DYNAMIC ANALYSIS OF BUILDING HYGROTHERMAL BEHAVIOR

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ABSTRACT

We describe a mathematical model applied to analysis of hygrothermal behavior of buildings. A lumped approach to model the room air temperature and humidity is used and a multi-layer model in finite differences for the building envelope is employed. The capacitance model allows studying the transient air humidity and temperature of a room when it is submitted to the weather of the city of Curitiba-PR, Brazil. To evaluate the building performance with thermal parameters, we have written a code which includes air infiltration, conduction loads, internal gains of people, lights and equipment and short and long wave radiation. In the results section, we show the influences of simulation time step on internal temperature and humidity and temperature profiles within the building envelope.

INTRODUCTION

The world-wide crisis of energy in the 70's and long periods of political instability and economy recession made with that the interest in energy consumption reduction were made in wide scale all over the world. For example, only in the U.S.A, many energy simulation programs such as BLAST (1977), DOE-1 (1978), NBSLD (1974) and TRNSYS (1975) had been developed to simulate the building energy performance and to adopt rational politics of energy conservation.

However, existing programs of simulation can present inconsistent scenes of what really occurs in buildings, especially in the heat and mass transfer area. The mathematical description for prediction of building hygrothermal dynamics is complex, due to the non-linearities and interdependence among several variables. The parametric uncertainties in the modeling, simulation time steps, external climate, building schedules, ground temperature and moisture content also contribute to increase this complexity.

Several investigators have developed models for building energy analysis by using different approaches such as response factor method, finite differences, finite volumes or even simple RC circuit analogy. However, independently on the method accuracy, many simplifications in input data have to be faced such as schedules and weather data. For instance, most of building simulation programs use 1-h time step since weather files normally give hourly values.

Hence, in this work, we present a mathematical model in order to test the hygrothermal performance of buildings and time step effects. Heat diffusion through building envelope is calculated by Fourier's law by considering only the pure transport of heat treated by the finite difference method. The room is submitted to loads of solar radiation, inter-surface long wave radiation, convection, infiltration and internal gains from light, equipment and people. To calculate the room air temperature and relative humidity, we have used a lumped formulation for energy and water vapor balances.

We also analyze the sensitivity of hygrothermal building performance and wall temperature profiles to the simulation time step.

METHODOLOGY

The present work uses a dynamic model for analysis of the hygrothermal behavior of a room without HVAC system. Thus, a lumped formulation for temperature as well as for water vapor is adopted. Eq. 1 describes the energy balance, where the room is submitted to loads of conduction, convection, short-wave solar radiation, inter-surface long-wave radiation and infiltration.

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

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

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

ρ_{air} air density (*kg/m³*)

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

V_{air} room volume (m^3)

T_{int} room air temperature (^oC)

The term $\dot{E}_t$, on the energy conservation equation, includes loads for building envelope (conduction), fenestration (conduction and solar radiation) and openings (ventilation and infiltration). The conduction heat flux - $\dot{Q}(t)$ - that crosses the room control surface is calculated by the Newton's law for cooling,

$$\dot{Q}(t) = hA\left[T_n(t) - T_{\text{int}}(t)\right] \quad (2)$$

where h represents the convection heat transfer coefficient, A, the heat transfer area, and $T_n(t)$ the envelope internal surface temperature. This temperature is calculated by the energy balance, in an elemental volume, using the Fourier's law as it is presented below:

$$\rho c \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2} \quad (3)$$

Thus, the temperature T shown in Eq. 3, is the temperature for a control volume within the building envelope, calculated as a function of the following thermophysical constants: density (ρ), specific heat (c) and thermal conductivy (λ).

On the external side of the room, the walls, ceiling, doors and windows are exposed to solar radiation and to convection heat transfer. This way, the external boundary condition ($x=0$) of Eq. 3 can be mathematically expressed as:

$$-\left(\lambda \frac{\partial T}{\partial x}\right)_{x=0} = h_{ext}\left(T_{ext} - T_{x=0}\right) + \alpha q_r \quad (4)$$

On the internal side($x=L$), we have included the inter-surface longwave radiation as:

$$\left(\lambda \frac{\partial T}{\partial x}\right)_{x=L} = h_{int}\left(T_{int} - T_{x=L}\right) + \sum f_f \varepsilon \theta \left(T^4_{sur} - T^4_{x=L}\right) \quad (5)$$

where:

f_f shape factor.

ε emissivity.

θ Stefan-Boltzmann constant ($5.67\text{x}10^{-8}\,\text{W}/(\text{m}^2\text{K}^4)$)

T_{sur} temperature of internal surfaces of surrounding walls (K).

The temperature $T_{x=L}$ of Eq. 5 is equivalent to a temperature of the n-th node of the wall; the temperature needed to calculate $\dot{Q}(t)$.

For the floor, we have adopted the imposed-temperature boundary condition, making $T_{x=0}$ equal to the ground temperature at a depth of 2m. On the other hand, for the ceiling, long-wave radiation losses were considered (Rlw) so that Eq. 4 has assumed the following form:

$$-\left(\lambda \frac{\partial T}{\partial x}\right)_{x=0} = h_{ext}\left(T_{ext} - T_{x=0}\right) + \alpha q_r - (\varepsilon)_{ceil} R_{lw} \quad (6)$$

where the term $(\varepsilon)_{ceil}$ represents the ceiling emissivity.

The infiltration loads formulation was taken from ASHRAE (1993). The solar radiation (direct and reflected) came from models presented by Szokolay (1993) and ASHRAE (1993).

In terms of water-vapor balance, it was considered ventilation, infiltration and internal generation from equipment and people breath so that the lumped formulation becomes:

$$\left(\dot{m}_{\inf} + \dot{m}_{vent}\right)\left(W_{ext} - W_{\text{int}}\right) + \dot{m}_b + \dot{m}_{ger} = \rho_{air} V_{air} \frac{dW_{\text{int}}}{dt} \quad (7)$$

where:

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

$\dot{m}_{vent}$ 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*)

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

$\dot{m}_{ger}$ internal water-vapor generation rate (*kg/s*)

ρ_{air} air density (*kg dry air/s*)

V_{air} room volume (m^3)

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

The equations of balance of energy and water-vapor can be described in the form:

$$\begin{bmatrix}\dot{T}\\ \dot{W}\end{bmatrix} = \begin{bmatrix}\dfrac{-\sum_{i=1}^{n} h_{\text{int}} A_i - \beta_{\inf-1}}{\rho c V} & \dfrac{-\beta_{\inf-2}}{\rho c V}\\ \dfrac{m_{b-1}}{\rho V} & \dfrac{-\rho \dot{V}_{\inf} - m_{b-2}}{\rho V}\end{bmatrix}\begin{bmatrix}T\\ W\end{bmatrix} +$$

$$
+\left[\begin{array}{c}
\dfrac{\sum_{i=1}^{n} h_{\text{int}} A_i T_{(x=L),i} + Q_{ger} + \beta_{\text{inf}-3} + \Re_{rad}}{\rho c V} \\
\dfrac{\rho \dot{V}_{\text{inf}} W_{ext} + m_{b-3} + \omega_{ger}}{\rho V}
\end{array}\right]
$$

where:

$\dot{T}$	Time derivative internal temperature
$\dot{W}$	Time derivative internal humidity
T	Room air temperature
W	Internal humidity ratio
$i = 1, n$	Number of surfaces of the room
h	Convection heat transfer coefficient
A	Heat transfer area
$\beta_{\text{inf}-1,2,3}$	Heat transfer by infiltration
$T_{(x=L)i}$	Internal temperature of surface i
Q_{ger}	Heat gain by peolple, equipments and lighting
$\Re_{rad}$	Heat gain by solar radiation
ρ	Air density
V	Room volume
c	Specific heat of air
$m_{b-1,2,3}$	Water vapor flow from the breath of occupants
$\dot{V}_{\text{inf}}$	Infiltration air flow
ω_{ger}	Water vapor generated
W_{ext}	External humidity ratio

SIMULATION

The analysis of hygrothermal building performance is made by the development of computational code, written in language C, using the equations of the model presented in section 2. These equations were treated by the finite difference method with a uniform grid in a fully implicit scheme.

For the simulation, a single-zone building located in the city of Curitiba-PR, Brazil was considered, with 25 m^2 of area and 2.5 m height, having 2 windows and 1 door, distributed as it is shown in Fig. 1. The concrete ceiling was considered flat.

For the conduction load calculation using the finite difference method, we have considered 0,19 m thick walls composed by 3 layers: mortar, brick and mortar. The windows were considered as a simple glass layer, while the floor, was composed by wood, concrete and soil.

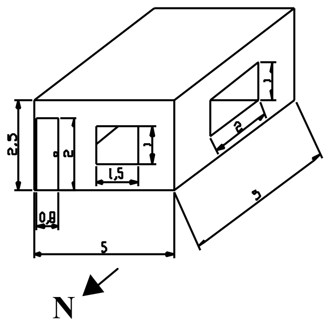

Figure 1: Dimensions of the single-zone building studied.

For the external conditions, we have adopted the Umidus program (Mendes et al., 1999) weather file for the city of Curitiba which provides dry bulb temperature, relative humidity, direct and diffuse solar radiation and wind velocity and direction.

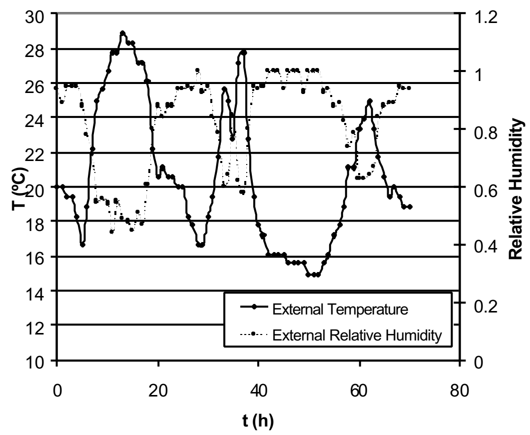

Figure 2: External temperature and relative humidity for Curitiba in the period from 1st to 3rd of January.

In Figure 2, we observe how the temperature and relative humidity vary along the three first days in January in Curitiba-PR (which is south of the equator at latitude -25.4°), Brazil.

As it was expected in Fig. 1, contrarily to the temperature behavior, the external relative humidity presents the highest values at night time. Fig. 3 illustrates values of total solar radiation (diffuse plus direct), for this same period. We observe in Fig. 3, that solar radiation might reach values as high as 900 W/m^2 at noon.

In order to reduce the initial condition influences, the program was submitted to three "pre-simulations" (warm-up) for these same 3 first days of January.

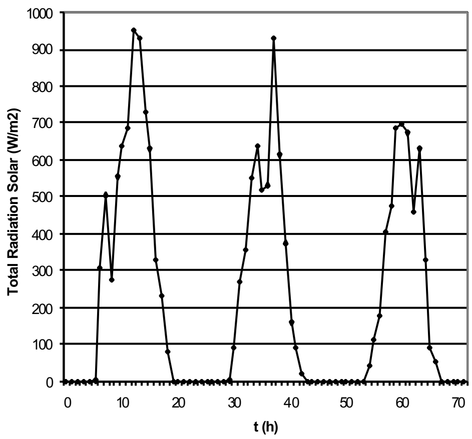

Figure 3: Total solar radiation for Curitiba in the period from 1st to 3rd of January.

We also have used sinusoidal weather functions to represent in a very well-behaved way a typical Brazilian weather climate for this summer period. In Fig. 4, we observe the sinusoidal variation for temperature and relative humidity.

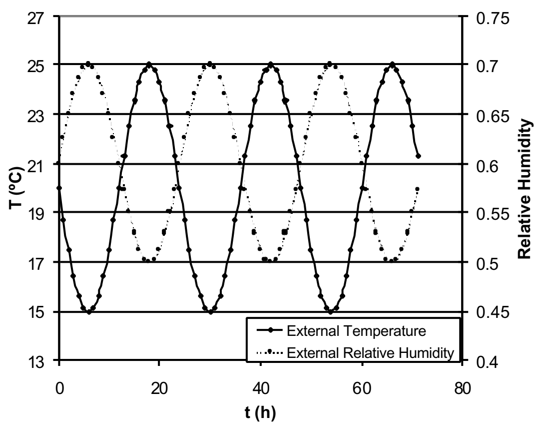

Figure 4: Sinusoidal weather function for external temperature and relative humidity.

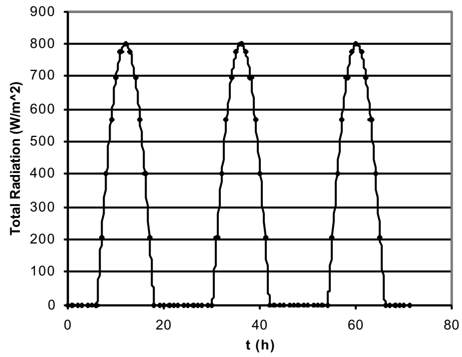

Figure 5: Sinusoidal total solar radiation for Curitiba.

The sinusoidal representation for total (direct + diffuse) solar radiation can be seen in Fig. 5. The function provides the sinusoidal behavior between 6 am and 6 pm, elsewhere the total solar radiation was considered 0. A peak value of 800 W/m^2 at the noon was set to this function.

RESULTS

The linearization of temperature time derivative, Eqs. 3-6 (transient conduction heat transfer), in the finite difference method, causes errors in building thermal simulation since it is normally used 1-h time step and most of the building simulation programs use a such high time step.

Therefore, we do a sensitivity analysis of building thermal performance to the simulation time step.

In Figures 6 to 11, we have neglected the effect of inter-surface long-wave radiation. Figs. 6 and 7 shows the room air temperature and relative humidity for 3 different time steps (*dt*). In terms of temperature, we have noticed a variation of up to 4 ºC for peaks. On the other hand, for relative humidity, it was observed a variation of up to 10%.

Fig. 7 shows the room air relative humidity. We notice that there is not much difference between external and internal relative humidities which is mainly due to the high infiltration load of 30l/s, according to the Brazilian standards (ABNT, NBR 6401).

High temperatures are attained when it is inserted within the room, an energy generation rate. Such temperatures are verified in Fig. 8, where an internal generation of 62 W/m^2 was adopted and it is typically find in offices.

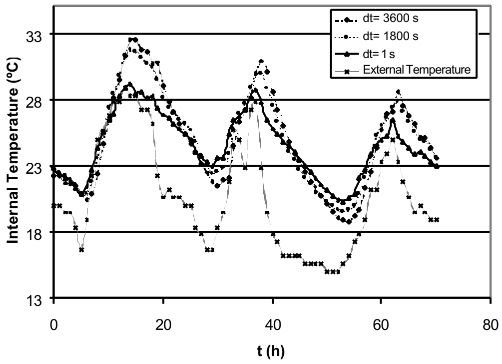

Figure 6: Room air temperature for Curitiba in the period of 1st to 3rd of January for time steps of 1s, 1800s and 3600 s

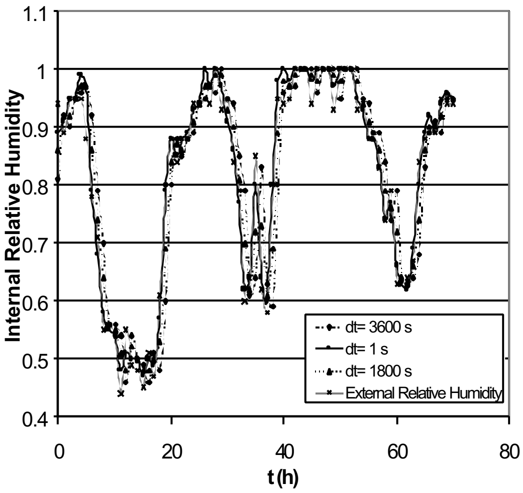

Figure 7: Room air relative humidity for Curitiba in the period of 1st to 3rd of January.

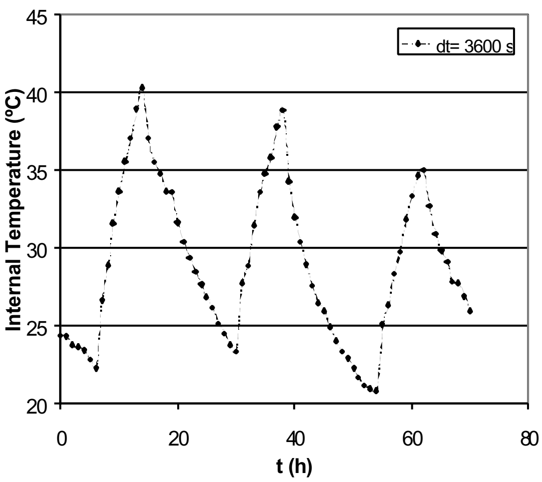

Figure 8: Internal temperature for Curitiba in the period of 1st to 3rd of January for 1-h time step and internal gain of 62 W/m^2

Another important factor that explains why high temperatures are presented in Fig.8, is the radiation energy flux that crosses the windows, therefore it is being considered as an instantaneous internal gain.

Fig. 9 presents the west facing wall temperature profile, at 3 pm on January 3rd.

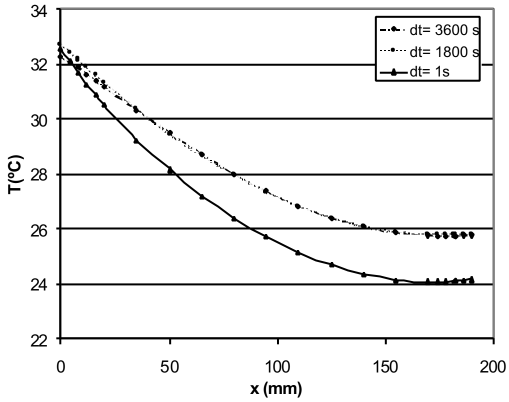

Figure 9: West facing wall temperature profile at 3 pm.

It is noticed, in Fig. 9, a considerable discrepancy between temperature profiles obtained with time steps of 1 s, 1800 s and 3600 s, within a sunny wall (facing west at 3 pm). This discrepancy is largely responsible to the temperature differences found in the figures above. It was noticed with this study the bigger is the the energy incidence on building envelope the greater will be the error due to 1-h time step adoption.

Figures 10 and 11 show room air temperature and relative humidity by using external sinusoidal functions. In this case, a maximum of 1.5 ºC for temperature peaks and 2% for relative humidity are verified.

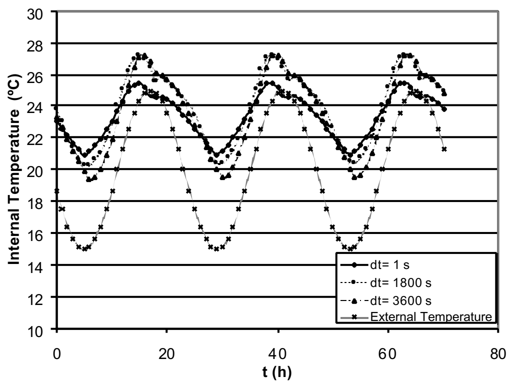

Figure 10: Room air temperature for Curitiba by using the sinusoidal weather file.

In Fig. 12, a temperature difference close to 0.8 ºC (peak value) was observed, by comparing simulations with and without inte-surface long wave radiation. In this case, an emissivity of 0.5 for all surfaces was used.

It is important to remember that the adoption of time steps different of 1h, implies in linear interpolations (except for the sinusoidal weather), adding errors to the estimation of temperature profiles. However, this is unavoidable since weather data files normally do not provide information at intervals smaller than 1h.

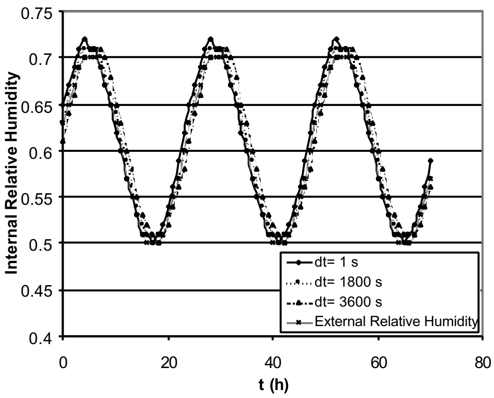

Figure 11: Room air relative humidity for Curitiba by using the sinusoidal weather file.

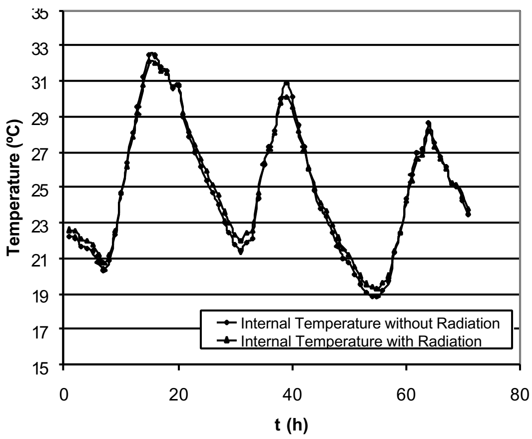

Figure 12: Comparison of room air temperature for Curitiba by considering or not the inter-surface long wave radiation for an 1-h time step.

CONCLUSIONS

A mathematical model to evaluate building hygrothermal performance was described the building hygrothermal behavior. It was used a global approach for the room and finite differences for the building envelope, ceiling and floor. It was shown the time step influence on simulation results, such as internal temperature and temperature and relative humidity profiles within the building envelope. Relevant differences between values obtained by different simulation time steps were observed, showing the relevance of this analysis.

For further work, we intend to include routines to calculate the heat transfer in attics and to simulate HVAC systems.

In conclusion, this work has shown the importance of time step choice for building simulation programs and that more work needs to be done to improve first order approaches for time derivatives applied to thermal building performance simulation models.

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NOMENCLATURE

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