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Elaboration of a simplified method for the normalisation of the hygric behaviour of envelope parts

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1. Abstract

The European Standard CEN ISO 13788 "Hygrothermal performance of building elements – internal surface temperature to avoid critical surface humidity and interstitial condensation – calculation method" is based on a simple water vapour transport model (Glaser-model) in porous building materials and building structures. There are several sources of error caused by this simplification:

- The liquid water transport occurs in many materials and influences significantly the moisture behaviour of structures.
- The most materials are more or less hygroscopic. The structure can store moisture without condensation processes.
- All thermic and hygric material properties are depending on the moisture content, temperature and thermodynamic processes. The moisture flow is coupled with an enthalpy flow. The coupled heat and moisture transfer will change the temperature and moisture distribution.
- By movement in leaks, in air spaces and in coarse porous materials a lot of moisture can penetrate into the structure.
- In frame of the boundary conditions only the indoor and outdoor temperature and relative humidity will be considered. The driving rain, and the shortwave and longwave radiation will be neglected.

The modern full models and computer codes for the coupled heat, vapour, liquid water, air, salt and pollution transfer in porous materials enable the exact calculation of the temperature, moisture, ice and salt concentration fields in building structures by given material functions and actual hourly values of all climatic components. However, standards should use simplified but also correct methods in order to guarantee the workability, reliability and durability of the structure.
In this contribution the liquid water transport and the hygroscopicity of materials have been integrated in the Glaser-scheme in a simple analytical way. As climate a simple jump (but worst case) climate has been used.

In the first chapter, the reason for the consideration of the capillary transport is given. In case of the renovation of a frame work house with a capillary active inside insulation the interstitial condensation amount can be reduced from 2.6 kg/m^2 to 0.6 kg/m^2.

In chapter two the simplified theory have been described. In winter, the penetrating vapour flow will the reduced by a liquid water flow from the condensation plane to the indoor surface and the outgoing vapour flow will be supported by a liquid water flow from the condensation plane to the outdoor surface. Hence, it follows a realistic moisture behaviour during the winter.

In chapter 3 an example will be explained in detail and in chapter 4 all results has been validated by means of the full model computercode DIM of the Institute of building physics of the TU Dresden.

In this shortened version only the simplified theory as base of a new regulation work for the moisture behaviour of envelope parts is written.

2. Simplified analytical model for the consideration of the liquid water transport in case of an interstitial condensation

For the simple case of the interstitial condensation, one condensation plane between the layer k and k+1, the general moisture transport scheme in Fig. 2.1 is presented. Like by the Glaser-model a vapour flow penetrates from the inside into the building part , moves along the vapour pressure or temperature gradient, respectively and condenses partially within the cold part of the layer k and the warm part of the layer k+1.The forming of a moisture field in this area is connected with a liquid water flow to the inside within the layer k and to the outside within the layer k+ 1. That means , a reduction of the vapour flow in the moist area of the layer k and an amplification of the vapour flow in the moist area of the layer k+1. In case of a simple jump climate as starting point, the loading process with inner condensation water follows about an exponential function. In the equilibrium (see Fig. 2.1) the total moisture flow density (sum of vapour and liquid water flow) is the same everywhere in the structure. In the dry layers 1 to k-1 and k+2 to n we have only vapour flow and in the moist areas we have vapour and liquid water flow. The capillary conductivity is described here by a constant value k which can be determined by the simple water uptake experiment (EN ISO 15148).
Hence, the symmetric formulation of the stationary flow densities is given

HEAT FLOW DENSITY $$q = \frac{\Delta T}{R} \quad (1) \qquad R = \frac{s}{\lambda} \quad (2)$$

WATER VAPOUR FLOW DENSITY $$gv = \frac{\Delta p}{rv} \quad (3) \qquad rv = \frac{\mu \cdot s}{\delta} \quad (4)$$

LIQUID WATER FLOW DENSITY $$gw = \frac{\Delta w}{rw} \quad (5) \qquad rw = \frac{s}{k \cdot \rho w} \quad (6)$$

The moisture capacity is determined in the hygroscopic area by the sorption isotherm (EN ISO 12571) w(ϕ) and in the overhygroscopic area by the water retention function w(pc).The sorption isotherm is linearized, the maximum value for $\phi = 1$ is wh. At the border between two layers e.g. 1 and 2 the potentials ϕ or pc are equal, but the moisture content has a jump.

$$w2 = \frac{w1}{G12} \quad (7) \qquad G12 = \frac{wh1}{wh2} \quad (8)$$

In the overhygroscopic area the moisture content increases from wh to the saturated moisture content ws (relative humidity is constant, $\phi = 1$). The moisture equilibrium e. g. between k and k+1 has been linearized, too.

$$w_{k+1} = wh_k + \frac{w_k - wh_k}{G_{kk+1}} \quad (9) \qquad G_{kk+1} = \frac{ws_k - wh_k}{ws_{k+1} - wh_{k+1}} \quad (10)$$

That means both materials have a similar only shifted pore size distribution.
Moreover in the potential condensation plane before the jump climate is applied the relative humidity is smaller than 1. At first the difference between input and output vapour flow densities stored as hygroscopic moisture. Later, after t > th the actual condensation process starts.

In figure 1 this situation is described. The moisture flow density from the indoor to the condensation plane is given by following equations

layer 1: only water vapour transport from the warm to the cold side of the layer

$$gi = \frac{\Delta pl}{rv_l} \tag{11}$$

layer 2: only water vapour transport from the warm to the cold side of the layer

$$gi = \frac{\Delta p2}{rv_2} \tag{12}$$

layer k: only water vapour transport within the dry area of the layer k

$$gi = \frac{\Delta pk1}{rv_k \cdot \left(1 - \frac{sK_k}{s_k}\right)} \tag{13}$$

contrary to the vapour flow density a capillary water flow density transports liquid water to the warm side within the moist area of the layer

$$gi = \frac{\Delta pk2}{rv_k \cdot \frac{sK_k}{s_k}} - \frac{\Delta we_k}{rw_k \cdot \frac{sK_k}{s_k}} \tag{14}$$

From equations (11) to (14) the vapour pressure differences follow

layer 1

$$\Delta pl = gi \cdot rv_l \tag{15}$$

layer 2

$$\Delta p2 = gi \cdot rv_2 \tag{16}$$

layer k

$$\Delta pk1 = gi \cdot rv_k \cdot \left(1 - \frac{sK_k}{s_k}\right) \tag{17}$$

layer k

$$\Delta pk2 = rv_k \cdot \left(\frac{sK_k}{s_k} \cdot gi + \frac{\Delta we_k}{rw_k}\right) \tag{18}$$

The sum of (15) to (18) is the whole vapour pressure difference from the inside to the condensation plane

layer 1 to k

$$\Delta pl = gi \cdot \left[\left(rv_l + rv_2 + rv_j + rv_k\right) + \frac{\Delta we_k}{rw_k} \cdot rv_k\right] \tag{19}$$

Hence it follows with the “inner” vapour resistance rvi

layer 1 to k

$$rvi = rv_l + rv_2 + rv_j + rv_k \tag{20}$$

the moisture flow density gi from the inside to the condensation plane at the cold side of the layer k

layer 1 to k

$$gi = \frac{\Delta pi}{rvi} - \frac{\Delta we_k}{rw_k} \cdot \frac{rv_k}{rvi} \tag{21}$$

$$gvi = \frac{\Delta pi}{rvi} \tag{22}$$

$$gw_k = \frac{\Delta we_k}{rw_k} \tag{23}$$

The same discussion gives for the layers k+1 to n, that means from the condensation plane to outdoor, the moisture flow density ge

layer k+1 to n
$$ge = \frac{\Delta pe}{rve} - \frac{\Delta wi_{k+1}}{rw_{k+1}} \cdot \frac{rv_{k+1}}{rve} \qquad (24)$$

$$gve = \frac{\Delta pe}{rve} \qquad gw_{k+1} = \frac{\Delta wi_{k+1}}{rw_{k+1}}$$

Δwi_{k+1} can be substituted by (9). In the equilibrium the moisture flow density is everywhere in the structure constant and gi = ge = g. From (21) and (24) follows the whole moisture flow density g as a kind of basic value of the simplified modelling for the interstitial condensation

$$g = \frac{gvi \cdot \frac{rvi}{rv_k} \cdot rw_k + gve \cdot \frac{rve}{rv_{k+1}} \cdot rw_{k+1} \cdot G_{kk+1}}{\frac{rvi}{rv_k} \cdot rw_k + \frac{rve}{rv_{k+1}} \cdot rw_{k+1} \cdot G_{kk+1}} \qquad (25)$$

Equations (21) and (24) respectively give with (25) also the amounts Δwe_k and Δwi_{k+1} of the overhygroscopic moisture between the layers k and k+1

$$\Delta we_k = (gvi - g) \cdot rw_k \cdot \frac{rvi}{rv_k} \qquad (26)$$

$$\Delta wi_{k+1} = (gvi - g) \cdot \frac{rw_k}{G_{kk+1}} \cdot \frac{rvi}{rv_k} \qquad (27)$$

Moreover the figure 1 is suitable to formulate the width of the overhygroscopic area in the layers k and k+1. Equation (18) and

$$\Delta ps_k = \Delta pk2 \cdot \frac{s_k}{sK_k}$$

give for the width of the moist area in the layer k

$$sK_k = \frac{gvi - g}{\frac{\Delta ps_k}{rv_k} - g} \cdot \frac{rvi}{rv_k} \cdot s_k \qquad (28)$$

and for the width of the moist area in the layer k+1

$$sK_{k+1} = \frac{gve - g}{\frac{\Delta ps_{k+1}}{rv_{k+1}} - g} \cdot \frac{rve}{rv_{k+1}} \cdot s_{k+1} \qquad (29)$$

Finally the amount of the condensation water within the layers k and k+1 can be calculated by (26), (27), (28) and (29).

$$mK_k = A \cdot \rho w \cdot \frac{\Delta we_k \cdot sK_k}{2} \quad (30)$$

$$mK_{k+1} = A \cdot \rho w \cdot \frac{\Delta wi_{k+1} \cdot sK_{k+1}}{2} \quad (31)$$

Up to now the developed model is valid for the equilibrium. The Glaser-model calculates for $t = \infty$ always the absurd value $mK = \infty$. The loading process for $t < \infty$ follows an exponential function. After the climatic jump the moisture balance equation is given by

$$\frac{d}{dt}\left(mK(t)_k + mK(t)_{k+1}\right) = (gi - ge) \cdot A \quad (32)$$

$mK(t)_k$ and $mK(t)_{k+1}$ follow from (30) and (31) with $\Delta wi_k = \Delta we_k / G_{k,k+1}$, gi and ge are formulated in (21) and (24)

$$\frac{d}{dt}\Delta we(t)_k \frac{\rho w}{2}\left(sK_k + \frac{sK_{k+1}}{G_{kk+1}}\right) = \left[\frac{\Delta pi}{rvi} - \frac{\Delta we(t)_k}{rw_k} \cdot \frac{rv_k}{rvi} - \frac{\Delta pe}{rve} + \frac{\Delta we(t)_k}{rw_{k+1} \cdot G_{kk+1}} \cdot \frac{rv_{k+1}}{rve}\right] \cdot A \quad (33)$$

The solution of the differential equation (33) gives the increasing of the condensation amounts $\Delta we(t)_k$, $\Delta wi(t)_{k+1}$ and $mK(t)$ in time

$$mK = mK_k + mK_{k+1} \quad (34)$$

tov: loading time for the overhygroscopic moisture

$$tov = 3 \cdot \frac{mK}{A \cdot (gvi - gve)} \quad (35)$$

$$\Delta we(t) = \Delta we_k \cdot \left(1 - e^{-\frac{3 \cdot t}{tov}}\right) \quad (36)$$

$$\Delta wi(t) = \Delta wi_{k+1} \cdot \left(1 - e^{-\frac{3 \cdot t}{tov}}\right) \quad (37)$$

$$mK(t) = mK \cdot \left(1 - e^{-\frac{3 \cdot t}{tov}}\right) \quad (38)$$

Note, the first term of the TAYLOR-polynom of (38) is identical with the increasing of interstitial condensate by Glaser

$$mK(t) = (gvi - gve) \cdot t \quad (39)$$

In the same way the cases of more linked or separated condensation planes have been formulated.

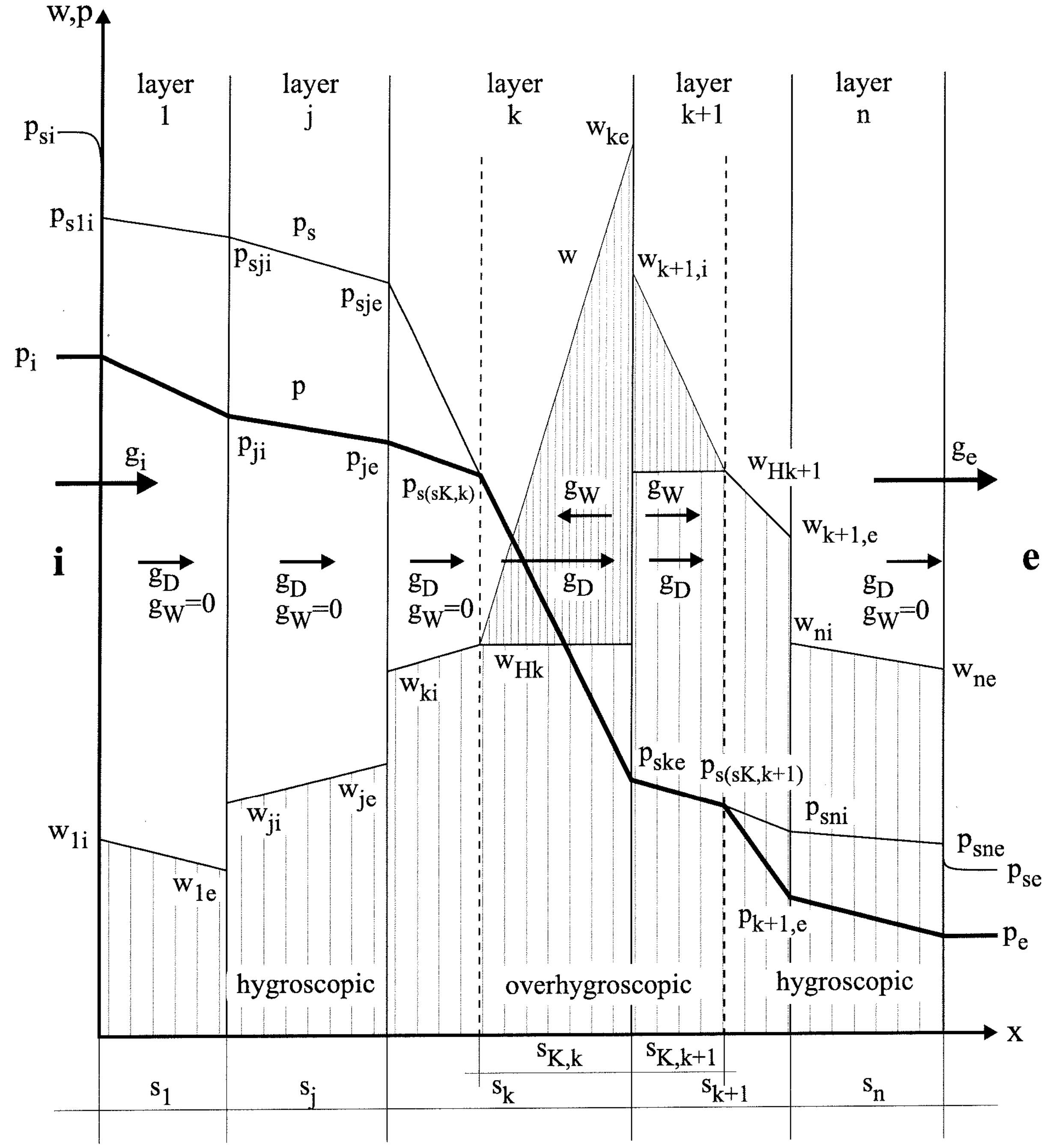

Fig. 1: Simplified moisture transport model for a construction with n layers
Case 1: condensation in the layer k and k+1

3. Example: 6-layered wall structure
case 1 – one condensation plane

The given algorithm is written in MATHCAD and will be used for a brickwall with an additional capillary active inside insulation

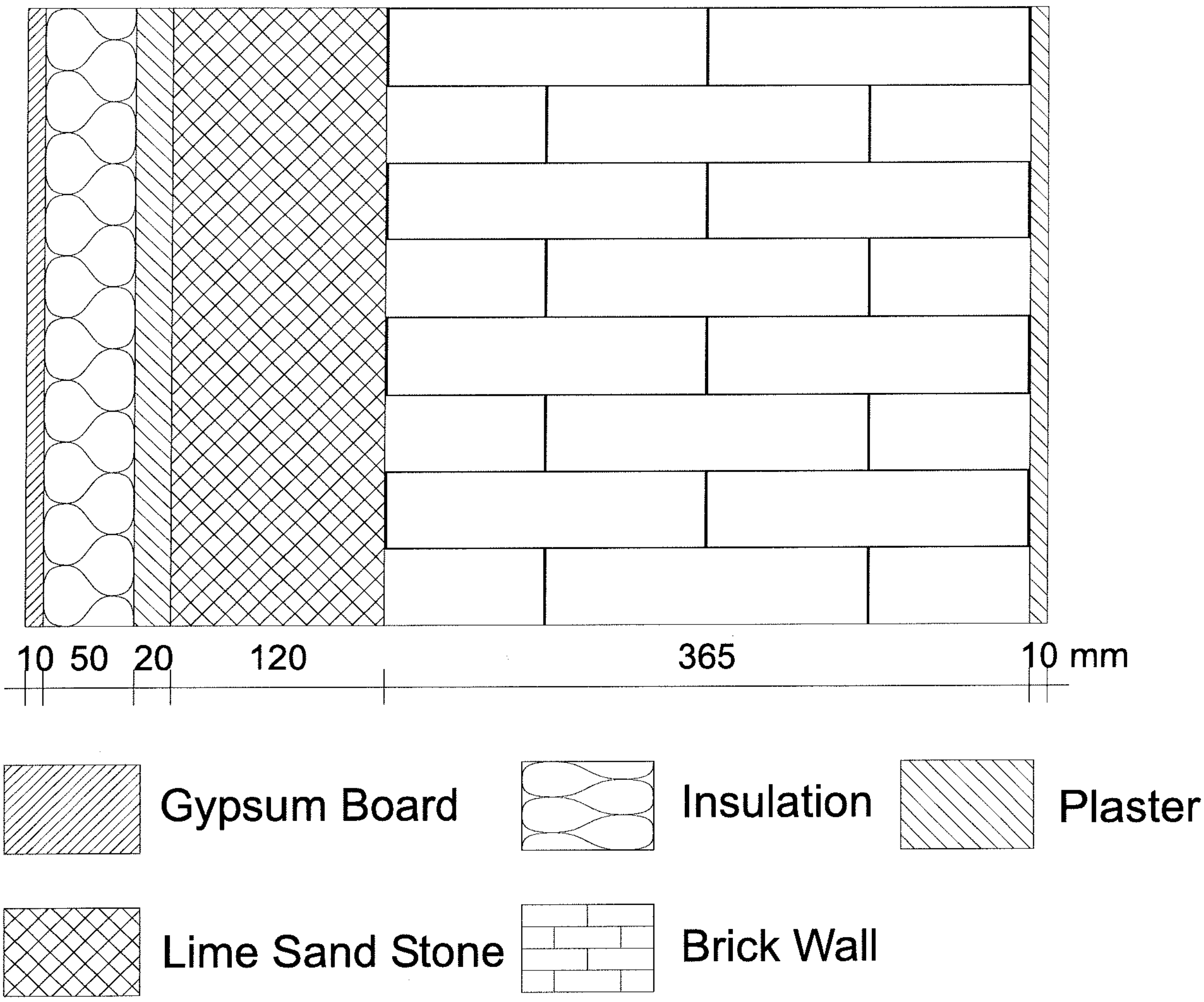

Fig. 2: Cross section of the structure

Page 9 contents the input data: material properties and winter jump climate.

Page 10 shows a summary of all results:
After one week (hygroscopic loading time) the condensation process starts. After 90 days the condensation amount is 0.64 kg/m². Without capillary forces (Glaser scheme, EN ISO 13788) 2.6 kg/m² liquid water will be calculated! Within two weeks in summer the structure can dry out.

MOISTURE BEHAVIOUR OF ENVELOPE PARTS

Calculation of interstitial condensation under consideration of liquid water transport and hygroscopicity

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MATERIAL PROPERTIES

Thermal conductivity λ in W/mK

Water vapour conductivity $1/\mu$ in 1

Liquid water conductivity k in m²/s (determination by means of the water uptake and the water penetration coefficient)

Maximum hygroscopic moisture content wh in m³/m³

Saturated moisture content ws in m³/m³

CASE 1 — 1 CONDENSATION PLANE

EXAMPLE
6-LAYERED WALL STRUCTURE

Condensation plane between 2/3

layer 1 : dry
interface 1/2 : dry
layer 2 : partially moistened
interface 2/3 : moist
layer 3 : partially moistened
interface 3/4 : dry
layer 4 : dry
interfac 4/5 : dry
layer 5 : dry
interface 5/6 : dry
layer 6 : dry

INPUT : JUMP CLIMATE 3 MONTHS WINTER

Indoor climate winter
T in °C , ϕ in %,p in Pa

$$Ti := 20$$

$$\phi i := \frac{50}{100}$$

$$psi := 288.68 \cdot \left(1.098 + \frac{Ti}{100}\right)^{8.02}$$

$$psi = 2338.1896$$

$$pi := \phi i \cdot psi$$

$$pi = 1169.0948$$

Initial relative humidity
in the plane 2/3

$$\phi o := \frac{98}{100}$$

Outdoor climate winter,
T in °C, ϕ in %, p in Pa

$$Te := -5$$

$$\phi e := \frac{80}{100}$$

$$pse := 4.689 \cdot \left(1.486 + \frac{Te}{100}\right)^{12.3}$$

$$pse = 401.8647$$

$$pe := \phi e \cdot pse$$

$$pe = 321.4917$$

INPUT : THICKNESSES, MATERIAL PROPERTIES

s in m, μ in 1, κ in m²/s, λ in W/mK, wh in m³/m³, ws in m³/m³

layer 1	$s1 := 0.01$	$\mu1 := 17$	$k1 := 1 \cdot 10^{-10}$	$\lambda1 := 0.34$	$wh1 := 0.01$	$ws1 := 0.40$
layer 2	$s2 := 0.05$	$\mu2 := 1$	$k2 := 1 \cdot 10^{-9}$	$\lambda2 := 0.04$	$wh2 := 0.005$	$ws2 := 0.80$
layer 3	$s3 := 0.02$	$\mu3 := 30$	$k3 := 5 \cdot 10^{-12}$	$\lambda3 := 0.95$	$wh3 := 0.03$	$ws3 := 0.30$
layer 4	$s4 := 0.12$	$\mu4 := 10$	$k4 := 3 \cdot 10^{-10}$	$\lambda4 := 1.25$	$wh4 := 0.08$	$ws4 := 0.30$
layer 5	$s5 := 0.365$	$\mu5 := 8$	$k5 := 6. \cdot 10^{-10}$	$\lambda5 := 0.75$	$wh5 := 0.01$	$ws5 := 0.30$
layer 6	$s6 := 0.01$	$\mu6 := 7$	$k6 := 1 \cdot 10^{-10}$	$\lambda6 := 0.95$	$wh6 := 0.02$	$ws6 := 0.40$

SUMMARY OF THE RESULTS

LAYER	TEMPERATURE in °C	VAPOUR PRESSURE in Pa	MOISTURE VALUE in m³/m³	WIDTH OF THE MOISTENED AREA in m	CONDENSATION AMOUNT in kg/m²
Inner surface	$Toi = 18.4251$	$pi = 1169.09$ $psoi = 2120.12$	$woi = 0.0055$		
layer 1 $s1 = 0.0100$ $\lambda 1 = 0.3400$ $\mu 1 = 17.0000$ $k1 = 1.0000 \times 10^{-10}$			$wh1 = 0.0100$ $w1e = 0.0056$	$sK1 := 0$	$mK1 := 0$
	$T12 = 18.0688$	$p12 = 1153.02$ $ps12 = 2073.33$			
layer 2 $s2 = 0.0500$ $\lambda 2 = 0.0400$ $\mu 2 = 1.0000$ $k2 = 1.0000 \times 10^{-9}$			$w2i = 0.0028$ $wh2 = 0.0050$ $w2e = 0.0779$ $w2et(90) = 0.0760$	$sK2 = 0.0150$	$mK2(90) = 0.5317$
	$T23 = 2.9258$	$ps23 = 754.4732$			
layer 3 $s3 = 0.0200$ $\lambda 3 = 0.9500$ $\mu 3 = 30.0000$ $k3 = 5.0000 \times 10^{-12}$			$w3it(90) = 0.0541$ $w3i = 0.0548$ $wh3 = 0.0300$ $w3e = 0.0291$	$sK3 = 0.0093$	$mK3(90) = 0.1120$
	$T34 = 2.6708$	$p34 = 717.7868$ $ps34 = 740.8915$			
layer 4 $s4 = 0.1200$ $\lambda 4 = 1.2500$ $\mu 4 = 10.0000$ $k4 = 3.0000 \times 10^{-10}$			$w4i = 0.0775$ $wh4 = 0.0800$ $w4e = 0.0709$	$sK4 = 0.0000$	$mK4 = 0.0000$
	$T45 = 1.5078$	$p45 = 604.2894$ $ps45 = 681.6341$			
layer 5 $s5 = 0.3650$ $\lambda 5 = 0.7500$ $\mu 5 = 8.0000$ $k5 = 6.0000 \times 10^{-10}$			$w5i = 0.0089$ $wh5 = 0.0100$ $w5e = 0.0077$	$sK5 = 0.0000$	$mK5 = 0.0000$
	$T56 = -4.3879$	$p56 = 328.1124$ $ps56 = 423.4489$			
layer 6 $s6 = 0.0100$ $\lambda 6 = 0.9500$ $\mu 6 = 7.0000$ $k6 = 1.0000 \times 10^{-10}$			$w6i = 0.0155$ $wh6 = 0.0200$	$sK6 := 0$	$mK6 := 0$
Outer surface	$Toe = -4.5154$	$psoe = 418.8663$ $pe = 321.4917$	$woe = 0.0154$		

U-VALUE in W/m²K		
$U = 0.4846$	START OF CONDENSATION after t = thd , thd in days	$thd = 6.7$
	CONDENSATION AMOUNT at the end of the condensation period in kg/m²	$mKt(90) = 0.644$
	CONDENSATION AMOUNT IN THE EQUILIBRIUM , $t \to \infty$ mK in kg/m²	$mK = 0.661$
	DRYING TIME , tevd in days	$tevd1 = 11.1$

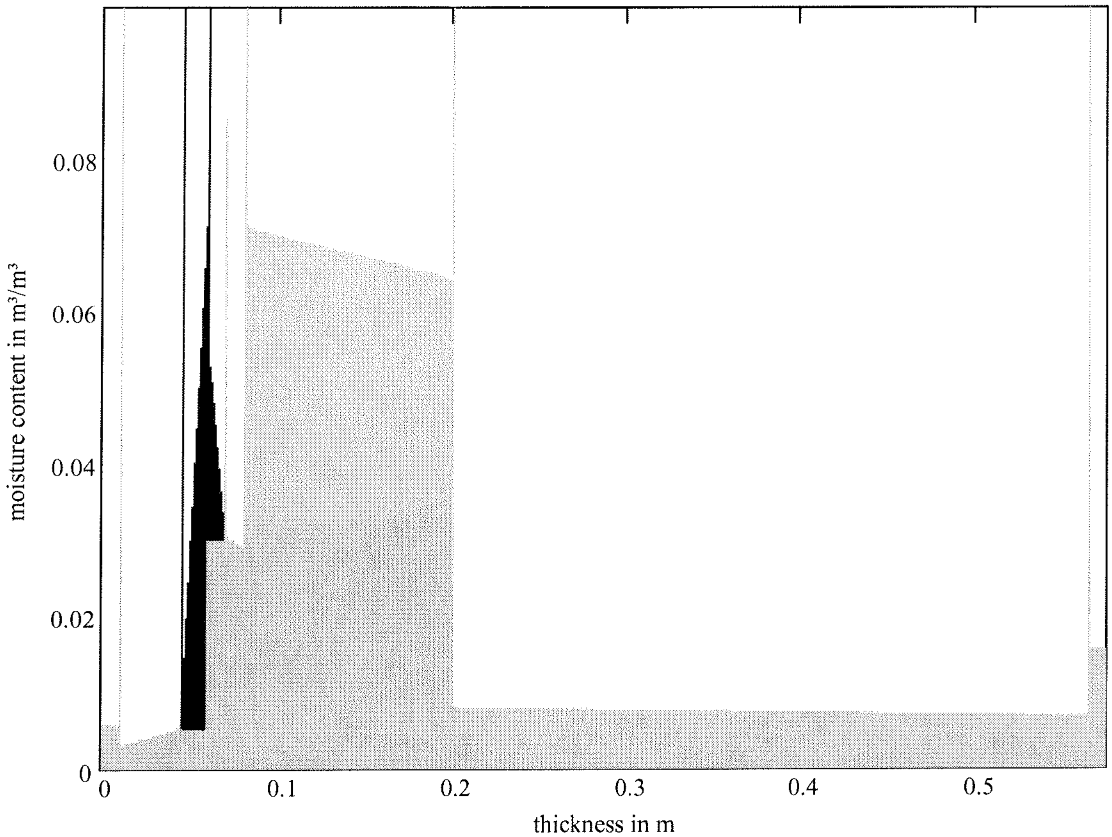

Fig. 3: Moisture distribution in the structure – dark color, liquid water

4. Validation of the results by means of the full-model and computercode DIM

The results of the example will be validated by the developed numerical code DIM. The material properties and the jump – climate (compare page 9) will be input. The loading process during the winter (90 days) leads also to 0.64 kg/m² liquid water (see Fig. 4). The drying time during the summer is about two weeks. The moisture distribution at the end of the condensation period corresponds approximately with the simplified calculation (compare Fig. 6 with the moisture profile Fig. 3).
Figure 7 shows the increasing (winter) and decreasing (summer) of moisture with and without capillary transport calculated by the exact code DIM. The results agree with the simplified calculations.
Finally all investigations have been done once again with the monthly climate values (proposal in the EN ISO 13788). The last Figure 8 shows again clearly: the liquid water transport can not be neglected, also not in the simple hand codes for the practice.

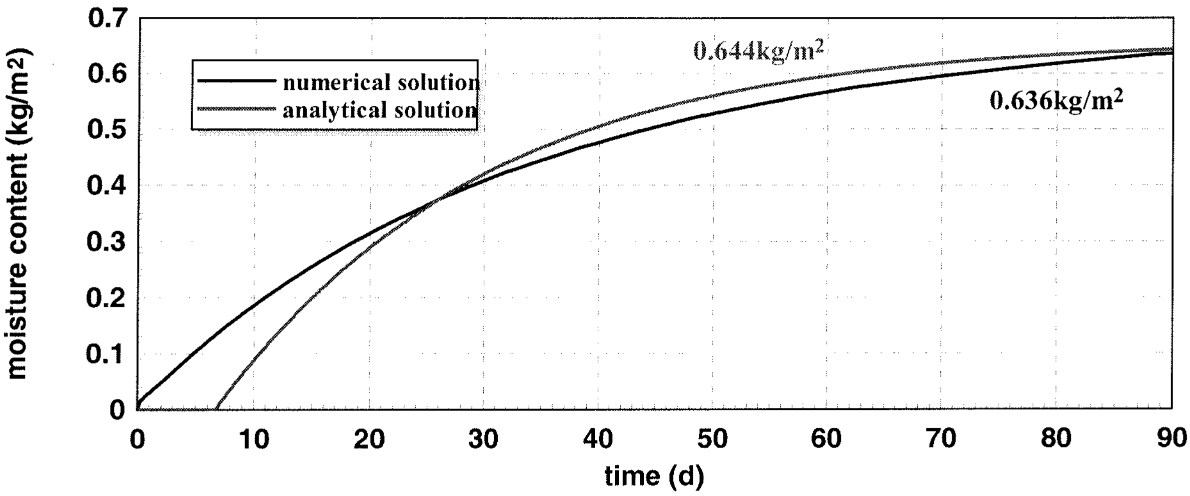

Fig. 4: Increasing of the condensation water, Comparison of the numerical simulation (DIM 3.1) with the simplified model

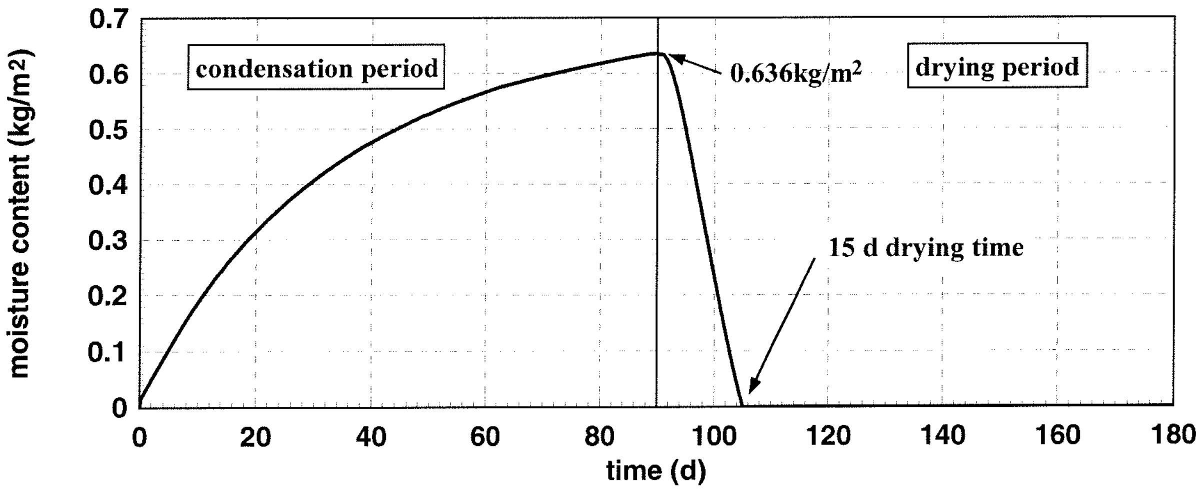

Fig. 5: Increasing of the condensation water and following drying process

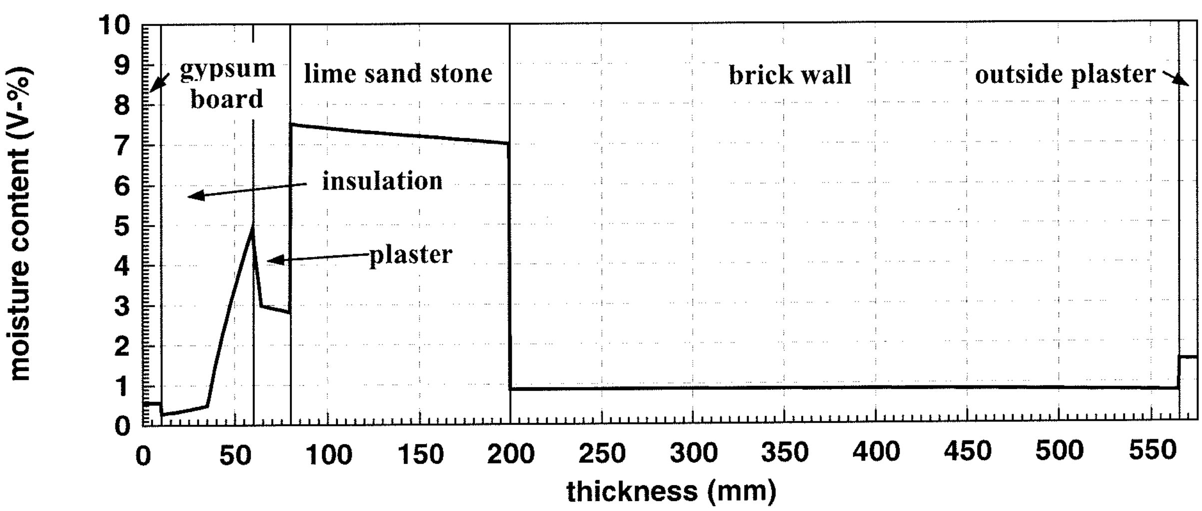

Fig. 6: Moisture distribution at the end of the condensation period by numerical simulation (DIM 3.1)

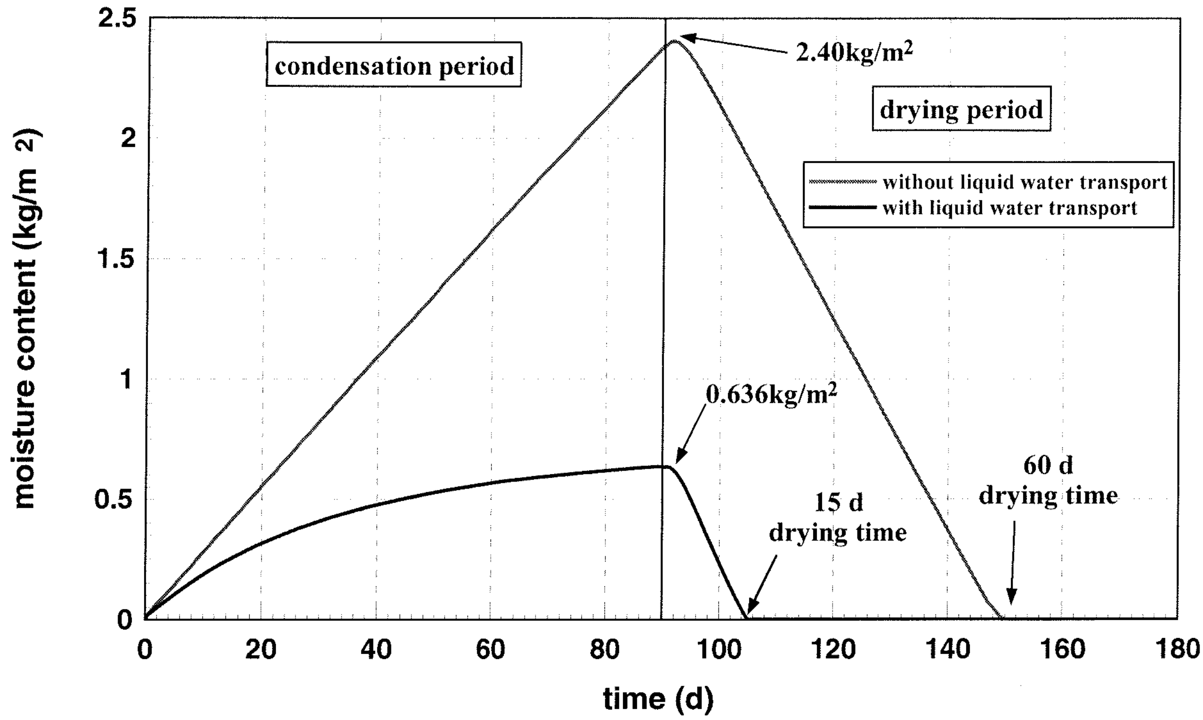

Fig. 7: Condensation and drying process with and without capillary forces (numerical simulation) – jump climate

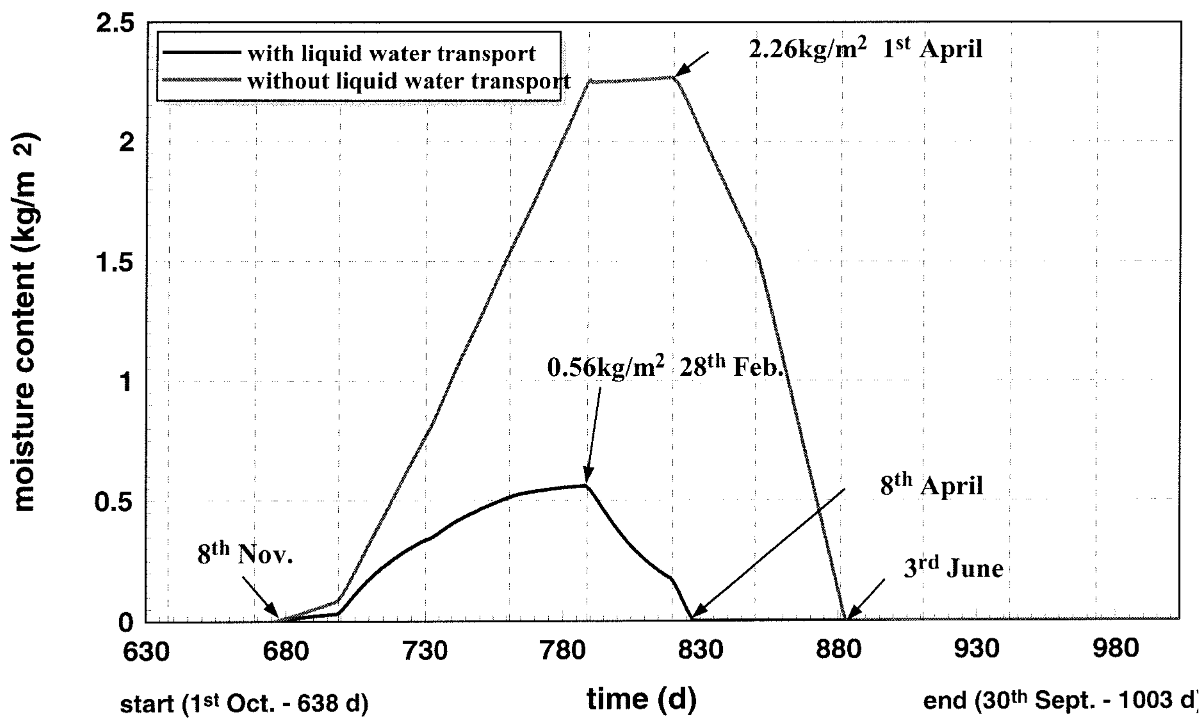

Fig. 8: Condensation and drying process with and without capillary forces (numerical simulation) – monthly climate given by EN ISO 13788