

Validation of a coupled BES-HAM model with experimental data

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ABSTRACT: The room moisture balance of buildings typically consists from moisture production, convective moisture exchange by ventilation or infiltration, moisture gains or removals by HVAC systems and moisture absorption and desorption by interaction with hygroscopic surfaces. In typical building energy simulation (BES) programs e.g. TRNSYS the latter is generally simplified since the focus is mainly on predicting temperature and energy use. On the other hand, many building applications require an accurate prediction of the interior relative humidity from the design stage. This paper presents the validation of a recently developed BES-HAM model by experiments in a climatic chamber (6.12m^3). In one of the walls of a well-insulated and vapour tight test chamber a calcium silicate test sample ($0.20 \times 0.20 \times 0.10\text{m}^3$) was installed. Additionally large calcium silicate plates were introduced in the test chamber. In the experiments the response of a test chamber to variations of the supply air relative humidity was investigated: the relative humidity was 50% for two hours, after a step change to 70% was imposed for two hours. This cycle was repeated several times. The measured temperature and the relative humidity both in the test chamber as on different depths in the calcium silicate sample were compared with calculated data and gave satisfactory agreement. Furthermore, the possible influence of hysteresis on the simulation results was evaluated.

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 climate (Simonson 2002, Svennberg 2004). For numerous building applications, a correct prediction of the relative humidity in buildings is necessary from the design stage. Steeman showed that accurately describing the hygrothermal interaction between the indoor air and hygroscopic books in a library has an important influence on the predicted indoor climate in the library (Steeman & De Paepe 2010). Yet the indoor climate is highly important to guarantee the conservation of valuable books (Pavlogeorgatos 2003). On the other hand a correct representation of moisture buffering is necessary to evaluate and size humidity-controlled HVAC systems such as indirect evaporative cooling or humidity controlled ventilation (Steeman & Janssens 2009, Woloszyn 2009) and to prevent moisture-induced damage to envelopes e.g. by mould and condensation.

Building Energy Simulation (BES) models e.g. TRNSYS (SEL 2004) calculate the temperature in buildings with respect to the outside climate, occupancy and the interaction with the air handling unit. While BES models focus on the prediction of thermal comfort and energy use, often they are not well-suited to describe moisture buffering in a detailed way. In contrast simplified models are used and assume isothermal conditions, periodic moisture loads and constant material properties (Janssens & De Paepe 2005). On the other hand transient HAM (Heat, Air and Moisture) models 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.

Coupling models on building scale (BES) with models on material level (HAM) is interesting: while BES models allow for a better prediction of the boundary conditions for HAM, HAM allows to predict the relative humidity in buildings in a more detailed way. Furthermore, coupled BES-HAM models allow for long term calculations and complex building geometries.

Recently, a transient 1D HAM model was integrated into the multizone BES model TRNSYS

(Steeman 2010). To evaluate whether the coupled BES-HAM is able to reproduce realistic data, a validation with measured data from a climatic chamber experiment is necessary. 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.

This paper focuses on the experimental validation of a coupled TRNSYS-HAM model by means of a climatic chamber experiment. First a brief description of the coupled model is given. Next, the test facility and the experimental procedure are amplified. Finally, the results of the validation study are presented and the effect of hysteresis is discussed.

2 COUPLED BES-HAM MODEL

A short description of the coupled BES-HAM model will be given first.

2.1 Heat and mass transfer in porous materials

The HAM model describes 1D heat and mass transfer in porous materials due to vapour diffusion. This assumption is valid in the hygroscopic range ($RH < 98\%$). Because the moisture penetration depth for daily or yearly humidity variations is generally limited to the first cm's or mm's of the wall, the hygric inertia of buildings generally consists from finishing materials and furnishings. Hence this assumption is fulfilled. Hysteresis is neglected in the model, only the main absorption isotherm is modelled.

Heat and mass transfer (Eq.1-2) in porous materials are coupled due to: (1) moisture dependency of material properties i.e. moisture capacity $\rho\xi(RH)$, vapour permeability $\delta(RH)$ and thermal conductivity $\lambda(w)$; (2) latent heat effects due to absorption and desorption; (3) saturation vapour pressure is a non-linear function of temperature.

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

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

with E the internal energy (J/m^3), ρ_{mat} and c_{mat} the density and specific heat of the dry material and c_l the specific heat of liquid water ($4187J/kgK$). T is the temperature (K), RH the relative humidity (%), w is the moisture content (kg/m^3) and p is the partial vapour pressure (Pa). h_v is the latent heat of evaporation ($2.5 \cdot 10^6 J/kg$).

Eq. 1 and 2 are solved simultaneously by means of a control volume method combined with a temporal discretization scheme.

2.2 Coupling with BES

The developed HAM model is coupled with the multizone building model in TRNSYS. The multizone building is characterized by a well-mixed air assumption, which means that temperature and vapour pressure are equal in each point in the room.

During each time step a vapour flow is exchanged between the HAM model and the multizone building model. Furthermore a feedback coupling allows to account for the effect of moisture-dependent thermal conductivity of the porous material and latent heat due to absorption and desorption. For more details about the coupling between both models the reader is referred to Steeman (2010) and Steeman and Janssens (2010).

In contrast to simplified models, the coupled BES-HAM model allows to account for (1) different hygroscopic surfaces in a room, (2) moisture-dependent thermal conductivity and influence of latent heat, (3) vapour diffusion through the construction, (4) an evaluation of the temperature and relative humidity in the wall. As a result, the coupled model predicts the relative humidity in a more correct way.

The model was previously verified by two verification exercises (Steeman 2010). To check whether the coupled BES-HAM model is able to reproduce realistic results, a validation study is performed.

3 DESCRIPTION OF EXPERIMENTS

3.1 Test facility

The test facility consists of an outer and an inner chamber (Fig. 1). The outer chamber is mainly used to minimize effects from the surroundings, for instance day/night temperature fluctuations. The actual test chamber is the inner chamber and measures 1.8m in width, 1.89m in depth and 1.8m in height (volume $6.12m^3$).

The wall panels of the inner and outer room consist of 6cm rigid high density polyurethane foam ($\lambda=0.0223W/mK$), sprayed in between two skins of white polyester lacquered, galvanized steel plate (thickness 0.63mm). The wall opposite to the air inlet is a test wall, consisting of 6cm mineral wool ($\lambda=0.04W/mK$) in a timber frame. A closed air handling unit (AHU)-circuit draws air from the inner room with a recirculation fan. The ventilation air inlet and outlet are positioned respectively at the top and bottom of the wall opposite to the test wall. The air is successively cooled and dehumidified by a cooling coil, reheated by a resistive heater and humidified to the required relative humidity (Fig. 1).

For further information on the implemented control strategy the reader is referred to (Van Belleghem 2008). The air change rate can vary between 0h^{-1} and 10h^{-1} . The air tightness of both the inner room and the AHU-circuit was measured with a CO_2 tracer gas decay experiment and proved satisfactory (0.033h^{-1}).

$$\lambda(w) = 0.06 + 5.6 \cdot 10^{-4} w \quad (3)$$

$$\mu(RH) = (0.16 + 2.6 \cdot 10^{-6} \cdot \exp(6.84RH))^{-1} \quad (4)$$

$$w(RH) = 110.9 \cdot \left(1 - \frac{\ln RH}{0.0015}\right)^{-1.76} \quad (5)$$

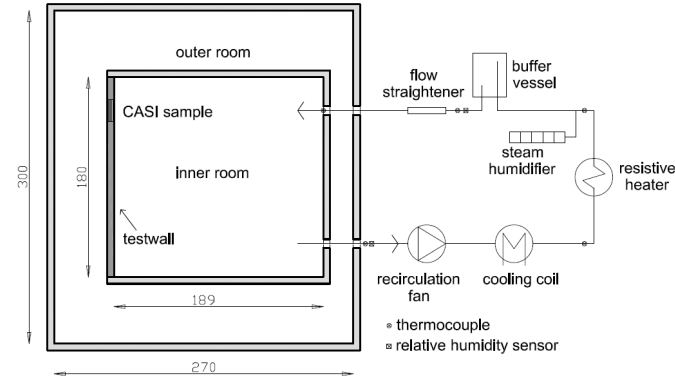


Figure 1. Schematic representation of the test facility and the air handling unit.

3.2 Test sample

In the test wall a calcium silicate sample is positioned (20cm x 20cm, thickness 10cm). Figure 2 represents a section of the test sample. The sample is sliced into four layers of respectively 10mm, 15mm, 25mm and 50mm thickness. Between each two material layers, a thermocouple (accuracy $\pm 0.1^\circ\text{C}$) and a small capacitance relative humidity sensor accuracy $\pm 1.4\%\text{RH}$) are placed. The test sample is placed in a plexiglass box. The four sides and the back side are sealed with paraffin to avoid moisture exchange. At the sides and the back the sample is insulated with 4cm mineral wool to avoid heat losses/gains to the surroundings.

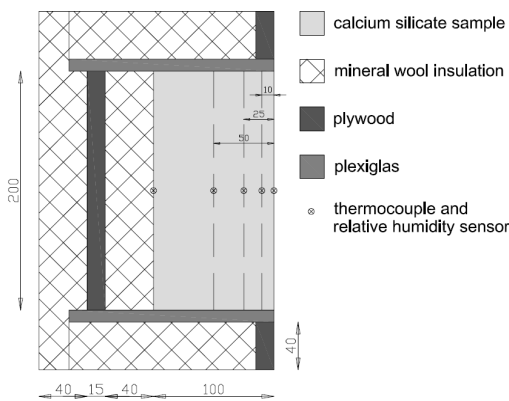


Figure 2. Schematic representation of the test sample.

Calcium silicate is a highly hygroscopic material which renders it suitable to validate the BES-HAM model. Material properties are given by Eq.(3)-Eq.(5). The density ρ is 270kg/m^3 and the heat capacity c is 1000J/kgK (Roels 2003). μ -dry is 5.42, the main absorption isotherm is shown in Figure 7.

3.2.1 Experiment

Apart from the calcium silicate sample in the test wall, four additional calcium silicate plates (each plate $950 \times 70 \times 10\text{mm}^3$) are placed in the test room. The plates are sealed at the four sides with moisture proof tape to ensure 1D vapour diffusion in the plates. The total exposed calcium silicate area is $\pm 5.2\text{m}^2$. Figure 3 shows a schematic representation of the layout of the plates (a) and a view on the plates in the test room (b). Beforehand the calcium silicate plates are preconditioned in the test room for four days at 25°C and $50\%\text{RH}$. During the actual experiment the temperature of the ventilation supply air is kept at 25°C while a step change in relative humidity is imposed from 50% to 70% for two hours each. This cycle is repeated several times, until quasi-stationary conditions are obtained in the test room. A supply air change rate of 5h^{-1} is considered.

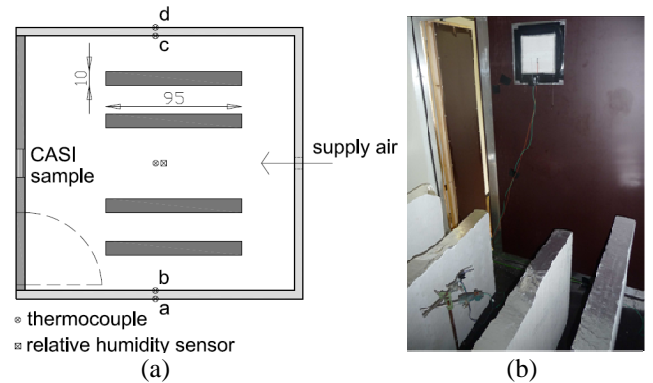


Figure 3. Layout of the calcium silicate plates in the test room: (a) top view of the room and (b) view in the test room

In the middle of the test room a thermocouple and a small capacitance relative humidity sensor measure the room conditions (accuracy $\pm 0.1^\circ\text{C}$ and $\pm 1.4\%\text{RH}$), as indicated in Figure 3a. Additionally the temperature and relative humidity at different depths in the calcium silicate sample in the test wall are measured during the test (Fig. 2). During the experiment, thermocouples are placed against the inside and outside surface of the side walls of the test chamber, as indicated by positions a to d in Figure 3a, to measure the boundary conditions of the inner room. In order to minimize the heat losses to the outer room, a small heater (i.e. a light bulb) is placed in the outer chamber (set point 25°C).

Supply air conditions (i.e. temperature, relative humidity and mass flow rate) are well registered during the test. All data are recorded every $\pm 3\text{sec}$ dur-

ing the experiment. Next, an identical experiment is performed without hygroscopic material in the test room. In this case the calcium silicate plates are removed and the calcium silicate sample in the test wall is covered by a plastic foil to prevent it from moisture uptake or release.

4 RESULTS

4.1.1 Hygroscopic vs. non-hygroscopic experiment

In Figure 4 the relative humidity course in the test room with and without the calcium silicate plates is shown. The available calcium silicate clearly damps the relative humidity variations. Even with a relatively large air change rate (i.e. $5h^{-1}$) this effect proves to be significant.

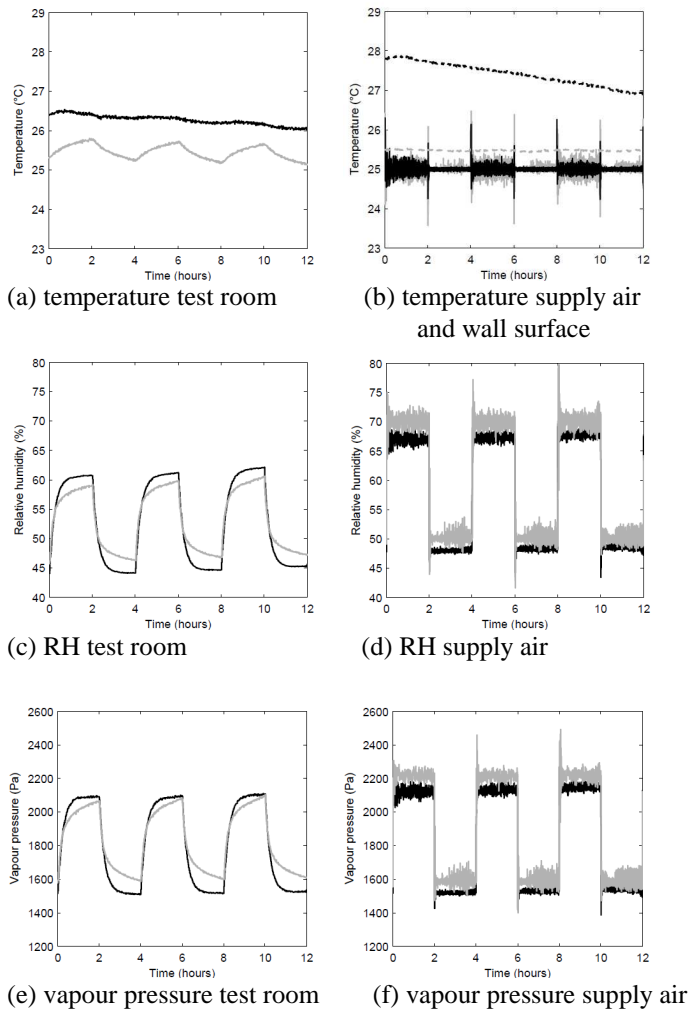


Figure 4. Measured temperature, relative humidity and vapour pressure in the test room (left) and of the supply air (right): non-hygroscopic (black) and hygroscopic (grey) experiment.

The average relative humidity amplitude is 17.1%RH without calcium silicate in the test room, compared to 13.6%RH when the hygroscopic material is introduced (Fig. 4c). The maximum and

minimum relative humidity in the empty room are 43.9%RH and 62.1%RH respectively. When calcium silicate is introduced into the room this is respectively 45.6%RH and 60.6%RH. Furthermore, the influence of the latent heat of evaporation is clearly shown in Figure 4a. When the relative humidity in the test room increases to 70%RH the calcium silicate plates start to absorb water vapour, which coincides with release of latent heat. A clear increase of the temperature measured in the test room is noted. When the relative humidity of the supply air drops to 50%RH, the plates start to release water vapour to the room air. This is clearly associated with an uptake of latent heat. As a result, the temperature in the test room varies between 25.1°C and 25.7°C, the average temperature variation is 0.4°C.

At the right side of Figure 4 the boundary conditions during both experiments are presented: Figures 4b, 4d and 4f respectively show the temperature of the supply air and the average temperature at the wall surface of the test room, the RH and the vapour pressure of the supply air. The average temperature at the wall surface of the test room is the average of the temperatures measured at positions a and d indicated in Figure 3a. Note that the boundary conditions of the test room, i.e. the temperature of the outer room and hence the surface temperature of the test room, were not identical in both experiments. The non-hygroscopic experiment was conducted in late summer, resulting in an average surface temperature between 27°C and 28°C. The experiment in which calcium silicate is introduced was carried out in autumn. During this experiment the surface temperature was on average 25.5°C (indicated by the dashed lines in Fig. 4b). Due to this, the temperature measured inside the test room is higher during the non-hygroscopic experiment. Because the boundary conditions in both experiments are not identical the supply vapour pressure is slightly lower in the experiment without calcium silicate in the test room (Fig. 4f). This can be explained by the fact that the temperature and relative humidity sensor which control the supply air conditions are not installed at the same position in the AHU-circuit. The relative humidity sensor is positioned earlier in the circuit (indicated by the small square between the buffer vessel and the flow straightener in Fig. 1), while the temperature sensor measures the supply air temperature just before entering the test room. In the experiments the desired supply air temperature is 25°C. When the temperature of the surroundings is higher than 25°C (here 27°C to 28°C), the temperature in the AHU-circuit at the position of the relative humidity sensor will be lower than 25°C because the air will still heat up along the circuit. As a result the absolute humidity added to the supply air by the humidifier to obtain a certain relative humidity, and hence the vapour pressure of the supply air, will be less high than with a lower ambient temperature. Consequently, small

differences in the absolute vapour content introduced to the test room are observed between both tests. Nevertheless, the stabilizing effect of the calcium silicate on the indoor climate is clearly shown.

4.2 Model settings

Next the coupled BES-HAM model was validated with the measurements in the climatic chamber. In the calculations one HAM model represents the calcium silicate sample in the test wall while the second HAM model represents the calcium silicate plates in the middle of the test room. 1D vapour diffusion in the calcium silicate plates is assumed. The HAM model describing the calcium silicate sample in the test wall is discretized into 20 equidistant calculation nodes of 5mm each. Preliminary calculations showed that a finer mesh did not significantly improve the calculated temperature and relative humidity at different depths in the sample. In the second HAM model the wall is discretized into 10 control volumes with a grid concentration factor 1. The node size ranges from 6.44mm at the edges to 14.34mm in the middle. Preliminary calculations with a finer grid (20 calculation nodes) showed no significantly different results for the calculated temperature and relative humidity in the test room.

The average temperature at the wall surface of the test room is used as a boundary condition in the calculations and is read in every 5s. Measured values of temperature, relative humidity and mass flow rate of the supply air are used every 5s as an input in the simulations. The average temperature and relative humidity measured at various depths in the calcium silicate sample at the beginning of the experiment are used as the initial condition for the calcium silicate material in the calculations. The simulation time step used is 5s.

In the calculations, the estimated convective heat and mass transfer coefficient are $3.5\text{W/m}^2\text{K}$ and $2.0 \cdot 10^{-8} \text{ kg/Pam}^2\text{s}$ respectively.

4.3 Validation results

Temperature and relative humidity in the test room

Figure 5 compares the calculated and measured relative humidity and temperature in the test room (last 3 RH cycles). A satisfactory agreement is found. The amplitude of the relative humidity variations in the test room is slightly underpredicted by the model: the predicted average relative humidity amplitude is 15.1%, while the measured amplitude is 13.7%. Maximum relative humidity values are predicted well (i.e. respectively 66.6%RH measured and 66.0%RH calculated), but the lower values are underestimated by the calculations (i.e. 52.2%RH measured and 50.9% calculated). On the other hand the predicted temperature variations are well within the

uncertainty interval and a good agreement with the measured data can be observed (temperature between 25.1°C and $25.6\text{--}25.7^\circ\text{C}$ and measured and calculated temperature variation both 0.4°C).

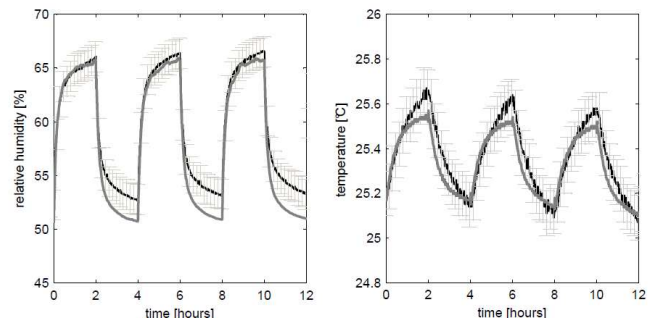


Figure 5. Measured (black) and calculated (grey) relative humidity and temperature in the test room

Temperature and relative humidity in the test sample

Apart from the conditions inside the test room, the temperature and relative humidity courses on various depths in the calcium silicate sample situated in the test wall are compared with the measured data. In Figure 6 the measured and calculated relative humidity and temperature respectively at 10mm, 25mm and 50mm in the sample for the last three RH cycles are given.

The predicted relative humidity at 10mm in the sample is higher than the measured relative humidity, i.e. the calculated average RH is 56.1% while the measured average RH is 54.7%. Furthermore the calculated amplitude of the relative humidity variations (i.e. 4.0%RH) is smaller than the measured amplitude (i.e. 5.5%RH) at 10mm. This means that the vapour resistance considered in the simulations is either too high or the sorption is too high. On the other hand the predicted temperature course at 10mm in the sample agrees well with the measured temperature. The measured average temperature variation is 1.0°C , the calculated average temperature variation is 0.7°C .

At 25mm depth in the sample relative humidity variations are still noticeable in the measurements. The measured average relative humidity amplitude is 2.9%. However, the calculations show that the relative humidity is much more damped. An almost flat relative humidity course is predicted, the average relative humidity amplitude is only 0.7%. Furthermore the phase shift estimated in the calculations is larger than the phase shift observed in the measurements. Again, the measured and predicted temperature variation agree better. The measured temperature variation is on average 0.9°C while the calculated variation is 0.6°C .

At 50mm in the sample relative humidity is almost entirely damped out in the sample. Variations of only 1.1% relative humidity are measured. The calculations overestimate the stabilizing effect of the porous material. As at 10mm and 25mm depth in the

sample, the measured and the predicted temperature agree quite well. The measured and calculated temperature variations are respectively about 0.5°C and 0.3°C .

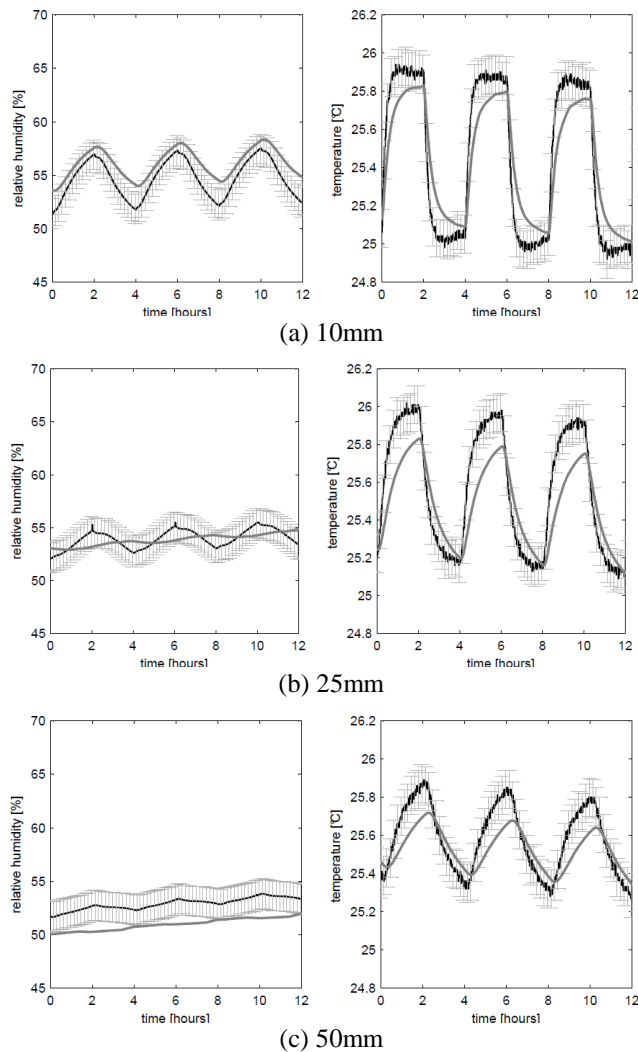


Figure 6. Measured (black) and calculated (grey) relative humidity and temperature at 10mm (a), 25mm (b) and 50mm (c) in the test sample

Note that a sensitivity analysis is needed to determine the parameters which are most decisive to the outcome of the simulations. For this, the reader is referred to Steeman & Van Belleghem (2010).

4.4 Influence of hysteresis

In the previous validation study, the main absorption isotherm was used to model vapour storage in the calcium silicate. However, in reality the sorption isotherm which determines moisture storage in the porous material depends on the history of the material and is situated between the main absorption and main desorption isotherm (intermediate scanning curves). The main absorption curve is only valid if the sample is wetted from an initially dry state.

In the HAMSTAD project (Roels 2003), different laboratories measured apart from the absorption isotherm also the desorption isotherm of the calcium

silicate samples. A large spread was observed between the results, various possible causes for this spread were reported e.g. a non-constant relative humidity in the desiccators. Due to the large uncertainty on the desorption isotherm, it is difficult to draw reliable conclusions.

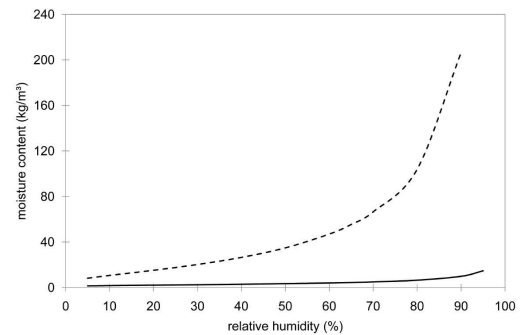


Figure 7. Main absorption (-) and main desorption (- -) isotherm (adapted from Roels 2003).

The moisture content of calcium silicate in desorption can increase more than ten times compared to the moisture content in absorption. For instance at 65%RH (which is situated in the relative humidity range of the climatic chamber experiments) in absorption a moisture content ranging from 0.015 to 0.02kg/kg is measured by different laboratories, compared to a moisture content varying from 0.061 to 0.32kg/kg in desorption at the same relative humidity. This indicates that hysteresis may have an effect on the temperature and relative humidity variations, both in the test room and inside the calcium silicate test sample. Figure 7 clearly shows that the moisture capacity of the porous material is higher in desorption than in absorption at the same relative humidity. At the same time, the actual sorption curve which is followed, and hence the history of the material or the hysteresis phenomenon, also affects the vapour resistance of the material. A higher moisture content of the material is associated with a higher vapour permeability or a decreased water vapour resistance factor.

In Figure 8 the temperature and relative humidity variations in the test room are shown. The dark grey line shows the variations calculated when using the absorption isotherm in the BES-HAM model, the light grey line gives the variations when the desorption isotherm is used. Note that in this case both in absorption and desorption the desorption isotherm is used, the same counts for the simulations in which the absorption isotherm is used. Figure 8 shows that simulations with the desorption isotherm result in smaller relative humidity variations in the test room than when the absorption isotherm is used. By consequence the calculations with the desorption isotherm show a larger vapour storage in the calcium silicate material. The average relative humidity variation in the test room is 12.7%RH, which agrees better with the measured relative humidity variation, i.e. 12.6%RH.

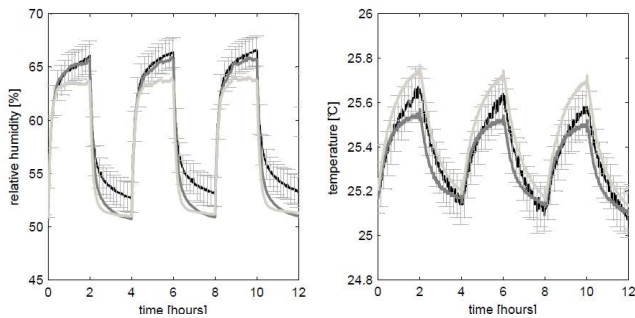


Figure 8. Relative humidity and temperature in the test room: measurements (black), absorption isotherm (dark grey) and desorption isotherm (light grey).

On the other hand the simulation in which the desorption isotherm is used predicts larger temperature variations in the test room than when the absorption isotherm is used. The average temperature variation in the test room measured and calculated with the desorption isotherm are both 0.5°C . Note that for the simulated temperature variations in Figure 8, in absorption the best fit is obtained when using the absorption isotherm in the calculations, while in desorption the simulation with the desorption isotherm gives the best agreement with the measurements.

5 CONCLUSIONS

In this paper a validation study of a coupled BES-HAM model was performed to check if the coupled model was able to reproduce realistic results. The response of a test room to humidity variations of the supply air was evaluated when calcium silicate plates were added to the room. During the experiments, the temperature and relative humidity in a well-insulated and vapour tight test room as well as on different depths in a calcium silicate sample were measured. A comparison between a hygroscopic and a non-hygroscopic experiment confirmed that the calcium silicate plates enabled to damp the relative humidity variations inside the test room. The agreement between the measured and predicted temperature and relative humidity in the test room gave satisfactory results. The relative humidity variations were slightly underestimated by the calculations. At 10mm inside the sample, the measured and calculated relative humidity and temperature agreed well. Deeper in the sample (i.e. at 25mm and 50mm) the predicted relative humidity reduction was overestimated by the coupled BES-HAM model. On the other hand, the agreement between the predicted and measured temperature was good. Simulations in which the desorption isotherm was used gave an indication of the possible effect of hysteresis and showed a larger vapour storage in the calcium silicate material. As a result the calculated relative humidity variations in the test room agreed better with the measured values.

ACKNOWLEDGEMENT

The results presented in this paper have been obtained within the frame of the project “Heat, air and moisture performance engineering a whole building approach” (IWT SBO-050451) and the research projects IWT-SB/51283/Steeman and IWT-SB/81322/Van Belleghem, funded by the Flemish Institute for the Promotion and Innovation by Science and Technology in Flanders. Their financial support is gratefully acknowledged.

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