Conjugate modelling of convective drying phenomena in porous building materials

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Abstract. Moisture storage and the associated heat and moisture transport in buildings have a large impact on the building envelope durability, the energy consumption in buildings and the indoor climate. Nowadays HAM (Heat, Air and Moisture transport) models are widely used to simulate and predict the effect of these transport phenomena in detail. Recently these HAM models are being coupled to CFD (Computational Fluid Dynamics) to study the moisture exchange between air and porous materials on a local scale (microclimates). The objective of this research is to develop such a model to study drying phenomena. In this paper the emphasis lies on the modelling of convective drying of porous building materials. An important aspect for the correct modelling of convective drying is the way the air boundary is implemented. A short literature review reveals that different modelling approaches can be used. This paper gives a short overview of the state of the art in conjugate heat and mass transport modelling for convective drying. In this review shortcomings of currently applied modelling approaches are highlighted. Finally the newly developed model is used to simulate the convective drying of a sample of ceramic brick. These simulations were then compared with measurements from literature. A good agreement was found.

1. Introduction: modelling convective drying
For the convective drying studied in this paper, the dried medium is a porous material (hygroscopic and/or porous active) and the drying medium is (moist) air. There is a wide range of literature available that studies the interaction of a wet porous material and the surrounding air. This section will only give a brief overview of models found in literature and does not have the ambition to be in any way complete. More complete overviews of drying models can be found in [1] and [2].

In the large collection of available models two groups can be distinguished: analytical models and numerical models. Analytical models are often confined to 1D models and are often limited to simple cases. For example the diffusivity is considered constant [3] or the drying is considered isothermal [4]. The applied boundary conditions are fixed temperature and humidity at the boundary (Dirichlet (first-type) boundary conditions), fixed fluxes at the boundaries (Neumann (second-type) boundary conditions) or fixed transfer coefficients (Robin (third-type) boundary conditions) [4-6]. Only

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boundary conditions of the third type can be used to model convective drying. If more complex
boundary conditions are present, like spatially and/or temporally varying boundary conditions, 1D
models no longer suffice and most often numerical models have to be used.

Numerical convective drying models can be subdivided into two main categories, depending on
how the interaction with the drying medium (often air) is modelled. The first category of models uses
transfer coefficients to model the convective heat and mass transfer. A second category of models uses
a conjugated approach. Momentum, heat and mass transport in the air is solved simultaneously with
the heat and mass transport in the porous material.

When numerical models are used there is still a vast group of models that apply constant transfer
coefficients at the boundary [e.g. 7-10]. These coefficients are often taken from experimental
correlations.

Some authors state that the use of a constant transfer coefficient is incorrect when a developing
boundary layer is present [11,12]. In this case it is necessary to use spatially varying transfer
coefficients. The boundary layer for heat and mass will be thinner at the leading edge of a wet surface
that is dried. This will result in higher transfer coefficient at this leading edge. As a result the moisture
and temperature distribution in the material will be two or even three dimensional.

The most advanced convective drying models today solve the heat, mass and momentum equation
simultaneously [13-15]. The conditions of the drying medium flowing over the porous material
determine the drying rate of the porous material while the surface conditions of the porous material
determine the heat and moisture distribution in the drying medium (air). It can however be stated that
the impact of this modelling approach is limited when forced convection is present. The time scale of
the convection problem solved in the air is much smaller than that of the drying process. However for
natural convection the impact of simultaneous modelling of air and material could be more important.
In this case the convection in the air is strongly determined by the material boundary conditions.
Setting a fixed boundary condition at the material (fixed transfer coefficient) would thus not
 correspond with reality.

It is clear from this discussion that there is still some uncertainty on how boundary conditions
should be implemented in drying models. Therefore a more thorough study of the impact of boundary
conditions on a drying model outcome is needed. In the present paper only forced convection is
considered. The drying model discussed in the next section assumes steady air conditions which allow
to take the transfer coefficients invariable in time. A finite volume drying model is developed and
validated with experiments found in literature.

2. Heat, air and moisture model
This section will only give a brief description of the heat, air and moisture model used in this paper. A
more detailed description can be found in [16] together with the material properties needed for the
simulations.

Moisture transport in a hygroscopic capillary porous material can be attributed to two transport
mechanisms: vapour transport described by Fick’s law (1) and liquid transport described by Darcy’s
law (2).

\[ \bar{g}_v = \frac{D_{va}}{\mu R T} \nabla p_v \]  

\[ \bar{g}_l = -K_l \nabla p_c \]  

\[ \mu (-) \] is the water vapour resistance factor which is the ratio of the water vapour diffusion
coefficient in still air to the diffusion coefficient in the porous material. \( K_l \) (s) is the liquid permeability
and \( p_c \) (Pa) is the capillary pressure, \( g_v \) the vapour flux (kg/m²s) and \( g_l \) the liquid water flux (kg/m²s).
The change of the total moisture content in time of a control volume of porous material is in other
words due to moisture flux leaving the control volume and moisture flux going into the volume. This can be expressed in differential form by (3).

\[
\frac{\partial w}{\partial p_c} \frac{\partial p_c}{\partial t} = \nabla \left( K_c \nabla p_c + \frac{D_{sw}}{\mu} \rho_c \frac{\partial p_c}{\partial T} \nabla p_c + \left( p_{sat} \frac{\partial RH}{\partial T} + RH \frac{\partial p_{sat}}{\partial T} \right) \nabla T \right)
\]

(3)

The vapour pressure \( p_v \) in (1) was transformed to the capillary pressure \( p_c \) using Kelvin’s law (4).

\[ p_v = \rho_c R \ln RH \]

(4)

The relative humidity RH is defined by (5) and the saturation vapour pressure \( p_{sat} \) is assumed only dependant on the temperature (6).

\[ RH = \frac{p_v}{p_{sat}} \]

(5)

\[ p_{sat} = 611 \exp \left( \frac{17.08(T - 273.15)}{T - 38.97} \right) \]

(6)

\( \partial w/\partial p_c \), represents the moisture capacity and can be determined from the moisture retention curve \( w(p_c) \) which gives the moisture content as a function of the capillary pressure.

Similar to the mass transport in a porous material also heat transport is only due to diffusion. Transport due to convection is neglected. Eq. (7) represents the heat conservation equation in a porous material. Heat is transported through the porous material due to heat conduction, sensible heat transported together with the liquid moisture and sensible and latent heat transported together with the vapour.

\[
\frac{\partial E}{\partial t} = \left( \rho_{mat} C_{mat} + w_l C_v + w_v C_l \right) \frac{\partial T}{\partial t} + C_T \frac{\partial w_l}{\partial t} + (C_T + L) \frac{\partial w_v}{\partial t} = \nabla \left[ \lambda_{mat} \nabla T - C_T g_l - (C_T + L) g_v \right]
\]

(7)

In (7) \( \lambda_{mat} \) (W/mK) is the heat conductivity of the porous material. This conductivity is a function of the moisture content of the porous material since moisture contained inside the porous material would result in an increase of the conductivity. \( \rho_{mat} \) (kg/m³) is the density of the porous material and \( C_{mat} \) is the heat capacity of the porous material. \( L \) is the latent heat of evaporation and is taken as a constant (2.5e6 J/kg). \( C_v \) and \( C_l \) are the heat capacities of vapour and liquid water respectively and are again assumed constant (\( C_v = 1875.2 \) J/kgK, \( C_l = 4192.1 \) J/kgK). The total moisture content \( w \) (kg/m³) can by divided into the liquid moisture content \( w_l \) and the vapour moisture content \( w_v \). Both are linked with the total moisture content through the open porosity \( \psi \) (-).

\[
w_l = \frac{\psi - w}{\rho_l - \rho_v} \quad w_v = \frac{w - \psi}{\rho_l - \rho_v}
\]

(8)

3. Modelling convective drying of ceramic brick

3.1. Experimental setup description

This section gives a short description of the experimental setup used in this paper to validate the HAM model described in the previous section. The experiment was performed by Defraeye [17] and his results are used here for the validation.

A schematic representation of the test setup is given in figure 1. In this experiment a sample of ceramic brick is dried by convection, by placing it in a wind tunnel. Dry air flows over the top side of the brick and the brick is dried out from one side, while the other sides are impermeable for moisture.
Defraeye [17] constructed a small wind tunnel from transparent polymethyl methacrylate (PMMA) to perform convective drying experiments on building materials such as ceramic brick. Air is drawn in by a fan, passes over a flow straightener (honeycomb) and flows through a convergent section before entering the test section. Because of the high width to height ratio, the flow in the tunnel can be assumed two-dimensional [18]. The open circuit wind tunnel was placed in a climate chamber were the mean temperature was set at 23.8°C (with a standard deviation of 0.2°C) and a mean relative humidity of 44% (with a standard deviation of 0.8%). The sample of ceramic brick was wetted and placed in the wind tunnel so that the top face of the sample becomes the bottom of the test section. The sample was wetted to a moisture content of 126kg/m³ which is approximately the capillary moisture content (130kg/m³). The sides of the sample were insulated with extruded polystyrene (XPS) and made impermeable for moisture. The velocity profile at the inlet of the test section was not fully developed so the velocity profile at the inlet of the test section and the turbulence intensity were measured with a PIV (particle image velocimetry) system and these results could then be used as inlet conditions for simulations. During the drying experiment temperatures at the side of the ceramic brick were measured with thermocouples. Figure 6.8 shows the location of these thermocouples. In total 6 thermocouples were installed at a side wall. The temperature was measured at a depth of 10mm, 20mm and 30mm from the material-air interface and 10mm in the lower insulation (at 40mm from interface). To measure the inflow effect and the effect of a developing moisture and temperature boundary layer, a thermocouple was installed upstream of the centre thermocouples and downstream both at a depth of 10mm. The weight change of the test sample was continuously monitored by a balance. The sample of ceramic brick measuring 10mm by 30mm by 90mm, is placed in a container of plexiglass (PMMA). At the bottom of the container a layer of 20mm insulation (XPS) is installed. The front and back side of the container are covered with 15mm of insulation (XPS), the side walls of the brick sample are insulated with 30mm of XPS. The test section can be assumed symmetric along the x-axis since the flow in the channel was found to be two-dimensional [18].

**Figure 1.** Schematic representation of the test section used by Defraeye [17]. x indicate the location of thermocouples.

3.2. 3D modelling: including the developing boundary layer effect
The setup depicted in figure 1 was simulated in 3D with the HAM model. The heat losses through the sides are incorporated by assuming a heat transfer coefficient of 8W/m²K. The insulation and plexiglass surrounding the test sample were included in the computational domain. The air flow at the
top of the sample was assumed 2D and spatially varying transfer coefficients were used. These coefficients were taken from [17] and included the developing boundary layer effect.

Graphs of the temperature evolution in the brick are reported in figures 2-5. Temperature at a depth of 10mm, 20mm, 30mm (at the interface brick/insulation) and 40mm (10mm in the insulation) are compared with measurements. A measurement uncertainty of 0.1 °C is indicated in the figures. A good agreement between the model and the experiments was found.

From the temperature curves the three drying periods typical for convective drying of capillary materials can be distinguished. Initially the temperature decreases, the latent heat needed for the evaporation from the surface cools the brick down. This is in literature often referred to as the decreasing drying rate period (DDRP). When the heat leaving the surface is in equilibrium with the heat going to the surface, the brick temperature stabilizes and the drying process enters the constant drying rate period (CDRP). Finally, when the brick starts to dry out, the drying rate decreases and the temperature at the surface starts to rise again. This is the falling rate period (FRP).

The largest deviations between simulation and measurements are found near the surface. The temperature at a depth of 10mm is slightly underestimated by the model. Also the CDRP continues longer. Deeper in the material the approximation becomes better. At a depth of 40mm (10mm in the insulation) the agreement is almost perfect. This indicates that the applied boundary conditions closely approach reality. Three main reasons for the deviations between the measurements and the simulations can be formulated. The first is the uncertainty in the material properties. This was also addressed by Defraeye [17]. Secondly there is an uncertainty on the implemented boundary conditions and initial conditions. The heat transfer coefficient at the side walls was not measured but estimated and the inlet temperature was taken constant, though in reality the temperature varied a little. Also radiation was not incorporated which could explain the underestimated temperatures. The inlet velocity profile was measured using PIV but as stated by Defraeye [17] it is difficult to estimate the uncertainty on these measurements. Here an uncertainty of 2% was assumed. An uncertainty in the inlet velocity profile will lead to an uncertainty on the transfer coefficients. Finally the deviations between measurements and simulations can be the result of flaws in the measurement setup such as defects in the insulation or an incorrect positioning of the sensors. This is however difficult to check and will not be considered here.

The good agreement between the predicted temperature at various depths and the measured temperature clearly shows that the boundary conditions are correctly implemented. Figure 6 shows the measurement results for the upstream and downstream thermocouples located away from the centre of the brick as indicated in figure 1. These measurements clearly show the leading edge effect. Closer to the leading edge (upstream of the centre) the heat and mass transfer is larger since the boundary layer and the corresponding resistance is smaller there. This results in a faster drying at the leading edge. If the brick dries out, the temperature starts to rise again and this temperature rise is clearly sooner at the leading edge. Although there is no perfect match between the measurements and simulations in figure 6, the graphs do show that the model predicts the correct trends.
Defraeye [17] also monitored the weight change of the sample of ceramic brick. The scaled mass loss is depicted in figure 7. This mass loss was scaled with the initial moisture content. During the CDRP the moisture content in the brick decreases linearly. This drying period is clearly shown in the experimental results in figure 7 where a constant slope in the mass loss curve continues for the first three hours. A similar duration was found by the simulations. Afterwards the FRP starts. The slope of the mass loss curve in figure 7 is no longer constant but decreases. Comparison of the measurements and the simulations shows that the mass loss during the CDRP is well predicted but that there is a deviation for the FRP. The cause of these deviations is again difficult to assess. Similar to the deviations in predicted and measured temperature, uncertainty in material properties (especially moisture permeability and retention curve) and boundary conditions can be put forward.

Figure 7 also shows a comparison of the current HAM model and a HAM model used by Defraeye [17]. There is a good agreement between both models. Initially the new model predicts slightly higher values for the mass loss than the model used by Defraeye. However during the FRP the mass loss
predicted by the new model increases slower which is in better agreement with the measurements. It is however difficult to assess which of the two models is better since none of both have a perfect agreement with the measurements.

![Figure 7](image)

**Figure 7.** Scalled mass loss. Comparison between simulation with new HAM model (—), HAM model developed at KULeuven [17] (- -) and measurement performed by Defraeye [17] (■).

4. Conclusions

In this paper a finite volume HAM model is discussed and validated. Experiments found in literature were used and a good agreement between the measurements and modelling results was found. The discrepancies between the experiments and the model were attributed to three causes. First the uncertainty of the material properties can have a significant impact on the modelling outcome. Secondly the deviations between measurements and simulations could be the result of flaws in the measurement setup such as defects in the insulation or an incorrect positioning of the sensors. This was however hard to check and was not considered in this study. Finally the correct implementation of the boundary conditions was found to be very crucial.

As stated in literature, neglecting the leading edge effect as a result of developing boundary layers can lead to significant errors. Therefore this leading edge effect was incorporated by using spatially varying transfer coefficients. As a result of the developing boundary layer the brick dries out faster at the leading edge where the boundary layers for heat and mass are thinner. The drying experiment was modelled in its full complexity by using a 3D model with the insulation and plexiglass included in the computational domain. This resulted in a very good agreement between the simulations and the experiments and demonstrated the importance of a correct implementation of the boundary conditions in order to have a good prediction of drying phenomena.

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