Validation of a coupled CFD-HAM model with a climate chamber experiment on a small wall sample

Van Belleghem M., Steeman M., Janssens A., De Paepe M.

In: Proceedings of the 9th Nordic Symposium on Building Physics, Tampere, Finland 29 May – 2 June 2011, NSB2011.

Van Belleghem M., Steeman M., Janssens A., De Paepe M. Validation of a coupled CFD-HAM model with a climate chamber experiment on a small wall sample. Proceedings of the 9th Nordic Symposium on Building Physics, NSB2011, Department of Civil Engineering, Tampere University of Technology, Tampere, Finland, vol.1, ISBN 978-952-15-2574-2

Validation of a coupled CFD-HAM model with a full scale climate chamber experiment

Marnix Van Belleghem, M.Sc. [1]
Marijke Steeman, Ph.D. [2]
Arnold Janssens, Professor [2]
Michel De Paepe, Professor [1]

[1] Ghent University, Department of Flow, Heat and Combustion Mechanics, Belgium
[2] Ghent University, Department of Architecture and Urban Planning, Belgium

KEYWORDS: *Moisture experiment, climatic chamber, validation, HAM, CFD*

SUMMARY:
The presence of hygroscopic materials has a large impact on the moisture balance of buildings. Nowadays, HAM (Heat, Air and Moisture) models are widely used to investigate the role of hygroscopic materials on the performance of buildings, i.e. on the building envelope, the indoor climate and valuable objects stored within the building. Recently, these HAM models are being coupled to CFD (Computational Fluid Dynamics) models to study the moisture exchange between air and porous materials on a local scale (microclimates). Validation of these numerical codes is essential to gain confidence in the codes. However, available experimental data are rather scarce.

The first part of this paper focuses on the design of a new experimental setup to measure heat and moisture transport in a room sized climatic chamber. A dedicated air handling unit supplies the climate chamber with air at a predefined temperature and relative humidity. In one of the walls of the room a sample of calcium silicate is installed. While the supply air temperature is kept constant, a step change in relative humidity is imposed. Temperature and humidity in the room close to the sample and at various depths in the sample are continuously measured during the experiment.

In the second part of the paper these measurement are used to validate a newly developed coupled CFD-HAM model. Overall a good agreement between measurements and simulations was found.

1. Introduction

The hygrothermal behaviour of buildings and building envelopes plays an important role in the performance of buildings. In the last years, international research projects and researchers focused on a better understanding and prediction of this hygrothermal behaviour (ECBCS Annex 41). To understand the phenomena well, numerical tools, i.e. HAM (Heat, Air and Moisture) models, are used. These HAM models allow to simultaneously describe heat and mass transfer in hygroscopic building objects. A good overview of existing HAM models is given in the scope of Annex 41 (Woloszyn 2008).

A new trend in HAM modelling is the coupling of these models to CFD (Computational Fluid Dynamics) models. These models are used to calculate 3D temperature and velocity distributions in rooms in a detailed way. By coupling CFD with HAM, 3D local hygrothermal interaction between air and porous surfaces can be studied (Steeman 2009a, 2009b). They can be applied to predict the local microclimate around valuable objects e.g. around a painting (Steeman 2009b) or at the proximity of thermal bridges.

In order to gain confidence in the codes and to investigate whether they are able to predict realistic conditions well, validation of these tools is necessary. Although a lot of numerical research has been undertaken with respect to HAM models, experimental campaigns remain rather limited. Many recent works have often focused on numerical and analytical investigations rather than experimental investigations e.g. benchmark cases developed in HAMSTAD project (Hagentoft 2004) or Annex 41 Common Exercises (Woloszyn 2008). There is a need for more experimental data that quantifies HAM transport in porous building materials. Therefore a new experimental setup has been designed and built and is shortly discussed in this paper together with the results of the measuring campaign and the validation of a newly developed coupled CFD-HAM model.

2. Climate chamber design

2.1 Test chamber

The test facility consists of an outer and an inner chamber. The outer chamber is mainly used to minimize effects from the surroundings, for instance day/night temperature fluctuations, the inner chamber is the actual test chamber. It represents a small room measuring 1.8m in width, 1.89m in depth and 1.8m in height (volume 6.12m^3). The test facility is schematically represented in FIG 1. The wall panels of the inner and outer room consist of 6cm rigid high density polyurethane foam with a thermal conductivity of 0.0223 W/m·K, sprayed in between two skins of white polyester lacquered, galvanized steel plate (thickness 0.63mm). The panels have an overall U-value of 0.372 W/m^2·K according to the manufacturer. The floor consists of multiplex panels with a phenol anti-slip surface reinforced with glass fibre. Its thermal conductivity is 0.366 W/m·K. The wall opposite to the air inlet is a test wall, consisting of 6cm mineral wool (λ~0.04W/m·K) in a timber frame. A calcium silicate sample is positioned in the test wall. This test sample is discussed more in detail later. Note that in order to minimize the heat losses to the outer room, a small heating device (i.e. a light bulb) was placed in the outer chamber.

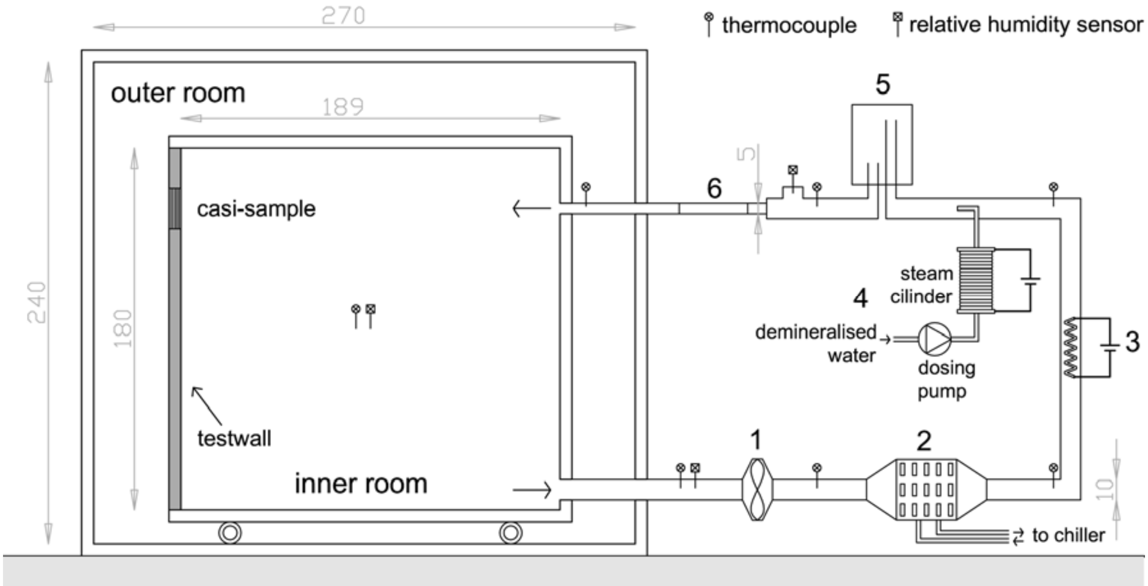

FIG 1. Schematic representation of the climate chamber and the air handling unit (dimensions in cm): (1) recirculation fan, (2) cooling coil, (3) resistive heater, (4) steam humidifier, (5) buffer vessel and (6) flow straightener.

2.2 Air handling unit

A closed-looped air handling unit (AHU) 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, as indicated in FIG 1. Temperature, relative humidity and velocity of the entering air jet are closely controlled with a dedicated air conditioning system. The air is successively cooled and dehumidified by a cooling coil. When the air reaches its dew point, condensation starts and the humidity ratio of the air drops. The air at lowered temperature passes through a heat exchanger where a resistive heater heats up the air to the desired temperature. By heating the air, its relative humidity drops. Steam is then added to the dry air to humidify the air to the required relative humidity set point.

The steam humidifier works as follows: a dosing pump supplies a heated cylinder with demineralised water. The cylinder is kept at a high temperature (± 300°C) by a resistance wire that is wrapped around the cylinder. The water that enters the cylinder immediately evaporates when it comes in contact with the hot cylinder wall. This way the time delay between the moment the liquid water enters the cylinder and the moment this water leaves the cylinder as steam is minimal. The dosing pump has a manually adjustable stroke length and the rotation speed is controllable. The produced steam is then injected into the air duct. Contact of the steam with colder duct walls must be kept to a minimum to avoid condensation.

The air then passes through a buffer vessel with a volume of 25 litres. The buffer vessel is placed not far from the steam injection point in the air circuit to ensure a good mixture of the water vapour in the air. This buffer vessel levels out the relative humidity fluctuations caused by the humidification system and damps out temperature fluctuations. Finally a flow straightener ensures a fully developed flow pattern when the air enters the climate chamber.

2.3 Test sample

In the test wall a calcium silicate sample is positioned (20cm x 20cm, thickness 10cm). The test sample is placed directly opposite to the air inlet of the test room. FIG 2a represents a section of the test sample; FIG 2b shows a front view of the calcium silicate sample in the test wall. The sample is sliced into four layers of respectively 10mm, 15mm, 25mm and 50mm thickness. Between each two material layers, in the middle, a thermocouple and a small capacitance relative humidity sensor are placed. The positions of the thermocouples and relative humidity sensors are indicated in FIG 2a. The layers are then pressed back together to ensure good contact. 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 exchange with the surroundings. These measures should ensure 1D moisture transport in the material sample.

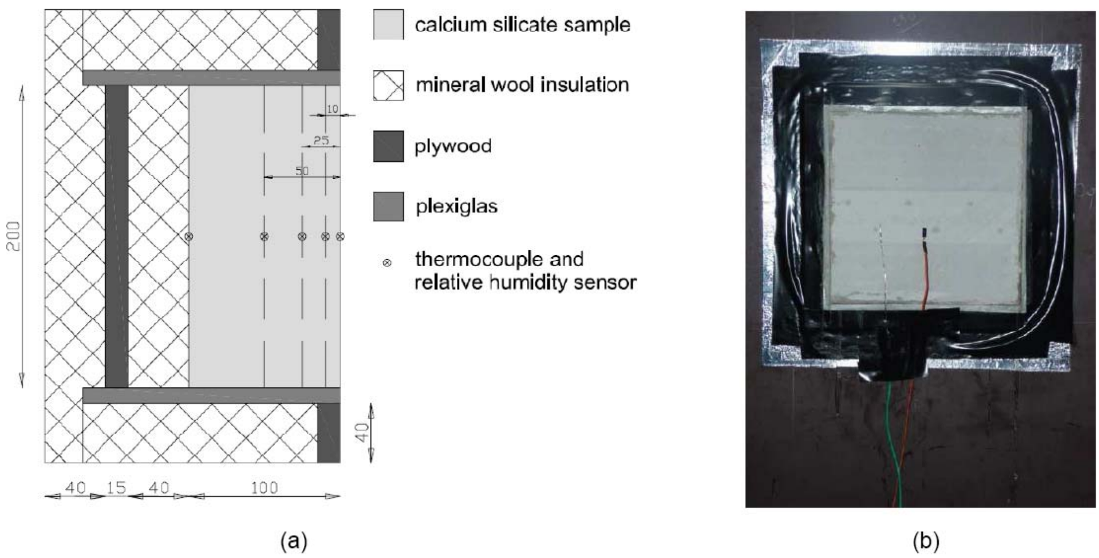

FIG 2 Schematic representation of the calcium silicate test sample (a) and view on the test sample (b)

The calcium silicate used in the tests is a highly hygroscopic material which renders it suitable to use in the validation experiments of a coupled CFD-HAM model. The material properties of the calcium silicate were extensively measured by different laboratories during the HAMSTAD-project (Heat, Air and Moisture Standards Development) (Roels 2003). The material properties measured by the KU Leuven laboratory were used in the validation study and are given in TABLE 1. A dry vapour resistance factor of 5.42 and a dry thermal conductivity of 0.06W/m·K were registered. However it was found in previous studies (Steeman 2010) that the measured value of 5.42 for the vapour resistance was too high and not in correspondence with measurements by other laboratories. Therefore a value of 3 was used.

TABLE 1. Measured material properties of calcium silicate (Roels 2003)

Material property	Measured value
Density (kg/m³)	$\rho_{\mu\alpha\tau} = 270$
Thermal conductivity (W/mK)	$\lambda = 0.06 + 5.6e\text{-}4 \cdot w$
Open porosity (-)	$\psi_0 = 0.894$
Water vapour resistance factor (-)	$\mu = [(0.33 + 2.49e\text{-}6 \cdot \exp(6.84 \cdot RH)]^{-1}$
Sorption isotherm (kg/m³)	$w = w_{sat}[1+(a\rho_{liq}R_vT\ln(RH))^n]^{(1-n)/n}$
Saturation moisture content (kg/m³)	$w_{sat} = 894$
	$a = -2.936e\text{-}5$
	$n = 1.7266$
Specific heat (J/kgK)	$C_{mat} = 1000$

3. Validation experiments

Before each experiment the calcium silicate sample is preconditioned for four days by supplying air (10ACH) at 25°C and 50% relative humidity until the temperature and relative humidity differences inside the sample are below the uncertainty interval of the sensors (i.e. ±0.1°C and ±1.4%RH). During the experiment the supply air temperature is kept at 25°C, while a relative humidity step is imposed from 50% to 70%: 8 hours of high relative humidity (70%) are followed by 16 hours of low relative humidity (50%). This cycle is repeated several times.

3.1 Preliminary experiment: effect of sample cutting

Preliminary experiments were carried out to check whether sample cutting may have an effect on the temperature and relative humidity profiles which are measured on different depths in the sample. Due to cutting of the calcium silicate sample at the different positions (at 10mm, 25mm and 50mm) for the installation of a thermocouple and a relative humidity sensor, it is possible that small air layers arise in between the different material parts when the sample is assembled again. Because of this, the material properties may no longer be homogeneous along the depth of the material, which can affect the overall permeability and sorption of the sample. In turn this may influence the temperature and relative humidity profiles measured inside the sample. To check the possible effect of the cutting edges in the sample, a new sample is prepared which is only sliced at 25mm depth. In this material sample the influence of a possible air layer at 10mm depth is hence excluded. Both samples are successively installed in the test wall and with each sample an identical experiment is performed.

FIG 3 compares the measured temperature and relative humidity profile at 25mm for the last three cycles. The relative humidity measured at 25mm in both samples is quasi identical. Also the associated temperature measured in the sample is comparable, in the third cycle a difference of about 0.2°C is noted. These measurements show that the boundaries in both cases are the same. Consequently, the experiments demonstrate that the cutting edges do not have a considerable effect on the temperature and relative humidity profile measured in the sample. Furthermore the experiments have shown to be reproducible.

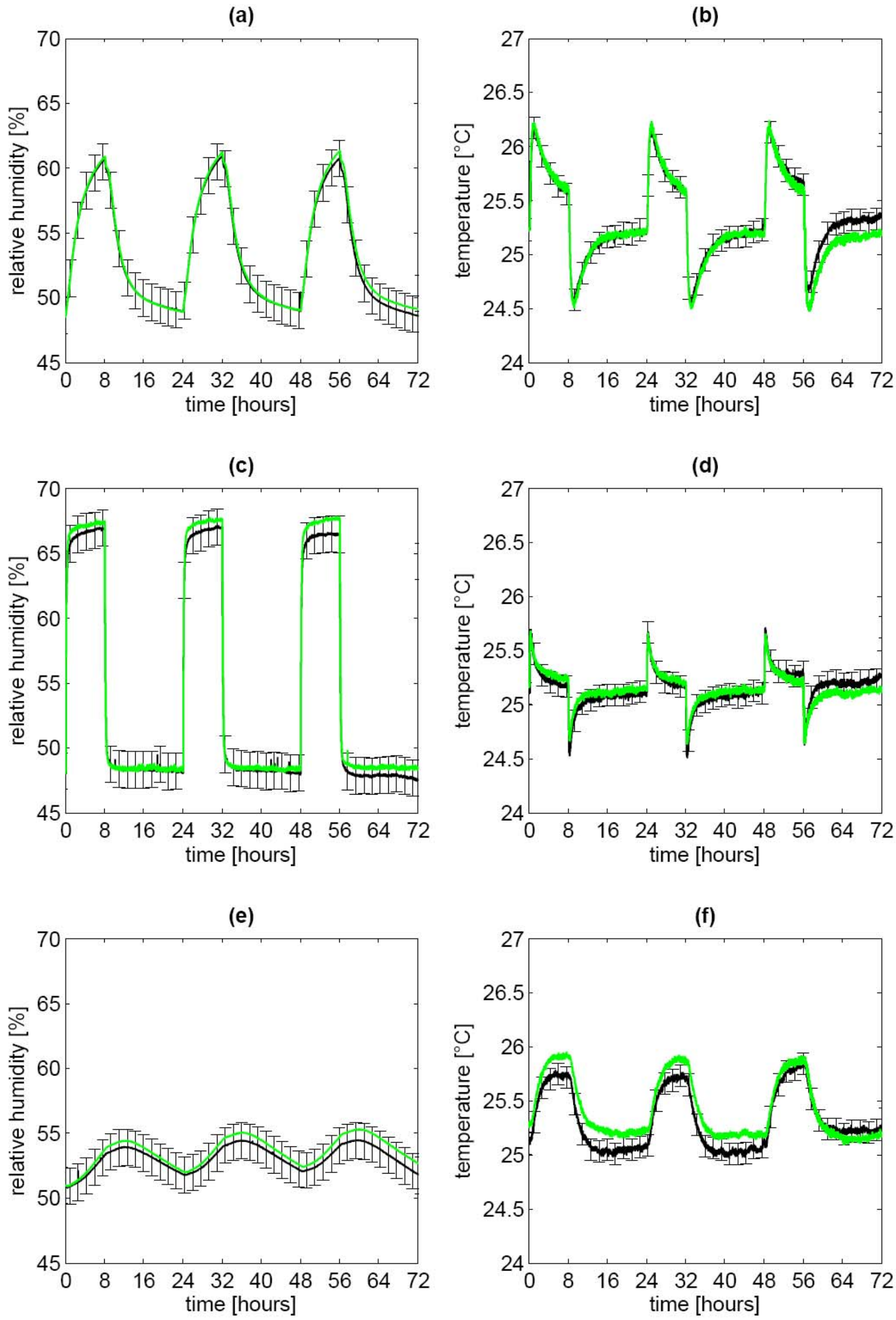

FIG 3. Influence of the cutting edge on the measured temperature and relative humidity in the sample: original sample (black line, with error bars) and adapted sample (light coloured line). Measurements in the sample at 25mm (a,b), measurements at the front surface of the sample (c,d) and measurements at the back of the sample (e,f).

3.2 Experimental validation of a coupled CFD-HAM model

Measured temperature and relative humidity at three depths in the material are compared to simulation results (see FIG 4) and used to validate a coupled CFD-HAM model. The CFD-HAM model computes the water vapour transport in the hygroscopic material as well as in the surrounding air. An internal coupling approach is used where both the porous material domain and the air domain are solved within the same solver. As a result there is no need for mass transfer coefficients to couple the mass transport between both domains. For more details on the model and the implemented equations the reader is referred to (Steeman 2009b, Van Belleghem 2010).

A commercial CFD package (Fluent®) was used to simulate the climate chamber. A 3D structured rectangular grid with 138708 elements was used to discretize the chamber and calcium silicate sample. A grid independency study was performed by comparing the results of a two times coarser grid with a two times refined grid. A constant inlet velocity of 10m/s was chosen with a turbulence intensity of 5%. The walls of the chamber are assumed adiabatic except for the back walls of the test sample. Here a constant temperature of 25.4°C is assumed. This value corresponds with the measured temperature at the back of the sample and gave the best results for the simulations. The incompressible ideal gas law was used to calculate the density. Constant values for the dynamic viscosity, thermal conductivity and mass diffusivity were used. As the interest of the study lies in the heat and mass transfer to the wall (the calcium silicate sample), it is important that the near wall behaviour of the flow is correctly represented. A sufficient refined grid is used near the wall ($y^+ < 4$) in combination with a k-ω LRN turbulence model. This turbulence model is known to perform well close to walls. A second order upwind scheme is used for the discretization of the convective terms in the transport equations in order to reduce numerical diffusion. The SIMPLE algorithm is used for the pressure-velocity coupling. A double precision representation of real numbers is used to reduce round-off errors. For the transient simulations a time step of 60 s was chosen.

Figure 9 shows a comparison of the measured and simulated relative humidity and temperature at three depths in the calcium silicate sample. This comparison shows a good agreement between measurement and simulations at a depth of 10mm. Deeper in the material (at 25mm and 50mm) the deviations are more pronounced. Several explanations for these deviations can be found. First the exact location of the sensors in the material will have an effect on the measurement results. Secondly the exact boundary conditions are of great importance and finally the input data of material properties can have a severe impact on the simulation results.

Figure 9c shows the relative humidity in the sample at a depth of 25mm. The simulation curve is shown together with the measured data (including the error bars). During adsorption there is a clear underestimation of the relative humidity. However slight changes in the position of the sensor will results in a higher or lower relative humidity measured in the material. It is not unlikely that the exact location of the sensor in the material deviates from the assumed 25mm, since the sensor has a thickness of 2mm. Simulation results at for example 23.3mm would result in a better agreement of the simulations with the measurements. Changing the position of the sensor in the order of 2mm has only little effect on the simulated temperature.

The temperature difference between measurements and simulations during desorption at a depth of 25mm (and also to a lesser extent at 10mm) can be attributed to an underestimation of the boundary conditions during desorption. It is assumed that the temperature of the incoming air is constant at 25°C. However in reality there is an uncertainty on this value of ±0.1°C. A wrong estimation of the incoming air temperature has a direct effect on the temperature in the sample. In other words, an increase of 0.1°C of the incoming air during desorption would result in an increase of the simulated temperature and thus a better fit with the measurements.

The largest discrepancies between model and measurements are found at a depth of 50mm. Although a good agreement for temperature is found, the relative humidity differs op to 4%RH. Previous studies (Steeman 2010, Van Belleghem 2010) showed that besides boundary conditions also material input data can have a severe impact on the modelling outcome. Wrong estimations of this data (especially sorption isotherm and vapour resistance factor) becomes more important deeper in the material as these effects accumulate. Also hysteresis is not taken into account, which will result in an error on the simulations of the same order of magnitude as a wrong sorption isotherm.

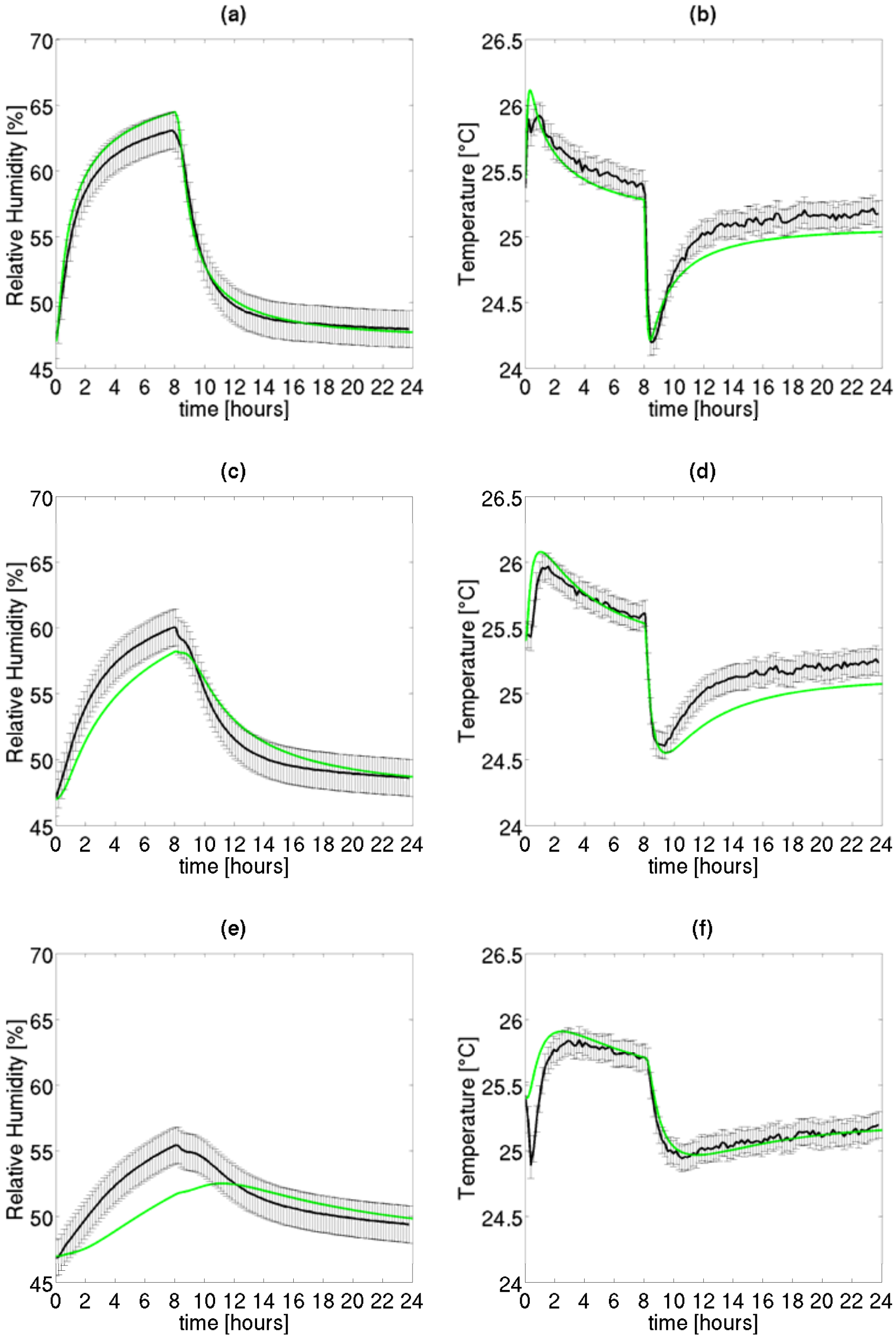

FIG 4. Relative humidity and temperature at a depth of 10mm (a, b), 25mm (c, d) and 50mm (e, f). Each graph shows simulations(green line) and measurements (black line with error bars).

4. Conclusions

In this paper a detailed description of a new test facility for room-size humidity experiments is presented. The climatic chamber allows to perform experiments for the validation of coupled CFD-HAM models. The generated data sets are available for other researchers. Additionally the detailed description may give insight in the design of future test facilities.

During the experiments, temperature and RH at different depths in a hygroscopic test sample installed in one of the walls of a room-size chamber, as well as the temperature and RH in the test room and of the supply air are measured. Preliminary experiments showed a good performance and repeatability of the experiments. During the experiment a jet enters the test room and blows onto the test sample. The supply air as well as the temperature outside the room is kept at a constant value of 25°C. A comparison between the measured temperature and RH inside the test sample and those computed with the recently developed CFD-HAM model, showed good agreement. Also measurements of the velocity field in the room were compared with simulation results. It was concluded that a quasi steady solution of the jet gives adequate precision to solve the heat and moisture transport accurately. The remaining discrepancies between model and experiment could be attributed to a combination of factors. The model appears to be rather sensitive to some boundary conditions and the implemented material property data. A good knowledge of these factors is necessary in order to have an adequate prediction of the temperature and humidity in microclimates.

5. Acknowledgements

The results presented in this paper have been obtained within the frame of the research project IWT-SB/51283/Steeman and IWT-SB/81322/VanBelleghem, and the IWT SBO-050451 project Heat, Air and Moisture Performance Engineering: A Whole Building Approach. All are funded by the Flemish Institute for the Promotion and Innovation by Science and Technology in Flanders. Its financial support is gratefully acknowledged.

References

Energy Conservation in Buildings and Community Systems (ECBCS). Annex 41 Whole Building Heat, Air and Moisture Response (MOIST-ENG). www.ecbcs.org/annexes/annex41.htm

Hagentoft C.E., Adl-Zarrabi B., Roels S., Carmeliet J., Hens H., Grunewald J., Funk M., Becker R., Shamir D., Adan O., Brocken H., Kumaran K., Djebbar R. 2004. Assessment method of numerical prediction models for combined heat, air and moisture transfer in building components. Journal of Building Physics 27(4) p.327-352.

Roels S., Carmeliet J. & Hens H. 2003. HAMSTAD WP1: Final report – Moisture transfer properties and materials characterization. Laboratory of Building Physics, KU Leuven.

Steeman H.-J., Janssens A., Carmeliet J. & De Paepe M. 2009a. Modelling indoor air and hygrothermal wall interaction in building simulation: Comparison between CFD and a well-mixed zonal model. Building and Environment 44(3) p.572-583.

Steeman H.-J., Van Belleghem M., Janssens A. & De Paepe M. 2009b. Coupled simulation of heat and moisture transport in air and porous materials for the assessment of moisture related damage. Building and Environment 44(10) p.2176-2184.

Steeman M., Van Belleghem M., De Paepe M. & Janssens A. 2010. Experimental validation and sensitivity analysis of a coupled BES-HAM model. Building and Environment 45(10) p.2201-2217.

Van Belleghem M., Steeman H.-J., Steeman M., Janssens A. & De Paepe M. 2010. Sensitivity analysis of CFD coupled non-isothermal heat and moisture modelling. Building and Environment 45(11) p.2485-2496.

Woloszyn M. & Rode C. 2008. IEA Annex 41: whole building heat, air, moisture response. Subtask 1: Modelling Principles and Common Exercises. Final report. ISBN: 978-90-334-7057-8