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Sensitivity analysis of CFD coupled non-isothermal heat and moisture modelling

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ABSTRACT

CFD (Computational Fluid Dynamics) is a useful tool to study air flow patterns in a room. Current CFD models are able to simulate air flow combined with temperature distributions and species distributions. In this paper a coupled CFD–HAM model is discussed. This model combines CFD with a HAM model (Heat, Air and Moisture) for hygroscopic materials. This coupled model is able to simulate air flow around a porous material and combines this with heat and moisture transport in the porous material. Validation with a small scale experiment in which gypsum board was used as a hygroscopic material showed good results. In this paper a further validation of the model is discussed based on a sensitivity analysis of some model parameters. Especially hygrothermal parameters like sorption isotherm and water vapour permeability proved to have a non negligible influence on the modelling outcome. Adding a hysteresis model showed improvement of the model during desorption. The model was also used to compare two modelling strategies. In one strategy the gypsum board was modelled as a uniform material, in a second approach the material was modelled as being layered. The difference between the two approaches showed to be negligible.

1. Introduction

Temperature and relative humidity are two important parameters for damage risk assessment of buildings, e.g. too high levels of indoor relative humidity can cause mould growth on the inside surfaces of the building envelope. When moisture migrates through the building envelope, interstitial condensation can occur which can lead to rot, deterioration of outside surfaces or other damage phenomena. Even if humidity levels are kept low enough, damage can still occur due to too strong variations, e.g. paintings and artefacts can show cracks when exposed to fluctuating temperatures and humidity levels [1]. Having a good knowledge of the heat, air and moisture transport in a building is also of great importance for many other applications. Moisture buffering by hygroscopic materials levels out indoor relative humidity fluctuations. This can reduce the energy use of HVAC systems [2] and improve the perceived indoor air quality at the same time [3]. In literature some examples are found where the importance of knowing the relative humidity in the design stage of an HVAC system is highlighted [4,5].

Buildings are complex systems and can be studied at different levels (whole buildings, rooms, building components…). Therefore, depending on the application, Heat, Air and Moisture (HAM) transfer in buildings is modelled through different approaches and a lot of different modelling tools are being developed. Overviews of recent developed HAM models are found in Refs. [6] and [7].

A new trend in HAM modelling is the coupling of these models to BES (Building Energy Simulation) models or CFD (Computational Fluid Dynamics) models depending on the application aimed at. Both modelling approaches were evaluated by Steeman et al. [8]. Coupling HAM models with BES is useful when the impact of moisture on energy use in a building is studied. Examples of such modelling approaches are found in Refs. [9] and [10]. Kwiatkowski et al. [9] used an isothermal modelling approach and neglected the latent heat in the porous material, where Steeman et al. [10] added this to their model. Combining CFD with a HAM model is interesting when a detailed study of the air flow field around a hygroscopic object is needed. For example microclimates can occur near artefacts. A detailed study of these microclimates is necessary for the assessment of damage risks [11,12].

Most BES programs are typically multizone models: they represent a room as one node and have the assumption that state variables (e.g. temperature, relative humidity…) are uniform for the entire zone (well-mixed air assumption). The coupling between the HAM model and the BES model is accomplished by using transfer coefficients. The heat transfer coefficient is used to model the heat transfer (convective and radiant) between the environment and the

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surface of the porous material (walls, furniture…). The mass transfer coefficient models the moisture transfer between the air and the porous material [13]. They have to be determined indirectly through empirical or analytical correlations or from CFD calculations. Often the heat and mass transfer analogy is used to convert heat transfer coefficients into mass transfer coefficients. Steeman et al. [14] however showed that this analogy does not always apply.

CFD on the other hand does not require transfer coefficients to model the interaction between the fluid and solid interface. At the same time CFD allows the analysis of complex geometries and provides detailed information on temperature and humidity distributions in the air. One major drawback of CFD is the high computational cost. Therefore, up till now, applications are limited to the study of microclimates and building details.

Whatever coupling approach is used, HAM models still need proper input data like boundary conditions, initial conditions and material property data. Extensive databases for these material properties can be found in literature [6,15,16]. However, recent studies revealed a large spread of some of these material properties when the same material was measured by different laboratories [16,17]. It is often not clear how this will affect the model outcome.

This paper highlights the importance of a sensitivity analysis for newly developed coupled HAM models. These models need a lot of material property data as input which introduce uncertainty to the model outcome. Therefore an elaborate sensitivity analysis is performed on a recently developed coupled CFD-HAM model [12]. The first part of this paper gives a brief description of the model. This model is then used to simulate air flow over a gypsum board surface. In the reference case predefined material properties are used. Afterwards different input parameters are evaluated based on a so-called One-at-a-Time sensitivity analysis. Also the air velocity, inlet temperature and humidity and the impact of hysteresis modelling are evaluated.

Finally uniform modelling of gypsum board is investigated. Gypsum board is built up out of layers (finishing paper and gypsum) but modelled with averaged material properties. This modelling approach is compared to an approach where each layer is modelled separately.

2. Model

Standard CFD packages do not include a HAM model to simulate the interaction with porous materials. Therefore a new model was added to an existing CFD package (Fluent®). This model is discussed more detailed in Steeman et al. [12]. In this paper only a short overview of the modelling approach is given.

Heat and moisture transfer in the air, porous material and at the interface is modelled in its full complexity. This makes the model very useful for the assessment of moisture related problems in microclimates.

A direct coupling approach is used. This implies that the computational domain encloses the air region as well as the porous material and both domains are solved by one and the same solver. Nevertheless, for each region (porous material or air) a different set of equations has to be solved.

By introducing the latent heat into the equations for heat transfer, the influence of phase change in the porous material is captured and the variation of temperature in the porous material can also be evaluated.

2.1. Heat and moisture transfer in the air

The air is modelled as an incompressible ideal gas. In this case the energy and moisture transport equations reduce to equations (1) and (2). Note that for the transported variables, temperature, T [K], is chosen for the energy equation and the mass fraction of water vapour, Y [kg/kg], for the moisture transport equation. The same transport variables are used in the transport equations for the porous material.

$$\frac{\partial}{\partial t}(\rho_{air}CT) + \nabla\cdot(\vec{v}\rho_{air}CT) = \nabla\cdot\left(\lambda_{air}\nabla(T) - (C_{vap} - C_{air})\vec{g}T\right) \tag{1}$$

$$\frac{\partial}{\partial t}(\rho_{air}Y) + \nabla\cdot(\rho_{air}\vec{v}Y) = \nabla\cdot(\rho_{air}D\nabla(Y)) = -\nabla\cdot\vec{g} \tag{2}$$

with

$$C = YC_{vap} + (1-Y)C_{air} \tag{3}$$

In these equations ρ_{air} [kg/m^3] is the density of the humid air, C_{vap} [J/kg K] is the specific heat capacity of water vapour, C_{air} [J/kg K] is the specific heat capacity of air and C [J/kg K] is the weighted average specific heat capacity according to equation (3), λ_{air} [W/m K] is the thermal conductivity of air and g [kg/m^2 s] the water vapour diffusion flux. D [m^2/s] is the diffusion coefficient of water vapour in air. The first term on the left hand side of each transport equation is the storage term, the second term represents the convective term while the right hand side represents the transport by diffusion.

2.2. Heat and moisture transfer in porous materials

For the porous material zone the following assumptions are made in the model:

- No air transfer occurs.
- Liquid transfer is not dominant.
- Moisture storage only depends on relative humidity.
- The temperature remains below the boiling point.
- There is no radiative transfer inside the porous material.

The model is only valid in the hygroscopic range (RH < 98%). Here moisture transfer by equivalent vapour diffusion is dominant. This implies that the moisture transfer can be modelled by a single water vapour diffusion coefficient. Equations (4) and (5) describe the moisture transfer and the heat transfer in the porous material. Again, temperature T and vapour mass fraction Y are used as the transported variables. Note how latent heat of vaporization L_{vap} (2.5×10^6 J/kg) appears in equation (5). Due to the capillary action of the porous material, part of the water vapour entering the porous material condenses, even at relative humidity lower than 100%. On the other hand liquid water evaporates from the pores when the porous material dries out. This phase change is accompanied by a latent heat effect. At low relative humidity (RH < 40%), sorption and desorption are governed by adsorption of water molecules at the porous walls. This is accompanied by a heat of adsorption. For this model heat of sorption is assumed to be equal to the latent heat of vaporization. This assumption is often used in hygroscopic modelling [3].

$$\frac{dw}{dt} = -\nabla\cdot\vec{g} \Leftrightarrow \frac{\partial w}{\partial RH}\frac{\partial RH}{\partial Y}\frac{\partial Y}{\partial t} + \frac{\partial w}{\partial RH}\frac{\partial RH}{\partial T}\frac{\partial T}{\partial t} = \nabla\left(\rho_{air}\frac{D}{\mu}\nabla(Y)\right) \tag{4}$$

$$\begin{aligned}\frac{dE}{dt} &= \nabla\cdot\left(\lambda_{mat}\nabla(T) - \left((C_{vap}-C_{air})T + L_{vap}\right)\vec{g}\right) \Leftrightarrow \rho_{mat}C\frac{\partial T}{\partial t} \\ &\quad + C_{liq}T\frac{\partial w_{liq}}{\partial t} + (C_{vap}T + L_{vap})\frac{\partial w_{vap}}{\partial t} \\ &= \nabla\cdot\left(\lambda\nabla(T) - \left((C_{vap}-C_{air})T + L_{vap}\right)\vec{g}\right)\end{aligned} \tag{5}$$

with