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Combined Heat and Moisture Transfer In Buildings Systems

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ABSTRACT

Temperature and humidity are the two main parameters indicating the comfort level of the building occupants. Although the effect of temperature is taken into account in thermal simulation of buildings, the moisture transfer through the rooms and porous building walls is sometimes neglected. The level of humidity can give different sensations of thermal comfort. It is necessary to take into account both heat and moisture transport in and around buildings to predict the hygrothermal behavior of rooms and building walls so as to calculate the energy demands correctly. In this work some benchmark exercises are worked out to see the performance of the heat and moisture transfer model implemented for rooms and porous walls. Finally, numerical results are compared with the measured data for a room exposed to varying outdoor conditions.

1. INTRODUCTION

Temperature and humidity are the two main parameters indicating the comfort level of the building occupants. Although the temperature effect is taken into account in thermal simulation of buildings, the moisture transfer through the rooms and porous building walls is often neglected. The level of humidity can give different sensations of thermal comfort. In addition to the discomfort caused by excess of humidity, mould formation and dust mites can affect the health of the occupants. Moreover it also damages the appearance of the walls. Low levels of humidity on the other hand cause dryness of the skin, throat and the nose. Dry air affects the muscous membrane reducing the barrier to airborne infections and augments the problems of allergic and asthma persons. Thus it is important to have appropriate levels of indoor humidity along with the room temperature. Movement of water through the building envelope also causes a lot of harm to the building structure and reduces the quality of its thermal insulation which can increase the energy demand. Buildings alone contribute to one third of the green house gas emissions and their energy requirement s is responsible for about 40% of the global energy consumption (UNEP, 2009). It is necessary to take into account both heat and moisture transport in and around buildings to predict the hygrothermal behavior of rooms and building walls and to calculate the energy demands correctly.

Many authors have studied heat and moisture transfer through building envelope. Künzel (1995) presented a comprehensive study of the combined heat and moisture transfer mechanisms along with numerical and experimental studies. Methodology of heat and moisture transfer modelling was documented by Hagentoft (2002), while Hagentoft et al. (2004) have presented benchmark results for one dimensional cases for the both heat and moisture transfer through porous building materials. The state of the art and the different programs for heat and moisture simulation is buildings is detailed by Woloszyn and Rode (2008) while an overview of the different approaches in heat and moisture transfer modelling has been presented by Woloszyn et al. (2009). Coupled heat and moisture simulation in air-conditioned buildings and its impact on energy demands was presented by Menghao et al. (2009). Comparison between CFD and well-mixed zonal models was presented by Steeman et al. (2009). Recently, Van Belleghem et al. (2011) have published benchmark experiments for moisture transfer modelling in air and porous materials along with the state of the art and CFD coupling.

The aim of this work is towards the numerical simulation of heat and moisture transfer in building systems. The numerical model of combined heat and moisture transfer based on Darcy's law of liquid transport and Fick's law of diffusion for water vapour found in the literature is tested in the work. Certain benchmark cases along with an experimental validation case of heat and moisture transfer are worked out to see the behaviour of the model. This model will be implemented in the general building simulation software ``NEST'' (Damle et al., 2011) for the combined heat and moisture transfer in building systems.

2. MATHEMATICAL MODEL

The mathematical model for heat and moisture transfer, to be implemented in the general building program, is described in this section. Both building walls and rooms are considered.

2.1 Heat and moisture transfer through walls

The moisture transfer equation (Tariku, et al. (2010a), Künzel, (1995)) obtained by applying the Fick's law for vapour diffusion and Darcy's law for liquid transport, in terms of relative humidity ϕ and temperature T is written as:

$$\theta \frac{\partial \emptyset}{\partial t} = \frac{\partial}{\partial x}\left(D_{\emptyset} \frac{\partial \emptyset}{\partial x}\right) + \frac{\partial}{\partial x}(D_T \frac{\partial T}{\partial x}) \tag{1}$$

where $D_{\emptyset}$=$\delta_v p_{sat}$ + $D_l \frac{\rho_w RT}{M\emptyset}$ and D_T=$\delta_v\ \phi \frac{\partial p_{sat}}{\partial T}$+ $D_l \frac{\rho_w R\ ln\phi}{M}$

The heat transfer equation for a moist porous material, by taking into account condensation/evaporation within the material (Hagentoft, 2002), can be written as:

$$\rho_0 C \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + h_{fg} \frac{\partial}{\partial x}(\delta_v \frac{\partial p}{\partial x}) \tag{2}$$

The equation (1) and equation (2) are solved simultaneously to resolve heat and moisture transfer in building walls with single or multiple material layers.

2.2 Heat and moisture transfer in rooms

The moisture balance equation for a single well mixed zone room can be written as:

$$V \frac{d(p_r/R_v T_r)}{dt} = \sum_{j=1}^{n} \dot{m}_{wj} + \dot{m}_g + \dot{m}_e(\omega_e - \omega_r) \tag{3}$$

where, the left hand side term represents moisture accumulation while the right hand side terms represent moisture transfer from room walls ($\dot{m}_{wj}$=$\beta_j A_j(p_j - p_r)$), internal moisture generation and moisture transported by the infiltrating ambient air respectively. The heat transfer equation (Tariku et al., 2010b) can be written as:

$$\frac{\rho V d((C_{pa}+\omega_r\, C_{pv})T_r)}{dt} = \sum_{j=1}^{n} \alpha_j A_j\left(T_{wj} - T_r\right) + \dot{m}_e C p_a(T_e - T_r) +$$
$$\dot{m}_e C p_a(\omega_e T_e - \omega_r T_r) + \sum_{j=1}^{n} \dot{m}_{wj}\, C p_v\, T_{sj} + \dot{m}_g C p_v\, T_g \tag{4}$$

where, the left hand side term represents accumulation of enthalpy while the right hand side terms represent convective heat from walls, heat brought by ambient air, heat added/removed by moisture coming from or going into the room walls ($\dot{m}_{wj}$) at temperature T_{sj}=T_w and T_{sj}=T_r respectively, and heat added due to moisture generation ($\dot{m}_g$) at temperature T_g.

2.3 Assumptions and limitations

The models implemented in this work are restricted with assumptions/limitations such as: temperature is assumed to be above 0°C and below 80°C; ice formation not considered; only regular building materials considered; no chemical reactions; no hysteresis; no ageing; no ventilated cavities in structure; material is never more than capillary moisture saturated; gravity effects not considered; drainage between material layers is not considered; and driving rain is put in a simplified way.

3. VERIFICATION OF THE HEAT AND MOISTURE MODEL

To verify the working of the aforementioned model equations for building rooms and walls, some benchmark cases are worked out in this section.

3.1 Isothermal moisture transfer in a wall

The HAMSTAD (Hagentoft, 2002) benchmark exercise #2 is a one dimensional case with isothermal moisture transfer in a single layer exposed to air with relative humidity of 65% on one side and 45% on the other side, while the temperature is held constant at 25 °C. Figure 1 shows how the numerical model is able to predict very well the transient moisture diffusion in the wall with the relative differences below 1.2 %.

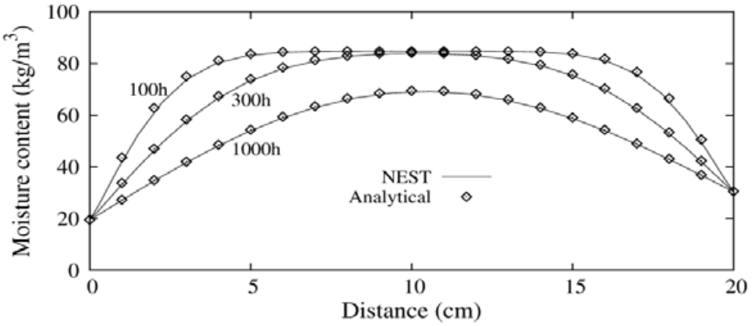

Figure 1: Moisture distribution along the wall with time.

3.2 Non-isothermal moisture transfer in a composite wall

Results for the benchmark exercise #4 (Hagentoft, 2002) with heat and moisture transfer in a two layer wall having a hygroscopic finish are presented in this section. The wall is subjected to changes in heat and moisture loads at its surfaces. Severe climatic load is imposed for having different phenomena of heat and moisture transfer generated by heating, cooling, alternating drying and wetting due to rain load along with fast liquid transfer properties of the first layer. These conditions allow a very good case for checking the heat and moisture transfer model.

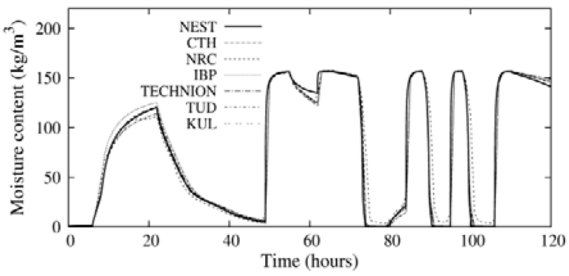

Figure 2a: Moisture variation of exterior surface.

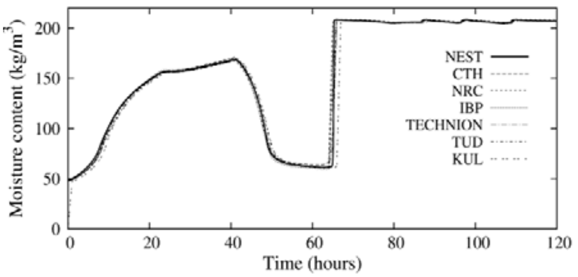

Figure 2b: Moisture variation of interior surface.

The case description is given by Hagentoft, et al. (2004). Figures 2-6 show the numerical results obtained with NEST in comparison with other numerical codes detailed also by Hagentoft, et al. (2004). It can be seen from these figures that the profiles predicted by NEST match very well over periods of gradual or no fluctuation of moisture and temperature values, and during the period of sudden changes lies between the curves of different programs. Thus in general, NEST shows a very good behaviour as compared to other programs.

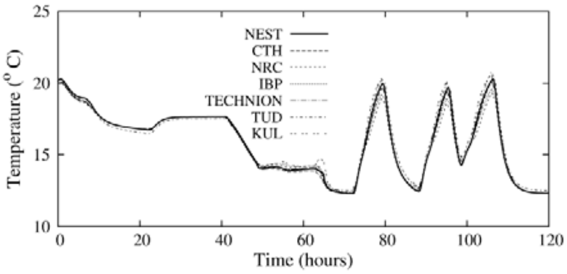

Figure 3a: Temperature variation of exterior surface.

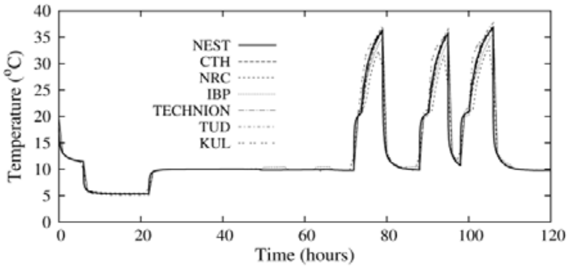

Figure 3b: Temperature variation of interior surface.

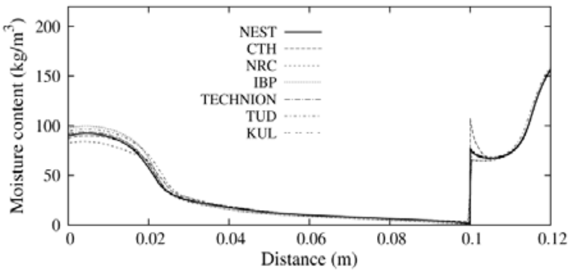

Figure 4a: Moisture profile after 24 hours.

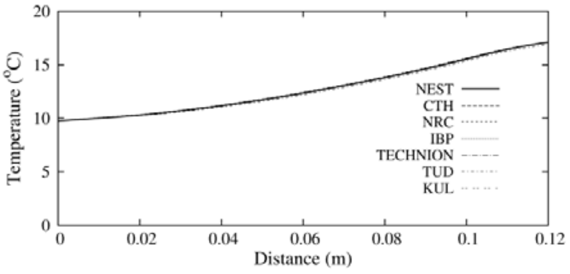

Figure 4a: Temperature profile after 24 hours.

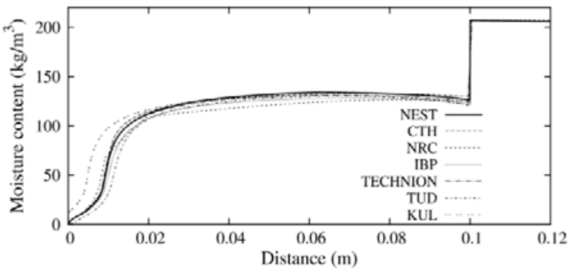

Figure 5a: Moisture profile after 78 hours.

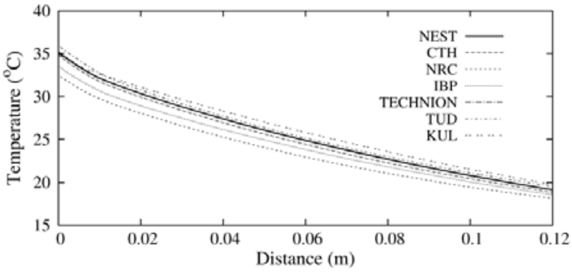

Figure 5a: Temperature profile after 78 hours.

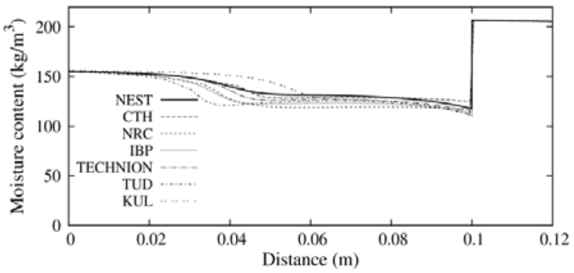

Figure 6a: Moisture profile after 96 hours.

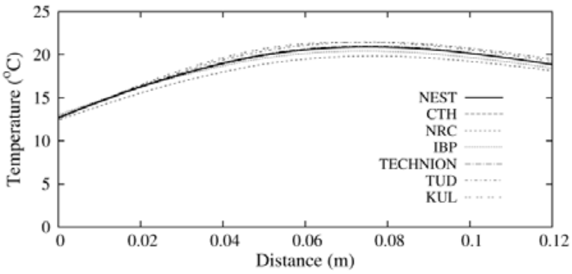

Figure 6a: Temperature profile after 96 hours.

3.3 Room and wall moisture transfer

To verify the behaviour of the room and wall objects with moisture transfer a verification analysis is presented against the analytical cases referenced in Bednar and Hagentoft (2005). A simplified building (a rectangular box shape) with walls made monolithic layer (150mm) of aerated concrete is tested under isothermal conditions, but with moisture transfer until cyclic steady state is reached. The single zone envelope exchanges moisture with outdoor (a constant ventilation rate of 0.5) with an internal moisture generation of 500 g/h between 9:00 h and 17:00 h. Two different cases (case 0A and case 0B) referenced in Bednar and Hagentoft (2005) are studied here: (a) vapour tight interior and exterior wall surfaces of the building (case 0A); b) only exterior surfaces vapour tight with absorption and desorption at interior wall surfaces (case 0B). The initial temperature and relative humidity are 20^{o}C and 30\% respectively which are the same as the outdoor temperature and outdoor relative humidity during the simulation period. the moisture transfer coefficient is 2x10^{-8} m/s. The properties of aerated concrete and other details of these cases can be found work aforementioned. The variation of the relative humidity over the length of the day for case 0A and case 0B is shown in Figure 7a and Figure 7b respectively. Numerical results show a good agreement with analytical solution with a maximum relative difference of 1.0573% and 1.42065 % for case 0A and case 0B respectively.

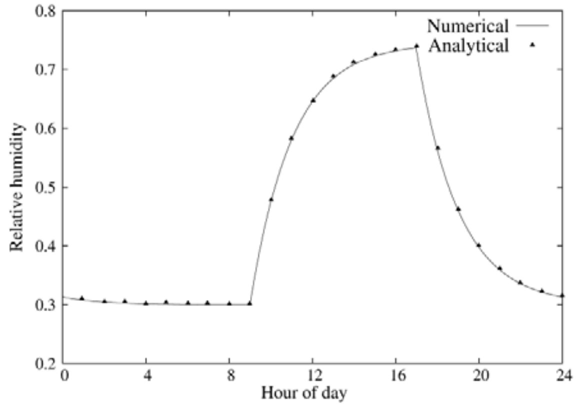

Figure 7a: Relative humidity variation of the room with vapour tight interior walls.

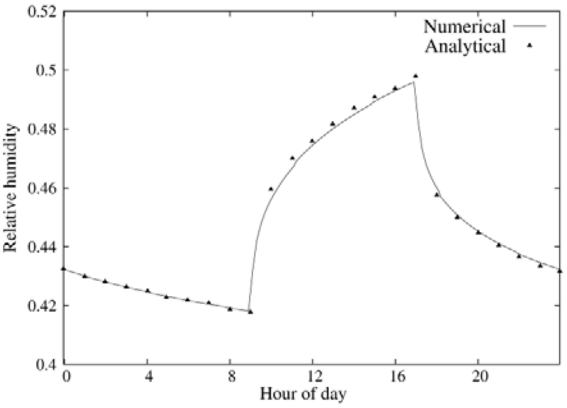

Figure 7a: Relative humidity variation of the room with absorption/desorption at interior walls

4. EXPERIMENTAL VALIDATION

In this section, the numerical values of the relative humidity are compared with experimental values for a real room with heat and moisture transfer with some walls exposed to outdoor climate (Holzkirchen, Germany). The experiment is performed to see the moisture buffering capacity of the gypsum boards published by Holm and Lengsfeld (2007). The internal wall surfaces of the test room are covered with standard gypsum boards without paint and ceiling covered with aluminium foil. The floor does not participate in moisture transfer. The floor area for the rooms is 19.34 m^2 and the room volume is 48.49 m^3. The duration of the experiment is from 14/02/2005 to 20/03/2005. The evolution of relative humidity with time is shown in Figure 8 and a magnified section of the temporal variation is shown in Figure 9. It can be seen that the numerical values agree well with the measured data. There is some disagreement during a small period of two days (during 28th February evening to 2nd March evening) which might be because of problems in measuring as the measured values drop severely and suddenly below 13% relative humidity even with moisture generation. These discrepancies disappear afterwards and we can see how the experimental values come to match again with the numerical values.

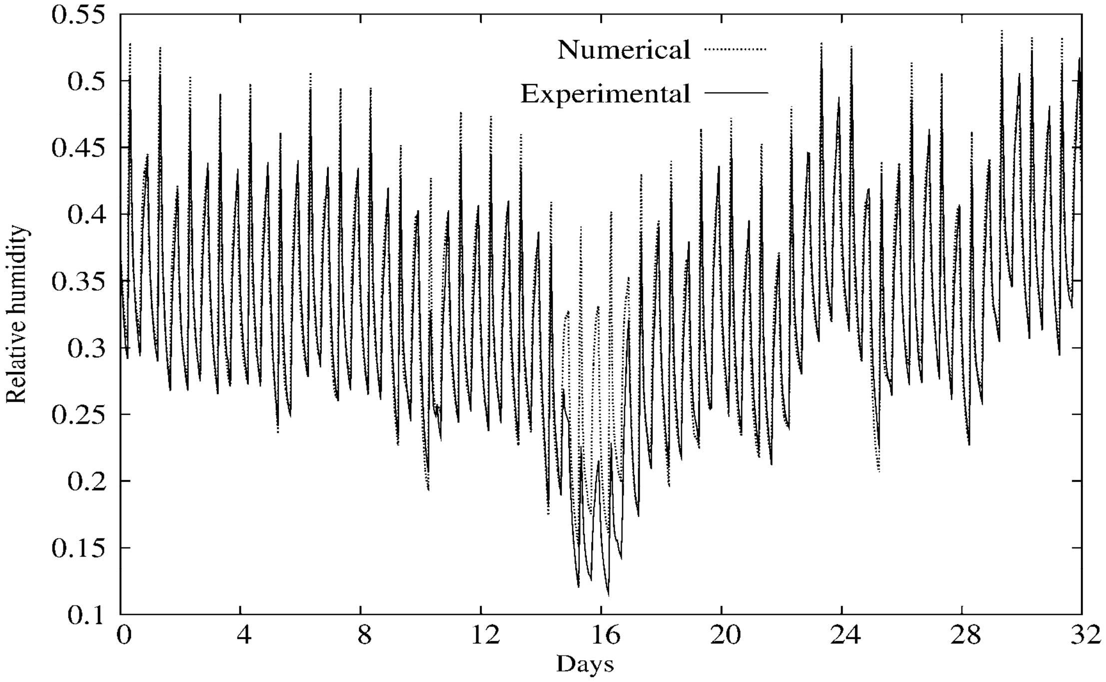

Figure 8: Indoor relative humidity variation with days.

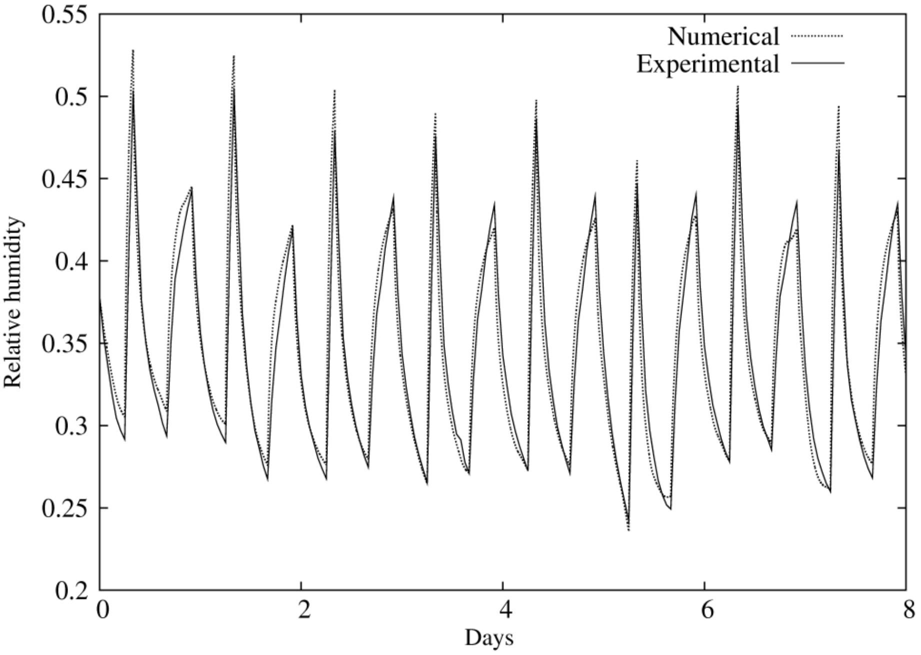

Figure 9: Magnified section of the indoor relative humidity variation.

5. CONCLUSIONS

Heat and moisture transfer model based on Fick's law of diffusion and Darcy's law of liquid transport has been implemented and incorporated in the building simulation software NEST. Benchmark cases for isothermal and non-isothermal moisture transfer have been worked out both for building walls and rooms. The rooms are exposed to infiltrating ambient air and moisture generation at specified periods. The numerical results show a very good agreement with the analytical solutions.

A hygrothermal simulation of a house, with available experimental data, was also carried out to see the performance of the heat and moisture model in a real case with moisture buffering wall materials, varying outdoor conditions and schedules for internal moisture generation. It was observed that the model was able to predict the variation of indoor relative humidity to a good extent over the period of the test except for a period of two days where the prediction was not good. But after that period the prediction again matches with the measured data. This could well be because of problems in measuring relative humidity over the concerned period. More tests will be carried out in the future to assure higher quality of the results.

NOMENCLATURE

A	area	(m^2)
C	bulk heat capacity	(J kg^{-1} K^{-1})
Cp_a	heat capacity of dry air	(J kg^{-1} K^{-1})
Cp_v	heat capacity of water vapour	(J kg^{-1} K^{-1})
CFD	computational fluid dynamics	
D_l	liquid conductivity	(s)
h_{fg}	latent heat of condensation/evaporation	(J kg$^{-1}\$$)
$\dot{m}_e$	mass flow rate of dry air	(kg/s)
$\dot{m}_p$	moisture production rate	(kg/s)
$\dot{m}_w$	moisture from wall surfaces	(kg/s)
M	molecular weight of water	(kg/ mol)
p	partial pressure	(N/m^2)
p_{sat}	saturation pressure	(N m^2)
R	universal gas constant	(J/mol K)
R_V	specific gas constant for water vapour	(J/ kg K)
T	temperature	(^{o}C)
t	time	(s)
dt	time step	(s)
V	volume	(m^3)
w	water content	(kg/m^3)

Subscripts

amb	ambient temperature
e	external/outdoor air flow rate
r	room
w	wall surface
g	moisture generation

Greek letters

α	heat transfer coefficient	(W/m^{2}K)
β	moisture transfer coefficient	(s/ m)
δ	vapor permeability	(s)
λ	thermal conductivity	(W/mK)
ϕ	relative humidity	
ρ	density of dry air	(kg/m^3)
ρ_w	density of water	(kg/m^3)
ρ_0	density of dry material	(kg/m^3)
θ	sorption capacity $\frac{\partial w}{\partial \emptyset}$	(kg/m^3)

ω	specific humidity ratio	(kg/kg-air)

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