Building and Environment 45 (2010) 2202–2217

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Experimental validation and sensitivity analysis of a coupled BES–HAM model

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ARTICLE INFO

Article history:
Received 22 January 2010
Received in revised form
8 April 2010
Accepted 10 April 2010

Keywords:
HAM model
TRNSYS
Validation study
Sensitivity analysis
Moisture buffering

ABSTRACT

In this paper the ability of a coupled BES–HAM model to reproduce realistic data is evaluated by comparing numerical results with measured data from a climatic chamber experiment. Calcium silicate plates are introduced into a test room and a small calcium silicate sample is installed in one of the walls. The response of the test room to relative humidity variations of the supply air is evaluated, while the supply air temperature is kept constant. The measurements confirm that due to the presence of hygroscopic materials in the test room, the relative humidity variations in the room are damped. The calculated temperature and relative humidity in the middle of the test room are well within the uncertainty interval of the measurements. On the other hand the coupled model predicts a larger damping and phase shift of the relative humidity variations inside the sample, yet the agreement between the calculated and the measured temperatures in the sample proves to be good. Finally, a sensitivity analysis is performed to evaluate the dependence of the numerical results on the uncertainty of the input parameters. It is demonstrated that by using a lower vapour resistance factor for the calcium silicate material, the agreement between the measured and calculated data is improved.

1. Introduction

Hygroscopic materials are able to absorb water vapour as the relative humidity increases and release water vapour if the relative humidity drops. As a result the indoor relative humidity peaks are damped and therefore these materials may contribute to a more stable indoor climate [1,2]. Apart from the building envelope, the hygroscopic content of a room or a building also includes furniture and furnishings which often consist of porous materials. While the envelope is mainly characterized by materials such as uncovered concrete, wooden floors, brick walls, etc, furnishings usually consist of lightweight materials such as papers, books, textiles, untreated wood, which are part of the interior of most buildings (e.g. dwellings, libraries…).

Since hygroscopic materials reduce relative humidity variations, not including them when predicting the indoor relative humidity will lead to incorrect estimations. Yet an accurate prediction of the indoor relative humidity is indispensable for numerous building applications, ranging from the assessment of the indoor climate to guarantee the conservation of valuable objects, e.g. in museums and libraries [3–5], to preventing moisture-induced damage to envelopes (e.g. by mould and condensation). Furthermore, literature proves that a correct prediction of the indoor relative humidity is important to evaluate and size humidity-controlled HVAC systems such as indirect evaporative cooling or humidity-controlled ventilation [6,7].

Currently available multizone Building Energy Simulation (BES) tools, e.g. TRNSYS, EnergyPlus [8,9], generally focus on the prediction of thermal comfort and energy use and simplify moisture buffering in hygroscopic materials. They enable to calculate the temperature in buildings with respect to the outside climate, occupancy and the interaction with the air handling unit. So far simplified models, such as the effective capacitance model and the effective moisture penetration depth model in TRNSYS, are not suited to describe moisture buffering in a detailed way since they assume isothermal conditions, periodic moisture loads and constant material properties [10]. On the other hand transient HAM (Heat, Air and Moisture) models allow to describe the combined heat and moisture transfer processes in complex porous building structures in detail and are appropriate to account for the hygrothermal interaction between the building air and the porous surfaces.

For applications on building scale, a coupled BES–HAM model is interesting since it allows for long term calculations and complex building geometries. In contrast, on object scale, a coupled CFD–HAM model allows the assessment of the microclimate around valuable artefacts [11].

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0360-1323/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.buildenv.2010.04.003

Previously, a transient 1D HAM model was integrated into the multizone BES model TRNSYS [12,13]. The coupled model enables to predict the boundary conditions for HAM in detail, while on the other hand the effect of the latent heat on the room conditions is taken into account. To evaluate whether this coupled TRNSYS–-HAM model is able to reproduce realistic data, a validation with measured data from a climatic chamber experiment is required. Therefore, the input parameters, e.g. boundary conditions, initial conditions, exposed hygroscopic surface…, necessary in the numerical model have to be precisely measured during the experiments. Additionally, material properties of hygroscopic materials have to be well known. Previous experiments in literature sometimes suffer from the problem that some of the measured data are insufficient or lacking. For instance Svennberg reported moisture buffering experiments in a room-size test cell in which furniture and furnishings were successively introduced [2]. While the room temperature was kept constant the humidity response of the test cell was measured. Uncertainties were due to some unexpected moisture buffering in the test room, a not well registered exposed hygroscopic area (i.e. of paper and books), uncertain material properties…. These uncertainties must be excluded in order to obtain a good agreement between the measurements and the numerical results. Another single room buffering experiment was reported by Fazio et al. In this test campaign the moisture buffering behaviour of two internal finishing materials (i.e. uncoated gypsum and pine paneling) and of furniture (i.e. bookshelf with books and full furnished room) was investigated [14].

Since a general assumption of BES models is that state variables (i.e. temperature and vapour pressure) are equal in every point of the room, a well-mixed air condition in the test chamber has to be guaranteed in order to validate the coupled BES-HAM model.

This paper focuses on an experimental validation of a coupled TRNSYS–HAM model by means of climatic chamber experiments. The paper starts with a brief description of the coupled BES–HAM model. Next, a description of the test facility and the experiments carried out in the climatic chamber is given. The experimental results are discussed. Finally, the sensitivity of the numerical results to the uncertainty of different parameters in the experiment is investigated.

2. Coupled BES–HAM model

The HAM model describes one-dimensional heat and mass transfer in porous materials. The model considers all moisture to be transported in the vapour phase (liquid moisture flow is excluded). This assumption is valid as long as the moisture content of the hygroscopic material remains below the hygroscopic moisture content (RH < 98%). Since the moisture penetration depth for daily or yearly humidity variations is limited to the first centimeters or millimeters of the wall, the hygroscopic materials which mainly contribute to the hygric inertia of buildings generally consist of finishing materials. Consequently the hygroscopic materials are situated in the hygroscopic region and the assumption is generally fulfilled for the intended building applications.

Equations (1) and (2) present the conservation equations for heat and mass transfer in porous materials. Following assumptions are made:

- The temperature remains well below the boiling point
- No convection occurs inside the porous structure, i.e. no air transfer
- Gravitational effects are neglected
- No radiative transfer occurs inside the porous material

The coupling between vapour transfer and storage in the air and the porous material requires the use of a mass transfer coefficient β, which yields to the boundary condition at the material surface (Eq. (3)).

$$\frac{\partial E}{\partial t} = (\rho_{\text{mat}}c_{\text{mat}} + c_l w)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[\lambda(w)\frac{\partial T}{\partial x}\right] + h_v\frac{\partial}{\partial x}\left[\delta(RH)\frac{\partial p}{\partial x}\right] \quad (1)$$

$$\frac{\partial w}{\partial t} = \frac{\partial w}{\partial RH}\frac{\partial RH}{\partial t} = \rho\xi(RH)\frac{\partial RH}{\partial t} = \frac{\partial}{\partial x}\left[\delta(RH)\frac{\partial p}{\partial x}\right] \quad (2)$$

$$\beta_i(p_i - p_s) = -\delta(\phi)\cdot\frac{\partial p}{\partial x}\Big|_s \quad (3)$$

with E the internal energy (J), c_{mat} and c_l the specific heat capacity of the dry material and of liquid water respectively (c_l = 4187 J/kgK), λ(w) the moisture-dependent thermal conductivity (W/mK) and h_v the latent heat of vaporization (h_v = 2500 kJ/kg). w is the moisture content (kg/m^3) and RH is the relative humidity (–), ρξ(RH) and δ(RH) are the volumetric moisture capacity (kg/m^3) and the vapour permeability (kg/Pam^{2}s). p_i and p_s are the vapour pressure in the room air and at the surface respectively (Pa), β is the convective mass transfer coefficient (kg/Pam^{2}s).

Both conservation equations for mass and energy transfer are coupled since the moisture content w is a function of the relative humidity, and hence of the temperature: w = f (RH) = f (T, p). On the other hand the internal energy E is a function of temperature and moisture content: E = f (T, w). Furthermore the latent heat of evaporation affects the heat transfer in the wall, material properties are function of the moisture content in the wall (Eq. (4)–(6)) and the saturation vapour pressure is a non-linear function of the temperature in the wall.

$$\text{Sorption isotherm}: w = a\left(1 - \frac{\ln(RH)}{b}\right)^{-1/c} \quad (4)$$

$$\text{Water vapour resistance factor}: \mu = (a + b\cdot\exp(c\cdot RH))^{-1} = \frac{\delta_a}{\delta} \quad (5)$$

$$\text{Thermal conductivity}: \lambda = a + bw \quad (6)$$

Equations (1) and (2) are simultaneously solved by means of a control volume method combined with an implicit temporal discretization scheme. The HAM model iterates between these equations until convergence is obtained for all nodes. Material data are described by (Eq. (4)–(6)) and are updated after each iteration [15]. Note that hysteresis is not included in the HAM model, and only the main absorption isotherm, given by Eq. (4), is modelled.

The HAM model is coupled with the multizone building model in TRNSYS. The coupled model accounts for the effect of latent heat on the heat balance of the room and includes the effect of a moisture-dependent thermal conductivity. In contrast to previously coupled models [16,17], the original multizone building model is retained. Unlike the simplified models available in BES, the coupled HAM model enables to account for the effects of temperature variations on moisture storage, to calculate vapour diffusion through the envelope, to use moisture-dependent material properties, to model multiple hygroscopic surfaces in a simulation and to evaluate temperature and humidity in a porous wall. Two verification exercises previously proved that the heat and mass conservation equations are implemented correctly in the HAM model and that the wall model and the multizone model in TRNSYS are coupled accurately [12,13].