SIMULATING COMBINED HEAT AND MOISTURE TRANSFER WITH ENERGYPLUS: AN UNCERTAINTY STUDY AND COMPARISON WITH EXPERIMENTAL DATA

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ABSTRACT

This article presents a comparison between experimental and numerical results in terms of coupled hygrothermal behavior. The measurements were taken on an experimental wooden-frame house located in France. Several sensors were installed in the room and in several locations inside the walls. The external climate was measured as well. Numerical simulations were performed with the EnergyPlus tool and its algorithm for combined heat and moisture transfer, available since September 2011. First, the simulated and measured values were compared for temperature and humidity in the walls. Then the most influential parameters were obtained using a global sensitivity analysis. This method classifies the impact of parameters in a model that contains many factors with a relatively small number of simulations. As a second step, an optimization analysis was performed to determine the optimal value of the most important parameters within the corresponding uncertainty band. Finally, an uncertainty analysis using Monte Carlo simulations was performed in order to complement the simulation results with uncertainty bands. A total of 1000 simulations were run to obtain a satisfactory result.

INTRODUCTION

Today, performance simulation is widely used to design buildings, given their very high energy performance. However, most users consider only heat transfer and ignore moisture transfer, even if many studies have shown that moisture can reduce the building's performance (Mendes, et al., 2003), (Barbosa, et al., 2008) and thermal comfort (Fang, et al., 1998). Moreover, only a few tools exist that are able to perform building simulation and optimization considering combined heat and moisture transfers, for exemple: CLIM 2000, DOMUS, WUFI, TRNSYS, SPARK, EnergyPlus ESP-r and HAM-Tools (Woloszyn and Rode, 2008).

The work reported herein aimed to improve the understanding of hygrothermal phenomena in a light-weight construction and to evaluate and order the uncertainties of simulation results for a combined heat and moisture transfer simulation in walls. It is important to evaluate the reliability of simulations as well as the uncertainty of temperature and humidity measurements so as to improve building design.

This study was decomposed in several steps and is described in the present paper. First, the existing experimental house used in this research is presented. Then, its model using a building performance simulation tool is described, along with preliminary comparison between simulation and measurements. Next, different sensitivity analyses are introduced and their potential role in validation process is discussed. Global sensitivity analysis, complemented with an optimization calculation, is then applied to reduce the spread between experimental and numerical values. Finally an application of uncertainty analysis is presented, and the difficulties of hygrothermal simulations are discussed.

EXPERIMENTAL SET-UP

General presentation

The experimental house is located in Grenoble, France (latitude, 45.2°E; longitude, 5.77°N). It is a full-scale wooden-frame house exposed to a natural exterior climate. It consists of a single-room building, representative of a living room (4.56 × 4.55 × 2.41 m interior dimensions), designed and instrumented to gain knowledge on whole-building heat-air-moisture behavior (Piot, et al., 2011), (Labat, et al., 2012). The insulation of the ceiling has been increased on the interior side to enable the study to focus on transfer within the vertical walls. The structure of the vertical walls is made of vertical spruce studs (section: 0.07 × 0.165 m), positioned every 0.60 m. The roof is a typical French tiled roof, with two 30° slopes, facing north and south. The floor has been elevated to 0.60 m above the ground to simplify the boundary conditions for the numerical models. The door, which is the only opening into the test house, is located in the middle of the north side. The composition of the vertical walls, during the experimental period considered here, is described in Figure 2. It consists of gypsum boards on the interior, a vapor barrier, cellulose wadding as insulation material between the spruce studs, particle boards on the exterior, a rain screen, a 0.027-m-wide ventilated air gap and a wooden cladding.

Figure 1 Photograph of the north and east of the experimental house

Monitoring system

The instrumentation was defined for both comprehensive and detailed monitoring of the hygrothermal behavior of the test house. The walls, in different sections, are equipped with thermohygrometers (RHT sensors). In this case, we chose to study only the east wall, which was extensively monitored. Figure 2 shows the location of the sensors placed in the east wall, at mid-height. They are positioned at different depths within the wall. The data acquisition was done by Campbell Data Loggers, combined with nine multiplexers. For each sensor, a measurement is taken every minute and the average values of ten consecutive measurements over 10-min periods are recorded. This data acquisition system is located inside the room volume. Local weather conditions were measured through an integrated weather station (temperature, humidity, wind speed and direction, and atmospheric pressure) on a 5-m-high mast close to the site with a time step equal to 10 min. The solar resource was characterized by various radiation sensors: pyranometer and pyrgeometer. The direct and diffuse solar irradiance was calculated from global radiation using the correlation of Orgill and Hollands (Orgill, et al., 1977).

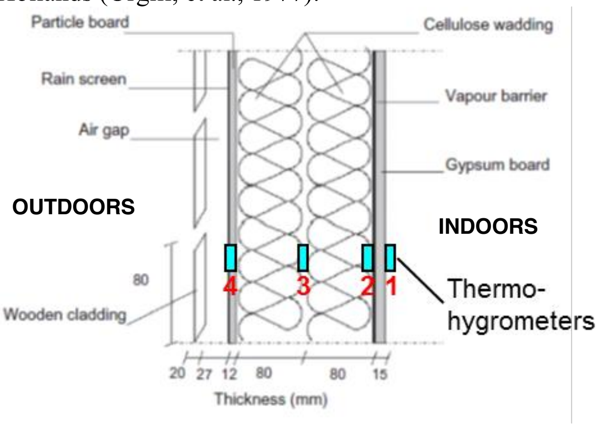

Figure 2 Scheme of a vertical wall section and instrumentation in the east wall

Period of interest

The period of interest extended from 1 to 22 February 2012. During this period, the heating was on, the temperature set point was 20°C, and water vapor was produced with a constant flow equal to 200 g.h^{-1} from 6 February at 12:30 pm to 7 February at 4:00 am (Figure 3). Exterior climate during this period is presented in Figure 4.

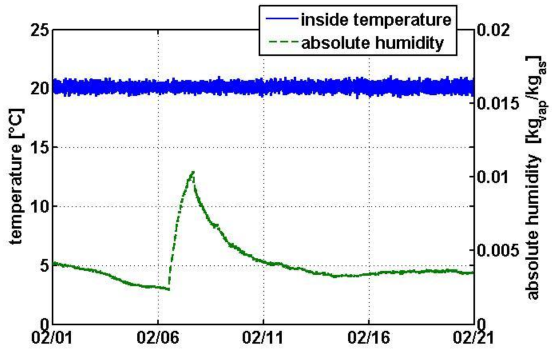

Figure 3 Inside conditions

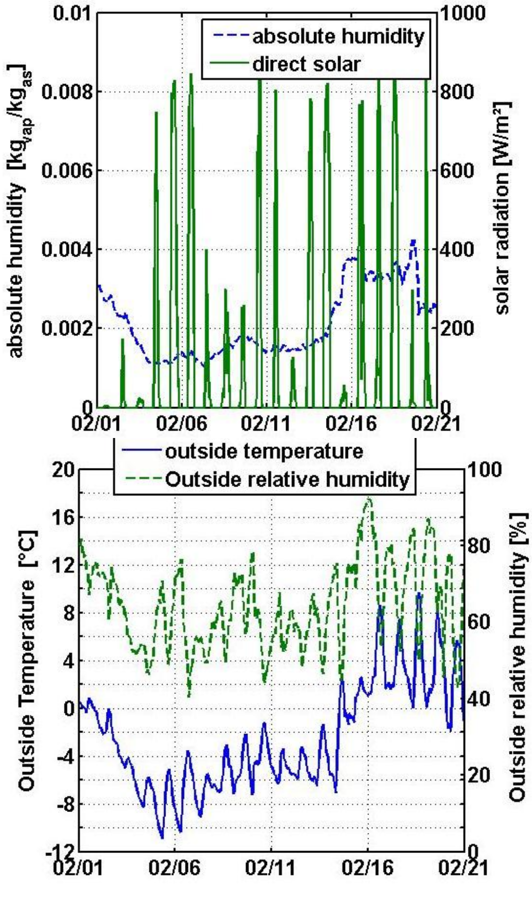

Figure 4 Outside conditions

NUMERICAL SIMULATIONS

The tool

The present study focuses on wall impact on building performance. As heat and moisture transfers in walls interact strongly with indoor condition, such study requires the use of simulation tools at whole building level. EnergyPlus (Crawley, et al., 2001) was selected for this study. It is a whole-building energy-performance simulation tool used worldwide by a very broad panel of engineers, architects, and researchers. The U.S. Department of Energy website presents several validations using EnergyPlus. An algorithm for combined heat and moisture transfer has been available since September 2011.

The combined heat and moisture transfer (HAMT) solution algorithm of EnergyPlus is a coupled, one-dimensional, heat and moisture transfer model simulating the movement and storage of heat and moisture in surfaces simultaneously from and to both the internal and external environments. Along with simulation of the effects of moisture buffering, HAMT is also able to provide temperature and moisture profiles through composite building walls, and helps identify surfaces with high surface humidity. The algorithm is based on the conservation equations as formulated by (Künzel, 1995) similarly to the well-known WUFI tool.

Conservation equations describe a coupled model for the transfer of heat and moisture through a material:

$$\frac{\partial H}{\partial T}\frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x} \quad k_w \frac{\partial T}{\partial x} \quad + h_v \frac{\partial}{\partial x} \quad \delta \frac{\partial P}{\partial x}$$

$$\frac{\partial w}{\partial RH}\frac{\partial RH}{\partial \tau} = \frac{\partial}{\partial x} \quad D_w \frac{\partial w}{\partial x} \quad + \frac{\partial}{\partial x} \quad \delta \frac{\partial P}{\partial x}$$

where H is the enthalpy per volume ($J.m^{-3}$), T the temperature (K), τ the time (s), k_w the thermal conductivity of moist material ($W.m^{-1}K^{-1}$), δ the vapor permeability ($kg.m^{-1}s^{-1}Pa^{-1}$), P the vapor pressure (Pa), w the moisture capacitance of the material (kg/kg), RH the relative humidity, dw/dRH the slope of the moisture capacitance curve (sorption isotherm), and D_w liquid permeability of material ($kg.\ m^{-1}s^{-1}$).

Numerical Model

The experimental house was simulated with two thermal zones: one temperature-controlled zone and one attic space. The electrical resistance and fan for the air supply modeled the HVAC system. Thermal bridges were taken into account.

A weather file for EnergyPlus was created with measured data. The time step of this file was 1 min (between two measured points, the values were linearly interpolated). The simulation began on 1 February 2012. **Erreur ! Source du renvoi introuvable.** shows the temperature, absolute humidity, and the direct solar radiation.

Exterior heat convection transfer coefficients were calculated with the TARP algorithm (natural convection based on temperature difference). Interior heat convection transfer coefficients were considered constant equal to 6 W/m .K. The internal and external vapor transfer coefficients were considered constant equal to 1.10^{-8} $kg.Pa^{-1}s^{-1}m^{-2}$. Inside the house, internal loads were due to the data acquisition system: 40 W were assumed, exchanged by convection only. Infiltration was estimated with the tracer gas method and we considered a constant value equal to 0.0019 m^3s^{-1}. For the study, the ventilated air gap for the east wall (the wall investigated in this study) was not represented. To simulate the air gap accurately, numerous parameters need to be known and accurate modeling is fairly complex. A representative model was for example proposed in (Labat, et al., 2012b). However it requires the introduction of a correlation calculating vertical airflow through the cavity and can not be done in the standard version of EnergyPlus. Therefore, only the effect of ventilated air gap on wall performance was represented. Indeed, the outside boundary conditions for the wall were simulated using measured data inside the ventilated air gap; instead of outdoor climate. Measured temperature on the rain screen was used as outdoor surface temperature; outdoor vapor pressure and no solar radiation were used for outdoor air. This approach enables precise investigations of transfer phenomena within the insulated part of the wall, as show previous results presented by (Piot, 2009). However, it is not suitable to investigate the ventilated cladding itself.

Preliminary comparison between measurements and simulation

The results from the simulation were compared with the experimental measurements. The results presented in Figures 5 and 6 show the period from 5 to 14 February 2012. Simulated and measured values are compared at different locations within the east wall. As a complement, figure 7 shows the residue for interior surface temperature and absolute humidity**.** The residue is:

$$r(t) = y_{mesure}(t) - y_{simulation}(t)$$

There is good agreement between the measured and predicted values for the temperature at different locations of the wall (Figure 5). The residue of the interior surface temperature is approximately equal to −1°C (Figure 6) which is close to measurement uncertainty.

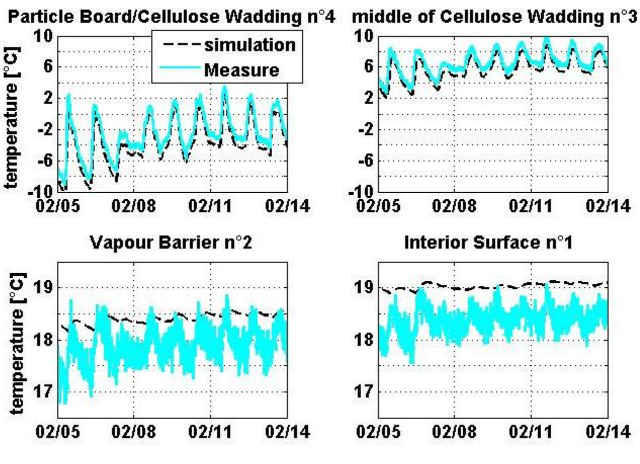

Figure 5 Comparison of measured and simulated temperatures in different sections of the wall

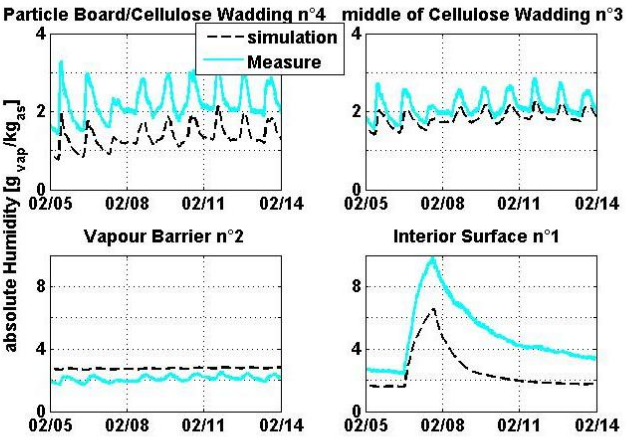

Figure 6 Comparison of measured and simulated absolute humidity in different sections of the wall

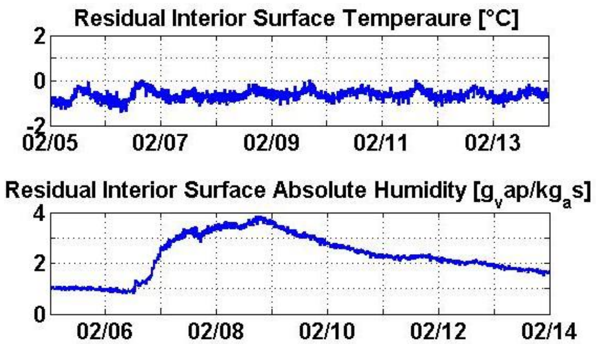

Figure 7 Residual interior surface temperature and absolute humidity

For humidity, the agreement between the measured and predicted values is less good than for temperature. In the middle of the cellulose wadding and on the vapor barrier, the simulated results satisfactorily represent the measurements. The residual is close to the uncertainty value of measurements: 0.0007 $kg_{vapor}kg_{dry\_air}^{-1}$. However, for the remaining two locations, the interface particle board/cellulose wadding and at the interior surface, the computed results represent correct tendency, but are far from the measured data. Several questions arise: why does the simulation result not intersect with the measured uncertainty for absolute humidity? Which parameter is not accurately represented? Which parameter most influences the simulation output? How can we calculate the impact of their uncertainty? Which parameters have no influence on the simulation output? How can the simulation results be improved?

We attempted to answer some of these questions using the powerful sensitivity analysis tool.

SENSITIVITY ANALYSIS

Literature review of sensitivity analysis

Saltelli et al. (2004) defined sensitivity analysis as: "the study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input." Sensitivity analysis is used in many fields, and Saltelli et al. (2008) and Campolongo et al. (2000) present a few examples for ecology, chemistry, semiconductor material, and economics.

There are several sensitivity analysis methods available (A. Saltelli, 2008): screening methods (N. Rahni, 1997), uncertainty analysis (Macdonald I., 2001), calibration (Heo, et al., 2012), and local and global sensitivity analyses (Spitz, et al., 2012).

Sensitivity analysis has been increasingly used in the building energy sector in the last few years. Spitz (Spitz, et al., 2012) used local and global sensitivity and uncertainty analysis to evaluate and order the uncertainty of the simulation results during the design process. This methodology was applied to an experimental platform and the main output of the simulation was the air temperature in the house. Garcia Sanchez et al. (2012) used the Morris method and its extension to perform a sensitivity analysis for a complex multizone building. The ESP-r tool was chosen for this study. Lu et al. (2012) proposed a method to quantify the uncertainty in energy consumption with sensitivity analysis and uncertainty analysis. Shen et al. (2012) identified the most important factors with respect to building thermal and lighting energy performance with uncertainty analysis and sensitivity analysis using the extended FAST method.

Sensitivity analysis

In the present study the aim was to investigate the impact of hygrothermal transfers in walls on building performance. Therefore the outputs selected for sensitivity analysis were the interior surface values, for both temperature and humidity, as they are situated on the interface between the wall and the indoor air. The sensitivity analysis was used first to define the most influential parameters, and then to use this information to progress on the comparison between experimental and simulated data. Additional comparisons between the experimental and the simulated data were performed on the temperature and humidity variations in the wall and in the indoor air during the different steps of the present study. The results and conclusions were very similar to the selected outputs, and therefore are not presented in the following paragraphs.

To calculate the most influential parameters, the global sensitivity analysis was used in the present study. It takes into account the variation range of the input factors and tries to apportion the output uncertainty to the uncertainty in the input factors. An extension of the RBD-FAST method developed by Mara (2009) and improved by Rabouille et al (2013), was used to calculate the first-order sensitivity indices. The advantage of this method is the relatively low number of simulation runs. In the present study, for 88 parameters considered, described in the following paragraphs, 220 simulations were performed and repeated ten times.

With this sensitivity analysis, we are able to evaluate the effects of uncertainties of most influential parameters on predicted interior surface temperature and absolute humidity.

The RBD-FAST method was used to break down the variance of the algorithm's output. From the variance analysis, the most influential uncertainty factors are found as well as the contribution of the interaction between the uncertainty factors. This method makes it possible to determine only one type of sensitivity index, the first-order indice, S_i, which measures the effect of the input parameter X_i on output y. The sensitivity index values are always included within the interval [0;1]. The higher the index's value is, the more influential the parameter. Unfortunately, the second-order indices cannot be calculated with the RBD-FAST algorithm.

The aim was to point out the parameters that may have an impact on main output values (temperature and humidity, relative and absolute, at the internal wall surface). Eighty-eight parameters were identified as having a potential influence on the results. They are mainly the thermal and physical properties of the different materials used in construction (all walls, ceiling and floor), the initial water content of the materials, as well as the values of air infiltration and the parameters of the HVAC system.

For all 88 parameters an uncertainty range was defined. For numerous parameters (conductivity, density, specific heat, thermal absorptance, visible absorptance, solar absorptance, ground reflectance, porosity, sorption isotherm, suction, and diffusion), an uncertainty of ± 10% was defined, because it clearly reflects the accuracy of the measurements. An uncertainty of ± 20% was associated with the convection coefficients, as this value may vary in time; similarly ± 20% uncertainty was chosen for release of water vapor. A value of ± 15% was defined for the insulation thickness, because it depends on workmanship. As we were not able to measure the infiltration rate accurately, an uncertainty of ± 50% was chosen; ± 30% uncertainty was associated with the initial water content ratio for each material.

The RBD-FAST method was applied to the problem. The sensitivity indices for all 88 parameters for two main model outputs (temperature and absolute humidity values at the internal wall surface) were computed at every time step. The uncertainty band for each sensitivity index was computed as well. Figures 8 and 9 show the most important results. The vertical axis represents the uncertainty value of the first-order sensitivity indices, the horizontal axis represents time.

To order the parameters in the legend (from most to least influential), the value of the distance $S_{i,d}$ was calculated:

$$S^2_{i,d} = S^2_{i,m} + S^2_{i,std}$$

where $S_{i,m}$ is the mean value and $S_{i,std}$ is the standard deviation of the sensitivity index for the period studied. Distance is a more useful criterion than the mean value only. Indeed, distance makes it possible

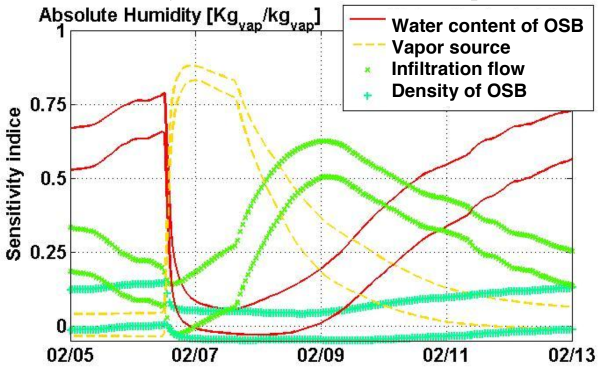

Figure 8 Values of the four most important first-order sensitivity indices for absolute humidity at the internal surface with associated uncertainty

to detect indices with a low mean value but with high variations. Only the parameters with a distance value higher than 0.02 are shown in the figures 8 and 9.

With the sensitivity analysis performed, we were able to evaluate the effects of the uncertainty of the most influential parameters on the predicted absolute humidity temperature at the internal surface.

Figures 8 and 9 show that the index values vary with time. For humidity values (Figure 8), the three most influential parameters are the initial water content of the OSB panel, the ventilation flow, and the source of water vapor (steam release). It should be noted, that in the experimental building the OSB panel is located at the floor.

It is interesting to analyze the strong temporal variations of sensitivity indices for humidity. On 6 February, the sensitivity indices of vapor (steam) release increased very quickly and in parallel the sensitivity indices of the water content of OSB decreased very quickly. The modification corresponds to the beginning of water vapor release in the experimental house. The "release of steam" parameter is therefore very influential on the absolute humidity at the internal surface. When the release of steam stopped, the sensitivity indices of the OSB water content increased and at the same time the sensitivity of steam release decreased. However, the slopes of the index variations are much more progressive than at the start of vapor release. The sensitivity indices for the ventilation flow vary differently. They progressively increased from 7 to 9 February and then decreased gradually. The maximum value was shifted from the stop of vapor release by approximately 24 h.

Three phases can be distinguished from this figure: phase 1 (beginning and end of the experimental period) when the humidity at the surface is governed by the initial moisture content of the OSB panel. Then the second phase corresponds to moisture release; humidity at the surface is influenced mainly by the vapor release. Finally, the third 'recovery' phase corresponds to the period following directly the end of vapor release (8-11 February). The most influencial factor is then the ventilation rate. The

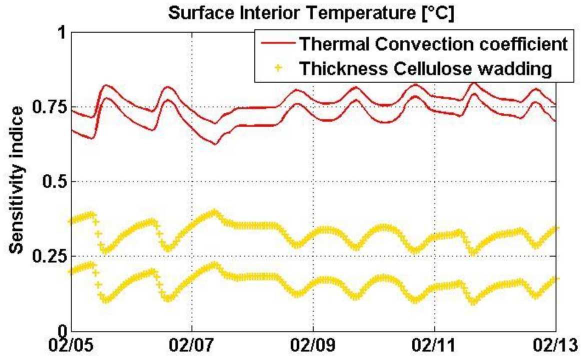

Figure 9 Value of the two most important first-order sensitivity indices of temperature at the internal surface with associated uncertainty

third phase is also a transition phase between 1 and 3, when the impact of vapor release decreases and impact of OSB panel increases.
The results are quite different for the surface temperature, as shown in **Erreur ! Source du renvoi introuvable.**. The most influential parameters are the internal thermal convection coefficient and the thickness of cellulose wadding. The sensitivity indices are almost constant: they have only very slight daily variations.

The presented results of sensitivity analysis show complex behavior. Indeed, the main investigated outputs are the surface values of temperature and humidity at the internal surface of eastern wall. The sensitivity of these values is extremely different. For the temperature values the results are straightforward: the most influential parameters are the insulation of the wall (impacting the heat flow from the surface to the outside) and internal convection coefficient (impacting the heat flow from the inside air to the surface). The investigated output depends on the equilibrium between both flows and is then strongly influenced by both parameters.
For absolute humidity at the internal surface the situation is very different. Here, the most influential parameters are these impacting the indoor climate: vapor source, infiltration rate and the initial water content of the floor material. No parameter impacting moisture flow through the investigated wall was ranked among the three most influential parameters.
Finally, six parameters were found to be the most influential on the selected outputs:

- Water content of the OSB
- Infiltration flow
- Vapor source
- Density of the OSB
- Internal thermal convection coefficient
- Thickness of the cellulose wadding

This information was then used to improve our understanding of hygrothermal phenomena in the experimental house.

Optimization

First, an optimization procedure was used to try to reduce the discrepancy between measured and simulated values. The aim was to verify if the discrepancy between the simulated and measured values can be explained by the uncertainty in the most influential inputs. The parameters for the optimization procedure were chosen following the results of the sensitivity analysis. The initial values of parameters together with the uncertainty intervals can be found in Table 1. A single cost function was implemented for optimization, combing the residuals of surface temperature and humidity.

Table 1 parameter uncertainties

PARAMETERS	VALUE	UNCERTAINTY
Initial water content of the OSB	0.15 kg/kg	*±30%*
Air infiltration	6.83 m^3/h	±50%
Latent heat representing vapor release	155W	±20%
Density of the OSB	601 kg/m^3	*±5%*
Internal thermal convection coefficient	$6W/m^2.K$	±20%
Thickness of the cellulose wadding	0.16m	±10%

Optimization calculations were performed using the GenOpt tool (Wetter, 2001), which is an optimization program for the minimization of a cost function that is evaluated by an external simulation program, such as EnergyPlus. Generalized Pattern Search algorithms (the Hooke-Jeeves and the Coordinate Search algorithm), were used for the calculations.
As shown in Figure 10, the difference between measurements and simulation is lower than in the preliminary study; however, discrepancies still exist between simulation and measurements.

Table 2: Parameter value after optimization

PARAMETERS	VALUE
Water content of the OSB	0.15 kg/kg
Flow of ventilation	3.24 m^3/h
Release of steam	186 W
Density of the OSB	632 kg/m^3
Internal thermal convection coefficient	4.8 $W/m^2.K$
Thickness of the cellulose wadding	0.176 m

It is also important to comment the values obtained after the optimization procedure. The final value, for five out of six parameters, is equal to the limit imposed by uncertainty bounds. The air infiltration rate and surface exchange coefficient are equal to the lower bound. Vapor release, OSB panel density and thickness of wall insulation are equal to the highest admissible values. The initial water content of OSB panel remained at the starting value. Such situation indicates the complexity of the problem. The optimized solution is slightly more representative of the measured values, however it is not completely satisfactory. Two problems remain. First, the final residual can not be neglected. Second, the optimized values for parameters are all equal to singular values (upper and lower bounds as well as starting solution). It can be concluded that the optimization is not able to fully explain discrepancies between the simulated and the calculated values.

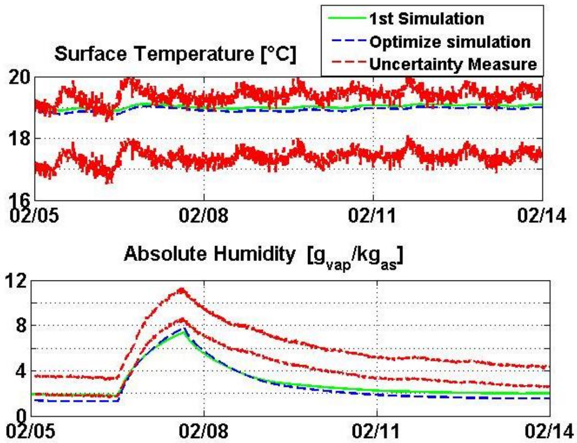

Figure 10 Comparison between measurements and optimized simulation for temperature and humidity at the internal surface.

Uncertainty analysis

Another possibility to better interpret the discrepancy between simulation and measurements is the uncertainty analysis, focusing on quantifying the uncertainty in model output. In the present study, six influential parameters were identified and were used to quantify the uncertainty in model output. The numerical values of influential parameters are considered to be uniformly distributed within the uncertainty interval given in Table 1. Monte Carlo method for sampling was used and 1000 simulation runs were performed.

Figure 11**Erreur ! Source du renvoi introuvable.** shows the measured and simulated values with the associated uncertainty band for temperature and humidity at the internal surface. For temperature, the uncertainty band of the simulation is situated within the uncertainty band of the measurements. For humidity, at the beginning of the simulations, the uncertainty bands partly overlap. However, when the vapor production begins the two bands start to differ. They are clearly dissociated during the recovery period, after vapor production stops (after 8 February). The presented results show that the model, including uncertainty values on the most influential parameter represents correctly the measured thermal behavior. However, the precision on moisture calculation, especially during the humidity variations, is not precisely represented.

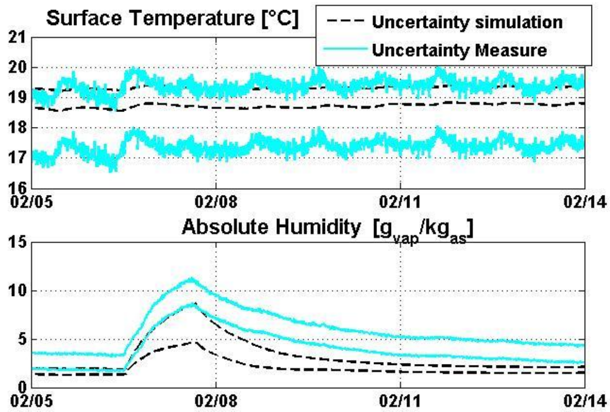

Figure 11: Uncertainty analysis of the temperature and humidity at the internal surface

DISCUSSION

Discussion of results

A comparison between experimental data and simulations was used in this study to investigate the potential benefits that can be obtained using sensitivity analysis. Such comparison itself in whole building hygrothermal simulations is a difficult task.

Despite difficulties, sensitivity analysis supported by experimental results is more valuable, as the experimental verification gives necessary corroboration of the results.

The test case used in this study is a comprehensively instrumented experimental house located in Grenoble (France). It shall be added that the experimental facility was previously used for validation and performance measurements purposes in several studies, showing high quality of measurements (Piot et al, 2011), (Labat et al., 2102), (Labat et al., 2102b).

The numerical model was built and simulated with a user-defined weather file using the widely known and validated EnergyPlus simulation tool. The HAMT algorithm, based on well-known WUFI software was used for hygrothermal calculations. Despite high quality of experimental and numerical tools, and correct overall agreement, some discrepancies persisted between measured and simulated data.

Extensive sensitivity analysis was then performed, to gain more understanding on complex hygrothermal phenomena. First, global sensitivity analysis was run in order to define a set of the most dominant input parameters. Temperature and humidity at the internal surface of the eastern wall were selected as model outputs. The FAST-RBD method was used with a relatively small number of simulations. At the beginning, a set of 88 parameters was considered, from which the six most influential parameters were selected stemming from the results of global sensitivity analysis. These parameters are:

- Initial water content of the OSB
- Infiltration flow
- Vapor source
- Density of the OSB
- Internal thermal convection coefficient
- Thickness of the cellulose wadding

It is important to notice that in presented configuration the value of the temperature depended mainly on parameters impacting the local heat flow though the wall; whereas the humidity depended on factors impacting the indoor air. The most influential material was the material with the highest hygroscopicity (OSB) situated on the floor and not on the investigated wall.

This result underlines the importance of using whole building simulation tool to investigate wall performance.

Then uncertainty intervals were associated with the six influential parameters. Within these intervals an optimization calculation was run aiming at minimizing the difference between measurements and simulation as a cost function.

Finally, the uncertainty analysis focused on quantifying uncertainty in model output. One thousand simulations were performed using Monte Carlo sampling. The numerical uncertainty bands were compared with the experimental data. The comparison gave satisfactory results for temperature but not for humidity.

The results presented in figure 11 in previous section indicate also some weaknesses of the model. The simulated results during vapor sorption are closer to the experimental values than those from the desorption phase. The somehow simplified representation of hygrothermal phenomena (the effect of hysteresis was not taken into account) could explain the discrepancies.

Several parameters appear to be important for reliable whole-building hygrothermal simulations. Most importantly, heat and moisture sources, infiltration rates, as well as initial conditions, especially for highly hygroscopic materials, must be precisely quantified. These results from the sensitivity analysis can be extended to the available models. Phenomena such as air infiltration, coupled heat and mass transfer in highly hygroscopic materials, indoor convection, as well as moisture and heat sources must be correctly modeled in the simulation tool.

Limitations

This study focused on the use of sensitivity analysis to determine the most influential parameters for hygrothermal simulations. The results are valid for analyzed outputs (temperature and humidity at the internal surface), representative period (stable values of temperatures and step change in vapor release), as well as selected construction and inputs.

The results underlined the importance of initial water content in the materials, particularly in highly hygroscopic elements. Longer simulation time, including significant preconditioning period would be interesting. Unfortunately, due to experimental difficulties such option was not possible in the present study.

We shall add that the hygrothermal model itself was not investigated. The simultaneous validation of hygrothermal models for both the envelope and the whole building scales is still a difficult and on-going task. The results show that some improvements are still needed. For example, the impact of hysteresis effect and the influence of ventilated cladding could not be investigated as they were not modeled in this study.

CONCLUSION

The aim of this work was to define a methodology that could be useful for identifying the most important parameters and determining uncertainty bands for whole-building hygrothermal simulations.

The results show the importance of using whole building simulation tool to investigate wall performance. The results were achieved using the association of three sensitivity analyses:

- Global sensitivity analysis
- Optimization analysis
- Uncertainty analysis.

This study highlighted the importance of precise assessment of several parameters, both at wall and at whole building scale for reliable whole-building hygrothermal simulations.

In addition, some of the discrepancies could not be fully explained by the uncertainty on the most influential parameters only. Some improvements of hygrothermal modes are still needed, especially for precise moisture predictions in dynamic variations of boundary conditions and in presence of highly hygroscopic materials.

For future work, the data for realistic assessment of uncertainty of input parameters appear to be a very important point. Moreover, better knowledge of the most influential parameters identified with global sensitivity analysis would reduce the uncertainty band and provide more reliable results.

NOMENCLATURE

H = enthalpy per volume ($J.m^{-3}$)
T = temperature (K)
τ = time (s),
k_w = thermal conductivity of moist material ($W.m^{-1}K^{-1}$)
δ = vapor permeability ($kg.m^{-1}s^{-1}Pa^{-1}$)
P = vapor pressure (Pa)
w = moisture capacitance of the material (kg/kg)
RH = relative humidity
dw/dRH = the slope of the moisture capacitance curve
D_w = liquid permeability of material ($kg.\ m^{-1}s^{-1}$)
r = residue
$S_{i,d}$ = value of the distance of sensitivity index
$S_{i,m}$ = mean of sensitivity index
$S_{i,std}$ = standard deviation of sensitivity index

ACKNOWLEDGEMENTS

This work has been supported by the French National Research Agency through the "Habitat intelligent et solaire photovoltaïque" program (projects HYGROBAT ANR-10-HABISOL-002 and FIABILITE ANR-10-HABISOL-005)

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