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Modelling indoor air and hygrothermal wall interaction in building simulation: Comparison between CFD and a well-mixed zonal model

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ABSTRACT

Traditional models for heat and moisture transport in buildings consider indoor air as a well-mixed gas with uniform properties. Computational fluid dynamics (CFD) offers the possibility of taking into account the effect of air distributions on the interaction with the walls. This paper compares simulations made with a traditional well-mixed model and a CFD model in search for the limitations of the well-mixed model. The possibility of improving the accuracy of the well-mixed results by using CFD generated surface transfer coefficients is investigated. To allow for a good comparison between both models the CFD model is extended with an effective penetration depth (EPD) model for the moisture buffering in the walls, an approach which is also used in the well-mixed model. The average indoor climate and the average relative humidity in the walls predicted by the CFD–EPD model and the well-mixed model with standard surface transfer coefficients agree quite well for the studied test case. The use of CFD generated surface transfer coefficients in the well-mixed model was able to improve the well-mixed results significantly in case a stable and physically relevant surface transfer coefficient could be related to the average indoor air conditions. The studied case showed that this is not always guaranteed.

1. Introduction

The application of numerical simulation models of heat, air and moisture (HAM) transfer in building components has become a common practise in building physics. Recently whole building hygrothermal simulation models have been developed, coupling the HAM models for walls to models describing the heat and moisture balance in and between different rooms [1–5]. Most models commonly assume perfect mixing of the indoor air, which allows the entire air volume of a zone to be represented by a single node. The heat and moisture balance equations are solved for this zonal node and for the surrounding walls, which gives the temperature and water vapour pressure in the room and in the walls. These models are referred to as ‘well-mixed zonal models’. Well-mixed zonal models allow to predict the average indoor climate and the average hygrothermal performance of the walls. However, the well-mixed air assumption does not allow the prediction of the local temperature and relative humidity in the air and walls. Knowledge of local conditions may be important for evaluating the local thermal comfort and for the assessment of the risk of moisture related damage to materials. An example is the damage to cultural heritage in churches due to fast changes of the indoor local (micro)climate [6].

Aim of this paper is to investigate the effect of the well-mixed air assumption on the prediction of the indoor temperature and relative humidity and on the hygrothermal behaviour of the walls. More specifically we want: (1) to determine how strong the local moisture behaviour of the wall deviates from the average wall behaviour predicted by a well-mixed zonal model; (2) to verify how accurately the average indoor temperature and relative humidity are predicted by well-mixed zonal models. To predict distributions in the indoor climate and local wall behaviour, the coupled HAM transport in the room and the heat and moisture transport in the walls have to be modelled taking into account the local interaction between air and wall. The simulation of HAM transport in the room and of the local interaction with the wall requires the use of computational fluid dynamics (CFD). Unfortunately commercially available CFD packages do not allow for the simulation of the coupled heat and moisture transport in hygroscopic materials. For this reason, a commercially available CFD package (Fluent®) is extended with a hygric wall model. The wall model used is the effective penetration depth (EPD) model as described in Ref. [7]. By comparing simulations of the CFD–EPD model and a well-mixed zonal model using the same EPD approach, it is possible to analyse the effect of the well-mixed air assumption on the accuracy of the predicted temperature and

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Nomenclature

A	porous wall surface (m^2)
C_p	heat capacity (J/kg K)
D	effective mass diffusivity of water vapour in air (m^2/s)
d_p	effective penetration depth for moisture transfer (m)
g	moisture flux to the porous walls ($kg/m^2\,s$)
G_v	ventilation rate (m^3/s)
h	surface heat transfer coefficient ($W/m^2\,K$)
M	mol mass (g/mol)
M_{prod}	moisture production (kg/s)
n	direction vector (m)
p	water vapour pressure (Pa)
R_V	specific gas constant for water vapour (J/kg K)
t	time (s)
T	temperature (K)
u	moisture content in the material (kg/kg)
V	indoor volume (m^3)

Greek letters

β	surface water vapour transfer coefficient with water vapour pressure as driving force (s/m)
δ	water vapour permeability (kg/ms Pa)
φ	relative humidity (–)
λ	thermal conductivity (W/mK)
μ	dynamic viscosity (kg/ms)
ρ	fluid density (kg/m^3)
ρ_{mat}	dry material density (kg/m^3)
τ_{var}	period of indoor humidity variation (s)
ξ	hygroscopic moisture capacity (kg/kg)
ω	mass fraction of water vapour in air (–)

Subscripts

a	indoor air volume (control volume discretization)
e	outdoor
i	indoor air volume (single node)
n	wall number
ref	free stream reference for surface transfer coefficient
sat	saturation
surf	porous wall surface
w	wall node located at half the penetration depth

moisture conditions in the room and surrounding materials. This analysis is performed for a test room setup described in Ref. [8]. The original tests were performed without hygric interaction with the walls (non-hygroscopic walls). In this paper, we first validated the CFD model by comparing the CFD result with the originally measured temperature, relative humidity and air velocity profiles in the test room without hygric interaction. In a second step, different cases with hygric interaction are considered for the same test setup. It is noted that these experimental results were already used to validate CFD results and a satisfying agreement with the experiment was found in Ref. [9].

The idea of coupling CFD to a Heat Air Moisture (HAM) material model or to multizone building models is not new. Bartak et al. [10], Beausoleil-Morrsion [11] and Zhai et al. [12] report the integration of CFD in a multizone whole building energy model. CFD is used to predict temperature distributions in indoor air and to accurately model the heat transfer between the indoor air and the building components. The hygric interaction between the indoor air and the building structure was not taken into account. An example of a coupled CFD-material model to study micro-climates in a room can be found in the work of Mortensen et al. [13]. The coupled model was capable of simulating heat and moisture transfer in porous walls for steady-state situations. Erriguible et al. [14] developed a coupled CFD-material model for unsteady-state conditions, which allowed simulation of drying processes of porous materials in situations where classical boundary layer theory is not applicable.

2. Well-mixed zonal model

This section describes the model used to predict the temperature and water vapour conditions in the indoor air assuming well-mixed air conditions. The room is represented in this model by a single node i. The indoor heat and moisture balance equations are solved taking into account heat/moisture production, ventilation gains and heat and moisture exchange with the walls. To facilitate the comparison with CFD results, no radiation heat transfer is considered. The heat exchange with the walls is modelled for each wall separately according to the transfer function relationships of Mitalas [15]. The effect of latent heat release in the walls is neglected in this model. The moisture balance for the indoor air in a room is given by:

$$V\frac{\mathrm{d}(p_i/R_V T_i)}{\mathrm{d}t} = M_{prod} + \frac{G_v}{R_V T_e}(p_e - p_i) - \sum_n A_n g_n. \tag{1}$$

The left hand side in Eq. (1) describes the moisture storage in the indoor air. The right hand side gives, respectively, the moisture production term, the moisture gains by ventilation and the convective water vapour transfer from the air to the surrounding walls. The surface area of wall n is equal to A_n. The water vapour transport to that wall, g_n, is given by:

$$g_n = \beta_n(p_i - p_{surf,n}). \tag{2}$$

To model the water vapour flux to the surrounding walls, the EPD model is used. The penetration depth is defined as the thickness of the surface layer, where hygric interaction with the indoor air occurs when a periodic boundary condition is imposed at the surface. The penetration depth is given by [7]:

$$d_p = \sqrt{\frac{\delta \times p_{sat} \times \tau_{var}}{\rho_{mat} \times \xi \times \pi}}. \tag{3}$$

In the EPD model, it is assumed that the hygroscopic moisture capacity (ξ) and water vapour permeability (δ) are constants, independent of the relative humidity. For most building materials, this assumption is a simplification. Yet in the limited relative humidity range between 40% and 80% RH, where the RH changes occur in this paper (and where most changes occur in practise), this simplification yields good results. Using the EPD model, the moisture balance equation for the wall surface layer can be written as:

$$g_n = d_p\frac{\mathrm{d}(\rho_{mat}u_n)}{\mathrm{d}t} = d_p\rho_{mat}\frac{\partial u_n}{\partial\varphi_{w,n}}\frac{\mathrm{d}\varphi_{w,n}}{\mathrm{d}t} = d_p\rho_{mat}\xi\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{p_{w,n}}{p_{sat}(T_n)}\right), \tag{4}$$