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Danish and Brazilian Modeling of Whole-Building Hygrothermal Performance – with Emphasis on Moisture Buffering

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Abstract. *The humidity of rooms and moisture conditions of materials in the enclosure of buildings depend much on each other because of the moisture exchange that takes place over the interior surfaces. These moisture influences also depend strongly on the thermal conditions of indoor spaces and enclosure elements of buildings. In turn, the moisture and humidity conditions have significant impact on how buildings are operated. In hot-humid climates it may be desirable to keep the ventilation rates low in order to avoid too high indoor humidity, while in cold climates ventilation can be used to keep the humidity low and thus reduce the risk of moisture damage in the building enclosure. In either case the indoor humidity has a direct or indirect impact on the energy performance of the HVAC system of a building.*
To analyze this situation, one could benefit from some recent developments in integrated computational analysis of the hygrothermal performance of whole buildings. Such developments have led to new hygrothermal models for whole buildings. The paper gives examples of two such recent developments and will illustrate some calculation results that can be obtained. Finally the paper will mention some further developments and international collaboration on the subject.

Keywords*. Heat, air, moisture, whole buildings, indoor climate*

1. Introduction

Indoor humidity is a result of vapor production caused by activities in indoor rooms and exchange of moisture with the surroundings, mainly through infiltration, ventilation and other forms of air exchange. Indoor humidity also depends on the exchange of moisture with the building enclosure, as well as with indoor furnishing. Most of this moisture exchange will be of a transient nature, such as the moisture exchange with indoor furnishing and materials on the interior surface of the building enclosure. Since the total surface area of materials in contact with the indoor environment can be significant, and many materials may be hygroscopic, this exchange of moisture will act to moderate the indoor humidity variations seen in rooms under varying exposures. In addition, some moisture will also be exchanged with the exterior environment through various moisture transport processes that work across the whole building enclosure. Such transports can normally be seen as unimportant in comparison to the amounts exchanged by ventilation (Elmroth et al., 1997).

The indoor humidity is one of the most important reasons for moisture accumulation in the building enclosure. Thus, there is a need to develop good analytical techniques to evaluate the integral moisture performance of the whole building, comprising the indoor environment and its enclosure. Attempts to develop such analytical techniques have been presented by Rode and Grau (2003), Mendes et al. (2003), Holm et al. (2001) and Simonson et al. (2002). In addition there is a need to make more experimental investigation in whole building such as done by Simonson (2000). Realization that these needs exist has led to the formation of an international research project in the framework of the International Energy Agency, which started by the end of 2003 and involves researchers from as many as 19 countries (Hens, 2003).

Ventilation of indoor rooms could be maintained as a way to avoid excess indoor humidity levels. Since the indoor humidity loads vary with a daily cycle, an interesting question is whether proper utilization of the moisture buffering capacity of materials, could keep the indoor humidity at moderate levels and thereby limit the requirement for ventilation as a means to control the vapor content in periods when the rooms are occupied. Moisture buffering might also avoid very dry indoor humidity levels such as seen in cold climates in wintertime. In short, moisture buffering may eliminate the peaks and valleys in indoor humidity levels, and thereby may contribute to an optimized indoor environment.

There is today a need for more knowledge about the extent to which such effects are worth pursuing (Rode et al., 2004). This paper will demonstrate the performance of two different whole-building hygrothermal simulation models.

They are used to quantify the daily moisture adsorption/desorption for building enclosures with different materials, different HVAC system operation and different outdoor climatic conditions.

The topic *Whole Building Heat, Air and Moisture Response* is also being dealt with in a major international research project which is Annex 41 in IEA's Energy Conservation in Buildings and Community Systems Programme. The project, which runs from 2003-2007, has participation of researchers of 39 institutions from 19 different countries (Hens 2003, and Annex 41, 2006). The project strives to stimulate new developments and exchange experiences, not the least through execution of "Common Exercises" within the subtasks: 1. Modeling principles; 2. Experimental investigations; 3. Boundary conditions; and 4. Long term performance and technology transfer. Participants in the project typically have a background in either thermal modeling of buildings, hygrothermal modeling of building envelopes, or in air flow modeling with Computational Fluid Dynamics (CFD). The interesting and difficult target for this research is to combine all the different physical processes and the different levels of detail in the building description – from materials, over constructions to the whole building..

2. Moisture Buffer Effect

In a general way, moisture buffer capacity can be defined as a material's ability to reduce variations within an enclosure. For example instead of relative humidity oscillating between say 40 % and 80 % due to indoor activities, proper use of moisture buffering material might limit variation between a range of 55 and 65 % RH, or maybe even less variation.

2.1. Moisture Buffer Definitions

Moisture buffer capacity is an essential term for the topic of this paper. Some material properties that influence the buffer capacity are density, moisture capacity and water vapor permeability.

- The *density* is of importance since a fixed volume of material with a high moisture capacity and a low density has only small ability to contain water as opposed to the same volume of a material with a higher density.
- The *moisture capacity* is expressed by the gradient of the sorption curve, where the sorption curve gives the relationship between the equilibrium moisture content (kg/m^3) of a material and the relative humidity of its surroundings. The sorption curve is not linear and thus, the moisture capacity depends on the actual moisture level.
- *Water vapor permeability* is a material property that describes the rate of moisture transport by diffusion per unit area and vapor pressure difference through a unit thickness of material.

Several different ways of defining moisture buffer capacity have been suggested. One way is analogous to thermal effusivity which expresses a material's capacity to absorb heat when exposed to a given thermal excitation (Hagentoft, 2001). Inspired by this definition, a buffer effect can be described as a *moisture accumulation ability* (or *moisture "effusivity"*), which derives from vapor permeability (δ_c, m^2/s), moisture capacity (ξ_w, kg/m^3) and the saturation vapor concentration (ν_s, kg/m^3).

Moisture effusivity, b_m : $$\sqrt{\frac{\delta_c \cdot \xi_w}{\nu_s}} \qquad (1)$$

The unit for moisture effusivity is m/s$^{1/2}$.

The moisture effusivity is different from the well known term, moisture diffusivity:

$$D_m = \frac{\delta_c \cdot \nu_s}{\xi_w} \qquad (2)$$

but the following relation can be established between the two:

$$b_m = \frac{\delta_c}{\sqrt{D_m}} \qquad (3)$$

Another measure of moisture buffer capacity is *penetration depth* (ε, m) which is also a combined parameter. It includes cycle time, water vapor permeability, saturation moisture content in the air (which is highly temperature dependent) and the moisture capacity. The penetration depth gives the active layer of a construction that is able to exchange moisture with its surroundings during a given cycle. The depth at which 37% of the variation at the surface can be registered is:

Moisture penetration depth, ε: $$\sqrt{\frac{D_m \cdot t_p}{\pi}} \quad (4)$$

where D_m is the moisture diffusivity of the material, m^2/s,
t_p is the period of the cycle, s

Tim Padfield (1999-2006) used the term, *available water* during a given period, to compare moisture buffer capacity of different materials. The available water is given by the product of moisture capacity ξ_w and penetration depth ε. The unit for available water is $g/m^2/day$.

A so-called *Feuchtepufferfunktion* was introduced by researchers from the University of Essen, Germany and an overview of its definition is given by Reick, 2001. The *Feuchtepufferfunktion* represents a mathematical paradigm to analyze the response of a material when subjected to a step change in surrounding moisture conditions. It is not a material property as such.

Mitamura et al. (2001) introduced yet another way to express the buffer capacity. The weight of a tested sample as a function of variation in ambient relative humidity was proposed. The drawback of this measure of buffer capacity is that it requires all materials to be tested experimentally for this specific parameter, rather than adapt data that is available from other moisture property measurements.

The different above mentioned measures of moisture buffer capacity are hard to compare. They have different units and contain different parameters. It is not clear which parameters are the most significant for buffer capacity. This topic was the issue of discussion of an international workshop (Rode et al., 2004), where illustrations were given of the different results that could be obtained using some of the possible units for moisture buffer capacity. The workshop was followed up by a Nordic which resulted in the definition the so-called *Moisture Buffer Value* which is suggested as a parameter to describe the moisture buffer capacity of building materials (Rode et al., 2005).

2.2. Material/air interactions and the moisture buffer effect

Daily cycles of temperature and relative humidity induce energy and mass pulses into walls of the building envelope. These pulses affect the spatial distributions of temperature and moisture content in the walls. The affected region has a penetration depth - ε – and oscillation amplitude - A(x). Thus, in an inner region, $\varepsilon_{ext} < x < (l - \varepsilon_{int})$, there is a stabilization kernel, where the moisture content does not change over a certain cycle time such as a day.

Figure 1 shows schematically this phenomenon for a wall with a high Biot number for moisture diffusion (Bi_m). This dimensionless number is the ratio of wall hygric resistance to surface hygric resistance. It can be mathematically defined as:

$$Bi_m = \frac{h_m L}{D_m} \quad (5)$$

where h_m is the mass transfer coefficient at the interface between the porous material and the air, m/s,
L is the wall thickness, m.

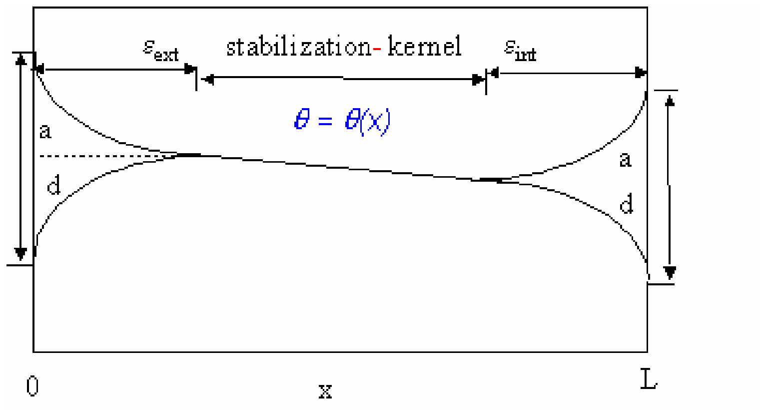

Figure 1 Typical daily oscillation of moisture content for walls of high Bi_m numbers.

High Bi_m numbers mean that wall hygric resistance dominates the moisture transport rate and moisture levels vary within the wall. In Figure 1, "*a*" and "*d*" mean adsorption and desorption, respectively, during the cycle time of interest (e.g. drying out of the wall during daytime because of the sun and air-conditioning system, and vapor absorption during nighttime). The moisture capacity for adsorption or desorption due to the characteristics of the air-material interface can be associated with the boundary condition for moisture conservation at the inside wall surface. If the convection mass transfer coefficient is high, the moisture transfer rate is governed by the moisture buffer capacity of the porous building materials. As defined above, moisture buffer capacity can be related to the moisture capacity, penetration depth, cycle time, density and moisture diffusivity.

Surface parameters such as surface roughness and treatment (e.g. paint) greatly influence the moisture buffer capacity of the system and can be implicitly considered in a modified convection moisture transfer coefficient ($h_m^{'}$) at the surface. As paints do not have accumulation ability, they can be considered to add a resistance besides the one for moisture flow through the boundary layer. The convection moisture transfer coefficient can be calculated as:

$$\mathrm{h}_{\mathrm{m}}^{'} = \left(\frac{\rho_{air} c_{air} \mathrm{Le}^{2/3}}{h} + \frac{1}{h_{m,coating}} \right)^{-1} \qquad (6)$$

where
- ρ_{air} is the density of air, kg/m^3,
- c_{air} is the specific heat of air, J/(kg·K),
- Le is the dimensionless Lewis number,
- h is the convection heat transfer coefficient, W/(m^2·K), and
- $h_{m,\,coating}$ is the permeance of the coating, m/s

For laminar and turbulent airflow, the Lewis number, *Le*, can be considered to have the values 0.9 and 1, respectively. The following values are considered to be typical for the parameters in Equation (6): c_{air} = 1.007 kJ/kg·K, ρ_{air} = 1.166 kg/m^3, and *Le* = 1.

2.3. An example of the importance of Moisture Buffer Capacity

An example is given here to illustrate the importance of moisture buffer capacity in relation to ventilation to temper the indoor humidity levels. The example case has a room with a square floor of area equal to 100 m² and four enclosing walls each 2.5 m high. Only the walls exchange moisture with the air (not the floor, the ceiling or other indoor materials). The material of the walls has no surface finish, so it is open to moisture flow, and consists of either brick, concrete, cellular concrete, “wood ⊤” (fibers are perpendicular to the vapor flow), or “wood ||” (fibers are parallel to the vapor transport). The air exchange rate is 0.25, 0.50 or 1.00 air changes per hour (ach). The initial condition and the condition of ventilation air is 40% relative humidity. The increase of indoor relative humidity is calculated for the first 8 hours after the moisture production rate changes from 0 to 417 g/h (10 kg/day).

An analytical solution for the increase in indoor vapor concentration is given by Hagentoft (2001). It considers the interior surface resistance but does not take the vapor capacity of the air itself into account:

$$v = v_0 + \Delta v \cdot \left[1 - \left(1 - \frac{d_v}{d_2} \right) e^{\frac{D_m t}{d_2^2}} \, erfc\left(\frac{\sqrt{D_m t}}{d_2} \right) \right] \qquad (7)$$

where
- v is the indoor vapor concentration at any time t, kg/m^3,
- v_0 is the initial indoor vapor concentration, kg/m^3,
- Δv is the increase of indoor vapor concentration after infinite time, kg/m^3,
- d_v is the material thickness equivalent to the surface resistance to vapor flow, m,
- D_m is the moisture diffusivity of the material, m^2/s,
- erfc( ) is the complementary error function.

In Equation (7), d_2 is calculated as:

$$d_2 = d_v + \frac{3600\,\mathrm{s/h} \cdot A \cdot \delta_v}{n \cdot V} \qquad (8)$$

where
- A is the total surface area of the walls, m^2,
- δ_v is the water vapor permeability of the material in the walls, m^2/s,
- n is the total air change rate, h^{-1}, and
- V is the volume of the indoor space, m^3.

A surface mass transfer coefficient of $2.7 \cdot 10^{-3}$ m/s is used, which is typical for unpainted walls. The results are shown in Figure 2. The surface resistance is the reason for the sudden increase from 40 to 42.3% relative humidity that can be seen for all walls at time 0 h.

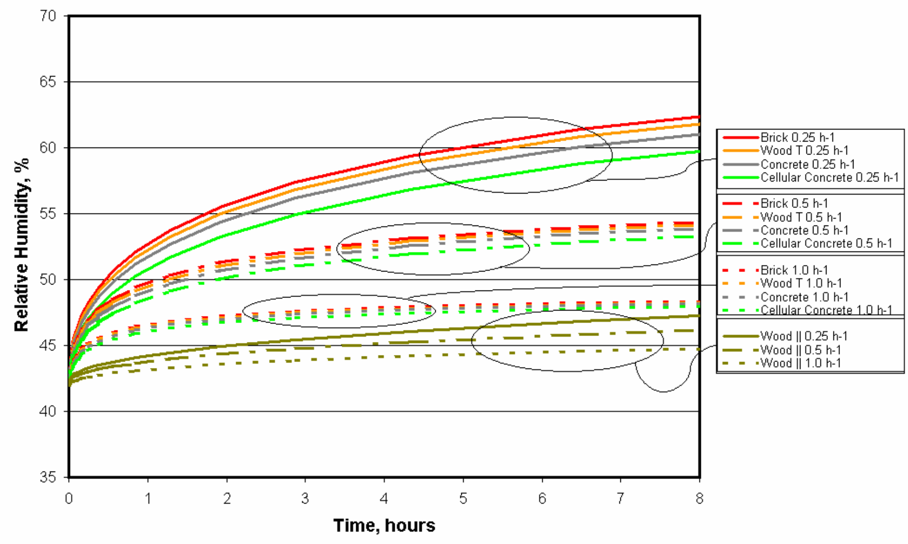

Figure 2 Increase in indoor relative humidity after step change in humidity production using various wall materials and levels of infiltration with outdoor air.

Imagine that this were an office where the occupants in business attire do not want to feel the air becoming too humid or stuffy during a working day. Could one minimize the requirement for ventilation just by choosing some appropriate building materials? Most materials behave the same, and after 8 hours with air exchange rate of 0.5 ach, the indoor relative humidity has increased to approximately 53%. It would have increased to just 48% RH, if the air exchange rate had been 1.0 ach. However, if one had used end-grain wood, "wood ||", as wall material, the relative humidity would have risen to only 47 %, even if the air exchange rate were as low as 0.25 ach.

Conclusions from this simple example are:

1. Most common building materials behave more or less the same.
2. Product development could possibly lead to new materials whose moisture buffer capacity could help to reduce the requirement for ventilation (if indoor humidity is a design criterion).

Due to the interaction between the indoor environment and the envelope materials, further analysis of moisture buffer capacity of materials and how they behave in buildings under normal conditions should be analyzed using whole building simulation tools as described in the following sections.

3. Simulation Tools for Evaluating the Moisture Buffer Effect

Hygrothermal simulations were performed in order to show some effects of the moisture buffer capacity of building materials using two dynamic models, which were implemented in each of two different whole-building hygrothermal simulation programs. The first one, the Danish building simulation model (Rode and Grau, 2003), has been developed at the *Danish Building Research Institute* and the second one, the Brazilian building simulation model (Mendes et al., 2003), at the *Pontifical Catholic University of Paraná* – Brazil. The two models have been used for different cases. A short description of each program follows.

3.1. The Danish Building Simulation Model

The theoretical basis of the Danish building simulation model for dynamic calculation of the moisture conditions in rooms and constructions is conservation of water. An equation for the moisture balance is set up separately for each zone. The balance equation expresses that moisture is exchanged by infiltration, ventilation and air exchange with the outdoor air and with adjacent zones. Furthermore, moisture is exchanged by convective transfer between the zone air and the adjacent constructions and furnishings. And finally, moisture is released as a result of activities in the zone. The balance equation is dynamic, so it takes into consideration the buffer capacity of the zone air. A dynamic calculation of moisture conditions is carried out for the interior of every single construction and furnishing. The zones on each side of the construction constitute the boundary conditions. The air in a zone is considered to be fully mixed.

Constructions (and furnishing) are considered as composite building components consisting of several layers of building materials. Every material layer is again subdivided into one or several control volumes for which the calculations are carried out. A node point in the center of each control volume represents the conditions in the whole volume. Node points are placed on the two surfaces of the construction.

At each time step, calculations of the temperatures in the constructions and zones are carried out before calculating the moisture conditions. Thus, the distribution of the saturation vapor pressure, p_s, is known at the new time step. The same control volumes are used for the thermal as for the moisture calculations.

3.1.1. Moisture balance for zone air

The following influences on the humidity of the air are considered:

- Moisture transfer from adjoining constructions
- Contribution of moisture from various sources and activities, e.g. occupant load, laundry and drying, bathing, cooking, industrial processes, humidification/drying, and other
- Penetration of moisture from outdoor air (by infiltration and venting)
- Supply of humid air from ventilation systems
- Humid air transferred from other zones (mixing)

3.1.2. Moisture in constructions

The model for moisture transport in the constructions considers moisture transport in the form of vapor diffusion. The moisture transport internally in the constructions is described in a transient way, so each layer's moisture buffering capacity is considered. A calculation of the local moisture balance is carried out for each control volume and time step. Using the sorption curves of the materials, the new moisture contents can be recalculated into new values for relative humidity and vapor pressures. The model uses an implicit calculation procedure, which ensures numerical stability even for relatively large time steps.

3.2. The Brazilian Building Simulation Model

The Brazilian model uses object-oriented programming and has been developed to predict the hygrothermal performance of multi-zone buildings considering both vapor diffusion and capillary migration.

A lumped formulation for temperature as well as for water vapor is adopted in each building zone. Eq. (9) describes the energy balance for a zone subjected to loads by conduction, convection, short-wave solar radiation, inter-surface long-wave radiation, infiltration and HVAC system related loads.

$$\dot{E}_t + \dot{E}_g = \rho_{air} c_{air} V_{air} \frac{dT_{\text{int}}}{dt} \qquad (9)$$

where
$\dot{E}_t$ is the energy gained from outside the room, W,
$\dot{E}_g$ is the internal energy generation rate, W,
ρ_{air} is the density of air, kg/m^3,
c_{air} is the specific heat of air, J/(kg·K),
V_{air} is the room volume, m^3,
T_{int} is the room air temperature, K, and
t is the time, s.

The term $\dot{E}_t$, in Equation (9), includes loads associated with the building envelope (sensible and latent conduction heat transfer), furniture (sensible and latent), fenestration (conduction and solar radiation), openings (ventilation and infiltration) and HVAC systems.

The total conduction heat flux that crosses the control surface of each zone is calculated as

$$Q_{wall,S}(t) = \sum_{i=1}^{m} h_{c,i} A_i \left[T_{i,x=L}(t) - T_{\text{int}}(t) \right] \qquad (10)$$

for the sensible conduction load and as

$$Q_{Wall,L}(t) = \sum_{i=1}^{m} L(T_{i,x=L}(t)) h_{m,i} A_i \left[\nu_i(t) - \nu_{\text{int}}(t) \right] \qquad (11)$$

for the latent load. In Equations (8) and (9) are used the following definitions:

A_i represents the area of the *i'th* surface, m^2,
h are the convection coefficients for heat (h_c, W/(m^2·K)) and mass (h_m, m/s),

$T_{n,i}(t)$ is the temperature at the *i'th* internal surface of the considered zone, K,
L is the vaporization latent heat, J/(kg·K), and
ν is the water vapor density, kg/m^3.

The temperature and vapor density are calculated by the combined heat and moisture transfer model based on the theory by Philip and deVries (1957) quoted by Mendes et al. (2002a). This model is based on moisture content as a driving potential for moisture within materials. However, the moisture content may be quite different between different materials, even when they are in equilibrium with one another. Thus, the moisture content profile may experience a jump over the interface between different materials, and the mathematical treatment of this discontinuity in the moisture content profile is described by Mendes et al. (2002b).

There is a strong coupling between the governing equations. It implies the usefulness of applying an algorithm which is capable of solving all equation sets simultaneously. Mendes and Philippi (2004) described the computational performance of the MTDMA (MultiTriDiagonal Matrix Algorithm), applied to the case of strongly-coupled heat and moisture transfer in porous building materials.

Engineers and researchers were motivated in the past to numerically decouple the governing equations because of the difference between the time scales for heat and moisture transfers. Nonetheless, besides the mathematical coupling between the heat and moisture terms in the conservation equations, the transport coefficients have a strong non-linear dependence on both moisture content and temperature. In fact:

i. for low moisture content, mass transfer is predominantly in the vapor phase;
ii. immediately after the liquid water has become a continuous phase, small changes in capillary potential may produce high variation in moisture content. Liquid transfer rates by capillarity will be greatly enhanced. This microscopic information about “liquid bridges” that speed up the moisture transport is embedded in the moisture diffusivity $D_{m;}$
iii. when the moisture content is high, it is likely that high evaporation rates occur at the boundaries, promoting high gradients of moisture content and temperature and causing the transport coefficients to change considerably through the physical domain of the porous structure;
iv. for the material chosen in this example (lime mortar), moisture transport coefficients may rapidly change their magnitude by a factor of 100 or even more;
v. thermal conductivity may also have a substantial variation of the order of 20%.
vi. These five facts might easily lead to problems with numerical divergence when the physical problem is mathematically de-coupled.

For the water vapor balance, different contributions were considered: ventilation, infiltration, internal generation, porous walls, furniture, HVAC system and respiration by occupants. In this way, the lumped formulation becomes:

$$\left(\dot{m}_{\text{inf}} + \dot{m}_{vent}\right)\left(W_{ext} - W_{\text{int}}\right) + J_b + J_{ger} + J_{surf} + J_{HVAC} = \rho_{air} V_{air} \frac{dW_{\text{int}}}{dt} \qquad (12)$$

where
$\dot{m}_{\text{inf}}$ is air mass flow by infiltration, kg/s
$\dot{m}_{vent}$ is air mass flow by ventilation, kg/s
W_{ext} is the external humidity ratio, kg water/kg dry air
W_{int} is the internal humidity ratio, kg water/kg dry air
J_b is water vapor flow from the respiration of occupants, kg/s
J_{ger} is internal water-vapor generation rate, kg/s
J_{surf} is water vapor flow from porous surfaces (walls, partitions and furniture), kg/s
J_{HVAC} is vapor flow from HVAC systems, kg/s

The water-vapor mass flow from the respiration of occupants is calculated as shown in ASHRAE (1993). It takes into account the room air temperature, humidity ratio and physical activity.

The Brazilian building simulation model uses also the *triangle* model (Shewchuk, 1996) that generates a finite-element mesh on walls and the ground floor in order to precisely calculate shape factors and shaded/sunny areas. The triangle model is fast, memory-efficient, and robust. It computes Delaunay triangulations and constrained Delaunay triangulations exactly. Guaranteed-quality meshes (having no small angles) are generated using Ruppert's Delaunay refinement algorithm (See the triangulation in the bottom right side of Figure 9).

4. Simulation Results

This section will illustrate some examples of use of the above-mentioned Danish and Brazilian whole-building hygrothermal simulation models.

4.1. Test case with the Danish building simulation program

In order to verify the moisture calculations with the Danish building simulation model and to illustrate the use of a practical test example for comparison and evaluation of whole building hygrothermal models, the IEA BESTEST model (Judkoff and Neymark, 1995) has been chosen to start. The IEA BESTEST represents an international effort to make intermodel comparisons of the thermal performance of some variations of a rather well described, and in principle simple test building. The undertaking was a joint activity between the International Energy Agency projects IEA SHC Task 12 and IEA ECBCS Annex 21. BESTEST has also been adopted for some common exercises in IEA ECBCS Annex 41 (Woloszyn et al., 2005).

The small model building is taken to be located in Denver, Colorado. It has a floor plan of 6.0 by 8.0 m internal dimension and room height 2.7 m (building internal volume: 129.7 m^3). It has two windows (2.0 by 3.0 m each) that are south-facing in this paper. Otherwise the building has only opaque surfaces. Different BESTEST test cases differ by the type of construction (heavy or light-weight), window orientations and use of overhangs, and by different operational strategies and set-points for the heating and cooling system. The different variations are described by Judkoff and Neymark (1995). In this paper we chose to freely interpret some of the variations of the light-weight form of the building with outer walls consisting of 12 mm plasterboard, 66 mm fiberglass insulation and external 9 mm wood siding. Between the plasterboard and the glassfiber insulation is a vapor retarder with vapor diffusion resistance of 250 $GPa \cdot m^2 \cdot s/kg$. The floor on ground and flat roof are also of a lightweight construction with timber and plaster board claddings. In order to thermally decouple the building from the ground, the floor insulation is more than 1 m thick.

Our use of the building has the windows facing south without overhang. The heating and cooling set points are both 20 °C and the systems have sufficient power to maintain this temperature. The air exchange with the outdoors is by constant infiltration of 0.5 h^{-1}. The building has no internal walls or furnishings, so the only possibility for indoor humidity exchange is by infiltration with the outdoor air and by moisture exchange with the constructions in the building enclosure. The thermophysical properties of the materials in the building have been entered in the database of the Danish building simulation program such that the thermal properties are in accordance with the specifications from the BESTEST examples. The moisture transport properties (sorption curve and water vapor permeability) are from similar materials in the program's database. The building as entered in the Danish building simulation model can be seen in Figure 3.

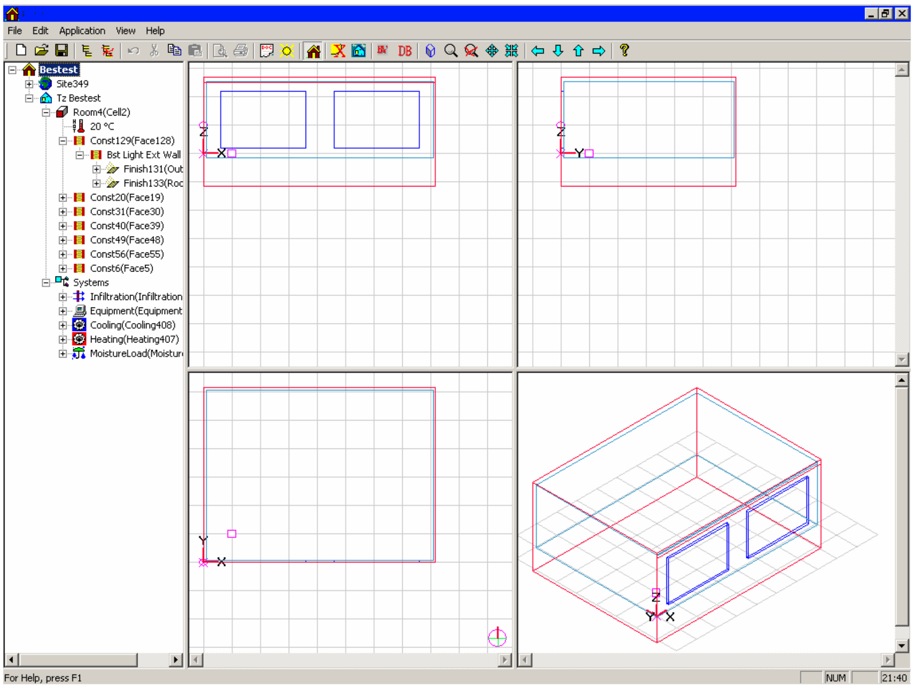

Figure 3 BESTEST building as entered in the Danish whole-building hygrothermal simulation model.

It is desired to test the program's ability to model the moisture exchange between the indoor environment and the building enclosure. Therefore, a usage pattern has been devised by which there is vapor production for eight hours during daytime. To further simplify conditions the floor and ceiling are assumed to have vapor tight inside finishes, i.e. only the walls participate in the moisture exchange. The interior surface of the plasterboards is supposed to be unpainted, but there is an interior surface resistance to convective moisture flow of 0.05 $GPa \cdot m^2 \cdot s/kg$

4.1.1. Base test of accumulation of indoor humidity

To initially test the model, two relatively simple analytical tests were carried out first, analyzing the situation after the indoor humidity generation suddenly starts at a rate of 0.417 kg/h. Initially, all interior conditions are at 20°C and 40% relative humidity, and an artificial weather data file has been generated also with this constant condition. A preconditioning period of one month without moisture production was run first.

The first test assumes all surfaces to be inert to vapor exchange. The walls are assumed to be clad with an impermeable liner. Thus, in theory, the indoor humidity would increase according to:

$$c = c_0 + \frac{G}{n \cdot V}\left(1 - e^{-n \cdot t}\right) \qquad (13)$$

where
- c is the indoor vapor concentration, kg/m^3, at any time, t,
- c_0 is the initial and outdoor vapor concentration, kg/m^3,
- G is the rate of indoor vapor release, kg/h,
- n is the air change rate, h^{-1}, and
- V is the volume of the indoor space, m^3.

The second test is similar, but now assumes the interior surface of the walls to be open. The theory to calculate this case is described in the example in Section 2.3.

Figure 4 shows the analytical and simulated evolution of the indoor relative humidity in the two cases. Generally, the agreement is good. But there is a clear deviation between simulated and analytical result shortly after the humidity production begins in the case when the plasterboard is not vapor tight. The reason is that the analytical solution does not take into account the moisture capacity of the zone air.

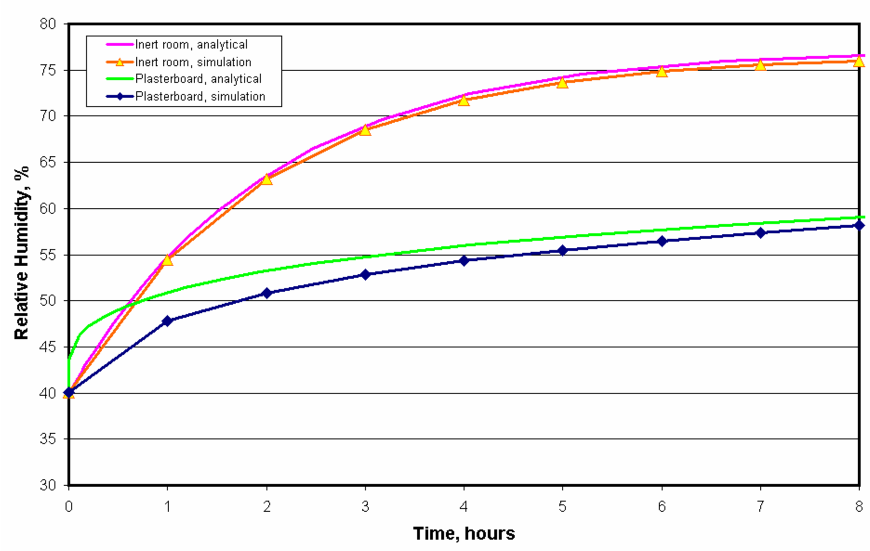

Figure 4 Analytical and simulated development of indoor relative humidity after sudden initiation of internal humidity production. Two cases: With and without vapor tight covering of the walls.

4.1.2. Indoor humidity variations in the BESTEST building under natural conditions

For natural conditions, the outdoor climate of Denver, Colorado is used (Department of Energy, 2006). The indoor humidity condition is investigated when the moisture production rate is 0.18 kg/h from 9 am to 5 pm every day. This would correspond to the situation if the room were used as an office by three people. Once again, two scenarios have been explored: One has a vapor tight covering on the inside of the walls, and the other has the plaster board open to moisture transport across it. Like before, the floor and ceiling are assumed to be impervious to moisture.

Figure 5 shows how the monthly average of the indoor relative humidity varies over the year from approximately 15 to 50% relative humidity. The values are the same for either tight or open interior wall surfaces. However, Figure 6 shows that the hourly distributions are different for the two cases despite the same imposed conditions during week 26 (the last week of June). The open structure buffers the indoor humidity so that the daytime maxima are lower and the nighttime minima are higher than they would be for the tight structure.

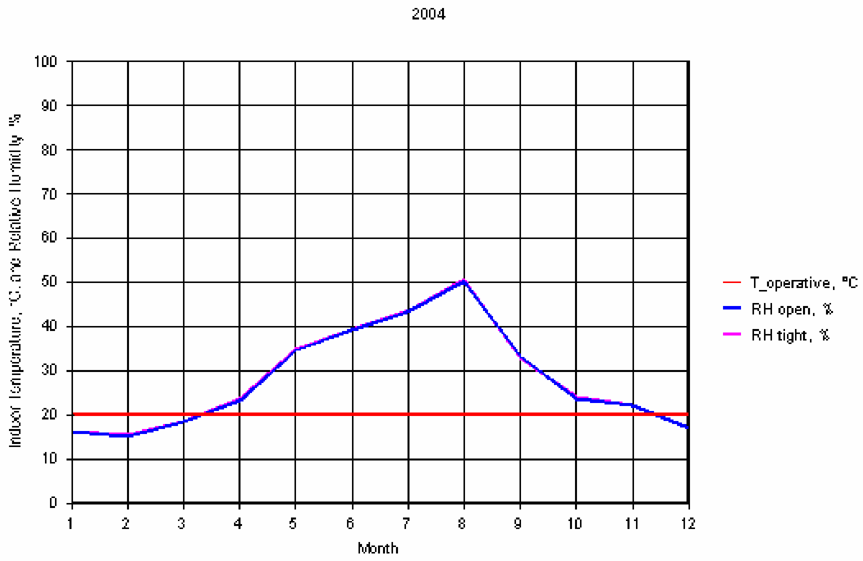

Figure 5 Annual distribution of the monthly mean values of indoor operative temperature and relative humidity of the BESTEST building in the simulations with open or vapor tight interior surfaces.

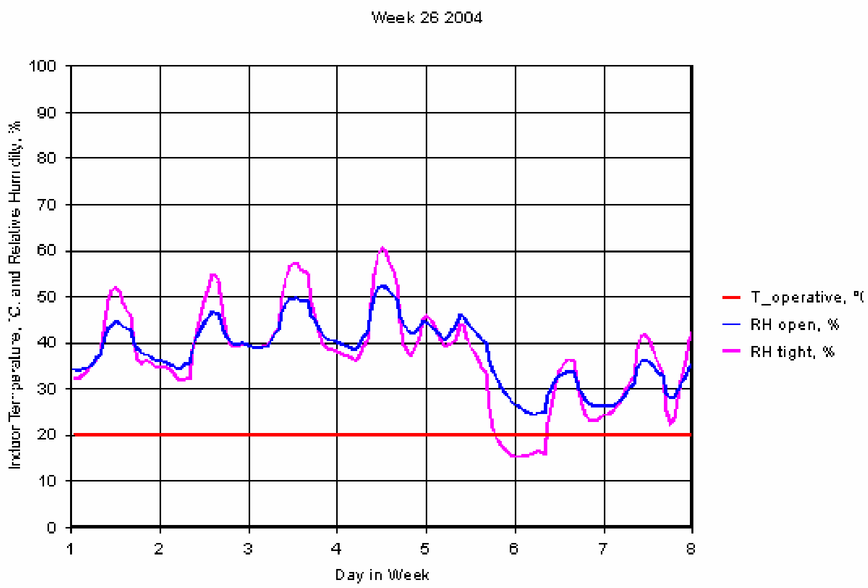

Figure 6 Distribution of the indoor operative temperature and relative humidity during week 26 (end of June) with open or vapor tight interior surfaces.

Fang et al. (1998) developed an expression to predict the voting of occupants with the acceptability of indoor air quality on a scale from -1: *Clearly Unacceptable* to 1: *Clearly Acceptable*. The predicted voting depends linearly on the enthalpy of the air. For clean air, the relationship is:

$$Acceptability = -0.033H + 1.662 \quad (14)$$

where H is the enthalpy of air (kJ/kg).

The enthalpy can be calculated from the temperature and humidity. Since both the indoor temperature and humidity are modeled, it is possible to get a prediction of the perceived indoor air quality according to Equation (14). Warm and humid air, which may feel comfortable from a normal thermal comfort viewpoint if activity or clothing levels are low, may be assessed as “stuffy” and not particularly acceptable according to the perceived air quality index. The resulting prediction of the acceptability is shown in Figure 7 for the two cases with and without a tight internal covering of the walls. The variations between cases are relatively small, and generally, the air quality is good. Nevertheless, it is interesting to analyze the values during the periods when the room is occupied. Table 1 shows the average perceived air quality values in the hours of week 26 when the room is occupied, and when the room is unoccupied. On average, the room experiences a very small improvement of perceived indoor air quality when wall materials are used which are open to vapor transport are used (perceived air quality increases from 0.41 to 0.45).

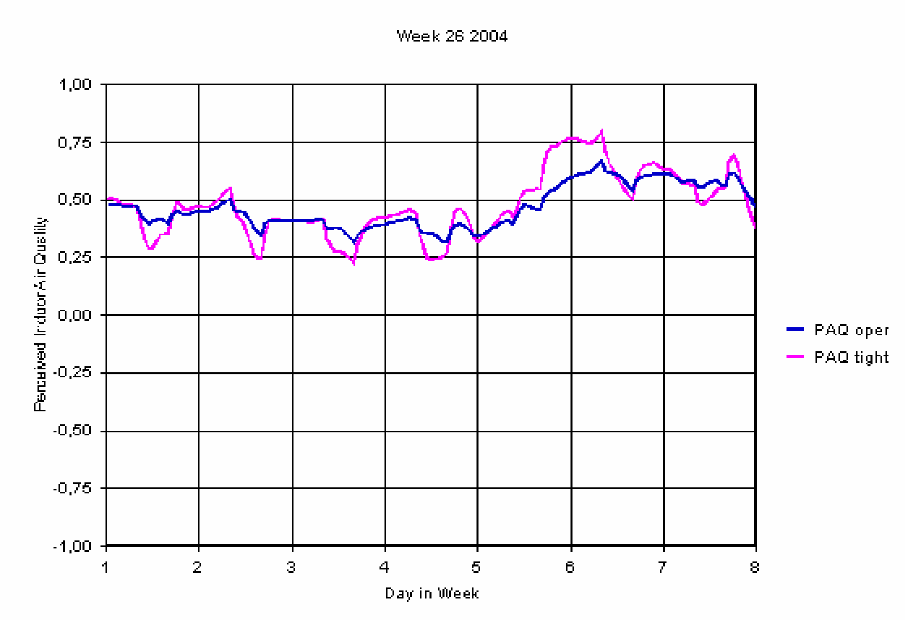

Figure 7 Hourly distribution of perceived indoor air quality (PAQ) during week 26 with interior cladding of the walls either open to diffusion or vapor tight.

Table 1 Average value of the Perceived indoor Air Quality during hours of the room being occupied or unoccupied in week 26 for the cases with and without tight covering of the walls.

Mean Perceived Air Quality	Open wall surfaces	Tight wall surfaces
Room occupied (9 am - 5 pm)	0.45	0.41
Room not occupied (6 pm - 8 am)	0.48	0.51

To illustrate the perspective of whole building moisture analysis, Figure 8 shows the calculated relative humidity in the layers of the south wall during week 26. From such analysis it could be interesting to see if the high outdoor humidity and warm conditions during summer causes too much moisture accumulation on the interface between the vapor retarder and the insulation layer, such that mould growth could occur. For week 26 the relative humidity reaches at most 82% at maximum, and only for a short period. The risk of mould growth is small.

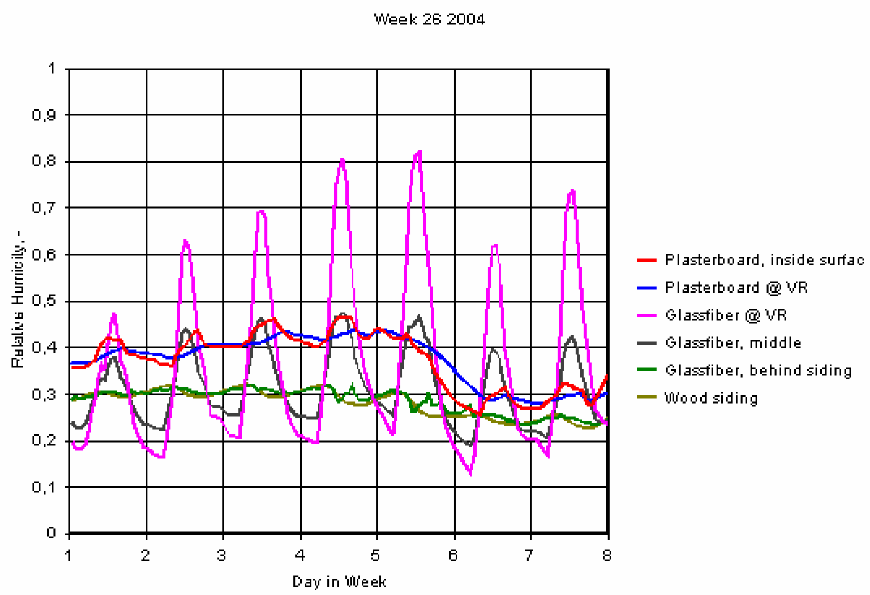

Figure 8 Distribution of relative humidity in the layers of the south wall during week 26.

4.2. Test case with the Brazilian building simulation program

To test the effects of moisture buffer capacity on indoor air conditions for a Brazilian climate, a single-zone building with a typical building envelope was simulated using the Brazilian hygrothermal model. Figure 9 shows the building that was modeled. Floor area is 25 m^2 and the walls are from different materials.

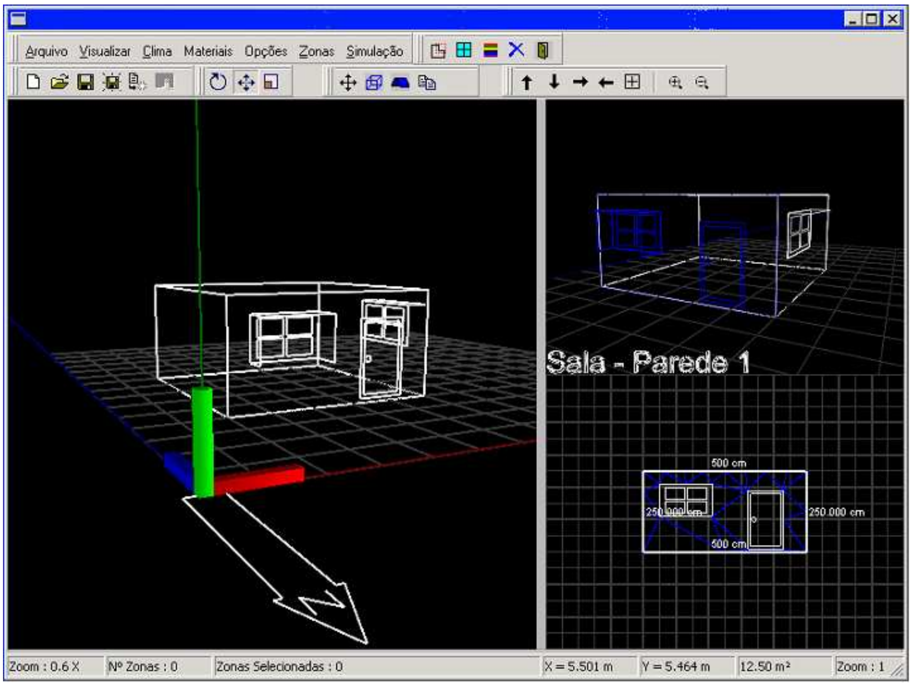

Figure 9 The simulated building on the main menu of the building Brazilian hygrothermal simulation model.

The Curitiba Test Reference Year weather data file was used in the simulation for week 52 (Dec. 25-31), which is a hot and humid period in Brazil. The initial conditions were set as 20°C and the humidity ratio as 10 g/kg. Within the walls, a moisture content corresponding to 60% relative humidity was used. First, the analysis was carried out for wall W1 comprising three layers: 20 mm of lime mortar, 100 mm of brick and 20 mm of lime mortar. The effects of moisture buffer capacity for it were compared to those for a second wall W2 made simply from 100 mm of brick.

Figure 10 presents the room air temperature evolution during the test week and allows comparisons when moisture effects in porous building materials are ignored. The maximum deviation between the curves with and without moisture effects in Figure 10 is around 2ºC when there is no ventilation. It occurs at the temperature peaks, which the moisture-based model tends to attenuate. This attenuation is mainly due to the higher thermal capacity of the building envelope when moisture is considered.

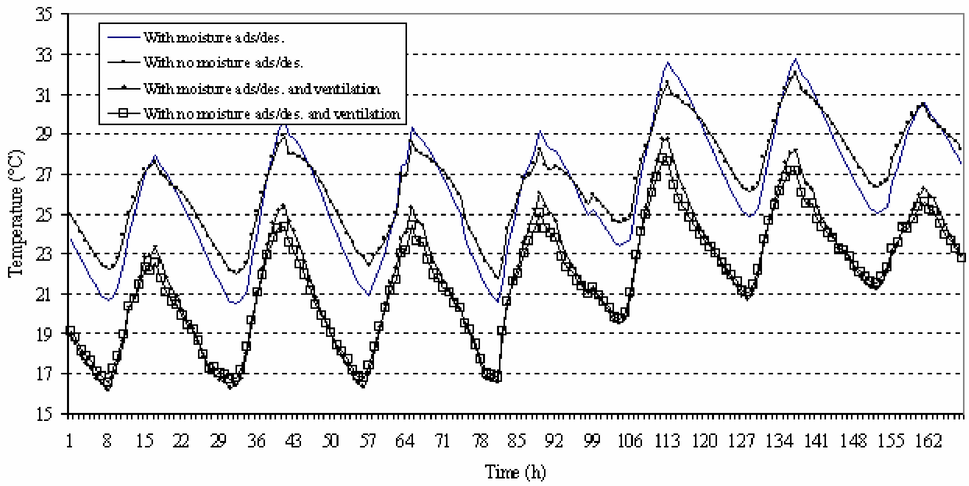

Figure 10 Temperature evolution for the 168 hours of the 52^{nd} week. Results of calculations with or without consideration of moisture adsorption/desorption (ads/des), and with or without ventilation.

Figure 10 also shows the effects on the temperature when 6 ach of ventilation is imposed during working hours (8 a.m. – 6 p.m.). The maximum difference due to the moisture buffer capacity effect in Figure 10 is around 1ºC between the curves with no ventilation.

The effect of moisture buffer capacity without ventilation is especially obvious when the relative humidity is plotted for the test week. This is done in Figure 11.

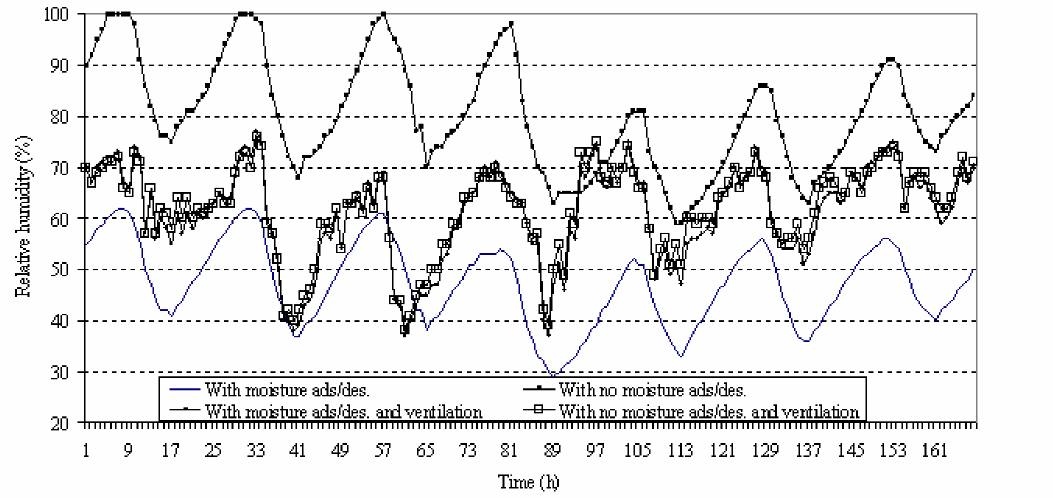

Figure 11 Relative humidity evolution for the 168 hours of the 52nd week.

The deviations between the predicted indoor air relative humidity with and without moisture effects are much higher. The difference can be as high as a 40% relative humidity during the week shown in Figure 11.

On the other hand, under the imposition of 6 ach of ventilation, the moisture buffer capacity hardly affects the prediction of relative humidity. With ventilation, the maximum deviation between the curves for the relative humidity with and without moisture capacity is 5% relative humidity.

Table 2 summarizes the daily-integrated moisture flow through the internal surfaces of the south- and north-oriented walls. Since the city of Curitiba is located at a latitude of 25.4°S, the north-oriented wall is the driest one. Solar insolation causes a high evaporation rate at the external surface and it only absorbs moisture from the indoor air. The south-oriented wall absorbs moisture from the room air and releases moisture to it. In Table 2, loss (negative numbers) denote that moisture is adsorbed by the wall during a cycle time of 1 day.

Table 2 Daily Moisture gain/loss for the south- and north-oriented walls.

		Date (mm/dd)						
Wall Orient.	Moisture $g/(m^2 \cdot day)$	12/25	12/26	12/27	12/28	12/29	12/30	12/31
South	Gain	0.71	9.98	13.25	54.86	28.9	12.13	2.45
	Loss	-54.54	-46.86	-15.98	-7.26	-16.22	-22.88	-32.03
North	Gain	0	0	0	0	0	0	0
	Loss	-106.85	-110.2	-155.77	-85.37	-101.94	-104.08	-97.12

The wall results are presented graphically in Figure 12. Vapor flow less than zero means that the flux is towards the outside. This drying behavior can be explained by the composition of typical building envelopes in Brazil. They are made of thin layers of porous materials with no vapor retarder. In addition, the hygric resistance of paint is very low so that considerably high moisture transport occurs. These results show that materials with a higher moisture buffer capacity can attenuate the room air relative humidity.

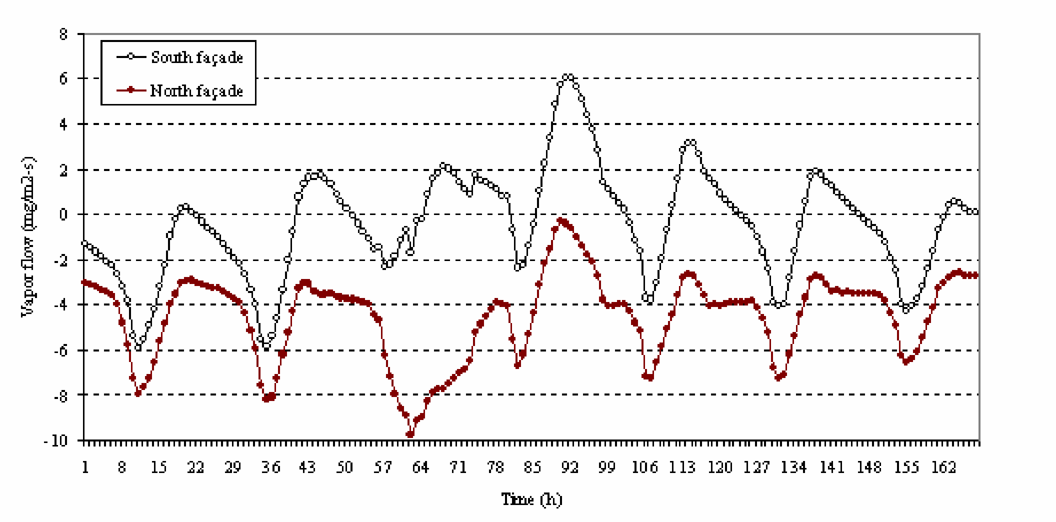

Figure 12 Vapor flow at the internal surface of north and south-oriented walls.

5. Experiences, challenges and follow-up work

The work with the whole-building models of combined heat, air and moisture transfer is still rather new, so experiences are just evolving. However, some impressions can be rendered:

- *Improved hygrothermal modeling*. Potentially there exists a huge advantage in modeling the heat, air and moisture conditions of all parts of a building at the same time. This facilitates the simultaneous prediction of the way in which one building component or zone forms boundary condition of another component or zone, and thus smooth and accurate calculations should result. However, the whole calculation gets rather complex, and therefore not easy to manage. Some important elements are listed in the following.
- *Knowledge of properties*. Like in all simulation, the quality of input data is paramount. The number of hygrothermal properties and other data about components and systems in buildings is very large, and much each one of these data may have very significant influence on the calculation results. Furthermore, many of the processes are nonlinear, and may even show some hysteretic effect. Thus there is a risk of very large spread in the calculation results.
- *Multidimensional effects and cracks.* Building components are far from just homogenous, layered structures which can be described sufficiently by one-dimensional models. Two- or three-dimensional models ought to be employed, and in this context it is very relevant to consider also the cracks and cavities that exist in building constructions – whether their presence is intentional or accidental.
- *Interfacial conditions.* The whole building perspective highlights the interactions between different elements of a building. In this perspective the heat and mass transfer coefficients and conditions in various micro-climatic loci become very important. Advanced building envelope models may be multidimensional, and models for building zones may apply a multi-zonal approach or use fine meshes such as in CFD calculations. But it is still not common that whole-building models have such fine granularity in description of both the building envelope and zones that accurate interfacial relationships can be developed.
- *Coupling of CFD with Heat, Air and Moisture (HAM) transfer models.* In the future, for more complete predictions, it may be necessary to establish closer links between CFD models for the fluid conditions of air in rooms and HAM models for building envelopes, such that the two types of model will directly provide the boundary conditions for one another.
- *Furnishing.* Real buildings are furnished with various objects, not only furniture but also paper/books and textiles. Walls and surfaces are treated with paint or varnish. We still need to develop the representation of this reality better, although some investigations and attempts have been made already (e.g. Svennberg, 2006).
- *Exterior boundary conditions*. The increased detail and completeness of models also demands better detail regarding the exterior boundary conditions., e.g. consideration of air flow around buildings and wind-driven rain, and better geometrical distribution of solar and long-wave gains and losses.
- *Distribution of solar gains in rooms* may have an influence also on the air and humidity conditions in rooms and on sunlit objects, and thus deserves to be accurately represented.
- *Ground coupling.* The hygrothermal influence from contact with the ground is important for most buildings. The ground is a multidimensional body, and the transport processes are highly transient. This should be considered not only from the thermal perspective, but also for the moisture flows in the soil (as by Janssen, 2002 and by Santos et al., 2006), and the effects should be coupled to the whole building.

- *Ageing and durability*. The development of properties over time, as well as dimensional changes that occur in real buildings is a challenge that in many aspects may be worth considering when trying to capture by modeling how buildings really perform. Eventually, whole building models should make it better possible to predict the physical processes that degrade building components, and thus integration of durability models into the whole-building analysis is an obvious further development.
- *Energy performance and indoor air quality analyses.* This topic forms the overall motivation for making the whole building models: To make available some complete and accurate tools to analyze the sustainability of buildings. The tools will comprise all parameters pertaining to heat, air and moisture flows which are relevant to consider, such that energy and IAQ optimizations can be made. Now as the tools are evolving, there is still some more work to do demonstrate the benefits of their use.

6. Conclusions

This paper has demonstrated use of two state-of-the-art models for integrated calculation of the hygrothermal behavior of indoor climates and building enclosures. With these models it is possible to predict both the variation of indoor humidity and moisture accumulation in building enclosures. As demonstrated in the paper, this capability is important because it gives insight into how moisture is exchanged between materials and indoor air.

Improved understanding of the integrated moisture conditions should foster new analytical investigations of how moisture control strategies can play an important role in energy optimization. Appropriate combinations of materials together with new operational strategies for HVAC systems may lead to new possibilities to obtain high indoor air quality but with reduced energy consumption.

As demonstrated in this paper, a possibility is to use some example buildings as test cases to explore the different features of hygrothermal simulation models for whole buildings. It has been suggested to develop these test cases as extensions to the IEA BESTEST method used previously for testing of energy simulation models. These and other calculation exercises concerning the moisture performance of whole buildings are developed and executed within the international research project IEA ECBCS Annex 41, *Whole Building Heat, Air And Moisture Response* (Hens, 2003, and Woloszyn et al. 2005).

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