SENSITIVITY ANALYSIS OF HYGROSCOPIC EFFECTS USING THE POWERDOMUS WHOLE-BUILDING SIMULATION TOOL

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ABSTRACT

The Brazilian whole-building simulation tool Domus has been recently renamed as PowerDomus for hygrothermal and energy simulation of multizone buildings. Enhancements have been accomplished by improving the features for input and output data, by adding HVAC systems and plants, by adding attics among other Graphical User Interface (GUI) features and by improving the numerical algorithms for calculating Sun angles, shading projections and moisture prediction through composite walls using moisture content as driving potential. In addition, the interface has been considerably improved so that simulations can be rapidly performed and the Sun kinematics and shadows from overhangs and adjacent buildings can be easily visualized using an OpenGL based interface. To conclude, simulations are performed in the frame of the IEA Annex 41 to verify hygroscopic effects, through a sensitivity analysis in terms of time step and grid refinement.

1. INTRODUCTION

In building energy analysis, calculated heat conduction through walls usually neglects the storage and transport of moisture in the porous structure of the walls. However, walls are normally subject to both thermal and moisture gradients so that an accurate heat transfer determination requires a simultaneous calculation of both sensible and latent effects.

Several investigators have developed models and tools for evaluating moisture transport in building porous components (Cunningham, 1988; Kerestecioglu and Gu, 1989; Burch and Thomas, 1991; Pedersen, 1991; El Diasty et al., 1993; Liesen, 1994; Kunzel, 1995; Yik et al., 1995; Grunewald et al., 1996; Mendes, 1997) in late eighties and nineties from models that use the simple electric circuit analogy to models that predicts both vapor and liquid transport using a combined model and strongly moisture-dependent transport coefficients. However, none of those research works have integrated the porous building elements (walls, roof and furniture) to a whole-building simulation code. Only from late nineties, hygrothermal simulation models that take moisture adsorption/desorption effects into account have been integrated to whole-building simulation codes such as BSim, EnergyPlus and ESP-r, which can now consider moisture effects but especially focused on physical adsorption/desorption.

Mendes et al. (1999) developed a simulation tool – called Umidus - for predicting heat and moisture transfer through unsaturated porous building elements heat transfer under high relative humidity environments, which has been fully integrated to the program Domus 1.0 (Mendes et al., 2001), resulting into the new version of the Domus program (Domus 2.0, Mendes et al., 2003). Mendonça

(2004) has also integrated the Umidus models into the Spark environment, using the zonal approach, for whole-building hygrothermal simulation.

Then the Domus program has been recently renamed as PowerDomus due to great enhancements reached by improving the features for input and output data applied to multizone buildings, by adding HVAC systems and plants, by adding attics among other Graphical User Interface (GUI) features and by improving the numerical algorithms for calculating Sun angles, shading projections and moisture prediction through composite walls using moisture content as driving potential (Mendes and Philippi, 2005).

In addition, PowerDomus allows users to visualize the Sun path and inter-buildings shading effects and provides reports with graphical results of zone temperature and relative humidity, PMV and PPD, thermal loads statistics, temperature and moisture content within user-selectable walls/roofs, surface vapor fluxes and daily-integrated moisture sorption/desorption capacity. On the other hand, on-off and PID control strategies can also be applied to individual heaters or DX-systems and 1-minute time intervals for schedules can be considered allover.

In order to present the PowerDomus capabilities and moisture effects, simulations have been carried out to analyze the software capabilities to handle moisture adsorption/desorption effects in the frame of the Annex 41 of the International Energy Agency (Hens, 2003).

2. MATHEMATICAL MODEL

The present building simulation program uses a dynamic model for the analysis of a whole-building hygrothermal behavior considering both vapor diffusion and capillary migration.

Equation 1 describes the energy balance, for a zone submitted to loads of conduction, convection, short-wave solar radiation, inter-surface long-wave radiation, infiltration, ventilation and HVAC system related loads.

$$\dot{E}_t + \dot{E}_g = \rho_{air} c_{air} V_{air} \frac{dT_{\text{int}}}{dt} \qquad \text{[Eq. 01]}$$

where $\dot{E}_t$ is the energy flow that crosses the room (W), $\dot{E}_g$, the internal energy generation rate (W), ρ_{air}, the air density (kg/m^3), c_{air}, the specific heat of air (J/kg-K), V_{air}, the room volume (m^3) and T_{int}, the room air temperature (^{o}C).

The term $\dot{E}_t$ is, on the energy conservation equation, includes loads associated to 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 sensible and latent heat released by the building envelope internal porous surfaces are calculated as

$$Q_{wall,S}(t) = \sum_{i=1}^{m} h_{c,i} A_i \left[T_{i,x=L}(t) - T_{\text{int}}(t)\right] \qquad \text{[Eq 02]}$$

$$Q_{Wall,L}(t) = \sum_{i=1}^{m} L(T_{i,x=L}(t)) h_{m,i} A_i \left[\rho_{v,n,i}(t) - \rho_{v,\text{int}}(t)\right] \qquad \text{[Eq. 03]}$$

In Eq. 02, A_i represents the area of the *i-th* surface, h the convection coefficients for (h_c) and mass (h_m), $T_{n,i}(t)$ the temperature at the *i-th* internal surface of the considered zone, L the vaporization latent heat e ρ_v the water vapor densities. The temperature and vapor density are calculated by the combined heat and moisture transfer model based on the Philip and DeVries (1957) theory (Mendes et al. 2002)

The vapor concentration difference, $\Delta\rho_v$, in Eq. 03, is normally determined by using the values of previous iterations for temperature and moisture content, generating additional instability. Due to the numerical instability created by this source term, Mendes et al. (2002) presented a mathematical procedure to calculate the vapor flow, independently of previous values of temperature and moisture content, which makes hygrothermal simulations much less unstable, especially in high relative humidity environments.

In terms of water vapor balance, it was considered different contributions: ventilation, infiltration, internal generation, porous walls, furniture, HVAC system and people breath. In this way, the lumped formulation becomes:

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

where $\dot{m}_{\inf}$ is the air mass flow by infiltration (kg/s), $\dot{m}_{vent}$, the air mass flow by ventilation (kg/s), W_{ext}, the external humidity ratio (kg water/kg dry air), W_{int}, the internal humidity ratio (kg water/kg dry air), $\mathrm{J_b}$, the water vapor flow from the breath of occupants (kg/s), $\mathrm{J_{ger}}$, the internal water-vapor generation rate (kg/s), $J_{porous\ surfaces}$, the water vapor flow from porous surfaces (walls, partitions and furniture) (kg/s), $\mathrm{J_{HVAC}}$ the vapor flow from HVAC systems (kg/s), ρ_{air}, the air density (kg dry air/s) and V_{air}, the room volume (m3).

The water-vapor mass flow from the people breath is calculated as shown in ASHRAE (1993), which takes into account the room air temperature, humidity ratio and physical activity as well.

2.1 Boundary Conditions

The external and internal boundary conditions consider long- and short-wave radiations and convection. The PowerDomus hourly weather files provide dry bulb temperature, relative humidity, direct and diffuse solar radiation, wind velocity and barometric pressure.

Presently, the program reads just weather files in the Domus format (*.dom). However, a weather data converter program is available to convert text files and weather file formats such as TRY (Test Reference Year), TMY (Typical Meteorological Year) and TMY2.

The internal and external convection heat transfer coefficients are also configured on a weather window. In the case, the user wants the coefficients to be calculated in time of execution, just has to click in the option.

For the floor, we can either consider the Dirichlet condition for temperature and moisture content at the lower soil surface or adiabatic and impermeable for deeper surfaces. The ground heat transfer is considered one-dimensional. There is also the possibility to read temperature and moisture content data generated by the Solum 3-D Simulation model, which provides spatial distribution of temperature and moisture content for each user-defined time sample.

3. BUILDING DESCRIPTION MODULE

PowerDomus has a very user-friendly edition interface, allowing the user to build a construction without much of specific knowledge. For the 3-D visualization panel, it is provided tools to rotate, translate and change building scale and colors. PowerDomus makes use of the OpenGL API to render both 2-D and 3-D panels. Nowadays OpenGL is the premier environment for developing portable, interactive 2-D and 3-D graphics applications. If hardware acceleration is detected, then high quality graphics can be affordable.

Further details about the software interface are provided in Mendes et al. (2001, 2003).

Figure 1 illustrates in solid mode two buildings that can be simultaneously simulated taking into account the inter-building shading effects and graphical reports containing energy consumption and evolution of temperature and relative humidity.

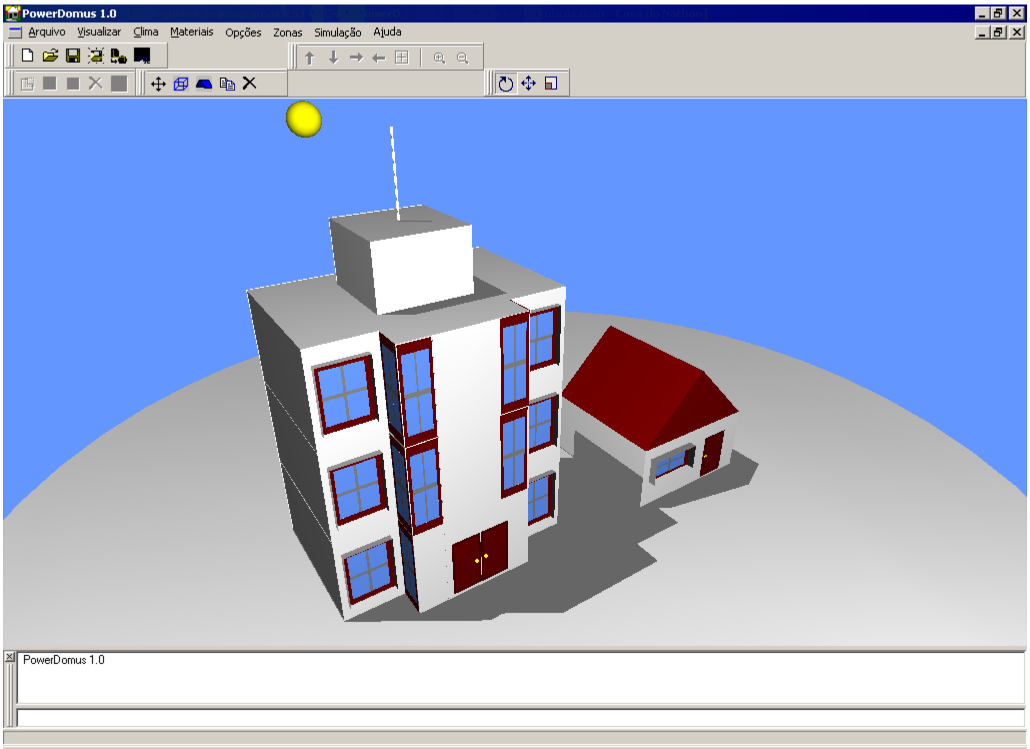

Figure 1 - Visualization of Sun projection on two buildings in the PowerDomus Solid Mode

4. SIMULATION PROCEDURE

The simulation has been performed in the frame of the "Common Exercise 1 - 0A & 0B revised" from the IEA Annex 41 (Hens, 2003). In this case, the building model is described as shown in Fig. 2 and the thermophysical and geometry properties are presented in Table 1. The buildings has no contact with the ground , no radiation is considered and, additionally, the internal and external temperatures and external relative humidity have been kept constant. A 500-g/h indoor moisture production between 9 am and 5 pm and a 24-h ventilation rate of 0.5 ach have been considered to illustrate the sensitivity of the variation of relative humidity under the presence of moisture adsorption/desorption phenomenon.

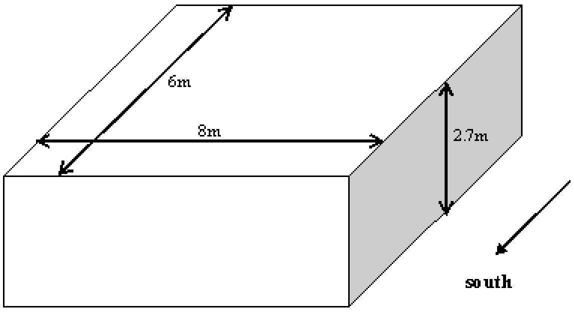

Figure 2 - BESTEST building

The aerated concrete building envelope wall properties have been considered constant as shown in Table 1. The vapor permeability has been assumed as a constant equal to $3.0 \cdot 10^{-11}$ kg/(m·s·Pa) and for the sorption isotherm the following relation has been used:

Mean sorption curve: $\theta = 0.042965 \cdot \varphi$,

where θ is the volumetric moisture content, and φ, the relative humidity

Table 1: Thermophysical properties

	Dry (W/mK)	Thickness (m)	U (W/m^2K)	R (m^2K/W)	Dry Density (kg/m^3)	Dry c_p (J/kgK)
Exterior wall (75.6 m^2) – Floor (48 m^2) – Roof (48 m^2)						
Int. surf. coeff.			8.29	0.121		
Aerated concrete	0.18	0.15	1.33	0.750	650	840
Ext. surf. coeff			29.30	0.034		

The results presented refer to the 365th day of simulation in order to prevent effects imposed by the assumed initial values of moisture content as moisture diffuses slowly.

5. SENSITIVITY ANALYSIS

In order to analyze the numerical robustness of the PowerDomus Algorithm, a sensitivity analysis has been carried out in terms of time step and grid refinement. As shown in Fig. 3, small differences can be observed when time step varies from 1 minute to 1 hour. In the worst case, the difference was as high as at 11 pm.

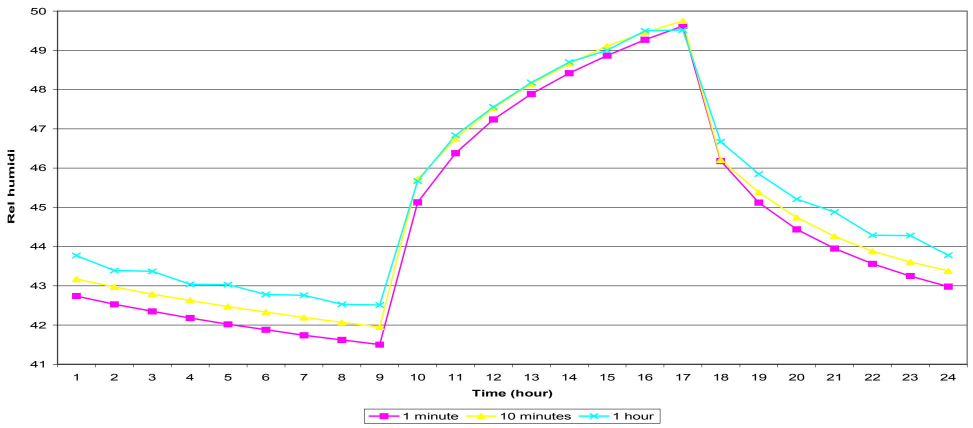

Figure 3 – Time step comparison

Figure 4 shows the influence of the grid refinement (number of nodes in each wall), for the case 0B with a 1-minute time step. It can be seen that the results are more sensitive to the grid refinement than to the time step. It can be also noticed that 40 nodes are as accurate as 80 nodes, however a number of nodes as small as 10 may be inaccurate when moisture content gradients are higher due to the internal variation of moisture gain.

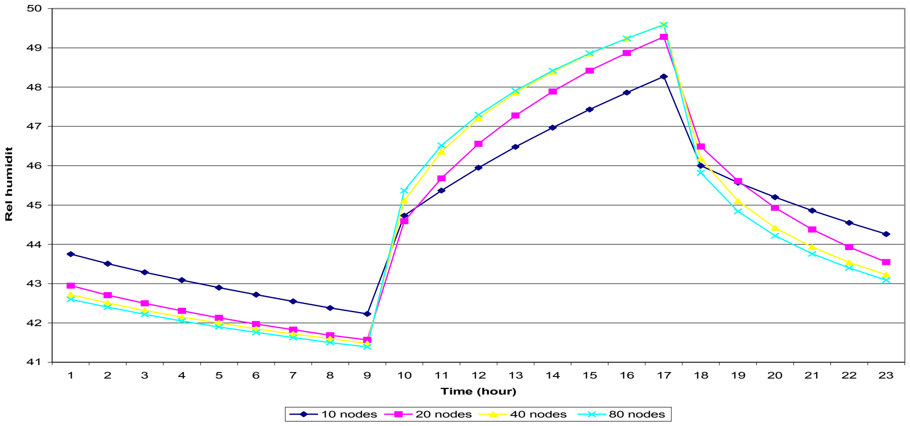

Figure 4 – Grid refinement effect

Figure 5 shows the moisture adsorption/desorption effects by comparing the results obtained for the relative humidity using the PowerDomus hygroscopic model (1-min. time step and 40 nodes) and ignoring the building envelope moisture buffer capacity. As one can observe, the daily amplitude varies from 30% for the hygroscopic model (Case 0B) to 73% (Case 0A) for the non-hygroscopic model, in the isothermal case study. Hypothetical building envelope walls with vapor diffusion coefficient 5 times greater and 5 times smaller are shown in Fig. 7, illustrating the importance of this coefficient when moisture is not ignored.

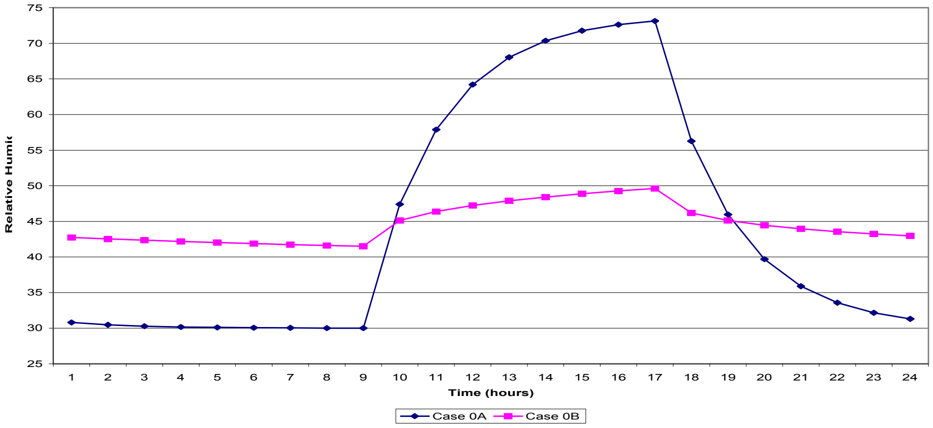

Figure 5 – Moisture adsorption/desorption effects on indoor relative humidity

Figure 6 shows the relative humidity distribution within each wall at 9 am and 5 pm. As one can notice, the outer surface relative humidity is an average value within the daily variation range. On the other hand, great variations occur only within the inner 30 mm, which is associated to a moisture penetration depth concept. Mendes (1997) proposed the following expression for predicting a moisture penetration depth:

$$\varepsilon_{\theta}^{2} = \tau D_{\theta} , \qquad \text{[Eq. 04]}$$

where $\varepsilon_{\theta}, \tau$ and D_{θ} are the penetration depth, time period (86400 s for daily periods) and moisture diffusivity.

Using Eq. 4 and the simulations performed, one can see in Fig. 6 quite good agreement for the moisture penetration depth under the presence of moisture content gradients for three different values of moisture diffusivity (see Table 3). Obviously, this agreement strongly depends on the grid refinement and on the moisture diffusivity invariability.

Figure 7 shows the sensible and latent heat fluxes and vapor flow at the inner wall surface. At night time, when there is no moisture generation, there is a positive (inward) vapor flow, which slightly decreases the wall inner surface temperature causing a negative sensible heat flux – for a constant 20ºC indoor air temperature -, which would be normally ignored. Reversely, between 9 am and 5 pm, when the vapor generator is on, a sensible heat flux has to be considered positively due to the vapor condensation and temperature augmentation at the wall inner surface. However, that was not relevant since the indoor air temperature has been kept constant all the time in order to observe changes on relative humidity only, those effects can be magnified especially in hot and humid climates.

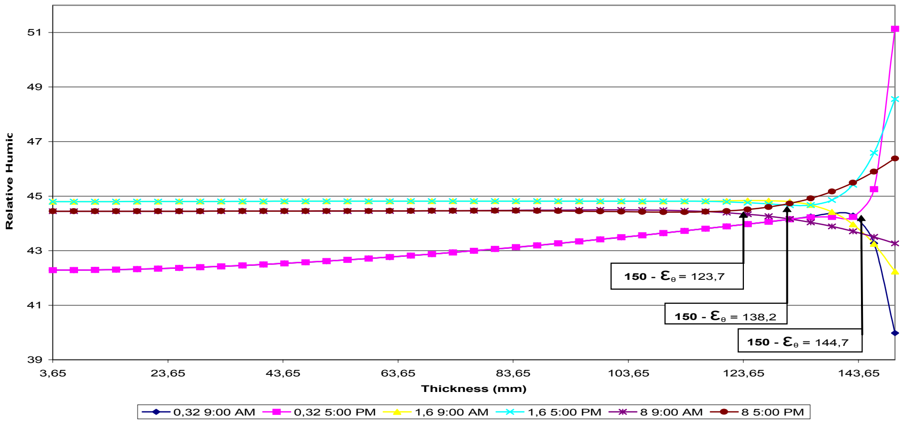

Figure 6 – Relative humidity distribution within the wall at 9 am and 5 pm and the moisture penetration depth calculated by Eq. 4.

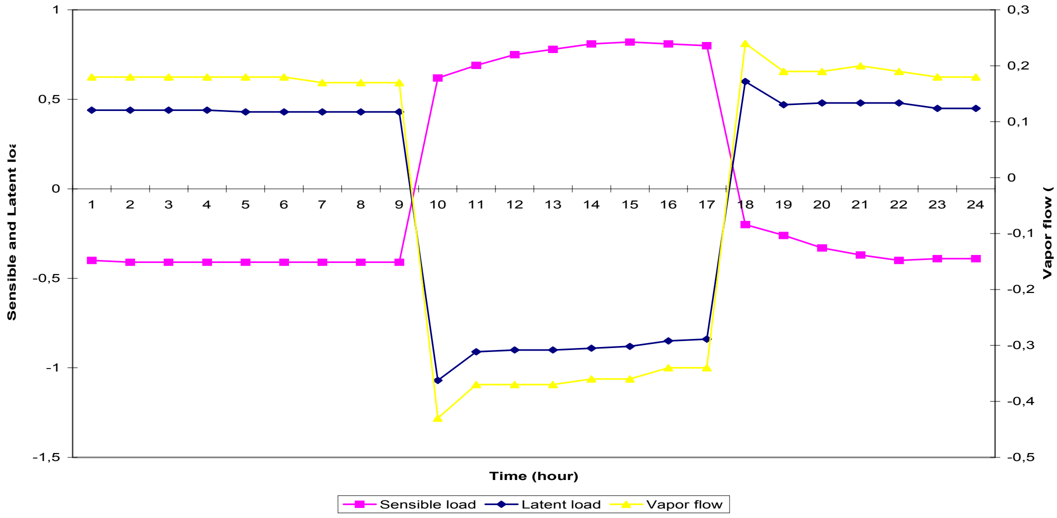

Figure 7 – Sensible and latent heat fluxes and vapor flow

6. CONCLUSIONS

The PowerDomus program has been presented as a whole-building simulation tool for analysis of both thermal comfort and energy use, which has been developed to model the combined heat and moisture transfer in buildings.

The program solver avoids numerical oscillations, since it keeps the discrete equations strongly coupled between themselves, preventing the occurrence of physically unrealistic behavior when time step is increased from one minute to one hour, which is very suitable to be used in building yearly energy simulation programs. Furthermore, the results have shown a higher sensitivity to the grid refinement rather than to the time step.

The moisture buffer capacity has been presented, showing how to take benefits of reducing indoor air relative humidity from the natural moisture movement, verifying the validity of a simple mathematical expression.

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