MODELLING OF HYDROUS AND THERMAL TRANSFERS IN TROPICAL CLIMATES AND BUFFERING MOISTURE WITH HYGROSCOPIC MATERIALS

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ABSTRACT

Controlling humidity to prevent moisture and condensation phenomena is a growing problem for building designers nowadays. Ventilation and air conditioning are common solutions to avoid mold and condensation. However, to promote low cost energy buildings, an alternate solution may be to decrease the daily variation of humidity with anti fungi treated absorbing material. In this case, a very accurate evaluation of room humidity is necessary to determine material ability to buffer moisture.

This paper briefly presents a model of moisture transfer between room air and walls for tropical climates. This model includes hygroscopic and non-hygroscopic wall behavior. The aim of the model is to calculate the water quantities buffered by walls and thus better evaluate room moisture. A validation of the model is presented consisting of a sensitivity analysis and an experimental comparison. The experiments carried out in a test cell are described. An application of the model is also proposed to tackle mold presence with various absorbing materials located in a tropical humid environment.

INTRODUCTION

Whatever the climatic conditions it is nowadays always possible to ensure satisfactory ambient conditions inside buildings. Heating or cooling systems are able to adjust very precisely the temperature of a room. Unfortunately, the price of the requested comfort for the building occupants is growing energy consumption. It is thus necessary to explore the solutions to design comfortable and energy saving housings. As inside temperature is now always well controlled thanks to HVAC system and thermal rules, humidity become a major concern for designers because controlling indoor humidity improves thermal comfort, energy consumption of housing, air quality but above all, protects the envelope against moisture and surface condensation.

Many simulation codes have been developed to evaluate the thermal behavior of buildings. Some of them calculate the relative humidity of air inside a zone considering exchanges with air and materials (El Diasty 1993, Kusuda 1983, Tsuchiya 93). Specific codes based on diffusion in porous media theory should also be mentioned (Kerestecioglu 1990, Kohonen 1989, Martin 1988). More recently global lumped parameter models include the contribution of materials through a hygroscopic buffer (Duforestel 1994, Plathner 1998, Trnsys 1997).

Improving the knowledge of the moisture transfer in buildings is becoming a major issue for researchers. Therefore, an international project is carried out by the International Energy Agency (Hens 2003). Recent studies concern the control of interior humidity and air quality using ventilation and materials. Carsten (Carsten Rode et al., 2004) presents a Danish and a Brazilian model to analyze the hygrothermal performance of the whole building. The models are applied to cold and hot climates to demonstrate how moisture interferes with material. Carey (Carey J. Simonson et al., 2004) establishes that ventilating a heated building located in Belgium with outdoor dry air is critical to ensure satisfactory comfort conditions. Moreover, to reach the same level of inside moisture, it is possible to reduce the ventilation rate significantly by using absorbing materials. Straube (Straube 2001) proposes an indoor air quality strategy to moderate indoor humidity and eliminate the fungal growth on building surface using cement bounded wood fiber material.

For cold and temperate climates, moisture loads come from internal vapor production related to occupants and their activities. As mentioned above, solutions to fight against moisture and condensation, relying mainly on ventilation, are, in this case, well known and efficient. In the humid climate of Reunion Island, outside air is very humid and the difference of the temperature inside and outside the building is small, leading to reduced thermal buoyancy through natural ventilation openings. Since mechanical ventilation is not often used in these climates, the internal moisture loads are hardly evacuated. A rundown of the assumptions concerning the buildings and the climate concerned in this study is given below:

- No heating or cooling system.

- Natural ventilation of the rooms through ventilation openings.
- Humid and cool outside conditions :
  - Average relative humidity: 70%.
  - Average outside temperature: 19°C.

For the reasons mentioned above, controlling internal moisture is a difficult task that need alternate solutions. One solution is to deaden the moisture cycling with appropriate material. For each building design, a level of humidity control must be defined. In highlands of tropical climates, fighting against mold and condensation is the main objective. The moisture transfer model proposed in this article determines the exchange of water vapor between interior air and all the materials inside the zone. It includes two different models: a wall model for the transfer between the air and walls and a buffer model for the transfers between the air and the furniture. The two models will be presented briefly. Then, after a sensitivity analysis, an experimental validation of both models separately is proposed in a separate section. The end of the paper puts forward an application of the models to improve building design in highlands of a tropical climate area and try solve mold and condensation problems.

MODEL DESCRIPTION

The hygrothermal model proposed is based on the thermal simulation code CODYRUN (Boyer 1996) developed in Reunion Island (France) for tropical humid climates. This simulation code considers exchanges of water vapor in a zone due to:

- Ventilation with exterior
- Air exchanges with adjacent zones
- Internal latent loads
- Exchanges of moisture between materials in the zone and air

Contribution of materials to moisture exchanges is implemented thanks to two different models:

- A wall model considering moisture exchanges of each wall of the building envelop separately.
- A global buffer model to take into account vapor exchanges between air and the furniture inside the zone.

The evolution of the zone humidity ratio is described by the equation below:

$$\rho_{as} V \frac{\partial w}{\partial t} = \phi_{vent} + \phi_{hvac} + \phi_{load} + \phi_{hygr} + \phi_{non\text{-}hygr} + \phi_{buffer} \quad (1)$$

The three last terms of the mass balance equation represent respectively:

- the vapor flux between air and hygroscopic walls : ϕ_{hygr}
- the vapor flux between air and non hygroscopic walls : $\phi_{non\text{-}hygr}$
- the vapor flux between air and furniture inside the zone : ϕ_{buffer}

Wall model description

The wall model (Lucas 2004) studies the case of hygroscopic walls and that of walls considered non-hygroscopic. Among building materials, glasses, metals and certain coatings exchanging very few water with air are classified as non-hygroscopic. In the model, non-hygroscopic wall will be taken into account only because they constitute a support to surface condensation. All other materials interact with air moisture and are defined as hygroscopic.

The mass balance below describes the behavior of hygroscopic walls:

$$\rho_g V_g C_h \frac{\partial w_{wall}}{\partial t} = -h_m S\left(w_{wall} - w\right) \quad (2)$$

In case of condensation on hygroscopic walls, exchanges occur in liquid phase between wall and water layer and in vapor phase between vapor layer and the air of the zone. The mass balance of the liquid film is:

$$\frac{\partial m_{liq}}{\partial t} = -h_m S\left(w_{wall,sat} - w\right) - 0{,}144\frac{K_m S}{r.e_{act}} \quad (3)$$

The moisture equation balance for the wall is then:

$$\rho_f V_f C_{h,f} \frac{\partial w_{wall}}{\partial t} = 0{,}144\frac{K_m S_f}{r.e_{act}} \quad (4)$$

For non-hygroscopic walls, the liquid mass in the condensation film is given by:

$$\frac{\partial m_{liq}}{\partial t} = h_m S(w - w_{sat}) \quad (5)$$

Global buffer model description

The global buffer model is based on the model designed by Duforestel (Duforestel 94). This buffer model evaluates the interaction of moisture and air through three parameters and three description nodes:

- The air of the zone.
- The surface of the buffer.
- The heart of the buffer.

The moisture flow between the air and the surface buffer is:

$$\phi_{buffer} = \gamma \; V \; \rho_{as} \; \left(w_{surf} - w\right) \tag{6}$$

The mass balance of the surface buffer follows the equation below:

$$\frac{\partial w_{surf}}{\partial t} = -(\gamma\alpha + \beta) \; w_{surf} + \gamma \; \alpha \; w + \beta w_{deep} \tag{7}$$

α, β, γ are the experimental coefficients describing the behavior of materials. Duforestel gives two set of values for these parameters, one for very hygroscopic furniture and another for low hygroscopic materials.

The author assumes a constant water content of the heart of the buffer.

$$\frac{\partial w_{deep}}{\partial t} = 0 \tag{8}$$

This assumption is acceptable for short time simulations. For simulations over long periods, as a year, the core of the buffer acts as an infinite sink or source.

Ten Wolde (Ten Wolde 87) and Plathner (Plathner 98) noticed that the variation of the water content of the furniture core is similar to variation of outside air water content. Like the Moisture Admittance Model (MAM) developed by Plathner the global buffer model presented in this paper, evaluates the water content of the core buffer as the average of the water content of the ambient air calculated in the previous time step. The calculation of water content of the core at time step *t* is:

$$w_{deep}(t) = \frac{\sum_{n=t-4\tau}^{n=t-1} e^{-\frac{n}{\tau}} \; w_{deep}(n)}{\sum_{n=t-4\tau}^{n=t-1} e^{-\frac{n}{\tau}}} \tag{9}$$

$e^{\left(-\frac{n}{\tau}\right)}$ is a weighting factor introduced to give greater importance to recent value of ambient water content.

τ is the moisture storage time constant for the material. According to P. Martin et J. Vershoors (Martin 98) the time constant can be 72 hours for slow reacting material (wood, plaster, concrete) and to 1,2 hour for fast reacting material (carpet, wallpaper, textiles).

EXPERIMENTS AND VALIDATION

Sensitive analysis

The aim of the sensitivity analysis procedure is to determine the most important parameters of the model. Exchanges of moisture between air and material occur in different phases and under different potentials. It is therefore very difficult to find digital data in the literature or evaluate experimentally the values of the parameters, which characterize absorption / desorption.

The method used resembles the FAST method (Fast Fourier Amplitude Transform), allows us to determine the most influential parameters on one or several outputs of a model. The procedure is analogous to a design of experiments. For each simulation, a new value of the parameters is calculated following a sinusoidal around their base values. The interested reader is referred to (Mara 2000) and (Mara 2002). As Duforestel already validates the buffer model, the sensitivity analysis is applied only to the wall model. The building and the climatic conditions used for this analysis are presented in the application of the model section. The walls and the floor are made of concrete. Ceiling is composed with plasterboard, insulation, and iron sheet. The output under study is the water content of the zone air. The variation of the parameters is set up to 20% around the base value.

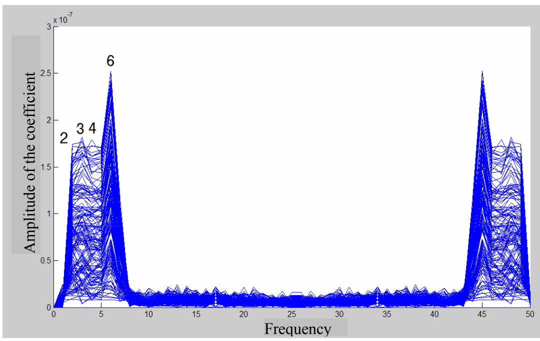

Figure 1 : Spectrum of the Fourier Transformed

The Fourier Transformed spectra highlights six main parameters related to hydrous characteristic of the envelope materials.

Table 1: The most influential parameters for the water content of the air in the zone, in order of importance

ORDER	FREQUENCY	PARAMETERS
1	6	C_h of the floor
2	3	C_h of the south wall
3	4	C_h of the west wall
4	2	C_h of the east wall
5	5	C_h of the north wall
6	7	C_h of the ceiling

Table 1 gives the screened most important parameters responsible for a deviation greater than 10% of the air water content. The hydrous capacity of walls and the floor comes out as the most important parameters and for this reason need to be specified with a special care.

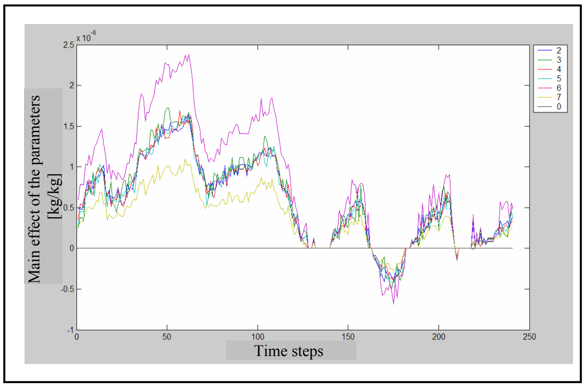

Figure 2: Main effect of the parameter on water content of air in the zone (screening at 10%).

The Figure 2 shows that the contribution of the hydrous capacities to the output deviation is not constant and follows a daily variation. The air volume of the zone and the permeability are responsible for a minor deviation (between 8% and 9%) of the output. An explanation could be that the permeability of the material intervenes only when condensation appears and when transfer occurs in the liquid phase.

Experimental validation

The first step of the validation procedure of the moisture transfer model is to validate the buffer model and the wall model separately. In order to evaluate the accuracy of the buffer model, the experiments carried out require a test cell, called LGI cell, where furniture is modeled as wood planks put inside the cell. A constant airflow rate is generated thanks to mechanical ventilation. A humidifier generates a sudden vapor inflow in the middle of the test cell. The temperature of the cell is free floating according to external climatic conditions. Moisture transfer is thus related to airflow transfer and absorption / desorption of water vapor by the wood. The test cell is shown in the following figure:

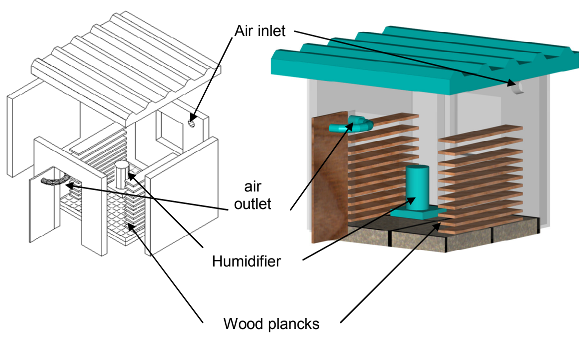

Figure 3 : LGI test cell for buffer model validation

To validate the wall model, experiments are carried out in a different test cell. As measurements should be used to optimize the hydrous parameter values an airtight cell is used in order to control moisture exchanges with outside air. This cell, called STAtron (Figure 4), includes two insulated rooms where artificial climates can be reproduced. Wooden paneling covers three interior walls of room 1. Temperature and relative humidity are controlled thanks to external heat sources. Thus, mainly moisture transfer between the air of the room and the hygroscopic walls are considered. The infiltration airflow through the joint of the walls and through the joints of the door is estimated to 0.7 m^3/h). The experimental procedure is similar to the procedure for the validation of the buffer model. A sudden injection of 0.746 kg of vapor is generated in the middle of the room. Temperature and relative humidity of the room are monitored as well as temperature and relative humidity at the surface of hygroscopic and non-hygroscopic walls.

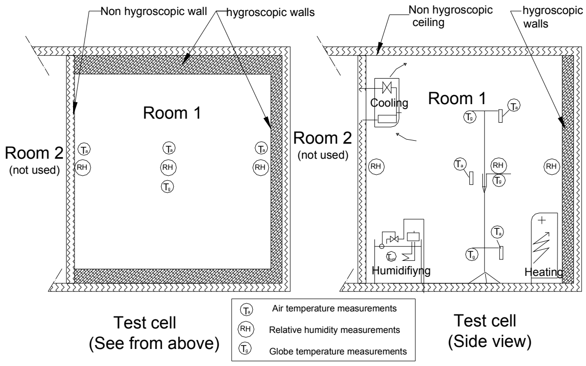

Figure 4 : Test cell called "STAtron" (side view and above)

RESULTS AND DISCUSION

The results for the validation of the global buffer model are presented on the following figure.

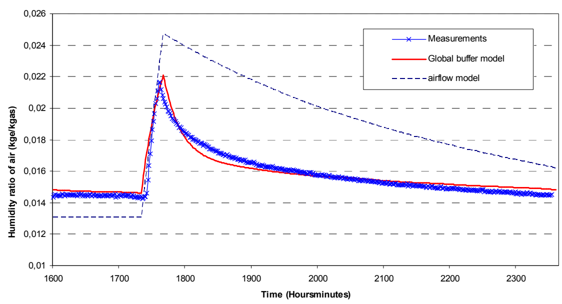

Figure 5 : Validation of global buffer model in the LGI test cell

Figure 5 compares measurements to the simulation results of the global buffer model and an airflow model. The airflow model is a very simple model considering only exchanges of moisture related to ventilation. This experiment shows that considering the behavior of furniture through a global buffer model improves significantly the evaluation of humidity in the room and is able to reproduce sudden variation of air water content.

Using a similar procedure, Figure 6 shows the change of the water content of the air in the room and the results of the wall model as a first step of the experimental validation for the wall model. The model matches experimental results.

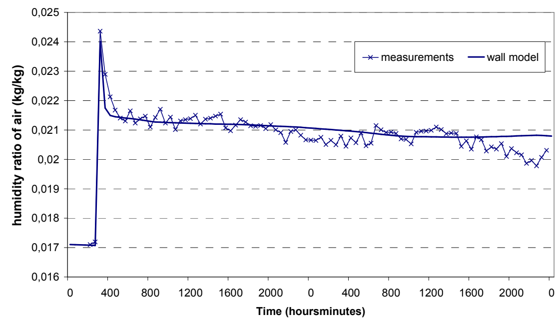

Figure 6 : Validation of wall model in the "STAtron" test cell

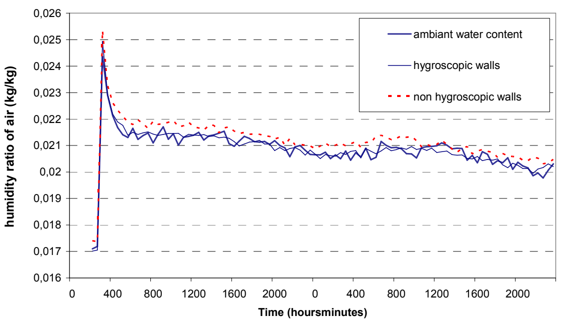

Figure 7 : Evolutions of water content of air in the room and nearby hygroscopic and non-hygroscopic walls

The results of the experiments (Figure 7) also show that the humidity ratio of the room is very close to the humidity ratio of the air nearby hygroscopic and non-hygroscopic walls. The difference is less than 0.001 kg/kg. There is no significant concentration of water near the walls. It appears that only thermal exchanges and temperature differences are responsible for vapor condensation on walls. Thus to propose building design adapted to humid climate and to prevent condensation, very simple rules can be applied. Raising the interior surface temperature of walls and reducing the water content of inside air are the common solutions to improve interiors condition. The moisture transfer model, which considers water transfer with furniture and each wall of the building, can help the designer to find solutions using suitable materials.

APPLICATION OF THE MOISTURE MODEL

As mentioned above, design of buildings should lead to an increase of comfort for occupants and control of the building consumption. The objective of the simulations carried out is to propose design solutions to avoid moisture and condensation problems for hot and humid climate, when ventilation with exterior air is not very efficient. Three buildings are tested. The hydrous properties of the internal side of each building walls are changed to represent the behavior of three different materials:

- Non-hygroscopic material (coating made of iron sheet, glass, tiled walls…).
- Low hygroscopic material: Concrete building (coating made of painted concrete).
- High hygroscopic material: Wooden building (wood shingle coating).

Only the hydrous properties of the coating are adjusted for the three buildings. The thermal properties are the same; indeed, simulations show that indoor air temperatures (see Figure 12) are similar for all the buildings. The study concerns the behavior of the room 1 of the building located in the highlands of Reunion Island and described on the figure below.

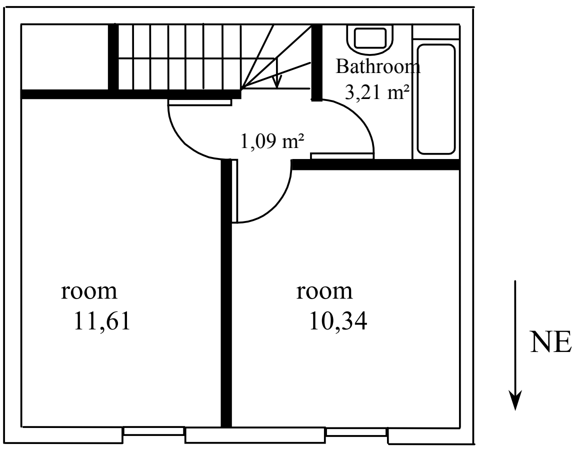

Figure 8 : Building under study.

Simulations assume a low air change rate (1volume per hour) and only internal moisture loads of 1.4 kg of vapor/day related to occupants and their activities. The moisture loads are scheduled as follows:

- 0 am to 6 am and 22pm to 0 am: 10^{-4} kg/s.
- 6 am to 9 am, 12pm to 14 pm and 19pm to 22 pm: 3.10^{-4} kg/s.
- 9 am to 12 am and 14pm to 19 am: 0 kg/s (vacant room).

The outside conditions are described on the Figure 9.

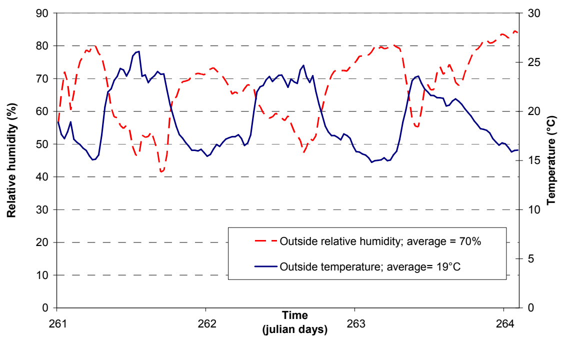

Figure 9 : Climatic conditions for simulations.

The results of this study are proposed on the figure below.

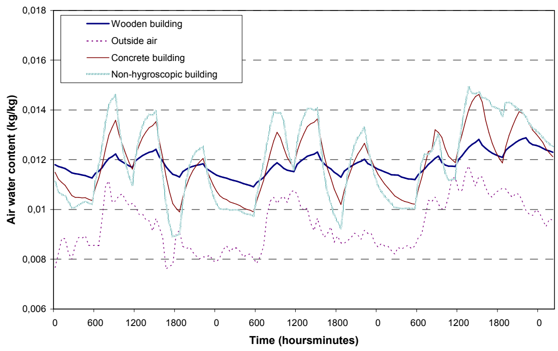

Figure 10: Change of air water content inside the room for the three buildings.

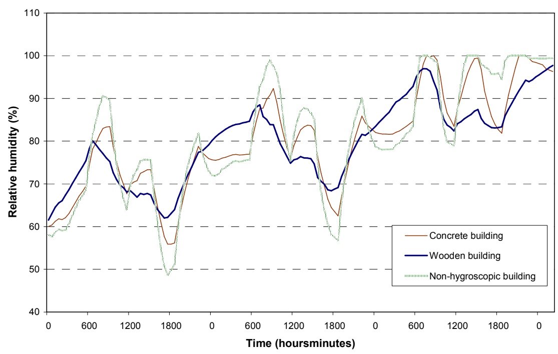

Figure 11 : Change of relative humidity inside the room for the three buildings.

Changes in both water content of air and relative humidity show that a hygroscopic material such as wood is essential to decrease moisture variation in a room. In humid climates, moisture loads combined with wet outside air produce saturated conditions inside buildings. In this case, indoor air quality and comfort are strongly reduced. Non-hygroscopic and low hygroscopic coatings cannot avoid saturation. Only the wooden coating is able to ensure a relative humidity always lower than 100%.

The results show also that if the internal loads are significant relative humidity is much higher than 80%. As it is difficult to avoid mold if the humidity surrounding the walls is over 80%, it appears that only a wooden coating may resolve the problem of mold growth if sensible loads are included in the zone. In order to focus on the hydrous behavior of the materials, thermal properties of the buildings are the same. Thus, indoor temperatures remain unchanged whatever the coating. Figure 12 shows that these temperatures coincide and are relatively low especially at night. This can explain the high relative humidity inside the room.

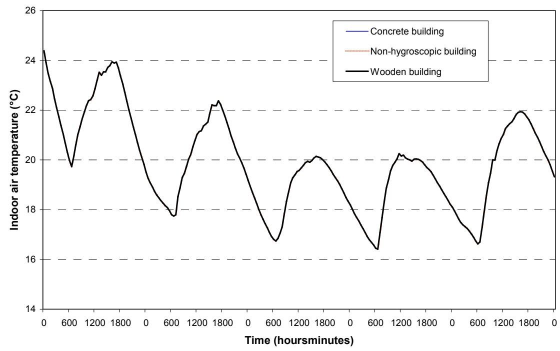

Figure 12: Evolution of indoor air temperature for the three buildings.

The results obtained match the previous studies since hygroscopic material such as wood can reduce the range of the moisture change in buildings even if the ventilation is weak. However, these results appear to be very sensitive to simulation assumptions. More particularly, ventilation rates and internal loads, which are often hardly known for a housing project, can significantly change the response of the building. The building design requires special attention to determine external and internal contributions before launching the simulation procedure.

CONCLUSION

As it is to be expected, the results of the simulation shows that hygroscopic materials can improve the indoor humidity especially when ventilation with outside air is not very efficient (low air change rate and outside air humid). This conclusion leads to advise designers to resort to hygroscopic material when mold and condensation risk appear especially for the wet rooms of the building. In this case, building loads must be well defined.

However, as the air quality in buildings is becoming a major concern for designers and occupants, particularly care must be taken when choosing the hygroscopic materials. These materials and the finish layer must meet two important requirements:

- Not providing organic support that favor mold development. Surfaces must be treated against fungal proliferation.
- Not providing unhealthy vapor. Timber is usually treated against insect and humidity with biocide products, which can generate serious healthy hazards for occupants.

- Not buckling or warping when moisture content of material is high.

Further work must focus on the determination of the airflow rates through small openings in order to quantify the air change in the zone. A study is now in progress concerning the use of wood siding in very wet rooms. More precisely, the aim is to verify in real conditions if mold and condensation on a bathroom ceiling can be prevented by covering one or two walls with wooden paneling. The first results are very encouraging, as mold and condensation no longer appear since the timber has been installed.

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NOMENCLATURE:

C_h	Hydrous capacity of material [kg/kg.Pa]
e	Thickness [m].
h_m	Mass exchange coefficient [kg/m².s].
K	Permeability [kg/m.Pa.s].
m	Mass [kg]
r	Pore radius [m]
S	Surface [m²]
T	Temperature [°C]
t	Time [s]

V	Volume [m^3]
w	Humidity ratio [kg/kg]
x	Distance [m]
α, β, γ	Coefficients related to the buffer
ϕ	Flux [kg/s] or [w]
ρ	Density [kg/m^3]

INDEX:

act	Active layer
as	Dry air
deep	Core of the buffer
hvac	Heating or cooling system
hygr	Hygroscopic wall
liq	Liquid
load	Internal load
m	Material
non-hygr	Non hygroscopic wall
vent	ventilation
sat	Saturation
surf	Surface