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Analysis of numerical methods and simulation time step effects on the prediction of building thermal performance

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Abstract

A mathematical model applied to the analysis of hygrothermal behavior of buildings is described in this paper. A lumped capacitive and transient approach to model the room air temperature and humidity is described. To evaluate the whole building performance, it was employed a multi-layer model in finite differences for the building envelope and, in this code, we can include air infiltration, conduction loads, internal gains of people, lights and equipment and short and long-wave radiation. Different numerical methods are used to integrate the differential governing equations in the air domain, and results in terms of accuracy and computer run time are discussed in the paper. In the results section, we also show the influences of simulation time step on both room air temperature and humidity and temperature profiles within the building envelope.

Keywords: Numerical methods; Building simulation

1. Introduction

The world-wide crisis of energy in the 70s and long periods of political instability and economy recession increased the interest in energy consumption reduction all over the world. For example, only in the USA, many energy simulation programs such as BLAST (1977), DOE (1978), NBSLD (1974) and TRNSYS (1975) were developed to simulate building energy performance and to adopt rational policies of energy conservation.

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

Several investigators [1–5] 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, independent of the method accuracy, many simplifications in input data have to be faced such as schedules and weather data. For instance, most building simulation programs use 1-h time step since weather files normally give hourly values and simulations of multi-zone buildings are very time consuming. Another problem in developing simulation software is the use of a numerical method for integrating governing equations in the time domain. The choice of the most appropriate numerical method has to be done in terms of robustness, accuracy and computer run time.

Most physical problems, not only in building physics, but in engineering as a whole, are mathematically represented by differential equations. Thus, an important question in the solution of a system of differential equations is how the independent variable is treated, in this case, the time. In the mass and energy conservation equations, the explicit treatment many times is avoided due to the requirement of small time steps for the solution of a numerical problem.

It is also well-known that analytical and numerical methods are equivalent only when the time step, at the limit, tends to zero. Thus, the choice of Δt is an important commitment between computer run time and results accuracy.

Gerald and Wheatley [6] presented some methods for the solution of differential equations, such as the Euler and Modified Euler methods. In these two methods the integration in time is solved in an explicit way, which might make building simulations very time consuming.

Cláudio and Marins [7] described a model for the solution of differential equations system by using the Euler method. In this method, the dependent variables are calculated simultaneously.

The dependent variables—T and W—can also be obtained at the same iteration level by solving the governing equations with mathematical packages as the commercial software Matlab, as illustrated in [8]. In this case, the equations are solved using a combination of symmetry methods and classification methods, including various decision algorithms to linear ordinary differential equations. However, the solution may result in great mathematical expressions, demanding a considerable computational processing time.

In order to speed up simulations, we describe also a hybrid method which combines the analytical solution of each ordinary differential governing equation with numerical coupling between the two dependent variables. This method is called in this paper a semi-analytical method.

To compare the different numerical methods, we present a mathematical model, which allows 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 occupants. To calculate the room air temperature and relative humidity, we used a lumped formulation for energy and water-vapor balances. The four different numerical methods to solve these room air balance equations were then: (i) Euler; (ii) Modified Euler; (iii) Matlab and (iv) Semi-Analytical.

These methods are compared in terms of numerical stability and computational performance, before carrying out sensitivity analyses of time step on the prediction of building thermal performance.

2. Mathematical model

The present work uses a dynamic model for analysis of hygrothermal behavior of a room without HVAC system. Thus, a lumped formulation for temperature as well as for humidity ratio 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:

$$\dot{E}_{\mathrm{t}} + \dot{E}_{\mathrm{g}} = \rho_{\mathrm{air}} c_{\mathrm{air}} V_{\mathrm{air}} \frac{\mathrm{d}T_{\mathrm{int}}}{\mathrm{d}t}, \tag{1}$$

where $\dot{E}_{\mathrm{t}}$ is the energy flow that crosses the room control surface (W), $\dot{E}_{\mathrm{g}}$ 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 (°C).

The term $\dot{E}_{\mathrm{t}}$, in 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,

$$\dot{Q}(t) = hA[T_{i,x=L}(t) - T_{\mathrm{int}}(t)], \tag{2}$$

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

$$\rho c \frac{\partial T_i}{\partial t} = \lambda \frac{\partial^2 T_i}{\partial x^2}. \tag{3}$$

Thus, the temperature T_i 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 conductivity (λ). We have neglected the contact resistance for walls made up of several layers.

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

$$-\left(\lambda \frac{\partial T_i}{\partial x}\right)_{x=0} = h_{\mathrm{ext}}(T_{\mathrm{ext}} - T_{i,x=0}) + \alpha q_r. \tag{4}$$

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

$$\left(\lambda\frac{\partial T_i}{\partial x}\right)_{x=L} = h_{\rm int}(T_{\rm int} - T_{i,x=L}) + \sum_{j=1}^{n} f_{i\to j}\varepsilon_i\varepsilon_j\sigma\left(T^4_{j,x=L} - T^4_{i,x=L}\right), \tag{5}$$

where f is the shape factor, ε, the emissivity, θ, the Stefan–Boltzmann constant (5.67×10^{-8} W/m^2 K^4) and $T_{j,x=L}$ the temperature of internal surfaces of surrounding walls (K). The temperature $T_{i,x=L}$ of Eq. (5) is equivalent to a temperature of the nth node of the wall, i.e., the temperature needed to calculate $\dot{Q}(t)$.

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

$$-\left(\lambda\frac{\partial T_i}{\partial x}\right)_{x=0} = h_{\rm ext}(T_{\rm ext} - T_{i,x=0}) + \alpha q_r - (\varepsilon)_{\rm ceil}R_{\rm lw}, \tag{6}$$

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

The infiltration load formulation was taken from ASHRAE [9]. The solar radiation (direct and reflected) came from models presented by ASHRAE [9] and Szokolay [10].

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

$$(\dot{m}_{\rm inf} + \dot{m}_{\rm vent})(W_{\rm ext} - W_{\rm int}) + \dot{m}_{\rm b} + \dot{m}_{\rm ger} = \rho_{\rm air}V_{\rm air}\frac{{\rm d}W_{\rm int}}{{\rm d}t}, \tag{7}$$

where $\dot{m}_{\rm inf}$ is the mass flow by infiltration (kg/s), $\dot{m}_{\rm vent}$, the mass flow by ventilation (kg/s), $W_{\rm ext}$ the external humidity ratio (kg water/kg dry air), $W_{\rm int}$, the internal humidity ratio (kg water/kg dry air), $\dot{m}_{\rm b}$, the water-vapor flow from the breath of occupants (kg/s), $\dot{m}_{\rm ger}$, the internal water-vapor generation rate (kg/s), $\rho_{\rm air}$, the air density (kg dry air/m^3) and $V_{\rm air}$ the room volume (m^3).

The water-vapor mass flow from the people breath is calculated according to ASHRAE [9] model which takes into account the room air temperature, humidity ratio and physical activity as well.

2.1. Numerical methods

The differential equations (1) and (7), correspondents to the room air control volume, can be written as

$$\frac{{\rm d}T_{\rm int}}{{\rm d}t} = aT_{\rm int} + bW_{\rm int} + c \tag{8}$$

and

$$\frac{{\rm d}W_{\rm int}}{{\rm d}t} = {\rm d}T_{\rm int} + eW_{\rm int} + f. \tag{9}$$

To numerically solve these two differential equations (Eqs. (8) and (9)), the explicit method of Euler was used first, truncated after the 2nd term of Taylor's series. In this method, the temperature and the humidity ratio at instant t are calculated as

$$ {}^{n+1}T = {}^{n}T + \Delta t^{n}\left(\frac{\mathrm{d}T}{\mathrm{d}t}\right) \tag{10} $$

and

$$ {}^{n+1}W = {}^{n}W + \Delta t^{n}\left(\frac{\mathrm{d}W}{\mathrm{d}t}\right), \tag{11} $$

where ${}^{n}T$ and ${}^{n}W$ are calculated from their previous values and, in the case of a system of differential equations composed by variables T and W, the time derivatives are considered as

$$ \left(\frac{\mathrm{d}T}{\mathrm{d}t}\right) = f(t,T,W) \quad \text{and} \quad \left(\frac{\mathrm{d}W}{\mathrm{d}t}\right) = g(t,T,W). \tag{12} $$

In this way, temperature and humidity ratio are simultaneously calculated from

$$ {}^{n+1}T = {}^{n}T + \Delta t f({}^{n}t, {}^{n}T, {}^{n}W) \quad \text{and} \quad {}^{n+1}W = {}^{n}W + \Delta t f({}^{n}t, {}^{n}T, {}^{n}W). \tag{13} $$

As the over all error is quite sensitive to the time step Δt, it is necessary to reduce it to very small values to get numerical stability.

In the Euler method, the both time derivatives are established at the way beginning of the interval to determine the slope of the function, what it would only occur for a linear function. This technique can be corrected by using the Modified Euler method. In this method, the slope within the interval considered is corrected by an arithmetic mean between the beginning and the end of the slope [6].

First, the value of ${}^{n+1}T$ and ${}^{n+1}W$ are estimated by the Euler method. In this way, these values are used to calculate the time derivatives ${}^{n+1}\left(\frac{\mathrm{d}T}{\mathrm{d}t}\right)$ and ${}^{n+1}\left(\frac{\mathrm{d}W}{\mathrm{d}t}\right)$, which gives a better estimation on values or correcting the value of ${}^{n+1}T$ and ${}^{n+1}W$ as shown by Eq. (14)

$$ {}^{n+1}T = {}^{n}T + \Delta t\left(\frac{{}^{n}\left(\frac{\mathrm{d}T}{\mathrm{d}t}\right) + {}^{n+1}\left(\frac{\mathrm{d}T}{\mathrm{d}t}\right)}{2}\right) \quad \text{and} \quad {}^{n+1}W = {}^{n}W + \Delta t\left(\frac{{}^{n}\left(\frac{\mathrm{d}W}{\mathrm{d}t}\right) + {}^{n+1}\left(\frac{\mathrm{d}W}{\mathrm{d}t}\right)}{2}\right). \tag{14} $$

The Euler and Modified Euler methods use only the first two terms of the Taylor series. The accuracy of these methods can be improved by taking smaller time steps. Some CFD investigators have used other numerical methods such as Runge–Kutta, which leads to much greater accuracy, for explicit approaches, since it is a higher-order method.

However, in the case of a over all building simulation, these explicit and accurate methods do not allow the use of high time steps, which makes simulations to be extremely time consuming.

In order to speed up simulations, we have used a hybrid method, called semi-analytical, which each governing differential equation is analytically solved, but with numerical interactions between themselves. In this way, Eqs. (1) and (7) can be written as

$$ A - BT_{\mathrm{int}} = \rho c V \frac{\mathrm{d}T_{\mathrm{int}}}{\mathrm{d}t} \tag{15} $$

and

$$ C + DW_{\mathrm{int}} = \rho V \frac{\mathrm{d}W_{\mathrm{int}}}{\mathrm{d}t}, \tag{16} $$

which gives

$$T_{\text{int}} = \frac{-e^{\frac{-B}{\rho c V}\Delta t}(A - BT_0) + A}{B} \tag{17}$$

and

$$W_{\text{int}} = \frac{e^{\frac{D}{\rho V}\Delta t}(C + DW_0) - C}{D}, \tag{18}$$

where T_0 and W_0 are the temperature and the humidity ratio calculated at the previous time step and

$$A = \sum_{i=1}^{n} hA_iT_i + \dot{E}_{\text{gs}} + \dot{E}_{\text{gl}}(W_{\text{prev}}), \quad B = \sum_{i=1}^{n} hA_i, \quad C = \dot{m}_{\text{inf}}W_{\text{ext}} + \dot{m}_{\text{resp}}(T_{\text{prev}}) + \dot{m}_{\text{ger}} \quad \text{and}$$
$$D = -\dot{m}_{\text{inf}}$$

with $\dot{E}_{\text{gs}}$ as the sensible energy (infiltration + generation) (W), $\dot{E}_{\text{gl}}$, the latent energy (infiltration + generation) (W), h, the internal convection heat transfer coefficient (W/m^2 K), A_i, the area of each surface of the building envelop (m^2), T_i, the temperature of each surface of the building envelope (°C) and n, the number of surfaces.

On the other hand, many computer mathematical packages such as Maple, Mathematica and Matlab can use symbolic methods to differentiate a function, but, the analytic derivatives considerable grow complicated [6]. In order to study and compare the use of these analytic derivatives, we have also used the Matlab program to solve the system of differential equations described by Eqs. (8) and (9). In this program, the equations are solved using a combination of symmetry methods and classification methods, including various decision algorithms to linear ordinary differential equations. Therefore, temperature and humidity ratio are simultaneously predicted by using the direct solution of the system, for the initial conditions $T_{\text{int}(t=0)} = T_0$ and $W_{\text{int}(t=0)} = W_0$.

Table 1 shows schematically the four methods discussed above to integrate the room air governing equations.

In Table 1, T_0 and W_0 are the temperature and humidity ratio at the previous time, T_{prev} and W_{prev}, the temperature and humidity ratio at the previous iteration, and t, the time. As we can see, the method obtained by the Matlab program is the only one that does not require any iteration to solve the system of differential governing equations for the room air control volume.

Table 1
Representation for the four methods

Method	Representation
Euler	$T = f(t, W_{\text{prev}}, T_{\text{prev}}, W_0, T_0)$ $W = f(t, W_{\text{prev}}, T_{\text{prev}}, W_0, T_0)$
Modified Euler	$T = f(t, W_{\text{prev}}, T_{\text{prev}}, W_0, T_0)$ $W = f(t, W_{\text{prev}}, T_{\text{prev}}, W_0, T_0)$
Matlab	$T = f(t, T_0, W_0)$ $W = f(t, T_0, W_0)$
Semi-Analytical	$T = f(t, T_0, W_{\text{prev}})$ $W = f(t, W_0, T_{\text{prev}})$

3. Simulation procedure

The analysis of numerical methods and simulation time step on the hygrothermal building performance is made by the development of a computational code, written in language C, using the building envelope equations of the model presented in Section 2. Those equations were treated by the finite difference method with a uniform grid with 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 two windows and one door, distributed as 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 three layers: mortar, brick and mortar. The windows were considered as a simple glass layer, while the floor, was composed by wood, concrete and soil.

For the external conditions, a Test Reference Year (TRY) weather file was used for the city of Curitiba [5]. Additionally, sinusoidal functions were also used to represent those conditions as shown in Eqs. (19)–(21). The value for total solar radiation (direct + diffuse) is valid between 6 am and 6 pm, with a peak value at noon, and, elsewhere, it is equal to zero.

$$T_{\text{ext}} = 20 + 5\sin\left(\pi + \frac{\pi t}{43\,200}\right), \tag{19}$$

$$\phi_{\text{ext}} = 0.60 - 0.10\sin\left(\pi + \frac{\pi t}{43\,200}\right), \tag{20}$$

$$q_r = 800\sin\left(\frac{3}{2}\pi + \frac{\pi t}{43\,200}\right). \tag{21}$$

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

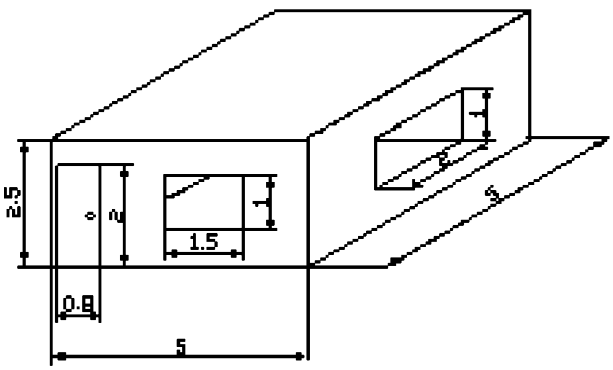

Fig. 1. Dimensions of the single-zone north-faced building.

4. Results

4.1. Analysis of the numerical methods

Fig. 2 shows the room air temperature calculated by using the semi-analytical method with time steps of 100 and 3600 s, the Euler method with a time step of 0.25 s and the one obtained by the Matlab program for time steps of 100 and 3600 s.

It can be noticed in Fig. 2, temperature differences higher than 4 °C when simulations are performed for time step of 0.25 and 3600 s. These differences are mainly due to errors on the temperature profiles of the building envelope, which are calculated by using a finite difference method with a first-order approach for the time derivatives.

In addition, the weather file shows strong variations with time for temperature, humidity and solar radiation, which are also responsible for the differences observed in Fig. 2 for time steps as high as 1 h. As showed in Fig. 2, we have experienced that a 100-s time step would be the limit to assure accuracy and reduce computer run time for either the semi-analytical method or the Matlab one, as they show a very similar dynamic behavior when compared to the one predicted by using the Euler method with a 0.25-s time step.

For assuring numerical stability, the longest time step used for both Euler and Modified Euler methods was 0.25 s and no difference was observed for shorter time steps.

Fig. 3 shows that the four methods lead to the same results when the time step is as small as 0.25 s. However, for yearly simulations of multi-zone buildings, the use of a such small time step would be impracticable for engineering purposes.

The discontinuities observed in the room air temperature time derivative (Figs. 2 and 3) are attributed to the effect of total solar radiation, which crosses the windows and are considered, in this case, as an instantaneous heat gain in the energy balance equation.

Table 2 shows the computer run time for a period of 10 days using a time step of 0.25 s. It was observed that among the methods used in this study, the Matlab was the one that required the longest run time, which is mainly due to the complexity of the analytical expressions given by that program.

Therefore, the use of the Matlab analytical expressions is not recommendable as their mathematical complexity makes the simulations to be very time consuming. However, the Matlab

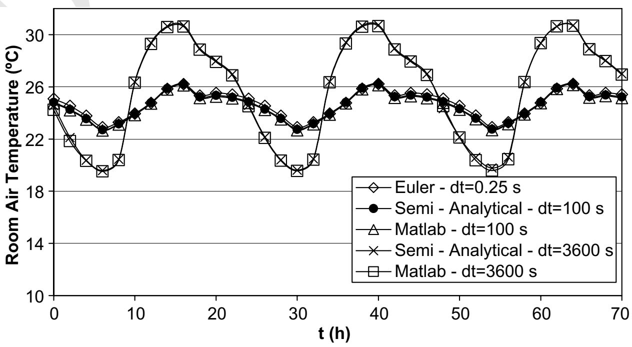

Fig. 2. Room air temperature according to different numerical methods and time steps.

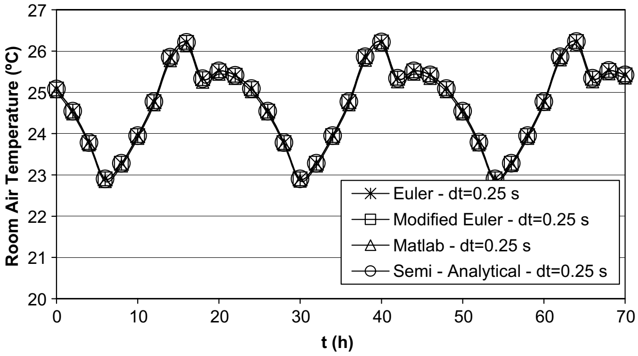

Fig. 3. Room air temperature calculated by the four numerical method, and a time step of 0.25 s.

Table 2
Computer run time for a 10-day period and a 0.25-s time step

Method	Computer run time
Semi-Analytical	12 min 35 s
Euler	12 min 25 s
Modified Euler	12 min 25 s
Matlab	18 min 00 s

formulation requires less iterations as the temperature and humidity ratio are simultaneously calculated.

In order to compare the computer run time for both semi-analytical and Matlab methods, yearly simulations were performed with a 3600-s time step. In spite of the semi-analytical method required more iterations, the program with the Matlab analytical expressions was 14% slower. In this way, this method was abandoned as well as the Euler and Modified Euler methods due to the requirement of very small time steps. A last comparison was carried out in terms of room air relative humidity as shown in Fig. 4.

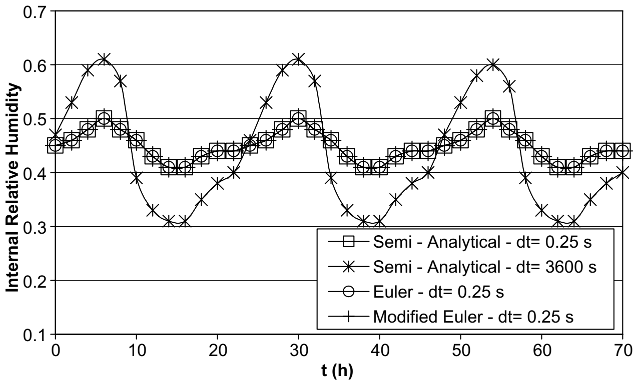

Fig. 4. Internal relative humidity calculated by different numerical methods and time steps.

It can be seen in Fig. 4 that the semi-analytical method shows also a good performance for relative humidity calculation since, for small time steps it gives values as accurate as the other two methods, and, for a time step as large as 3600 s, it shows robustness.

As a final conclusion about the numerical methods is that the semi-analytical combines better rapidness and accuracy so that we chose it for the analysis of simulation time step effects, which is carried out in the section below.

4.2. Influence of simulation time step

A first-order approach to numerically solve the time derivatives, specially those in Eqs. (3)–(6) concerned to the conductive heat transfer through the building envelope, may imply in significant errors for high time steps. At this point, it is important to remind that most of multi-zone building simulations are performed by using a time step as high as 1 h.

Therefore, a study on the sensitivity analysis of building thermal performance to the simulation time step was carried out by using the semi-analytical method described above for solving the room air governing equations.

In Figs. 5–10, we have neglected the effect of inter-surface long-wave radiation. Figs. 5 and 6 shows the room air temperature and humidity ratio for three different time steps. In terms of temperature, we have noticed a difference of up to 4 °C. On the other hand, for humidity ratio, it was observed a variation of up to 10%.

Fig. 6 shows the room air humidity ratio. We notice that there is not much difference between external and internal humidity ratio, which is mainly due to the high infiltration load of 30 l/s, according to the Brazilian standards (ABNT, NBR 6401).

Fig. 7 presents the effect of adding a 62 W/m^2 heat generation rate, which is a common value for commercial building offices. We can see temperatures as high as 40 °C, which are about 30% higher than the case where there is no heat gain.

Another important factor, that explains why high temperatures are presented in Figs. 4 and 7, is the solar radiation energy flux that crosses the windows, which was considered as an instantaneous internal gain.

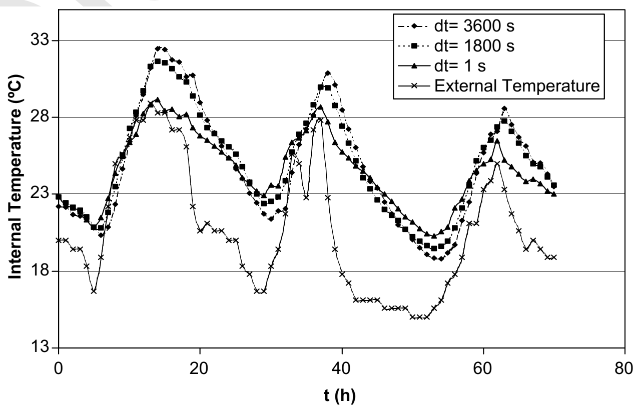

Fig. 5. Room air temperature for Curitiba in the period of 1st to 3rd of January for time steps of 1, 1800 and 3600 s.

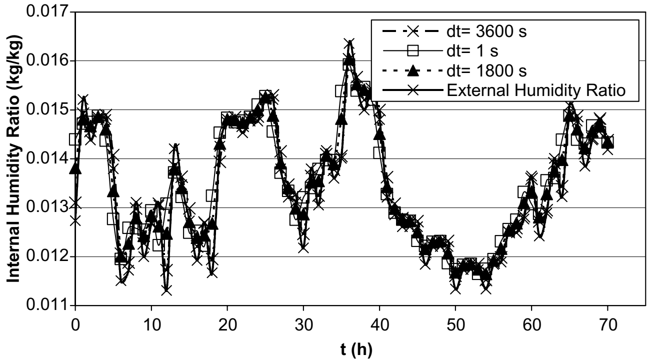

Fig. 6. Room air humidity ratio for Curitiba in the period of 1st to 3rd of January.

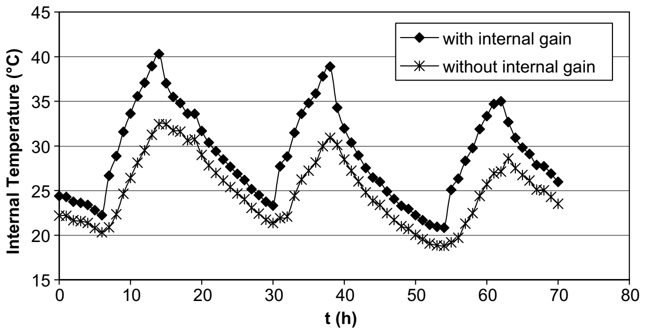

Fig. 7. Internal temperature for Curitiba in the period of 1st to 3rd of January for 1-h time step and internal heat gain of 62 W/m^2 and a time step of 3600 s.

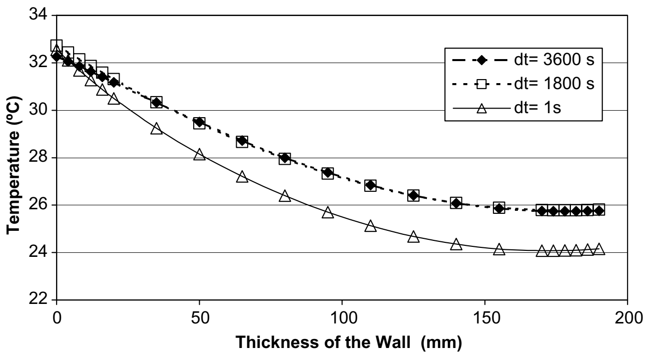

Fig. 8. West facing wall temperature profile at 3 pm on January 3rd.

Fig. 8 presents the west facing wall temperature profile at 3 pm on January 3rd. In this figure, we can see a tendency in over estimating the room air temperature when higher time steps are used.

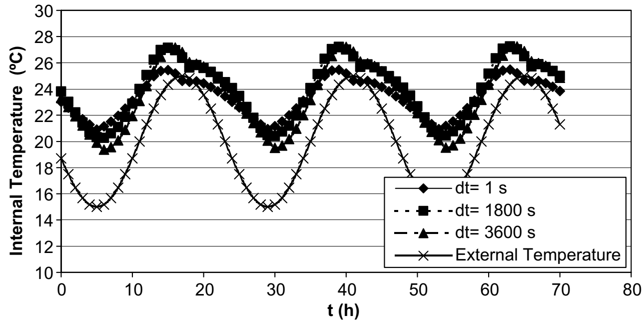

Fig. 9. Room air temperature for Curitiba by using the sinusoidal weather file.

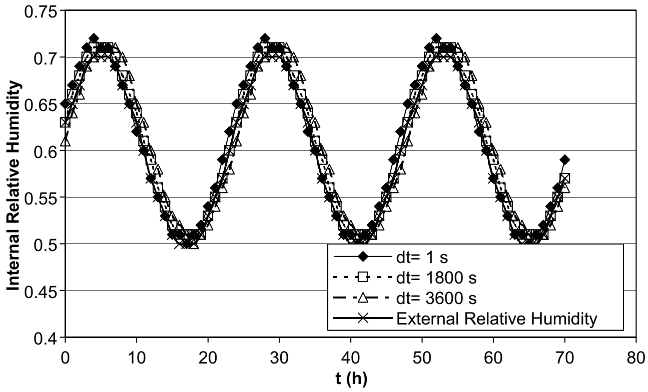

Fig. 10. Room air relative humidity for Curitiba by using the sinusoidal weather file.

It is noticed, also in Fig. 8, a considerable discrepancy between temperature profiles obtained with time steps of 1, 1800 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 higher the energy incidence on building envelope the greater the error due to 1-h time step adoption.

Figs. 9 and 10 show room air temperature and relative humidity by using external sinusoidal functions. In this case, a maximum difference of 1.5 °C for temperature peaks and 2% for relative humidity were verified. This shows that linear interpolation for outdoor variables, such as temperature, relative humidity and solar radiation, is also an important source of errors.

In Fig. 11, a temperature difference close to 0.8 °C (peak value) was observed, by comparing simulations with and without inter-surface long-wave radiation. In this case, an emissivity of 0.5 for all surfaces was used, showing that long-wave radiation heat transfer is important to be taken into account, especially when the walls have low thermal insulation.

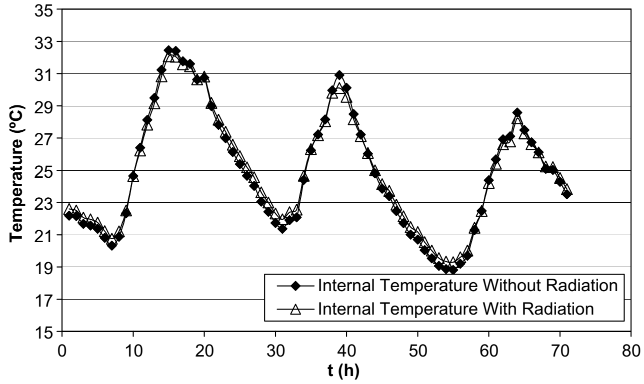

Fig. 11. Comparison of room air temperature for Curitiba by considering or not the inter-surface long-wave radiation for an 1-h time step.

5. Conclusions

A mathematical model to evaluate building hygrothermal performance was described. It was used a lumped approach for the room and the finite difference method for the conduction heat transfer through the building envelope. It was shown the time step influence on simulation results in terms of internal temperature, relative humidity and temperature profiles within the building envelope. Relevant differences between values obtained by different simulation time steps were observed, showing the relevance of this analysis.

The analysis of the numerical methods for integrating the governing equations was also presented. It was shown that the use of explicit methods such as Euler and Modified Euler requires very small time steps, making simulations extremely time consuming. A third method used was the one obtained by the Matlab program, which provides analytical expressions to be solved in a real simultaneous way. However, these expressions are of great size so that simulations are slower, even though the require less iterations with numerical robustness.

In order to avoid limitations such as the requirement of small time steps and high computer run time, we have shown that the use of a semi-analytical method could be a good strategy to solve the differential governing equations for the room air, as it combines robustness and rapidness, which are important criteria in whole building simulation programs. This last method solves analytically each equation (mass and energy balances), but with numerical coupling between each other.

In the second point of this paper, a time step sensitivity analysis was carried out, showing that the use of time steps as high as 1 h can lead to errors of significant magnitude, specially for calculating conduction loads.

On the other hand, very small time steps such 0.25 or 1 s can provide great accuracy, but making simulations to be extremely time consuming. Additionally, the use of those small time steps require linear interpolation of outdoor variables, which can also lead to errors when applied to hourly weather files.

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. In a general way, we believe that the use of the semi-analytical method with 100-s time step would be accurate, allowing fast simulations, specially with the computer processor capacity improvement nowadays. In addition, equipment and people schedule and HVAC systems on–off controls cannot be appropriately taken into account when using high time steps.

For further work, we intend to analyze effects of simulation warm-up period and time step on ground heat transfer, as soils have a very high thermal capacity and their 3-D nature may strongly slow down simulations.

6. Uncited reference

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