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ENERGY EFFICIENCY AND THERMAL COMFORT ANALYSIS USING THE POWERDOMUS HYGROTHERMAL SIMULATION TOOL

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ABSTRACT

The building simulation tool Domus has been recently renamed as PowerDomus for whole-building hygrothermal and energy simulation. Enhancements have been accomplished 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. 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 for the TRY weather data of Curitiba, Brazil, comparing the results when time step and grid refinement are altered. Moreover, moisture effects by adding a building envelope coating and energy efficiency analysis are presented for two room air conditioner models.

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 compare results in terms of room air temperature and relative humidity, paint permeance effects, besides the evaluation of energy consumption and thermal comfort for two DX room air conditioners.

MATHEMATICAL MODEL

The present building simulation program uses a dynamic model for the analysis of a whole- building hygrothermal behavior as physically represented in Fig. 1.

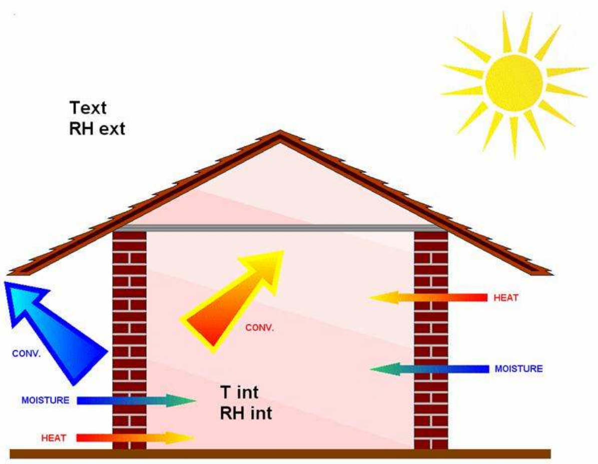

Figure 1: Physical model

The moisture transport through the wall occurs due vapor diffusion and capillary migration as shown schematically in Fig. 2.

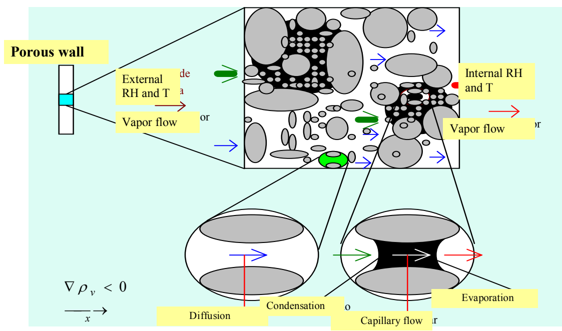

Figure 2: Moisture flow through the wall

Therefore, a lumped formulation for temperature as well as for water vapor is adopted in each building zone.

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.

$$\dot{E}_t + \dot{E}_g = \rho_{air} c_{air} V_{air} \frac{dT_{\text{int}}}{dt} \qquad (1)$$

where:

$\dot{E}_t$ energy flow that crosses the room (W)

$\dot{E}_g$ internal energy generation rate (W)

ρ_{air} air density (kg/m^3)

c_{air} specific heat of air (J/kg-K)

V_{air} room volume (m^3)

T_{int} room air temperature (^{o}C)

The term $\dot{E}_t$, 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 total conduction heat flux that crosses the control surface of each zone is described below.

Building envelope

The heat released by the building envelope internal porous surfaces is calculated as

$$Q_{wall,S}(t) = \sum_{i=1}^{m} h_{c,i} A_i \left[T_{i,x=L}(t) - T_{\text{int}}(t)\right] \qquad (2a)$$

for the sensible conduction load and as

$$Q_{Wall,L}(t) = \sum_{i=1}^{m} L(T_{i,x=L}(t)) h_{m,i} A_i \left[\rho_{v,n,i}(t) - \rho_{v,\text{int}}(t)\right] \qquad (2b)$$

for the latent load.

In Eqs. 2a and 2b where 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. 2b, 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.

The calculation of total moisture (vapor and liquid) flow is based on the Philip and DeVries model (1957), which uses as driving potential the temperature and moisture content gradients. Nevertheless, it is well known that there is discontinuity on the moisture content profile at the interface between two porous media, due to their different hygroscopic behavior; material with high higroscopicity retains more for moisture at the same relative humidity and temperature. To model systems made up of different porous media, with the runabout of moisture content discontinuity problem, some authors modified the Philip and De Vries model so that to use capillary pressure or relative humidity gradient instead of moisture content. Mendes and Philippi (2005) have presented a mathematical approach, which can take the moisture profile discontinuity into account by using Eq. 3:

$$\left(\frac{\partial\phi}{\partial\theta}\right)_A^{prev}\left(\theta_A(s)-\theta_A(s)^{prev}\right)=\left(\frac{\partial\phi}{\partial\theta}\right)_B^{prev}\left(\theta_B(s)-\theta_B(s)^{prev}\right), \quad (3)$$

where A and B represent each material and ϕ the relative humidity.

Equation 3 is equivalent to write the equality for vapor pressure $(\rho_v)_A = (\rho_v)_B$, when the temperatures of both materials at the interface are the same.

It is remarkable the strong coupling between the governing equations. In this way, the use of an algorithm capable to solve simultaneously all equations sets is undeniably useful. Mendes and Philippi (2004) presented the computational performance of the MTDMA (MultiTriDiagonal Matrix Algorithm), applied to the case of strongly-coupled heat and moisture transfer in porous building materials.

Therefore, for the combined heat and moisture transfer problem through a porous medium, Mendes et al. (2002) discretized the conservation equations by using the control-volume formulation method with a central difference scheme and linearized vapor concentration difference at the boundaries in terms of temperature and moisture content. The use of MTDMA to solve the discretized set of those governing equations represents an important step to improve calculation methods, because the source term may become smaller and the main diagonal stronger, making the solver much more robust in building simulations where strongly coupled phenomena are present.

Water vapor mass balance

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:

$\dot{m}_{\inf}$ air mass flow by infiltration (kg/s)

$\dot{m}_{vent}$ air mass flow by ventilation (kg/s)

W_{ext} external humidity ratio (kg water/kg dry air)

W_{int} internal humidity ratio (kg water/kg dry air)

J_b water vapor flow from the breath of occupants (kg/s)

J_{ger} internal water-vapor generation rate (kg/s)

$J_{porous\ surfaces}$ water vapor flow from porous surfaces (walls, partitions and furniture) (kg/s)

J_{HVAC} vapor flow from HVAC systems (kg/s)

ρ_{air} air density (kg dry air/s)

V_{air} 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.

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.

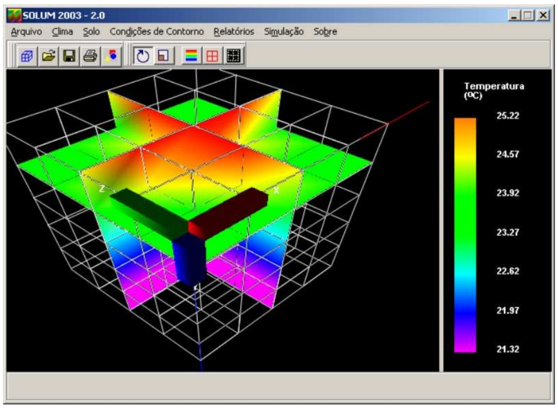

Figure 3: The Solum program main menu

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 (Fig. 1; Santos et al., 2003), which provides spatial distribution of temperature and moisture content for each user-defined time sample.

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). Fig. 4 shows the Brazilian typical wall used in the building model presented in Fig. 5.

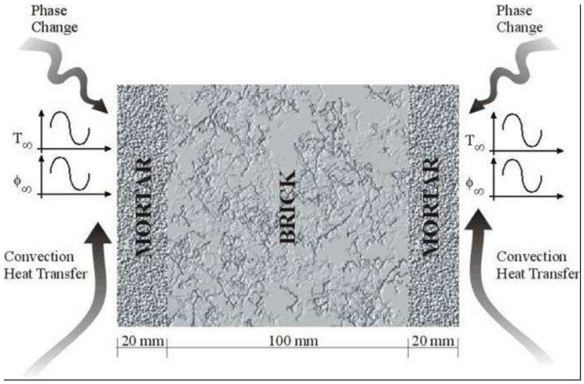

Fig. 4: Wall model and physical processes

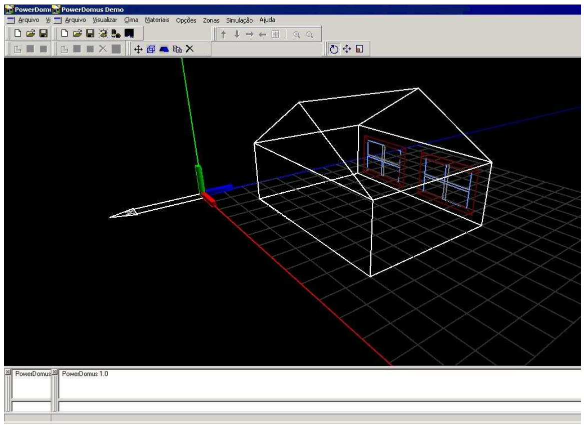

Fig. 5: Building model visualized in the PowerDomus wire frame mode.

Figure 6 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.

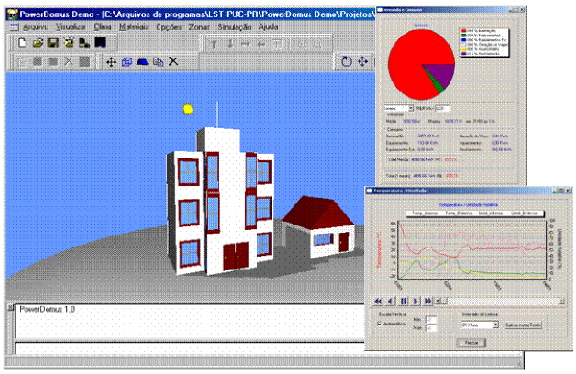

Fig. 6: Visualization of Sun projection on two buildings in the PowerDomus Solid Mode.

SIMULATION PROCEDURE

A Bestest-like building with a conventional attic (Fig. 5) and a typical Brazilian wall has been simulated. The weather data used was the Curitiba TRY file (Figs 7-8). A constant 0.5-ach ventilation rate and a 500-g/h vapor production between 9 am and 5 pm have been considered.

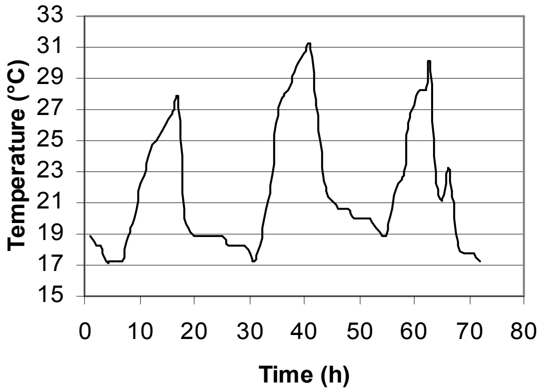

Fig. 7: Temperature data for the three last days of the TRY file for the city of Curitiba, Brazil

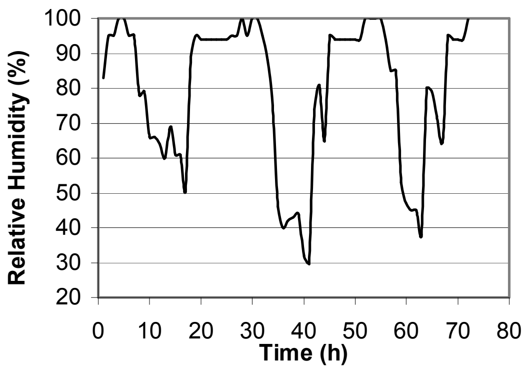

Fig. 8: Relative humidity data for the three last days of the TRY file for the city of Curitiba, Brazil

The hygrothermal properties for brick and lime mortar are presented in Mendes et al. (2003)

SENSITIVITY ANALYSIS

A sensitivity analysis has been previously carried out in terms of grid refinement and time step effects on room air temperature and relative humidity. Figure 9 presents a time step sensitivity analysis, while Fig. 10 shows the grid refinement effects.

Figure 9 shows clearly the robustness of PowerDomus solver as the variation in terms of room air temperature are very small when time steps increases from 1 second to 1 hour.

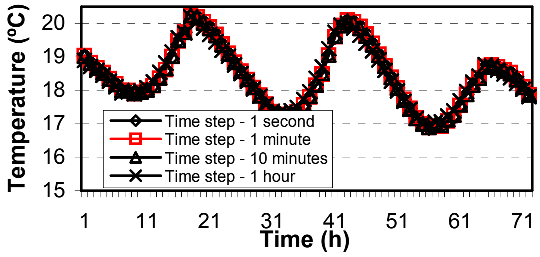

Fig. 9: Time step effects on room air temperature

Figure 10 presents the grid refinement effect when the finite-volume approach has its number of nodes multiplied by two and by four. The default number is 10 for the brick layer and 5 for each of the lime mortar layers.

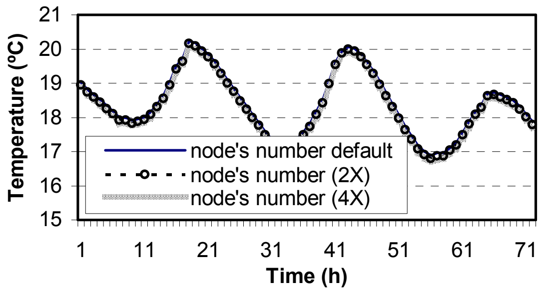

Fig. 10: Grid refinement sensitivity analysis

Figure 11 shows the paint effects on temperature varying the vapor permeance from 1e-8 to 1e-12 kg/m^2-s. As it can be noticed, latent loads can be significant and energy consumption can be considerably affected when moisture adsorption/desorption plays an important role. Mendes (2000) has shown that, for Brazilian humid climates, a good strategy to save energy by reducing conduction cooling loads is the one with no paint on the outside layer and zero permeance paint at the internal surface. This strategy is even better than fully obstructing (null permeance) vapor flow at both sides, what can be explained by the fact of when moisture can freely enter or leave the external layer of the wall, it will naturally condense at night time and evaporate along the day, removing heat from the room.

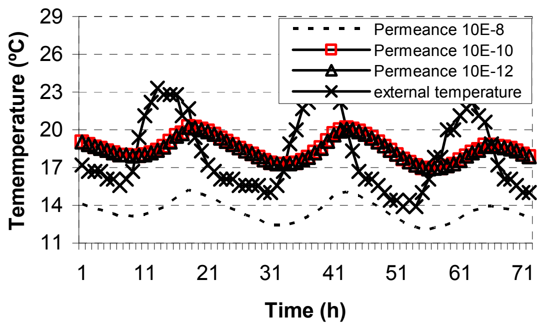

Fig. 11: paint vapor permeance effects on temperature

ENERGY EFFICIENCY AND THERMAL COMFORT ANALYSIS

In order to illustrate the use of a practical test example for comparison and evaluation of two different room air conditioner (RAC) systems, the 48-m^2 IEA BESTEST model (Judkoff and Neymark, 1995) has been selected. In this case, no thermal gains such as people, equipment and lighting have been considered in the simulation, neither moisture sources. The Curitiba TRY weather data file - obtained from the Umidus program (Mendes et al., 1999) - has been chosen and simulations have been carried out from Jan. 1st to Jan. 31st, using a 1-min simulation time step to avoid non-steady information loss, which could affect the temperature and relative humidity evolution within the room. Another point to consider using very small time steps is the accuracy on the equipment power time integration for calculating the room air conditioner monthly energy consumption.

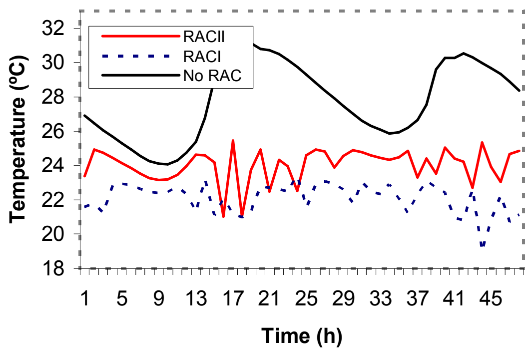

Figure 12: Room air temperature using two different air conditioners.

Figures 12-15 present a comparison in terms of room air temperature, relative humidity and PPD (Predicted Percentage of Dissatisfied) for the two last days of January, showing simulation results with no air conditioning and comparing them with data obtained by simulating the single-zone building with two different air conditioners; one equipped with a reciprocating compressor (RAC I, 10000-Btu capacity) and the other one with a rotating compressor (RAC II, 12000-Btu capacity). Both equipment models can be found in Pereira (2003).

In Figure 12, RAC II results show higher temperature oscillations due to its higher capacity when a simple on-off strategy is applied. However, no difference can be noticed between the room air temperatures obtained by using the two air conditioners, for the same set-point, when the thermal loads are much lower. In spite of lower temperatures can be reached with the more powerful air conditioner (RACII), a lower energy consumption and demand can be achieved due to its higher energy efficiency as shown in Table 1. The replacement of RAC I by RAC II led to energy consumption reduction of 14.9%, which is mainly due to the energy-efficient rotating compressor. Furthermore, as shown in Fig. 13, RAC II leads to lower difference between the temperature signal and its set-point

Table 1: January energy consumption and demand for each air conditioner.

	Consumption (kWh)	Demand (kW)
No RAC	--------	--------
RAC I – 22ºC	88.50	1104.74
RAC II – 22ºC	69.27	952.00
RAC I – 24ºC	54.37	1117.30
RAC II – 24ºC	43.76	952.00

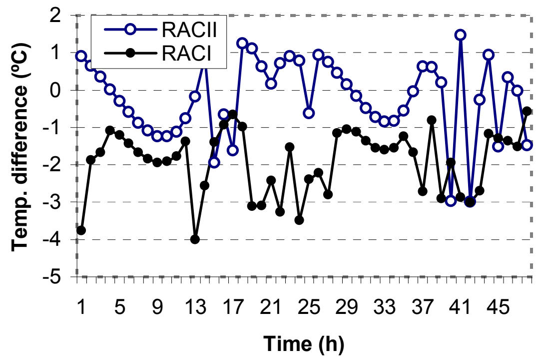

Figure 13: Set-point temperature difference for the two air conditioners.

Figure 14 shows that the RAC II dries out the air more than RAC I, as expected especially when no air change has been taken into account.

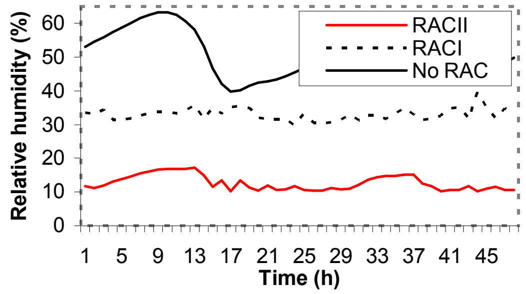

Figure 14: Room air relative humidity using two different set-points for two air conditioners.

Figure 15 shows the comfort index PPD (Fanger, 1970), assuming 0.1 m/s, 0.11 clo and 0.79 met for the air velocity, clothing thermal resistance and metabolic activity.

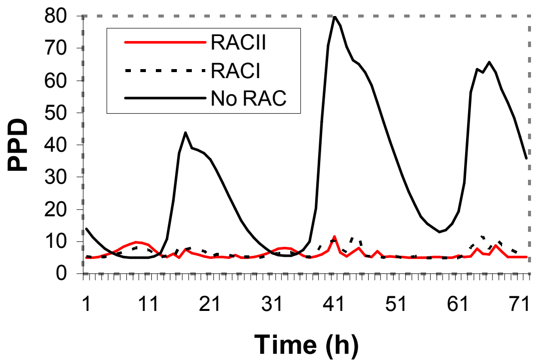

Figure 15: PPD index.

It can be observed in Fig. 15 that both air conditioners improve substantially the indoor thermal comfort. However, in the early morning, no room air conditioner may lead to better thermal conditions as the thermal loads are very low in the case presented. In this case, a variable metabolic rate could have also been implemented in order to improve air conditioners thermal regulations on a 24-h basis.

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 coupled heat and moisture transfer in buildings subject to any kind of climate conditions, i.e., considering both vapor diffusion and capillary migration. PowerDomus models predict temperature and moisture content profiles within multi-layer walls for any time step and temperature and relative humidity for each zone.

The use of this method 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 second to one hour, which is very suitable to be used in building yearly energy simulation programs.

The paint effect simulation performed has also illustrated the importance of taking moisture effects into account.

Additionally, the energy performance of two direct expansion room air conditioner models have been analyzed. Their mathematical correlations have been easily inserted into the PowerDomus simulation environment and the integration results showed that the energy-efficient rotating-compressor air conditioner can considerably reduce the energy consumption.

Thermal comfort indices have also been provided, illustrating that PMV-based control strategies should be investigated in the near future.

REFERENCES

ASHRAE Handbook-Fundamentals, Atlanta: ASHRAE, 1993.

Burch D.M. and Thomas W.C. 1991. An analysis of moisture accumulation in wood frame wall subjected to winter climate, NISTIR 4674, National Institute of Standards and Technology, Gaithersburg.

Cunningham. M. J. 1988. The moisture performance of framed structures: a mathematical model, Building and Environment (23), 123–135.

El Diasty R., Fazio P. and Budaiwi I. 1993. Dynamic modeling of moisture absorption and desorption in buildings, Building and Environment (28), 21-32.

Fanger, P. O. 1970. Thermal Comfort. Copenhagen: Danish Technical Press.

Grunewald, J.; Häupl, P.; Stopp, H. 1996. Modelling of the coupled heat, air and moisture transfer in porous building materials – Application to building structures. Proceedings of the Building Physics Conference in the Nordic Countries, Helsinki.

IEA (International Energy Agency) Annex 24 Final Report, Heat, Air, and Moisture Transfer in Insulated Envelope Parts, Vol 1, Task 1: Modelling, Belgium, 1996.

Judkoff R. and Neymark J. 1995. International Energy Agency Building Energy Simulation Test (BESTEST) and Diagnosis Method, NREL/TP - 471-6231. Golden, CO National Renewable Energy Laboratory.

Kerestecioglu A. and Gu L. 1989. Incorporation of the effective penetration depth theory into TRNSYS, Draft Report, Florida Solar Energy Center, Cape Canaveral, Fl.

Künzel H.M. 1995. Simultaneous heat and moisture transport in building components – One- and two-dimensional calculation using simple parameters. IRB Verlag.

Liesen R. J. 1994. Development of a response factor approach for modeling the energy effects of combined heat and mass transfer with vapor adsorption in building elements, Ph.D. thesis, Mechanical Engineering Department, University of Illinois, Chicago, Il.

Mendes N. 1997. Models for prediction of heat and moisture transfer through porous building elements, Ph.D. Thesis, 225p., Federal University of Santa Catarina - UFSC, Florianópolis - SC, Brazil. (*In Portuguese*)

Mendes N., Oliveira R.C.L.F. e Santos G.H. 2001. DOMUS 1.0: A Brazilian PC Program for Building Simulation, Seventh International Conference on Building Performance Simulation (IBPSA´01), V.1, n.1, p.83-89, Rio de Janeiro, Brazil.

Mendes N., Oliveira R.C.L.F. e Santos G.H. 2003. Domus 2.0: A Whole-Building Hygrothermal Simulation Program, Eighth International Conference on Building Performance Simulation (IBPSA´03), Eindhoven, Netherlands, 2003.

Mendes N., Ridey I., Lamberts R., Philippi P.C. and Budag K. 1999." UMIDUS: A PC Program for the Prediction of Heat and Moisture Transfer in Porous Building Elements"; Building Simulation Conference - IBPSA 99, p.277-283, Japan.

Mendes, N. and Philippi, P. C. 2004. MultiTriDiagonal Matrix Algorithm for Coupled Heat Transfer in Porous Media: Stability Analysis and Computational Performance, Journal of Porous Media, , v. 7, n. 3, p. 193-211.

Mendes, N. and Philippi, P. C. 2005. A Method for Predicting Heat and Moisture Transfer through Multilayered Based on Temperature and Moisture Content Gradients (in press), International Journal of Heat and Mass Transfer, V. 48, p. 37-51.

Mendes, N., Philippi, P. C., Lamberts, R. 2002. A new Mathematical Method to Solve Highly Coupled Equations of Heat and Mass Transfer in Porous Media. International Journal of Heat and Mass Transfer, V. 45, p. 509-518.

Mendes, N., Winkelmann, F. C.; Lamberts, R. and Philippi P.C. 2003. Moisture Effects on Conduction Loads. Energy and Buildings, v. 35, n. 7, p. 631-644.

Mendes, N. 2000. The Potential of Passive Latent Cooling in Brazil. In: Passive and Low Energy Architecture Conference, Cambridge. Proceedings of Passive and Low Energy Architecture Conference.

Mendes, N.; Winkelmann, F. C.; Lamberts, R. 2003. Moisture Effects on Conduction Loads. Energy and Buildings, v. 35, n. 7, p. 631-644.

Mendonça K.C. 2004. Predicting temperature and moisture distributions in conditioned spaces using the zonal approach, Ph. D. dissertation, University of La Rochelle, France. (*in French*)

Pedersen C.R. 1991. A Transient Model for Analyzing the Hygrothermal Behavior of Building Constructions, Building & Simulation'91, proceedings of the 3rd IBPSA – International Building Performance Simulation Association - Conference, France.

Pereira G. C. C. 2003. Modeling of Residential Air Conditioners, Master thesis, Pontifical Catholic University of Parana, Mechanical Engineering Department, Curitiba, Brazil Residenciais. (*in portuguese*)

Philip J. R. and De Vries D. A. 1957. Moisture movement in porous materials under temperature gradients, Transactions of the American Geophysical Union 38, n.2, 222-232.

Santos, G.H.; Mendes, N. 2003. The Solum Program for Predicting Temperature Profiles in Soils: Mathematical Models and Boundary Conditions Analyses. Eighth International Conference on Building Performance Simulation (IBPSA´03), Eindhoven, Netherlands.

Yik F. W. H., Underwood C. P. and Chow W. K. 1995. Simultaneous modeling of heat and moisture transfer and air-conditioning systems in buildings, Proceedings of 4th IBPSA – International Building Performance Simulation Association - Conference, Madison, WI.