Numerical investigation of influence of the temperature and relative humidity of air on the drying process of porous building

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Abstract. The impact of the relative humidity and temperature of air on drying rates of the porous building material was investigated by the non-equilibrium heat and moisture transfer model implemented in the ANSYS Fluent software. Simulations of 24 hours drying process of a brick initially saturated in 97% by water were conducted for two drying air temperature, i.e., 23.8°C and 40°C and relative humidity in the range from 10% to 50%. The relative moisture content at the end of simulations and times needed to reach the relative moisture content bellow 0.3 were determined. Not only the temperature but also the relative humidity of drying air had impact on the drying rate during the first drying period when water evaporated from the sample surface. The temperature of drying medium was more important than the relative humidity during the second drying period when water evaporated inside the brick. The drying process was faster in the higher temperature than in the lower one, even for the high relative humidity.

1. Introduction

Masonry walls and building foundations are under threat of presence of excessive moisture. Natural disasters like floods and storms, the high level of ground water and the lack or worn out of the waterproof insulations are typical reasons of accumulation of excessive moisture in the building structure. Consequences of increased damp in walls are very serious, i.e., it deteriorates the physical and chemical conditions of the wall [1, 2] and increases heat gains and losses to the surroundings which results in the generation of higher cooling and heating costs [3, 4]. Moreover, excessive moisture in the wall encourages growth of mildew and microorganisms, which are dangerous for occupants [5]. Hence, renovation of damp walls, i.e., drying and preventing against water re-penetration, is very important.

There are several methods of moist solids drying, e.g., convective [6, 7], microwave [8, 9] and vacuum [10]. For damp walls the thermo-injection method [11-13] which relies on the convective drying is very effective. The method was developed in Poland in the nineties of the previous century. It is based on drilling an array of boreholes in the damp wall. In the first step, these boreholes are used for heating and drying of the wall by special heating probes. Then in the second step, boreholes are used again for injection of a special fluid mixture which creates waterproof membrane. The membrane is an effective and durable way of preventing against water re-penetration through the wall. The dryness and temperature of the wall during injection of the hydrophobic fluid have an impact on the effectiveness of the membrane creation, i.e., the lower moisture content and the higher temperature of the wall, the better
membrane quality. However, temperature during the membrane formation should be lower than approx. 60°C because the cross-linking of the hydrophobic mixture occurs for temperature above 60°C.

The drying process of masonry walls is characterized by long duration and high energy consumption. Hence, the renovation and protection of walls against water re-penetration is very expensive. Preconditioning of air used as drying medium allows to speed up the process but increases energy consumption due to air heating or dehumidification. On the other hand, long operation of drying devices generates the spending and decreases the income. All these aspects should be considered and balanced to get optimal economic conditions for the drying of building structure. The numerical modeling and optimization of drying process may help to achieve this objective.

Combined heat and moisture transfer in porous medium is common not only in building materials but also in insulations [14, 15], protecting clothing [16-19], wood drying [20] and food processing [21]. In the field of simulation of transport phenomena in building materials two main groups of models are distinguished, i.e., building energy simulation (BES) models as well as heat and air and moisture (HAM) transfer models. The commercial software like TRNSYS, ESP-r and EnergyPlus are based on BES models in which heat and moisture transfer is treated in a simplified way. On the other hand, the WUFI and Delphin software utilize simplified HAM models. To achieve better results HAM models are combined with computational fluid dynamics (CFD) models. For example, equilibrium CFD-HAM models with two equations, i.e., energy and moisture balance equations, were proposed in [21-24]. These models predict the total moisture content and then by applying additional relations allow for computation of vapor and water fractions in the porous material.

In this paper the novel non-equilibrium heat and moisture transfer model is presented and was applied to find the impact of air parameters, i.e., the temperature and relative humidity on drying rates of porous building material. The new model was configured to simulate one-dimensional (1D) transport process in the brick. The analysis carried out showed utility of the model for investigation and optimization of the drying process of building materials and structures.

2. Non-equilibrium mathematical model of transport phenomena in the porous building material

Moisture which resided in the porous building material was assumed to consist of two phases, i.e., water vapor and free liquid water (in funicular and pendular state). Bound water at the surface of the solid component was neglected. The sum of volume fractions of all phases satisfied the following condition:

$$\varepsilon_s + \varepsilon_l + \varepsilon_g = 1$$  \hspace{1cm} (1)

where: subscripts $g$, $l$ and $s$ denote moist air, water and solid component, respectively and $\varepsilon$ is the volume fraction. The volume fraction of solid ($\varepsilon_s$) was constant during analysis, while the sum of volume fraction of water and moist air was equal to the volume fraction of pores ($\varepsilon_p = \varepsilon_l + \varepsilon_g$).

For considered problem three balance equations were formulated, i.e., water vapor, liquid water and energy balance equations instead of four balance equations as in [25, 26]. The pressure in pores was assumed constant and equal to $p = 101325$ Pa, which allowed for simplification of mathematical description and elimination of the dry air balance equation.

2.1. Balance of moisture

The amount of moisture in pores changed due to the diffusion and capillary pressure gradient. Moreover, the amount of vapor and water varied due to mass transfer between phases, i.e., evaporation and condensation. Hence, balance of vapor and liquid water were given by the following equations:

$$\frac{\partial}{\partial t}(\varepsilon_g \rho_g) = \nabla \cdot (D_{v+g} \nabla \rho_g) + \dot{m}_g$$ \hspace{1cm} (2)

$$\frac{\partial}{\partial t}(\varepsilon_l \rho_l) = -\nabla \cdot (K_l \nabla p_l) - \dot{m}_l$$ \hspace{1cm} (3)
where: subscript \( v \) denotes vapor, \( D_{v,ef} \) is the vapor effective diffusivity in pores, \( K_l \) – liquid water permeability, \( m_{lv} \) – intensity (mass flow rate per unit volume) of evaporation/condensation, \( p_c \) – capillary pressure and \( \rho \) – density. Application of two separated balance equations for gaseous and liquid moisture allowed for formulation of the model with non-equilibrium between moisture phases. Moreover, evaporation and condensation were assumed to have finite rate and their intensities were described by following equations:

\[
\begin{align*}
\dot{m}_{lv} &= \frac{h_{a,s} e_p}{e_p} (\rho_{v,sat} - \rho_v) \quad \text{for evaporation} \\
\dot{m}_{lv} &= \frac{h_{a,s} \rho_v}{e_p} (\rho_{v,sat} - \rho_v) \quad \text{for condensation}
\end{align*}
\]

where: \( a_s \) denotes the pores area per unit volume of the porous medium, \( h_{vl} \) – mass transfer coefficient between vapor and water in the porous medium and \( \rho_{v,sat} \) – vapor density for the saturation conditions. The \( \varepsilon_{lp} \) ratio denotes the part of the pores area (volume) occupied by liquid moisture. The mass flow rate per unit volume had positive value for evaporation and negative one for condensation.

2.2. Balance of energy

In the model the thermal equilibrium between different components and phases in the porous medium was assumed, i.e., all constituents had the same temperature. Moreover, heat transfer due to moisture movement (i.e., the diffusion and capillary transport) was neglected. The energy balance equation in the porous building material was following:

\[
\frac{\partial}{\partial t} \left( \rho c_T \right) = \nabla \cdot \left( k_{ef} \nabla T \right) - \dot{m}_{lv} \Delta h_{lv}
\]

where: \( k_{ef} \) is the effective thermal conductivity, \( T \) – temperature and \( \Delta h_{lv} \) – latent heat of evaporation. The effective heat capacity was described by the formula:

\[
(\rho c)_T = c_a \rho_v e_a + c_l \rho_v e_l + c_p \rho_p e_p + c_p \rho_p e_p
\]

where: subscript \( a \) stands for dry air and \( c \) and \( c_p \) denote the specific heat and specific heat at constant pressure, respectively.

### Table 1. Thermophysical properties assumed in simulations [27].

| Property                      | Symbol | Value    |
|-------------------------------|--------|----------|
| Universal gas constant        | \( B \) (J/mol/K) | 8.314    |
| Dry air specific heat         | \( c_a \) (J/kg/K) | 1005.0   |
| Water specific heat           | \( c_l \) (J/kg/K) | 4192.1   |
| Brick specific heat           | \( c_s \) (J/kg/K) | 840.0    |
| Vapor specific heat           | \( c_v \) (J/kg/K) | 1875.2   |
| Water vapor resistance diffusion factor | \( C_{dry} \) | 24.79    |
| Average pore diameter         | \( d_{av} \) (m) | 1.610^{-5} |
| Mass transfer coefficient     | \( h_{lf} \) (m/s) | 10^{-4}  |
| Dry air molecular mass        | \( M_a \) (kg/kmol) | 28.86    |
| Vapor molecular mass          | \( M_v \) (kg/kmol) | 18.0     |
| Capillary moisture content    | \( W_{cap} \) (kg/m³) | 130.0    |
| Brick porosity                | \( \varepsilon_p \) | 0.13     |
| Latent heat of evaporation    | \( \Delta h_{lv} \) (J/kg) | 2.610^{6} |
| Water density                 | \( \rho_l \) (kg/m³) | 1000.0   |
| Brick density                 | \( \rho_s \) (kg/m³) | 2087.0   |

3. Numerical simulations

Preparation of the numerical model consisted of the following steps: creation of the computational geometry, generation of the mesh and implementation of transport equations in the commercial software.
ANSYS Fluent which based on the Finite Volume Method. Advanced customisation interfaces, i.e., the User Define Function (UDF), User Define Scalar (UDS) and User Define Memory (UDM) were used during development of the numerical model. The computational model was constrained to two-dimensional (2D) space.

The developed 2D numerical model was configured to simulate 1D heat and moisture transport in the brick of 3 cm thickness by applying symmetry boundary conditions at lateral walls. The mesh had 90 elements along the thickness of the brick and was refined to the top wall. The time step size was equal to 0.5 s. This allowed to carry out simulations in reliable time.

3.1. Material properties and closing relationships

Computations were conducted for the ceramic brick whose thermophysical properties used in simulations are given in table 1. Dry and moist air as well as vapor parameters were calculated using the ideal gas relationship. Closing relationships for the system of governing equations, eq. (2), (3) and (5), were following [27]:

- Pores area per unit volume:

\[
a_v = \frac{6}{d_v (1-\epsilon_v)}
\]

- Vapor diffusivity in pores:

\[
D_{v,ef} = \frac{2.61 \times 10^{-3} M_v \left[ 1 - \left( \frac{W}{W_{cap}} \right) \right]}{C_{d_v BT} \left[ 0.503 \left( 1 - \frac{W}{W_{cap}} \right)^2 + 0.497 \right]}
\]

- Effective thermal conductivity of the moist brick:

\[
k_{ef} = k_s + 0.0047 W
\]

- Water permeability in the brick:

\[
K_i = \frac{1.1437 \times 10^{-9}}{\left[ 1 + (1.76 \times 10^{-5} \rho_s)^{4.6} \right]^{\frac{1}{3}}}
\]

- Vapor saturation pressure:

\[
p_{v, sat} = 614.3 \exp \left( 17.06 \frac{T - 273.15}{T - 40.25} \right)
\]

- Modified saturation pressure:

\[
p_{v, sat}^* = p_{v, sat} \exp \left( -\frac{p_s}{\rho_s BT} \right)
\]

- Volumetric moisture content:

\[
W = \epsilon_s \rho_s + \epsilon_v \rho_v
\]

- Retention curve which is applied to find the capillary pressure:

\[
W(p_s) = W_{cap} \left\{ 0.846 \left[ 1 + (1.394 \times 10^{-5} p_s)^{0.4} \right]^{0.75} + 0.154 \left[ 1 + (0.9011 \times 10^{-5} p_s)^{1.69} \right]^{-0.406} \right\}
\]
Water vapor density for saturation conditions:

\[ \rho_{v,\text{sat}} = \frac{p_{v,\text{sat}} M_v}{BT} \]  

where: \( B \) is the universal gas constant, \( C_{\text{dry}} \) – water vapor resistance diffusion factor, \( d_{av} \) – average pore diameter, \( M_v \) – molecular mass of vapor and \( W_{\text{cap}} \) – capillary moisture content.

### 3.2. Boundary and initial conditions

For simulated 1D case only the top wall was in the contact with flowing (drying) air. The bottom wall was adiabatic and impermeable for moisture. Side walls were symmetry planes. On the top wall the following convective boundary condition with liquid moisture evaporation accounted for was applied:

\[ q = h_T (T_{\text{amb}} - T_s) + \Delta h_{j_{v,\text{w}}} \]  

where: subscript \( w \) denotes the wall, \( h_T \) is the convective heat transfer coefficient (\( h_T = 22.5 \text{ W/m}^2\text{K} \)), \( T_{\text{amb}} \) – temperature of drying air and \( j \) – liquid moisture flux which evaporated/condensed at the surface.

For the first period of drying (evaporation from the surface) when liquid moisture in the pendular state is present at the boundary (the liquid saturation \( s \) is higher than the minimal saturation for water in the pendular form \( s > s_{\text{min}} = 0.25 \)), mass fluxes of vapor and liquid moisture were following:

\[ j_{v,\text{w}} = (-K_i \nabla \rho_{v})_{\text{w}} = h_m \left( Y_v - \frac{\rho_{v,\text{w}}}{\rho_{g,\text{w}}} \right) \quad \text{and} \quad j_{v,\text{w}} = (D_{v,\text{ef}} \nabla \rho_{v})_{\text{w}} = 0 \]  

where: \( h_m \) is the mass transfer coefficient (\( h_m = 0.0258 \text{ kg/m}^2\text{s} \)) and \( Y_v \) – vapor mass fraction in flowing air. When liquid saturation dropped below minimum saturation (i.e., \( s < s_{\text{min}} = 0.25 \)) boundary conditions were following:

\[ j_{v,\text{w}} = (-K_i \nabla \rho_{v})_{\text{w}} = 0 \quad \text{and} \quad j_{v,\text{w}} = (D_{v,\text{ef}} \nabla \rho_{v})_{\text{w}} = h_m \left( Y_v - \frac{\rho_{v,\text{w}}}{\rho_{g,\text{w}}} \right) \]  

Initial conditions were following: the uniform brick temperature of \( T_{\text{init}} = 23.8^\circ\text{C} \) and water saturation of \( s_{\text{init}} = 97\% \) which corresponded to the volumetric moisture content of \( W_{\text{init}} = 126.1 \text{ kg/m}^3 \).

### Table 2. Boundary conditions assumed in simulations.

| Case no. | Temperature (°C) | Relative humidity (%) | Humidity ratio (g H₂O/kg dry air) |
|----------|------------------|-----------------------|-----------------------------------|
| 1        | 23.8             | 10                    | 1.848                             |
| 2        | 23.8             | 20                    | 3.706                             |
| 3        | 23.8             | 30                    | 5.576                             |
| 4        | 23.8             | 40                    | 7.457                             |
| 5        | 23.8             | 50                    | 9.349                             |
| 6        | 40               | 10                    | 4.649                             |
| 7        | 40               | 20                    | 9.367                             |
| 8        | 40               | 30                    | 14.158                            |
| 9        | 40               | 40                    | 19.021                            |
| 10       | 40               | 50                    | 23.960                            |

All together 10 cases were analysed with various drying air temperature (i.e., 23.8 and 40°C) and relative humidity (i.e., from 10 to 50%). Duration of the drying process was 24 h. First four cases corresponded to the low drying medium temperature equal to the initial temperature of the brick. In the next five cases the higher temperature than the initial one was assumed which speeded up the drying process. The assumed air parameters for each case were presented in table 2.
Table 3. Relative moisture content after 24 h and drying time to the relative moisture content of 0.3.

| Case no. | Relative moisture content after 24 h | Drying time to the relative moisture content of 0.3 (h) |
|----------|-------------------------------------|-------------------------------------------------------|
| 1        | 0.237                               | 13.35                                                 |
| 2        | 0.245                               | 14.04                                                 |
| 3        | 0.269                               | 14.94                                                 |
| 4        | 0.277                               | 16.17                                                 |
| 5        | 0.284                               | 17.92                                                 |
| 6        | 0.166                               | 10.89                                                 |
| 7        | 0.180                               | 11.75                                                 |
| 8        | 0.197                               | 12.81                                                 |
| 9        | 0.218                               | 14.17                                                 |
| 10       | 0.241                               | 15.95                                                 |

Figure 1. Temporal variations of the relative moisture content (the ratio of current to initial moisture content) for different temperatures and relative humidities of drying air: A) 23.8°C and B) 40°C.

4. Results and discussion
Two parameters were monitored during simulations: the relative moisture content (the ratio of current to initial moisture content) after 24 h of drying process and the time instant for which the relative moisture content dropped below 0.3, which corresponded to 2% of the mass fraction of moisture in the brick – see table 3. It was found that the temperature of drying medium had significant impact on the drying rate. This influence was more important than the impact of humidity ratio (relative humidity).
For example, cases no. 5 and 7 had almost the same humidity ratio (see table 2) but large difference in the drying rates between these cases was found. For case no. 7 the relative moisture content of 3% was achieved 6 h earlier than for case no. 5. On figure 1 temporal variations of the relative moisture content are presented against variable temperature and relative humidity of drying air. It is noticed that in the first drying period almost 50% of water was removed from the sample. Moreover, drying rates for the first drying period, when water evaporated from the surface and specimen temperature decreased, were larger for the higher temperature of drying air due to more intensive evaporation from the sample surface. It is also interesting that for case no. 9 and 10 initial temperature of the sample was lower than the wet bulb temperature for drying air. Hence, at the beginning of the drying process vapor from air was condensed at the surface of the brick—see short plateau on figure 1 B for the relative humidity of 40 and 50%. When the brick surface temperature raised above the wet bulb temperature the relative moisture content in the specimen started decreasing. During the second drying period, when the temperature of the specimen started rising and the drying process was controlled by the diffusion of vapor in the specimen, differences between drying rates for analysed cases were not so large but the higher drying rates were found for the higher temperature of drying air. The relative humidity had minor influence on drying rates in this period.

5. Conclusions
In this paper the new non-equilibrium HAM model for porous building materials was presented. The model was then applied for analysis of drying process of the brick. Influence of the temperature and relative humidity of drying air was investigated. Both the temperature and relative humidity of drying air were found to have impact on drying rates. However, the temperature more significantly influenced on the drying rates than the relative humidity especially in the first drying period. Drying rates in this period were controlled by the water evaporation from the surface of the sample. The intensity of evaporation was larger in higher temperatures. The relative humidity of drying air also affected this intensity as it influenced on the wet bulb temperature. During the second drying period, when the drying process was controlled by the diffusion of vapor in the brick, slight influence of the drying air temperature and very weak influence of the relative humidity on drying rates were found. Concluding, to obtain high drying rates, warm and dry air should be used in the first drying period, while warm with the normal relative humidity in the second one. The ambient air, not preheated, may be also used for the drying but the drying rate will be lower than for warm air.

In the presented work calculations were conducted applying the simplified model and geometry. Therefore, the results obtained should be used for the initial optimization of the drying process. In the future the model will be applied for the more complex 2D and 3D cases with the air flow accounted for.

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