

# HAWK

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## Building Physics

Introduction  
Heat Transport and Heat Protection  
Climate in Building  
Moisture Transport and Moisture Protection

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The Script of Building Physics shows the endeavour to reach an uniform base of the students education at the Universities of Applied Sciences and Arts of Germany in the areas of architecture, civil engineering and wood engineering.

For this reason, it is specifically wished that this script is to be used for the lectures in the field of Building Physics. Supplementary contributions and comments are desired.

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## 1 Introduction of Building Physics

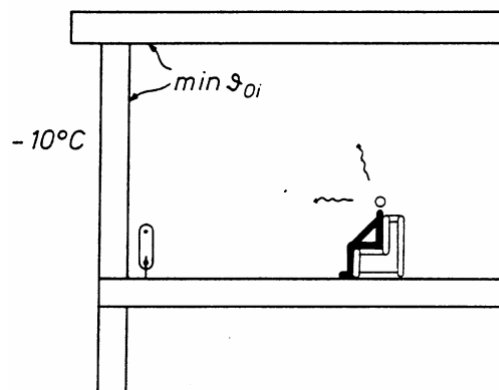
### 1.1 Which areas does Building Physics include?

#### 1.1.1 Heat Protection

The area of heat protection consists the tasks in selecting, dimensioning and detail planning of heat insulation measurements for new and old buildings as well as for reconstruction of historical buildings for winter and summer. With introduction of the new Energy economise rule, a more varied planning of the building from the view of construction physics is necessary. Hereby, it is essential to optimise the heat demand in regard of manufacture- and maintenance- costs and the energetic behaviour of the building. Consequently, the components according to the current relevant requirements and standards and to customise under consideration of structural matters and - if appropriate - monument preservation matters.

The functions are consequently

- a) Minimum heat protection
- b) Energy saving heat protection
- c) Summer heat protection



#### Form 2-1 Heat protection of a building

Minimum heat protection of the component means minimum surface temperature, consequently

1. No condensate on the surface of the component (moisture-protection)
2. Confidence in the area

Energy saving heat protection of the building means

1. Improvement of the environmental protection
2. Reduction of energy costs

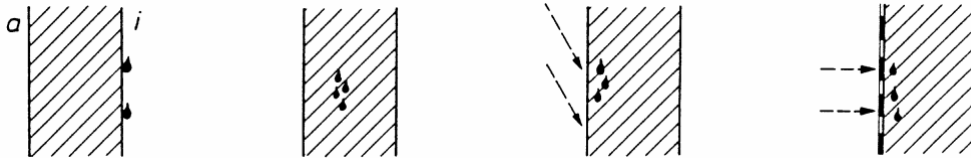
#### 1.1.2 Moisture protection

Evaluating the incriminating moisture of a building and preventing damages on the fabric of a building are the fundamental problems in construction physics.

It has become necessary to reduce congestion of moisture in buildings, for example, by dimensioned drainage,

and planned insulation measurement. With the judgement of the driving rain protection of outer parts and the regulation of the condensate on the interior surface, if the wall with bad heat absorption outer parts, here mostly in the area of heat bridges is the moisture technique can be conceived for perfect building.

Hereby, the basic of each calculation is capillary, diffusion and heat technical characteristics of the construction materials.



### Form 2-2 Condensate protection (surface, cross-section)

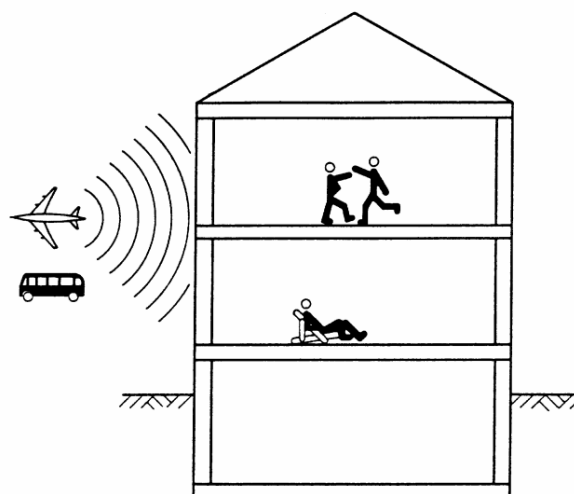
Moisture protection of the prefabricated parts means avoidance of loss because of

1. Condensate at the surface
2. In the cross-section
3. Precipitation
4. Moisture from soil or adjoining moist materials
5. Moisture from adjoining moist materials

### 1.1.3 Noise Protection

The field of the noise protection comprised moderate engineer tasks in the area of construction and room acoustics. On this occasion however, the technical acoustic planning includes also measurements and check-ups of the measurement of airborne sound as well as the level of impact sound of the constructional elements in the foreground. The regulation of the room acoustics takes place analytically or by means of evaluation of simulation.

In the area of the emission protection, the emerging emission for example from traffic noise, sport and recreation facilities is collected and evaluated. Based on these results, necessary noise precautions can be developed and dimensioned.



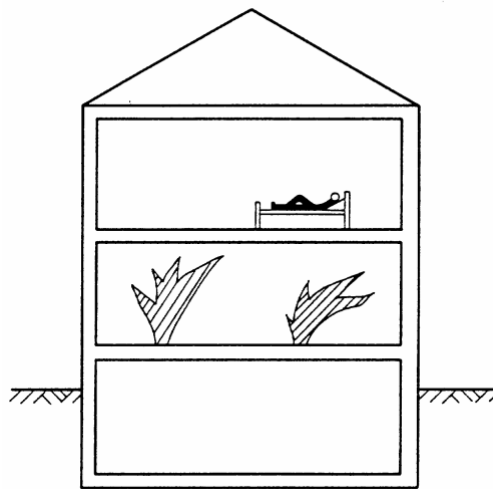
### Form 2-3 Noise protection in buildings

Noise protection of the construction materials means health and comfort of the inhabitants

1. With outside noise
2. With building inner noise

#### 1.1.4 Fire Protection

The main task of the fire protection technical treatment in constructional project is the formulation of the integral fire protection concept. On this occasion, the optimisation of the whole conception includes consideration of the versatile provisions, norms and guidelines under adjustment and under coordination with the participants in the foreground, without neglecting the safety related demands. Fire protection technical calculation supplements the concept like the preparation of escape and rescue planning for people as well as the planning of the guarantee of the packaging precious at historic buildings.



Form 2-4      Fire protection of the construction means: Safety for the inhabitants and Protection of real values

## 2 Thermal conduction

### 2.1 Definition

Thermal conduction is energy transferred by atomic and molecular impulse exchange supported by electron diffusion with metals. Thermal conduction arises in solid, liquid and gaseous media. With liquid and gaseous media heat transport contains conduction and convection. In vacuum no thermal conduction can take place.

### 2.2 Intransient linear thermal conduction through an even wall (without heat source)

The steady state case is a special case, to which applies:

$$\rho c \frac{\partial \theta}{\partial t} = 0 \quad (2-1)$$

This simplification is permissible, if

- it is subject to building materials, which possess a small storage capability due to their material properties or their thickness (e.g. glass for windows or insulating material) or
- if the temporal change of temperature is small. Proof computations to the winter thermal protection may be regarded steady state, since one proceeds a proof always from the most unfavourable case ( $\vartheta_e = -15^\circ\text{C}$ , no solar radiation). With computations to the heating energy need the stationary case is permissible, if daily, monthly or annual average values are taken into account.

To the linear case applies:

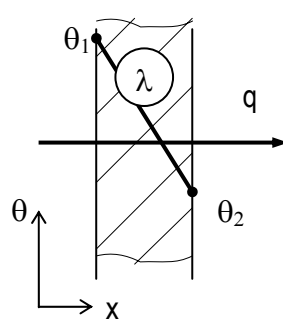
$$\frac{\partial^2 \theta}{\partial y^2} = 0 ; \quad \frac{\partial^2 \theta}{\partial z^2} = 0 \quad (2-2)$$

The heat flow is mathematically described by the Fourier function law of the thermal conduction:

The Fourier experience law reduces to

$$\lambda \frac{\partial^2 \theta}{\partial x^2} = 0 \quad (2-3)$$

- Resolution:
1. Integration:  $\frac{d\theta}{dx} = C_1$
  2. Integration:  $\theta = C_1 x + C_2$  (course of Temperature linear)
  1. Boundary condition:  $\theta(x=0) = \theta_1 \Rightarrow C_2 = \theta_1$
  2. Boundary condition:  $\theta(x=d) = \theta_2 \Rightarrow C_1 = \frac{\theta_2 - \theta_1}{d}$ ; d...thickness of the wall

$$\Rightarrow \theta(x) = \theta_1 + \frac{\theta_2 - \theta_1}{d} x$$


The heat flow is described mathematically by the Fourier experience law of the thermal conduction:

$$\Phi_{cd} = -\lambda \frac{d\theta}{dx} A \quad \text{Minus sign means: The heat flow is of opposite direction as the temperature gradient (see sketch above)} \quad (2-4)$$

$\Phi_{cd}$ ... Heat flow due to thermal conduction [W]

Frequently one uses the heat flow referred to a surface, the heat flow density in such a way is then specified

$$q_{cd} = -\lambda \frac{d\theta}{dx} \quad (2-5)$$

$q_{cd}$ ... Heat flow density in  $W/m^2$

### 3 Convection

#### 3.1 Definition

Heat convection is the heat transport from a fluid medium to the surface of a firm body or vice versa. Heat convection is always bound to the transport of mass particles (e.g. air flow). One differentiates in free convection (e.g. thermal lift) and forced convection (e.g. warm air heating or wind).

Principal equation:  $q_{cv} = h_{cv} \cdot (\theta - \theta_s)$  (3-1)

Characteristic:  $h_{cv}$ ... convective heat transmission coefficient

$q_{cv}$ ... heat flow density (convective)

$\theta$ ... fluid temperature (e.g. Air temperature)

$\theta_s$ ... surface temperature

## 4 Heat radiation (basics)

### 4.1 Definition

Heat radiation (also called temperature radiation) is energy transfer by electromagnetic waves. Heat radiation is thermally excited. The wavelength of heat radiation covers range of  $\lambda = 0,8...300 \text{ E-6 m}$  and is also called long-wave radiation.

For the heat transfer by radiation no material carrier is necessary. Radiation can take place therefore also via a vacuum.

### 4.2 Balance of radiation

Incident radiation:  $F = A + R + D$

Emitted radiation:  $S = E + R + D$

F... incident radiation

A... absorbed radiation

R... reflected radiation

D... conducted radiation

S... emitted radiation

E... emitted radiation

Energy balance for a body:

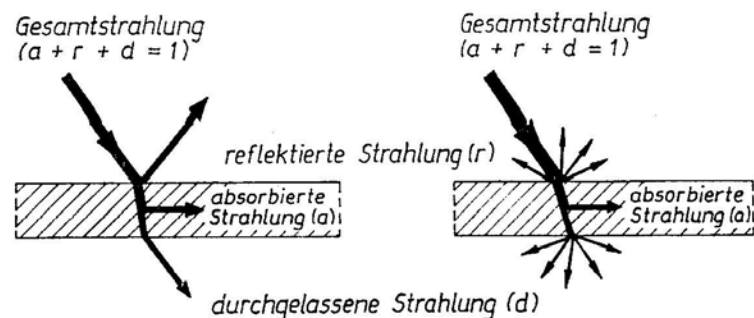


Figure 4-1a Possible spreading of the radiation impinging on a material:left: smooth surface; right: roughens surface

incident radiation energy = emitted radiation energy

It applies:  $F = S \Rightarrow A = E$

$$F = A + R + D \quad | :F \quad \Rightarrow \quad 1 = \frac{A}{F} + \frac{R}{F} + \frac{D}{F}$$

$$1 = a + r + d$$

a... Absorption factor

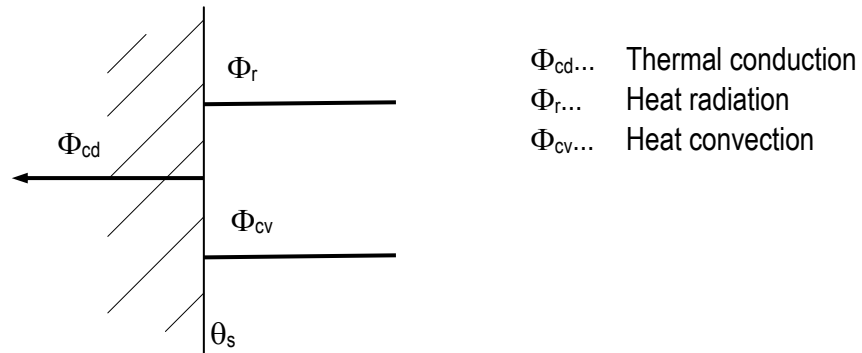
r... Reflection degree

d... Transmission factor

Border lines: a = 1... black body  
 r = 1... ideal mirror  
 d = 1... diathermal body

### 4.3 Survey of heat exchange in practical computations

In the context of applied thermodynamics one simplifies the representation of heat radiation often by transferring it to the model of heat convection.



It applies: 
$$\Phi_{cd} = \Phi_r + \Phi_{cv} \tag{4-1}$$

with 
$$\Phi_r = C_{1,2} \cdot A \cdot \left[ \left( \frac{T_a}{100} \right)^4 - \left( \frac{T_s}{100} \right)^4 \right] \tag{4-2}$$

$$\Phi_{cv} = h_{cv} \cdot A \cdot (\theta - \theta_s) \tag{4-3}$$

T<sub>a</sub>... absolute temperature of the environment (the ambient temperature can be simplified as the surface-weighted means of all surface temperatures of the surrounding construction units.)

T<sub>s</sub>... absolute surface temperature

θ<sub>s</sub>... surface temperature (θ<sub>s</sub> + 273,15 K = T<sub>s</sub>)

θ... air temperature

From this follows:

$$\Phi = \Phi_{cv} + \Phi_r \quad | : A \tag{4-4}$$

$$q = q_{cv} + q_r \tag{4-5}$$

$$q = h_{cv}(\theta - \theta_s) + C_{1,2} \left[ \left( \frac{T_a}{100} \right)^4 - \left( \frac{T_s}{100} \right)^4 \right] \tag{4-6}$$

**Definition:** 
$$q = h_{cv}(\theta - \theta_s) + h_r(\theta - \theta_s) \quad \text{with} \quad h_r = \frac{C_{1,2} \left[ \left( \frac{T_a}{100} \right)^4 - \left( \frac{T_s}{100} \right)^4 \right]}{(\theta - \theta_s)} \tag{4-7}$$

h<sub>r</sub>... equivalent heat transmission coefficient due to radiation. That is a fictitious size for simpler description of the heat transfer. This size does not possess a physical back-

ground.

Now applies:  $q = h (\theta - \theta_s)$  with  $h = h_{cv} + h_r$  (4-8)

$h...$  combined heat transmission coefficient due to convection and radiation. This value is basis to computations from the building design aspect and in the relevant standards (e.g. DIN 4108) embodied.

$(\theta - \theta_s)...$  Temperature difference between surface and air

## 5 Heat transfer

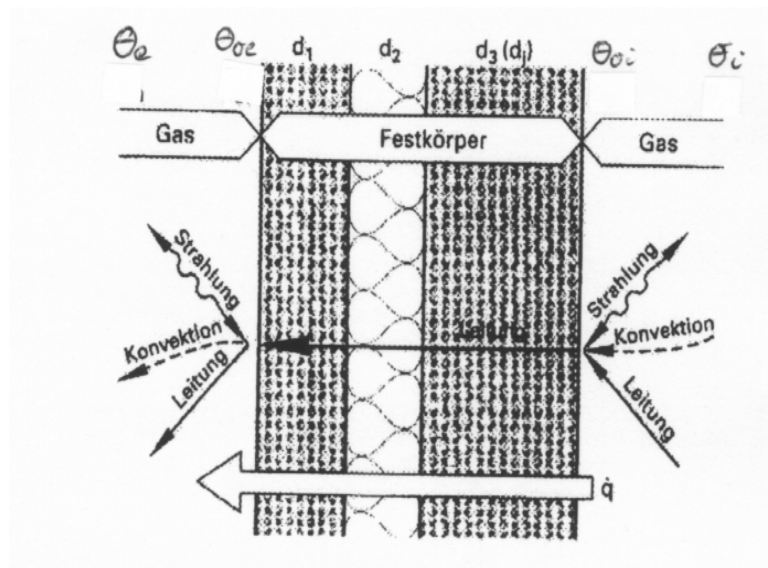


Figure 5-0 Heat transport mechanisms at a wall ( $\theta_i > \theta_e$ )

### 5.1 Linear heat transfer by a homogeneous wall

The linear heat transfer is divided into three individual processes:

- Heat transfer of the fluid to the wall
- Thermal conduction in the wall (see section 2.3)
- Heat transfer of the wall to the fluid

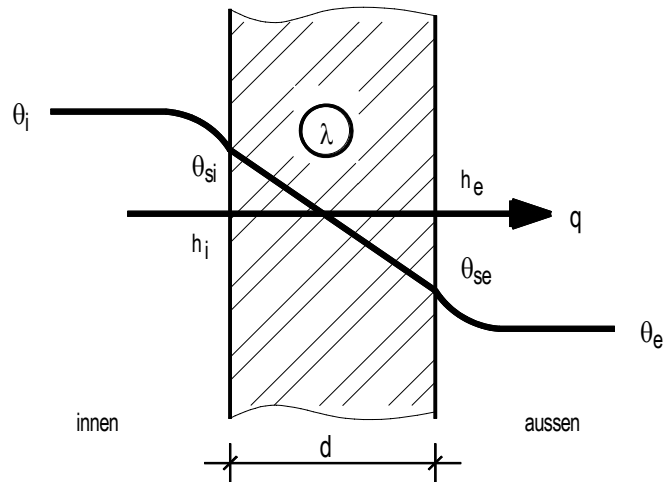


Figure 6 1 Linear heat transfer

The heat transfer is described by Newton's law. It applies:

Internal heat transfer:  $q = h_i(\theta_i - \theta_{si})$

External heat transfer:  $q = h_e(\theta_{se} - \theta_e)$

The surface-related heat transmission coefficient  $h$  is a characteristic for the description of the heat transfer between surface and environment due to convection and radiation. In thermal building physics the reciprocal value, what is known as the thermal transfer resistance  $R_s$ , becomes common. It applies:

Thermal resistance internal:  $R_{si} = 1 / h_i$

Thermal resistance external:  $R_{se} = 1 / h_e$

	Richtung des Wärmestromes		
	Aufwärts	Horizontal	Abwärts
$R_{si}$	0,10	0,13	0,17
$R_{se}$	0,04	0,04	0,04

Tab. 6 1 Characteristic values of the thermal resistance in  $m^2 K/W$  according to DIN EN ISO 6946

To the thermal conduction applies:

$$q = \frac{\lambda}{d}(\theta_{si} - \theta_{se}) \tag{5-1}$$

The characteristic values of the heat conductivity for different building materials are given in DIN 4108 part 4.

The quotient  $\frac{\lambda}{d}$  is also known as the heat transmission coefficient  $\Lambda$ .

$$q = \Lambda (\theta_{si} - \theta_{se}) \quad (5-2)$$

The reciprocal value of the heat transmission coefficient is called thermal resistance R:

$$q = \frac{1}{R} (\theta_{si} - \theta_{se}) \quad (5-3)$$

To the heat transfer through an even homogeneous wall applies:

$$q = \frac{1}{R_{si}} (\theta_i - \theta_{si}) = \frac{1}{R} (\theta_{si} - \theta_{se}) = \frac{1}{R_{se}} (\theta_{se} - \theta_e) \quad (5-4)$$

and/or. 
$$q = \frac{1}{R_T} (\theta_i - \theta_e) \quad (5-5)$$

with  $R_{T...}$  Heat transfer resistance  $R_T = R_{si} + R + R_{se}$

Instead of the heat transfer resistance more frequently the heat transition coefficient U (U-value, thermal transmittance) is used.

$$q = U (\theta_i - \theta_e) \quad (5-6)$$

Including the heat-transferring surface A, the thermal transfer through an even wall can be described as followed:

$$\boxed{\Phi = U A (\theta_i - \theta_e)} \quad (5-7)$$

The heat transition coefficient U is a characteristic for the structural thermal protection of a construction unit. It can be determined for a one layer construction unit as followed:

$$\boxed{U = \frac{1}{R_{si} + \frac{d}{\lambda} + R_{se}}} \quad (5-8)$$

## 5.2 The linear heat transfer through a multilayer construction unit

Real constructions mostly exist of several layers.

The heat transfer by a multilayer construction unit is to be treated in a general manner like a serial connection from resistances. It applies:

$$R_T = R_{si} + \sum_{i=1}^n R_i + R_{se} \quad (5-9)$$

The heat transition coefficient can be computed therefore as followed:

$$U = \frac{1}{R_{si} + \sum_{i=1}^n \left( \frac{d}{\lambda} \right)_i + R_{se}} \quad (5-10)$$

The linear heat flow through a multilayer construction unit is constant in each layer. It applies:

$$\Phi = qA = U A (\theta_i - \theta_e) = const. \quad (5-11)$$

## 5.3 Linear heat transfer through a construction unit with air layers

Air layers in construction units are differentiated in

- non-ventilated air layers within the construction unit without connection to the environment and
- ventilated air layers with staggered openings for supply and exhaust air.

Contrary to solid construction unit layers, where the heat transfer exclusively results from thermal conduction, heat in resting air layers is transferred via conduction and radiation. In DIN EN ISO 6946 heat-insulating properties are indicated in dependence of the air layer thickness.

Dicke der Luftschicht mm	Richtung des Wärmestromes		
	Aufwärts	Horizontal	Abwärts
0	0,00	0,00	0,00
5	0,11	0,11	0,11
7	0,13	0,13	0,13
10	0,15	0,15	0,15
15	0,16	0,17	0,17
25	0,16	0,18	0,19
50	0,16	0,18	0,21
100	0,16	0,18	0,22
300	0,16	0,18	0,23

ANMERKUNG: Zwischenwerte können mittels linearer Interpolation ermittelt werden.

Tab. 6.2 Thermal resistances R in m<sup>2</sup> K/W from resting air layers to DIN EN ISO 6946

In ventilated air layers, an air current takes place due to thermal lift. Apart from the heat transfer procedures conduction and radiation, also the heat transfer due to free convection is to be considered. The thermal resistance of a ventilated air layer is therefore smaller than the one of a non-ventilated air layer.

## 6 Heat transfer procedures due to solar radiation

### 6.1 General Information

The spectrum of the solar radiation is approximately distributed as followed:

$\lambda < 0,4 \mu\text{m}$	(UV- radiation)	6 %
$\lambda = 0,4...0,75 \mu\text{m}$	(visible radiation)	50 %
$\lambda > 0,75 \mu\text{m}$	(heat radiation)	44 %

The energy maximum is at about  $\lambda = 0,5 \mu\text{m}$ .

The solar radiation covers a wavelength range which exceeds the range of heat radiation. The laws of heat radiation are therefore not applicable for solar radiation. While heat radiation concerns long-wave radiation, one denotes solar radiation in the context of building design aspects *short-wave radiation*.

### 6.2 Heat transfer through non-transparent construction units with solar radiation

The thermal load of the external construction components is an effect of four climatic components:

- solar radiation
- outside air temperature
- long-wave radiation (from the environment absorbed solar radiation which is converted into heat radiation .)
- wind

In consideration of the components above, the heat transfer of the external environment can be described as :

$$\boxed{q = h_e (\theta_e - \theta_{se}) + a \cdot I} \quad (6-1)$$

with

- q... area-related heat flow
- h<sub>e</sub>... outside heat transmission coefficient for convection and radiation (considers the influence of long-wave radiation and wind)
- θ<sub>e</sub>... Outside temperature
- θ<sub>se</sub>... Surface temperature outside
- a... Absorption coefficient for solar radiation (note! Do not confound with absorption coefficient for heat radiation)
- I... Total radiation (= direct radiation + diffuse radiation)

To simplify computations, the complex operand *sun-air-temperature* is introduced.

$$\theta_s = \theta_e + \frac{a \cdot I}{h_e} \tag{6-2}$$

$\theta_s$ ... Sun-air-temperature

The sun-air-temperature is a fictitious temperature, which air and environment would have to reach, in order to transfer the the same heat quantity without solar radiation as in reality.

By means of the sun-air-temperature the heat transfer can be represented as followed:

$$q = h_e(\theta_s - \theta_{se}) = \frac{\lambda}{d}(\theta_{se} - \theta_{si}) = h_i(\theta_{si} - \theta_i) \tag{6-3}$$

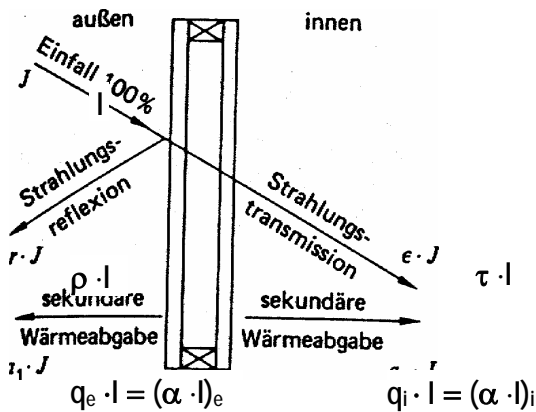
$$q = U(\theta_s - \theta_i) \tag{6-4}$$

### 6.3 Heat transfer through transparent construction units with solar radiation

Transparent construction units are permeable for short-wave solar radiation. The ratio of the passing solar radiation depends on the radiations wavelength , the angle of incidence and the composition of the glass.

The ratio of the radiation which is not let through is reflected and absorbed. The absorbed part is emitted by convection and long-wave heat radiation.

Schematic representation of the balance of radiation at a two-fold glazing:



l...Gesamtstrahlung

$\tau$ ...Transmittance

$\rho$ ...Reflection-degree

$\alpha$ ...Absorption factor

$q_e$ ...secondary heat emission degree outward

$q_i$ ...secondary heat emission degree inward

it applies:  $\tau + \rho + \alpha = 1$

The heat gain due to solar radiation builds consists of:

$$\Phi_S = (\tau \cdot I + q_i \cdot I) \cdot A = g \cdot I \cdot A \tag{6-5}$$

with

$$g = \tau + q_i \quad (6-6)$$

g... Total energy transmission factor of the glazing

The total energy transmission factor is a characteristic value of the glazing. It indicates the relationship of the heat energy transferred by the glazing into the building inside to the impinging solar radiation energy.

Apart from the heat transition coefficient (U-value) the total energy transmission factor (g-value) is an important glass characteristic value for computations from the building design aspect.

The total heat balance for the heat transfer of an external glazing with the influence of sun reads:

$$q = \underbrace{U_g (\theta_i - \theta_e)}_{\text{Losses}} - \underbrace{g \cdot I}_{\text{Profits}} \quad (6-7)$$

The heat transfer procedure that considerably affects the room air temperature out of the heating season can be described as followed:

The short-wave solar radiation imitting through the external glazing is absorbed by building construction (floor, walls etc.). The surfaces of these construction units warm up and the room air is heated up be means of convection. There is a long-wave thermal irradiation to the construction unit surfaces which are in a radiation exchange. This procedure is strongly time-dependent, i.e. transient and depends among other things on the heat storage behaviour in particular of the interior construction units. I.e. from the time of the radiation incidence up to the time when the room air temperature is rising, several hours, possibly also one day can elapse. Apart from the temporal delay also attenuation of the temperature gradient takes place. In extreme cases, no daily amplitudes of the room air temperature are formed (e.g. historical church).

For the computation of room air temperatures or cooling loads, the transient behaviour must be considered. For this there are the most different computation models, like e.g.

- Factor of correction of equivalent temperature differences (q.v. VDI 2078)
- Analytic methods such as Laplace transformation
- Numerical methods such as finite difference methods, finite element method or responds factor method

For energetic computations, frequently a time constant is introduced. This term is emanated from control engineering. The basis of this control engineering model is that the room or the building is described as controlled system with delay of 1. order (PT1-Glied). The time constant describes the time delay and/or inertia of the room.

### Greenhouse effect

Radiation in the wavelength range of  $0,3 \mu\text{m} < \lambda < 3 \mu\text{m}$  passes a single glazing to approximately 87%, so that the predominant ratio of the solar radiation arrives in the inside. The permeability of a windowpane for long-wave radiation ( $\lambda > 5 \mu\text{m}$ ) is - however - only about 5%. That results in the well-known heat trap effect of the glass. The solar radiation passing the external glazing is absorbed by the interior surfaces and emitted as long-wave heat radiation. This is again absorbed and reflected by the external glazing and can therefore not exit the room.

## 7 Minimum thermal protection

### 7.1 Purpose

- With the minimum requirements to the structural thermal protection the building construction is to be protected durably against climatic conditioned demands from the outside by influences of the weather and from the inside due to the building use and protected thus moisture damages. Additionally the heat transfer is to be reduced by the construction units as much as hygienic room climate conditions for the intended building use can be ensured.

#### 7.1.1 Prevention of condensate interior surfaces

Construction units of lounges - essentially external construction components - are to be designed in general in such a way that their interior construction unit surface remains condensate free. Otherwise building damage would be possible, since such condensation water masses can achieve precarious orders of magnitude. Such construction units are excluded, where

- due to at least occasional unfavourable room climatic conditions (e.g. high relative humidity, like in baths or such) a temporary condensation water formation is not to prevent and
- damp surface design is present (e.g. tiles, sealing painting).

In the following the following moisture-protection-technical sizes are used among others (remaining sizes see reprint "building climatic TIC and humidity protection"):

$\phi$	relative humidity, dimensionless or in %
$p$	Water vapour partial pressure in Pa (=N/m <sup>2</sup> )
$p_s$	Water vapour saturation pressure in Pa
$\theta_s$	Dew point temperature of a water vapour air mixture in °C

#### Conditions for condensation water liberty

Condensate at the construction unit surface is as long not possible, as one of the following conditions is met :

- Surface temperature  $\theta_{si}$  > dew point temperature  $\theta_s$  of the room air within this range
- present vapour pressure  $p$  of the room air < vapour saturation pressure  $p_{s,si}$  at the construction unit surface.

Both conditions are equivalent. For construction unit surfaces one uses - contrary to the proof of condensate protection for the construction unit cross section - temperature conditions in practice because of the better descriptiveness in general:

$$\theta_{si} > \theta_s \quad (7-1)$$

#### Necessary thermal protection for prevention of condensate

The condition (7-1) can be fulfilled - apart from special cases, e.g. geometrically caused thermal bridges – exclusively by means of the size of the thermal insulation of the construction unit (R or U).

To the two sizes in (7-1):

- $\theta_s$  of the room air results immediately from the given, room climate tables values  $\theta_L$  and  $\theta_U$

- $\theta_{si}$  at the construction unit surface is for the respective construction unit from the temperatures of the room air ( $\theta_i$ ) and outside air ( $\theta_e$ ) to determine computationally.

Proof for plane construction units with steady state climate conditions under use of the equations:

$$q_i = h_i (\theta_i - \theta_{si}) = q = U \cdot (\theta_i - \theta_e) \quad (7-2)$$

From this follows also

$$\theta_{si} \geq \theta_s \quad (7-3)$$

the necessary thermal protection for the prevention of condensate at the interior surface of plane construction units:

$$U \leq h_i \cdot (\theta_i - \theta_s) / (\theta_i - \theta_e) \quad (7-4)$$

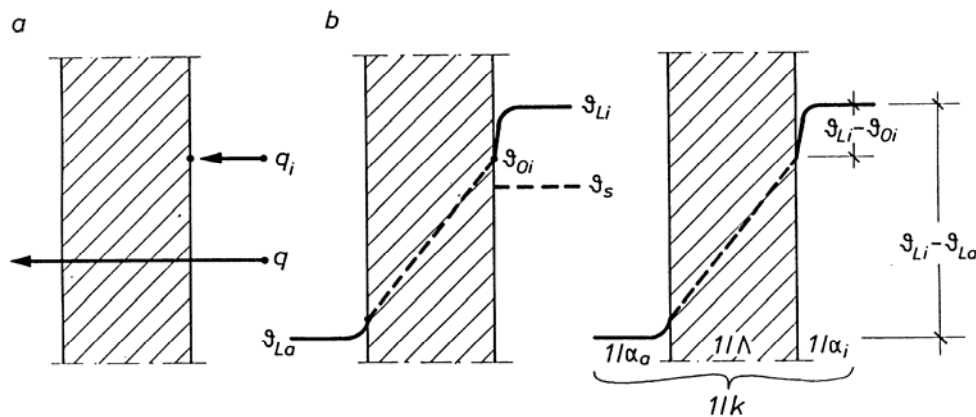


Figure 7.1 External construction component A) Heat transmission  $q_i$  and heat transfer  $q_i$ , b) temperature gradient  $\theta$ , within the range of the construction unit surfaces

From (2-2) e.g. follows.

$$(\theta_i - \theta_{si}) / (\theta_i - \theta_e) = R_{si} / R_T \quad (7-5)$$

**That means** the temperature differences within the range of a construction unit behave to each other like respective resistances.

The temperature difference  $\theta_i - \theta_{si}$  is as much larger, i.e. the surface temperature  $\theta_{si}$  as much lower (more critically), as the transmission resistance  $R_{si}$  is larger. For safety reasons larger thermal resistance by at least  $R_{si} \geq 0.17$  (opposite to 0,13) must be taken into account for the proof of the condensation water risk at the construction unit surface - deviating from the values for the proof of the thermal protection and the condensation water protection for the construction unit cross section.

If the necessary thermal protection is not reached after equation (2-3) as a function of the climatic boundary conditions on a construction unit, then the thermal protection is to be improved.

## 8 Thermal bridges

Thermal bridges are locally limited areas or parts of the construction, which exhibit an increased heat flow density and lower interior surface temperatures in relation to the neighbouring material layers. Each building has

numerous, often latent thermal bridges of different kind and effect.

## 8.1 Classification

### 8.1.1 Material-caused thermal bridges

Material-conditioned thermal bridges result from heat conducting inclusions (e.g. Reinforced concrete or steel girder) in building materials with smaller heat conductivity (e.g. Brick-work). The material-conditioned cold bridge effect leads to a change of the surface temperature and to an increased transmission heat flow within the cold bridge area, i.e. to additional heating calorific losses.

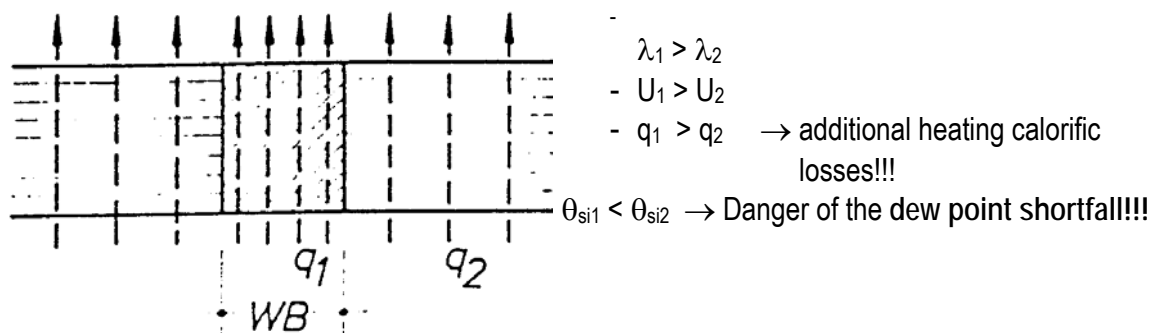


Figure 8-1 Principle of a material-conditioned cold bridge

### 8.1.2 Geometrically caused thermal bridges

Geometrically conditioned thermal bridges result from the form of the construction unit during homogeneous material composition. They occur regularly e.g. in the form of corners of a building. The geometrically caused cold bridge effect leads to a change of the surface temperatures

## 8.2 Minimum requirements to the thermal protection within the range of thermal bridges

### 8.2.1 Single check for the avoidance of mould fungus formation

For material and construction dependent thermal bridges which deviate from the reference examples from DIN 4108, supplement 2, a single check must be lead e.g. with a computation of the interior surface temperature. Alternatively, also the use of cold bridge Atlases is possible.

Within the range of thermal bridges the heat transfer and the temperature field cannot be regarded any longer only linear. Rather the solution of the FOURIER differential equation is necessary for the two or possibly also for the three-dimensional case. In practice the cold bridge computation is accomplished computer-supported using numeric algorithms (finite element or finite difference method).

For each cold bridge computation a computation model must be provided. The computation rules with all numeric boundary conditions for a exemplary illustration of the constructional detail (mesh size of the grid network,

definition of the cutting planes etc.) are to be inferred from the standards DIN EN ISO 10211-1 and/or DIN EN ISO 10211-2.

The execution of the proof procedure for the minimum thermal protection within the range of thermal bridges for preventing of surface condensation and mould fungus formation is standardised. The boundary conditions which can be set and the requirement level are codified in DIN 4108-2.

Climatic boundary conditions:

Outside temperature:	$\theta_e = -5 \text{ }^\circ\text{C}$	(That is the lowest daily average of a five-daily Period in Germany)
Interior air temperature:	$\theta_i = +20 \text{ }^\circ\text{C}$	(and/or in accordance with use)
relative interior humidity:	$\phi_i = +50 \%$	(and/or in accordance with use)

To the explanation: Due to the temperature inertia of the construction units and due to the necessary longer short working period condensation water only cooling periods of more than five days entail mould fungus problems.

- other temperature boundary conditions:

Cellar, soil:	$\theta = +10 \text{ }^\circ\text{C}$
unheated buffer zone:	$\theta = +10 \text{ }^\circ\text{C}$
unheated roof space:	$\theta = -5 \text{ }^\circ\text{C}$

Heat transfer resistances:

outside:  $R_{se} = 0,04 \text{ m}^2\text{K/W}$

heated areas:  $R_{si} = 0,25 \text{ m}^2\text{K/W}$  (when substantial impairment of the heat transfer, e.g. by furnishing before the wall,  $R_{si}$  is to be set to  $= 0.50 \text{ m}^2 \text{ K/W}$ )

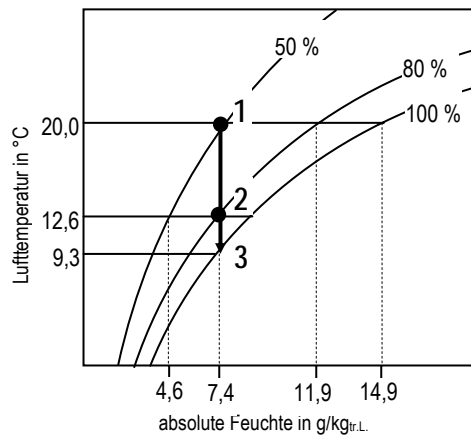
unheated areas:  $R_{si} = 0,17 \text{ m}^2\text{K/W}$

Mould fungus formation can not, as frequently assumed, only begin within the dew point range, but due to capillary condensation in porous materials already with a relative surface humidity of

$$\phi_{si} \approx 80 \%$$

However as a condition for mould fungus growth still further influences are crucially, apart from the surface humidity. E.g. surface finish (tile pavements are e.g. relatively unproblematic), food offer at organic materials (glue for wallpapers, dust or the like), duration of the humidity effect etc.

Evaluation and requirement criterion for the minimum thermal protection within the area of thermal bridges is therefore the temperature, on which the room air must be cooled down, around a relative humidity of  $\phi$  to assume  $= 80\%$ . Construction unit surfaces under stationary conditions with the above mentioned climatic edge and heat transfer conditions this temperature  $\theta_{80}$  during a longer period (e.g. five days) falls below is potentially mould fungus-endangered.



- 1...room air condition
- 2...beginning danger of mould fungus formation
  - 3...dew point

Figure 8-6 Representation of the climatic conditions in the Mollier-diagram

## 9 Summer thermal protection

### 9.1 Purpose

- With the minimum requirements to the summer thermal protection according to DIN 4108-2 it is to be achieved that not-air-conditioned lounges get along if possible without equipment technology for cooling in summer and the cooling power requirement by use air-conditioned areas is kept as small as possible. In particular it is to be ensured with not-air-conditioned areas that the limit value of the interior temperature (operational temperature and/or feeling temperature) at any more than 10% of the residence time is not crossed. The limit value of the interior temperature depends on the climatic region and amounts to  $\theta_{o,limit}$ , = + 25... + 27 °C, depending upon location.

### 9.2 Comfort level

The comfort level, basis to the DIN 4108-2, mirrors the range of still tolerable climates in the summer period. Within this comfort range, a reduction of the satisfaction and efficiency is already counted on. At temperature perception over 26 °C the average waste of the productivity amounts to about 5% for each Kelvin. However an endangerment of the health is not to be feared in the climatic range guaranteed by the minimum requirements according to DIN 4108-2.

### 9.3 The sun entry characteristic value

The summer thermal protection according to DIN 4108-2 makes constructional demands, in particular against kind and size of the external glazing and the shielding qualities of a build-lateral sun protection. In the context of the verification no ambient temperatures are determined.

As structural characteristic for the evaluation of the summer thermal protection of an area in accordance with DIN 4108-2 the sun entry characteristic value in such a way specified is introduced.

$$S = \frac{\sum_j (A_{w,j} \cdot g_{total,j})}{A_G} \quad (9-1)$$

S... Sun entry characteristic value

$A_w$ ... Window area in  $m^2$

$A_G$ ... Net surface area of the area or the space range in  $m^2$

$g_{total}$ ... resulting total energy transmission factor of glazing and sun protection

The resulting total energy transmission factor made of glazing and sun protection  $g_{total}$  can be computed simplified as follows:

$$g_{total} = g \cdot F_C \quad (9-2)$$

$g$ ... Total energy transmission factor of the glazing according to DIN EN 410

$F_C$ ... Reducing coefficient of the sun protection

Reference values for reducing coefficients of sun safety devices may be inferred from table Tab.9-1 from DIN 4108 2.

However in reality exists also a dependence of the reducing coefficient of the sun protection on the total energy transmission factor of the glazing, which is very pronounced with sun safety devices on the inside in particular:

$$F_C = f(g) ! \quad (9-3)$$

Therefore the shielding qualities of a sun protection, in particular a sun protection on the inside, can be judged only in connection with the glazing. For the formulation of the sun protection requirements it is therefore even more favourable to work with the resulting total energy transmission factor  $g_{total}$ .

## 10 Thermal energetic computer simulation for buildings

Regarding the developments in building engineering and the changes of legal standards and regulations, the building physics evaluation of building measures of new houses as well as the existing, mostly historic structure, becomes more and more important.

Thereby it is necessary to answer the questions related to thermal, fire, noise and moisture protection, without leaving out the close linkage of the individual areas.

One of the numerous possibilities to describe the future behaviour of buildings and components with regard to their thermal and humidity performance is the usage of dynamic building and component simulation computations. Hereby it is possible to optimise the buildings and components economically and to not endanger the serviceability of the structure materials.

### 10.1 Basics

Thermal building physics deals with energy and material flows, which act on a building from the inside because of the building usage and from the outside because of the outside climate.

These thermal and hygrical processes behave time dependent, e.g. transient. The transient behaviour of heat transfer processes can be reduced to the steady state special case, if it is dealt with building physics detection computations, especially in case of winter times. If however temporal courses of temperature and humidity are required, the intermittent behaviour of heat and moisture flow has to be taken in consideration.

The mathematical modelling of transient processes is done via differential equations, the analytic solutions which are always related to idealised start-up and boundary conditions. The results from analytic evaluations of transient heat transfer processes are generally apt to sufficiently describe the physical facts but because these evaluations are partly time consumptive they cannot cope with modern planning demands. With the help of analytic computation processes analyses of sensitivity, computation of variants, the realistic reproduction of influence factors, especially of factors concerning the outside temperature, and a graphic presentation of the evaluation results which, a layman can understand, can be realised only to a certain degree.

To reproduce the thermal behaviour of buildings computationally nowadays more and more numeric solutions are used, which in the course of a more capable computer technology have already found a wide range of application on the PC sector. For this kind of building physics computation the term *thermal energetic building computation* has been introduced, where besides thermal processes also hygric, photometric and partly also aerodynamic processes as well as arbitrary mass flow balances can be taken into account.

Furthermore these computation models are not limited to the thermal behaviour of the building. Even the energy and material flows of the plant technology that is contained in the building can be realistically reproduced either separately or in combination with the building. With the help of the *thermal energetic building and plant simulation* there are numerous possibilities to realise an optimisation of the in service behaviour of plants inside buildings, especially with a focus on control engineering.

There is a great availability of suitable simulation programmes. Accordingly great is the number of the applied

computation models and mean variation of the results under identical demands. Until now the acceptance of thermal building simulations at possible clients has been low because of this fact. For a very long time the programme JULOTTA that had been developed at the University of Lund was considered as a reference programme and standard for other simulation programmes. Because there were no fixed agreements about the way of verification, an universal quality standard could not be developed from this.

The demand concerning a quality assurance of the building simulation that is more and more common in the planning process and has become an independent performance area that has been complied within the VDI standard 6020 (publication May 2001) Germany. In this standard the minimum demands on the computation processes are defined and the boundary conditions and evaluation criteria for a building simulation are unified on a case-to-case basis. Furthermore test examples are given with which arbitrary simulation programmes can be verified and parameterised. Within the framework of the test examples given in the VDI standard, the simulation programmes DOE-2, DS-THERM, GEBSIMU, TAS and TRNSYS have been used. These programmes are representatives of different computation models with which the quality level according to VDI 6020 can be guaranteed.

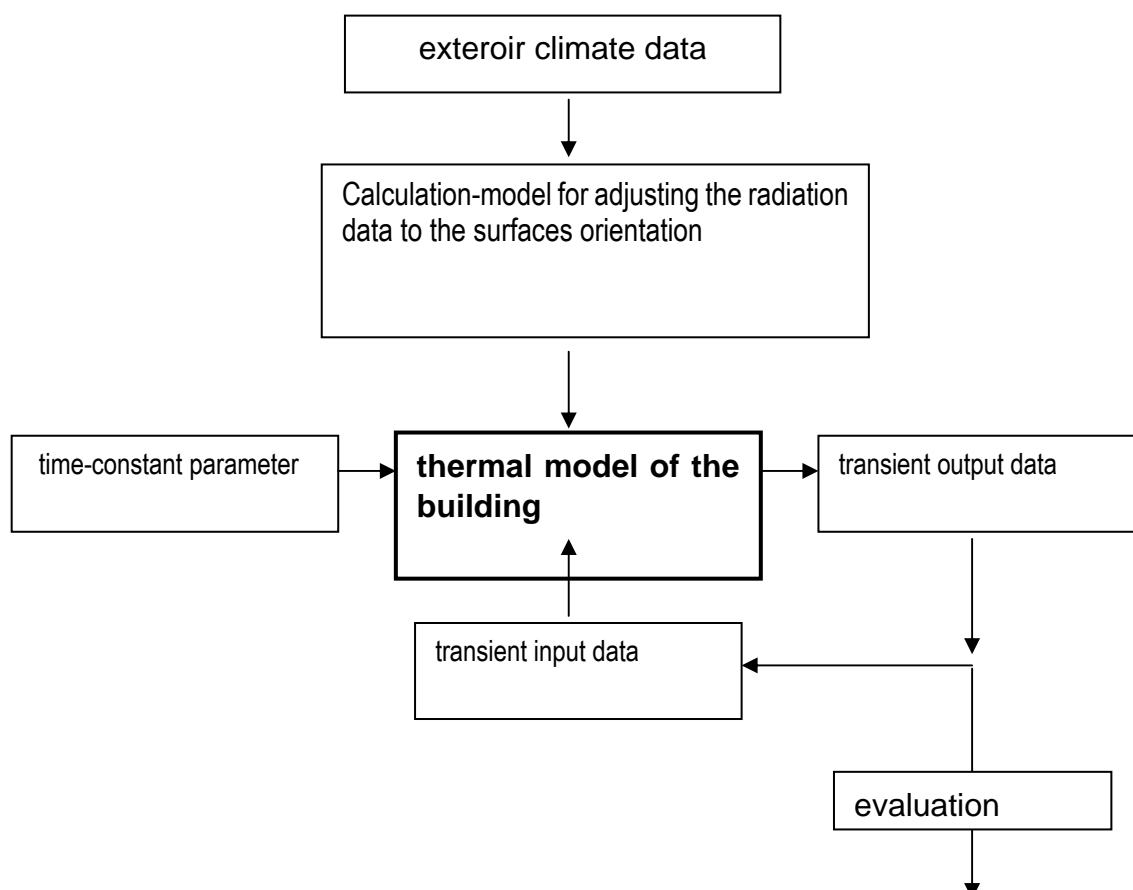
More detailed facts concerning standardised boundary conditions and validation processes for simulation programmes are to be found in E DIN 4108-20 (version July 1995) and E DIN EN ISO 13792 (version October 1997). They especially refer to the thermal behaviour of buildings without plant technology during summer.

## 10.2 Simulation model

### 10.2.1 Scheme of information flow

The information flow of a common building simulation can be represented in a very simple way as followed:

Flow chart diagram of a computation of a building simulation



### 10.2.2 Data of the outside climate

The data of the outside climate is generally prepared as external data records in which all the necessary meteorological data should be found as hourly values. The following climate parts are required for a thermal energetic building simulation at least:

- Temperature of the outside air
- Humidity of the outside air
- Sun radiation (horizontal or vertical)
- Wind speed (possibly)

For simulating yearly courses what is known as test reference years have stood the test. The test reference years (TRY) are a collection of hourly data of any meteorological parameter throughout the whole year. Because

a TRY is composed of 29 characteristic weather periods of one year and one area the typical seasonal weather phenomena of the respective area are reproduced.

With respect to the monthly average the TRY are statistically secured. However they do not contain any maximum values or frequencies, how they can occur in the course of extreme climate years. Because of this TRY are in the first place only suitable for energetic or climate considerations, whose statistic evaluation for the *normal case* is in the front line. If the maximum load under extreme climate conditions or the course of a load for the evaluation of a plant is to be checked, one should go back to other data of the outside climate (e.g. VDI 2078).

The Deutsche Wetterdienst (German weather service) sells TRYs for 12 climate areas, which however are restricted to the old German Federal States. For several selected European countries so called Short Reference Years (SRY) are available, developed by the EU commission, managing director office XII for Science, Research and Development, and which are available through the EU offices.

### 10.2.3 Model of the conversion of radiation data into surface orientation

In the framework of a radiation conversion the astronomic boundary conditions with respect to declination and ecliptic of the earth's circular path have to be considered at first. The real local time is generally used for a computation basis of the simulation. If the radiation data is submitted as zone time (e.g. central European time), how it is the case for commercial data records (TRY, SRY), a conversion has to be made via the time difference with respect to the degree of longitude and the time equation, which results from the eccentricity of the earth's circular path. In this case the degree of longitude of the building's place has to be known. For computing the sun's position also the parallel of the place is required.

The radiation data in the climate data records to be used are generally separated into direct and diffuse part for horizontal areas (e.g. TRY, SRY). For this case a process for a conversion into the respective area declinations and the celestial orientations of the building's outside areas is given in VDI 6020. This model is implemented in all current simulation programmes. Radiation data, which is present for the normal direction of the sun, can also be processed in most of the programmes. It can occur in special cases that measurement values of the total radiation are given, without a separation into direct and diffuse part. For this case an approximate determination of these radiation parts can be realised with the help of different correlation models.

Values that are a result of e.g. projections or adjacent buildings are to be considered to a great extent if the receiver area is a transparent outside component. For this a sun factor  $f_s$  is determined, that shows the ratio of direct radiated area to the respective total area. The computation of  $f_s$  is among others defined in E DIN EN ISO 13792.

### 10.2.4 Thermal building model

The thermal building model is essentially composed of the following two sub models:

- convection and radiation in a room and
- heat transfer through walls and windows

The balancing of the heat flows of convection and radiation is done inside of so called zones, where these zones could represent a single room, a group of rooms or a building. The determination of the zones for a building simulation is dependent from the respective demand and has to be defined by the programme user.

To solve the heat balance system inside a zone there are two completely different attempts:

- complex network model: this model reproduces the physical connections in a very detailed way by e.g. considering the spatial radiation conditions of the heat radiation in a room. This model requires that the user does an input of a geometric room model.
- Simplified star or temperature knot model: in this heat balance model the long-wave radiation exchange between the walls and the convective heat transfer from the walls to the room air is respectively represented by fictitious temperature knots (two star model). It is further simplified if the two temperature knots are combined to one temperature knot for radiation and convection (one star model). The thermodynamic coupling of the component surfaces to the temperature knot as well as the conversion of the knot temperature into the room air temperature is done by approximated connections. The simplification needs no room geometry, so that the processing time and the computation times in contrast to complex network models are far more decreased. But on the other hand one has to take into account losses with regard to the accuracy of the results.

The heat transfer through the build-up of a component is described by Fourier's differential equation. In the framework of a building simulation it is generally sufficient to reproduce the three-dimensional problem of heat conduction to a one-dimensional heat conduction process and to comprise heat build-ups extra if necessary. For solving the heat conduction equation numerically three different methods have stood the test:

- finite-difference method: this method is far spread in the area of heat technology. Here the differential coefficients according to place and time are replaced by difference quotients and are solved by time steps. The smaller the porosity of the place discrediting is and the closer the convergence limits are set, the more accurate results are achieved; the computation time increases. One advantage of this difference method is that even inside a component a temperature course can be reproduced, so that e.g. temperatures inside of the component can be measured.
- weight factor method: this method is based on the attempt that a component (e.g. a wall) is represented as a p-transfer element with a 1. order delay (PT1-element). The dynamic behaviour of the component is described by a transfer function  $G(p)$ , which results in a Laplace transformed output function  $A(p)$  after a multiplication with an arbitrary dynamic input function  $E(p)$ . If this problem is transformed from the Laplace into the time area the system answer  $a(t)$  can be derived from a convolution integral, whereby the transfer function  $G(p)$  becomes the weight function  $g(t)$ . To solve the convolution integral numerically it has to be approximated with a sum. The functional values  $g(\lambda t)$  contained in the sum are designated as weight factors (transfer factors). The weight factors contain the dynamic features of the component with regard to the heat technology for every time step till the transient state (generally  $t = 1h$ ). The dynamic behaviour of the component is then reproduced by solving the approximated summation formula  $a(\lambda t) = f(e[\lambda t], g[\lambda t])$  from time step to time step, where  $e(\lambda t)$  can be an arbitrary input function, e.g. a temperature wave. Because of the approximation the weight factors are only valid for a special value range, which can limit the universality of the model and therefore of the simulation programme under certain circumstances. No iterations are required, therefore the

computation time is very low and no convergence problems occur. Temperature courses inside of the component cannot be measured because of the “Black –Box” view.

- Replacement models: these have to be divided into thermal and electric replacement models, of which the Beuken model is the oldest and most known. It is an electric analogy model which bases on the fact that heat conduction in a solid and the processes in an idealised electric conductor can be described with the same type of differential equations. That way any component (e.g. a wall) can be realised by an electric equivalent circuit diagram, where the voltage is the similitude to temperature and the electric current is the similitude to the heat flow. The heat conductivity resistance is reproduced by an ohmic resistance and the storage capacity of the component by an electric capacity. If the wall is separated into an arbitrary number of disks a system of matrices arises the solution of which requires a lot of computer power. Besides, the transition of demands concerning the heat technology to the Beuken model is very costly and is only partly adapted for frequently occurring problems. The main advantage however is that after a separation into an arbitrary number of disks the Beuken model shows arbitrary high computation accuracy. In the framework of VDI 6020 the simulation programme PSPICE is applied for testing the test examples because it is based on the Beuken model.

### 10.2.5 Time-independent parameter

Time-independent parameter are input values, which remain constant in the course of the simulation or whose dependency from time or temperature and velocity conditions is so low that resulting errors that could affect the results of the simulation are kept adequately low.

Among the time-independent parameters are:

Geometric data of the building and the component superstructures. They can be taken from the prepared planning documents.

Material parameter of the structural materials such as raw density, heat conduction capacity and specific heat capacity. For this the computation values in DIN V 4108-4 can be applied.

All the relevant parameter related to building physics. Among them are e.g. heat transfer coefficient of glazing and framework, share of framework, degree of transfer of the total energy and the transmission degree as well as relevant facts related to heat technology concerning sun protection devices. For these parameter it is favourable to use manufacturer data. If they are not available the computation values in DIN 4108-2 and DIN V 4108-4 have to be used.

Heat transfer coefficient for convection and radiation. The given values in E DIN EN ISO 13792 are to be applied.

Absorption coefficient for sun radiation. According to E DIN EN ISO 13792 a classification of the absorption coefficients into the area magnitude light, average and dark is considered as being sufficiently accurate.

### 10.2.6 Time-variant input values

Besides the outside climate data the programme user has to come up with further time-dependent, i.e. dynamic input values. Especially it has to deal with time profiles that are connected to the usage of the building or respectively the room, such as e.g. density, outside air change, activation of sun protection and additional inner loads.

Generally the processes inside the building caused by usage are defined in the form of periodically occurring daily and weekly courses, where the basis is either the working times of the staff, the opening times of the building or other usage times that are to be verified. Defining further time profiles within the usage times is not appropriate because they have to be selected more or less at random and therefore they make it more difficult to verify the results of a simulation.

Sometimes it is sufficient to give the averaged values of a usage period, which can be taken from technical literature or the current standards, such as e.g. average density, heat increase in offices and apartments compared to the area, time-averaged outside air change, ...

In summer times the thermal and energetic effects of extreme shock loads are often to be computed. In this case the extreme values should be applied concerning the inside load profiles because of the usage as well as the outside climate data (e.g. VDI 2078), where the computation should be realised for only five days according to VDI 6020.

Time-variant input values may also be required if a time control of the plant technology or of the building's sun protection is to be reproduced. If these input values are linked to time-variant output values such as e.g. temperature, humidity, heat flow or airflow it is further possible to reproduce adaptive control constraints or complete control loops for respective plant components.

## 10.3 Typical demands for a building simulation

The range of application of a thermal energetic building simulation in the framework of an advisory service related to building physics is far spread. In the following, several frequently occurring demands are to be presented:

### 10.3.1 Climate simulation for the summer

Thermal building simulations for the summer are apt for checking the thermal comfort inside the building and for avoiding an over-dimensioning of air-conditioning devices. In the framework of a comfort study it is possible to achieve a certain degree of planning security especially for the following aspects:

*In the case of naturally ventilated rooms without air-conditioning:*

Whether a natural ventilation of rooms is possible or whether it is necessary to build-in a ventilation device (with or without cooling system).

What kind of ventilation is necessary in naturally ventilated rooms (number of air changes) and how they can be achieved, i.e. how the vent holes are designed.

What levels of inside temperatures are to be expected if one chooses natural room ventilation and whether and

when critical inside climate conditions can occur.

To which degree can additional measures improve the climatic situation, such as e.g. sun protection glazing, sun protection devices, decrease in glazing areas, optimising of heat storage masses in the room etc.

*In the case of air-conditioned rooms:*

How different sun protection measures or specific building parameter have an effect on the yearly demand for heat and cooling energy, where the contrary effect of sun protection measures on the demand for heat and cooling energy can be determined.

Which levels of inside climate conditions are to be expected if the cooling power is not sufficient to reject the heat load at any time and how this situation can be improved by sun protection measures.

### 10.3.2 Energy diagnosis

In the framework of energy diagnosis where the energy balance of a building is checked the following major planning aspects can be worked:

Computation of the energy demand for heating, cooling, damping and dehumidification.

Energetic optimisation of component designs, glazing, building orientation etc.

Detection of energy saving possibilities (e.g. operation of services)

Dynamic computations of heating and cooling load as a design model for air-conditions and sun protection devices. The dynamic load simulation does not replace the heat demand computation according to DIN 4701 or the cooling load computation according to VDI 2078.

Determination of heat demand curves for designing block-type thermal power stations.

### 10.3.3 Further areas of application

Besides the above mentioned planning demands several other demands can be solved with the help of a thermal building simulation. Without saying that this statement claims to be complete a few more examples are to be named:

Checking of the surface condensation at specified climate conditions in correlation with the respective room usage profiles.

Energetic checking and checking of the control technology of different air-conditioning concepts, e.g. to keep the costs for air-conditioning as low as possible (example: air dehumidification with a summer heating).

Evaluations concerning the hygienic comfort in rooms, e.g. to realise the hygienically necessary outside air change with the help of a self-sufficient ventilation. With a mass flow balance of the CO<sub>2</sub> content the temporal course of the room air quality can be reproduced in dependence from the usage of the room and the window ventilation caused by thermal buoyancy.

Computation of the expected temperature fluctuations of steel profiles to determine the temperature elongation

resulting from this.

#### 10.4 Final remark

Despite the mathematical accuracy of the formula that are the basis of the simulation models thermal energetic building simulations can only result in approximate values. Most of all the results always have to be connected in relation to the agreed assumptions and boundary conditions. The greatest incalculability is the user behaviour. Within the simulation model the user behaviour can only be defined strictly periodical and sometimes arbitrary, although it is time-variant. In the real world the user behaviour adapts in many ways to the environmental conditions. Because of this not the individual numerical values of the results but the tendencies and the size of the different variant computations compose the real result of a building simulation. But the prerequisite is that the programme user has got the necessary basic knowledge about building physics and is familiar with the handling of the programme in connection with VDI 6020.

## 11 Building climatic

### 11.1 Thermodynamics of humid air

The computation and evaluation of build-climatic conditions and climatic technical processes presuppose the knowledge of the thermodynamic condition behaviour of atmospheric air. Because normal air always contains a more or less large water vapour quantity, one speaks in this connection also of „humid air“.

#### Definition:

Humid air is the mixture of two ideal gases:

- Dry air and
- Water vapour

#### Variables of state:

The thermodynamic condition of the gas steam mixture is described by the following Variables of state:

- Air pressure  $p$  in Pa
- Seals  $\rho$  in  $\text{kg}_{\text{humid air}}/\text{m}^3$
- Air temperature  $\theta$  in  $^{\circ}\text{C}$
- Dew point temperature  $\theta_{\text{Rope}}$  in  $^{\circ}\text{C}$
- Wet and dry bulb temperature  $\theta_{\text{Humid}}$  in  $^{\circ}\text{C}$
- Water content (absolute humidity)  $x$  in  $\text{g}/\text{kg}_{\text{dry air}}$
- Relative humidity  $\phi$  in %
- Specific enthalpy  $h$  into  $\text{kJ}/\text{kg}_{\text{dry air}}$

For the description of an air state only two further that variables of state indicated above are necessary with a given air pressure.

For the determination of an air state or description of a change in status the in such a way mentioned Mollier diagram or h-x-diagram worked satisfactorily.

In the h-x-diagram shows

- Variables of state as points
- Changes in Status as line
- Condition ranges as surfaces
- Process directions as co-ordinate directions

Represent and reconstruct visually. Due to the clear and visually stamping seeds Handling is superior the h-x-diagram to content wise identical computer often commodity. The h-x-diagram is an important planning instrument for climatic engineering and climatic technicians.

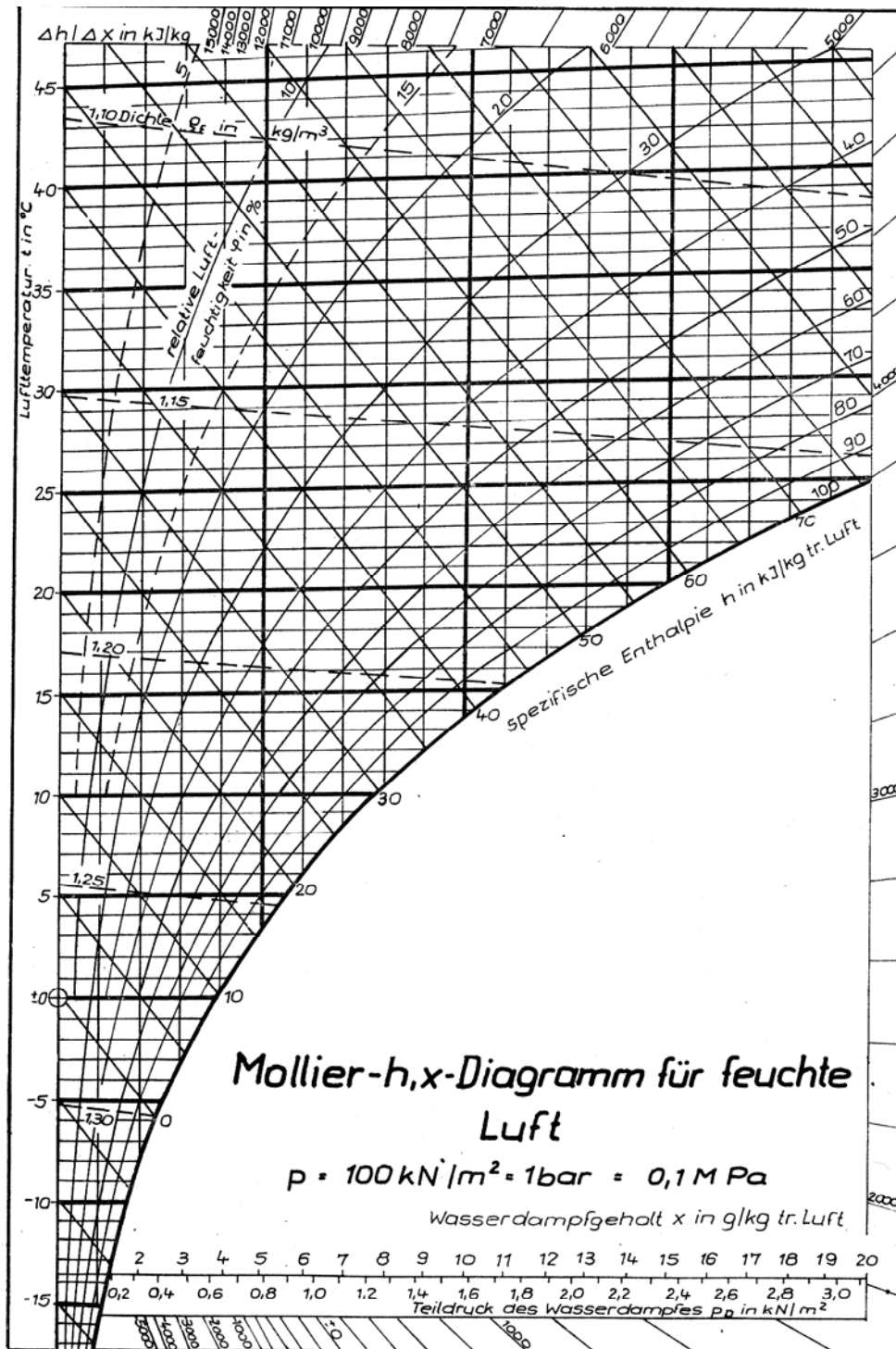


Figure 11-1 Mollier-h,x graph

The air pressure  $p$  is the sum out of

- Partial pressure of dry air  $p_L$
- Partial pressure of the water vapour (water vapour partial pressure)  $p_W$

It applies:

$$p = p_L + p_W \quad (11-1)$$

The absolute humidity describes the absolute water content in the material mixture „humid air“. The absolute humidity is the water vapour quantity, which is contained in one kg dry air:

$$x = m_W / m_L \quad (11-2)$$

with

$m_W$ ... Mass of the water vapour

$m_L$ ... Mass of dry air

It applies:

$$x = 0,6222 p_W / p_L \text{ in kg/kg tr.L.} \quad (11-3)$$

with

$p_W$ ... Partial pressure of the water vapour

$p_L$ ... Partial pressure of dry air

Application in building physics:

- Water vapour diffusion is based on the pressure (and/or concentration) reconciliation of two „humid air“-gas mixtures of different water vapour partial pressures. Water vapour diffusion can take place both through solid bodies and through fluid media (e.g. Air).
- For reasons of the climatic conditioned humidity protection the absolute humidity should within buildings on  $x \leq 11,5 \text{ g/kg}_{\text{dry air}}$  to be limited. (condensate, protection from micro organisms, corrosion).
- The absolute outside air humidity possesses a stressed yearly variation with maximum in the Summer and minimum in the winter. From this planning principles from the building design aspect for the climatic conditioned humidity protection (references result: Ventilation strategies, summer condensation in thermally slow-acting areas)

The in satiated gas steam mixture „humidity air“ can take up a certain water vapour quantity to dependence of the air temperature only. One calls the maximally possible water vapour quantity with an air temperature saturation quantity  $x_S$  (state of saturation). The more highly the air temperature of humid air, the more largely is the saturation quantity.

$$x_S = f(\theta) \quad (11-4)$$

One calls the water vapour partial pressure in the state of saturation pressure

$$p_S = f(\theta). \quad (11-5)$$

The function  $p_S = f(\theta)$  also saturation curve one calls.

Moistens air also

$$x > x_s \quad (11-6)$$

surfeited air is called. Here into the ranges liquid fog and ice fog are differentiated.

The relative humidity is a relationship size, which indicates how much per cent of the maximally possible water vapour in air is contained. It applies:

$$\phi = p_w / p_s(\theta) \quad (11-7)$$

Because of  $p_s = f(\theta)$  applies

$$\phi = f(\theta), \text{ bei } p_w = \text{const.} \quad (11-8)$$

Behaviour of the relative humidity with thermodynamic changes in status:

- Heat:  $\phi \downarrow$
- Cool:  $\phi \uparrow$
- Moisten:  $\phi \uparrow$
- Dehumidify:  $\phi \downarrow$

The relative humidity is apart from the air temperature the most important variable of state for the evaluation of build-climatic conditions and operational sequence. The hygrostatic performance of all materials (also building materials) is closely connected with the relative humidity. The dependence of the material humidity on the relative humidity is called sorption isotherm (Isotherm:  $\theta = \text{const.}$ ).

Application in building physics:

- Estimation from the building design aspect of the room climate of stockrooms with humid-sensitive stored material (e.g. Paper  $\rightarrow$  Libraries, office camps in cellars, etc.); References: Selection of suitable building materials, residual moisture, sealing engineering, ventilation strategy, user behaviour, summer heating.
- Estimation from the building design aspect of the room climate in museum-like used areas with requirements on conservation. The relative humidity possesses the highest priority from all **conservation** relevant sizes. In particular their range and fluctuation frequency. Fluctuations of the relative humidity lead artificial ageing of valuable exhibits to a constant change of sources and shrinking are accelerated. Planning rule: Only the possibilities from the building design aspect for the self-sufficient air conditioning exhaust and only then with equipment technology intervene.
- The comfort parameter relative humidity plays a role rather subordinated with normal air temperatures. Critical states can occur however with rel. Air humidifies  $\phi \geq 80\%$  (sultriness feeling) or  $\phi \leq 30\%$  (drain the mucous membranes, contact lens carriers). With air temperatures of  $\theta \geq +28^\circ\text{C}$  increases the influence of the relative humidity for the thermal comfort strongly. The bearable border runs with rising air temperature with removing relative humidity. Self-regulation of the body core temperature over evaporative cooling (transpiration).  
 $\Rightarrow$  therefore with  $\theta \uparrow (\geq +28^\circ\text{C}) \rightarrow \phi \downarrow$ .

The dew point temperature is the temperature, up to which humid air must be cooled down with constant absolute humidity content, so that the state of saturation is reached. It is the temperature at what the water vapour

contained in air begins to condense. The water vapour partial pressure associated to the dew point temperature is the  $p_s$ . The relative humidity of the dew point amounts to  $\phi = 100 \%$ .

The dew point temperature of an air state can in the h-x-diagram with a vertical line from the point of condition to the saturation line  $\phi = 100 \%$  to be determined.

Application in building physics:

- As soon as the interior surface temperature of a construction unit the dew point temperature of interior air falls below comes it to the formation of surface condensate. Test criteria for the evaluation of thermal bridges and window glazing (climatic conditioned humidity protection on the construction unit surface).
- The dew point temperature can be fallen below also within the construction unit cross section. In the context of a proof procedure 4108 permissible for this limit values are indicated in the DIN (climatic conditioned humidity protection in the construction unit inside).

The density of humid air is defined as follows:

$$\rho = (m_L + m_W) / V \quad (11-9)$$

with

- $m_L$ ... Mass of dry air
- $m_W$ ... Mass of the water vapour
- $V$ ... Volume of humid air

**BUT:**

The specific volume of humid air is defined as follows:

$$v = V / m_L \quad (11-10)$$

with

- $v$ ... specific volume of humid air
- $V$ ... Volume of humid air
- $m_L$ ... Mass of dry air

Application in building physics:

- Warm air is lighter than cold air
- Humid air is lighter than dry air

The thermodynamic state variables wet and dry bulb temperature and specific enthalpy are not relevant in building physics.

The specific enthalpy is a size describing the energetic condition of humid air. It is composed as follows:

- heat quantity of dry air
- heat quantity of the water vapour

The specific enthalpy of humid air is defined as a base factor with the point of reference  $\theta = 0 \text{ }^\circ\text{C}$ .

To the unsaturated condition applies:

$$h = h_L + x h_w \quad (11-11)$$

with

- $h...$  Enthalpy of humid air
- $h_L...$  Enthalpy of dry air
- $h_w...$  Enthalpy of the water vapour
- $x...$  absolute humidity of air in  $\text{kg}/\text{kg}_{\text{dry air}}$

Further applies:

$$h_L = c_{p,L} \theta \quad (11-12)$$

with

- $c_{p,L}...$  thermal capacity (with constant pressure) of dry air;  $c_{p,L} = 1,01 \text{ kJ}/\text{kgK}$
- $\theta...$  temperature of humid air in  $^\circ\text{C}$

$$h_w = r_0 + c_{p,w} \theta \quad (11-13)$$

with

- $r_0...$  evaporation heat of the water at the Triple Point;  $r_0 = 2501 \text{ kJ}/\text{kg}$
- $c_{p,w}...$  specific thermal capacity (at constant pressure) of the water vapour;  $c_{p,w} = 1,86 \text{ J}/(\text{kgK})$

From this the numerical value equation follows for the unsaturated condition:

$$h = 1,01 \theta + x (2501 + 1,86 \theta) \text{ in kJ}/\text{kg}_{\text{trockene Luft}} \quad (11-14)$$

To the surfeited range further dependences apply, with which one does not deal more in greater detail here. The enthalpy is very often needed in the air condition technology, since for each change of the air state energy is needed.

## 12 Humidity protection

Humidity has influence on

- Comfortable and healthy room climate
- Humidity demand of construction units

A goal of the humidity protection is the avoidance of building damage, which is caused by ice, liquid water (and water vapour).

Demands the construction unit:

- Building humidity (e.g. by mixing water with concrete)
- ascending humidity, pressing water (water from the building ground)
- Precipitation humidity (e.g. by driving rain)
- Water vapour by the living humidity

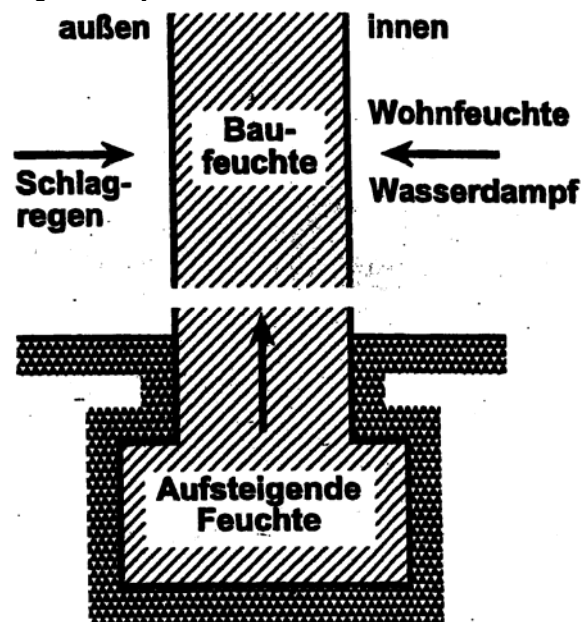


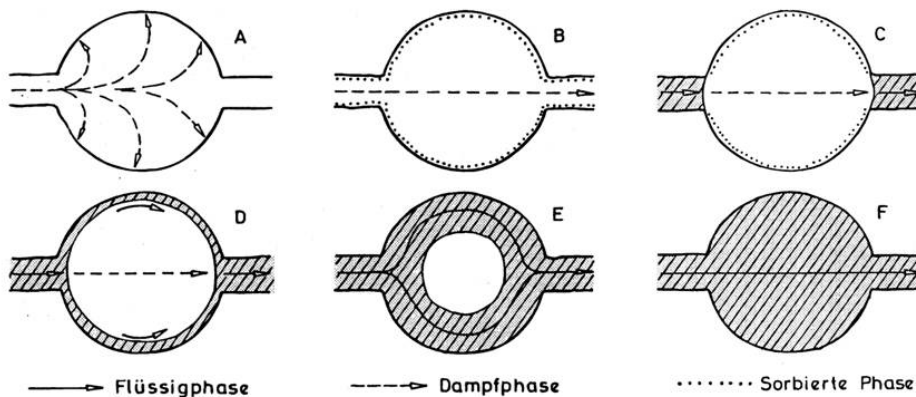
Figure 12-1 Schematic representation of different humidity effects on construction units

Since water in all three states of aggregation can affect damaging on buildings, different preventive measures must be made, e.g.:

- Seals (possibly pressure-holding) against flowing and seepage water as well as groundwater
- Roofs, finery, painting, wall linings against rain and splash-water
- Barrier layers against capillary transport of water in porous, absorbent building materials with ground connection and building humidity
- Vapour barriers for the protection from diffusing water vapour and condensate formation in construction units air conditioning and ventilation.

## 12.1 The basic stages of moisture transport

Building materials can emit water (drying process) or absorb moisture (moisturisation). In the building material bound or free water is subject to a movement, which is caused by driving potentials such as differences in pressure, temperature or concentration.



The following substantial

transportation mechanisms are to be differentiated:

- Pure vapour diffusion:
  - Thermal independent movement of the molecules
  - Transport is determined by impacts of the water molecules among themselves
  - Driving potential: Partial pressure difference
- Effusion:
  - Transport is determined by impacts of the water molecules with the pore wall
  - Driving potential: Partial pressure difference
  - Due to different pore sizes diffusion and effusion cannot be delimited clearly;
- Surface diffusion:
  - arises with hygroscopic materials
  - the sample surfaces humidity contents adjust themselves in accordance with sorption curves
  - The sorbat water covers the pore surface in a layer
  - Sorbat water flow and diffusion current are usually superposed
  - In the isotherm case of addition of the two transportation mechanisms: smaller  $\mu$ -values
- External wall in winter: Subtraction of the two flows
- Solution diffusion:
  - With non porous materials, e.g. organic polymers or dispersions, the water transportation occurs by means of adsorption and storage of water molecules into the macromolecules of the polymers on the humid side. By expansion processes the water is passed on.
- Capillary conduction:
  - Liquid water transportation in capillary-porous building materials. In this connection, the capillary pressure as driving strength is convertible on the relative humidity. Transport is described together with surface diffusion.

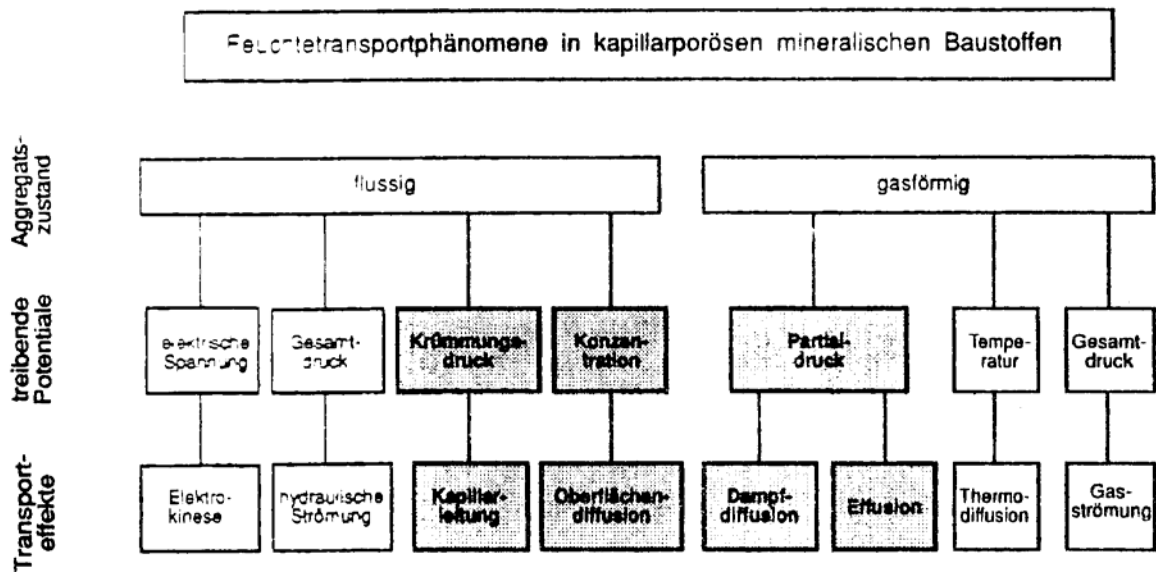


Figure 12 2 Schematic overview of the moisture transport phenomena in porous mineral building materials. Hatched areas are relevant from the building design aspect.

### 12.1.1 Building material moisture content

Building materials exhibit generally internal cavities, which range from the macro pore area (mm to 10  $\mu\text{m}$ ) to the microbe realm ( $< \mu\text{m}$ ). Depending upon building material different relative frequentness of the pore volumes can result within the different dimension ranges. The water vapour contained in air is transported into these building material pores and/or bound there.

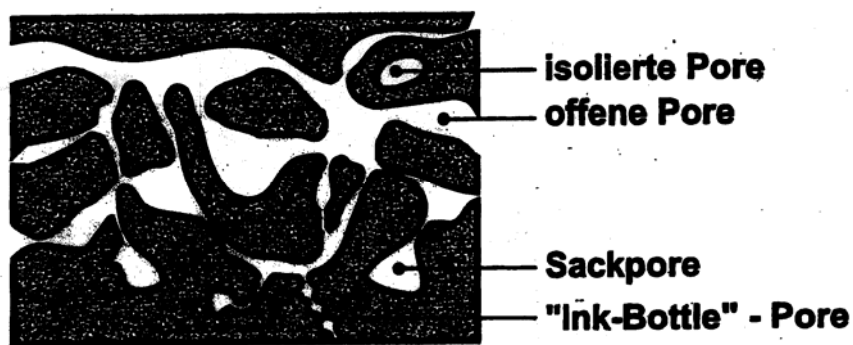


Figure 12 3 Microporous structure of building materials

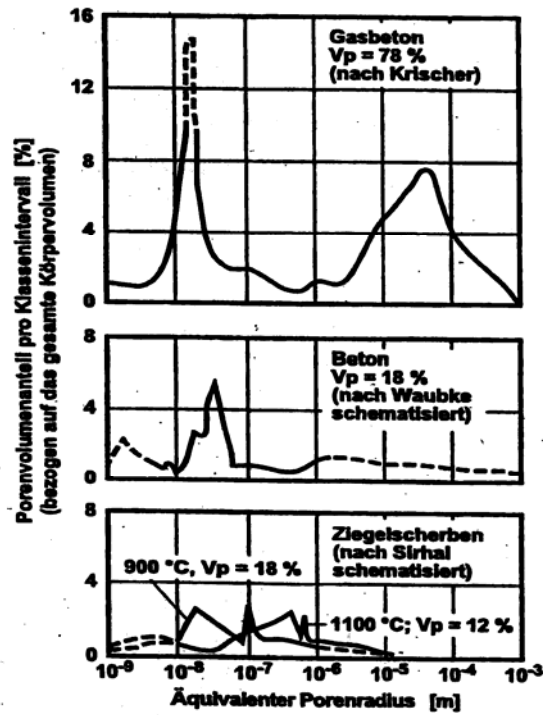


Figure 12 4 Comparisons of pore size distributions of different porous building materials as a function of the equivalent pore radius

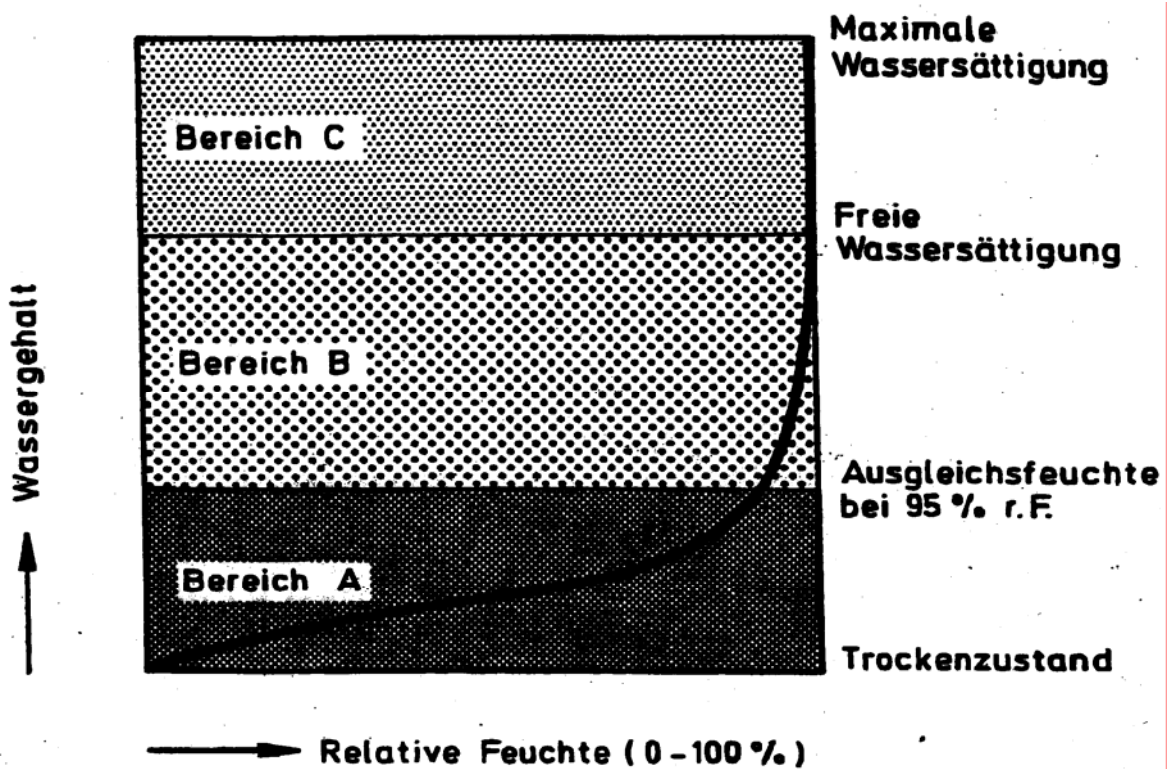


Figure 12 5 Schematic representation of the humidity storage function of a hygroscopic, capillary-active building material

- Range A: this range characterises the sorption humidity range up to a relative humidity of 95%. It is described in building physics by sorption isotherms.
- Range B: Within this range, which is called also super-hygroscopic range, increasingly larger building material pores filled with water up to the free water saturation, the equilibrium moisture with contact with water.
- Range C: Within this range, super saturation range, there are no more equilibrium conditions. The relative humidity amounts always to 100% independently of the water content.

### 12.1.2 Sorption

- The humidity connection within the hygroscopic humidity range (sorptive connection) takes place via water sorption, as at internal surfaces of the pore structure water molecules are accumulated in mono or multi-molecular layers, which is not to be confounded with chemical connection.
- Under the concept of sorption, one summarises absorption and capillary condensation. In the super-hygroscopic range, unbounded water (capillary-water) is existing in the structural materials.
- Labelling the water quantity contained in the construction materials serves the mass referential water content:

$$u_m = \frac{m_f - m_t}{m_t} = \frac{m_W}{m_M} \quad [\% \text{ oder Gew.}\%] \quad (12-1)$$

mf: Mass of the moist material [kg]

mt: Mass of the dry material, also mm, [kg]

mW: Mass of the water [kg]

- for the volume referential moist content:

$$u_v = u_m \frac{\rho_M}{\rho_W} \quad [\% \text{ oder Gew.}\%] \quad (12-2)$$

$\rho_M$ : Molded density of the material [kg/m<sup>3</sup>]

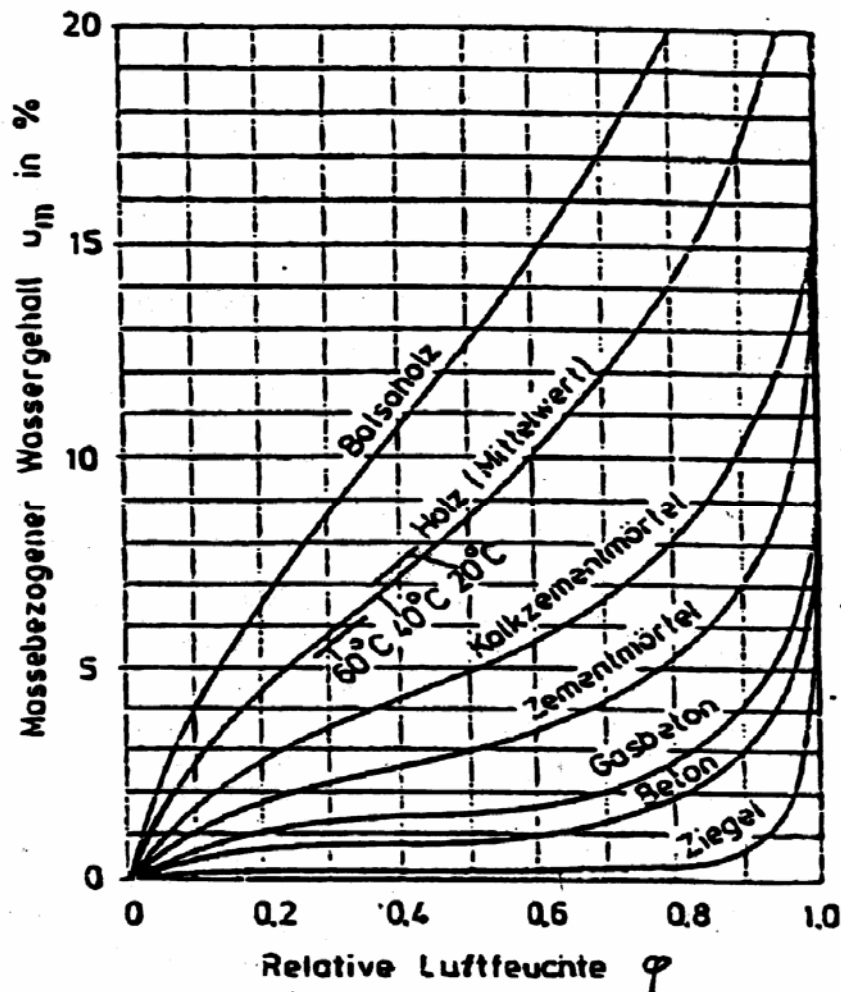
$\rho_W$ : Molded density of the water (1000 kg/m<sup>3</sup>s) [kg/m<sup>3</sup>]

structural materials	Common (Practice) Volume -%	Maximum (Practice) Volume -%	maximum possible Volume -%
Brick	1	10 ...12cas	20
Pore concrete	3 ...4cas.	about 30	80
Normal concrete	5	.about 10	20

Table 12-1 Referential volume moisture content of some construction materials

Most construction materials are hygroscopic or sorption-able, i.e. they pick up a certain water quantity at longer storage in humid air („balancing humidity“). We represent this interrelationship by humidity of the construction materials and relative air moisture in the sorption isothermal. It turns out that the absorbed moisture quantity depends on the temperature.

Since prefabricated parts, in the practice, won't dry up totally, this is described by the term “practical moisture content”. This corresponds to statistical evaluation of the permanent water content in the construction materials, that is not exceeded of a multiplicity of tests in 90% of all examinations.



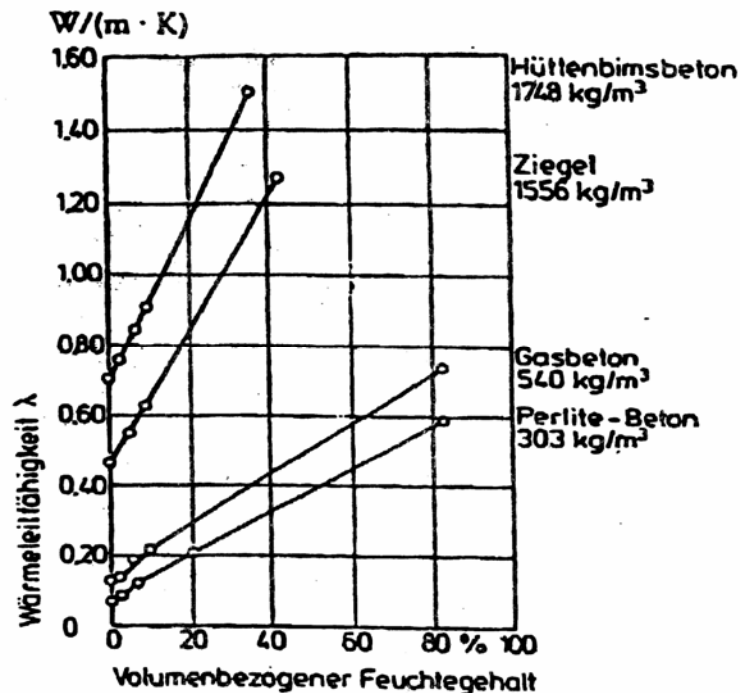
Form 12-6 Sorption isotherms for different construction materials at 20 °C; more practically moisture content emerges at 80% sorption humidity (reference humidity; comprises certain reserve)

Zeile	Baustoffe	Praktischer Feuchtegehalt <sup>1)</sup>	
		volumenbezogen <sup>2)</sup> H <sub>v</sub> %	massebezogen H <sub>m</sub> %
1	Ziegel	1,5	-
2	Kalksandsteine	5	-
3	3.1 Beton mit geschlossenem Gefüge mit dichten Zuschlägen	5	-
	3.2 Beton mit geschlossenem Gefüge mit porigen Zuschlägen	15	-
4	4.1 Leichtbeton mit haufwerksporigem Gefüge mit dichten Zuschlägen nach DIN 4226 Teil 1	5	-
	4.2 Leichtbeton mit haufwerksporigem Gefüge mit porigen Zuschlägen nach DIN 4226 Teil 2	4	-
5	Gasbeton	3,5	-
6	Gips, Anhydrit	2	-
7	Gußasphalt, Asphaltmastix	≈ 0	≈ 0
8	Anorganische Stoffe in loser Schüttung; Expandiertes Gesteinsglas (z. B. Blähpelrit)	-	5
9	Minerale Faserdämmstoffe aus Glas-, Stein-, Hochofenschlacken-(Hütten-)Fasern	-	1,5
10	Schaumglas	≈ 0	≈ 0
11	Holz, Sperrholz, Spanplatten, Holzfaserplatten, Holzwole-Leichtbauplatten, Schilfrohrplatten und -matten, Organische Faserdämmstoffe	-	15
12	Pflanzliche Faserdämmstoffe aus Seegrass, Holz-, Torf- und Kokosfasern und sonstigen Fasern	-	15
13	Korkdämmstoffe	-	10
14	Schaumkunststoffe aus Polystyrol, Polyurethan (hart)	-	5

<sup>1)</sup> Unter praktischem Feuchtegehalt versteht man den Feuchtegehalt, der bei der Untersuchung genügend ausgetrockneter Bauten, die zum dauernden Aufenthalt von Menschen dienen, in 90 % aller Fälle nicht überschritten wurde.  
<sup>2)</sup> Der volumenbezogene Feuchtegehalt bezieht sich auch bei Lochsteinen, Hohldielen oder sonstigen Bauelementen mit Lufthohlräumen immer auf das Material allein ohne die Hohlräume.

Form12-7 More practically moisture content of construction materials DIN 4108, T. 4, 1985,

The heat conductivity of construction materials increases with increasing moisture content. The tabular characteristics of the heat conductivity given in the standards consequently refer to the convenient moisture content.



Form 12-8 Heat conductivity of different construction materials dependent on the moisture content; for insulation materials often strongly not linear

### 12.2 Capillary conduction

- Water fluid transportation in capillary porous construction materials is depend on the suction tensions of the water, evoked through the surface tension of the water and the capillary surface.

The driving force, the

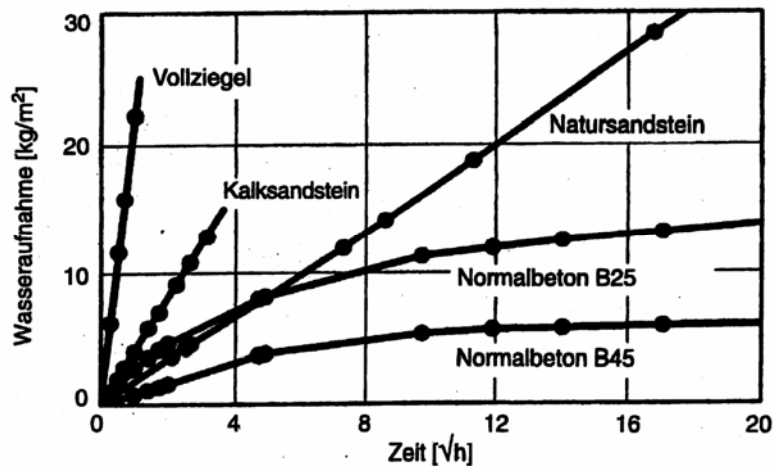
- Capillary pressure is not to be determined in simple manner. This transportation coefficient is not a constant, but a complex function permitting an analytical view only by means of numeric methods.

Capillary water absorption of a material is quantified by immersing a sample in water and determining the

- Mass increases over the time. It is valid following „root-t-principle “ (emerging from the diffusion basis):

$$W = w \cdot \sqrt{t} \quad \text{[kg/m}^2\text{]} \quad (12-3)$$

W:	absorbed water quantity per area	[kg/m <sup>2</sup> ]
t:	time of the suction	[h]
w:	Water reception coefficient	[kg/(m <sup>2</sup> h <sup>0,5</sup> ,)]



Form 12-9 Capillary water reception of different mineral materials in dependence on the square-root of the time

The straightness of the measure value drawing only applies if the pore-structure experiences no change through the water-effect , for example through source-processes (for example concrete).

- Larger capillaries suck more quickly because of inferior current resistance and quantitatively more effective than smaller pores. Smaller pores have a bigger suction strength than bigger pores, but on the basis of even larger flow resistance a more inferior suction speed. If the water supply is stopped at the suction surface, for example end of sprinkling, the water transportation nevertheless continues. On this occasion the smaller capillaries suck water from the bigger capillaries and distribute this in the structural materials.

Following equation is valid:

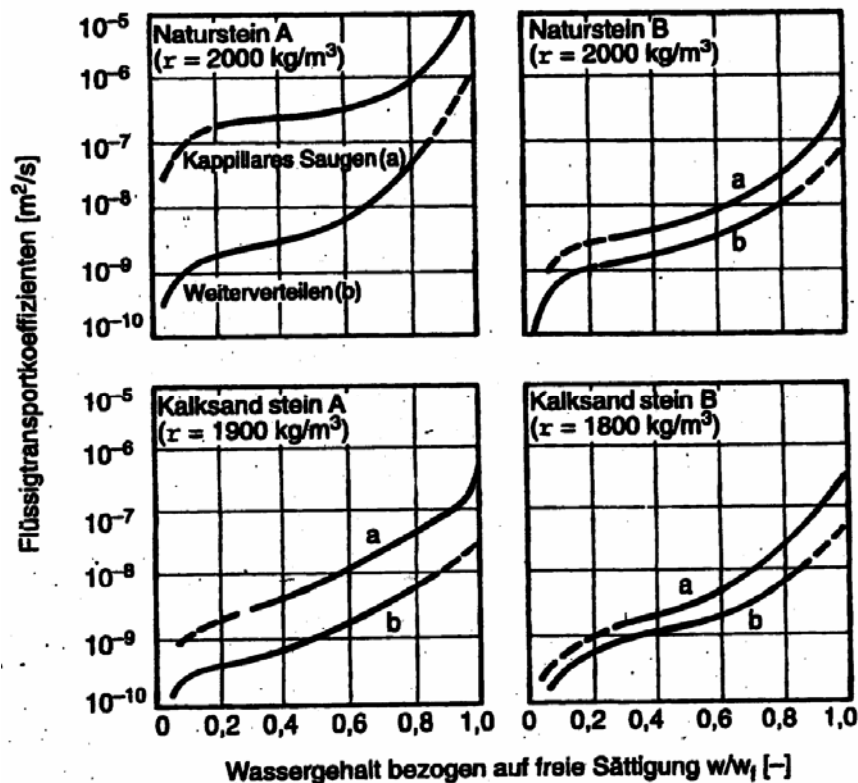
$$g = D(w^*) (dw^*/dx) \quad \text{[kg/(m}^2 \text{ s)]} \quad (12-4)$$

G:	Capillary-water-flow-density	[kg/(m <sup>2</sup> s,)]
----	------------------------------	--------------------------

$D(w^*):$	Capillary-water-conduction-coefficient (depend on $w^*$ ) [ $m^2/s$ ]
$W^*:$	Water-content [ $kg/m^3$ ]
$X:$	site coordinates [ $m$ ]

A technical measurement survey of the capillary water conduction coefficients is done by means of NMR equipment (nuclear-magnetic resonance). The water content in suction direction during a suction process is virtually continuously detected. From the water content and the respective water content gradients one is able to determine the two conduction coefficients:

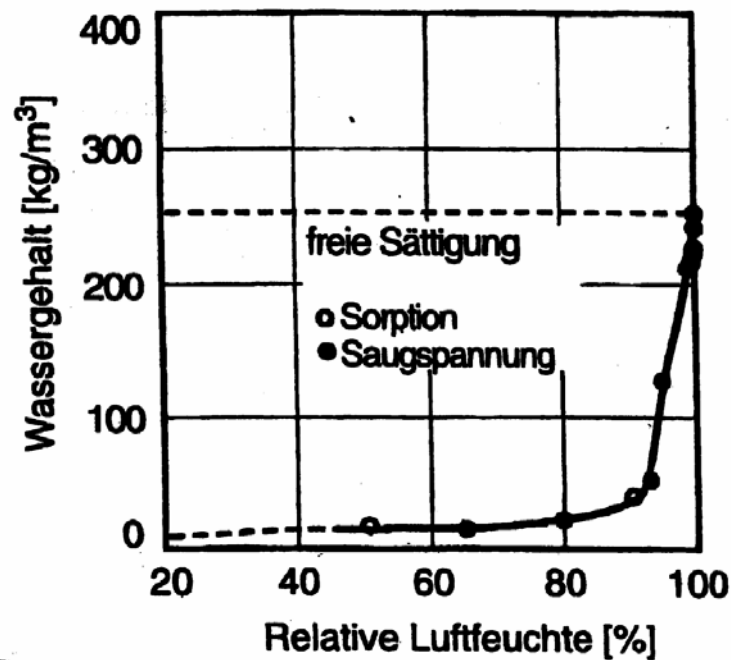
- for the suction with water supply
- for the further distribution at discontinuous suction



Form 12-10

Fluid transportation coefficients of components depending on standardised water content

An indication concerning the adjusting humidity content as a function of the capillary structure of the material in the equilibrium with the site conditions takes place in the hygroscopic range via the sorption isotherm, within the over-hygroscopic range up to the free water saturation is accomplished by the measurements of the suction power depending on the water content, here both curves are merged..



Form 12-11 Moisture storage function for lime sand brick for the hygroscopic and over-hygroscopic humidity range; determined from the sorption isotherm and suction rate measurement curve

### 12.3 Numerical investigation of the heat and moist conveyance

In the construction unit different transmission mechanisms arise in practice, at the same time, overlay with different transportation intensities.

Until now, two methods were essentially available:

- pure stationary vapour diffusion (see section "glazier procedure"), this means, sorption and liquid transport are not considered.
- capillary suction, (root-t-principle) impossible to investigate moisture distributions,

Since both procedures are inappropriate to describe real [moisturisation](#) and drying processes, a method of calculation has to be developed. For numerical calculation of transient heat and moisture transport in prefabricated parts, at least the following physical effects are to be considered:

Diffusion

- Solution diffusion
- Capillary conduction and surface diffusion
- Hygroscope influence on heat conduction
- Latent heat effects at transition from water to ice as well as vapour and liquid water and conversely

Following boundary conditions must be considered transient:

- Temperature
- Relative humidity at the surface and the surrounding

- Solar radiation
- Precipitation

Numerical calculation takes place by means of two coupled partial differential equations for the heat and moist transport. For calculation, some software is available:

- WUFI from the Fraunhofer-Institute for Building Physics;
- DIM from the University of Dresden
- MATCH from the University of Copenhagen

Hints for use of calculation programs:

- validating (comparison with measure consequence) is always necessary
- sensitivity analysis should be enforced to control the results

## 12.4 Thermal and Hygric Computer Simulation for Building Components

In contrast to the purely steady-state, diffusion computation of a construction unit according to DIN 4108, with the thermal and hygric simulator routine WUFI (Fraunhofer society - Institute for building physics -) also transient, sorptive and capillary conducting processes can be considered. Thereby it is possible, to seize the construction unit, in view from the building design aspect, more exactly and to reproduce humidity processes visually by a film representation, too.

As boundary conditions of the calculation the meteorological data, such as temperature, radiation, raining/driving rain, relative humidity is applied to the construction component according to individual specifications or according to what is known as test-reference-years .

The interior climate data, temperature and relative humidity, are applied to the construction unit and the moisture development is calculated during one or several periods of years.

With the calculation of the heat transportation, WUFI considers the following transportation mechanism:

- Heat conduction,
- Enthalpy flow by vapour diffusion with changing phase,
- Short wave solar radiation,
- Long wave nightly radiation (only with TRY-Climate data)

Convective heat transportation through air flow is unrecorded, since it is usually difficult to detect and seldom one-dimensional.

With the calculation of moisture transport, WUFI considers the following transportation mechanisms:

- Moisture diffusion,
- Solution diffusion.

With the calculation of the fluid transport, WUFI considers the following transportation mechanisms:

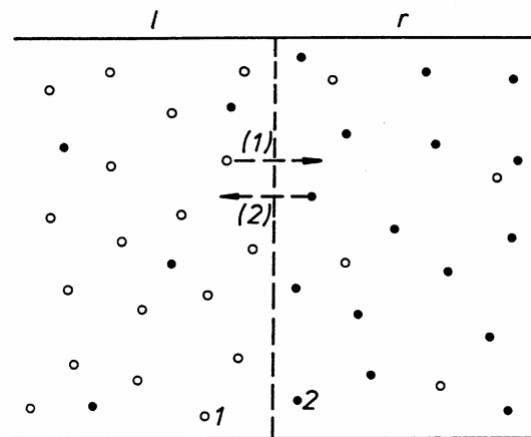
- Capillary conduction,

Surface diffusion.

The seepage flows due to gravity, hydraulic currents due to total pressure differences, electrical kinetic and osmotic effects as well as convective vapour transport caused by air flow are not taken into account.

## 12.5 Water Vapour diffusion

A gas mixture in 2 connected areas has overall the same total pressure, but in each area can present another concentration of the individual gases (gas components), thus can obtain different pressure of gas components. Then, the exchange of the molecules of every gas between the areas take places as long, until the individual concentrations (pressure of gas components) are of same magnitude everywhere.



### Form 12-1 Exchange of Gas Molecules Between Two Areas

$t = 0:$	$p_{1l} + p_{2l} = p_{1r} + p_{2r}$	$p_{1l} > p_{1r}$	$p_{2l} < p_{2r}$
$t:$	$p_{1l} + p_{2l} = p_{1r} + p_{2r}$	$p_{1l} = p_{1r}$	$p_{2l} = p_{2r}$

The same procedure occurs, for example, with the water vapour-air mixture concerning water vapour transport through a construction component, with both sides presenting different water vapour partial pressures (e.g. Room air - outside air). Then the vapour diffusion begins, due to the vapour pressure differences between both sides for example, i.e. vapour transport through the separating prefabricated part.

Diffusion is particle transportation, that takes place between areas of different particle density through the thermal movement:

- the mathematical description of the diffusion is carried out by the Ficksche law
- the diffusion speed is small compared to the thermal speed:
  - approximately  $10^{-6}$  m/s in gases and
  - $10^{-7}$  m/s in liquids and solid materials

Water vapour diffusion takes place through a prefabricated part because of different partial pressure of water vapour on the two sides of the prefabricated part.

So, it follows: 
$$g_D = \frac{P_{Li} - P_{Le}}{\frac{1}{\beta_i} + \frac{s}{\delta} + \frac{1}{\beta_e}} \quad [\text{kg}/(\text{m}^2\text{h}) \quad (12-5)$$

$g_D$ :	Vapour flow density	[kg/(m <sup>2</sup> h,)]
$p_{Li/e}$ :	Partial pressure of the inside and outside air	[Pa]
$\beta_{i/e}$ :	Material transition coefficients inner/outer	[kg/(m <sup>2</sup> h Pa,)]
$\delta$ :	Vapour diffusion conductivity	[kg/(m h Pa,)]
$s$ :	Thickness of the prefabricated part	[m]
$s/\delta$ :	$= Z = 1 / \Delta =$ diffusion resistance of water vapour $\Delta$	[m <sup>2</sup> h Pa/kg]

The computational survey of the vapour transmittance through a construction unit due to the vapour pressure gradient between the two adjacent areas takes place similarly to the heat transfer. It is therefore - in accordance with  $q = U \cdot (t_i - t_e)$  - the water vapour diffusion flow density  $g$ :

$$g = U_D \cdot (p_i - p_e) \quad \text{kg/(m}^2\text{h)} \quad (12-1)$$

whereby, analogously  $U = 1/(R_{si} + R + R_{se})$ :

$$U_D = 1/(1/\beta'_i + Z + 1/\beta'_e) \quad \text{kg/(m}^2\text{h Pa)}$$

with  $1/\beta'_{i,e}$  : inner, outer vapour transition resistance (m<sup>2</sup>h Pa/kg)  
 $Z$ : Water vapour diffusion transfer resistance (m<sup>2</sup>h Pa/kg)

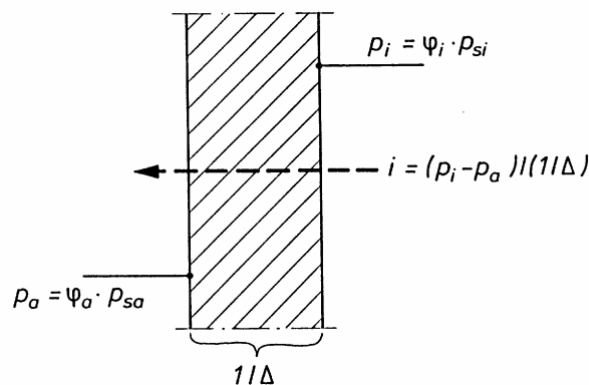
The values  $1/\beta'_i$  and  $1/\beta'_e$  are however in relation to  $Z$  infinitesimal small, so, they can be assumed as zero. Consequently it follows from (Gln. 3-14):

$$g = (p_i - p_e) / Z \quad \text{kg/(m}^2\text{h)} \quad (12-2)$$

A decrease of the partial pressure of water vapour,  $p$ , in the area of the surface of prefabricated part- like the temperature at heat transfer – thus approximately does not take place (Figure 3-6).

The vapour transmission resistance  $Z$  of a building material layer is calculated from:

$$Z = 1,5 \cdot 10^6 \cdot \mu \cdot s \quad (\text{m}^2\text{h Pa/kg)} \quad (12-3)$$



Form 12-2 Process of the vapor partial pressure,  $p_{i,e}$ , in the area of the construction unit surfaces and (water vapour) diffusion current density,  $i$ .

In it are

- $1,5 \times 10^6$  (m h Pa/kg): Vapour transmission resistance of a non-ventilated air film of the thickness  $d =$

1m at a temperature of 10 C

- $s$  (m): Thickness of the building material layer
- $\mu$  (-): Water vapour diffusion resistance value (short: "μ-value") of the construction material; indicates, how much more dense the construction material is than a non-ventilated air film of same thickness. In DIN 4108 μ-values are given besides the R-values for several construction materials. If there are 2 values declared for one construction material, the more unfavourable value in each case is to be used ( usually, for outer layers the bigger value, for inner a smaller value.

Examples for μ-value:

Mineral fibrous insulation material,  $\mu = 1$ ,  
 Masonry (according to type),  $\mu = 5 \dots 100$ ,  
 Normal concrete,  $\mu = 70/150$ ,  
 Polythene,  $\mu = 100.000$ .

The product  $\mu \times s$  for a construction material layer is also marked as water vapour diffusion equivalent (short: equivalent ) air film thickness, named  $s_d$ .

For the vapour diffusion equivalent air film thickness ( $s_d$ -value) of a construction material is valid:

$$s_d = \mu \cdot s \quad [\text{m}] \quad (12-4)$$

The  $s_d$ -value is the thickness of an air film in meters that shows the same vapour diffusion resistance, like the construction material with the thickness,  $s$ , and vapour diffusion resistance value,  $\mu$ .

With several consecutively lying layers of a prefabricated part is valid:

$$s_d = \sum \mu_i s_i \quad [\text{m}] \quad (12-5)$$

In DIN 4108 standard values for the diffusion resistance value,  $\mu$ , are given:

frequently, a range of values is declared (for example, vertically perforated brick:  $\mu = 5 / 10$ ); the more unfavourable values shall be used in application case:

- in general for the cold outside, the bigger
- for the warm inside, the smaller

The vapour transmission resistance  $Z$  of a multiplayer prefabricated part follows through addition of the resistances of the individual layers:

$$Z = 1,5 \cdot 10^6 \cdot \sum \mu_i \cdot s_i = 1,5 \cdot 10^6 \cdot \sum s_{di} \quad (\text{m}^2\text{h Pa/kg}) \quad (12-6)$$

## 13 Practical moisture protection

### 13.1 Moisture production in rooms

In average dwellings some 100 g water vapour develop on the day typical moisture delivery by cooking, transpiration (sweat) and evaporation with plants:

room plants:	7... 15 g/h
Humans with more easily activity:	30... 40 g/h
free water surface with 20 °C:	40 g (m <sup>2</sup> h)

Humidity balance in the room:

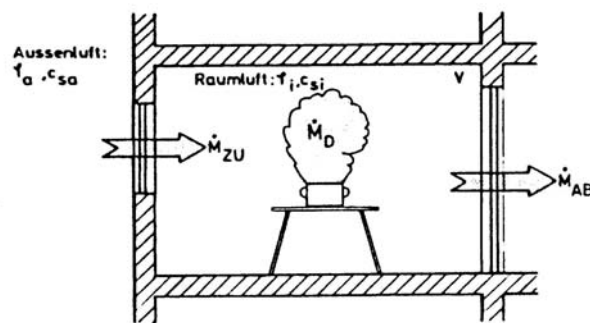


Figure 13.1-1 Schematic representation of moisture flows in a room

It applies the following balance equation

$$M_{zu} + M_D = M_{ab} \quad [\text{kg/h}] \quad (13.1-1)$$

$M_{zu}$ : supplied water vapour stream [kg/h]

$M_{ab}$ : exhausted water vapour stream [kg/h]

$M_D$ : in the room produced water vapour [kg/h]

furthermore applies to the individual components:

$$M_{zu} = n V c_a \quad [\text{kg/h}] \quad (13.1-2)$$

$$M_{ab} = n V c_i \quad [\text{kg/h}] \quad (13.1-3)$$

$n$ : Change of air [1/h]

$V$ : room volume [m<sup>3</sup>]

$c_{a/i}$ : absolute moisture content outside/inside [kg/m<sup>3</sup>]

thus applies to the relative humidity in the room:

$$\varphi_i = \left( \frac{T_i}{p_{Si}} \right) \left( \frac{p_{Sa} \cdot \varphi_a}{T_a} + \frac{M_D \cdot R_D}{n \cdot V} \right) \quad [-] \quad (13.1-4)$$

$\varphi_i$ :	relative humidity in the room inside	[-]
$\varphi_a$ :	relative humidity outside	[-]
$T_i$ :	temperature in the room	[K]
$T_a$ :	temperature outside	[K]
$p_{si}$ :	saturation vapour pressure inside	[Pa]
$p_{sa}$ :	saturation vapour pressure outside	[Pa]
$R_D$ :	Gas constant (0,462 kJ/(kg K))	[kJ/(kg K)]

### 13.2 Condensate in construction units due to water vapour convection

During not solid, air-permeable constructions (e.g. with timber panel constructions) the humidity entry must be considered by air flows. Leakages in a construction entail air flows:

- under the influence of differences of pressure (wind accumulation) or
- Temperature differences between room air and outside air (thermal lift)

This leads to increased calorific losses and to condensation water formation, by water vapour convection caused with the air passage can be brought in substantially more humidity into a construction than by diffusion, therefore leaks in external construction components must be avoided:

- Necessity for one „wind barrier“ or „convection barrier“
- can be attached to the outside or inside of a construction
- usually it is thus attached in connection with the vapour barrier - on the inside

### 13.3 Summer condensation and reversal diffusion

Condensate arises in dwellings or building constructions mainly in winter:

- warm-humid room air comes into contact with cold surfaces
- the water content or the dew point temperature of the room air causes the condensation water formation

in addition, there is also the summer condensation:

- the water content of outside air is the cause for condensate at surfaces or inside a construction
- Examples for this are the condensate due to nocturnal cooling on meadows („rope-wet grass“) or on the car-roof

Reversal diffusion:

- arises, if the direction of the diffusion current is turned around by high outside surface temperatures, e.g. due to high solar irradiation
- Humidity is then transported to the room inside and can condense there at diffusion-dense layers

### 13.4 Driving rain protection

If rain and wind (driving rain) affect a building, water can penetrate into walls and can be distributed in cracks or via capillar conduction in the building material pores. This causes increased heat losses due to damp wall material and a high risk of frost damages. E.g. water-rejecting or water-restraining plaster or coatings create remedy.

The stress of buildings is defined by so-called „stress groups“ (I, II, III) (DIN 4108):

- Stress group I: Small driving rain demand: applies to areas with yearly amounts of precipitation under 600 mm and particularly wind-protected situations
- Stress group II: Middle driving rain demand: in areas with yearly amounts of precipitation from 600 mm to 800 mm, in wind-protected areas with larger amounts of precipitation, with multi-storied buildings in exposed situation, but in areas with little precipitation
- Stress group III: Strong driving rain demand: in areas with yearly amounts of precipitation over 800 mm and strong wind, with multi-storey buildings in exposed situation, but in areas with middle driving rain demand.

In DIN 4108 is fixed for the 3 stress groups, which plasters, plates or boardings are permitted according to the water-absorbing characteristics.

#### Definition of the driving rain characteristics of plasters:

The water absorption characteristics are described with the w-value (water absorption coefficient) in combination with the  $s_d$ -value:

- Water-restraining plasters:
  - $w \leq 2 \text{ kg}/(\text{m}^2\text{h}^{0.5})$  with  $s_d \leq 2 \text{ m}$
  - External plasters from mortars of the group of II and III, DIN 18550
- Water-rejecting plasters:
  - $w \leq 0,5 \text{ kg}/(\text{m}^2\text{h}^{0.5})$  with  $s_d \leq 2 \text{ m}$  or
  - $w * s_d \leq 0,5 \text{ kg}/(\text{m}^2\text{h}^{0.5})$