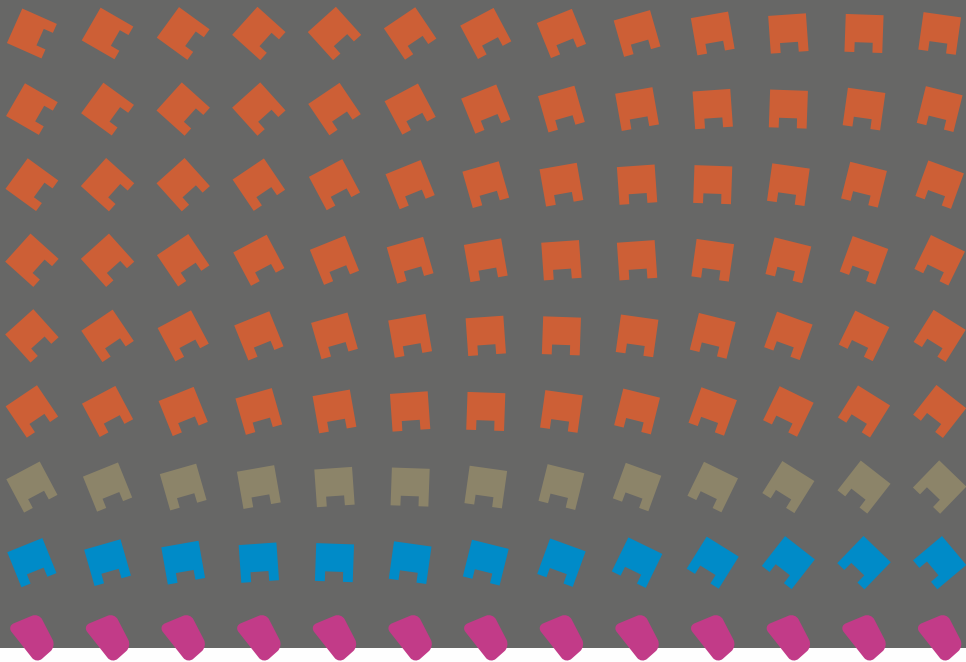


# Building Physics

2nd  
edition



ir. A.C. van der Linden

ir. I.M. Kuijpers-Van Gaalen

ir. A. Zeegers





# **BUILDING PHYSICS**

**Design inside**

Peter van Dongen, Amsterdam;  
Fabrique, Delft

**Layout**

PPMP Prepress, Wolvega

**Design outside**

Ineke de Graaff, Amsterdam

**About ThiemeMeulenhoff**

ThiemeMeulenhoff is developing from being an educative publisher to a modern learning design company. Our growing expertise, experience and learning solutions makes us a partner for schools in modernizing and improving their education. Together we can highlight the differences between the students and schools, and also make sure that learning becomes more personal, more effective and more efficient. ThiemeMeulenhoff offers books, but more often digital teaching methods. ThiemeMeulenhoff develops these materials along with the schools.

[www.thiememeulenhoff.nl/en](http://www.thiememeulenhoff.nl/en)

ISBN 978 9006 10612 1

Second edition, first print, 2018

© ThiemeMeulenhoff, Amersfoort 2018

All rights reserved. No part of this edition may be reproduced, stored in an electronic database, or made public, in any form or by any means, be it electronic or mechanical, including photocopying, recording, or in any other way, without the prior written permission of the publisher.

In as much as photocopying material from this edition is allowed according to article 16B of the Dutch Copyright Law 1912 j° ruling August 23rd 1985, statute 471 and article 17 Dutch Copyright Law 1912, one must pay the obligatory compensation to the PRO foundation – the Publication and Reproduction Rights Organisation, PO Box 3060, 2130 KB Hoofddorp ([www.stiching-pro.nl](http://www.stiching-pro.nl)).

To be able to use a part of this edition in an anthology, reader or other compilation (article 16 Dutch Copyright Law) one must first contact the publisher. Further information about the use of music, film and photocopying in education can be found at [www.auteursrechtenonderwijs.nl](http://www.auteursrechtenonderwijs.nl).

The publisher has endeavoured to regulate the authors' rights according to law. However, those who believe that certain rights can still be claimed, may contact the publisher.

This edition has been manufactured in a CO<sub>2</sub>-neutral way.

This edition has been printed on FSC® trademark paper.

This paper is produced from environmentally responsible forestry.

# Building Physics



## Authors

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

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

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

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

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

- *Heat, heat transport, thermal insulation*
- *Moisture, moisture transport, condensation*
- *Heat and moisture transport in practice*
- *Lighting*
- *Thermal comfort*
- *Ventilation and infiltration*
- *Solar gain and solar control*
- *Acoustics*
- *Sound insulation and sound proofing*
- *Applied sound insulation*
- *Fire safety*

*Chapter 13 Fire safety is based on material of  
ing. T.A.J. Selten, moBius consult b.v., Driebergen  
and ir. R.H.P. van Herpen, Nieman Raadgevende  
Ingenieurs, Zwolle.*

## Editing

ir. A.C. van der Linden

## Preface

The daily use quality of a building depends to a large extent on the performance achieved with respect to indoor climate: thermal comfort, air quality, day light, artificial light, acoustics, etc. There also is a strong relation between the way these performances are achieved and the energy use of the building.

Furthermore one takes it for granted that the building structures (facade, roof) fulfill their function for many years and are not damaged by interstitial condensation or other problems. All these aspects are subject of the study of Building Physics.

Energy conservation, a careful choice of building materials and a healthy indoor climate are very important with regard to sustainability.

Building Physics bridges different knowledge domains. For this reason it is of importance for all parties involved in building: project developer, architect, consultants on structural design, building services, building contractor, etc.

Basic knowledge on Building Physics is built up in this book step by step and made applicable by examples from building practice.

The book is meant for higher technical education as well as BSc-students in building sciences at universities. After studying the basics the book remains very useful as reference book when making assignments and graduate projects.

For students and also for those who are working in building practice special attention is paid to rules of thumb and figures to be used, material properties, etc.

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

principles that form the bases are discussed these examples also give an entrance to European standards and standards and legislation overall.

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

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

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

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

March 2018  
Kees van der Linden





## Table of contents

### 1 Heat, heat transport, thermal insulation 1

- 1.1 Basic principles of heat transport 2
- 1.2 Heat resistance of constructions 8
- 1.3 Temperature progression in constructions 13
- 1.4 Heat accumulation 15
- 1.5 Schematization of a construction; thermal bridges 19
- 1.6 Thermal stress 24

### 2 Moisture, moisture transport, condensation 27

- 2.1 Vapour transport 28
- 2.2 Relative humidity in buildings 31
- 2.3 Surface condensation 36
- 2.4 Vapour diffusion 39
- 2.5 Interstitial condensation 41
- 2.6 Climate categories and condensation 45
- 2.7 Position of insulation and vapour-retardant layers 46
- 2.8 Other forms of moisture transport 47

### 3 Heat and moisture transport in practice 51

- 3.1 Outer walls 52
- 3.2 Floors, foundations and cellars 59
- 3.3 Roofs 62

### 4 Lighting 71

- 4.1 Basic principles 72
- 4.2 Artificial lighting 77
- 4.3 Daylighting 81

### 5 Thermal comfort 87

- 5.1 Fanger's thermal comfort model 88
- 5.2 Desired indoor temperature based on PMV 89
- 5.3 Adaptive thermal comfort 93
- 5.4 Local discomfort 97

### 6 Ventilation and infiltration 99

- 6.1 Basic ventilation 100
- 6.2 Summer ventilation 105
- 6.3 Driving forces behind natural ventilation 106
- 6.4 Air permeability through the building shell 110

### 7 Solar gain and solar control 117

- 7.1 Amount of sunlight received 118
- 7.2 Sunscreens 121

### 8 Energy and energy performance 127

- 8.1 Energy use 128
- 8.2 Energy savings and financial analyses 131
- 8.3 European energy performance legislation 133
- 8.4 Energy performance of new buildings: the EPC calculation 134
- 8.5 Energy efficiency of existing buildings: the energy label 138
- 8.6 Nearly zero energy buildings 138
- 8.7 Passive building 139

### 9 Sustainable construction 141

- 9.1 BREEAM-NL 142
- 9.2 GPR 143

### 10 Acoustics 145

- 10.1 Basic terms 146
- 10.2 Evaluating sound 155
- 10.3 Sound absorption 158
- 10.4 Acoustics of the room 162

### 11 Sound insulation and sound proofing 167

- 11.1 Sound insulation between rooms 168
- 11.2 Measuring airborne sound insulation in a laboratory 178
- 11.3 Sound insulation in practice 181
- 11.4 Installation noise 186
- 11.5 Sound insulation and sound proofing of facades 186

**12 Applied sound insulation** 195

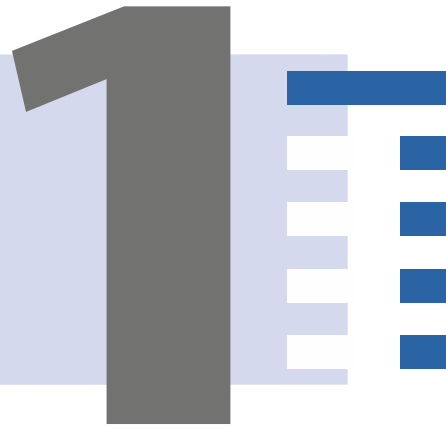
- 12.1 Desired sound insulation 196
- 12.2 Construction of the walls 197
- 12.3 Floor construction 204
- 12.4 Circulation noise 207
- 12.5 Construction of installations 209

**13 Fire safety** 213

- 13.1 Fire safety in rules and regulations 214
- 13.2 How a fire originates 215
- 13.3 Fire penetration, fire spread and strength of buildings during fire 216
- 13.4 Fire compartmentalisation and escape routes 219
- 13.5 Measures for limiting and fighting fire 220

**Register** 223**Tables and formulas**

The book of tables to which is referred in the text can be found on [www.techniekvoorhbo.nl](http://www.techniekvoorhbo.nl). Additional information can also be found on [www.klimapedia.nl](http://www.klimapedia.nl).



# Heat, heat transport, thermal insulation

*A.C. van der Linden; A. Zeegers*

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

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

## 1.1 Basic principles of heat transport

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

### Convection

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

#### Example

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

### Radiation

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

#### Example

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

### Conduction

Heat conduction takes place because of molecules in a solid are in vibration. As the temperature rises, the molecules will start to

vibrate faster. This vibration is passed on to bordering molecules.

Liquids and gases are poor conductors, while conduction is the only method for solids to transport heat.

#### Example

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

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

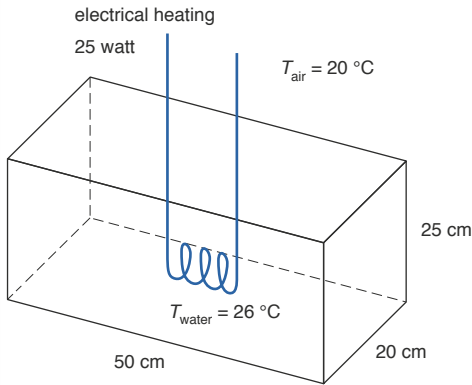
When assessing a particular construction, you look at the heat flow density. That refers to the amount of heat flowing through one square metre in the construction. Heat flow density  $q$  is therefore expressed as  $\text{W}/(\text{m}^2)$ . If a wall has a surface area of  $15\text{ m}^2$ , then the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

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

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

### Heat transport through convection

Heat transport through convection in the example, the heat element heats up the water in the aquarium. The water where the heat



**Figure 1.1** Example of heat flow

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

To warm up a room with a radiator, convection (among other means) is used with

the help of air. The air flows past a radiator and is warmed up as it does so. The warmer air gives off this heat to cold glass surfaces and other walls in the room.

It is clear that the degree to which heat is transferred depends on the speed of the flow of the transport medium (air or wind speed) and the difference in temperature between the object and the medium that is flowing past. This is expressed using the following formula:

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

The meaning of the symbols is:

$q_c$  the heat flow density in  $\text{W/m}^2$

$\alpha_c$  the heat transfer coefficient in  $\text{W}/(\text{m}^2\cdot\text{K})$

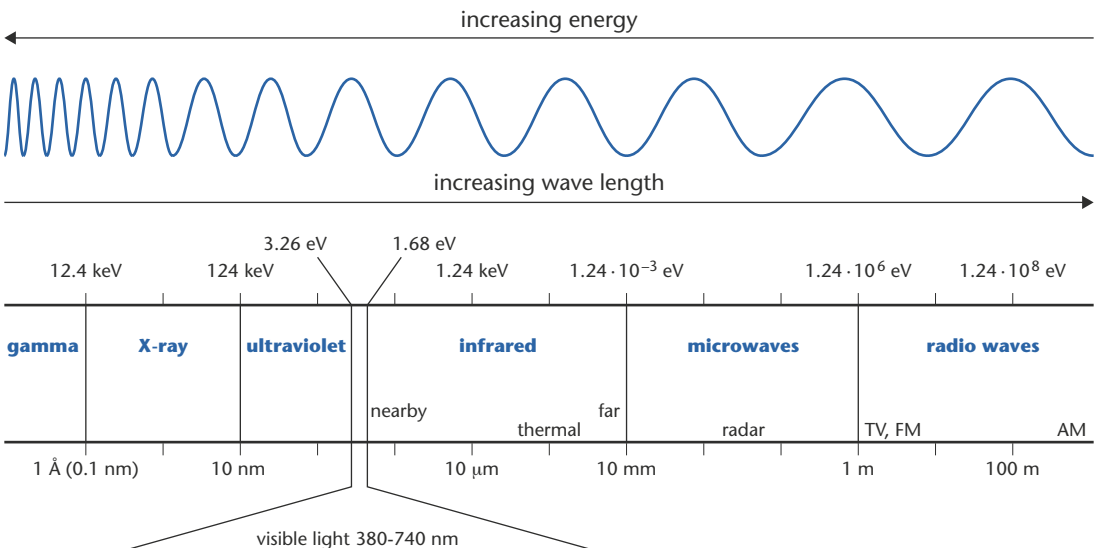
$T_1 - T_2$  the difference in temperature ( $\Delta T$ ) between for example the surface of the construction and the air flowing past in  $^{\circ}\text{C}$  or  $\text{K}$

Common values for  $\alpha_c$  are:

- indoors:  $\alpha_c = 2$  to  $2.5 \text{ W}/(\text{m}^2\cdot\text{K})$ ;
- outdoors: average wind  $\alpha_c = 19$  to  $20 \text{ W}/(\text{m}^2\cdot\text{K})$ , strong wind  $\alpha_c = 100 \text{ W}/(\text{m}^2\cdot\text{K})$ .

### Heat transport through radiation

Heat transport through radiation is part of the electromagnetic spectrum.



**Figure 1.2** Electromagnetic radiation

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



**Figure 1.3** Temperature portrayed by an infrared camera

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

By placing a warm radiator underneath the glass, for example, it can be made warmer. In the example of the aquarium, the warm glass of the aquarium radiates heat out onto the colder walls in the room.

The quantity of heat that is given off by a particular surface can be calculated with the following formula:

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

The meaning of the symbols is:

- $q_s$  the heat flow density of the radiation that is given off in  $\text{W/m}^2$
- $\varepsilon$  the emission coefficient of the surface of the material
- $T$  the absolute temperature in K

### Emission and absorption coefficient

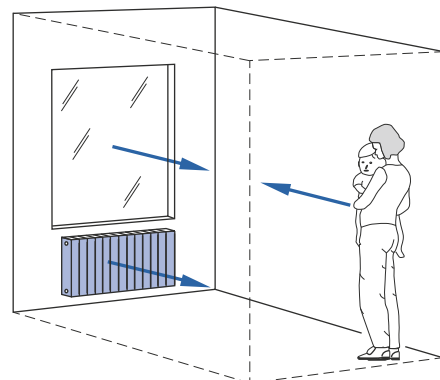
For most building materials, the emission coefficient is  $\varepsilon = 0.9$  to  $0.95$ . This value also applies to all paint colours (so white paint, as far as heat radiation is concerned, is just as ‘black’ as green). Only metallic paints, such as aluminium lacquer, have a value of  $\varepsilon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

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

- window, surface temperature around  $0\text{ }^{\circ}\text{C}$ ,  $q_s = 290\text{ W/m}^2$ ;
- person, body surface temperature around  $30\text{ }^{\circ}\text{C}$ ,  $q_s = 430\text{ W/m}^2$ ;
- radiator, surface temperature around  $50\text{ }^{\circ}\text{C}$ ,  $q_s = 555\text{ W/m}^2$ .

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

In general, the portion of the radiation that is absorbed is equivalent to the emission coefficient. This emission coefficient is



**Figure 1.4** Emissions of radiation from person, glass and radiator

therefore automatically the absorption coefficient as well.

### Visible light

Heat radiation is very different to visible light (also energy), although it belongs to the same family of electromagnetic radiation (see figure 1.2). A surface that is painted white absorbs around 90% of radiated heat, but the proportion of visible light absorbed is only about 20%. A brown or black surface absorbs some 90% of radiated heat, and 90% of visible light. Most of the energy in solar radiation is found in visible light. That is why houses in southern European countries are often whitewashed.

As far as heat radiation is concerned, the heat given off by a radiator will not be increased by painting it black or brown. But painting a radiator with a metallic paint will have a detrimental effect on the amount of heat it gives off.

### Greenhouse effect

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

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

	radiation transmission	reflection	absorption
sunlight	86%	9%	5%
heat radiation	0%	10%	90%

**Figure 1.5** Transmission, reflection and absorption normal glass



**Figure 1.6** White paint preventing overheating

### Radiative heat transfer

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

$$q_s = \frac{\varepsilon_1 \cdot \varepsilon_2}{\varepsilon_1 - \varepsilon_1 \cdot \varepsilon_2 + \varepsilon_2} \cdot 56.7 \cdot 10^{-9} \cdot (T_1^4 - T_2^4) \quad [\text{W/m}^2]$$

The meaning of the symbols is:

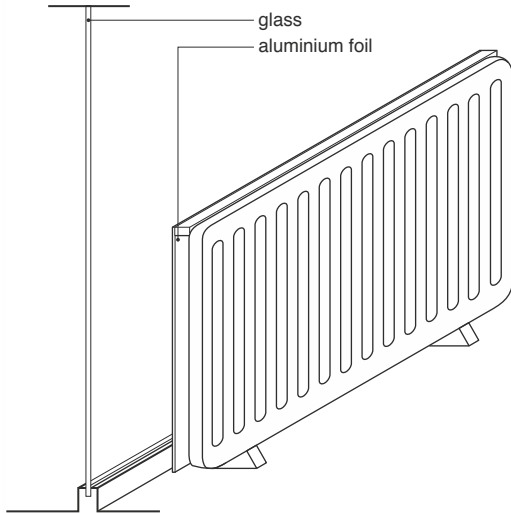
$q_s$  the net radiation transfer in  $\text{W/m}^2$

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

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

When aluminium foil radiation screens are placed between radiators and glass, or poorly insulated outer walls (see figure 1.7), the effect of the various emission coefficients is used. The low emission coefficient of the aluminium foil will restrict the radiative exchange. However, the effectiveness of the screen will diminish as a result of dirt. It should therefore be cleaned regularly or replaced after a few years. Using the above formula will give you a rough idea of the effect of radiation foil in a cavity wall or

behind a radiator. This principle is also used in the application of low-emissivity windows (low-E window). By applying an emission lowering coating, the radiant heat exchange is limited.



**Figure 1.7** Heat shield behind radiator

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

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

The meaning of the symbols is:

- $q_s$  heat transfer through radiation in W/m<sup>2</sup>
- $\alpha_s$  heat transfer coefficient in W/(m<sup>2</sup>·K)
- $T_1 - T_2$  difference in temperature ( $\Delta T$ ) between both surfaces in °C or K

In normal building practice, the value of  $\alpha_s$  is often 4.7 to 5.2 W/(m<sup>2</sup>·K).

Simplifying the formula with regard to radiation transfer is wrong in principle, but the error that is made is generally only slight.

When calculating the radiative transfer, you need to look carefully at what outside temperature you are working with. There is the potential to make a serious error here. For example, the roof of a car may be frozen in the morning, even though the outside air

temperature has not been below zero degrees. If you are using the outside air temperature as your starting point, you cannot explain this phenomenon, but if, instead of the outside air temperature, you were to use the 'sky' temperature in the calculation, then you can explain it. If there is a clear sky, the roof is 'facing' a temperature of approximately -30 °C. This makes the roof surface cool down to a temperature lower than the temperature of the environment. Outside the Earth's atmosphere, you 'face' -273 °C (0 K). The atmosphere lets us keep a little heat.

### Heat transport through conduction

Heat can only be conducted through a construction if there is a difference in temperature. It always 'flows' from the high-temperature location to the low-temperature one.

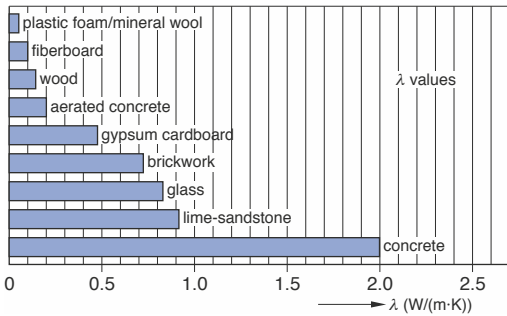
In the example of the aquarium (figure 1.1), there is water at 26 °C, on one side of the glass, and on the other, air at 20 °C. Therefore heat will 'flow' through the glass. The heat moves from one part of the glass to the next. This kind of heat transport, in a material, is known as conduction.

An example of this is the copper rod in a soldering bolt. The rod is heated on one side, and the heat moves through the rod towards the soldering point.

### Heat conduction coefficient

The heat conduction coefficient  $\lambda$  (lambda) shows how much heat 'flows' through a layer of material 1 m thick and with a surface area of 1 m<sup>2</sup>, where the difference in temperature is 1 K (1 °C). The unit of  $\lambda$  is therefore: W/(m·K). Different materials have their own heat conduction capacity, that is, some materials conduct heat better than others. The greater  $\lambda$  is, the more easily the material can conduct heat. In figure 1.8, the heat conduction coefficients of several different materials are compared.





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

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

### Heat resistance

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

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

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

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

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

The meaning of the symbols is:

- $q_g$  the heat flow density as a result of conduction in  $\text{W}/\text{m}^2$
- $T_1 - T_2$  the difference in temperature ( $\Delta T$ ) throughout the relevant construction in  $^\circ\text{C}$  or  $\text{K}$
- $R_m$  the heat resistance in  $\text{m}^2 \cdot \text{K}/\text{W}$

	heat conduction coefficient	thickness	heat resistance
material	$\lambda$ [W/(m·K)]	$d$ [m]	$R_m = \frac{d}{\lambda}$ [m <sup>2</sup> ·K/W]
concrete	2.0	0.18	$\frac{0.18}{2.0} = 0.09$
chipboard	0.2	0.018	$\frac{0.018}{0.2} = 0.09$
insulation material	0.04	0.10	$\frac{0.10}{0.04} = 2.50$

**Figure 1.9** Examples of heat resistance levels

The greater the difference in temperature ( $\Delta T$ ), the greater the heat flow density ( $q_g$ ). Conversely, the greater the heat resistance ( $R_m$ ), the smaller the heat flow density ( $q_g$ ) (in other words, 'the less heat goes through the construction').

## 1.2 Heat resistance of constructions

### Layered constructions

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

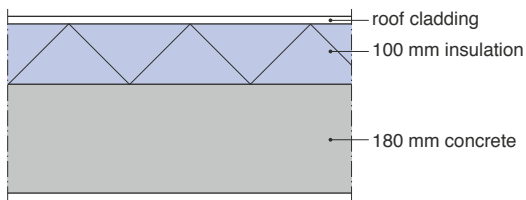


Figure 1.10 Multi-layered construction

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

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

The meaning of the symbols is:

$R_c$  the heat resistance of the total construction in  $\text{m}^2 \cdot \text{K}/\text{W}$   
 $R_{m1}, R_{m2}, R_{m3}, \dots$  the heat resistance of the individual layers in  $\text{m}^2 \cdot \text{K}/\text{W}$

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

layer	heat resistance $R_m$ [ $\text{m}^2 \cdot \text{K}/\text{W}$ ]
roof covering	0.04
insulation	2.50
concrete	0.09
	$R_c = 2.63$

Figure 1.11 Heat resistance roof construction

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

### Heat transfer resistance

The heat resistance of the layered constructions examined above refers to the heat transfer from one surface (on the inside) through the material to the other surface (on the outside). Of course, heat transfer also occurs from the air on the inside to the surface on the inside, and from the outside surface to the outside air. This heat transfer takes place through radiation and convection. The role of conduction on the surface of the construction is virtually nil. Convection depends, among other things, on the speed of the air flow over the surface. The level of heat transfer through convection will be greater on the outside than on the inside because of the wind.

To be able to calculate what the total heat transfer between the inside air and the outside air will be, you therefore have to consider the heat transfer on the surface of the construction (both inside and outside). For this, the heat transfer coefficient on the surface of the construction should be expressed in terms of heat resistance: the heat transfer resistance ( $R_s$ ). A distinction is made in the heat transfer resistance on the inside ( $R_{si}$ ) and the heat transfer resistance on the outside ( $R_{se}$ ) of the construction. The heat transfer resistance is inversely proportional to the heat transfer coefficient ( $R = 1/\alpha$ ).

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

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

- The speed of air brushing past inside surfaces is lower than 0.2 m/s.

For vertical constructions bordering the outside air the following values are used:

$$R_{si} = 0.13 \text{ m}^2\cdot\text{K}/\text{W}$$

$$R_{se} = 0.04 \text{ m}^2\cdot\text{K}/\text{W}$$

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

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

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

The meaning of the symbols is:

$R_T$  total heat resistance of the construction [ $\text{m}^2\cdot\text{K}/\text{W}$ ]

$R_{si}$  heat transfer resistance at the inside surface [ $\text{m}^2\cdot\text{K}/\text{W}$ ]

$R_c$  heat resistance of a (construction) part [ $\text{m}^2\cdot\text{K}/\text{W}$ ]

$R_{se}$  heat transfer resistance at the outside surface [ $\text{m}^2\cdot\text{K}/\text{W}$ ]

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

direction of heat flow	construction part	$R_{si}$ [ $\text{m}^2\cdot\text{K}/\text{W}$ ]	$R_{se}$ [ $\text{m}^2\cdot\text{K}/\text{W}$ ]
downward (horizontal construction deviating up to 60° from horizontal)	floors above outside air	0.17	0.04
	floors above unheated space or crawlspace	0.17	0.17
	floor in contact with ground	*	*
horizontal (vertically placed construction, slanting up to 30°)	partition construction bordering on outside air	0.13	0.04
	internal partition construction	0.13	0.13
upward (horizontal constructions deviating up to 60° from horizontal)	outside partition construction on top of heated space	0.10	0.04
	internal partition constructions	0.10	0.10

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

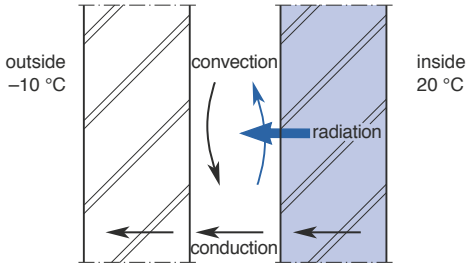
**Figure 1.12** Heat transfer resistance of construction parts in different heat flow directions

## Cavity constructions

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

### Vertical cavity

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



**Figure 1.13** Heat transfer in cavity constructions

Air is a good insulator. The following applies to still air:  $\lambda = \text{approx. } 0.025 \text{ W/(m}\cdot\text{K)}$ . This means that a 50-mm layer of air would have a heat resistance of:

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

That is very high. However, the air in a cavity construction unfortunately does not remain still. There is a flow present – convection, that is – even if the cavity is not ventilated. The air is heated up next to the ‘warm’ cavity leaf.

The warm air rises, cools off when next to the outer cavity leaf, becomes heavier, and falls. A rotating convection flow is thus created in the cavity, which transfers heat from the inner to the outer cavity leaf.

Because the surface temperatures of the cavity leaves (on the cavity side) are different, heat transfer also takes place through radiation.

It is clear that the large level of heat resistance in the air is significantly reduced through radiation and convection. This is of course not helped by the cavity ventilation that is so often to be found.

So how great is the heat resistance of a cavity? Conduction and convection depend on the width of the cavity. Convection flows will not be able to develop so easily in a very narrow

cavity, and that is a good thing. The  $\alpha_c$  therefore decreases. On the other hand, the layer of air will be so thin that levels of heat resistance against conduction will be very low. The  $\alpha_g$  therefore increases. The proportion taken up by radiation does not depend on the width of the cavity, but it is affected by the surface temperatures in the cavity leaves. The reverse applies to wider cavities.

Because of these conflicting effects, the heat resistance of a vertical cavity is relatively dependent on the thickness (see figure 1.14). It is only with very narrow cavities that heat transport sharply increases through conduction.

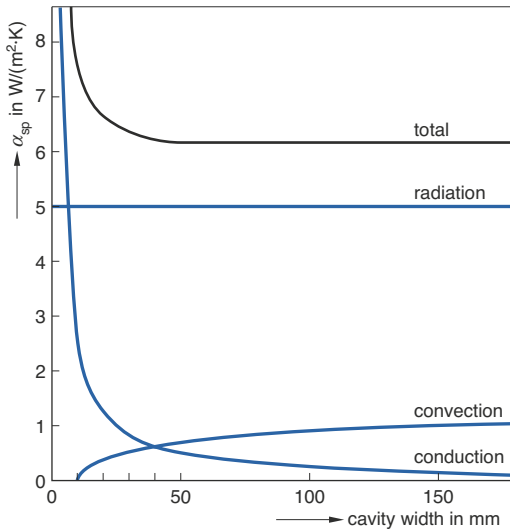
For this reason, the cavity of low-E windows is not filled with air but with a different gas (argon, krypton), which has a lower heat conduction coefficient than air.

For lightly ventilated or unventilated cavities of  $\geq 20 \text{ mm}$ , heat resistance  $R_{sp} = 0.17 \text{ m}^2\cdot\text{K/W}$  can be used. This value results from the assumptions for transfer through conduction, convection and radiation:  $\alpha_{gsp} = 0.5 \text{ W/(m}^2\cdot\text{K)}$ ;  $\alpha_{csp} = 0.5 \text{ W/(m}^2\cdot\text{K)}$ ;  $\alpha_{ssp} = 5.0 \text{ W/(m}^2\cdot\text{K)}$ .

From this we can derive  $R_{sp} = 1/(\alpha_{gsp} + \alpha_{csp} + \alpha_{ssp}) = 1/(0.5 + 0.5 + 5.0) = 0.17 \text{ m}^2\cdot\text{K/W}$ . This is of course a global value. The transfer coefficients will differ in different situations. The influence on  $R_{sp}$  is seldom more than a couple of hundredths, except when there is a radiation screen in the cavity as is the case with insulation sheets cached with aluminium foil, radiation screens of plastic foil with deposited aluminium and double glazing with a deposited metal layer on one of the window panes. The radiation transfer can then drop significantly to  $\alpha_{ssp} = 0.1 \text{ W/(m}^2\cdot\text{K)}$  or lower, for example. The heat resistance of the cavity will then be  $R_{sp} = 1/(0.5 + 0.5 + 0.1) = 0.9 \text{ m}^2\cdot\text{K/W}$  or more. For all kinds of specific situations values are provided in standards and reference books.

### Horizontal cavity

As with transfer resistances, the direction of the heat flow plays an important role with horizontal cavities (see figure 1.15). If the heat flow is in an upward direction, like the



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

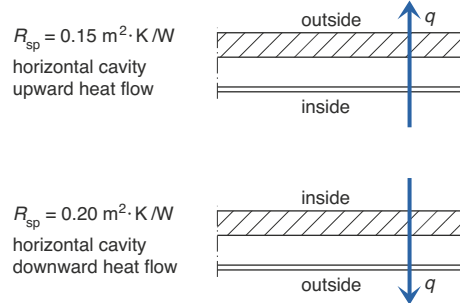
convection flow, the heat resistance will be lower than when the heat flow is moving in a downward direction, that is, against the convection flow.

In the standards values are included which should be used in calculations. A distinction is made between cavities that are not, lightly or strongly ventilated (see figure 1.16). For cavities that are not or lightly ventilated, these specified values differ only slightly from the numbers given here.

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

### Calculating heat resistance for constructions with a cavity

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



**Figure 1.15** Heat resistance of horizontal cavity

$$R_T = R_{si} + R_{bibil} + R_{iso} + R_{spw} + R_{bubli} + R_{se}$$

The meaning of the symbols is:

- $R_T$  total heat resistance of the construction
- $R_{si}$  the inside surface resistance
- $R_{bibil}$  the heat resistance of the inside cavity sheet [ $m^2 \cdot K/W$ ]
- $R_{iso}$  the heat resistance of the insulation [ $m^2 \cdot K/W$ ]
- $R_{spw}$  the cavity resistance [ $m^2 \cdot K/W$ ]
- $R_{bubli}$  the heat resistance of the outside cavity sheet [ $m^2 \cdot K/W$ ]
- $R_{se}$  the outside surface resistance [ $m^2 \cdot K/W$ ]

If there is a strongly ventilated layer of air in a construction, the calculations of  $R_c$  must include only the specific heat resistances of those layers on the inside of the relevant layer of air. From this point, you use a replacing heat transfer resistance  $R_{se} = 0.13 m^2 \cdot K/W$  in calculations, in which  $R_{spw}$ ,  $R_{bubli}$  and  $R_{se}$  are combined.

### Heat transmission coefficient

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

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

**Figure 1.16** Definition of not, slightly and strongly ventilated cavities

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

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

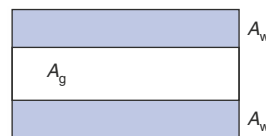
As an illustration, the table in figure 1.17 shows the heat resistance ( $R_c$  and  $R_T$ ) and the heat transmission coefficient ( $U_T$ ) for a number of constructions with  $R_{si} = 0.13 \text{ m}^2\cdot\text{K/W}$  and  $R_{se} = 0.04 \text{ m}^2\cdot\text{K/W}$ .

The building regulations in the Buildings Decree include requirements for the  $U_T$  value of windows, doors and frames in partition

constructions. The amount of heat passing through the surface to be considered at a temperature difference of 1 K, is called the heat loss through transmission coefficient ( $H_T$ ).

#### Average heat transmission coefficient

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



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

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

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

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

- The direction of the heat flow is perpendicular to the surfaces.
- The heat flow density is the same everywhere.
- The surfaces parallel to the main surface are isothermal (i.e. the same temperature).

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

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

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

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

The meaning of the symbols is:

$H_T$  the total heat flow in W  
 $A_g$  the surface area of glass in  $\text{m}^2$

$A_w$  the surface area of the non-open parts of the outside wall in  $\text{m}^2$   
 $A_{\text{total}}$  the total surface area of the outside wall ( $A_g + A_w$ ) in  $\text{m}^2$   
 $U_g$  the  $U$  value of the glass in  $\text{W}/(\text{m}^2 \cdot \text{K})$   
 $U_w$  the  $U$  value of the non-open parts of the outside wall  $\text{W}/(\text{m}^2 \cdot \text{K})$   
 $\bar{U}_{\text{outside wall}}$  the average  $U$  value of the outside wall in  $\text{W}/(\text{m}^2 \cdot \text{K})$

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

### 1.3 Temperature progression in constructions

The total heat resistance can be calculated for a construction that consists of various layers. This can be used to determine the heat flow density. Assuming that the building is already heated and that a uniform (stationary) situation has been achieved, the heat flow density ( $q$ ) will be the same in every layer of

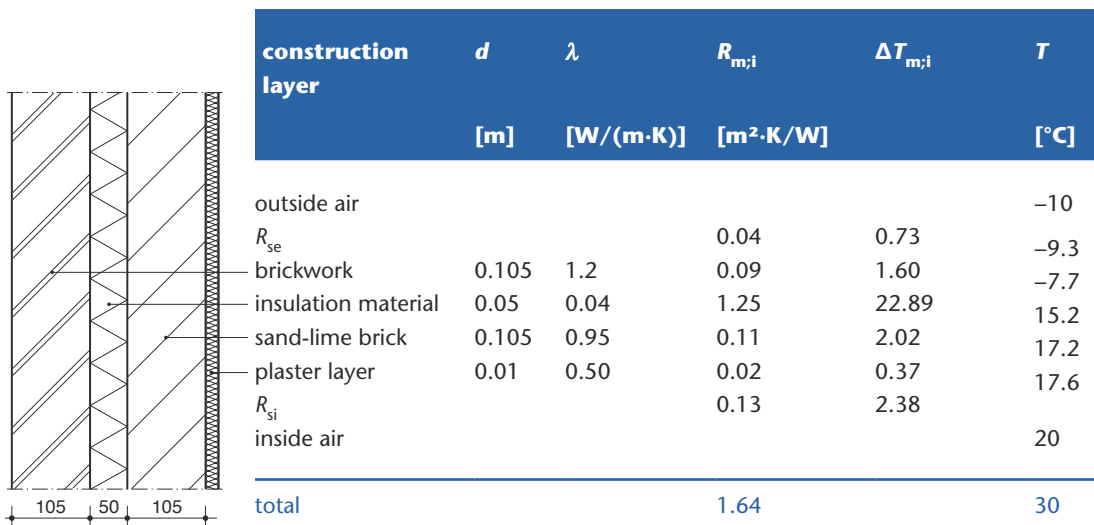


Figure 1.19 Calculation of progression of the temperature in a completely insulated cavity wall

the construction. After all, there will be no heat left in the construction, nor will there be any heat generated in it.

The following applies to each layer:

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

This means that where  $q$  is the same, the difference in temperature in a layer with a high level of heat resistance should also be greater than in the case of a layer with a low level of heat resistance.

The difference in temperature throughout the construction is distributed evenly across the various layers, according to the levels of heat resistance of the layers.

The jump in temperature in a layer can be calculated using the following formula:

$$\Delta T_{m,i} = \frac{R_{m,i}}{R_T} \cdot \Delta T \text{ [}^\circ\text{C]}$$

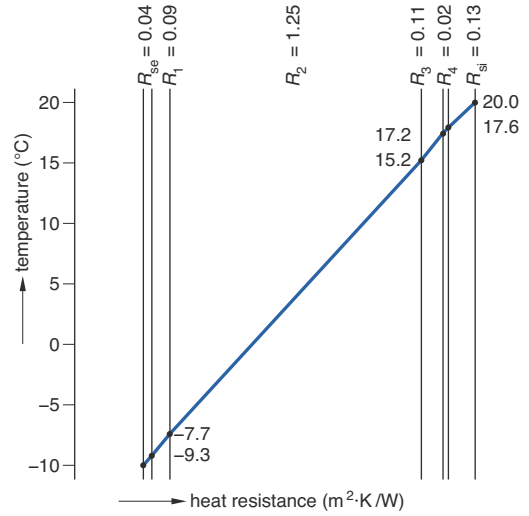
The meaning of the symbols is:

- $\Delta T_{m,i}$  the jump in temperature across layer  $i$
- $R_{m,i}$  the heat resistance of layer  $i$
- $\Delta T$  the difference in temperature between the air on both sides of the construction
- $R_T$  the total heat resistance of the total construction (air to air)

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

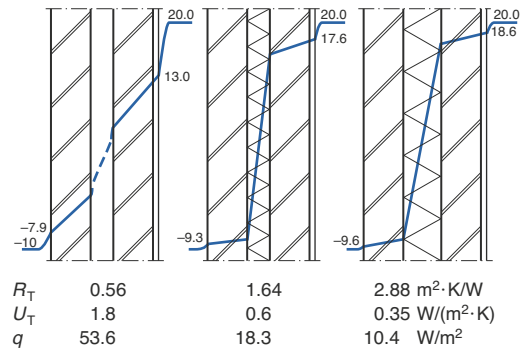
It is also possible to determine temperature progression using graphs, where the wall is drawn on the scale of the heat resistance (see figure 1.20). The temperature progression is then depicted by a straight line.

By linking the temperatures that are known (inside and outside) to this straight line, you can read the temperature at all the intermediate locations.



**Figure 1.20** Determining the temperature progression using graphs

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



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

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



Knowing the overall temperature progression in a construction is important in connection with being able to determine whether, and if so where, interstitial condensation will occur in the construction (see Chapter 2).

Better insulation will not only restrict heat loss, but the temperature of the inner surface will increase too with the greater level of insulation. This makes the spaces concerned considerably more comfortable. Modern building assumes higher heat resistances than shown here. Values of  $R_T = 5$  or  $6 \text{ m}^2 \cdot \text{K}/\text{W}$  are normal up to  $R_T = 10$  or  $12 \text{ m}^2 \cdot \text{K}/\text{W}$  in 'passive houses'.

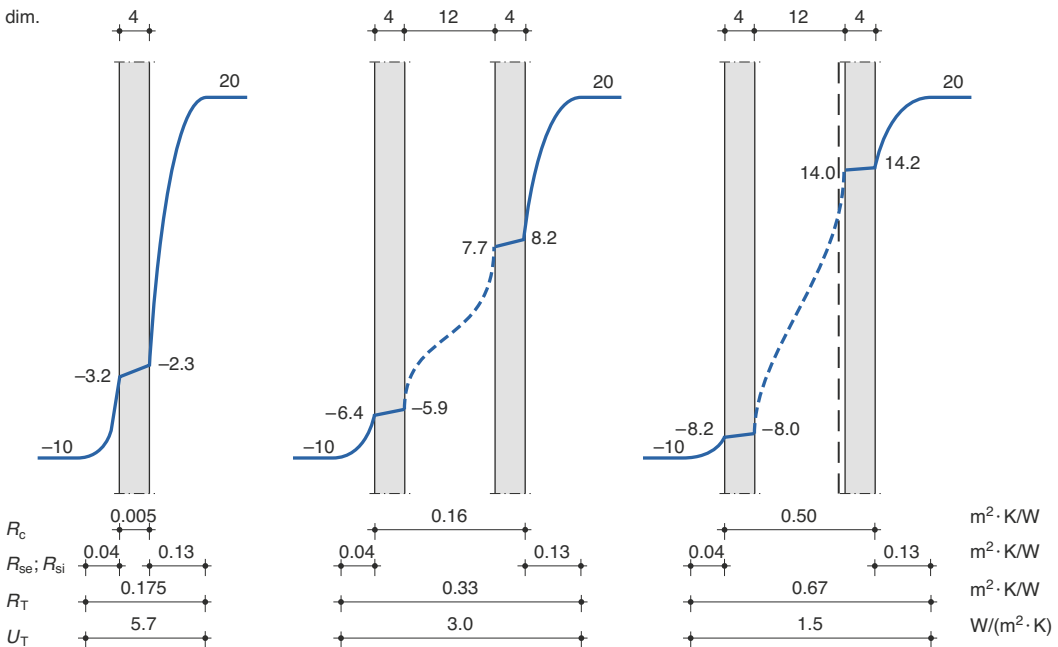
The temperature progression and surface temperature of different types of glazing can be determined in the same way as with a cavity wall (see figure 1.22).

Glass has a fairly high heat conduction coefficient ( $\lambda = 0.8 \text{ W}/(\text{m} \cdot \text{K})$ ). As a result the total thermal resistance of the construction ( $R_T$ ) is determined primarily by the levels of heat transfer resistances and the cavity. The thickness of the glass has only a slight influence. In the case of single-glazing, the

surface temperature falls to  $-2.3 \text{ }^\circ\text{C}$  in the situation described (outside temperature of  $-10 \text{ }^\circ\text{C}$ ), to  $8.2 \text{ }^\circ\text{C}$  in the case of double-glazing, and with high-efficiency glass (with a coating for reducing emissions, and with argon gas in the gap), it is  $14.2 \text{ }^\circ\text{C}$ , very important in the scope of thermal comfort. The surface temperature determines whether condensation forms on the window pane (see Chapter 2).

## 1.4 Heat accumulation

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



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

the construction will adapt itself more slowly or more quickly to the new situation, depending on the mass of the construction.

### **In summer**

Heat accumulation refers to the phenomenon where a large, sturdy building (such as an old church or a bunker) remains relatively cool by day and by night during the summer, while a light wooden building gets very warm in the daytime and cold at night.

This is caused by the difference in mass of the buildings.

When the outside temperature rises or the sun starts to shine, the whole of the building begins to warm up. In the case of a light building, this does not take much time. Within just a few hours, it is warm not only due to the rising temperature of the inside air, but also the heat radiation from the walls, to the point where it affects levels of comfort for those inside.

Things are different with large, sturdy buildings. Because of their greater mass, they require much more heat in order to be warmed up, but before they get much warmer, the day is over and they start to cool down again. As a result, the temperature in large buildings is almost the same as the average outdoor temperature measured over a few days or a week. If you know that the average temperature in the month of July is around 17 °C, then it is not surprising that old churches are often so pleasantly cool during the summer.

### **In winter**

In the winter, too, heat accumulation plays a role. A light building warms up quickly when the heating is switched on, a process that takes several hours or even a few days in the case of a building with more thermal mass. In some offices with a not or not sufficient insulated floor above outside air, it is not until the afternoon that it starts to feel comfortable if the heating has been off during the weekend. For example, if the heating comes on at 6 o'clock on Monday morning, the air temperature may be warm enough by

9 o'clock, but the walls and floor will still be cold, resulting in a feeling of cold radiation. Nevertheless, buildings with more thermal mass are more pleasant. Changes in the outside temperature are not so noticeable thanks to heat accumulation. The heating system, the effect of which can take time to be felt anyway, does not need to respond so quickly, and the result is a much more constant indoor temperature.

Mass is also necessary if you wish to use passive sun energy and internal heat sources in the building. The indoor temperature of a small building will quickly rise when the sun shines through the windows, even when the outdoor temperature is low (5 to 10 °C). Any excess heat is removed through ventilation, or perhaps with a cooling system.

The temperature in a larger building will not rise as quickly, as the construction itself has to be heated as well. If, for example, a 3 to 4 °C rise in indoor temperature is allowed for, then there is no excess heat to be removed. The heat is conserved – it accumulates – in the building itself until such time that it is needed. At night this heat keeps the temperature of the building up, so that in the morning there is hardly any necessity, if at all, to provide extra heating.

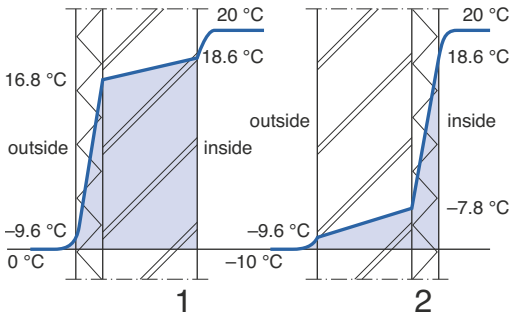
For that reason, thermally open ceilings are often used in offices where the mass of the construction is generally light (because of the use of plasterboard walls and carpets on the floor). The free-hanging ceilings are about 20% open so that the heat can be stored in the floor above. However, the top side of the ceiling has to be kept clean to prevent the build up of dust.

### **Position of insulation**

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

A lot of heat is stored (accumulated) in walls where the insulation is on the outside (see figure 1.23-1). This results in equable conditions indoors. It is also possible for the heating to be switched off for an hour without

any problems – there is, after all, enough heat in the walls. It goes without saying that the process of heating up a building like this takes a long time.



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

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

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

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

The meaning of the symbols is:

- $Q$  the amount of heat that is accumulated in the construction layer per  $\text{m}^2$
- $\rho$  the density of the material in  $\text{kg/m}^3$
- $c$  the specific heat in  $\text{J}/(\text{kg}\cdot\text{K})$
- $d$  the thickness of the layer in  $\text{m}$
- $\Delta T$  the rise in temperature of the layer in  $\text{K}$  of  $^\circ\text{C}$

Values for  $\rho$  and  $c$  for various materials are shown in the book of tables.

You can use the above formula to calculate how much heat has been accumulated in different situations, such as the one in figure 1.23.

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

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

The meaning of the symbols is:

- $\tau$  the length of time needed to heat up the construction in  $\text{s}$
- $Q_{\text{acc}}$  the amount of accumulated energy in  $\text{J/m}^2$
- $q$  the amount of energy 'supplied' to the construction in  $\text{W/m}^2$



TECHNICAL EDUCATION



BUILDING SCIENCES



BUILDING PHYSICS

Building Physics is meant for students in institutes for higher technical education as well as BSc-students in building sciences at universities.

It treats all the basic knowledge: heat and moisture transfer and the implication of these for energy household of buildings and the durability of structures (interstitial condensation, etc.), daylighting and artificial lighting, passive solar gain and sun shading, ventilation and air quality, etc. Of course attention is paid to energy performance and energy conservation, a special topic of sustainability.

With regard to sound all basics are treated and applied in room acoustics (reverberation time, etc.) and sound insulation of buildings.

The book winds up with a chapter about the basics of fire safety engineering, a growing field of activities in the consultancy firms on Building Physics.

The clear structure and the many clarifying figures and tables make this book, besides a first lesson-book being very useful as reference in making assignments and graduate projects for students, also useful for those working in the professional practice as well.

In this second edition of Building physics examples in all chapters are actualized. The chapters Ventilation, Sound proofing and Fires safety are extended and actualized. Energy Performance and the relation with Sustainable Building are covered in two completely new chapters.

ir. A.C. van der Linden

ir. I.M. Kuijpers-Van Gaalen

ir. A. Zeegers



HIGHER EDUCATION



9 789006 106121