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# COUPLED TRIDIMENSIONAL HEAT AND MOISTURE TRANSFER IN THE SOIL UNDER BUILDINGS

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Abstract: *After the wide world crisis of energy in the 70's and the interest in energy consumption reduction, some computational programs had been developed to simulate the building energy performance. However, these codes present some simplifications on their calculation routines of heat transfer through the ground.*

*In this way, we have described a mathematical model applied to building hygrothermal behavior analysis. We have used a lumped approach to model the room air temperature and humidity and a multi-layer model in finite volumes for the building envelope. The capacitance model allows studying the dynamic performance of both humidity and temperature of a building zone when it is submitted to the different climatic factors. In order to evaluate the building performance, a C program has been written, which includes solar radiation (direct and diffuse), air infiltration, conduction loads, internal gains of people, lights and equipment.*

*In the results section, we show the moisture effects on the heat and mass transfer through the floor and ground. The methodology presented for the was based on the Philip and De Vries theory, using the thermophysical properties for dissimilar soils with transport coefficients highly dependent on moisture content. The governing equations were discretized in finite volumes and a 3-D model was used for ground and floor.*

*Keywords: Building Simulation, Building Hygrothermal Performance, Heat and Moisture Transfer*

## 1-Introduction

Since the seventies, due to the worldwide energy crisis, some countries have adopted severe legislations aiming to promote energy efficiency of equipment and buildings. In the Brazil, a committe to develop regulations for energy efficiency in buildings, such as national standards and building codes, was created so that rational policies of energy conservation could be applied. In this context, to evaluate the building performance with thermal parameters, several codes have been developed. However, most of those codes do not take into account the moisture presence within building envelopes. The moisture in the furniture and envelope of buildings implies an additional mechanism of transport absorbing or releasing latent heat of vaporization, affecting the hygrothermal building performance or causing mold growth.

Actually, some studies were carried out to model the moisture storage and transport mechanisms and their effects on heat transport through walls and roofs of buildings (Künzel, 1995; Mendes, 1997 and Holm, 2003). However, these works present some simplifications on their calculation routines by not considering the three-dimensional aspects of heat and moisture transfer and neither focused these effects on highly-capillary soils.

Some building physics studies involving the pure conduction heat transfer through the ground can be found in the literature. The first experimental study concluded that the heat loss through the ground is proportional to the size of its perimeter. However, Bahnfleth (1989) observed that the area and shape must be taken into account as well.

Davies *et al.* (1995), using the finite-volume approach, compared multidimensional models and observed that the use of three-dimensional simulation provides better prediction of building temperature and heating loads than two-dimensional simulation, when these results are compared with experimental data.

Computer programs for transient and steady-state pure conduction heat transfer in two and three dimensions were developed by Blomberg (1996). These codes can be used for analyses of thermal bridge effects, heat transfer through the corners of a window and ground heat transfer. However, the moisture presence has been ignored.

In the works mentioned above, the conductivity and the thermal capacity are considered constant and the moisture effect is ignored. However, the presence of moisture in the ground implies an additional mechanism of transport: in the pores of unsaturated soil, liquid water evaporates at the warm side, absorbing latent heat of vaporization, while, due to the vapor-pressure gradient, vapor condenses on the coldest side of the pore, releasing latent heat of vaporization (Deru and Kirkpatrick, 2002). This added or removed latent heat can cause great discrepancies on the prediction of room air temperature and relative humidity, when compared to values obtained by pure conduction heat transfer (Mendes, 1997).

Ogura *et al.* (1999) analyzed the heat and moisture behavior in underground space in a two-dimensional model using the quasi-linearized method. The outdoor temperature, relative humidity, solar radiation and precipitation were investigated as outdoor conditions.

Janssen et al. (2002) elaborated an analysis of heat loss through a basement and presented as false a generally accepted postulate in building simulation: the combined heat and mass transfer in ground can be ignored for the heat flow calculation through the building foundation.

Combined heat and moisture transfer in soils may require the use of very small time steps, especially at highly permeable surfaces, which may prohibit the use of high time step for long-term simulations. For ensuring numerical stability in the present model, the linearized set of equations was obtained by using the finite-volume method and the MultiTriDiagonal-Matrix Algorithm (Mendes et. al, 2002) to solve a 3-D model to describe the physical phenomena of heat and mass transfer in sandy-silt porous soil. In this way, the code has been conceived to be numerically robust with a fast-simulating procedure. The heat and moisture transfer in the soil was based on the theory of Philip and De Vries (1957), which is one of the most disseminated and accepted mathematical formulation for studying heat and moisture transfer through porous soils, considering both vapor diffusion and capillary migration.

In soil simulation, some parameters such as the boundary conditions, initial conditions, simulation time period (warm-up), simulation time step and grid refinement have to be carefully chosen and combined in order to reach accuracy without using excessive computational processing.

In this way, it is presented a mathematical model in order to test the hygrothermal performance of buildings by considering the combined three-dimensional heat and moisture transport through the ground for capillary unsaturated porous soil. Heat diffusion through building envelope (walls and roof) is calculated by using the Fourier's law. The importance of considering a three-dimensional approach for the soil domain for low-rise buildings was verified in a previous work (Santos and Mendes, 2004), using a simply conductive model for ground heat transfer calculation.

The room can be submitted to loads of solar radiation, inter-surface long wave radiation, convection, infiltration and internal gains from light, equipment and people. A lumped approach for energy and water vapor balances is used to calculate the room air temperature and relative humidity.

## 2- Mathematical Model

The physical problem is divided into three domains: ground, building envelope (walls and roof) and room air. The solar radiation and convection were considered as boundary condition at the external surfaces (walls, roof and ground) and the long-wave radiation losses for the ground and roof. In the internal surfaces of building, beyond the convection heat transfer, long-wave radiation exchange between the surfaces was considered and for the ground and floor a combined heat and mass transfer model was used.

### 2.1- Soil and Floor Domain

The governing equations, based on the theory of Philip and De Vries (1957), to model heat and mass transfer through porous media, are given by Eqs. (1) and (2). The energy conservation equation is written in the form

$$\rho_0 c_m(T,\theta)\frac{\partial T}{\partial t} = \nabla.(\lambda\ (T,\theta)\nabla T) - L(T)(\nabla.\mathbf{j}_v) \tag{1}$$

and the mass conservation equation as

$$\frac{\partial \theta}{\partial t} = -\nabla.\left(\frac{\mathbf{j}}{\rho_l}\right). \tag{2}$$

The total flow (j) is given by summing the vapor flow ($j_v$) and the liquid flow ($j_l$). The vapor flow can be described as

$$\frac{\mathbf{j}}{\rho_l} = -\left(D_T(T,\theta)\frac{\partial T}{\partial x} + D_\theta(T,\theta)\frac{\partial \theta}{\partial x}\right)\mathbf{i} - \left(D_T(T,\theta)\frac{\partial T}{\partial y} + D_\theta(T,\theta)\frac{\partial \theta}{\partial y}\right)\mathbf{j} - \left(D_T(T,\theta)\frac{\partial T}{\partial z} + D_\theta(T,\theta)\frac{\partial \theta}{\partial z} + \frac{\partial K_g}{\partial z}\right)\mathbf{k} \quad , \tag{3}$$

where $\rho_0$ is the solid matrix density (m³/kg), $c_m$, the mean specific heat (J/kg K), $T$, temperature (°C), $\lambda$, thermal conductivity (W/m K), $L$, latent heat of vaporization (J/kg), $\theta$, volumetric moisture content (m³/m³), $j_v$ ,vapor flow (kg/m² K), $j$ total flow (kg/m² K) and $\rho_l$ the water density (kg/m³).

The total flow (j) is given by summing the vapor flow ($j_v$) and the liquid flow ($j_l$). The total moisture flow can be calculated as

$$\frac{\mathbf{j}}{\rho_l} = -\left( D_T(T,\theta)\frac{\partial T}{\partial x} + D_\theta(T,\theta)\frac{\partial \theta}{\partial x}\right)\mathbf{i} - \left( D_T(T,\theta)\frac{\partial T}{\partial y} + D_\theta(T,\theta)\frac{\partial \theta}{\partial y}\right)\mathbf{j} - \left( D_T(T,\theta)\frac{\partial T}{\partial z} + D_\theta(T,\theta)\frac{\partial \theta}{\partial z} + \frac{\partial K_g}{\partial z}\right)\mathbf{k}, \tag{4}$$

with $D_T = D_{Tl} + D_{Tv}$ and $D_\theta = D_{\theta l} + D_{\theta v}$, where $D_{Tl}$ is the liquid phase transport coefficient associated to a temperature gradient (m²/s K), $D_{Tv}$, vapor phase transport coefficient associated to a temperature gradient (m²/s K), $D_{\theta l}$, liquid phase transport coefficient associated to a moisture content gradient (m²/s), $D_{\theta v}$, vapor phase transport coefficient associated to a moisture content gradient (m²/s), $D_T$, mass transport coefficient associated to a temperature gradient (m²/s K) and $D_\theta$, mass transport coefficient associated to a moisture content gradient (m²/s) and $K_g$ the hydraulic conductivity (m/s).

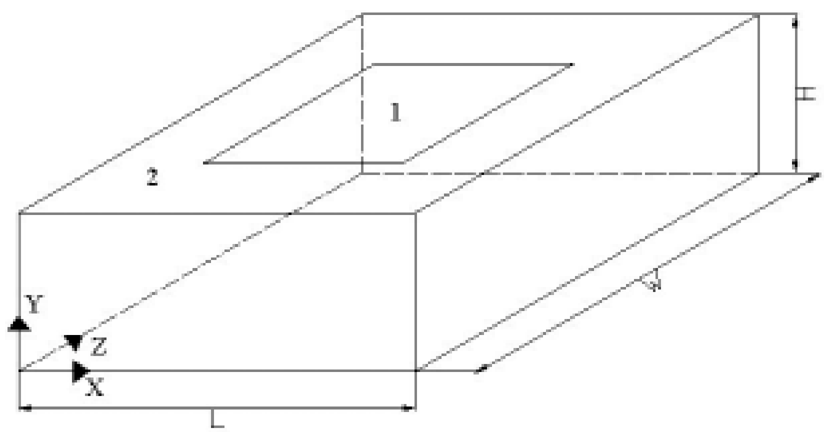


Figure 1: Physical domain for ground and floor.

Figure 1 shows the physical domain. According to Fig. 1, the boundary conditions, for the most generic case (3-D), can be mathematically expressed as:

Surface1 (in contact with internal air):

$$\left(\lambda_f(T,\theta)\frac{\partial T}{\partial y}\right)_{y=H} + \left(L(T)j_v\right)_{y=H} = h_f\left(T_{\text{int}} - T_{y=H}\right) + \sum_{i=1}^{m} f_v \varepsilon_f \sigma (T^4{}_{sur} - T^4{}_{y=H}) + L(T) h_{m\,f}\left(\rho_{v,\text{int}} - \rho_{v,y=H}\right). \tag{5}$$

Surface 2 (in contact with external air):

$$\left(\lambda_s(T,\theta)\frac{\partial T}{\partial y}\right)_{y=H} + \left(L(T)j_v\right)_{y=H} = h_s\left(T_{ext} - T_{y=H}\right) + \alpha_s q_r + L(T) h_{m\,s}\left(\rho_{v,ext} - \rho_{v,y=H}\right) - \varepsilon_s\, R_{lw}, \tag{6}$$

where $h(T_\infty - T_{y=H})$ represents the heat exchanged by convection with the external air, described by the surface conductance $h$, $\alpha_s q_r$ is the absorbed short-wave radiation and $L(T)h_m(\rho_{v,\infty} - \rho_{v,y=H})$, the phase-change energy term. The loss from long-wave radiation is defined as $R_{lw}$ (W/m²), $\varepsilon$, the surface emissivity. The solar absorptivity is represented by $\alpha$ and the mass convection coefficient by $h_m$ (m/s), which is related to $h$ by the Lewis' relation.

Similarly, the mass balance at the upper surface is written as

$$\left( D_{\theta f}(T,\theta)\frac{\partial \theta}{\partial y} + D_{Tf}(T,\theta)\frac{\partial T}{\partial y} \right)_{y=H} = \frac{h_{mf}}{\rho_l}\left(\rho_{v,\mathrm{int}} - \rho_{y=H}\right), \tag{7}$$

for surface1 (in contact with internal air), and as

$$\left( D_{\theta s}(T,\theta)\frac{\partial \theta}{\partial y} + D_{Ts}(T,\theta)\frac{\partial T}{\partial y} \right)_{y=H} = \frac{h_{ms}}{\rho_l}\left(\rho_{v,ext} - \rho_{y=H}\right), \tag{8}$$

for surface 2 (in contact with external air).

The other soil domain surfaces were all considered adiabatic and impermeable.

Equations 7 and 8 show a vapor concentration difference, $\Delta\rho_v$, on their right-hand side. This difference is between the porous surface and air and 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, the solution of the linear set of discretized equations normally requires the use of very small time steps, which can be exceedingly time consuming especially in long-term soil simulations; in some research cases, a time period of several decades is simulated, taking into account the three-dimensional transfer of heat and moisture transfer through a very refined grid. In order to raise the simulation time step, Mendes *et al.* (2002) presented a procedure to calculate the vapor flow, independently of previous values of temperature and moisture content.

**2.2- Building Envelope Domain**

As the escope of this work is to analyze the coupled three-dimensional heat and moisture transfer through the ground, a simple one-dimensional conductive heat transfer model was considered for the building envelope including walls and roof (Fig. 2). In this way, the internal surface temperature is calculated by an energy balance equation, in an elemental control volume, using the Fourier's law:

$$\rho c \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2}. \tag{9}$$

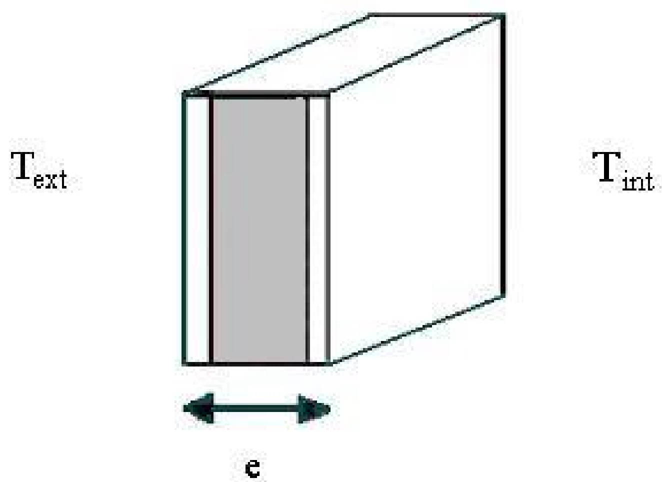


Figure 2: Building envelope schematic representation.

On the external side of the room, the walls, roof, doors and windows are exposed to solar radiation and to convection heat transfer. In this way, the external boundary condition (*x=0*) can be mathematically expressed as:

$$-\left(\lambda_w \frac{\partial T}{\partial x}\right)_{x=0} = h_{ext}\left(T_{ext} - T_{x=0}\right) + \alpha_w q_r. \tag{10}$$

On the internal side (*x=L*), the inter-surface long-wave radiation was included as:

$$\left(\lambda_w \frac{\partial T}{\partial x}\right)_{x=e} = h_{\text{int}}\left(T_{\text{int}} - T_{x=e}\right) + \sum_{i-1}^{m} f_v \varepsilon_w \sigma (T^4{}_{sur} - T^4{}_{x=e}) . \tag{11}$$

On the other hand, for the roof, long-wave radiation losses were considered ($R_{lw}$) so that Eq. (9) has assumed the following form:

$$-\left(\lambda_{roof} \frac{\partial T}{\partial x}\right)_{x=0} = h_{roof}\left(T_{ext} - T_{x=0}\right) + \alpha_{roof} q_r - \varepsilon_{roof} R_{lw} , \tag{12}$$

where the term $\varepsilon_{roof}$ represents the roof emissivity at the surface.

It has been assumed that surrounding surfaces that face the building envelope and the building envelope surfaces are nearly at the same temperature. In this way, the long-wave radiation term was only considered in Eq. (13).

The solar radiation (direct, reflected and diffuse) came from models presented by ASHRAE (1997) and are conveniently projected to each surface considered in both envelope and soil domains. In this way, the numerical value of "$q_r$", shown in Eqs. (6, 10 and 12), is modified according to the projection of the solar beam at each simulation time step.

**2.3 - Internal Air Domain**

The present work uses a dynamic model for analysis of hygrothermal behavior of a room without HVAC system. Thus, a lumped formulation for both temperature and water vapor is adopted. Equation (13) describes the energy conservation equation applied to a control volume involves the room air, which is submitted to loads of conduction, convection, short-wave solar radiation, inter-surface long-wave radiation and infiltration:

$$\dot{E}_t + \dot{E}_g = \rho_{air} c_{air} V_{air} \frac{dT_{\text{int}}}{dt} , \tag{13}$$

where:

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

The term $\dot{E}_t$, on the energy conservation equation, includes loads associated to the building envelope (sensible heat) and latent conduction from floor, fenestration (conduction and solar radiation), and openings (ventilation and infiltration).

The heat released by the building envelope and floor is calculated as

$$Q_S(t) = \sum_{i=1}^{m} h_{\text{int}} A_i \left[T_{x=e}(t) - T_{\text{int}}(t)\right] \tag{14}$$

for the sensible conduction load and as

$$Q_{floor}(t) = \sum_{j=1}^{n} L(T_{Y=H}(t)) h_{mf} A_{j,f} \left[\rho_{v,\text{int}}(t) - \rho_{v,f}(t)\right] \tag{15}$$

for the latent load from floor.

In Eq. 14 $A_i$ represents the area of the *i-th* surface (*m²*), $h_{int}$ the convection heat transfer coefficients (*W/m² K*), $T_{x=e}(t)$ the temperature at the *i-th* internal surface of the building (°*C*) and $T_{\text{int}}(t)$ the room air temperature (°*C*). In Eq. 15, *n*, is the number of control volumes of the floor surface discretized by using the finite-volume method, *L*, the vaporization latent heat (*J/kg*), $h_{mf}$, the floor mass convection coefficient (*m/s*), $A_{j,f}$, the area of *j-th* control volumes of the floor surface discretized by using the finite-volume method (*m²*), $\rho_{v,\text{int}}$, the internal air water vapor densities (*kg/m³*) and $\rho_{v,f}$ the water vapor densities of each control volume (*kg/m³*). The temperature and vapor density are calculated by the combined heat and moisture transfer model described in section 2.1 by using the values of temperature, moisture content and sorption isotherm.

In terms of water vapor mass balance, it was considered different contributions: ventilation, infiltration, internal generation, people breath and floor surface. In this way, the lumped formulation becomes:

$$(\dot{m}_{\text{inf}} + \dot{m}_{vent})(W_{ext} - W_{\text{int}}) + \dot{m}_b + \dot{m}_{ger} + \sum_{j=1}^{n} h_D A_{j,f} \left[W_{v,f} - W_{\text{int}}\right] = \rho_{air} V_{air} \frac{dW_{\text{int}}}{dt}, \quad (16)$$

where $\dot{m}_{\text{inf}}$ is the mass flow by infiltration (*kg/s*), $\dot{m}_{vent}$, the mass flow by ventilation (*kg/s*), $W_{ext}$ the external humidity ratio (*kg water/kg dry air*), $W_{\text{int}}$, the internal humidity ratio (*kg water/kg dry air*), $\dot{m}_b$, the water vapor flow from the breath of occupants (*kg/s*), $\dot{m}_{ger}$, the internal water-vapor generation rate (*kg/s*), $h_D$, the massa transfer coefficient (*kg/m²s*), $A_{j,f}$ represents the area of *j-th* control volumes of the floor surface (*m²*), $W_{v,f}$, the humidity ratio of each control volume (*kg water/kg dry air*), $\rho_{air}$, the air density (*kg dry air/m³*) and $V_{air}$ the room volume (*m³*).

The water-vapor mass flow from the people breath is calculated as shown in ASHRAE (1997), which takes into account the room air temperature, humidity ratio and physical activity as well.

Santos and Mendes (2004) presented and discussed different numerical methods used to integrate the differential governing equations in the air domain (Eqs. 13 and 16), showing the results in terms of accuracy and computer run time. In this analysis, it was shown that the use of explicit methods such as Euler and Modified Euler requires imperatively 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 time consuming due to their great size, even though they require less iterations due to the numerical robustness.

In order to avoid limitations such as the requirement of small time steps and high computer run time, it was 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.

**3- Simulation Procedure**

A *C*-code was elaborated for the prediction of the building hygrothermal performance. For the simulation, a 25-m² single-zone building with 2 windows (single glass layer) and 1 door, distributed as shown in Fig. 3 was considered. For the conduction load calculation, 0.19-m thick walls composed of 3 layers were used: mortar (2 cm), brick (15 cm) and mortar (2cm). In those typical Brazilian walls, the contact resistance between two different layers was not considered.

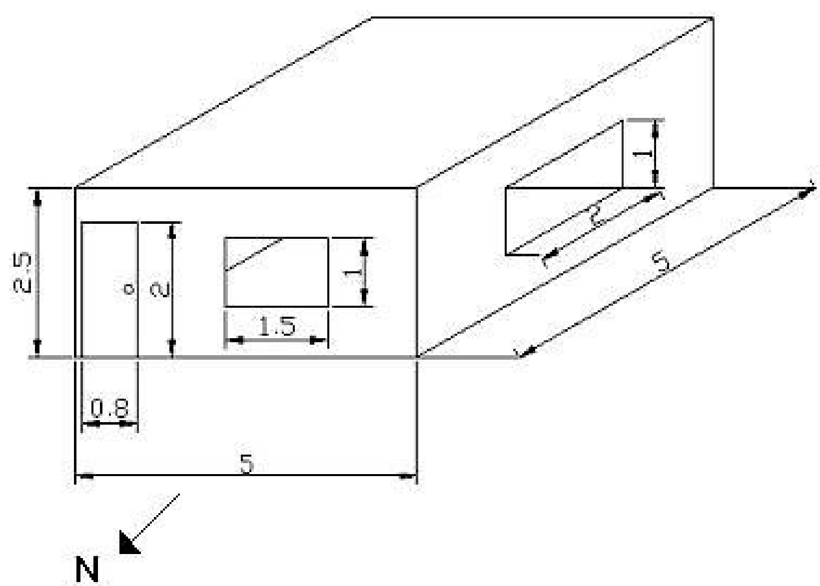


Figure 3: Dimensions of the single-zone building studied (units are in meters).

The differential equations of energy conservation for each node of the building envelope (walls and roof) were discretized by using the finite-volume method (Patankar, 1980), with a central difference scheme, a uniform grid and a fully-implicit approach. The solution of the set of algebraic equations was obtained by using the TDMA (TriDiagonal-Matrix Algorithm).

For the building envelope, a 1-D model was considered since the temperature gradients are much higher on the normal direction. The thermophysical properties of the building envelope materials were gathered from Incropera (1998) and considered constant as shown in Table 1.

Table 1: Thermophysical Properties (Incropera, 1998).

| **Material** | $\lambda$ **(W/mK)** | $\rho$ **(kg/m³)** | $c_p$ **(J/kgK)** |
|---|---|---|---|
| Mortar | 0.72 | 1860 | 780 |
| Brick | 0.72 | 1920 | 835 |
| Wood | 0.16 | 720 | 1255 |
| Glass | 1.4 | 2500 | 750 |

For the presented single-zone building, a 0.35-m concrete floor was considered within the soil domain as it can be seen in Fig. 4. The governing partial differential equations were discretized by using the control-volume formulation method (Patankar, 1980). The spatial interpolation method used is the control-difference scheme (CDS) and the time derivatives are integrated using a fully-implicit approach. In the 3-D model for the ground and floor, an amount of 9,261 (21 x 21 x 21) nodes were used.

The MTDMA (MultiTriDiagonal-Matrix Algorithm; Mendes *et al.*, 2002) was used to solve a 3-D model to describe the physical phenomena of the strongly coupled heat and mass transfer in porous soils. In this algorithm, the dependent variables are obtained simultaneously, avoiding numerical divergence caused by the evaluation of coupled terms from previous iteration values.

In this work, the properties of soil (sandy silt soil) strongly affected by temperature and moisture content were taken from Oliveira *et al.* (1993). The basic dry-basis material properties are shown in Table 2.

Table 2: Dry-basis properties of the soil.

| soil | $\rho_0$ (m³/kg) | $c_m$ (J/kg K) | porosity |
|---|---|---|---|
| sandy silt | 1280 | 880 | 0.517 |

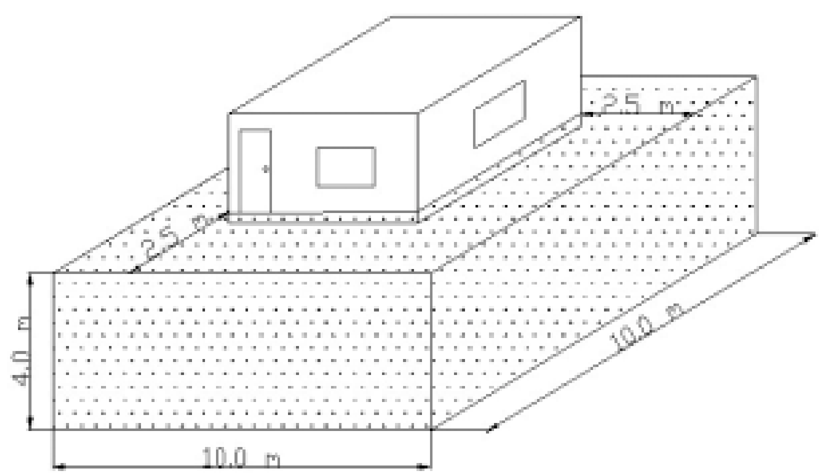


Figure 4: Dimensions of the soil and floor domain used in the simulation period.

In this work, internal generation of both energy and mass was not considered and an infiltration rate of 1 L/s was adopted.

The Sun effect (short-wave radiation) on the ground was considered on East side until noon, and on West side, from noon until 6 pm. On North side, solar radiation was considered during all day and at no moment on the South side as the analyzed buildings is located in the city of Curitiba (South of Brazil at a latitude of –25.4°).

The external climate was represented by equations 17, 18 and 19 for temperature, relative humidity and solar radiation, respectively. It was considered sinusoidal variation of temperature during the day between 15 ºC and 25 ºC and of external relative humidity between 50 % and 70 %. 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.

$$T_{ext} = 20 + 5sin\left(\pi + \frac{\pi t}{43200}\right) \tag{17}$$

$$\phi_{ext} = 0.60 - 0.10sin\left(\pi + \frac{\pi t}{43200}\right) \tag{18}$$

$$q_r = 400sin\left(\frac{3}{2}\pi + \frac{\pi t}{43200}\right) \tag{19}$$

**4- Results**

A warm-up period of 2 years was employed for the analysis of the moisture effects on the heat and mass transfer calculation through the floor and ground. In Figs. 5-8, for the soil a sandy-silt type was considered, which properties were obtained from Oliveira *et al.* (1993) and for the floor, properties from mortar (Perrin, 1985) were used. Those strongly moisture-content-dependent properties include specific heat, density, thermal conductivity and liquid and vapor transport coefficients associated to temperature and moisture content gradients.

Three different boundary conditions were considered for the external ground upper soil surface: i) solar radiation; ii) rain with no solar radiation effect and iii) rain followed by solar radiation. For the purely conductive model, rain is not considered.

Convection heat transfer has been taken into account in all cases. For all external surfaces, a constant convection heat transfer coefficient of 12 W/m²K was adopted and, for all internal surfaces, 3 W/m²K was considered. A constant long-wave radiation loss of 100 W/m² was attributed for the ground and roof as well as an absorptivity of 0.5 for the ground and 0.3 for other surfaces. In the soil domain, the laterals and lower surface were considered adiabatic and impermeable.

In Figs. 5-8, a temperature of 20 °C for all domains and a volumetric moisture content of 4 % for the soil and floor were considered as initial condition.

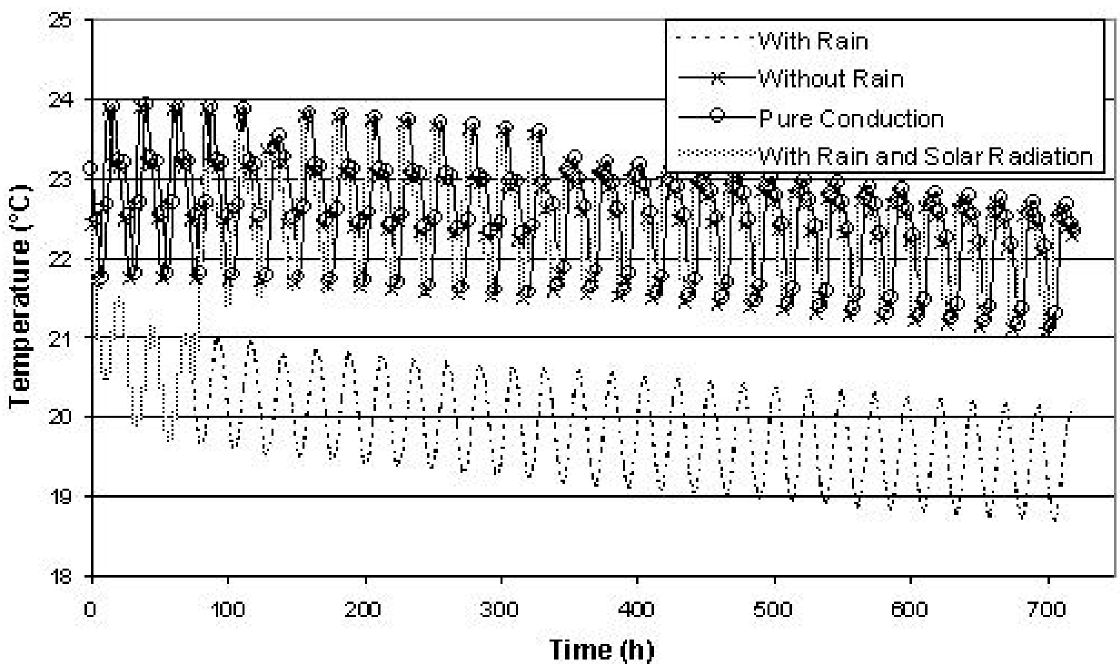


Figure 5: Internal temperature after 2 years of pre-simulation.

Figure 5 shows the evolution of the room air temperature. During the simulation period, it was not verified a significant variation between the purely conductive model and the model that takes moisture transport through the ground and floor into account. The decrease of the internal temperature in the rain case is mainly due to the absence of solar radiation during the 1-month period for the first case (With Rain) and 3 days, for the second case (With Rain and Solar Radiation). Therefore, it can be clearly noticeable that solar radiation, in this case, is the uppermost thermal load source considered in the room air energy balance.

A higher difference of approximately 15% on the internal humidity ratio was verified in Fig. 6, when the purely conductive model for the ground and floor is considered. This effect on internal humidity ratio implies a direct variation of nearly 10% in the room air enthalpy, *i.e.*, it may considerably affect thermal confort and cooling capacity (energy consumption prediction) of air conditionning systems.

It was also noticed in Fig. 6, a low daily variation of humidity ratio when moisture is considered, *i.e.*, a lower buffer effect of humidity in air occurs when moisture buffer capacity materials are employed.

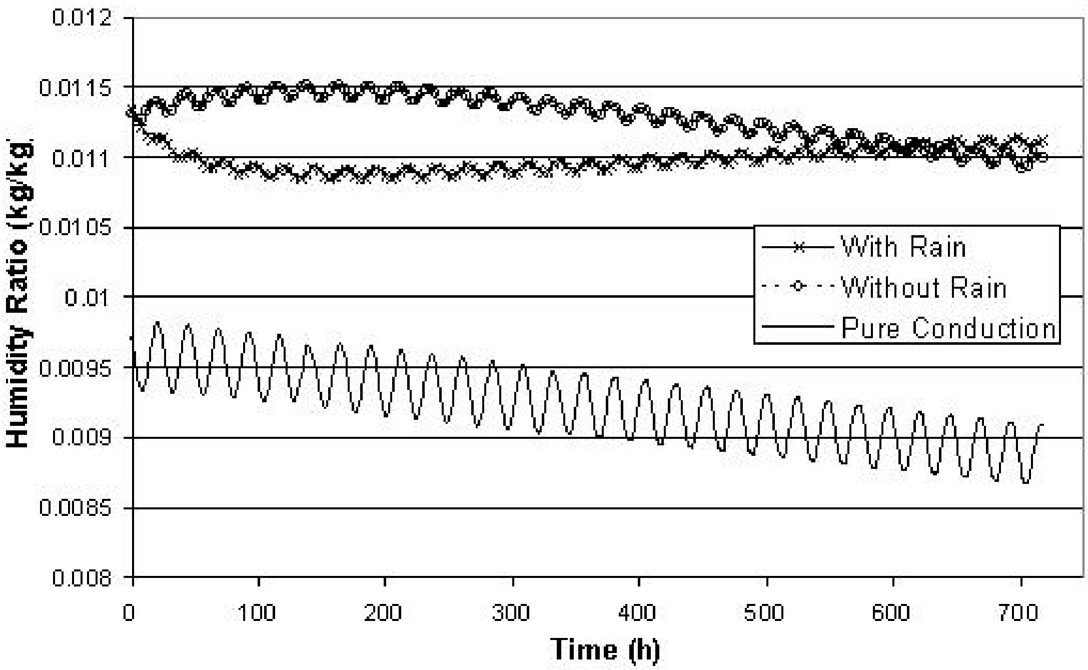


Figure 6: Internal humidity ratio after 2 years of pre-simulation period.

In the case moisture is disregarded, water vapor is only exchanged by ex- or infiltration. Nevertheless, when moisture is considered, the vapor flow exchanged with the floor can be a significant counterpoise on the room air moisture balance.

Some research (Moon e Augenbroe, 2003 and Hens, 2003) has also been conducted to aware about the importance of indoor relative humidity, which significantly affects: i) thermal and respiratory comfort; ii) perception of indoor air quality; iii) occupant health; iv) durability of building materials v) energy consumption. For example, there will be twice as many occupants dissatisfied with the indoor comfort conditions at 24°C and 70% relative humidity than at 24°C and 40%. At the same time, the occupants will perceive the IAQ to be better at lower humidity (in fact enthalpy) and recent research results show that ventilation rates could be decreased notably by maintaining a moderate enthalpy in spaces. Humidity also influences the growth of dust mites and fungi and the occurrence of respiratory infections, with values between 30% and 55% relative humidity recommended (Hens, 2003).

Besides, Salonvaara and Ojanen (2003) showed also that materials with hygroscopic capacity have the ability to improve the performance of building envelope structures even to such level that condensation and mold growth conditions are eliminated. In this context, there is a need to improve awareness of the importance of humidity in buildings and develop energy conscience methods of humidity control by incorporating accurate moisture models in building thermal simulation programs.

Figure 7 shows the heat exchanged with the floor. It can be noticed that the absence of the solar radiation during the rain period, causes the decrease of the internal temperature of the building, increasing the heat flux from the floor. In this case, a superior difference to 100% was observed in the Fig. 7, for the heat flux between the model that does not consider moisture and one that considers moisture with boundary condition of rain.

Figure 8 shows the evolution of room air temperature when an infiltration rate of 10 *L*/s is applied. In this case, a maximum difference of 0.5°C is verified between the peaks values, attributed to the increase of vapor concentration difference between internal air and floor surface, caused by an increase of the infiltration air flow.

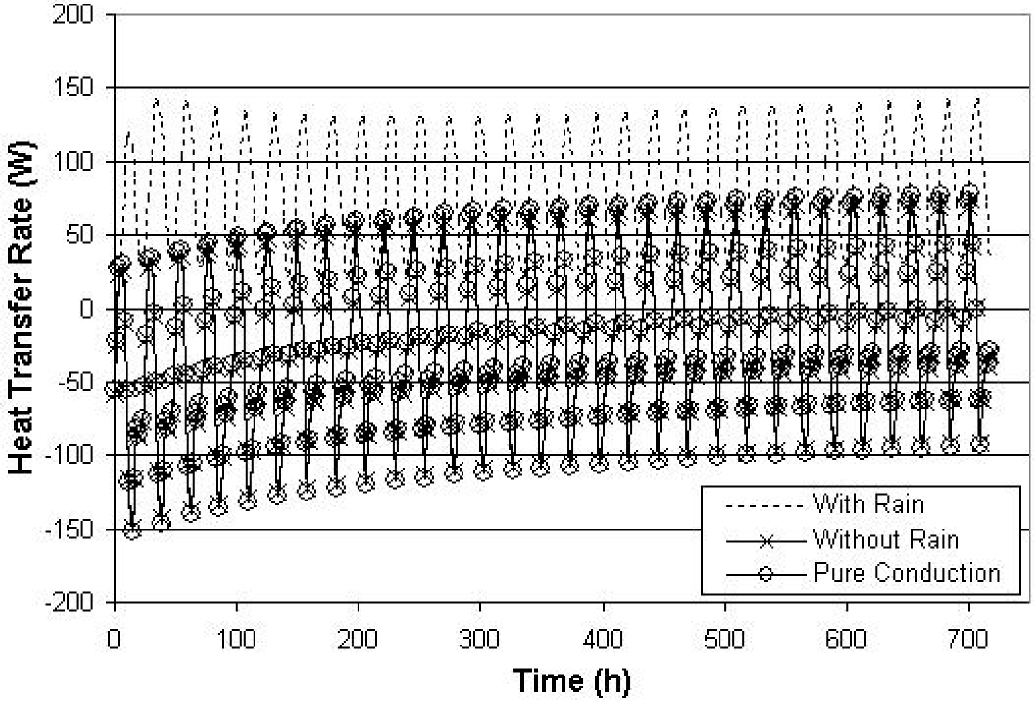


Figure 7: Heat transfer rate from floor (25 m²) in the simulation period of one month.

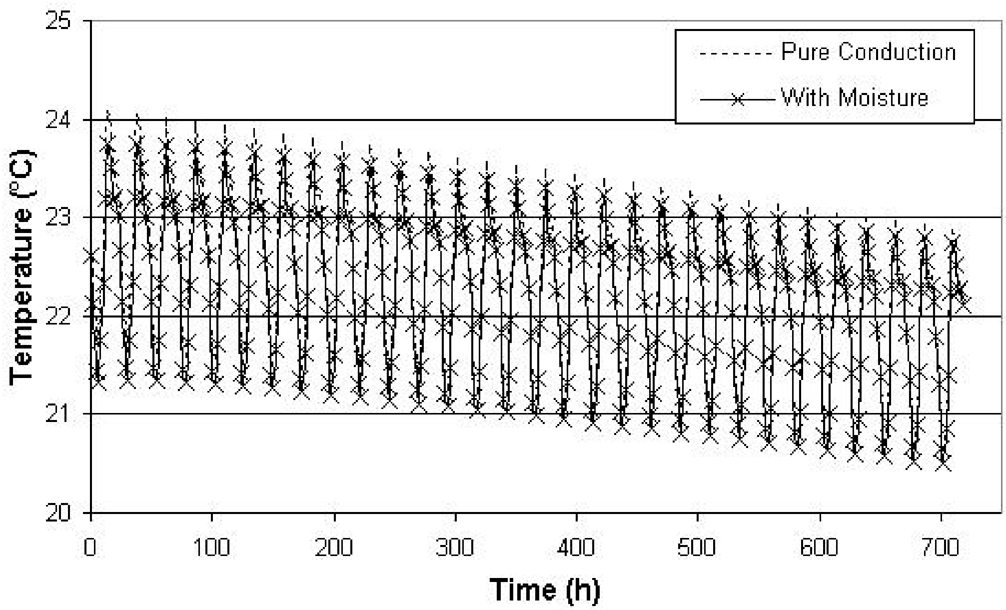


Figure 8: Internal temperature after 2 years of pre-simulation period with an infiltration rate of 10 *L/s*.

## 5- Conclusion

Building simulation codes present some simplifications on their calculation routines of heat transfer through the ground. Regarding the ground heat transfer some aspects should be clarified: the multidimensional phenomenon; the transient behavior and the great number of involved parameters, mainly when moisture is considered.

A review in the literature showed divergences about moisture effects on the ground heat transfer. In addition, most of programs do not consider the 3-D effect in the soil.

The first analysis showed a very slight difference in terms of room air temperature between the purely conductive model for the ground and the moisture model, due to the importance of solar gains compared to ground heat transfer in the room energy balance and due to different time scales between room air and soil. However, a significant difference of 15 % was noticed on the room air humidity ratio, even for the high infiltration rate considered in the analysis. Therefore, higher energy consumption could be expected when an air conditioning system is used due to the augmentation of building latent loads; a 15 % humidity ratio variation may correspond to a 10 % enthalpy variation. Besides the energy related aspects, moisture models are recommended to be incorporated into building simulation codes due to other indoor relative humidity effects such as perception of indoor air quality, occupant's health and durability of building materials.

Regarding the heat flux through building floor, it was noted a small thermal load contribution in both models. However, the absence of solar radiation during the rain period caused a room temperature reduction, occasioning an increase of ground heat transfer of approximately 100 %.

Although the moisture effect has caused no significant difference on the room air temperature, a building with a bigger area of contact with the ground or in underground zones where the solar radiation effect is not predominant, the moisture flux through the floor could contribute more effectively for the room air energy balance.

To conclude, some recommendations are addressed for further work: *i)* Simulation of underground zones and include the moisture effects on the building envelope as well; *ii)* determine empirical correlations for ground heat transfer and compare them to those presented in ASHRAE handbooks; *iii)* improvement of the rain model.

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