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Coupled heat air and moisture transfer in building structures

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Abstract—Based on the energy, mass and linear momentum conservation laws as well as the entropy law, a coupled, partial, non-linear, differential equation system for the heat, air and moisture transfer in porous materials follows, and for the more-dimensional solution of it, a suitable algorithm including the simulation software has been developed. Its efficiency is demonstrated by a recent building structure—chuted concrete between fibre board with polystyrol-foam outside insulation—under the boundary conditions of the TRY Essen: hourly values of outdoor climate. As a result of the high built-in moisture, moisture damages (mould growing) in the base level (exterior wall/concrete plate over the basement garage) and inadmissible high heat losses caused by the moisture depending thermal conductivity and the additional enthalpy flows coupled to the moisture movement and phase changing are observed in the first years. Copyright © 1996 Elsevier Science Ltd.

1. TRANSPORT PROCESSES IN POROUS MEDIA

The development of the general theory of transport phenomena in porous media and the application to the coupled heat, air and moisture transfer in building materials is a necessary assumption for a close to reality judgement of hygric and thermal behaviour of building components. The liquid moisture flow, the transport of inner energy (heat conduction and enthalpy flows) and especially the mass diffusion under the influence of temperature gradients and laminar-convective flow conditions are phenomena of interest, which can be described by means of continuum mechanics and irreversible thermodynamics [1–3].

The first step is the introduction of a continuum model which replaces the real phase system consisting of different phases and components by a set of fields of differentiable variables depending on time and the spatial coordinates. The concept of representative elementary volume (see ref. [1]) is used for this purpose. Then the flows of the extensive and transportable quantities of the phase system have to be formulated by products of densities and velocities. By introducing a certain reference velocity, each flow is divided into a convective and diffusive part. The choice of the reference velocity determines a reference coordinate system which is used to define transport coefficients within.

Based on the modeled flows, the balance equations for general extensive quantities can be established, and employing the fundamental equation of thermodynamics (Gibbs relation) the entropy production term is expressed by characteristic products of generalized thermodynamic flows and forces. Each product of flow and force is a contribution to the energy dissipation in a phase system in which irreversible processes occur.

The entropy term gives substantial information about which flows in a multi phase system appear and which the assigned forces are. The assigned force of the reduced heat flow (inner energy minus the enthalpy diffusion) is the temperature gradient, and this flow can be defined as total heat conduction. The gradient of the chemical potential can be formulated as assigned force of the mass diffusion of a component. Based on this knowledge, one can establish the so-called Onsager scheme, adopting that each flow depends linearly on each force. From that, a matrix of phenomenological coefficients connecting the flows and forces follows. The number of coefficients can be reduced by eliminating one depending flow and by the Onsager relations between the coefficients.

The gradient of the chemical potential of a component as a function of mass concentrations, phase pressure and temperature can be expressed by gradients of these variables. Considering the phenomenological coefficients, this leads to the definition of

NOMENCLATURE

m_α, m_ν	mass of an α-phase, ν-component
H_α, H_ν	enthalpy of an α-phase, ν-component
U	inner energy
ρ_α, ρ_ν	mass density of an α-phase, ν-component
c_ν	mass concentration of a ν-component
$v_k^{E_\alpha}$	velocity of an extensive quantity E of an α-phase
$j_k^{tE_\alpha}$	total flow of an extensive quantity E on an α-phase
$j_k^{c_aE_\alpha}$	convective flow of an extensive quantity E of an α-phase in the a-reference system
$j_k^{d_aE_\alpha}$	diffusive flow of an extensive quantity E of an α-phase in the a-reference system
σ^{tE_α}	total E-production rate of an α-phase
θ_α	volumetric fraction of an α-phase (fluid content)
T	temperature
p_α, p_ν	pressure of an α-phase, partial pressure of a ν-component
h_α, h_ν	specific enthalpy of an α-phase, ν-component
K_α	convective transport coefficient of an α-phase
$D_\nu^{c_a}$	normal diffusion coefficient of a v-component in the a-reference system
$D_\nu^{p_a}$	pressure diffusion coefficient of a ν-component in the a-reference system
λ	global thermal conductivity
R_ν	gas constant of a ν-component
x_k	position vector components
t	time
g_k	gravity acceleration
s_{ij}	storage coefficients
u	specific inner energy, transmission coefficient (u-value).

Subscripts

L	liquid
G	gaseous
V	vapour
A	air
M	moisture
k	index of spatial coordinates (= 1, 2, 3)
i, j	storage matrix indices.

the transport coefficients for mass diffusion (normal, pressure and thermal diffusion) and for heat conduction (global thermal conductivity).

Besides the diffusive flows, the convective flows of fluid phases also have to be formulated. Starting point of formulation is the local momentum balance equation written for a moving phase. Adopting Newton's law expressing the dependence between the mass velocity gradients and the viscous pressures, one gets the information about the driving forces—the hydrostatic pressure gradient and the gravity force—and the influence of material properties on the convective transport coefficient. The result may be applied to each fluid phase, such as the liquid and the gaseous one. The convective transport coefficient is strongly dependent on the solid configuration and the volumetric content of the phase in the porous medium. The result of application of the general theory to the coupled heat, air and moisture transfer in building materials is presented by balance equations and flow expressions in the following discussion.

2. MASS AND ENERGY BALANCE EQUATIONS

For the description of heat, air and moisture transport, the general mass balance equation is applied to the liquid phase and to both components of the gaseous phase: (dry) air and vapour. Eliminating the phase change rates, the liquid water balance and the vapour balance are added to the moisture balance. The sum of the liquid water mass and the vapour mass is called moisture mass. Furthermore the balance equation of inner energy is needed to describe the thermal behaviour. In this equation the production of inner energy by compression and friction is neglected, because this contribution is very small. The three balance equations, the moisture mass balance (1a), the air mass balance (1b) and the inner energy balance (1c) can be written in local formulation as:

$$\frac{\partial(\rho_L\theta_L+\rho_V\theta_G}{\partial t}=-\frac{\partial j_k^{tm_M}}{\partial x_k}+\sigma^{tm_M} \qquad (1a)$$

$$\frac{\partial(\rho_A\theta_G)}{\partial t}=-\frac{\partial j_k^{tm_A}}{\partial x_k}+\sigma^{tm_A} \qquad (1b)$$

$$\frac{\partial(\rho \mathrm{u})}{\partial t}=-\frac{\partial j_k^{tU}}{\partial x_k}+\sigma^{tU}. \qquad (1c)$$

The l.h.s. of equation (1a–c) describes the storage of moisture, air and inner energy, and the r.h.s. the divergences of the total flows of moisture $j_k^{tm_M}$, of air $j_k^{tm_A}$ and of inner energy j_k^{tU} and the production terms of these quantities. The production terms containing also chemical transmutations have to be formulated relating to the matter.

The following compilation of the flows is the result of the phenomenological description of mass and inner energy diffusion processes neglecting the overlaying phenomena (Dufour and Soret effect). The reference system for liquid flow and mass diffusion is the barycentric one (indicated by subscript *m*), in the other cases—heat conduction and enthalpy flows—a stationary coordinate system (indicated by subscript 0) is used. The convective flows are derived from the momentum balance equations of the liquid and gaseous phase.

Moisture flow equations:

$$j_k^{\mathrm{c_m m_L}} = \rho_\mathrm{L} v_k^{\mathrm{m_L}} = -\rho_\mathrm{L} K_\mathrm{L}\left(\frac{\partial p_\mathrm{L}}{\partial x_k} - \rho_\mathrm{L} \boldsymbol{g}_k\right)$$

convective liquid flow (2a)

$$j_k^{\mathrm{c_m m_V}} = \rho_\mathrm{V} v_k^{\mathrm{m_G}} = -\rho_\mathrm{V} K_\mathrm{G}\left(\frac{\partial p_\mathrm{G}}{\partial x_k} - \rho_\mathrm{G} \boldsymbol{g}_k\right)$$

convective vapour flow (2b)

$$j_k^{\mathrm{d_m m_v}} = -\rho_\mathrm{V} D_\mathrm{V}^{\mathrm{c_m}} \frac{\partial c_\mathrm{V}}{\partial x_k} - \frac{\rho_\mathrm{V}}{p_\mathrm{V}} D_\mathrm{V}^{\mathrm{p_m}} \frac{\partial p_\mathrm{G}}{\partial x_k}$$

diffusive vapour flow (2c)

$$j_k^{\mathrm{tm_M}} = j_k^{\mathrm{c_m m_L}}\,\theta_\mathrm{L} + (j_k^{\mathrm{c_m m_v}} + j_k^{\mathrm{d_m m_v}})\theta_\mathrm{G}$$

total moisture flow. (2d)

Air flow equations:

$$j_k^{\mathrm{c_m m_A}} = \rho_\mathrm{A} v_k^{\mathrm{m_G}} = -\rho_\mathrm{A} K_\mathrm{G}\left(\frac{\partial p_\mathrm{G}}{\partial x_k} - \rho_\mathrm{G} \boldsymbol{g}_k\right)$$

convective air flow (3a)

$$j_k^{\mathrm{d_m m_A}} = --j_k^{\mathrm{d_m m_v}} \quad \text{diffusive air flow} \qquad (3b)$$

$$j_k^{\mathrm{tm_A}} = (j_k^{\mathrm{c_m m_A}} - j_k^{\mathrm{d_m m_A}})\theta_\mathrm{G} \quad \text{total air flow.} \qquad (3c)$$

Inner energy flow equations:

$$j_k^{\mathrm{d_0 Q}} = -\lambda \frac{\partial T}{\partial x_k} \quad \text{global heat conduction} \qquad (4a)$$

$$j_k^{\mathrm{d_0 H_L}} = j_k^{\mathrm{c_m m_L}}\, h_\mathrm{L} \quad \text{liquid enthalpy flow} \qquad (4b)$$

$$j_k^{\mathrm{d_0 H_V}} = (J_k^{\mathrm{c_m m_V}} + j_k^{\mathrm{d_m m_V}}) h_\mathrm{V} \quad \text{vapour enthalpy flow} \qquad (4c)$$

$$j_k^{\mathrm{d_0 H_A}} = (j_k^{\mathrm{c_m m_A}} - j_k^{\mathrm{d_m m_A}}) h_\mathrm{A} \quad \text{air enthalpy flow} \qquad (4d)$$

$$j_k^{\mathrm{tU}} = j_k^{\mathrm{d_0 Q}} + j_k^{\mathrm{d_0 H_L}}\,\theta_\mathrm{L} + (j_k^{\mathrm{d_0 H_V}} + j_k^{\mathrm{d_0 H_A}})\theta_\mathrm{G}$$

total inner energy flow. (4e)

The gaseous phase is considered as binary system consisting of dry air and vapour. The partial pressures of air p_A and vapour p_V form the gas pressure p_G. The transport coefficients defined by the flow expression are the following:

K_L, laminar convection coefficient for the liquid phase;

K_G, laminar convection coefficient for the gaseous phase;

$D_\mathrm{V}^{\mathrm{c_m}}$, barycentric normal diffusion coefficient for vapour;

$D_\mathrm{V}^{\mathrm{p_m}}$, barycentric pressure diffusion coefficient for vapour;

λ, global thermal conductivity.

For calculations without moving air (where gas pressure gradients can be neglected) K_G and $D_\mathrm{V}^{\mathrm{p_m}}$ are not needed. In such cases, the normal diffusion coefficient will be used in a stationary reference coordinate system: $D_\mathrm{V}^{\mathrm{c_m}} \to D_\mathrm{V}^{\mathrm{c_0}}$. The transport coefficients are material properties and have to be determined experimentally (especially K_L, see ref. [4]). It is advantageous to express the transport coefficients by material parameters.

3. MOISTURE POTENTIAL FUNCTIONS

The flows formulated above are caused by thermodynamic forces which can be expressed by field gradients of state variables and the gravity force. These are the liquid pressure p_L, the gas pressure p_G, the vapour concentration c_V and the temperature T for the considered case of heat, air and moisture transfer.

The l.h.s. of equation (1a–c) may be expressed by the temporal change of moisture content θ_L, gas pressure p_G and temperature T. That means, in order to create a closed solvable equation system, two additional dependencies have to be found, which are the vapour mass concentration and the liquid pressure both depending on the variables of the (numerical) solution: moisture content, gas pressure and temperature.

$$c_\mathrm{V} = c_\mathrm{V}(\theta_\mathrm{L}, p_\mathrm{G}, T)$$

$$p_\mathrm{L} = p_\mathrm{L}(\theta_\mathrm{L}, p_\mathrm{G}, T)$$

Two material functions, the reverse sorption isotherm φ (θ_L, T) and the water potential/water content relationship $p_\mathrm{C}(\theta_\mathrm{L}, T)$, are needed to establish both dependencies.

The vapour mass concentration is defined as vapour mass divided by gaseous mass. It can be written also as ratio of partial densities.

$$c_\mathrm{V} = \frac{\rho_\mathrm{V}}{\rho_\mathrm{G}} = \frac{\rho_\mathrm{V}}{\rho_\mathrm{V} + \rho_\mathrm{A}} \qquad (5)$$

The densities may be expressed by the pressures with the ideal gas equations for vapour and air.

$$\rho_\mathrm{V} = \frac{p_\mathrm{V}}{R_\mathrm{V} T} \qquad (6a)$$

$$\rho_\mathrm{A} = \frac{p_\mathrm{A}}{R_\mathrm{A} T} = \frac{p_\mathrm{G} - p_\mathrm{V}}{R_\mathrm{A} T} \qquad (6b)$$

The vapour pressure in equation (6) is a function of the reverse sorption isotherm $\varphi(\theta_\mathrm{L}, T)$ and the temperature depending saturation vapour pressure $p_\mathrm{s}(T)$.

$$p_\mathrm{V}(\theta_\mathrm{L}, T) = \varphi(\theta_\mathrm{L}, T) p_\mathrm{S}(T) \qquad (7)$$

With equations (5)–(7), the vapour mass concentration can be expressed as function of the solution variables. The reverse sorption isotherm $\varphi(\theta_L, T)$ has to be determined experimentally. In order to establish a relation between the liquid pressure and the solution variables, the water potential/water content relationship (capillary tension) $p_C(\theta_L, T)$ is used. The capillary tension can be introduced as mean pressure difference between the liquid and the gaseous phase in a representative elementary volume.

$$p_L(\theta_L, p_G, T) = p_C(\theta_L, T) + p_G \tag{8}$$

Also the water potential/water content relationship $p_C(\theta_L, T)$ has to be determined experimentally (see ref. [4]).

Both material functions describe a relation between the water content and other variables of state: the relative humidity and the capillary tension. On the other hand, a thermodynamical equilibrium between the liquid phase and the gaseous one exists in such case when the temperatures, the pressures and the specific Gibbs functions of the two phases are equal. The thermodynamic equilibrium condition leads to the well known Kelvin equation describing the relation between the capillary tension and the relative humidity.

$$p_C = \rho_L R_V T \ln(\varphi) \tag{9}$$

That means, the reverse sorption isotherm and the water potential/water content relationship contain (theoretically) the same information. Both functions have to be convertible in each other. Figure 1 shows this fact.

In the presentation, Fig. 1, two moisture ranges can be distinguished. In the hygroscopic moisture range $0 \leqslant \theta_L \leqslant \theta_{Hyg}$ the sorption isotherm is measurable, and in the overhygroscopic moisture range $\theta_{Hyg} < \theta_L \leqslant \theta_{Sat}$ the water potential/water content relationship has to be determined. The θ_{Hyg} is called hygroscopic moisture content, and θ_{Sat} represents the saturation moisture content. The 'bubble point' p_B marks the maximal capillary tension which can be applied to the porous medium without moisture release. The measurement limits for non-steady-state methods given by the technical equipment are about $0 \leqslant \varphi \leqslant 95$–$98\%$ and $-850 \leqslant p_C \leqslant 0$ hPa. The range $-70\,000$ to $-27\,500 \leqslant p_C \leqslant -850$ hPa is measurable only with steady-state methods up to now, therefore, a parameterisation is advantageous. Both functions may be called moisture potential functions because they are, in counterpart to the water content, differentiable functions at the material boundaries. They are so more suitable for characterizing a 'moisture state'.

4. NUMERICAL SOLUTION

The storage of moisture, air and inner energy described by the l.h.s. of the balance equation system (1a–c) can be expressed by the temporal change of moisture content, gas pressure and temperature (see ref. [5]). That leads to the definition of a matrix of storage coefficients s_{ij} $(i,j = 1, 2, 3)$. Besides the dependence on the solution fields, the storage coefficients depend on the material properties sorption isotherm, saturation moisture content, specific heat capacity and density. With the storage matrix $S = s_{ij}$, a system of three coupled parabolic differential equations describing the non-steady state heat, air and moisture transfer in porous building materials follows.

$$S\frac{\partial Z}{\partial t} = -\frac{\partial J_k}{\partial x_k} + Q \tag{10}$$

$$\begin{array}{cccc} \text{storage matrix} & \text{solution vector} & \text{flow vector} & \text{source vector} \\ S = \begin{bmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{32} \end{bmatrix} & Z = \begin{bmatrix} \theta_L \\ p_G \\ T \end{bmatrix} & J_k = \begin{bmatrix} j_k^{\mathrm{tn}_M} \\ j_k^{\mathrm{tm}_A} \\ j_k^{\mathrm{tU}} \end{bmatrix} & Q = \begin{bmatrix} \sigma^{\mathrm{tm}_M} \\ \sigma^{\mathrm{tm}_A} \\ \sigma^{\mathrm{tU}} \end{bmatrix}. \end{array}$$

The numerical solution of equation (10) follows for general three dimensional geometrical domains being discretisizible by a selection of given element types. One gets the integral formulation of equation (10) by

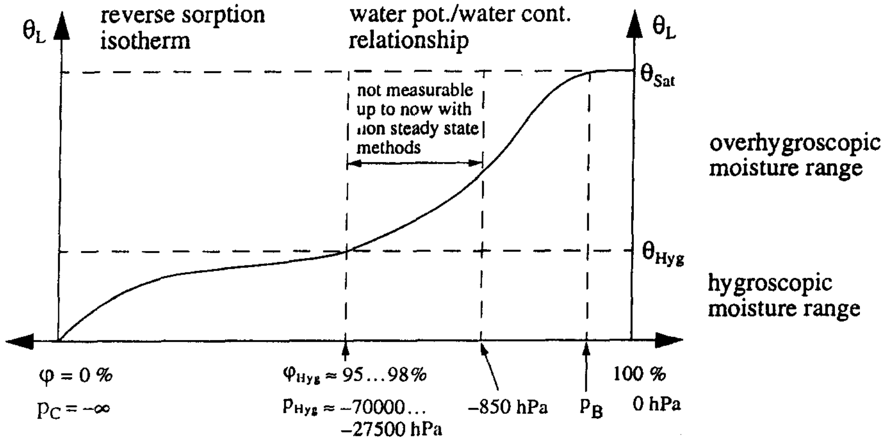
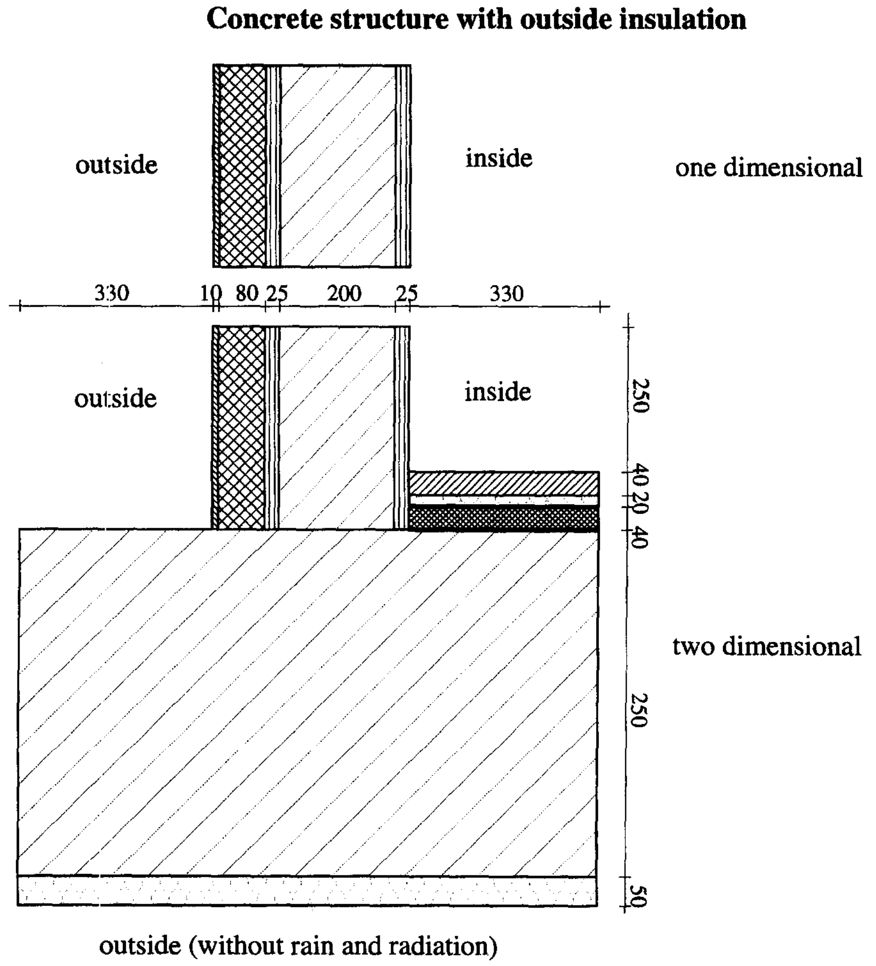


Fig. 1. Moisture potential functions.



	material parameters									
	material	Θ_{Hyg}	Θ_{Sat}	a_{wSat}	k	μ_0	λ_0	λ_1	ρ	c
		Vol%	Vol%	m^2/s	-	-	W/mK	W/mK	kg/m^3	Ws/Kkg
▥	fibre board	10.0	26.0	1.0E-10	0.7	120.0	0.35	1.80	1250	1100
░	heavy concrete	6.0	15.0	1.0E-09	0.7	150.0	2.10	-	2000	1000
▓	PUR-foam	0.1	80.0	1.0E-11	0.5	70.0	0.03	0.40	15	1320
▨	cement plaster	4.0	20.0	1.0E-10	0.5	45.0	1.30	-	2000	1000
⁘	mineral wool	0.5	80.0	4.0E-11	0.7	1.5	0.04	0.44	40	840
▩	PS-foam	0.1	80.0	5.0E-11	0.5	50.0	0.04	0.44	15	1380
▧	lime-cement plaster	3.0	25.0	1.0E-09	0.5	35.0	0.87	-	1800	1000

Fig. 2. Cross section of the construction : above—regular wall structure ; below—connection to the concrete plate over the basement garage.

the integration over an arbitrary volume V and the following transformation by the Gaussian theorem being also valid for tensors of higher orders.

$$\int_V S\frac{\partial Z}{\partial t}\mathrm{d}V = -\int_A J_k n_k \,\mathrm{d}A + \int_V Q\,\mathrm{d}V. \qquad (11)$$

The surface of the volume V is A to which n_k (normal vector) is perpendicular. Equation (11) may be interpreted as follows : the change of a extensive transportable quantity in a volume V is equal to the sum of all flows perpendicular to the surface of the volume and the inner production density of this quantity.

As it will be shown below, with validity of equation (11) for each volume element the discretisation of a geometrical domain leads to the definition of the global quantities : storage matrix **S**, solution vector **Z** and divergence vector **D** by superposing of the local quantities : storage matrix S, solution vector Z, flow vector J_k and source vector Q. This method is called semi discretisation, and it transforms the system of three parabolic differential equations to a system of

$3n$ ordinary differential equations describing the temporal course of water content, gas pressure and temperature in each element. The transformation yields

$$\begin{bmatrix} S_1\Delta V_1 & & & & \\ & S_2\Delta V_2 & & & \\ & & \ddots & & \\ & & & S_i\Delta V_i & & \\ & & & & \ddots & \\ & & & & & S_n\Delta V_n \end{bmatrix} \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} Z_1 \\ Z_2 \\ \vdots \\ Z_i \\ \vdots \\ Z_n \end{bmatrix}$$

$$= \begin{bmatrix} \sum_{j=1}^{a_1} \bar{J}_{1j}\Delta A_{1j} + Q_1\Delta V_1 \\ \sum_{j=1}^{a_2} \bar{J}_{2j}\Delta A_{2j} + Q_2\Delta V_2 \\ \vdots \\ \sum_{j=1}^{a_j} \bar{J}_{ij}\Delta A_{ji} + Q_i\Delta V_i \\ \vdots \\ \sum_{j=1}^{a_n} \bar{J}_{nj}\Delta A_{nj} + Q_n\Delta V_n \end{bmatrix}$$

and in shorter form, respectively:

$$\mathbf{S}\frac{\mathrm{d}\mathbf{Z}}{\mathrm{d}t} = \mathbf{D}. \qquad (12)$$

Each component of the divergence vector **D** on the r.h.s. of equation (12) contains the weighted sum of perpendicular flow J_{ij}. The weights are the surface areas ΔA_{ij}. By temporal integration of equation (12), one gets the non-steady state fields of water content, gas pressure and temperature.

$$\mathbf{Z}(t) = \int_0^t \mathbf{S}^{-1}\mathbf{D}\,\mathrm{d}t \qquad (13)$$

There are solver packages for integration of ordinary differential equation systems controlling the error tolerances and the time step length automatically. Different multi step methods are used for this purpose (BDF-method, ADAMS-methods).

The FEM- and FDM-based solution of heat, air and moisture transfer problems is marked by a high amount of input and output work. The required work can be reduced by using the so-called pre- and postprocessors.

Furthermore it is an effective way to handle input data collecting all the material and climatical data in project-independent data bases. The information about the contents of the data bases must be accessible for the preprocessor, because, besides the task of discretisation, the preprocessor is used to assign the material properties and the boundary, climatical and initial conditions to the geometrical structure. The information is stored as resource files written and updated by the data base managing program, which is also used for inputting and converting of new (measured) material and climatical data.

The preprocessor places all the information about a project in the interface files to the numerical package. The numerical package tests the input information for validity and gives error messages (e.g. if climatical conditions are missing which are needed according the assigned boundary conditions).

Then the numerical calculation starts, and the results are given graphically and numerically. The postprocessing tools are highly developed at the time being, and the results can be shown and integrated in documents in many different ways.

5. HYGROTHERMAL BEHAVIOUR OF A CONCRETE WALL WITH PS-FOAM OUTSIDE INSULATION

Recently, suburban settlements have been built with a wall structure manufactured by chuted concrete between fibre boards as lost boardings and a tight PS-outside insulation. During the first years, the measured heating energy consumption is very high, and in the ground floor directly over the basement garage, moisture damages are observed.

By means of the developed numerical simulation methods, the hygrothermal behaviour (without moving air) of this structure is quantified and explained. Figure 2 shows the cross-section of the constructions above: the undisturbed wall for a one-dimensional calculation; below: the connection to the concrete ceiling over the basement garage for a two-dimensional calculation. The material properties are given by the following functions [6]

$$K_\mathrm{L} = a_\mathrm{wSat}((k+1)\cdot(\Theta_\mathrm{L}/\Theta_\mathrm{Sat})^{1/k}$$
$$-k\cdot(\Theta_\mathrm{L}/\Theta_\mathrm{Sat})^{2/k})\cdot\frac{\partial\Theta_\mathrm{L}}{\partial p_\mathrm{c}}$$

$$p_\mathrm{c} = 7.0\ \mathrm{MPa}\cdot\left(1-\frac{\Theta_\mathrm{L}/\Theta_\mathrm{Hyg}-1}{\Theta_\mathrm{Sat}/\Theta_\mathrm{Hyg}-1}\right)$$

$$D_\mathrm{V}^{\mathrm{c}_0} = \frac{p_\mathrm{G}}{p_\mathrm{G}-p_\mathrm{v}}\cdot\frac{2.4\cdot10^{-5}\ \mathrm{m\,s^{-1}}}{\mu_0}$$

$$\cdot\frac{1-\Theta_\mathrm{L}/\Theta_\mathrm{Sat}}{0.8(1-\Theta_\mathrm{L}/\Theta_\mathrm{Sat})^2+0.2} \quad \varphi = 1-(1-\Theta_\mathrm{L}/\Theta_\mathrm{Hyg})^2$$

$$\lambda = \lambda_0 + \lambda_1\Theta_\mathrm{L}.$$

The structure is loaded with the outdoor climate TRY Essen, that means the hourly values of the outdoor temperature and relative humidity, of the direct and diffuse shortwave radiation balance, of the longwave radiation balance and finally of the driving rain are used as boundary conditions. Especially the last mentioned climate component is quite difficult to quantify. It is a function of the wind speed, the wind direction, the precipitation amount and the air flow around the building [7, 8].

Figures 3 and 4 show the one-dimensional moisture

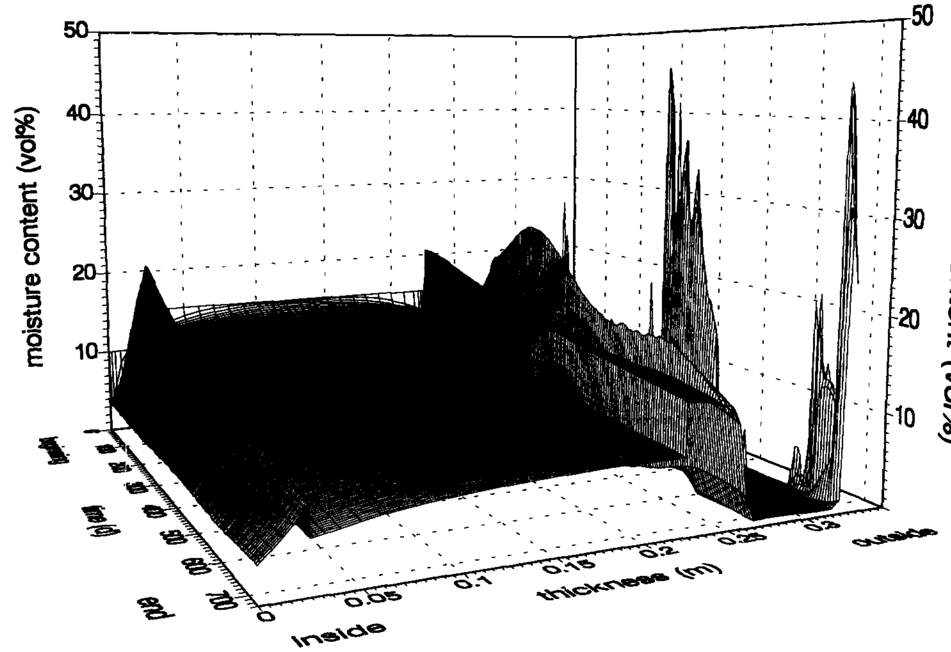


Fig. 3. Moisture field on the westside in the 1st and 2nd year, TRY Essen, one-dimensional.

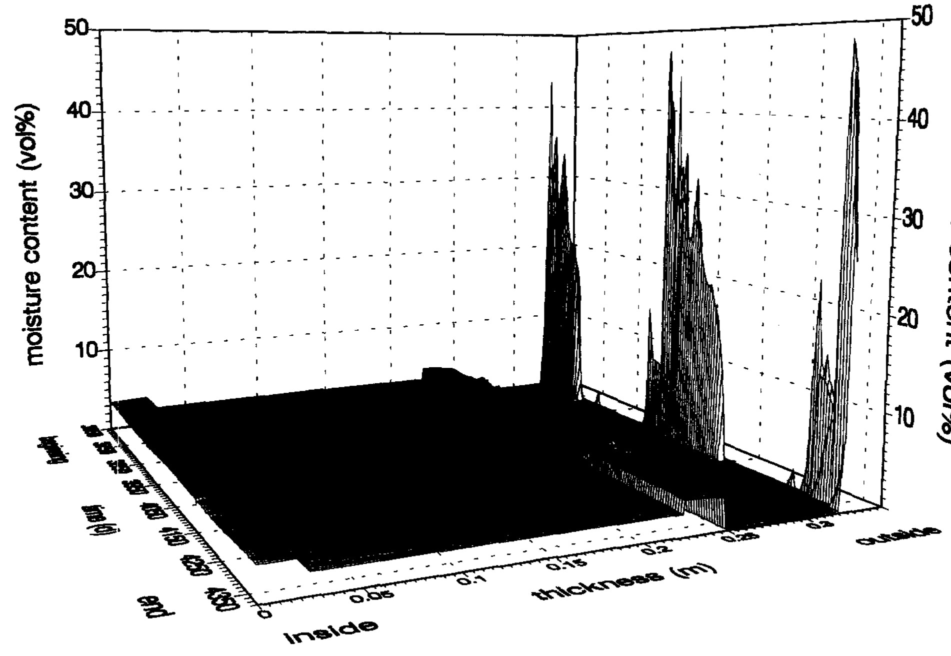


Fig. 4. Moisture field on the westside in the 11th and 12th year, TRY Essen, one-dimensional.

distribution in the regular wall structure (westside) during the first two years and during the 11th and 12th year viewed from the inside of building. The built-in moisture of the concrete layer has dried out very slowly (compare also the decreasing of the whole moisture content in Fig. 5). A part of this moisture penetrates as liquid water into both fibre boards, a part goes as water vapour through the outside fibre board and the PS-foam layer and condenses on the cold side of this insulation layer. This process is supported by driving rain due to the moistening of the outside plaster (have a look at the moisture peaks on the right in Figs. 3 and 4). The insulation layer contains more than 3 kg m^{-2} moisture content during the first three years (see Fig. 6).

From that follows, in connection with additional enthalpy flows coupled to the moisture movement and phase changing, the heat transmission coefficient u is about 20% higher (0.52 W m^{-2} K^{-1} instead of 0.43 W m^{-2} K^{-1}) than in equilibrium after about 6 years

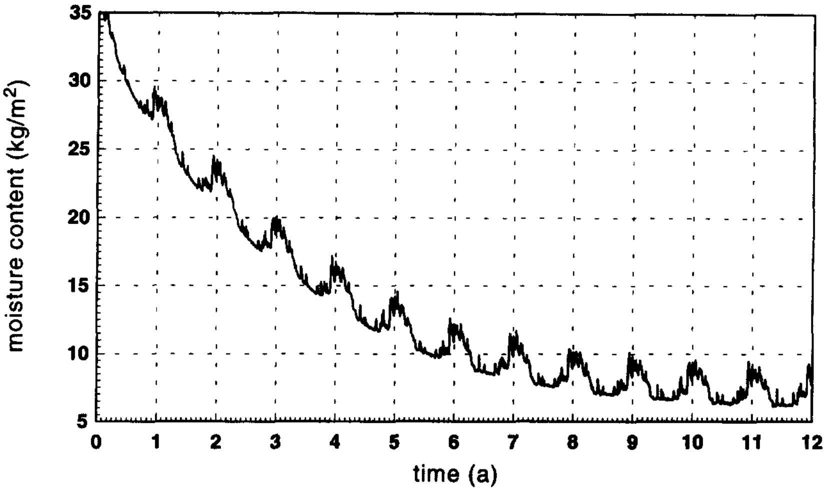


Fig. 5. Whole moisture content of the structure over 12 years, TRY Essen, one-dimensional.

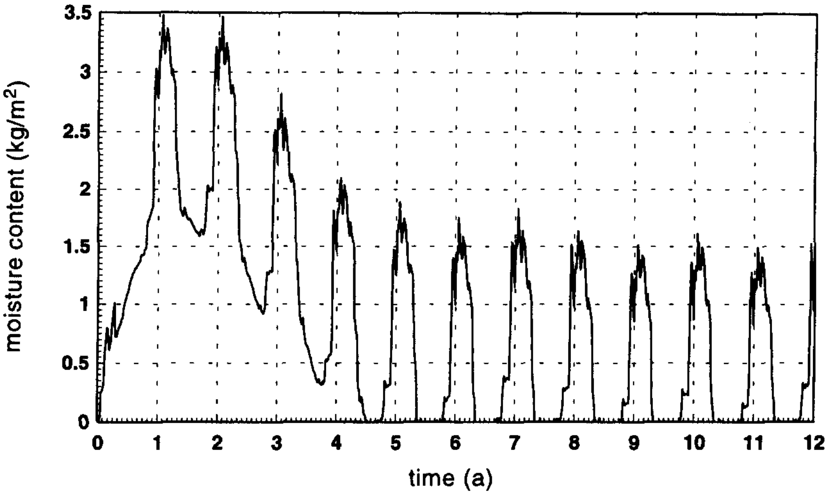


Fig. 6. Overhygroscopic moisture content of PS-foam layer, TRY Essen, one-dimensional.

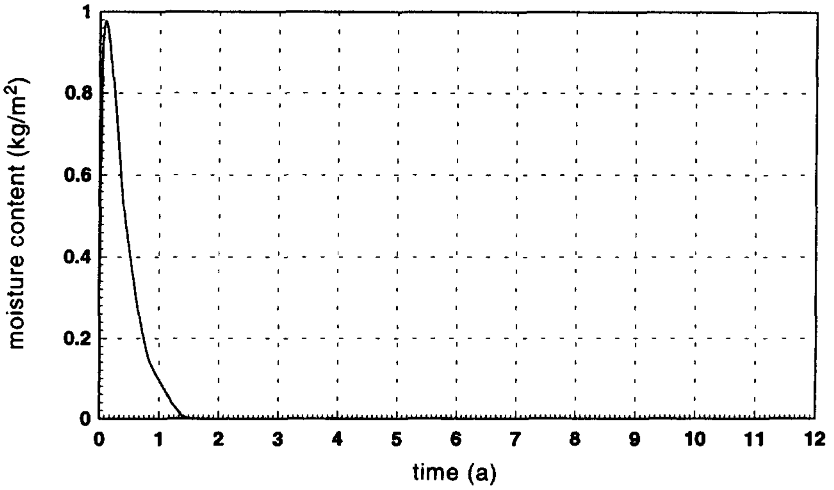


Fig. 7. Overhygroscopic moisture content of inner fibre-board layer, TRY Essen, one-dimensional.

(see Fig. 11). The outside fibre board layer is also very wet for a long time, the inner fibre board layer reaches the overhygroscopic moisture maximum (about 1 kg m^{-2}) after 4 month and will be dried out after 18 month (see Fig. 7).

Figures 8 and 9 show the hygrothermal situation in

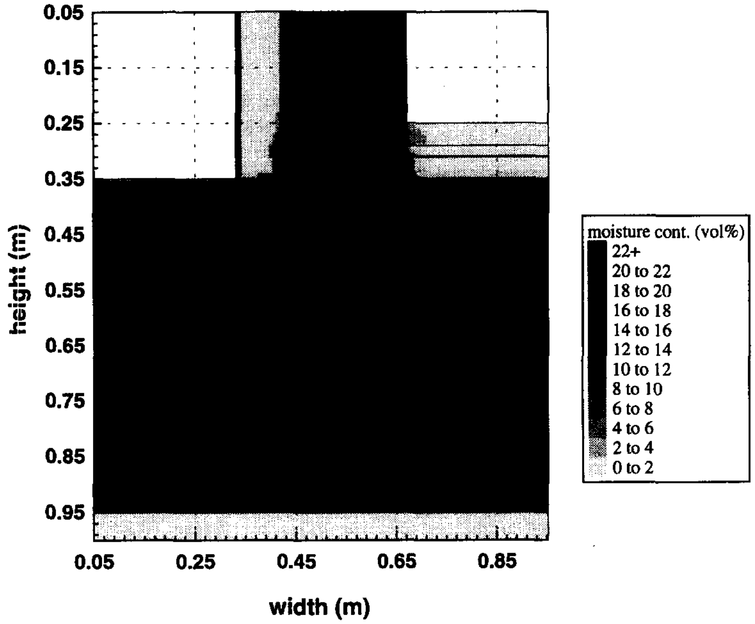


Fig. 8. Moisture field on January 1st in the 2nd year, TRY Essen westside, two-dimensional.

the two-dimensional area of the bottom of the construction, e.g. on the January 1st in the 2nd year. Caused by the built-in moisture of the concrete plate over the basement garage, the drying out process is still slower than in the undisturbed wall. In the base level, the moisture content even increases because the concrete ceiling has the effect of a thermal bridge (compare isotherms in Fig. 9), and condensation takes place.

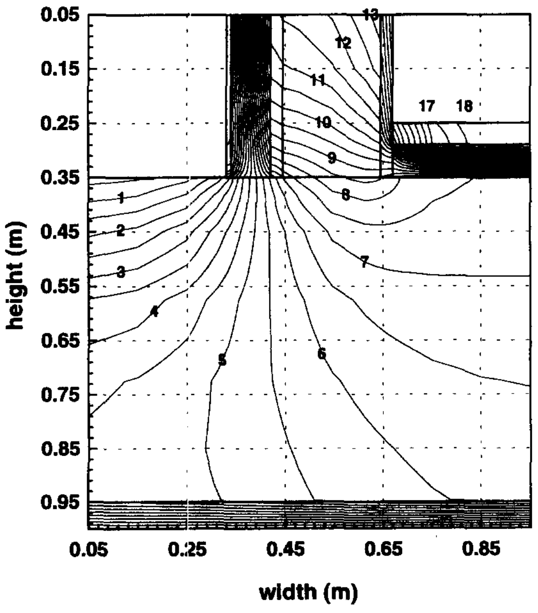


Fig. 9. Temperature field on January 1st in the 2nd year, TRY Essen westside, two-dimensional.

In Fig. 10 the whole moisture content in the lowest part of the inner fibre board layer from Fig. 2 is demonstrated. After three years this part of the wall is still moist leading to the well known mould growing as a typical moisture damage.

An experimental verification of this numerical simulation results is given in ref. [9] or by the solution of the HAMTIE-common exercises [10].

6. SUMMARY AND CONCLUSIONS

The coupled heat-, air- and moisture transfer processes in the porous materials and building components are modeled on the thermodynamic foundations, are prepared for a computer calculation and are available for the practice. In the present time the most important task is the defining and the measuring of all transport coefficients depending on the structure and the driving potentials, and, if necessary, depending on the hygrothermal processes. The further development of known measurement methods, the combination with numerical simulation tools and their application to a larger number of building materials is to be done in future in order to get statistical information about the property distributions within material classes. Moreover the European normalisation offers an additional chance to prepare the results for rules of heat and moisture of building constructions.

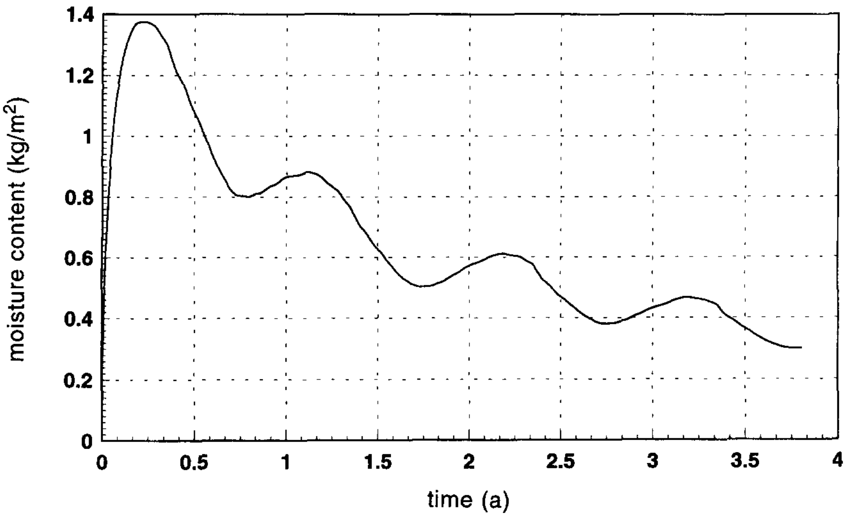


Fig. 10. Overhygroscopic moisture content of the inner fibre board layer, TRY Essen westwall, two-dimensional.

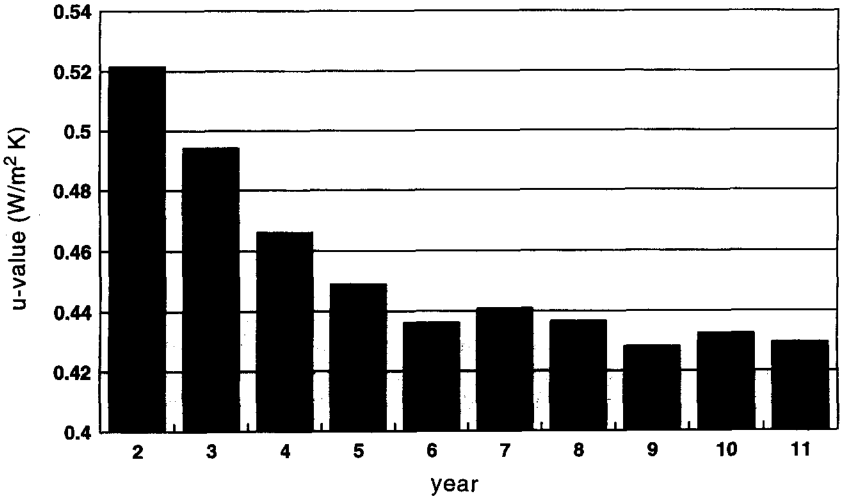


Fig. 11. U-values in the heating period over 12 years, TRY Essen, one-dimensional.

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