UMIDUS: A PC PROGRAM FOR THE PREDICTION OF HEAT AND MOISTURE TRANSFER IN POROUS BUILDING ELEMENTS

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ABSTRACT

This paper presents the *Umidus* program which has been developed to model coupled heat and moisture transfer within porous media, in order to analyze higrothemal performance of building elements when subjected to any kind of climate conditions. Both diffusion and capillary regimes are taken into account, that is the transfer of water in the vapor and liquid phases through the material can be analyzed. The model predicts moisture and temperature profiles within multi-layer walls and low-slope roofs for any time step and calculates heat and mass transfer. *Umidus* has been built in an OOP language to be a fast and precise easy-to-use software.

INTRODUCTION

The calculation of energy consumption in buildings by simulation software normally assumes that heat is transferred through building envelopes by pure conduction. However most building materials are porous, and therefore contain air and water in different phases. Walls are therefore subject to thermal and moisture gradients, and the transfer of heat and mass occurs simultaneously and are interdependent.

Several investigators have developed models for the study of heat and moisture transport in buildings. Cunningham (1988) developed a mathematical model for hygroscopic materials in flat structures that uses an electrical analogy with resistances for the vapor flow and an exponential approximation function with constant mass transport coefficients. Kerestecioglu and Gu (1989) investigated the phenomenon using evaporation-condensation theory in the pendular state (unsaturated liquid flow stage). The application of this theory is limited to low moisture content. Burch and Thomas (1991) developed a computational model, *Moist*, using the finite-difference method to estimate the heat and mass transfer through composite walls under non-isothermal conditions. The thermal conductivity is normally considered constant and the latent heat due to phase change within the wall was neglected. This program is also limited to low moisture content. Liesen (1994) used evaporation-condensation theory and a response factor method to develop and implement a model of heat and mass transfer in the building thermal simulation program IBLAST (Integrated Building Loads Analysis and System Thermodynamics). To use this method, hygrothermal property variations were neglected. There is no liquid transfer. This program is restricted to very low moisture content but has the advantage of short calculation time.

The software *Umidus* has been developed to model coupled heat and moisture transfer within porous building elements avoiding limitations such as low moisture content, high computer run time and low accuracy. Both diffusion and capillary regimes are taken into account, that is the transfer of water in the vapor and liquid phases through the material can be analyzed for any kind of climate. The model predicts moisture and temperature profiles within multi-layer walls or low-slope roofs for any time step and calculates heat and mass transfer. Input files containing hourly data provide information on the conditions at the interior and exterior of the wall. A library of material properties is also available. The orientation and tilt of the wall are considered and convection heat transfer coefficients at the exterior of the wall are calculated hourly from wind velocity data.

Umidus has been built in *C++Builder* which is an OOP language to be a fast and precise easy-to-use software. The program runs in the Windows 95, 98 and NT operating systems. The user interface consists of a series of windows in which the user can enter the relevant input data and review the results. The user can move between other applications when the *Umidus* simulations are running and several *Umidus* projects can be open and running at the same time. *Umidus* projects with all their input information and results may be saved and reopened.

UMIDUS MODELS

MATHEMATICAL FORMULATION

The governing partial differential equations are given by equations (1) and (2). They were derived from conservation of mass and energy flow in an elemental volume of porous material.

Energy Conservation Equation.

$$\rho_0 c_m(T,\theta)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda(T,\theta)\frac{\partial T}{\partial x}) - L(T)\frac{\partial}{\partial x}(j_V) \quad (1)$$

Mass Conservation Equation.

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial x}\left(\frac{j}{\rho_l}\right) \quad (2)$$

Note that eq. (1) differs from Fourier's equation for transient heat flow by an added convective transport term (due to moisture diffusion associated with evaporation and condensation of water in the pores of the medium) and by a dependence on the moisture content (so that it is coupled to eq. (2)). The driving forces for convective transport are temperature and moisture gradients.

The vapor flow and total flow (vapor plus liquid) are expressed in terms of transport coefficients, D, associated with the thermal and moisture gradients. According to Philip and DeVries (1957), the equations are:

For vapor flow

$$\frac{j_v}{\rho_l} = -D_{Tv}(T,\theta)\frac{\partial T}{\partial x} - D_{\theta v}(T,\theta)\frac{\partial \theta}{\partial x} \quad (3)$$

For total (vapor plus liquid) flow

$$\frac{j}{\rho_l} = -D_T(T,\theta)\frac{\partial T}{\partial x} - D_\theta(T,\theta)\frac{\partial \theta}{\partial x} \quad (4)$$

Note that the model does not take into account the gravity influence on the transfer of liquid water through roofs. This effect is very small compared to the capillary effect specially for microporous materials.

Boundary Conditions

The outside surface of the wall is exposed to solar radiation, heat and mass convection, and phase change. Internally, the wall is exposed to heat and mass convection and phase change.

Submodels

In order to reduce CPU time and in the case there is a lacking of data, we derived 6 submodels from eq. (1) as follows:

$$\rho_0 c_m(T,\theta)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda(T,\theta)\frac{\partial T}{\partial x}) + L(T)\rho_l\frac{\partial}{\partial x}\left(D_{Tv}(T,\theta)\frac{\partial T}{\partial x}\right) + L(T)\rho_l\frac{\partial}{\partial x}\left(D_{\theta v}(T,\theta)\frac{\partial \theta}{\partial x}\right) \quad (5)$$

To simplify writing this equation, we will use V_T and V_θ to designate the second and third right hand terms of eq. (5) which was derived from eq. (1). Table 1 schematically describes the submodels derived from the original model.

Table 1: Schematic description of the submodels

Submodel	Assumptions
0	none (original model)
1	$D_\theta, D_T, D_{\theta V}, D_{TV}, c_m$ and λ = constant
2	$V_\theta = 0$
3	$V_T, V_\theta = 0$
4	$V_T, V_\theta = 0$ and λ = constant.
5	$V_T, V_\theta = 0$ and D_T, D_θ, c_m and λ = constant

The "apparent" thermal conductivity is related to the "pure" thermal conductivity, l, by the following expression:

$$\lambda_{app}(T,\theta) = \lambda(T,\theta) + L(T)\rho_l D_{Tv}(T,\theta) \quad (6)$$

Submodel 0 is the same as the original model given by eqs. (1-4). Submodel 1 is the same as the original model except that all coefficients are taken to be constant. Submodel 2 omits the source term in eq. (1), which is associated with a moisture gradient (V_θ). In this case, the equation resulting from eq. (1) can be written as a function of λ_{app} as:

$$\rho_0 c_m(T,\theta)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda app(T,\theta)\frac{\partial T}{\partial x}) \quad (8)$$

Therefore, Submodel 2 is obtained by combining eq. (7) and eqs. (2-4). Now, if we disregard the term $L\rho_l D_{TV}$ in eq. (6), we obtain Submodel 3 by transforming eq. (7) to:

$$\rho_0 c_m(T,\theta)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda(T,\theta)\frac{\partial T}{\partial x}) \quad (12)$$

Submodel 4 is the same as Submodel 3, except that the pure thermal conductivity, *l*, is constant. Submodel 5 takes the coefficients D_θ, D_T and λ to be constant.

The *Umidus* submodel 0 is the most precise, therefore the most time consuming model. Submodel 5 is the simplest and fastest heat and mass transfer model.

Submodel 4 is equivalent to the model employed in *Moist* program version 2.

Table 2 compares the mean run time for the different submodels relative to Submodel 0.

Table 2: Percent of Submodel 0 run time.

	Submodel					
	0	1	2	3	4	5
Time (%)	100	16	88	65	38	10

The accuracy of each submodel depends basically on the material properties and on the moisture content levels. For hygroscopic walls, for example, submodel simplifications can result on large errors.

The *Umidus* submodels are solved with a finite-volume approach that uses a fully implicit solution scheme with coupling between the conservation equations. Using the Patankar (1980) method with uniform nodal spacing and a generic tridiagonal-matrix solution algorithm (Mendes, 1997), the code solves the temperature and moisture content distributions simultaneously at each time step.

MATHEMATICAL CORRELATIONS

The solar radiation incident on a wall with a given orientation is calculated using the equation given in ASHRAE Handbook A30.3; the solar altitude and azimuth are included in the weather file.

The albedo of the ground in front of the outside surface of the wall, and the solar absorptivity of the external surface of the wall are user defined. *Umidus* includes a feature that allows walls with paint on the interior and exterior surface to be modelled; the permeance of the paint is entered in units of ng/(Pa-m^2-s).

The heat and mass transfer coefficients at both the external and internal surfaces may be calculated by *Umidus* every hour or entered as fixed values by the user. The external convection heat transfer coefficient is calculated using the wind velocity data from the external weather file. The algorithm used is that proposed by Yazdanian and Klems (1994). The internal convection coefficient can be chosen to be fixed, or to be calculated using either natural or forced convection according to Alamdari and Hammond (Clarke, 1985). If forced convection coefficient is to be calculated, the user must enter the air velocity, in m/s, on the internal surface of the wall. The mass transfer convection coefficients are calculated by using the Lewis relation.

The conditions experienced on either side of the wall are defined in the Weather window as shown in Figure 1.

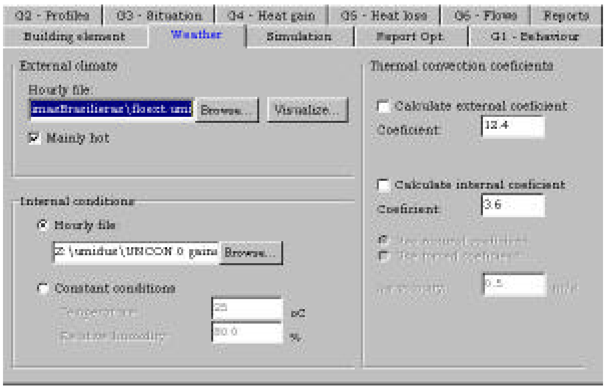

Figure 1: Weather window

UMIDUS WEATHER DATA

External Weather

The conditions on the external side of the element are defined by the external weather file. Weather files for 14 Brazilian cities are available. Each file contains hourly data of dry bulb temperature, relative humidity, direct and diffuse solar radiation, wind speed and direction for a typical year. These files are given the termination UMI, and are in space separated text format. The source of the data for these weather files was the TRY files with solar radiation calculated by the building simulation program DOE 2.1-E.

Hourly weather data can be viewed on the *Umidus* psychrometrics charts.

Internal Conditions

The conditions on the internal side of the element may be defined in two ways: An annual internal conditions file may be used to define the hourly condition of temperature and relative humidity. *Umidus* includes 3 internal condition files, with internal gains of respectively 0, 10 and 30 W/m^2, for each of the 14 Brazillian cities. These files were generated using the building simulation program TRNSYS. Alternatively the values of dry bulb temperature and relative humidity at the inside of the element may be fixed as constant values entered by the user.

LAYERS AND THEIR PROPERTIES

Details of the construction of the element to be simulated are entered in the Construction Element window (see Figure 2).

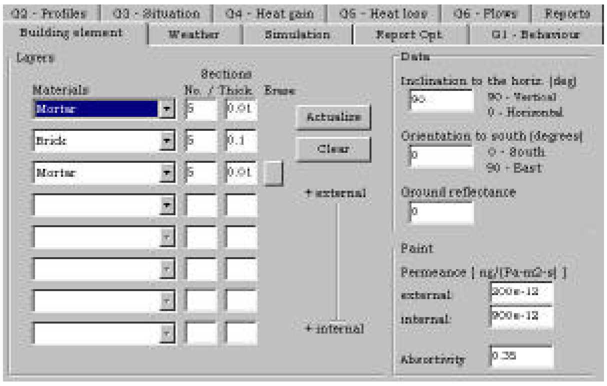

Figure 2: Construction Element Window

Each layer of the element is entered as a row in a table. The element can have a maximum of 10 layers. The user defines the material of each layer from the pull-down menu. There is a choice of 20 materials.

The material in the first row is the external layer, the material in the last row is the innermost layer. After choosing the material the user enters how many sections the layer is to be divided into during the simulations. The number of nodes in a layer is equal to the number of sections plus 1. Therefore if the layer is divided into 4 sections, the layer will have 5 nodes.

The thickness of the layer in metres (m) is entered in the next column. The orientation north/south of the wall and the vertical inclination are user defined.The properties data for aerated celular concrete were obtained from Cunha Neto (1992) and for wood from Siau (1984). Properties for brick and mortar were obtained from Perrin (1985). Laurent and Guerre-Chaley (1995) present the data of thermal conductivity for the same aerated celular concrete.

The properties of the remaining materials are taken from the values given by Burch and Thomas (1991) in version 2 of the Moisture simulation software *Moist*. However, those materials can not be simulated using models higher than Submodel 4.

The *Umidus* material properties files matriz_ are a look up table for thermal conductivity, moisture transport coefficients and sorption isotherms as a function of water content, 0 to 100%. The format of the file is given in Figure 3.

Material Name					
Dry density	Dry porosity	Specific Heat Capacity			
Moisture content	Conductivity	D_T	D_θ	D_{TV}	$D_{\theta v}$
0					
"	"	"	"	"	"
1					
Isotherms					
500	0.002				
Relative Humidity	Isothern Function	Derivative of isotherm Function			
0					
"	"	"	"	"	"
1					

Figure 3: Format of Material File

The values of mass transport coefficients ("Diffusivities") as a function of moisture content are calculated using the coefficients of sorption and permeability given in *Moist*. A very useful feature of *Umidus* is the visualisation of the properties of the materials. In the Visualise Material window of *Umidus*, Figure 4, the mass transport coefficients, conductivities and sorption isotherms of up to 8 materials can be plotted as a function of moisture content.

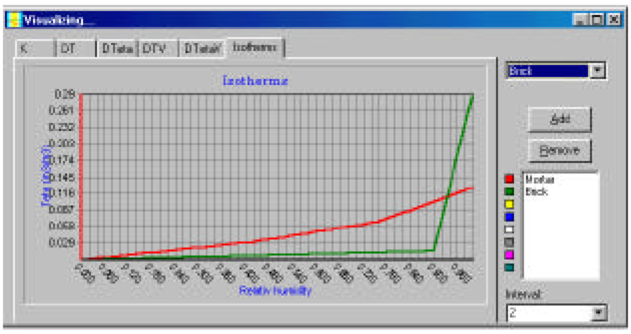

Figure 4: Properties Data Visualisation Window

The details of the simulation to be performed are entered in the Simulation window, Figure 5. The user enters the day, month and hour, when then simulation should start and stop. The time step, convergence criteria, and the maximum number of iterations permitted are also required.

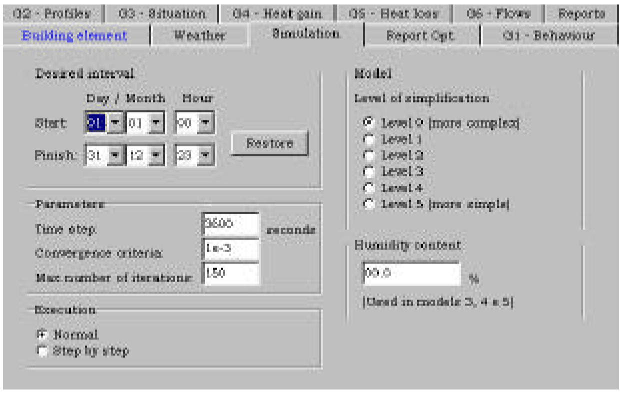

Figure 5: Simulation Window

UMIDUS OUTPUTS

The desired output options are chosen by the user in the Report Options window, Figure 6.

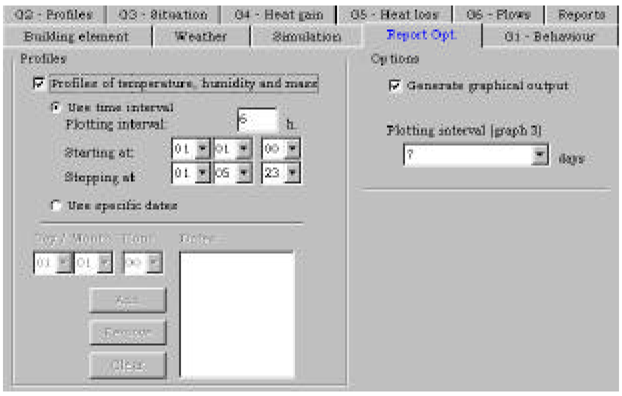

Figure 6: Report Options window

Umidus generates profiles of temperature, moisture content, and fluxes of heat and mass within and through the wall. The time period for which the results are required are entered by the user.

The results of a *Umidus* simulation are presented in the form of 6 graphs. The Behaviour graph, Figure 7, displays the monthly average value of temperature and moisture content at the centre node of the element.

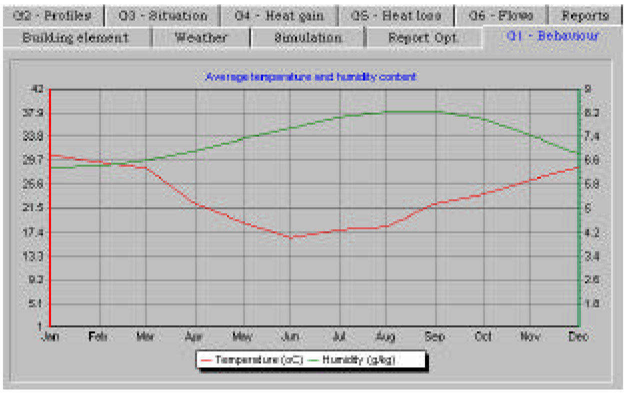

Figure 7: Output Graph 1: Behaviour

The Profiles graph, presented in Figure 8, shows the profiles of temperature and moisture content for a specific hour, day and month which was selected in the report options window of the input section. A list of the chosen hours is displayed on the left of the screen. The user selects the hour to be displayed, by highlighting a date from the list on the left of the window.

Figure 8: Output Graph 2: Profiles

The x-axis is divided into the number of nodes in the building element, the temperature and moisture content at each node is displayed. The temperature scale is on the left, the moisture content scale on the right.

The Situation graph, Figure 9, displays the temperatures and moisture contents at the external and internal faces of the building element and at the central node.

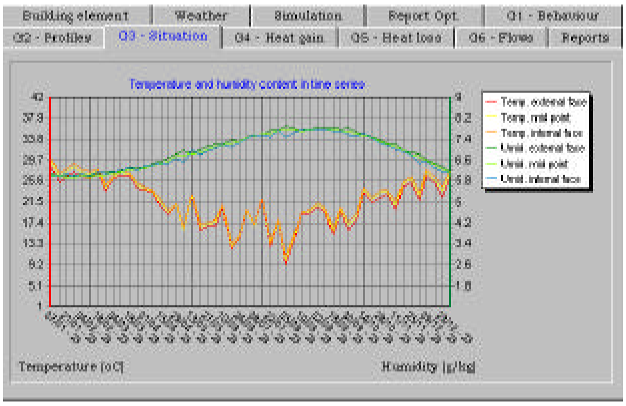

Figure 9: Output Graph 3: Situation

The Heat Gains and Heat Loss graphs, Figures 10 and 11, show the monthly flux of heat through the building element from the outside to the inside (positive heat flow) and the monthly flow of heat through the building element from the inside to the outside (negative heat flow). The percentages of heat gain or loss due to latent heat are also presented.

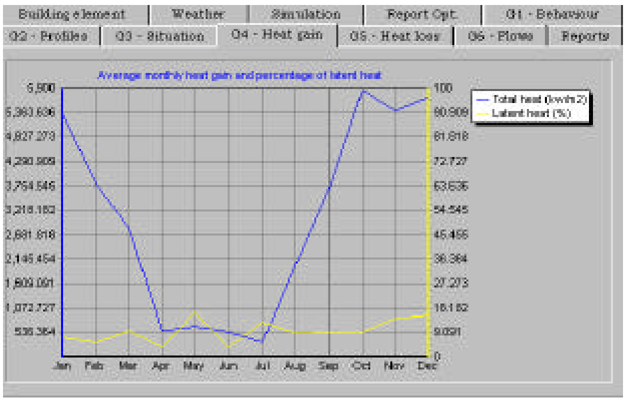

Figure 10: Output Graph 4: Heat Gain

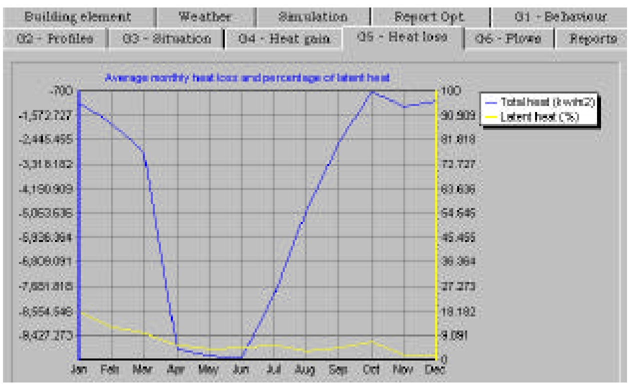

Figure 11: Output Graph 5: Heat Loss

The Flux of Heat and Flow of Mass graph, Figure 12, shows the flux of sensible and latent heat, and flow of mass for the dates chosen by the user in the reports options window.

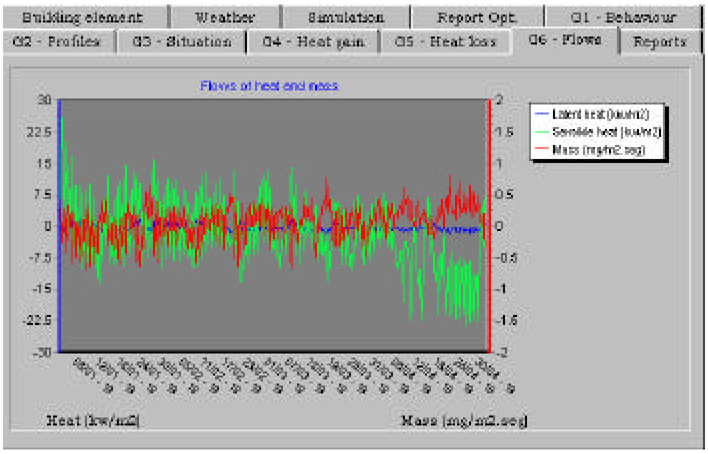

Figure 12: Output Graph 6: Flux of Heat and Flow of Mass.

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CONCLUSIONS

The models presented here for *Umidus* allow calculation of 1-D sensible and latent heat transfer through building elements. Higher accuracy in the heat tranfer calculation and the associated thermal loads calculation is achieved by allowing the basic thermal properties of the wall material to depend on moisture content.

The next step of our work with Umidus is to implement calculus routines, developed by Mendes (1997) in his Ph.D. thesis, that allow evaluation of all heat and mass transport coefficients from basic data such as pore size distribution, sorption isotherm and dry-basis thermal conductivity.

In conclusion, *Umidus* is an user friendly software which can be used for studying higrothermal behaviours of walls, helping architects, air-conditioners designers and building material consultants.

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NOMENCLATURE

c	specific heat [J/kg-K].
D_{Tv}	vapor phase transport coefficient associated with a temperature gradient [m^2/s-K].
$D_{\theta v}$	vapor phase transport coefficient associated with a moisture content gradient [m^2/s].
D_T	mass (liquid plus vapor) transport coefficient associated with a temperature gradient [m^2/s-K].
D_θ	mass transport coefficient associated with a moisture content gradient [m^2/s].
j_l	liquid flow [kg/m^2-s].
j_v	vapor flow [kg/m^2-s].
L	heat of vaporization [J/kg].
T	temperature [°C].
t	time [s].
x	distance into wall or roof [m].
λ	thermal conductivity [W/m-K].
θ	moisture volumetric content [m^3 of water / m^3 of porous material].
ρ	mass density [kg/m^3].

Subscripts

ext	exterior air.
int	interior air.
m	mean.
v	vapor.
l	liquid.