EFFECT OF MOISTURE INERTIA MODELS ON THE PREDICTED INDOOR HUMIDITY IN A ROOM

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ABSTRACT

This paper investigates the sensitivity of indoor humidity models to the numerical description of water vapour buffering in porous materials in the room. Three different numerical models are compared: a lumped capacity model, which lumps the moisture inertia in a single capacity for the room, a two-node model, which differentiates between the room air humidity and the representative humidity of an equivalent humidity buffering material, and finally a room-wall model, which describes the water vapour transfer and storage in the building fabric through a continuum model.

KEYWORDS

Moisture buffer, numerical simulation, HAM

INTRODUCTION

Various applications in building design require a proper assessment of the indoor humidity in buildings during the design stage. The indoor humidity should be controlled within a certain range for instance to improve the acceptability of the indoor environment to occupants, or to prevent deterioration of artefacts and materials in museums or libraries. For this purpose mechanical systems, such as ventilation and humidification systems, may be incorporated in the building design. In order to evaluate the need and performance of such systems, a sufficiently accurate dynamic model is needed to predict the achieved indoor humidity and to size the mechanical systems.

Today different numerical models are available to describe the transient water vapour balance of a room and predict indoor humidity. A typical room moisture balance includes water vapour production by moisture sources (humans, plants,…), convective water vapour transfer with ventilation air, and water vapour exchange with the building fabric and furniture. The water vapour exchange between room air and surrounding materials (walls and furniture) is governed by three physical processes: the transfer of water vapour between the air and the material surface, the moisture transfer within the material and the moisture storage within the material. The existing models mainly differ in the way this last part of the moisture balance is described.

A first group of indoor humidity models are the ones incorporated in the commercial thermal building simulation codes, e.g. TRNSYS or EnergyPlus. The main focus of these models is to predict the temperature fluctuations and energy demands of individual rooms. As a result the water vapour exchange with surrounding materials is described in a simplified way. Two approaches are found. In the simplest approach it is assumed that the room and material humidity’s are always the same, and so the moisture capacities of walls and furniture are combined into a single room moisture capacity (the so-called effective capacitance or lumped capacity model). In the second approach a differentiation is made between the room humidity and a representative material humidity. In this case the material, which exchanges moisture

with the room air, is represented by a single equivalent volume representative of the average moisture transfer and storage in the material (the so-called effective moisture penetration depth model). In the TRNSYS code this approach is further elaborated by dividing the equivalent volume into a surface layer and a deep layer.
A second group of indoor humidity models are the ones produced by combining the previous models for thermal building simulation with models for heat-, air and moisture transfer in building components (HAM-models). Several HAM-models have been developed and validated worldwide in the last decade (Hens 1996, Trechsel 2001). Since HAM-models are capable of describing heat and mass transfer within the layers of the building envelope in a very precise way, the exchange of water vapour between the room air and the surrounding walls may be accurately defined. Working combinations of such integrated hygrothermal simulation models are about to be developed and may be available to the practitioner in the near future (Künzel et al. 2005).
Both groups of models described above are so-called multi-zone models. They have one basic simplification in common, namely that the air in a room is well mixed, such that the room conditions (temperature, humidity, air pressure) are equal in the whole zone. A new generation of indoor humidity models is currently under development in order to make a prediction of humidity variations within the room air possible. To achieve this, models to describe the vapour exchange between air and porous materials are combined with CFD-codes (Computational Fluid Dynamics). Examples of this approach are given by Steeman et al. (2006).

The scope of this paper is however limited to the multi-zone models. At the moment there is no guidance on the validity and accuracy of the simplified humidity models incorporated in the existing commercial codes. Therefore this paper presents results of a sensitivity study where the different approaches are compared to describe the moisture exchange between the air and surrounding materials. In a first part the numerical description of the various models is explained. The second part presents the calculation results.

INDOOR HUMIDITY MODELLING

Governing equations

Eqn. 1 gives the non-steady-state moisture balance for the indoor air in a room, in terms of the partial pressure of water vapour.

$$\dot{M}_{prod} + \dot{M}_{sys} + \frac{nV}{R_v T_i}(p_e - p_i) = 3600\left[\frac{V}{R_v T_i}\frac{dp_i}{dt} + \sum_j A_j \beta_i (p_i - p_{s,j})\right] \qquad (1)$$

The left hand side contains all moisture sources: indoor vapour production M_{prod} by the users (kg/h), vapour addition by the HVAC-system M_{sys} (kg/h) and vapour gains by ventilation. The right hand side contains the terms describing the vapour storage in the air, and the convective vapour transfer from the air to the interior surfaces of the enclosure walls. Further symbols are: p_i and p_e for the partial water vapour pressures of the indoor and outside air (Pa), R_v the gas constant for water vapour (462 J/kg/K), T_i the indoor air temperature (K), n the ventilation rate (ac/h), V the room volume (m^3), A_j the area of the interior surface of wall j (m²), β_i the convective surface film coefficient for vapour transfer (s/m) and $p_{s,j}$ the vapour pressure at the interior surface of wall j (Pa).
This latter variable couples the enclosure moisture balance to the moisture conservation equations of the walls and materials surrounding the enclosure. Eqn. 2 describes the mass balance equation for 1D-transfer and storage of water vapour in a wall with porous building materials:

$$\frac{\partial}{\partial x}\left[\delta(\varphi)\frac{\partial p}{\partial x}\right]=\rho\xi(\varphi)\frac{\partial}{\partial t}\left[\frac{p}{p_{sat}(\theta)}\right] \tag{2}$$

where δ is the vapour permeability (s), φ the relative humidity (-), $\rho\xi$ the moisture capacity in terms of relative humidity, derived from the material sorption isotherm (kg/m^3) and $p_{sat}(\theta)$ the water vapour pressure at saturation at temperature θ. Vapour transfer and storage properties are typically a function of ambient humidity.

Finally the boundary condition at the interior material surface is:

$$\beta_i \cdot (p_i - p_s) = -\,\delta(\varphi)\left.\frac{\partial p}{\partial x}\right|_s \tag{3}$$

Simplified approaches

In the simplified approaches incorporated in thermal building simulation codes, Eqn. 2 and 3 are solved by assuming that only a thin layer near the interior surface interacts with the indoor air. This thin layer with uniform moisture content absorbs and releases moisture to the room air when exposed to cyclic air humidity variations. This approach implies that water vapour transfer between inside and outside through exterior walls is neglected. The depth of the affected layer is related to the effective moisture penetration depth EMPD associated with the period of typical fluctuations in the vapour pressure at the wall surface (Cunningham 2003):

$$\mathrm{EMPD}=\sqrt{\frac{\delta\cdot p_{sat}(\theta)\cdot T}{\rho\xi\cdot\pi}} \tag{4}$$

In Eqn. 4 T is the period of the cyclic variation (s). For porous building materials the effective penetration depth for moisture exchange is typically in the order of millimetres for daily variations and in the order of centimetres for yearly fluctuations. It can be shown that 95% of the moisture exchange between the wall and the air occurs in a region of 3 times EMPD near the wall surface.

In the assumption that the wall-air interaction occurs in a humidity buffering layer with thickness Δ and uniform humidity conditions equal to the surface conditions, than the equations 2 and 3 are reduced to a single equation:

$$\beta_i(p_i - p_s)=\rho\xi(\varphi_s)\Delta\frac{d}{dt}\left[\frac{p_s}{p_{sat}(\theta_s)}\right] \tag{5}$$

The calculation of indoor humidity as a function of time now requires the numerical solution of the set of ordinary differential equations 1 and 5. In the existing building simulation codes three different approaches are found to do so:

1. Eqn. 5 is applied to all wall surfaces. The number of equations to be solved per room is j+1. Non-isothermal conditions are assumed: the surface temperature that appears in Eqn. 5 follows from the solution of the energy conservation equations for the individual walls. The moisture capacity of the intervening layer is a function of the relative humidity of the layer. This more complete approach is used in the computer code EnergyPlus (so-called EMPD-model, EnergyPlus 2005).
2. Eqn. 5 is applied to a single humidity buffering layer with properties representative of the average moisture storage properties of all room surrounding surfaces. Isothermal conditions are assumed when solving the buffering layer mass balance: the temperature of the humidity buffering layer is constant. Also the moisture capacity is constant and independent of the layer humidity. This simplified approach may be used in the computer code Trnsys (so-called buffer storage humidity model, SEL et al. 2004).
3. The previous approach is further simplified by assuming that the thermal and humidity conditions in the humidity buffering layer are the same as in the room air. Hence the vapour pressure of the layer is eliminated from Eqn. 1, and the set of 2 equations reduces

to Eqn. 6. This simplest approach may also be used in the Trnsys code (effective capacitance humidity model). The factor on the right hand side is then treated as a constant capacitance, independent of temperature.

$$\dot{M}_{prod} + \dot{M}_{sys} + \frac{nV}{R_v T_i}(p_e - p_i) = 3600\left[\frac{V}{R_v T_i} + \frac{(A\rho\xi)_{eq}\Delta}{p_{sat}(\theta_i)}\right]\frac{dp_i}{dt} \tag{6}$$

HAM-model

In the following these three simplified approaches based on the humidity buffering layer are compared to a solution where the water vapour transfer within the whole of the surrounding walls is described by means of a HAM-model. In this case the coupled set of Eqn. 1, 2 and 3 is solved simultaneously. In the numerical solution a control volume formulation is used here for discretization in space and a fully implicit scheme for discretization in time (Janssens 1998).

The use of a HAM-model also allows a more detailed investigation of the influence of moisture on the heat transfer in the wall and on the resulting heating and cooling demand of a room. This may be explained by means of Eqn. 7, which shows the governing energy conservation equation for a wall.

$$\frac{\partial}{\partial x}\left[\lambda(w)\frac{\partial\theta}{\partial x}\right] + h_{ev}\frac{\partial}{\partial x}\left[\delta(\varphi)\frac{\partial p}{\partial x}\right] = \frac{\partial}{\partial t}\left[(\rho c + c_w w)\theta\right] \tag{7}$$

In this equation λ is the thermal conductivity (W/mK), w the moisture content (kg/m^3), θ the temperature (°C), h_{ev} the latent heat of evaporation (J/kg), ρc the volumetric heat capacity of the material (J/m^{3}K) and c_w the specific heat capacity of water (J/kgK). The first term in the left hand side represents the volumetric heat efflux by heat conduction in the material. The second term describes the latent heat sink as a result of absorption and desorption processes in the material. The right hand side is the rate of heat storage in the material. As the equation shows the presence of moisture affects the heat transfer in two ways: first through the moisture dependency of the apparent heat transfer and storage properties, second through the latent heat of absorption and desorption.

MODEL COMPARISON

Calculation case

For the model comparison a room geometry was adopted from a hypothetical base case building used in the IEA BESTEST procedure. Peuhkuri and Rode (2005) added information to perform an analysis of the indoor and building envelope moisture conditions on the BESTEST building as an input for the work performed for the Annex 41 of the IEA-ECBCS-program (Hens 2003).

TABLE 1: Material properties and boundary conditions (Peuhkuri and Rode 2005)

Internal surface coefficient for heat transfer	8.3 W/(m²K)
External surface coefficient for heat transfer	29.4 W/(m²K)
Internal surface coefficient for vapour transfer β_i	2.0 10^{-8} kg/(m²sPa)
External surface coefficient for vapour transfer β_e	6.25 10^{-8} kg/(m²sPa)
Aerated concrete dry density ρ	600 kg/m^3
Aerated concrete dry heat capacity c	840 J/kgK
Aerated concrete thermal conductivity λ	0.18+ 8 10^{-4}w W/mK
Aerated concrete vapour permeability δ	2 10^{-11}+ 1 10^{-12} exp(4.2φ) kg/(msPa)
Aerated concrete sorption isotherm w	300(1-909lnφ)$^{-0.5}$ kg/m^3

The internal dimensions of the BESTEST building (one single room) are 6m by 8m by 2.7m. For simplicity it is assumed that the building walls, roof and floor are made of monolithic aerated concrete with thickness 15 cm and face the outdoor air on every side of the building. This means that the exterior and interior boundary conditions for walls, roof and floor are the same. One of the walls contains windows with a total surface area of 12 m². Table 1 lists the remaining information on material properties and boundary conditions.
It can be shown that the EMPD of aerated concrete, according to the definition of Eqn. 4, amounts to 11 mm for a cyclic period of 24 h and ambient conditions of 20°C and 50% RH.

Preliminary isothermal analysis

In literature little guidance exists on the choice of the buffering layer thickness Δ to be used in the simplified humidity models. Therefore a preliminary analysis is performed to study the effect of the chosen buffering layer thickness on the predicted indoor humidity. The analysis is performed for constant boundary conditions: indoor and outdoor temperature 20°C, outdoor relative humidity 50% and air exchange rate 0.5 volumes/h. Only the release of water vapour is variable: it is released in the room from 9.00h until 17.00h at a constant rate of 0.5 kg/h. No heat source is present.
The periodic state solution of the indoor relative humidity is calculated by means of the three models described above: the effective capacitance model (EC), the effective moisture penetration depth model (EMPD) and the HAM-model. In all cases the differential equations are solved numerically using a fully implicit scheme for discretization in time and a time step of 1 hour. In the HAM-model the aerated concrete wall contains 30 control volumes in total. In the center of the wall the discretization is 5 mm, near the surface the discretization refines to 1 mm in steps of 1 mm.
Table 2 lists the results of the calculations in terms of the average and daily variation of the periodic state solution. Figure 1 compares the solution of the three models, represented as the humidity variation around the daily average. The EC- and EMPD-models were solved for different values of the buffering layer thickness to show the influence of the choice of Δ. In these two models material properties were taken constant and evaluated at 50% RH.
The results in Table 2 show that the predicted humidity variation is very sensitive to the choice of the buffering layer thickness, both for the EC- and the EMPD-model. In case the buffering layer thickness is taken equal to the effective moisture penetration depth, the order of magnitude of the daily variation predicted by the simplified models corresponds to the variation predicted by the HAM-model. However, as Figure 1 shows, the simplified models are not able to predict the initial fast response of indoor humidity to changes in moisture production, compared to the HAM-model. Further the simplified models overestimate the daily average indoor humidity. This is due to the fact that these models neglect the transmission of water vapour through the exterior walls. In this exercise, the vapour diffusion transfer through the aerated concrete walls is not insignificant: it amounts to 28% of the convective transfer by ventilation.

TABLE 2: Periodic state solution: daily average and variation of indoor relative humidity (%) (EMPD = 11mm)

Model		Daily average	Daily variation (max-min)
EC	Δ = 0	64.9	42.9
	Δ = 0.5*EMPD		14.3
	Δ = EMPD		8.0
	Δ = 3*EMPD		2.8
EMPD	Δ = 0.5*EMPD	64.9	14.8
	Δ = EMPD		9.0
	Δ = 3*EMPD		4.3
HAM		61.8	9.9

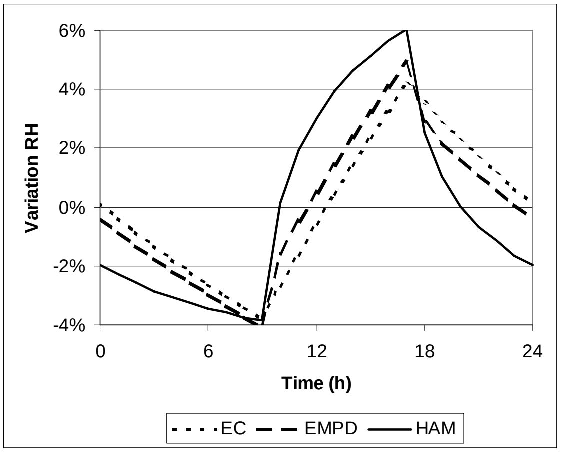

Figure 1: Periodic state solution of three models: relative humidity variation around the daily average

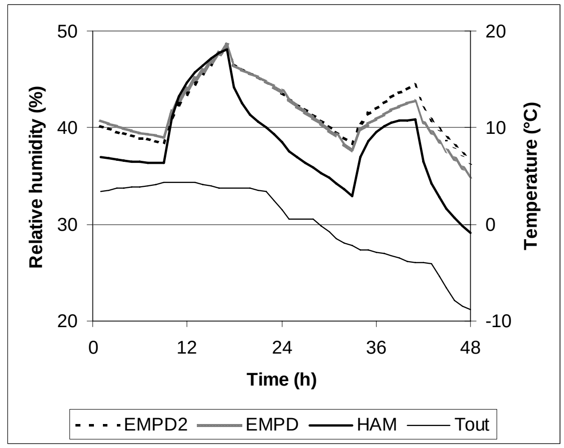

Figure 2: Predicted relative humidity of three models during outside temperature drop (9-10 December)

Model comparison

The evolution of indoor humidity is now predicted in response to variations of exterior climate and building use. A weather file with hourly mean climate data describes the exterior conditions: the IWEC-file for the location of Copenhagen is used. Only temperature and humidity data are considered, solar radiation is not taken into account. Again water vapour is released at a constant rate of 0.5 kg/h from 9.00h until 17.00h every day. Also a heat source is active during these hours with a total power of 800 W (100% convective). An ideal convective heating and cooling system keeps the air temperature in between 20°C and 27°C. The ventilation rate is 0.5 air changes per hour continuously.
As in the preliminary analysis this case is solved with the three models. Based on the previous results the thickness of the humidity-buffering layer in the EC- and EMPD-models is taken equal to the effective moisture penetration depth (11 mm). The two versions of the EMPD-model described above are now part of the comparison. In the first version, referred to as EMPD, changes in the indoor surface temperature have an impact on the water vapour balance of the humidity-buffering layer (non-isothermal assumption). In the second version, referred to as EMPD2, the factors in the vapour balance equation for the humidity-buffering layer have constant values (isothermal assumption).

Table 3: Predicted inside conditions for the different models

OUTSIDE	mean	minimum	10-percentile	90-percentile	maximum
Temperature	8.3	-9.6	0.2	17.0	26.8
Vapour pressure	892	191	470	1389	2162
R. Humidity	77	21	56	94	100
INSIDE	mean	minimum	10-percentile	90-percentile	maximum
HAM					
Temperature	20.1	20	20	20	26.8
Vapour pressure	1177	589	798	1610	2404
R. Humidity	50	25	34	67	78
EMPD					
Temperature	20.1	20	20	20	26.5
Vapour pressure	1244	557	847	1721	2483
R. Humidity	53	24	36	72	84
EMPD2					
Temperature	20.1	20	20	20	26.5
Vapour pressure	1243	577	847	1709	2318
R. Humidity	53	25	36	71	95

Table 3 gives a summary of calculation results. Figures 2-4 show some details of the simulations. Since the solutions of the EC- and the EMPD2-model appeared to match quite well, the results of the EC-model are not listed and not discussed anymore.
As the table shows, the indoor air temperatures predicted by the HAM-model during free floating conditions (no heating nor cooling) slightly deviate from the results of the EMPD-models. This is caused by the fact that the HAM-model incorporates the dependency of thermal material properties on moisture content.
With regard to the predicted humidity, some clear differences appear between the results of the HAM-model and the EMPD-models. In addition to the explanation made in the preliminary analysis, a major cause of observed deviations lies in the interaction between the heat transfer in the walls and the moisture balance in the enclosure. This interaction is accurately described in the HAM-model, but totally absent in the EMPD2-model (the humidity buffering layer is considered isothermal). The effect of this interaction becomes clear during periods with sudden changes in exterior or interior temperature. Figure 2 shows the evolution in relative humidity during a drop in exterior temperature. The HAM-model predicts a faster humidity decrease than the EMPD-models. This is explained by the fact that the temperature in the hygroscopic monolithic walls drops in response to the exterior temperature, after which the absorption of water vapour by the walls increases. For, the immediate effect of a drop of temperature in a hygroscopic material is to leave the moisture content and corresponding relative humidity unchanged, but to decrease the vapour pressure (Cunningham 2003). Since this effect is not modelled in the EMPD2-model, changes in outdoor temperature do not affect the predicted relative humidity (as far as the outside vapour pressure does not change).
A similar response is observed during changes in interior temperature, as shown in Figures 3-4. Here the indoor temperature increases above the heating set point of 20°C during the day, followed by an increase of the interior surface temperature of the walls, and a resulting release of absorbed moisture to the interior. As the EMPD-model incorporates the interaction between interior surface temperature and moisture balance of the humidity buffering layer, its results are well in line with the HAM-simulations. However the results of the isothermal EMPD2-model deviate from the other two.

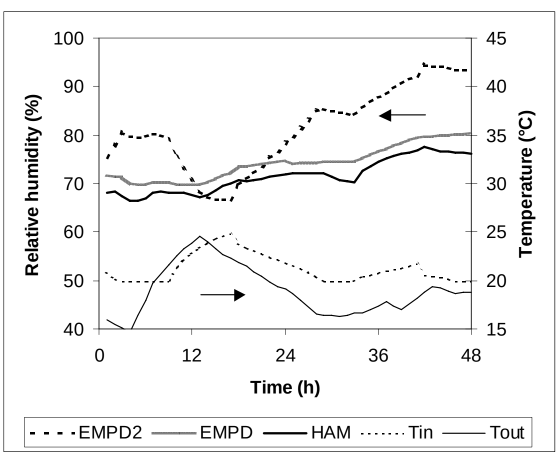

Figure 3: Predicted relative humidity of three models during warm summer days (7-8 August)

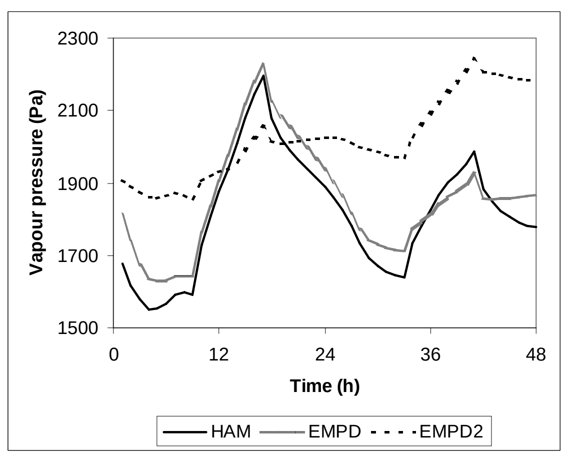

Figure 4: Predicted water vapour pressure of three models during warm summer days (7-8 August)

CONCLUSIONS

This paper investigated the sensitivity of indoor humidity models to the numerical description of water vapour buffering in porous materials in the room. Three different numerical models were compared: an effective capacitance model, an effective moisture penetration depth model, which differentiates between the room air humidity and the representative humidity of an equivalent humidity buffering layer, and finally a room-wall model, which describes the water vapour transfer and storage in the building fabric through a continuum HAM-model. Deviations between calculation results of the various models have been related to different assumptions in modelling. The results of the simplified models appeared sensitive to the choice of thickness of the humidity buffering layer. The interaction between the temperature and the moisture balance of the hygroscopic materials had a major impact on humidity predictions and should be well described.

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