [m^2]$$

The meaning of the symbols is:

A_e the equivalent surface in m^2

C the air permeability coefficient in $dm^3/(s \cdot Pa^{\frac{1}{n}})$

ρ the density of the air (approx. 1.25 kg/m^3)

n the flow exponent (2 for turbulent flow, 1 for laminar flow)

In the example, with $n = 1.66$ A_e is:

$$A_e = \frac{145 \cdot \sqrt{1.25}}{1000 \cdot 2^{\frac{1}{1.66}}} = 0.11 \ m^2$$

Note that the value for total air permeability of the shell of the building is not a direct measure for the quantity of air that enters the house through infiltration in realistic circumstances. In determining the air permeability of the shell of a building, it is always assumed that the air pressure on the outer walls is at a constant 10 Pa. In reality, air pressure around the house is distributed differently as a result of wind direction and strength, surrounding buildings, the difference between the indoor and outdoor temperatures, etc. In practice, the way in which the leaks are distributed over the shell of the building affects air permeability. In publications concerning air-tight buildings, calculation methods for determining the air permeability of a building in advance are given, based on the exterior surface area of the shell of the building, and the joints in metres.

Buildings larger than 3000 m³

The method described before cannot be used for buildings with a volume in excess of 3000 m³. Buildings of this size are too large for achieving enough pressure difference with the usual equipment.
One method that does make it possible to gain an impression of the air permeability of the shell of a building with a volume greater than 3000 m³ focuses on the air permeability of a so-called representative section of the outer wall. The method assumes that the air permeability of the roof and the ground level floor in larger office buildings and factories is generally adequate. It is accepted that air leaks are found predominantly in the outer walls and at the point where the outer walls meet both the roof and the floors. For test purposes, an airtight box is placed around 1 to 2 m away from the inside of the outer wall. The box is built up of sheet material on the spot and pressed up – air-tight – against the surrounding construction (see figure 6.12).

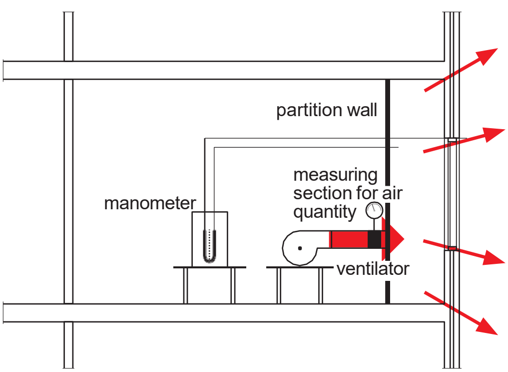


Figure 6.12 Principle of the measuring system

Air permeability of the outer wall elements

The building legislation only contains requirements with regard to the air permeability of the building as a whole. The requirements themselves are not very severe and mainly intended as minimum limits. To achieve a good indoor climate in an energy efficient building, strict requirements on, for example, the permeability of outer wall elements and windows are desirable. For evaluating windows and facade elements which are produced in a factory, separate guidelines exist. Demands are made on an air permeability test in a test cabinet. No more than 2.5 dm³/(s·m) of air can be allowed to pass through cracks at test pressures as given for the Dutch situation in figure 6.13.

height* in m	test pressure in Pa	
	inland	*coast ***
15	75	300
40	150	300
100	300	450

* Height of the top of the topmost outer wall element above ground level which is assumed to be flat.

** The coastal area includes the IJsselmeer region and a 2.5-km zone inland from the North Sea.

Figure 6.13 Test pressures for determining the air permeability of outer wall fillings

The connections between the fixed elements and between the glass and the rabbets are considered 'closed' if no more than 0.14 dm³/(m·s) of air can pass, based on the test pressures in the table in figure 6.13.
In addition to the requirements mentioned above, outer wall fillings should be constructed in such a way that the air that is admitted is distributed as equably as possible. Localized concentrated leaks are permissible as long as their air permeability does not exceed 0.5 dm³/s per 100 mm.

Basic principle of airtightness

The basic principle for making the shell of a building properly airtight is to have a double sealing system. A double sealing system consists of a moisture barrier and an air seal. It is essential that the water barrier is positioned on the outside and the air seal on the inside. A simple overlap on the connections between the various elements is sufficient for the outermost seal (the moisture barrier). Because the cavity between the two seals is directly exposed to the outside air, there is no difference in air pressure on the seal (moisture barrier). This means that rainwater that flows down on the outside of the seal is not drawn inside. However, rainwater that is driven into the cavity by strong winds may flow down the inside face of the outer wall. The airtightness in a double sealing system is provided by the innermost seal. As this seal has to be continuous, some difference in air pressure does generally occur along it. However, this is not a problem as there is no downwardly running rainwater present at this location. Examples of an outer wall surface with a double seal system include the brick wall of a cavity or a tiled roof with a deck. In both cases, there is a moisture barrier on the outside which is generally so open that little or no difference in pressure exists between the cavity and the outside air. Where there is a single seal, it has to fulfill the function of both moisture barrier and air seal. As a result, there is a risk that any difference in pressure over the outer wall will draw rainwater inwards wherever there are any ruptures on the seal.

Detailing building components

One of the most important aspects in constructing a building that complies with the requirements relating to air permeability is the detailing. Although insufficient airtightness of an outer wall may be caused by areas of porosity in the wall, it is usually the direct result of inattention to design details. Firstly, it is important when working on the details to think three-dimensionally. A specific detail that may appear to be airtight when viewed from a vertical or horizontal cross-section, may turn out not to be so from a three-dimensional perspective. This can be clearly seen in the example in figure 6.14. The joins where the

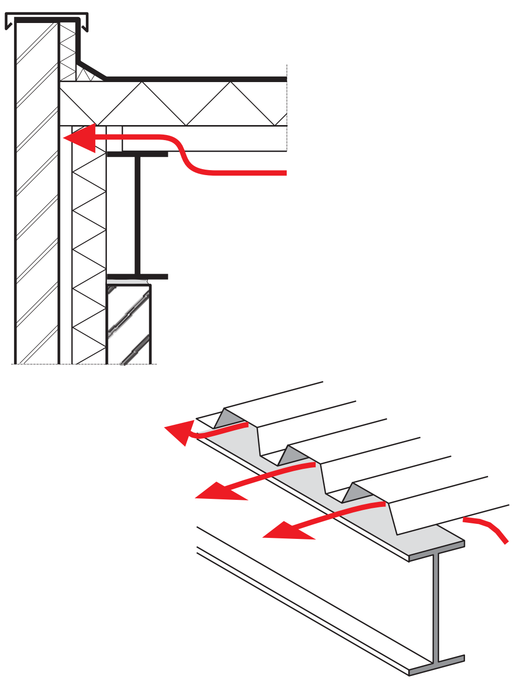


Figure 6.14 Example of air leak at join locations

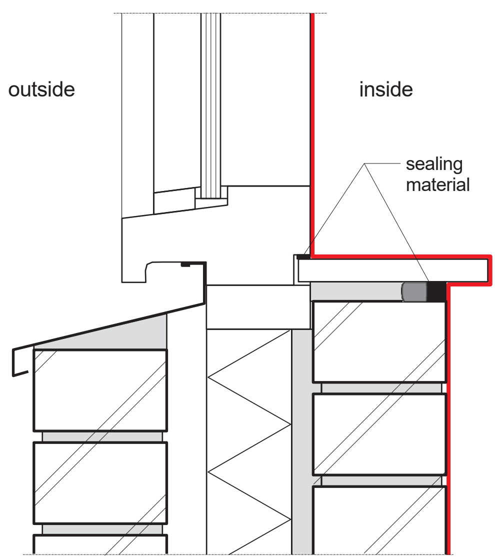


Figure 6.15 Example of 'continuity check' of the air seal on the inside of the shell of the building

steel roof sheets meet the outer wall are, on closer inspection, anything but airtight. Secondly, it is important not only that the air seal is positioned on the inside of the shell of the building, but also that it is continuous. In fact, every detail on the inside should be constructed in such a way that it should be possible to draw an uninterrupted line, symbolizing the air seal. Anywhere that two (or more) materials border each other should have a permanent (mostly flexible) seal. This continuous line is shown in the example in figure 6.15. The air seal in the innermost cavity wall has been achieved by putting a layer of plaster (not a layer of mortar) on the cavity side. This makes the entire innermost cavity wall air-tight.

The transition from the innermost cavity wall to the window sill and from the window sill to the window frame has been achieved using a flexible sealant. Although this is generally used for this purpose, sealing band is preferred from an environmental point of view. However, the use of sealing band does require different detailing techniques to those needed when sealant is applied.

7

Solar gain and solar control

A.C. van der Linden

The strength of the solar radiation that falls on the outer wall of a building can be as much as 900 W/(m^2, depending on the time of year and its orientation. If the radiation is able to enter the building, it will heat it up considerably. During the winter, spring and autumn this can be pleasant, and the radiation may help save energy. In the summer, however, it can lead to unwanted increases in temperature.

There are various factors that determine the amount of solar gain: the orientation of the outer wall, shade from protruding parts of the building (canopies, etc.) or indeed from other buildings themselves, characteristics of the glass, sunscreens, etc. All of this determines the possibilities to realise energy savings with solar heat. This chapter covers the basic principles of solar gain, and there is also a section on preventing overheating. Allowing too much sun into a room can cause problems in the summer, and sometimes in the spring and autumn, as the indoor temperature can reach a high level. Solar radiation can also lead to large differences in levels of brightness, with the associated problems of dazzle. On the other hand, the admission of sun into a room can be particularly pleasant. The sun's rays provide agreeable heat and brightness, drive out the gloom and heighten contact with the outside world. In other words, there are advantages, disadvantages, and conflicting interests, all of which mean that the totality of measures needs careful consideration.

7.1 Amount of sunlight received

Recommendations and guidelines

The building legislation has no requirements relating to sunlight shining into buildings. For houses especially however, it is important that a minimum level of sunlight gets in. This can be determined by using the amount of sunlight received by a 'norm point' as given in already long existing guidelines. This 'norm point' is located in the middle of the window sill on the inside of the outer wall. If the 'norm point' is exposed to the sun for at least three hours on 20 January (and 22 November) between 9.00 and 15.00 hrs, then it can be qualified as 'good', while any point subject to at least two hours' exposure on 19 February (and 23 October) could be described as 'moderate'. In the case of factories, working areas, offices and so on, users have to have the choice of being protected from exposure to direct sunlight. Rules governing this are given in working conditions guidelines. There are no further generally accepted detailed guidelines on this subject, so the personal vision of the individual designer is decisive.

Influence of orientation

Figure 7.1 shows how the intensity of the solar radiation progresses during the day, for four different orientations. As well as direct solar radiation, there is also so-called diffused radiation (sunlight that is dispersed by the atmosphere) and radiation reflected off the ground. In figure 7.1, the direct and total radiation (that is, direct + diffused + reflected) is given.

This graph applies to the month of July. It can clearly be seen that the intensity on the western and eastern outer wall is greater than that on their southern counterpart. This is because the sun is much higher in the middle

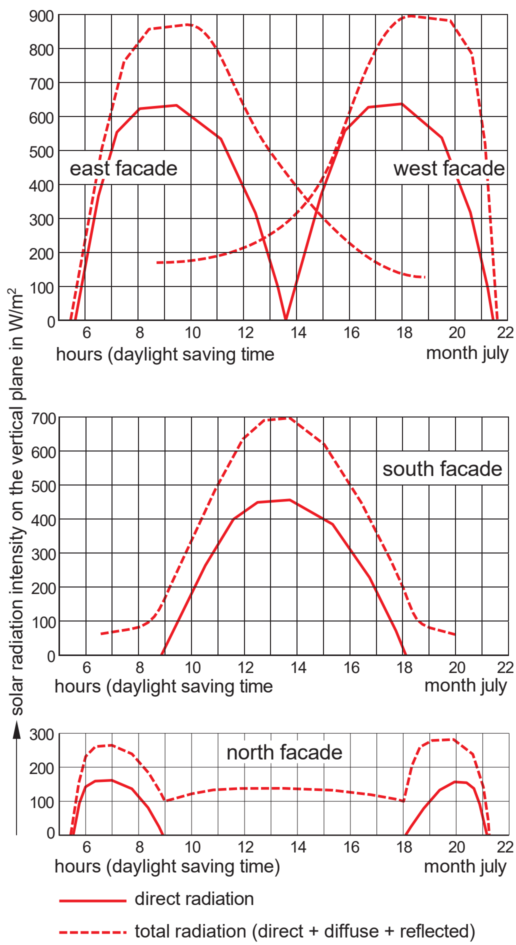


Figure 7.1 Daily progress of the intensity of solar radiation during July, for four orientations

of the day when it shines on the southern outer wall, than at the beginning or end of the day, when it is directed at the eastern and western sides (see figure 7.2).

The intensity perpendicular to the direction of the solar radiation is more or less the same in both cases. Calculated per square metre of the surface area of the outer wall (the vertical surface) however, the intensity of the solar radiation is relatively low when the sun is high in the sky. Things are different in the month of September, when the position of the sun is much lower, even for the south-facing outer wall, which therefore receives a greater radiation intensity than during the summer months. See figure 7.3. In these circumstances, the western side will get less radiation as the position of the sun is relatively very low and the intensity of the radiation strongly reduced by the atmosphere.

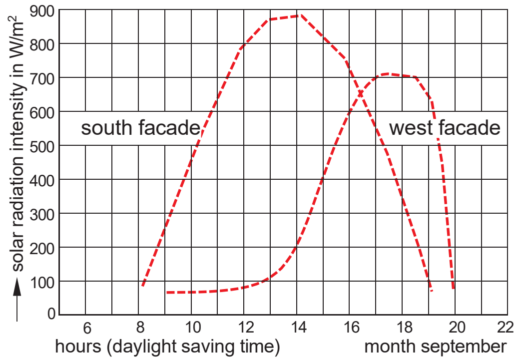


Figure 7.3 Daily progress of the intensity of solar radiation during September, for two orientations

Western or southwestern facing orientations provide most of the problems when it comes to overheating. Solar radiation is high in the afternoon, precisely when the outside temperature is also at its peak.

It should be pointed out that daylight saving time has a favourable effect on the situation in offices. The indoor temperature reaches its maximum at the end of the working day, slightly later than the outdoor temperature. This means that sunscreens have to be kept closed outside office hours in order to prevent the building from heating up. If the sunscreens are outside, they more or less have to be operated automatically, because they have to be raised when the wind is strong to prevent their being damaged. The same applies to east and south facing walls, where the sunscreens should be left down before the working day begins, to prevent employees walking into a room that has already been considerably heated up.

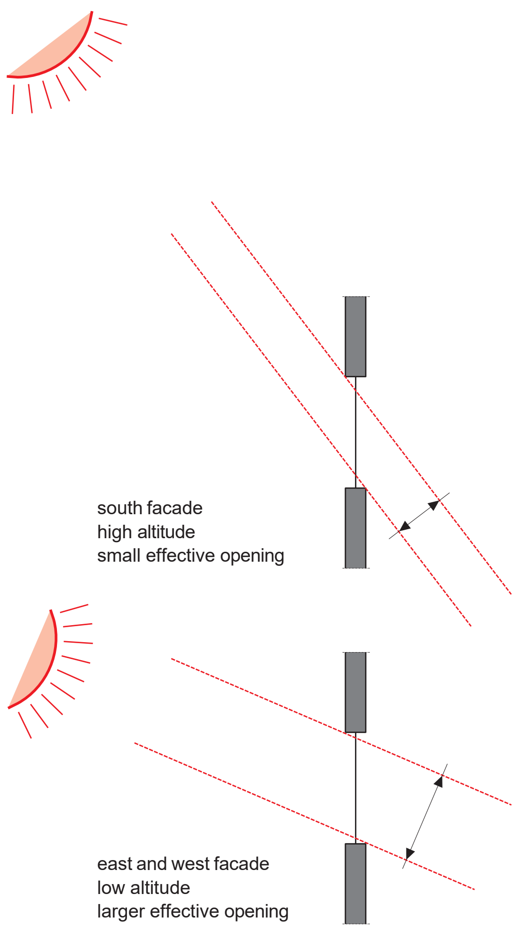


Figure 7.2 Influence of the height of the sun on the solar radiation intensity reaching the outer wall

Shadow

It is clear that in determining the solar load on an outer wall, the shadows cast by other buildings or objects such as trees play a role. If part of a building is hardly ever exposed to the sun because of the shadow of an adjacent building, then of course there is no need for any kind of sunscreen.

The design of an outer wall is also an important factor with sunlight. If the windows are deeply recessed, part of the glass will be in the shade for long periods of time (see figure 7.4), but where the glass is near the surface of the wall, a greater proportion of it will be exposed to the sun.

Canopies and horizontal screens can also function as sunscreens. The effect of the former is only very slight on western and eastern-facing outer walls because of the low position of the sun.

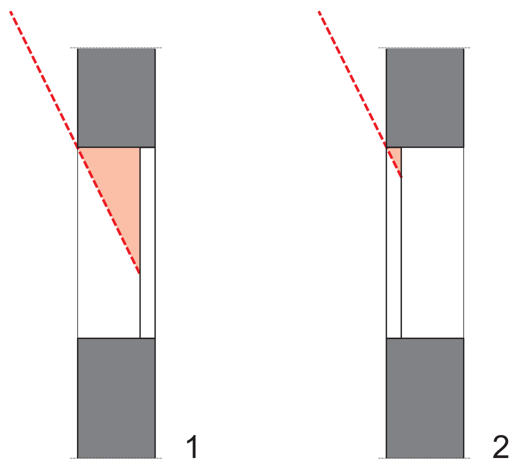


Figure 7.4 Influence of position of window on solar energy entering the building

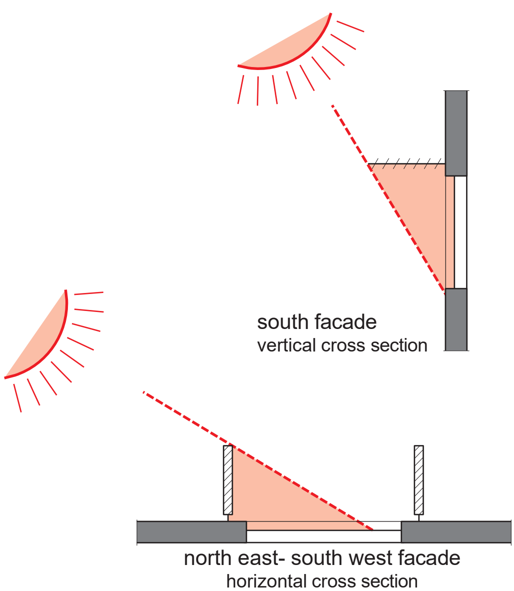


Figure 7.5 Canopies and screens as sunscreens

A canopy is suitable for southern-facing outer walls, as the sun rises high in the sky during the summer months. Outer walls facing towards the north-east or north-west can be shielded with vertical screens, for example, because the sun is always at an angle to such walls, rather than facing them directly (see figure 7.5).

Greenhouse effect

Figure 7.6 shows how solar energy is distributed over the various wavelengths of light. A very large part of the sun's energy reaches the earth in the form of visible light, with another part as infrared (heat) radiation, and a small proportion as ultraviolet (UV).

Insulation glazing (HR^{++}) without sun-repelling features allows around 60% of solar radiation through. Depending on the angle of incidence, it is partly reflected, and partly absorbed, so that the glass heats up (see figure 7.7). This results in the interior becoming also warmer due to convection heat being given off by the glass.

Walls, floors and objects reached by radiation after it has passed through glass will be heated up as a result. Their higher temperatures will cause them to radiate heat to the other walls and items in the room. The wavelength of this radiation amounts to around 10 μm. However, these wavelengths hardly penetrate glass, which means the heat becomes trapped in the room. This is known as the greenhouse effect.

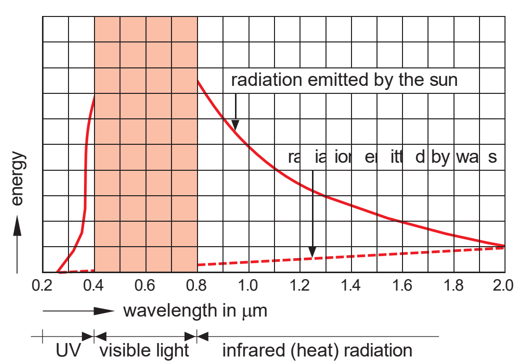


Figure 7.6 Distribution of solar energy over various wavelengths

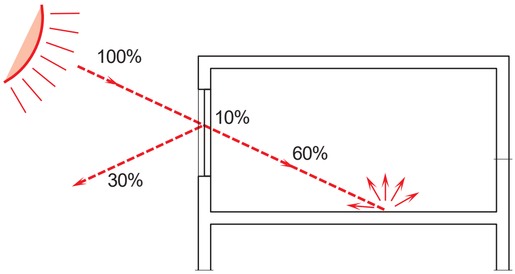


Figure 7.7 Greenhouse effect

7.2 Sunscreens

To keep the sun out of a building to a sufficient degree, some kind of sunscreen or shield is generally necessary. The most common types are external blinds, and reflective windows. The solar transmission quality of a construction is represented by the so-called solar transmission factor (g) and the convection factor (CF).

The g factor indicates the proportion of the solar energy that ends up inside the room. If it is 0.45, this means that 45% of the solar energy ultimately finds it way into the room, while 55% remains outside. The energy that enters as radiation influences the air temperature of the room at a very slow rate. The walls and objects in the room are heated up first before they give off the heat to the air, by convection.
The proportion of the energy that enters as convection heat affects the air temperature directly however. For that reason, the convection factor (CF) is at least as important as the g factor. The convection factor indicates which part of the incoming solar energy is convective. A CF of 0.30 means that, of the total incoming solar heat, 30% is instantly given off into the air by convection. A high convection factor is unfavourable as this quickly leads to a rise in temperature and consequently raises the capacity needed for any cooling system that may be present.

Figure 7.8 shows diagrammatically what energy flows occur with a window system as a result of solar radiation. The meaning of the symbols is:

- q_{ze} the totality of solar energy directed at the building
- q_r radiation that is reflected
- q_d radiation that is admitted
- q_a radiation that is absorbed
- q_{ce} heat that is given off outside through convection
- q_{se} heat radiation that is given off outside
- q_{ci} heat that is given off inside through convection
- q_{si} heat radiation that is given off inside

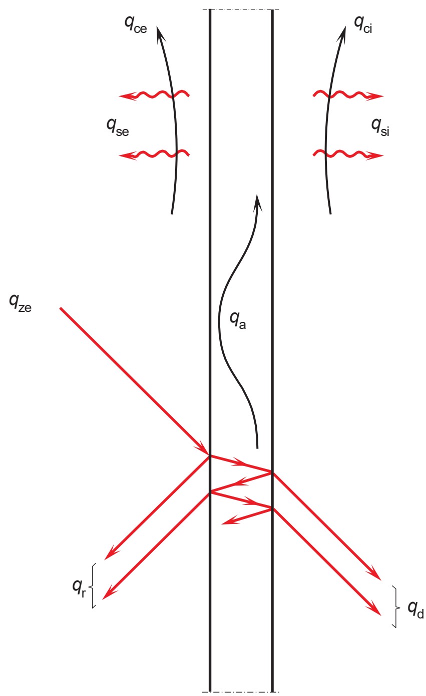


Figure 7.8 Energy flows that occur with a window system as a result of solar radiation

The g factor and CF can also be written as formulas:

$$g = \frac{q_d + q_{ci} + q_{si}}{q_{ze}}$$

$$CF = \frac{q_{ci}}{q_d + q_{ci} + q_{si}}$$

A disadvantage of sunscreens is that they also keep daylight out. Another unit of measurement that merits attention in this context is the light transmission factor (LTA). If this is low, it may mean that artificial lighting is required during the day, which consumes extra energy. It also results in extra heat being brought into the room and therefore a greater need for cooling, something that sunscreens are intended to prevent. In other words, it is important to find an optimum situation between keeping out the sun and allowing in sufficient daylight.

External sunscreens

To prevent the exclusion of solar energy in the winter, adjustable external sunscreens are generally preferred. This means it is possible to use the screens only when necessary, as a means of preventing either overheating or the need to use a cooling system. External sunscreens reflect a significant proportion of the sun's rays before they reach the glass. Another proportion, again significant in size, is absorbed by the screens, but rereleased through convection (air movements, wind) into the outside air. The solar heat that gets in consists mostly of directly admitted radiation. Solar transmission factors of up to around 0.15 can be achieved with effective external sunscreens, and an extra advantage of external sunscreens is that the CF is often no greater than 0.1. This means that just $0.15 \cdot 0.1 = 1.5\,\%$ of the solar heat that lands on the sunscreens is eventually released into the room by convection (see figure 7.9).

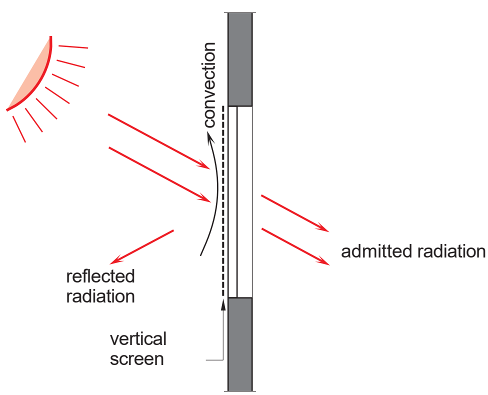


Figure 7.9 External sunscreens (the most important energy flows)

As already mentioned, adjustable external sunscreens are preferred. Commonly used systems include vertical blinds, screens that can be rolled up, and canopy blinds. The disadvantages of adjustable external sunscreens are that they have to be constantly maintained and the fact that they are ineffective where there are strong air movements. In addition, where a significant proportion of a building is made up of glass, external screens may not be sufficient, quite apart from the aesthetic objections that they give rise to when present in large numbers. It is partly for this reason that in recent years attempts have been made with many new buildings to use other kinds of solar exclusion, at least to a degree. Examples include perforated metal panels, or panels with etched glass, placed parallel to the outer wall, but at some distance. The drawbacks to this type of sun exclusion are the permanent reduction of the amount of daylight that gets in, and the diminishing of the view from the inside.

Another downside to external sunscreens is that the flow of air through open windows or ventilation grids is often seriously hindered, and the heat that has been captured by the sun excluders is then ventilated into the building anyway. There are various options for preventing this problem. One is to place separate panels that can be opened, for

Figure 7.10 The ventilation through open windows or ventilation grids can be seriously hindered by external sunscreens

summer ventilation. As these panels do not have any glass, no sunscreens are needed for them.

Solar control glazing

There are two main types of solar control glazing: absorbing glass and reflecting glass. Figure 7.11 highlights how these types of glass work (only the most important arrows are drawn).

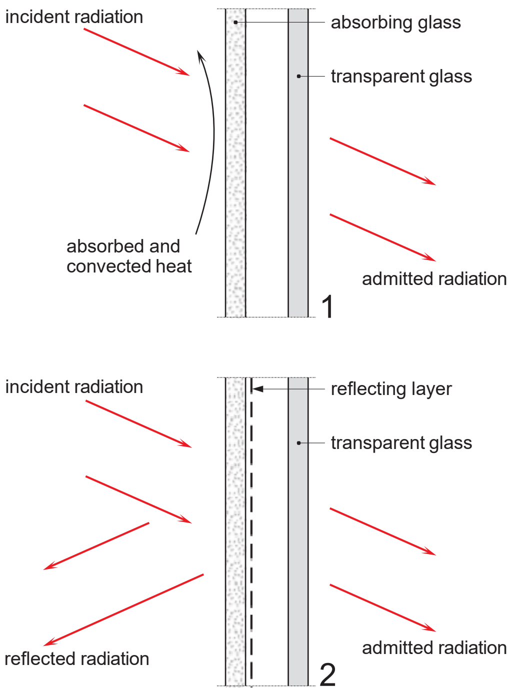


Figure 7.11 Sun resistant glass (the most important energy flows)

An extra component, usually metal oxides, is added to absorbing glass to make window panes capable of absorbing a significantly large proportion of the sun's radiation. As a result, the windows become relatively very warm. Most of this heat is released to the outside air through convection (air flows, wind), with a small amount to the inside air through radiation and convection. Absorbing windows are often dark in colour, resulting in a low level of light permeability. Another disadvantage of absorbing glass is its gloomy appearance. In the case of reflecting glass, the solar radiation is largely reflected, with a small portion being absorbed. The solar heat that does manage to enter consists mostly of directly admitted radiation. The reflective layers are usually made of a layer of metal produced by vapour deposition, metal oxide or a coating. This layer is very fragile and is therefore attached to the inside of the outer window. A drawback of reflective glass is its mirror-like character. This effect also occurs to a limited degree with high-efficiency glazing. The development of solar control glazing has seen huge strides in the last ten years. Nowadays there are very good spectrally selective types of glass available; they hold back most of the heat-producing part of the sun's radiation, while allowing the light-producing section to pass. Glass with a *g* value of 0.35 or less, and an LTA of 0.6 or more, is now available. Any further improvement to the features of solar control glazing will not be easy with current technology, given the partial overlap that exists between the heat-producing and light-producing part of the spectrum.
The sun-resistant features of the open areas of the outer wall could be improved by combining solar control glazing with external sun blinds, but this option is not exercised very often, as any such improvement would only be modest in relation to the relatively large investment that would be required.

Internal sunscreens

Internal sunscreens merit a particular mention. As far as their sun-resistant capacities are concerned, they perform considerably worse than their external counterparts. Some of the sun's radiation is reflected back outside through the glass, but a significant proportion is absorbed by the excluders, causing them to become much warmer (see figure 7.12). The rise in temperature causes the screens to emit heat by convection, but because of their position, this occurs into the inside air.

In addition to convection heat, the internal sunscreens also give off heat radiation. As has already been explained this heat radiation cannot, because of its wavelength, pass

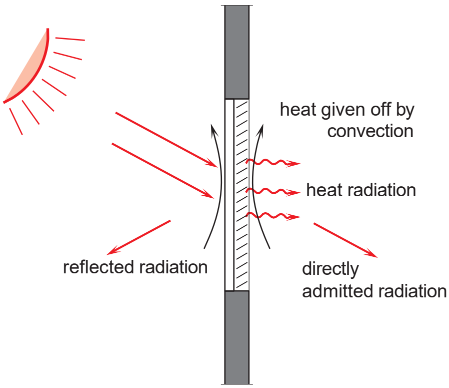


Figure 7.12 Effects of internal sunscreens

through the glass to the outside, leaving it trapped inside the room. Internal sunscreens will never achieve better results than a *g* factor of 0.40 in combination with relatively high CF levels. Besides Venetian blinds also fabrics (curtains) with a reflective layer of aluminium are used, the CF levels of which are often lower than those of Venetian blinds, for example. Due to the limited results that can be achieved through the use of internal sunscreens, they should really only be applied where it is not possible to have external screens or solar control glazing, for example with restoration projects. The Venetian blinds that are used on the inside of many buildings are often referred to as sunscreens, but are generally only intended to regulate the incoming light, a function for which they are highly suitable.

Overview of sun transmission characteristics

Figure 7.13 shows the *g* factor and the LTA for various solar control constructions, and which part is given off as convection heat by the solar control system (CF). The table in figure 7.14 gives these specific values for sunscreens and different types of high-efficiency glazing.

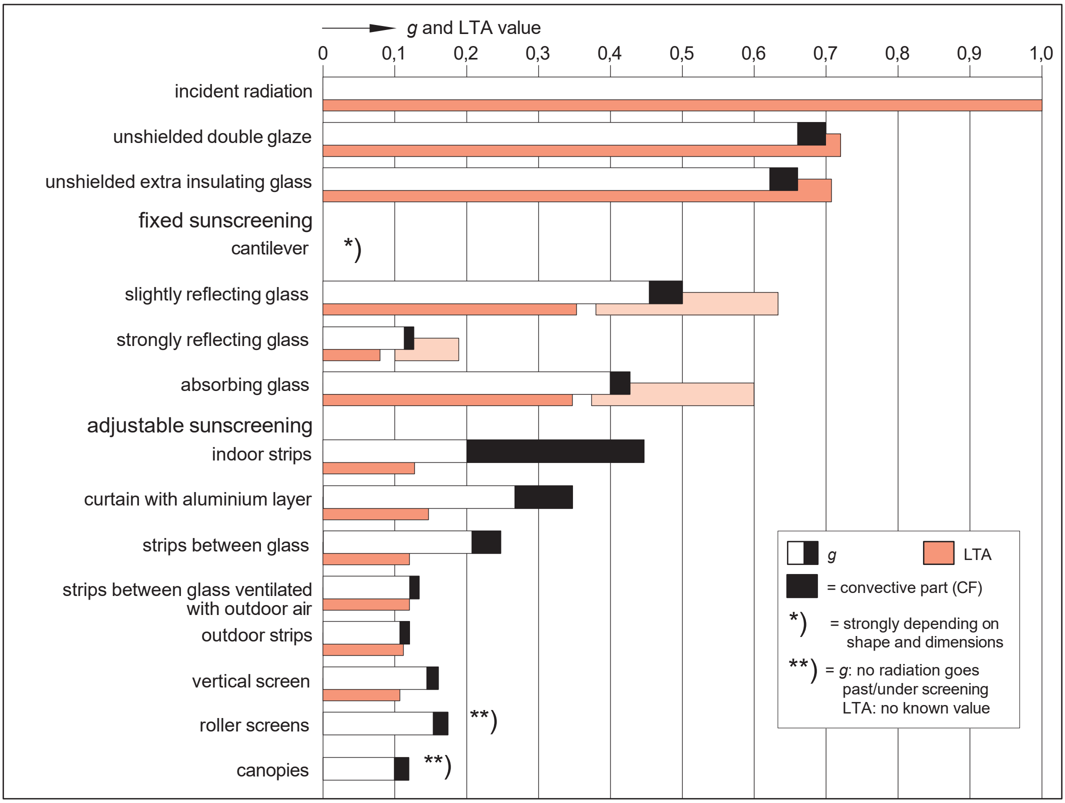


Figure 7.13 Standard values for sun transmission characteristics of several window systems (source: SBR/ISSO publication 213, *Ontwerpen van energie-efficiënte kantoorgebouwen* (Designing energy-efficient office buildings). The values shown should be regarded as an indication – certain products may have characteristics that significantly deviate from them. The angle of incidence of the solar radiation is often important as well, as is the position of the blinds in the form of strips. In this case, both the angle of incidence of the sun and the position of the blinds are assumed to be 45° (that is, perpendicular to the solar radiation).

window system	*g*	CF	LTA
high-efficiency glass, unprotected	0.60	0.04	0.70
high-efficiency glass, Venetian blinds (light colour)	0.47	0.55	0.12
high-efficiency glass, outdoor blinds	0.12	0.05	0.10
high-efficiency glass, screens			
light	0.20	0.10	0.15
heavy	0.13	0.15	0.05
high-efficiency glass, roller screens (not connected)	0.15	0.15	0.14
high-efficiency, canopy screens	0.11	0.18	0.05

The values given in the table should be regarded as standard values certain products may have characteristics that significantly deviate from them. Additionally, with many constructions (glass surfaces), the angle of incidence of direct solar radiation affects the reflection onto the outer surface. This table is based on an angle of incidence of 45°. In the case of sun blinds, the level of solar control depends strongly on the angle of the blinds. The table assumes an angle of 45°, in other words perpendicular to the sun's radiation.

Figure 7.14 Standard values for the *g*, LTA and CF, for combinations of solar control systems and high-efficiency glass.