V International Conference on Computational Methods for Coupled Problems in Science and Engineering
COUPLED PROBLEMS 2013
S. Idelsohn, M. Papadrakakis and B. Schrefler (Eds)

# ON NUMERICAL MODELING OF COUPLE HEAT, AIR AND MOISTURE TRANSFER THROUGH MULTILAYERED WALLS

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**Key words:** Coupled transfer, heat, air, moisture, multi-layer wall, porous media, simulation.

**Abstract.** This paper reports on numerical modeling of heat, air, and moisture transfer through multilayered walls. Building materials are often subjected to temporal climatic variations, which can induce a transfer of heat and moisture through the walls of the building and the foundation soil. These materials are generally considered as porous media. The coupled heat, air and moisture transfer in building materials is of paramount importance in the construction area. In this way, a mathematical model has been elaborated and validated using a benchmark example. Here, we aim to determine the energy losses. The capillary pressure is considered as potential moisture which represents both the transport of vapor and liquid phases of the water. Basing on basic functions of partial differential equations, one can convert certain measurable properties of porous media as coefficients depending on the temperature and the capillary pressure. The results obtained compare favorably with other available in the literature.

## 1 INTRODUCTION

Heat, air and moisture transfer through porous media is explored in many engineering areas such as pollutants infiltration, granular materials drying, heat exchangers and thermal insulation among others. Building envelopes are constantly subjected to random climatic loads on the outer surface and relatively stable conditions on its inner face. These loads generate a transport of heat, air and moisture through the structure. The flow's direction of these entities depends on the gradient of the potential director of each entity. It should be noted that all porous media, in which the combined heat, air and moisture transport occurs simultaneously and strongly coupled, does have to be taken into account. In addition to these temporal variations of external load due, thermal characteristics and those related to storage moisture's layers of the wall should be added. This combination makes the transport of heat and moisture transient and relatively complex in the building envelope. Despite this complexity, we can numerically simulate the dynamic processes drying-moistening of the envelope component. In this context, hygrothermal models have been used to evaluate the performance of a wall exposed to the weather in different geographical sites [1, 2, 3].

To carry out this study, a model has been developed to describe the transfer of heat, air and moisture in building envelopes. The model developed here belongs to the class of models that have recently emerged to handle the coupled transfer mentioned above. These are implemented using commercial softwares to solve problems inherent to buildings physics [4, 5].

It is advisable to note that these models are more flexible for future extensions (e.g. for 2D and/or 3D simulations), because allowing the addition of new features, as well as an easy integration with other existing models. One advantage of having a transient heat, air and moisture (HAM) model as a whole building hygrothermal model is that it enables to capture the potential moisture release from the building enclosure to the indoor space. In fact, moisture sources from construction and from wet soil through foundation walls and floor slab could dominate all internal moisture sources. Similarly, the importance of quantification of the moisture release from foundation slabs when calculating indoor humidity levels was recently emphasized.

The use of a transient HAM model when conducting whole building performance analysis yields also to a better estimation of energy demand for heating or cooling of a building. This is possible due to the fact that a transient HAM model takes into account the effect of moisture in the heat transfer through building enclosures. Usually energy simulation models ignore the moisture effect when conducting the thermal analysis [6], and use constant thermal storage and transport (thermal conductivity and heat capacity, respectively) property values despite the fact that these properties can be strongly dependent on moisture content.

The aim of this work is towards the numerical simulation of heat, air and moisture transfer in building systems. The numerical model of combined heat and moisture transfer based on basic functions of partial differential equations is tested in this work leaning on a benchmark case.

The remaining of this paper is organized as follows: in the next section, description of the physical problem and the mathematical model herein used are supplied. Section 3 is devoted to boundary conditions. Subsequently, in section 4, we present the model validation and we discuss the obtained results. Finally, section 5 outlines conclusions drawn from the present simulations.

## 2 MATHEMATICAL MODELING

The mathematical model for heat and moisture transfer, to be implemented for building materials, is described in this section.

It is worth noting that, in the coupled transfer, the moisture transport in building materials appears under two different phases: liquid and vapor. The phase vapor is divided into diffusion and convection parts. Indeed, the diffusive flow of vapor is engendered by vapor pressure gradient and the corresponding conductivity represents the permeability of the vapor. As for, the convective vapor flow (the vapor flow), it is advected by the moving air [3].

The modeling of the transfer in vapor phase by the gradient of capillary pressure as conductive potential, and the permeability of the liquid as the conductivity of moisture transfer became the most appropriate approach and the most used one in this kind of modeling [7]. For the liquid flow, moisture content gradient has been used as the driving potential in some hygrothermal tools, and moisture diffusivity was used as the moisture transfer conductivity.

According to the principle of the preservation of the combined transport of heat and humidity of a representative elementary volume (REV), which is defined as being large enough when compared to pore dimensions but small enough compared to the size of the sample, governing equations of the coupled transfer in building materials can be formulated. Below, the balance equations for moisture and heat transport are described.

### 2.1 Moisture transport

The moisture content being the mainspring of transfer, its distribution can be expressed by the following equation:

$$\frac{\partial w}{\partial t} = \nabla\left(\delta_P \nabla p_V - K_l \nabla P_C\right) - v \cdot \nabla \rho_V + F_m \tag{1}$$

where $w$ (kg/m3) is the moisture content, $t$ (s) is the time, $\delta_P$ (kg/m.s.Pa) is the water vapor permeability, $p_V$ (Pa) is the partial water vapor pressure, $K_l$ (s) is the liquid water permeability, $P_C$ (Pa) is the capillary pressure, $v$ (m/s) is the air velocity, $\rho_V$ (kg/m$^3$) is the water vapor density and $F_m$ is the moisture source term.

### 2.2 Heat transport

Here, we conjecture that the main mechanisms which govern the transfer of heat are the thermal conduction and the convection due to air movement and latent heat. This is due to the presence of low temperature gradients

The the energy conservation equation can be written as

$$\left(c_P \rho + c_{P,l} w\right)\frac{\partial T}{\partial t} = \nabla\left(\lambda \nabla T\right) + L_V \nabla\left(\delta_P \nabla p_V\right) - v L_V \cdot \nabla \rho_V - v \rho_a c_{P,a} . \nabla T + F_h \tag{2}$$

where $c_P$ (J/kg.K) is the dry specific heat of material, $\rho$ (kg/m3) is the dry density of the material, $c_{P,l}$ (J/kg.K) is the specific heat of liquid water, $T$ (K) is the temperature, $\lambda$ (W/m.K) is the thermal conductivity, $L_V$ (J/kg) is the enthalpy of evaporation, $\rho_a$ (kg/m$^3$) is the dry air density, $c_{P,a}$ (J/kg.K) is the specific heat of dry air and $F_h$ (W/m$^3$) is the heat source term.

### 2.3 Conservation equations and modeling

In this approach, we transformed variables depending on moisture (see Eqs. 1-2) into a single variable called capillary pressure, denoted *Pc*.

The relation between the partial water vaporpressure and the relative humidity can be expressed as:

$$p_V = \phi P_{sat} \tag{3}$$

where $\phi$ is relative humidity, et $P_{sat}$ (Pa) is the saturated water vaporpressure.

The relation between relative humidity and capillary pressure is given by Kelvin's law:

$$\phi = exp\left(\frac{-P_C}{\rho_l R_V T}\right) \tag{4}$$

where $\rho_l$ (kg/m$^3$) is the water density and $R_V$ (J/kg.K) is the gas constant for water vapour.

It ensues from this that the conservation equations of the combined heat and moisture transfer can be rewritten in term of coefficients, and by considering temperature as independent variable for heat transfer and capillary pressure as independent variable for moisture transfer, as shown in Eq. (5) and (6).

$$C_T \frac{\partial T}{\partial t} = \nabla\left(C_{11}\nabla T + C_{12}\nabla P_C\right) + v\left(D_{11}\nabla T + D_{12}\nabla P_C\right) + F_h \tag{5}$$

$$\delta \frac{\partial P_C}{\partial t} = \nabla\left(C_{21}\nabla T + C_{22}\nabla P_C\right) + v\left(D_{21}\nabla T + D_{22}\nabla P_C\right) + F_m \tag{6}$$

with $C_T = c_P \rho + c_{P,l} w$; $\Omega = \partial w / \partial P_C$, and $\Omega$ is the moisture storage capacity, defined as the slope of water retention curve.

It is worth noting that Eqs. (5) and (6) can be written in the following matrix form:

$$d_a \begin{bmatrix} \frac{\partial T}{\partial t} \\ \frac{\partial P_C}{\partial t} \end{bmatrix} = \nabla\left(C\, \nabla \begin{bmatrix} T \\ P_C \end{bmatrix}\right) + \beta \cdot \nabla \begin{bmatrix} T \\ P_C \end{bmatrix} + \begin{bmatrix} F_h \\ F_m \end{bmatrix} \tag{7}$$

where damping ($d_a$), diffusion ($C$) and convection ($\beta$) matrices are respectively defined by:

$$d_a = \begin{bmatrix} C_T & 0 \\ 0 & \Omega \end{bmatrix} \tag{8}$$

$$C=\begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}=\begin{bmatrix} \lambda + L_V\delta_P\phi P'_{sat} & -\dfrac{L_V\delta_P\phi P_{sat}}{\rho_l R_V T} \\ -\delta_P\phi P'_{sat} & K_l+\dfrac{\delta_P\phi P_{sat}}{\rho_l R_V T} \end{bmatrix} \tag{9}$$

where $P'_{sat}=\partial P_{sat}/\partial T$ is the derivative of saturation vapor pressure.

$$\beta=\begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix}=\begin{bmatrix} -\left(\rho_a c_{P,a}+L_V\dfrac{\partial\rho_V}{\partial T}\right) & -\dfrac{L_V\phi}{\rho_l R_V T}\dfrac{\partial\rho_V}{\partial\phi} \\ \dfrac{\partial\rho_V}{\partial T} & -\left(\dfrac{\phi}{\rho_l R_V T}\dfrac{\partial\rho_V}{\partial\phi}\right) \end{bmatrix} \tag{10}$$

where $F_h$ and $F_m$ represent respectively, heat and moisture source.

To go further, the current model consists of converting, via MatLab, the measurable physical properties of the material such as $K_l$, $\phi$, $\delta_P$ and $\lambda$ which depend on moisture content $w$ into partial differential equations (PDE) $C_{11}, C_{12}, D_{11}, D_{12}, \Omega$ and $C_T$ which are dependent on $P_C$ and $T$ [8]. This is schematically depicted in Fig. 1.

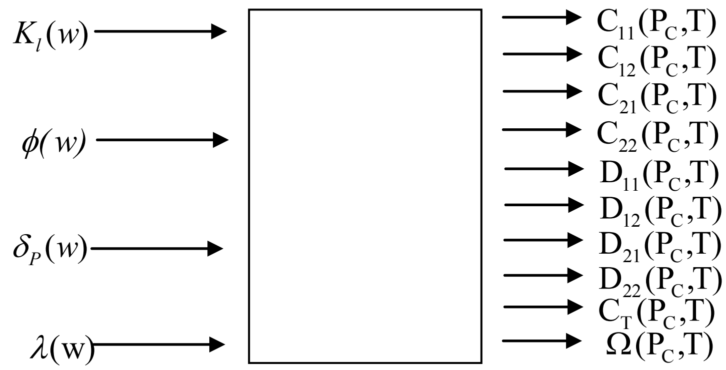


**Figure 1:** Conversion of measurable material properties

## 3 BOUNDARY CONDITIONS (BCS)

External boundary conditions of building envelopes can be grouped in three categories [9]: moisture saturation, constant heat and moisture flow, and heat/moisture flow through surface resistance film fixed on external surface. Eqs. (11) and (12 ) describe the exterior boundary conditions. For the internal surface of the wall, the temperature and pressure are maintained constant.

### 3.1 Moisture BCs

The moisture flux through the outside surface of the envelope, $g_{n,e}$ (kg/m².s), is based on the following relationship:

$$g_{n,e} = \beta_{P,e}\left(p_{v,e} - p_{surf,e}\right) \tag{11}$$

where $\beta_{P,e}$ (kg/m².s.Pa) is the vapor transfer coefficient of the exterior surface, $p_{v,e}$ (Pa) is the water vapor pressure of the outdoor air, and $p_{surf,e}$ (Pa) is the water vapor pressure on the exterior surface.

For the external side of the wall, the moisture flux is obtained according to the following relationship:

$$g_{n,i} = \beta_{P,i}\left(p_{v,i} - p_{surf,i}\right) \tag{12}$$

where $\beta_{P,i}$ (kg/m².s.Pa) is the vapor transfer coefficient of the interior surface, $p_{v,i}$ (Pa) is the water vapor pressure of the indoor air and $p_{surf,i}$ (Pa) is the water vapor pressure of the interior surface.

### 3.2 Heat BC

Recall that the heat flux through external surface, $q_{n,e}$ (W/m²), includes conductive, convective and latent heat effects only. It can be expressed as:

$$q_{n,e} = \alpha_e\left(T^{eq} - T_{surf,e}\right) + L_V\beta_{p,e}\left(p_{v,e} - p_{surf,e}\right) \tag{13}$$

where $\alpha_e$ (W/m².K) is the heat transfer coefficient of the exterior surface, $T^{eq}$ (K) is the equivalent exterior temperature and $T_{surf,e}$ (K) is the temperature of the exterior surface.

Heat transfer through internal surface of the building envelope, $q_{n,i}$ (W/m²), is given by:

$$q_{n,i} = \alpha_i\left(T_i - T_{surf,i}\right) + L_V\beta_{p,i}\left(p_{v,i} - p_{surf,i}\right) \tag{14}$$

where $\alpha_i$ (W/m².K) is the heat transfer coefficient of the interior surface, $T_i$ (K) is the temperature of the indoor air, and $T_{surf,i}$ (K) is the temperature of the interior surface.

## 4 VALIDATION OF THE HEAT AND MOISTURE MODEL

As was stated above, the working of the aforementioned model equations has been cheeked considering a benchmark case. The latter arises from a series of five benchmark cases from a work outcome of the UE-initiated project for standardization of heat, air and moisture calculation methods (HAMSTAD WP2) [10,11].

The benchmark considered here deals with interstitial condensation occurring at the contact surface between two materials. The construction, from lowest x-coordinate (external side) to the highest, is built up as follows; vapor tight seal, 100 mm load bearing material and 50 mm thermal insulation as shown in fig. 2. The materials have different thermal and moisture properties: the load bearing material is capillary active, while the insulation is hygroscopic but capillary non-active (infinite resistance to liquid flow), and thermal conductivities differ by a factor 50 (at dry conditions). The structure is perfectly airtight.

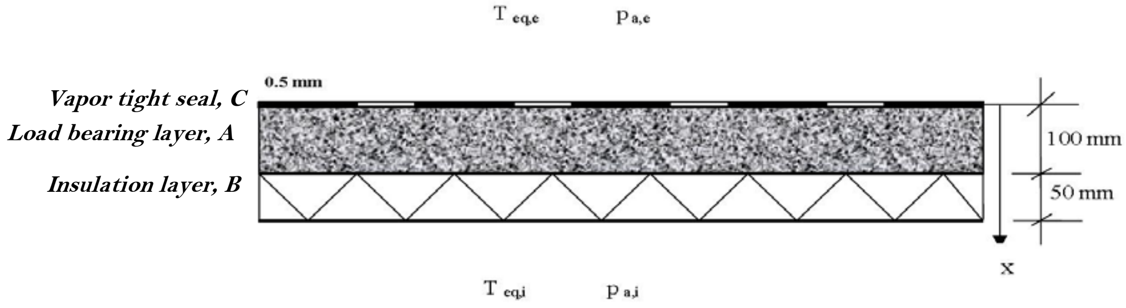


**Figure 2:** Construction details for the analyzed benchmark case

### 4.1 Initial conditions

The following initial conditions were adopted:

- For load bearing material: $w = 145\,kg/m^3,\ T = 10\ C$
- For insulation: $w = 0.065\ kg/m^3,\ T = 10\ C$

### 4.2 Boundary conditions

The boundary conditions corresponding to the considered problem are as follows:

- For heat and moisture, a data file supplies the hourly values for a period lasting over one year. For intermediate values of time, they are obtained by interpolation.
- The outside equivalent temperatures encompass both the temperatures of the ambient air and that of the radiation.
- No difference in pressure is considered.

The surface transfer coefficients are given by:

$\alpha_{e,e} = 25W/m^2.K,\ \alpha_{e,i} = 7W/m^2.K,\ \beta_{p,e} = 0\,s/m,\ \beta_{p,i} = 2.10^{-8}\,s/m$

Note that these conditions allow a very good case for checking the heat and moisture transfer model.

The numerical simulation was carried out using the multi-physics software COMSOL V3.5 [12], and the required results are the following ones:

- Capillary pressure Pc in space and time for load bearing element A, and insulation B (see Fig. 2).
- Temperature T(x,t).
- Total moisture weight M (kg/m²) in each layer.
- Heat flux q (W/m²) crossing the structure from interior to the wall.

The model simulates, for over a period of one year, the distributions of the capillary pressure Pc and the temperature T

The model simulates for over a period of one year, the distributions of the capillary pressure Pc and the temperature T. In Fig. 3, the temperature distribution in load bearing element and insulation is depicted.

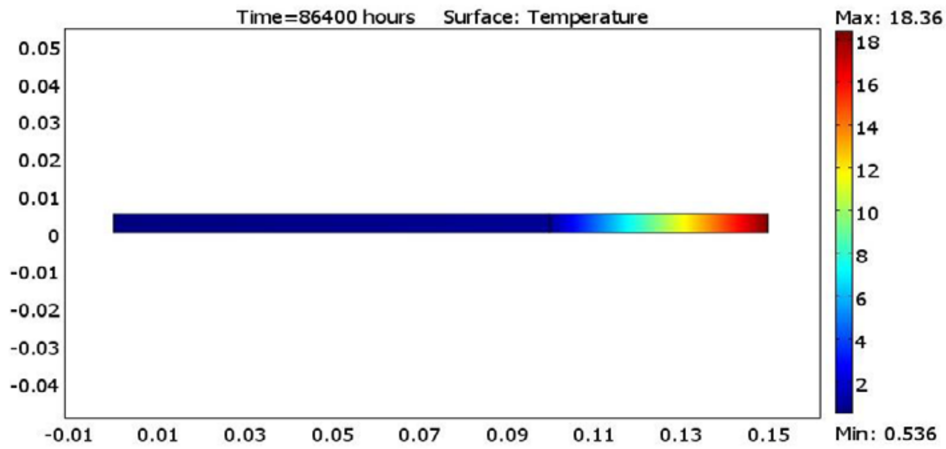


**Figure 3:** Temperature distribution in the wall (end of cycle)

## 4.3 Results and discussion

- **Moisture transport**

Using properties of the material, the total moisture content can be easily computed from the distribution of capillary pressure Pc. In Fig. 4, the total moisture content in load bearing during the first year is presented.

It can be seen from this figure that the predicted profile generally corroborates over the considered period with a maximum relative difference of 1.65%. This allows us to state that the current model is able to reproduce available results in literature.

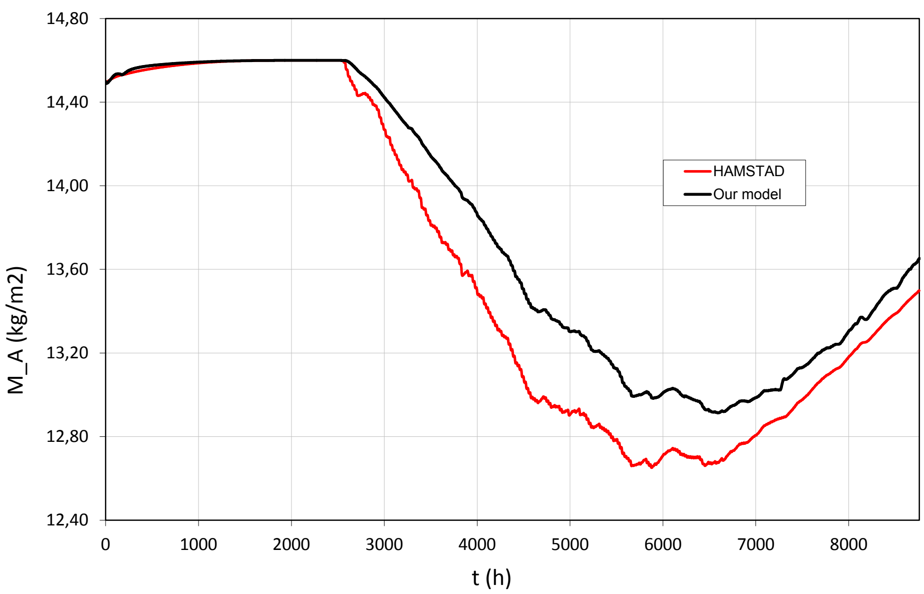


**Figure 4:** Total moisture content in load bearing during the first year

- **Heat transport**

Figure 5 displays the heat flow crossing the structure from the inside during the first 500 hours obtained with the current model in comparison with HAMSTAD test. From this figure, we observe that our prediction is very close to that of the test case. Moreover, some peaks appear suggesting a possible numerical instability. This is going to be elucidated soon.

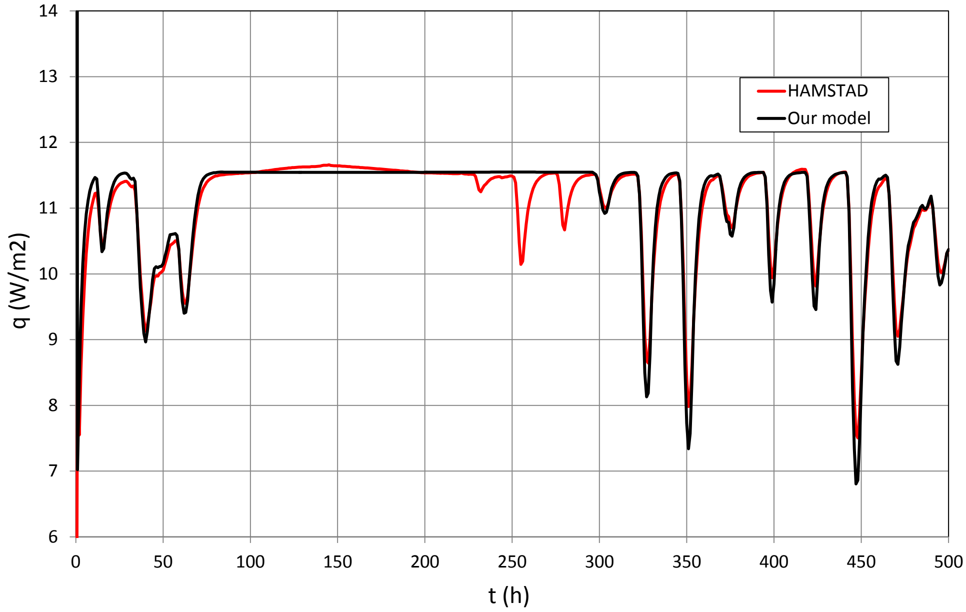


**Figure 5:** Heat flux from interior to the wall

## 5 CONCLUSION

A mathematical model considering the coupled heat, air and moisture transport through porous media has been elaborated and validated using a benchmark case. It has been designed to handle the coupling between processes of transfer of heat and moisture in the building envelopes. A hygrothermal simulation of a porous medium has been carried out to see the performance of the heat and moisture model. The commercial code COMSOL was used to solve the governing equations of HAM transport, which provides the flexibility for building science researchers to operate and modify the presented model. The numerical results show good agreement with available data.

Finally, the proposed model can be readily extended to predict the hygrothermal behavior of building envelopes, and the relevant work will be reported in the future.

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