COMBINED HEAT AND MASS TRANSFER THROUGH A BACKFILL SOIL

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Abstract. *Building simulation programs normally do not take into account moisture effects in soils temperature determination. However, the presence of humidity can strongly affect the temperature distribution in soils due especially to the evaporation/condensation mechanisms and the strong variation of their thermophysical properties. In order to calculate the temperature profiles in a more accurate way, we have developed a computational code, which was conceived to model the coupled heat and moisture transfer in soils. The presented methodology is based on the theory of Philip and De Vries, using the thermophysical properties for backfill soil chemical composition. The governing equations were discretized using the finite volume method and a 3-D model was used for describing physical phenomena of heat and mass transfer in porous soils. The robust MultiTridiagonal-Matrix Algorithm (MTDMA) was used to solve the strongly-coupled problem. To conclude, we have shown the temperature and moisture content profiles and water mass flow at the upper surface of a backfill soil when submitted to the Test Reference Year (TRY) weather data of Florianópolis-Brazil.*

Keywords*. ground heat and mass transfer, sandy-sil soil simulation.*

1. Introduction

In the 70´s many simulation programs such as BLAST (1977), DOE-1 (1978), NBSLD (1974), ESP (1974), TRNSYS (1975) and more recently ENERGY PLUS (1999) and DOMUS (2001) had been developed to simulate the building energy performance so that rational policies of energy conservation could be efficiently applied. However, most of those codes present some simplifications on their calculation routines of heat transfer through the ground.

Some studies involving the pure conduction heat transfer through the ground can be found in the literature. 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. Zoras (2001) used a combination which incorporates structural response factors into a three-dimensional numerical solution of the conduction heat transfer equation.

In the works mentioned above, the conductivity and the thermal capacity are considered constant and the moisture effect is ignored.

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).

Soil simulations are a research subject of other different scientific areas such as agronomy. Among other works found in literature, Brink and Hoogendoorn (1983) should be mentioned. In their work, groundwater losses due to conduction and natural convection heat transfer modes were analyzed and verified that convection losses are mainly dependent on soil permeability.

Freitas and Prata (1996) elaborated a numerical methodology for thermal performance analysis of power cables on the presence of moisture migration in the surrounding soil. They utilized a two-dimension finite-volume approach to solve the governing equations.

Krarti (1996) discussed the effect of spatial variation of soil thermal properties on slab-on-ground heat transfer by using the Interzone Temperature Profile Estimation (ITPE) technique.

Onmura et al. (2001) investigated the evaporative cooling effect of roofs lawn gardens and observed a reduction of up to 50 % in the heat flux through the ceiling.

The effects of humidity can also generate other problems in buildings. Lucas *et al.* (2002) carried out a curative and preventive study on two different types of residences for hot and humid climates.

Due to the numerical instabilities caused by the effect of latent heat at the boundaries, Wang and Hagentoft (2001) presented numerical method based on an algorithm that combines an explicit model with relaxation schemes. In this model, a criterion for time step determination is developed to improve numerical stability.

For ensuring numerical stability, the linearized set of equations was obtained by using the finite-volume method and the MultiTridiagonal-Matrix Algorithm (Mendes and Philippi, ,2003) to solve a 3-D model to describe the physical phenomena of heat and mass transfer in backfill porous soils. In this way, the code has been conceived to be numerically robust with a fast simulation code. The heat and moisture transfer in soils 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 the results section of the present paper, we show also the temperature and moisture content profiles for a backfill soil when submitted to weather data of Florianópolis-Brazil, as well as the water vapor flow at its upper surface.

2. Mathematical Model

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 are 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

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

where ρ_0 is the solid matrix density (m³/kg), c_m, the mean specific heat (J/kg K), T, temperature (°C), t, time (s), λ, thermal conductivity (W/m K), L, latent heat of vaporation (J/kg), θ, volumetric moisture content (m³/m³), j_v ,vapor flow (kg/m² K), j, total flow (kg/m² K) and ρ_l the water density (kg/m³).

The total flow (**j**) is calculated by summing the vapor flow ($\mathbf{j}_v$) and the liquid flow ($\mathbf{j}_l$). The vapor flow can be described as

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

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_θ, mass transport coefficient associated to a moisture content gradient (m²/s).

The upper surface of the physical domain (Fig.1) is exposed to short and long-wave radiations, convection heat transfer and phase change as boundary conditions.

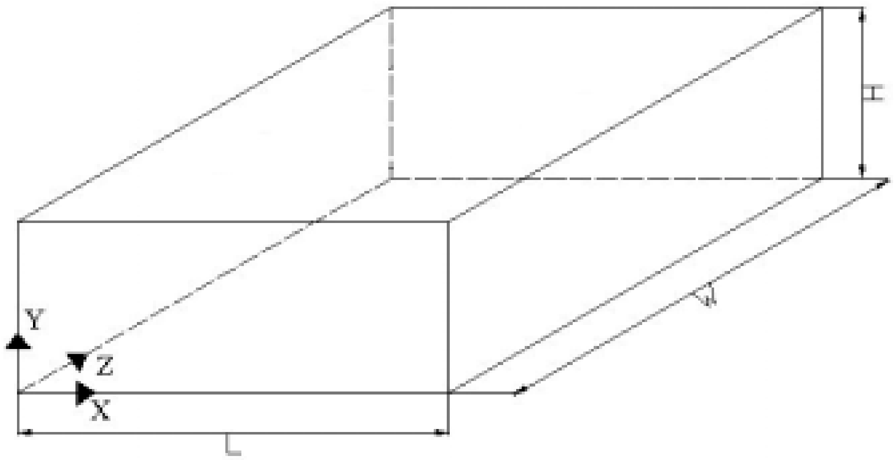

Figure 1. Physical domain of soil.

In this way, for *Y=H*, the energy balance becomes

$$-\left(\lambda(T,\theta)\frac{\partial T}{\partial y}\right)_{y=H} - \left(L(T)j_v\right)_{y=H} = h\left(T_\infty - T_{y=H}\right) + \alpha q_r + L(T)h_m\left(\rho_{v,\infty} - \rho_{v,y=H}\right) - \varepsilon R_{ol} \quad (4)$$

where $h\left(T_\infty - T_{y=H}\right)$ represents the heat exchanged with the external air, described by the surface conductance *h*, αq_r is the absorved short-wave radiation and $L(T)h_m\left(\rho_{v,\infty} - \rho_{v,y=H}\right)$, the phase change energy term. The loss from long-wave radiation is defined as R_{ol} (W/m²), ε, the surface emissivity, α, the solar absorptivity and the mass convection coefficient as h_m, which is related to *h* by the Lewis' relation.

Similarly, the mass balance is written as

$$-\frac{\partial}{\partial y}\left(D_\theta(T,\theta)\frac{\partial \theta}{\partial y} + D_T(T,\theta)\frac{\partial T}{\partial y}\right)_{y=H} = \frac{h_m}{\rho_l}\left(\rho_{v,\infty} - \rho_{y=H}\right). \quad (5)$$

The others surfaces are all considered adiabatic and impermeable as well.

Equations 4 and 5 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 unstability. 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 rise that simulation time step, Mendes et al. (2002) presented a procedure to calculate the vapor flow, independently of previous values of temperature and moisture content. In this way, the term ($\Delta\rho_v$) was linearized as a linear combination of temperature and moisture content, viz.,

$$\left(\rho_{v,\infty} - \rho_v(s)\right) = M_1(T_\infty - T(s)) + M_2(\theta_\infty - \theta(s)) + M_3 \quad (6)$$

with

$$M_1 = A\frac{M}{\Re}\phi \ ,$$

$$M_2 = \frac{M}{\Re}\left(\frac{P_s(s)}{T(s)}\right)^{prev}\left(\frac{\partial\phi}{\partial\theta(s)}\right)^{prev},$$

$$M_3 = \frac{M}{\Re}\left[\left(\frac{P_s(s)}{T(s)}\right)^{prev} R(\theta^{prev}(s)) + \phi_\infty (R(T_\infty) - R(T^{prev}(s)))\right],$$

where

R is a residual function of $\left(\frac{P_s}{T}\right)$, $P_{s,}$ saturated pressure (Pa), $\Re$, universal gas constant (J/kmol K), M, molecular mass (kg/kmol), ϕ, relative humidity, *prev*, previous iteration and A is the straight-line coefficient from the approximation $\left(\frac{P_s}{T}\right) = AT + B$.

3. Simulation Procedure

The governing equations were solved using the finite- volume methodology (Patankar, 1980). It was used the Cartesian coordinates for the geometry of the problem. The differential equations were integrated in each control volume and a fully-implicit scheme was adopted for the time derivatives. The MTDMA (MultiTridiagonal-Matrix Algorithm; Mendes e*t al*., 2002) was used to solve a 3-D model to robustly 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 study, the soil was considered backfill type and its hygrothermal properties were taken from Oliveira *et al.*,1993. This soil type can be used in buried power cables, due its capacity to hold back humidity and to dissipate heat. The backfill composition allows that its thermal resistivity becomes below of the acceptable values, even when it becomes completely dry (Freitas, 1995).

A 10-m depth was considered to study the non-steady coupled heat and moisture transfer. Due to the boundary conditions chosen in the presented case, the flow will be unidimensional so that the domain was distribuided in 816 nodes (4 x 51 x 4). The lenght and width of the physical domain are equal to 0.6m.

The initial temperature assume all over the domaisn was 20°C while the initial moisture content was 0.00675 m^3/m^3 (backfill porosity is 0.265). The upper surface of the domain was submitted to the TRY (Test Reference Year) weather data of the city of Florianópolis-Brazil (Latitude = -27.67°), a convection coefficient of 10 W/m^2 K, a solar absorptivity of 0.5 for short-wave and a constant loss for long-wave radiation of 30 W/m^2 were considered. The other surfaces were assumed to be adiabatic and impermeable.

4. Results and Discussions

For the results presented in Figs. 2 and 3, the weather data of the city of Florianópolis was repeated for a period of 2 years, using a time step of 1 hour. Opposing behaviors between the temperature and the moisture content were verified at the soil surface (Fig. 2). As expected, Fig. 2 shows that the higher the temperature at the soil surface the higher the evaporation rate and the lower the moisture content.

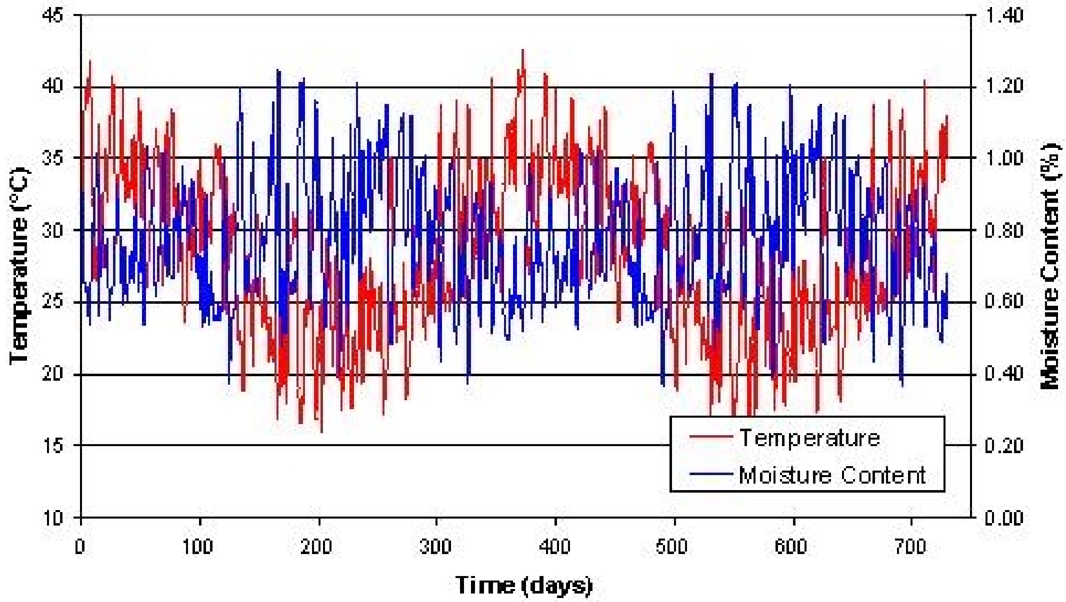

Figure 2. Temperature and moisture content average values at the soil surface for a period of 2 years.

Although the moisture flow represented in Fig. 3 was described for the three first days of July, similar profiles were observed along the whole year. Fig. 3 shows that evaporation takes palace during the day, due to the increase on the soil surface temperature. On the other hand, at night time, the condensation process is the predominant rather than evaporation.

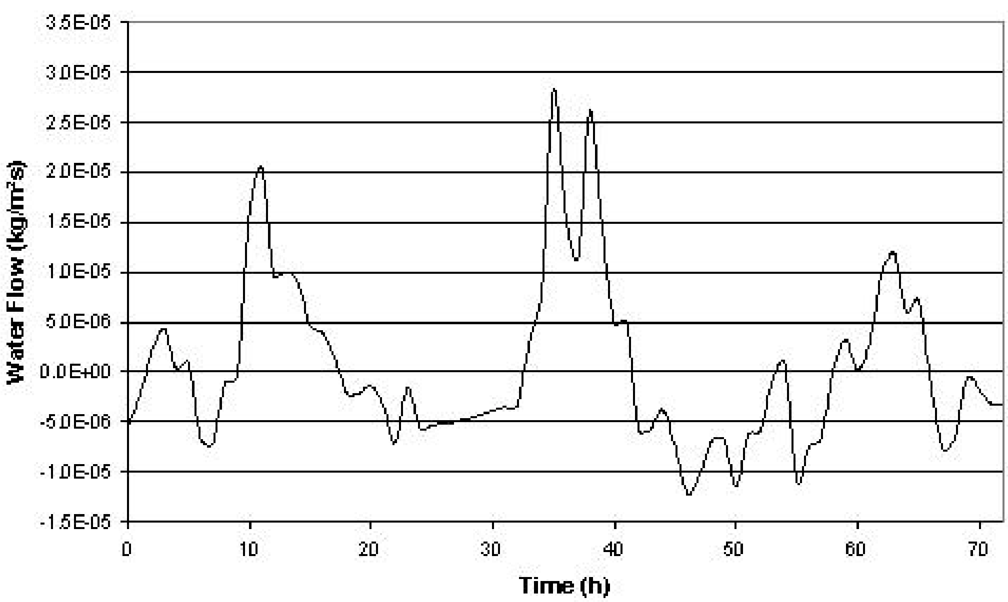

Figure 3. Water vapor flow at the soil surface within the period of 1st to 3rd of July.

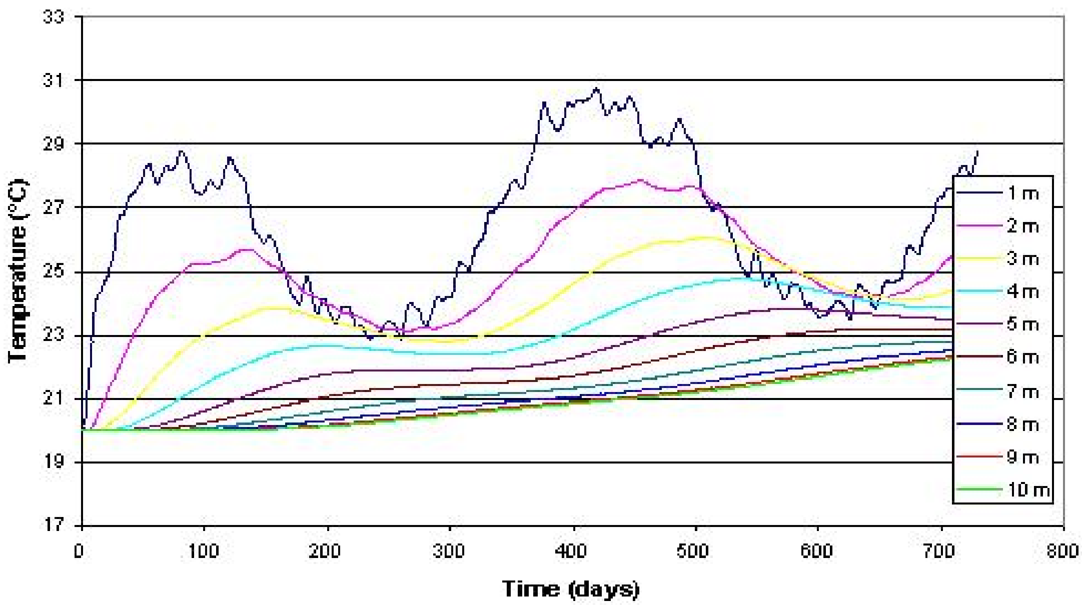

Figure 4. Daily average temperature profiles of the backfill soil for a period of 2 years.

A comparison between Figs. 4 and 5 shows expeditiously the difference between the development of temperature and moisture content profiles within the silt-sandy soil. This difference can be explained by the Luikov number, which is an important parameter to analyze the coupling intensity of simultaneous heat and moisture transfer problems in porous media. It represents the evolution rapidness between moisture content and temperature spatial distributions. Thereupon, for low Luikov numbers, temperature profiles are developed much more rapidly than moisture content ones. In general, soils have very low Luikov numbers ($Lu < 0.01$) so that temperature profiles are rapidly established independently on θ variations. However, for the boundary control volumes, the coupling between T and θ is very important due to water vapor exchanged between the air and the surfaces. Figs. 4 and 5 shows also that a 2-year soil simulation period may be not enough, except at the boundaries, which is also explained by the Biot number for both moisture and heat diffusions. This number gives the relation between the convective and diffusive resistances, which means that, for high mass diffusion Biot numbers, the porous structure hygric resistance is much higher than the corresponding resistance at the free surface.

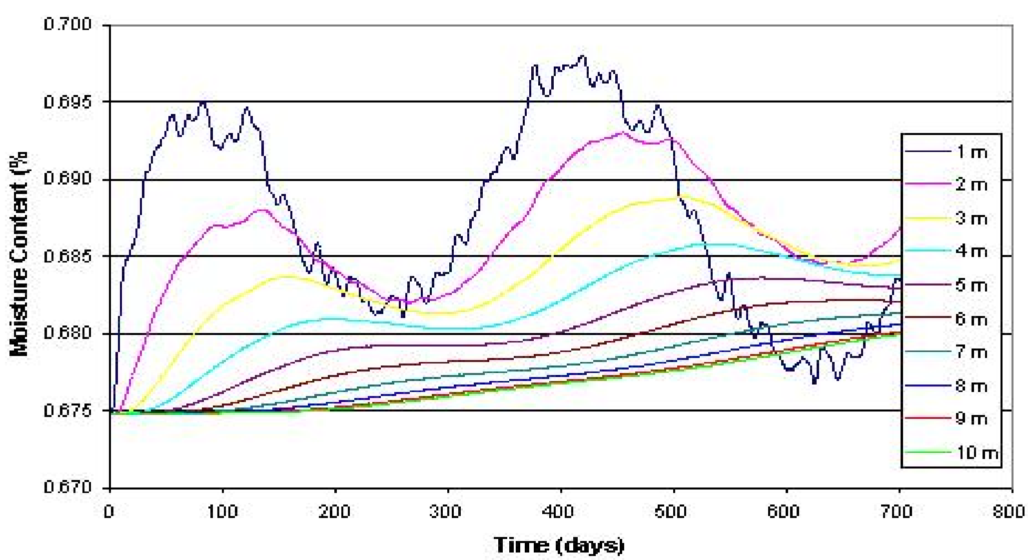

Figure 5. Daily average moisture content profiles of the backfill soil for a period of 2 years.

6. Conclusions

In this work, we presented a mathematical model to analyze the coupled heat and moisture transfer in soils. The MTDMA (MultiTridiagonal-Matrix Algorithm) was utilized to solve the heat and mass transfer governing equations in porous soils. This method avoids numerical instabilities (Mendes *et al*., 2002) by solving simultaneously the governing equations, allowing the use of high time steps which are very important for long-term simulation of the tridimensional heat and mass transfer in soils, with transport coefficients highly dependent on the moisture content.

Temperature and moisture content profiles and water mass flow at the upper surface of a backfill soil were shown when submitted to the Test Reference Year (TRY) weather data of Florianópolis-Brazil.

For further work, the research has been conducted in order to analyze the simultaneous 3-D ground heat and moisture transfer integrated to a building simulation code, where the use of a 3-D model for the soil domain shall be imperative.

5. References

Brink, G. J. VAN DEN, Hoogendoorn, C. J., 1983, Ground Water Flow Heat Losses for Seasonal heat Storage in the Soil. Solar Energy, Vol. 30, N°4, p. 362-371.

Davies M., Tindale A., Litter J, 1995, Importance of Multi-Dimensional Condutive Heat Flow In and Around Buildings. Building Serv Eng Res Technol, V. 16, N° 2, p.83-90.

Deru, M. P., Kirkpatrick, A.T, 2002, Ground-Coupled Heat and Moisture transfer from building –Part 1 – Analysis and Modeling. Journal of Solar Energy Engineering, Vol.124, p. 10-16.

Freitas, D. S., Prata, A.T., 1996, Thermal Performance of Underground Power Cables with Constant and Cyclic Currents in Presence of Misture Migration in the Surrounding Soil. IEEE Transactions on Power Delivery, Vol. 11, N. 3.

Krarti, M., 1996, Effect of Spacial Variation of Soil Thermal Properties on Slab-on-Ground Heat Transfer. Building and Environment, Vol. 31, No. 1, pp. 51-57.

Lucas, F., Adelard, L., Garde, F., Boyer, H., 2002, Study of moisture in buildings for Hot Humid Climates. Energy and Building, Vol. 34, p. 345-355.

Mendes, N., Oliveira, R. C. L. F., Santos, G. H., 2001, DOMUS 1.0: A Brazilian PC Program for Building Simulation In: BUILDING SIMULATION 2001, Rio de Janeiro. Seventh International IBPSA Conference. International Building Performance Simulation Association, 2001. v.1. p.83 – 89.

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. and Philippi, P. C., MultiTridiagonal Matrix Algorithm for Coupled Heat Transfer in Porous Media:Stability Analysis and Computational Performance, Journal of Porous Media, 2003. (In press)

Oliveira Jr, A. A. M., Freitas, D. S., Prata, A. T., 1993, Influência das Propriedades do meio nas difusividades do Modelo de Phillip e de Vries em Solos Insaturados. Relatório de Pesquisa. UFSC.

Onmura, S., Matsumuto, M., Hokoi, S., 2001, Study on evaporative Cooling Effect of Roof Lawn Gardens. Energy and Building, Vol. 33, p. 653-666.

Patankar S., 1980, Numerical Heat Transfer and Fluid Flow, Hemisphere Publishing Corp., New York.

Philip, J. R., De Vries, D. A.,1957, Moisture Moviment in Porous media under Temperature Gradients. Trans Am Geophysical Union, V. 38, P. 222-232.

Wang, J., Hagentoft, C. E., 2001, A Numerical Method for Calculating Combined Heat, Air and Moisture Transport in Building Envelope Components. Nordic Journal of building Physics, Vol. 2.

Zoras S, Davies M., Wrobel L. C., 2001, Earth-Contact Heat Transfer: A Novel Simulation Technique. 7th REHVA World Congress – CLIMA 2000, Napoli.