WUFI ORNL/IBP Hygrothermal Model

Karagiozis[1] Achilles, Kuenzel[2] Hartwig and Holm[3], Andreas.

Abstract:

Moisture engineering is becoming an important task in the overall design of building enclosures in both North America and Europe. Several methods may be used to design wall systems, and modeling is definitively the most flexible approach. There is an increasing demand for calculation methods to assess the moisture behavior of building components. In North America alone, the estimated cost in increased energy consumption due to the presence of moisture is approximately $1 billion dollars annually. Current tasks, such as preserving historical buildings or restoring and insulating existing buildings are closely related to the moisture tolerance in a building structure. Calculative analyses are becoming increasingly important due to the expensive and time-consuming experimental investigations and the limited transferability to real situations.

The Oak Ridge National Laboratory (Building Technology Center) and the Fraunhofer Institute for Building Physics in an international collaboration have jointly developed a moisture engineering assessment model that predicts the transient transport of heat and moisture. This model, WUFI-ORNL/IBP is now available in North America free of charge, and can be downloaded via the Internet at: www.ornl.gov/btc/moisture.

The unique features of this particular model are that it incorporates vapor and diffusion transport mechanism, along with realistic boundary conditions that include wind-driven rain. This alone may account for more than 80% of the total moisture load in envelopes. In addition this model is tailored to North American materials and construction practices and has a very friendly user interface that appeals to both architects and engineers. The model is also the most benchmarked hygrothermal model developed, since 1994.

In this paper a brief description of the model will be given showing all needed inputs for a brick wall envelope system located in Montreal CANADA.

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Introduction

In civil and architecture engineering there is an increasing demand for calculative methods to access and predict the long-term heat, air and moisture (hygrothermal) performance of building envelope systems. Accessing the performance of particular performance of a complete envelope system or a sub-system is critical an architect or building envelope designer. This need for better tools to access the hygrothermal performance of designed systems have been necessitated by numerous catastrophic moisture related failures, codes and higher expectations and demands by the consumer. Indeed, even today the majority of the building envelope designs rarely undergo a design assessment for moisture control, instead prescriptive requirements are sometimes followed that occasionally apply. Until very recently even if a North American building envelope designer applied a moisture design assessment approach, such as the one recommended by ASHRAE, the analysis was steady state (stagnant environmental loads) and did not account for the important dynamic and thermal and moisture transport mechanisms.

Recent advancements however by Kuenzel, (1994), Salonvaara and Karagiozis (1998), Karagiozis (1997, 2000) and IEA Annex 24, Hens (1996) in fundamental understanding of the transport of the combined heat, air and moisture transport have aided in the development of advanced hygrothermal computer models. Several advanced models have been developed, and detailed reviews of these are included in a new chapter in the ASTM Manual on “Moisture Analysis for Buildings” by Karagiozis (2001). At present only a limited number of the these models have been termed as “moisture engineering models”.

Essentially moisture engineering models deal with the characterization the complex heat, air and moisture transport behavior of building envelope systems. The service life of a building envelope is strongly correlated with how the individual systems of building envelope components (walls, roofs and basements) mange their responses to heat, air and moisture transport excitations. The main advantage of modeling is that, if the building envelope system has been carefully characterized, modeling can predict the long-term hygrothermal performance of the system under different climatic conditions, effect of changes in the interior conditions (HVAC), and the effect of various energy retrofit to the building durability (hygrothermal performance). Moisture load tolerances of various envelope designs can also be investigated with respect to the drying potential and the total system effect of various design alternatives, by employing modeling. Modeling however is not meant to replace valuable lab and field investigations but to challenge them, and extend the information they may provide. In many experimental evaluations of complex envelope systems, simulations can be performed to design, explain and interpret the experimental results.

Over the last 30 years, moisture engineering heavily relied on experimental approaches to resolve moisture performances of building envelopes. Hundreds of examples, research investigations, employing laboratory and field monitoring, Hens (1996), Treschel, (1994) have been performed in both North America and Europe on specific building envelope case studies. A disppoporiationate number of these have only concentrated on the thermal performance characterization of building systems. However, the majority of our current design guidelines have essentially been generated by past experimental analysis. This has provided in-valuable results in some case, but in others more questions than answers. During the same period, 1960-1990, moisture modeling of building envelope systems was not developed at the same level of expertise as that provided by experimental approaches.

In 1997 one of the author's (Karagiozis, 1997) paper to the 7th Conference on Building Science stated "*Sophisticated hygrothermal models have not yet been available to building envelope designers, as they are mainly research models. As the shift of regulatory design code (NBCC) approaches from the limited prescriptive design to performance and objected based building envelope codes is being adopted, the demand for design assessment and performance models will increase many-fold. Scaled down versions of these sophisticated moisture modeling tools will* *eventually be distributed to building envelope designers."* This North American gap has been recently bridged by the development of the WUFI-ORNL/IBP hygrothermal model by a joint international collaboration between the Oak Ridge National Laboratory and the Fraunhofer in Building Physics. This is the first advanced hygrothermal model that is available freely to North American residents by accessing ORNL web site at: www.ornl.gov/btc/moisture.

In this paper, a brief description, of the WUFI-ORNL/IBP hygrothermal model is given. WUFI ORNL/IBP is an advanced hygrothermal model that was specifically tailored to the needs of architects and building envelope designers.

BACKGROUND ON WUFI-ORNL/IBP

The WUFI-ORNL/IBP hygrothermal model, is a Windows-based PC program for the hygrothermal (heat and moisture) analysis of building envelope constructions. WUFI ORNL/IBP software is an easy-to-use, menu-driven program for use on a personal computer that can provide customized solutions to moisture engineering and damage assessment problems for various building envelope systems. The model was jointly developed by the Fraunhofer Institute for Building Physics (IBP) in Holzkirchen, Germany, and Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee, USA, both internationally established in the area of building energy performance and durability assessments. The joint effort of these two laboratories has created the easiest-to-use and most intuitively accessible building moisture engineering software on the market. This model is an excellent educational tool for both the experienced and the novice user, building envelope design engineer and architect. This advanced model has been described in detail in a new ASTM handbook, Moisture Analysis for Buildings, MNL 40 Treschel (2001).

WUFI-ORNL/IBP Model is a transient, one-dimensional heat and mass transfer model that can be used to assess the heat and moisture distributions for a wide range of building material classes and climatic conditions found in North America. This version of the model was specifically developed to provide an educational overview of the complicated moisture transport phenomena occurring in construction assemblies, and to allow both building envelope designers and architects' insight into design decisions. The WUFI-ORNL/IBP Model can be used to estimate the drying times of masonry and lightweight structures with trapped or concealed construction moisture, investigate the danger of interstitial condensation, or study the influence of driving rain on exterior building components. The program can also help to select repair and retrofit strategies with respect to the hygrothermal response of particular wall assembly subjected to various climates. This allows the comparison and ranking of different designs with respect to total hygrothermal performance. This design tool can aid in the development and optimization of innovative building materials and components. For example, WUFI (Künzel 1994) simulations led to the development of the smart vapor retarder [1], a successful application of a software tool to a practical moisture control problem.

Once you have supplied WUFI ORNL/IBP with the data it needs, it will calculate the time evolution of the temperature and moisture fields in the building component. During or at the end of the simulation you will be given three types of distributions results that describe the temporal evolution of certain quantities, taken at specified locations or as mean values over specified layers.

The following parameters are given as courses:

- the heat flux densities through the interior and exterior surface, respectively;
- the temperatures and relative humidities at monitoring positions of your choice (e.g., at the interior and exterior surfaces, or in the middle of an insulation layer);
- the mean moisture content of each material and the total moisture content of the entire building component.

Additionally profiles (graphs), which show the spatial distribution of a quantity across the building component at a specified point in time of the following quantities, are available:

- the temperature across the assembly,
- the relative humidity across the assembly,
- the moisture content across the assembly.

A film file, which contains the transient profiles over all time steps and thus allows to display the thermal and hygric processes in the building component as an animation .

Courses, profiles, and the film are written to a single file in a compact binary format. This file is currently imbedded in the input file to allow better control of each simulation case. WUFI ORNL/IBP offers graphics functions that allow you to view the computed courses and profiles and print them. The film viewer allows you to view the film at your leisure after completion of the calculation.

The predecessor of this program WUFI was released in Europe in 1994 (Künzel 1994) and has since been widely used by building envelope designers, architects, building physicists, consulting specialists, and universities in Europe. The WUFI ORNL/IBP model is an excellent educational tool for understanding the basic principles and interactions present during moisture transport.

In addition to the educational version WUFI ORNL/IBP, IBP (www.wufi.de) offers the professional version WUFI-pro V3.0 with advanced features and options. The commercially available WUFI-pro V3.0 mainly addresses users with some previous experience in the fields of hygrothermal analysis and moisture transport simulations.

Theoretical Development

Physical Background

The WUFI ORNL/IBP model is a heat and moisture transport model that is customized for predicting the performance of building envelope systems in North and South America. In this section of the paper some of the fundamental equations used in the main WUFI engine by Künzel 1994) are discussed. For more details on the theory, consult the corresponding chapter in the new ASTM manual 40 on “Moisture Analysis for Buildings” chapter authored by Künzel et al (2001).

Moisture storage

The application of hygrothermal simulation tools requires some basic knowledge about material properties. Most building materials are hygroscopic which means that they absorb water vapor from the environment until equilibrium conditions are achieved. This behavior can be described by sorption curves over a humidity range between 0 and 95% R.H.. For some materials the equilibrium water content is not very sensitive to changes in temperature, these sorption curves are also called sorption isotherms. From 95% R.H. up to the capillary saturation at 100 % R.H. stretches the capillary water range. In this range the equilibrium water content of a material is still a function of relative humidity. However, this function can no longer be determined by sorption tests in climatic chambers. Here, a pressure plate apparatus is necessary in order to complete the sorption curve in the high humidity range. The resulting water retention curve is a prerequisite for simulations including liquid transport. Fig.1 shows some examples of these curves for typical building materials with different sorption capacities. While wood has a similar moisture capacity in both humidity ranges, clay brick has a very low sorption capacity in the hygroscopic range but a high water retention in the capillary water range. For concrete the opposite is true. These differences have an important effect on the transient moisture behavior of the materials and may not be neglected. The hysteresis between absorption and desorption isotherms is usually not very pronounced, this is approximated in the model as the absorption isotherm.

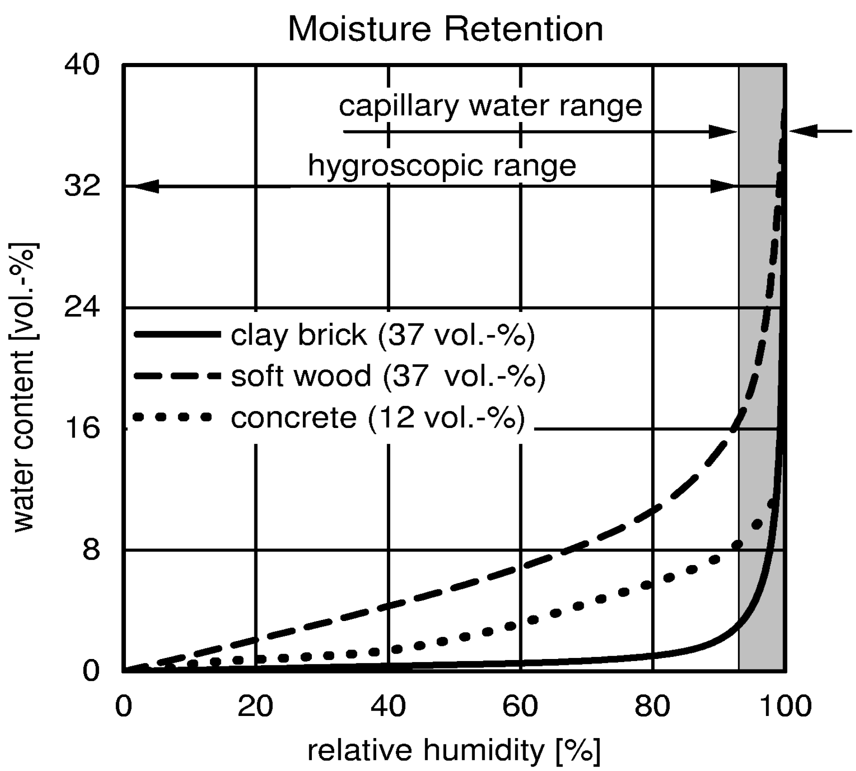

Fig. 1: Moisture retention curve for three typical building materials. The shaded area represents the part the capillary water range which is determined with pressure plate apparatus.

Moisture Transport

The moisture transport in porous materials is largely due to vapor diffusion, surface diffusion and capillary conduction. The coincidence of theses transport phenomena in practice will be explained by Fig. 2. Considered is a capillary in a masonry wall under winter conditions, when the vapor pressure indoors is higher than outdoors and the inverse is true for the relative humidity. In the dry state the vapor is driven outwards by the vapor pressure gradient. However such a dry state rarely exists and there is a layer of absorbed water at the inner surface of the pore. This layer has a higher molecular density (it is ‘thicker’) at the outdoor end compared to the indoor end of the capillary due to the gradient in relative humidity which is opposed to the vapor pressure gradient. By molecular motion in the surface film moisture is thus transported inwards. Vapor and surface diffusion can counterbalance each other to such an extend that the overall moisture transport and therefore also the amount of condensation are considerably reduced. In the case of wet conditions, e.g. after rain penetration, when the pores are filled with water, capillary conduction sets in. This very efficient moisture transport is governed by differences in capillary pressure. Since there is a direct relation between the capillary pressure and the relative humidity (Kelvin’s law) the latter can also be considered as driving force for capillary flow.

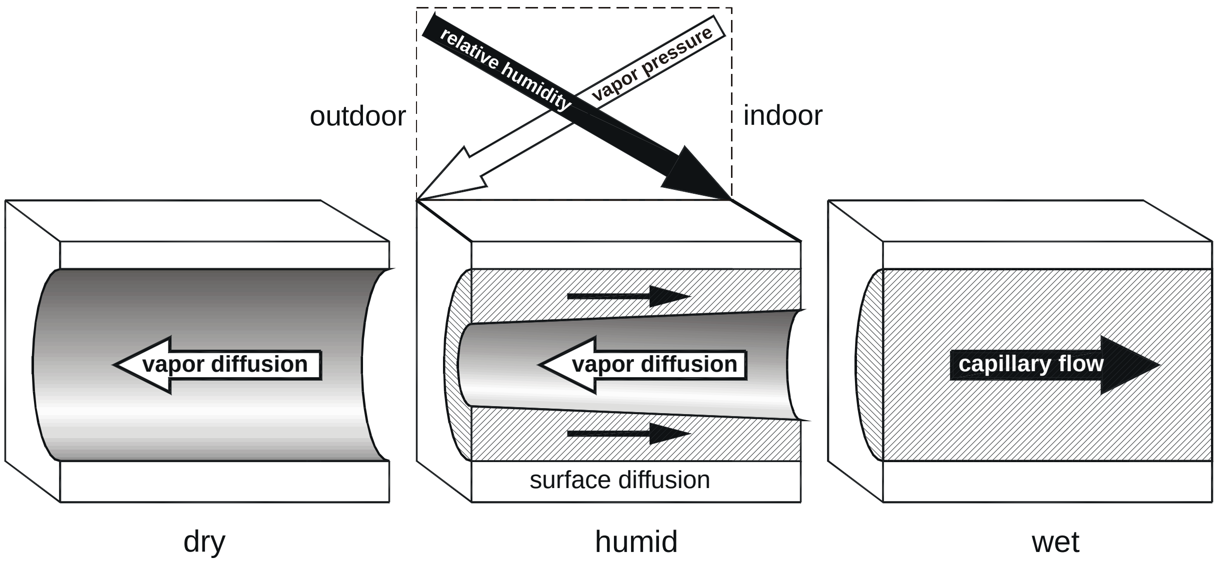

Fig. 2: Moisture Transport Mechanism

Governing Transport Equations

The governing equations employed in the WUFI ORNL/IBP model for mass and energy transfer are as follows:

Moisture transfer

$$\frac{\partial w}{\partial \phi} \cdot \frac{\partial \phi}{\partial t} = \nabla \cdot \left(D_\phi \nabla \phi + \delta_p \nabla (\phi \ p_{sat}) \right) \qquad \text{(Eq. 1)}$$

Energy transfer

$$\frac{\partial H}{\partial T} \cdot \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + h_v \nabla \cdot \left(\delta_p \nabla (\phi \ p_{sat}) \right) \qquad \text{(Eq. 2)}$$

where

ϕ	=	relative humidity, -
t	=	time, s
T	=	temperature, K
c	=	specific heat, J/kgK
w	=	moisture content, kg/m³
psat	=	saturation vapor pressure, Pa
k	=	thermal conductivity, W/(mK)
H	=	total enthalpy, J/m³
Dϕ	=	liquid conduction coefficient, kg/ms
δp	=	vapor permeability, kg/(msPa)
hv	=	latent heat of phase change, J/kg

On the left-hand side of Eqs. (1) and (2) are the storage terms. The fluxes on the right-hand side in both equations are influenced by heat as well as moisture: the conductive heat flux and the enthalpy flux by vapor diffusion with phase changes in the energy equation strongly depend on the moisture fields and fluxes. The liquid flux in the moisture transport equation is only slightly influenced by the temperature effect on the liquid viscosity and consequently on Dϕ. The vapor flux, however, is simultaneously governed by the temperature and the moisture field because of the exponential changes in the saturation vapor pressure with temperature. Due to this close coupling and the strong non-linearity of both transport equations, a stable and efficient numerical solver had to be designed for their solution.

Material properties and boundary conditions

The accuracy of simulation results depends largely on the availability of consistent material properties. The lack of reliable material data has been the main handicap for the large-scale application of modern simulation tools. Therefore a temporary educational North American material property database (ASHRAE 2000) is included in WUFI-ORNL/IBP program. The minimum parameters required for each material are specific heat capacity c, thermal conductivity *k*, bulk density ρ, total porosity ε and the vapor diffusion resistance factor μ. If hygroscopicity and capillarity should be accounted for the moisture retention curve (see Fig.1) and the liquid conductivity D_φ have to be added.

All building components interact with their hygrothermal environment. This means that the ambient conditions influence the building component and vice versa. This reciprocal influence which is mainly confined to the interior environment may have to be considered for the formulation of the boundary conditions. For most applications an annual sine wave for indoor temperature and humidity is appropriate. The formulation of the exterior climate conditions is more complex. If solar radiation or precipitation should be accounted for, hourly weather data become necessary. A complete data set (including precipitation) for more then 50 North American locations are included in the WUFI-ORNL/IBP model. Bill Seaton from ASHRAE is gratefully acknowledged for his assistance.

Calculation Procedure

The transient calculation procedure of the WUFI-ORNL/IBP model is outlined in Fig.3. The necessary input data include the composition of the examined building component, its orientation and inclination as well as the initial conditions and the time period of interest. The material parameters and the climate conditions can be selected from the attached database or from other available sources. Starting from the initial temperature and water content distributions in the component, the moisture and energy balance equations have to be solved for all time steps of the calculation period. Both equations contain the storage terms on the left and the transport terms on the right hand side. The moisture balance includes the derivative of the moisture retention curve (l.h.s.), the liquid transport the vapor diffusion which are related to gradients in relative humidity and vapor pressure respectively. The enthalpy of solid and moisture forms the storage of the energy balance. The energy flux consists of the thermal transmittance and the latent heat due to condensation and evaporation of moisture. The coupled transfer equations are solved numerically by an implicit finite volume scheme. The resulting output contains the calculated moisture and temperature distributions and the related fluxes for each time step. The results may be presented as animated moisture and temperature profiles over the cross-section of the building component or as plots of the temporal evolution of the variables.

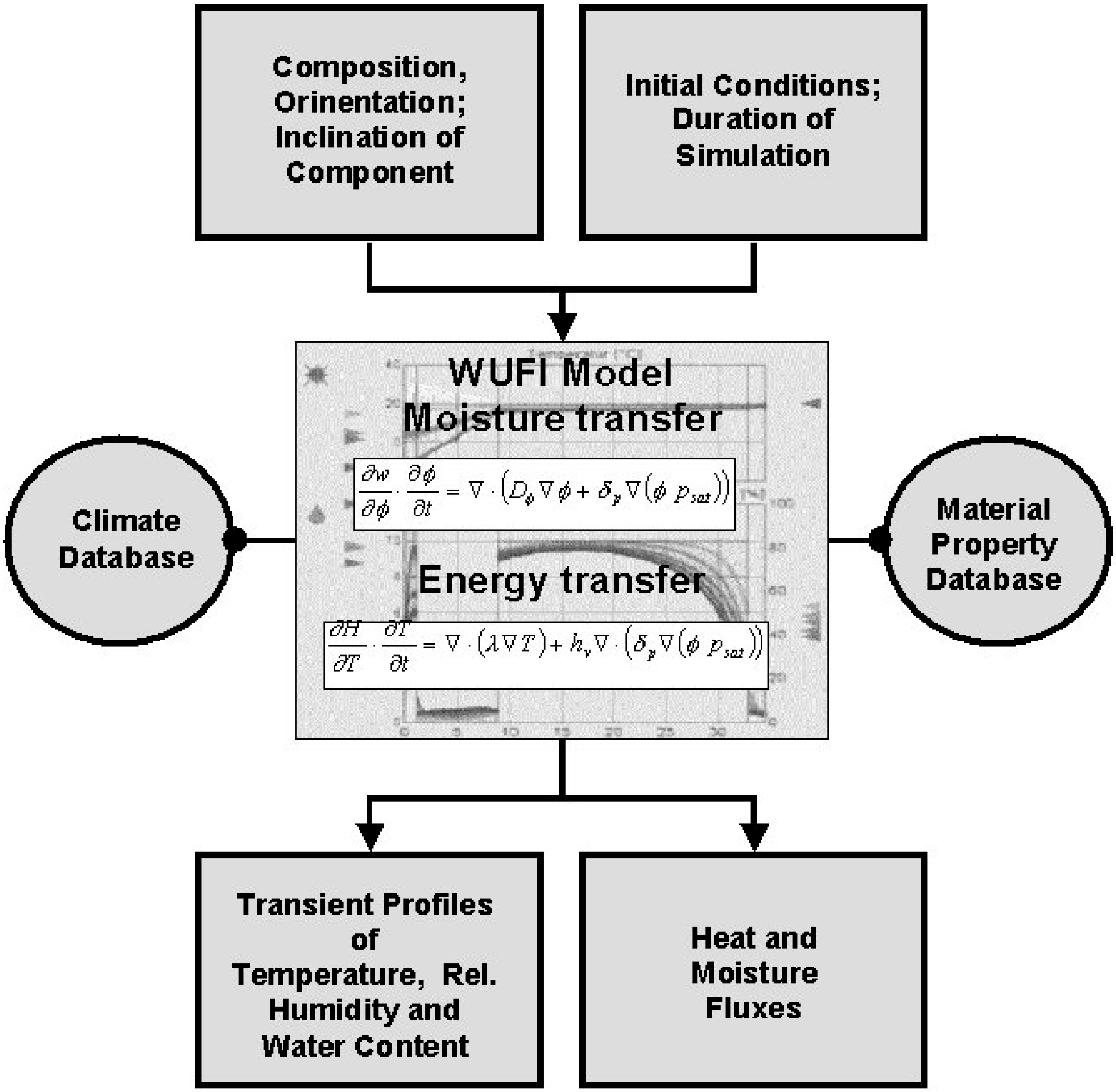

Fig. 3: Flow Chart of WUFI-ORNL/IBP

At each time step the heat and moisture transport equations are solved alternately with a continuous update of the transport and storage coefficients until the convergence criteria are achieved. The calculated temperature and moisture fields as well as the heat and moisture fluxes at the surfaces of the building component form the output data.

WUFI-ORNL/IBP Hygrothermal Model Features

The WUFI ORNL/IBP model is the most advanced hygrothermal model for building envelope analysis for architects, engineers, and consultants. The WUFI ORNL/IBP model is based on a state-of-the-art understanding of building physics in regard to sorption and suction isotherms, vapor diffusion, liquid transport, and phase changes. This model is well documented and has been validated by many comparisons between calculated and field performance data. [Kuenzel, 1994], [Kuenzel 1996], [Holm, 1999], [Holm, 2000].

The model requires a limited number of standard, readily available material properties. A materials database that is part of the program includes a full range of materials commonly used in North America. At present existing data are used from ASHRAE and other sources, but these will be upgraded to complete material properties by the Oak Ridge National Laboratory Advanced Hygrothermal Property Facility in the near future. This database will also be published on the Internet and registered WUFI ORNL/IBP users can download it for free.

The WUFI-ORNL requires hourly weather data such as temperature, relative humidity, wind speed and orientation, driving rain, and solar radiation are employed in the hygrothermal calculations. These data are available for a wide range of North American climate zones The model has several enhanced features. Some attractive modeling capabilities are as follows:

- The WUFI ORNL/IBP model is an excellent professional and educational tool for understanding the complex interactions during the transport of heat and moisture in construction assemblies. The visual design allows one to understand the complex effects that non-linear material properties play in the transport of moisture.
- The WUFI ORNL/IBP model may be used to understand the transient heat and moisture diffusion and capillarity in any one-dimensional wall geometry
- The WUFI ORNL/IBP model can employ either SI or IP units. This is particularly useful for design consultants, students, or architects who may be familiar with one system and not with the other.
- The WUFI ORNL/IBP model is equipped with a limited North American material property database. Future upgrades will introduce a wider range of materials, as manufacturers test all properties in a consistent manner.

- The model accounts for night sky radiation, as this can be an important thermal and moisture load in various climates in North America. This new feature allows one to take into account surface wetting during the night.
- The model contains new algorithms for modeling the effect of wind-driven rain as a function of building height.
- The model uses real-time meteorological data to account for the exterior environmental conditions that affect the performance of the envelope system. (For all U.S. locations two weather data sets have been included, representing the 10% coldest and warmest weather periods from a 30-year period; for Canadian cities, one weather data set is included. The WYEC2 files are used for Canadian cities because data are not readily available to the public at present.) This new feature allows the user to compare the effect of climate on the performance of the structure.
- The combined influence of sky radiation and cloud cover is a new feature in the model.

The model's new visual interface was designed for simplicity and to assist the user by offering lists of predefined parameters for selection.

WUFI ORNL/IBP Model Interface/Application Case

To demonstrate the user-friendly capabilities of the WUFI ORNL/IBP model/interface an example case was developed. A brick cavity wall is used in the example case. This wall is composed of 6 layers which , starting from the outside of the building are: 104 mm brick, 25 mm air layer, 60 minute building paper, 89 mm fiber glass insulation, a polyethylene vapor retarder and a gyspum board. In addition, a further resistance of the same magnitude of the gypsum board is used as a paint. The exterior climate was chosen as Montreal, Quebec and it was used for this simulation. A medium class of interior vapor load is employed for the inside of the building. Both environmental loads vary as a function of hour and time of year. The step by step implementation of this case is very easily done by following the steps:

1. First the user develops a **Project**, see Fig 4. Within each project, the user may introduce up to two (professional version: an arbitrary number of) separate sets of modeling cases. The WUFI ORNL/IBP interface functions for data input are organized in three groups:

2. **Component:** The user specifies the modeling scenario and details of the envelope system of the modeling, such as geometrical makeup in Fig 5, the material parameters Fig 6, example cases in Fig 7, Orientation, Rain parameters in Fig 8, surface characteristics in Fig. 9 and initial conditions in Figure 10.
3. **Control:** The user defines the time period for which the simulation is to be carried out as shown in Figure 11.
4. **Climate:** The user defines the exterior and interior environmental exposure conditions of the construction as displayed in figures 12 and 13 respectively.

Run: The user starts the simulation. During the calculation WUFI-ORNL/IBP displays the computed thermal and hygric profiles as an animation, as shown in Figure 14.

Output: The user can display and print out the input data summary, check the status of the simulation, view and print the results. Figure 15, 16 and 17 show typical results from the simulation

Options: The user can define the unit system, configure warnings, and select save options.

All these functions are needed to establish each case within a Project. Following the sequence order in the project explorer or in the menu bar, you can successfully prepare all inputs, perform the simulation, and review output results.

Discussions

Following the step by step brick wall example explained above, it becomes obvious that obstacles in setting up a wall case to determined whether or not the wall performs hygrothermally satisfactory have been significantly reduced. Indeed, the only requirement needed to run an advanced hygrothermal simulation is that the user needs to understand the geometrical parameters of the wall envelope.

Of significant value is that the user can watch the simulated performance of the wall envelope graphically while the simulation is being performed. This graphical presentation of the all the important quantities as a function of time while the simulation us being performed is of excellent educational value. This was one of the main objectives during the development of the WUFI-ORNL/IBP model, to provide an educational value imparted by visually displaying the simultaneous heat, and moisture performance of building envelope systems as a function of time and space. Also providing many drop down menus whether the user simply selects rather than inputs the required parameters permits a higher level of confidence that the simulation is being performed correctly. It is expected that future upgrades of the WUFI-ORNL/IBP model will aim at further simplifying the input parameters.

Conclusions

Major progress has been achieved in the last few years in the development of advanced hygrothermal models. For the first time in North America, a simple to use moisture engineering model is available to building envelope design community. By keeping the input requirements to simply defining the wall structure, the user can easily determine the performance of a wide range of wall systems as a function of climate and interior environment.

It is expected that as more accurate material properties are measured at ORNL, the existing limited material property database will be improved and is available to designers.

Currently both the WUFI-ORNL/IBP educational version is freely available to the North American from the ORNL web site and the WUFI-Pro (Professional version) from the Fraunhofer web site to Architectural and building envelope community.

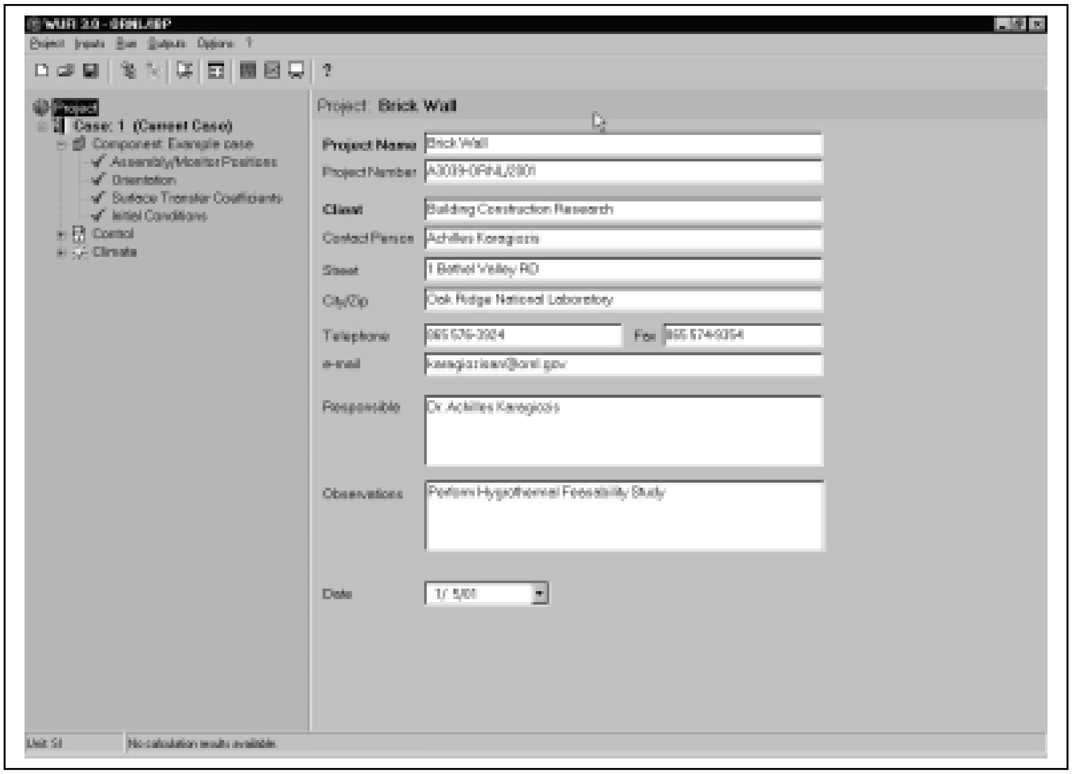

Fig. 4: Enter Project Account Details

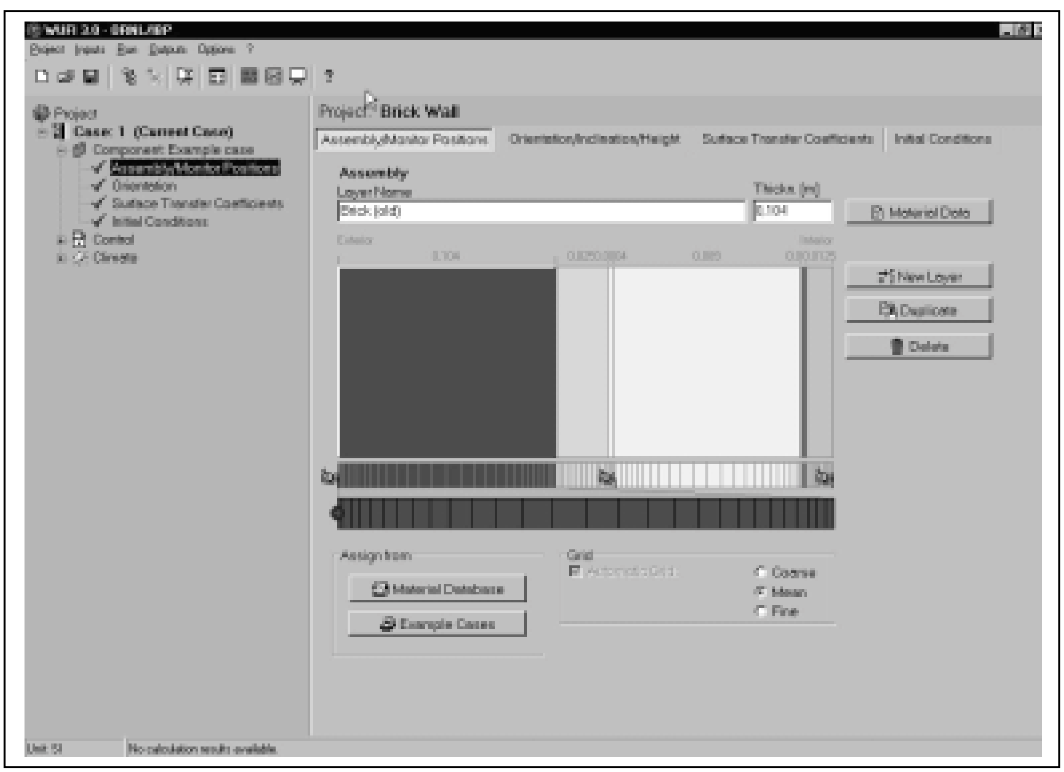

Fig. 5: Enter Envelope Detail (dimensions, layout and monitors)

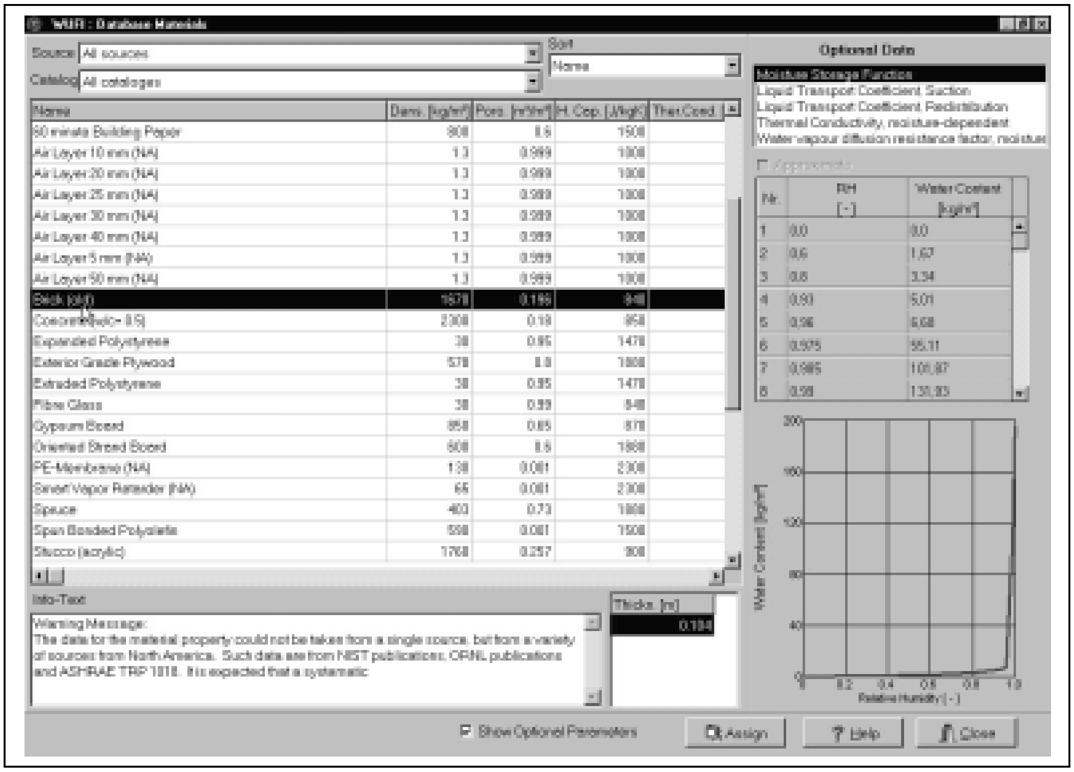

Fig. 6: Predefined Material Properties

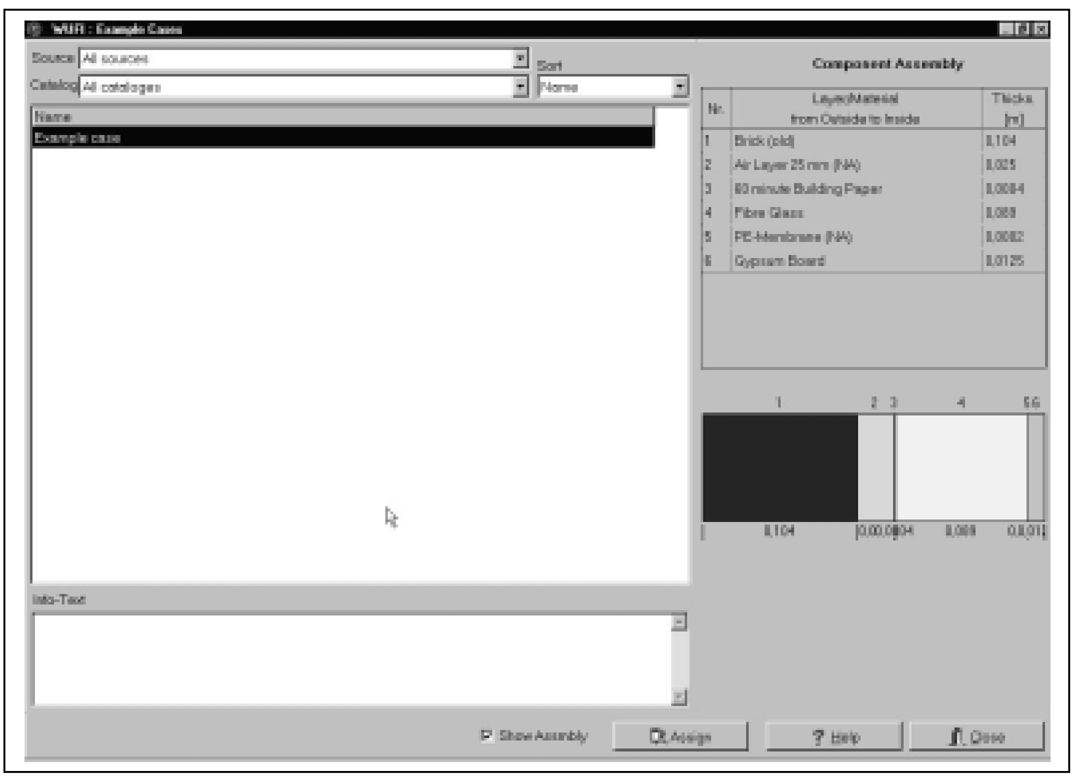

Fig. 7: Predefined Example Detail

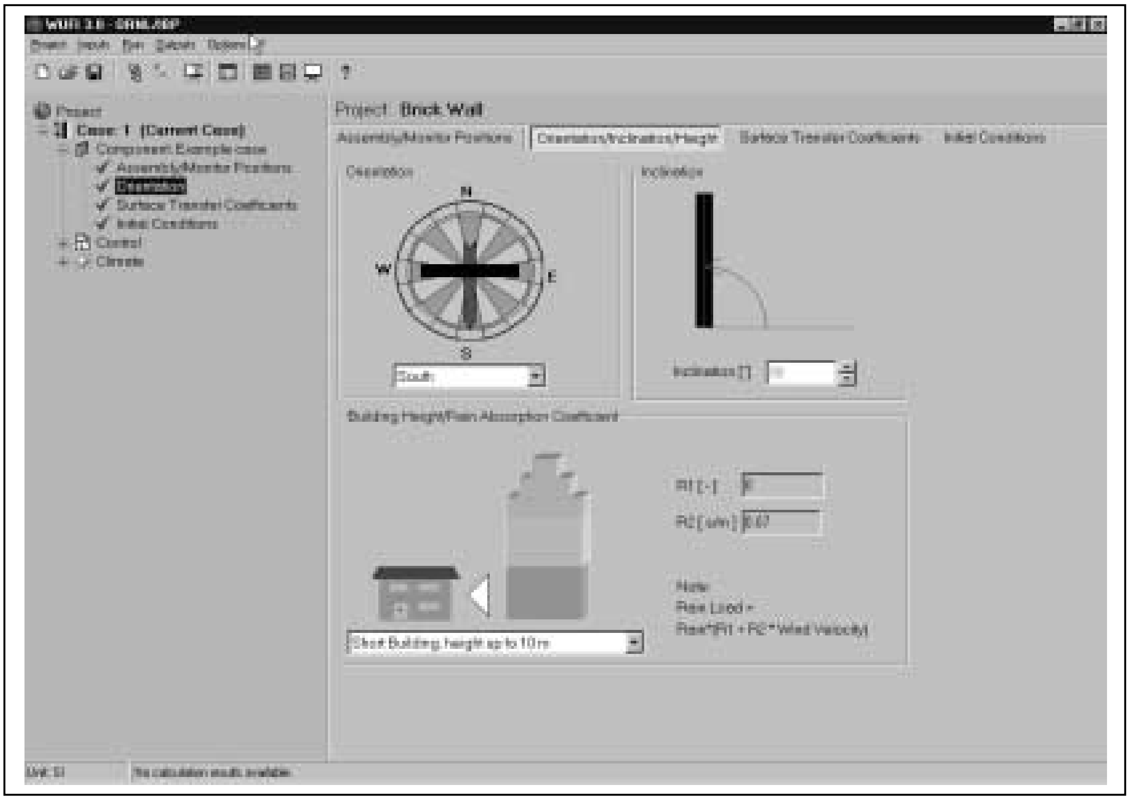

Fig. 8: Enter Orientation and Building Type Details

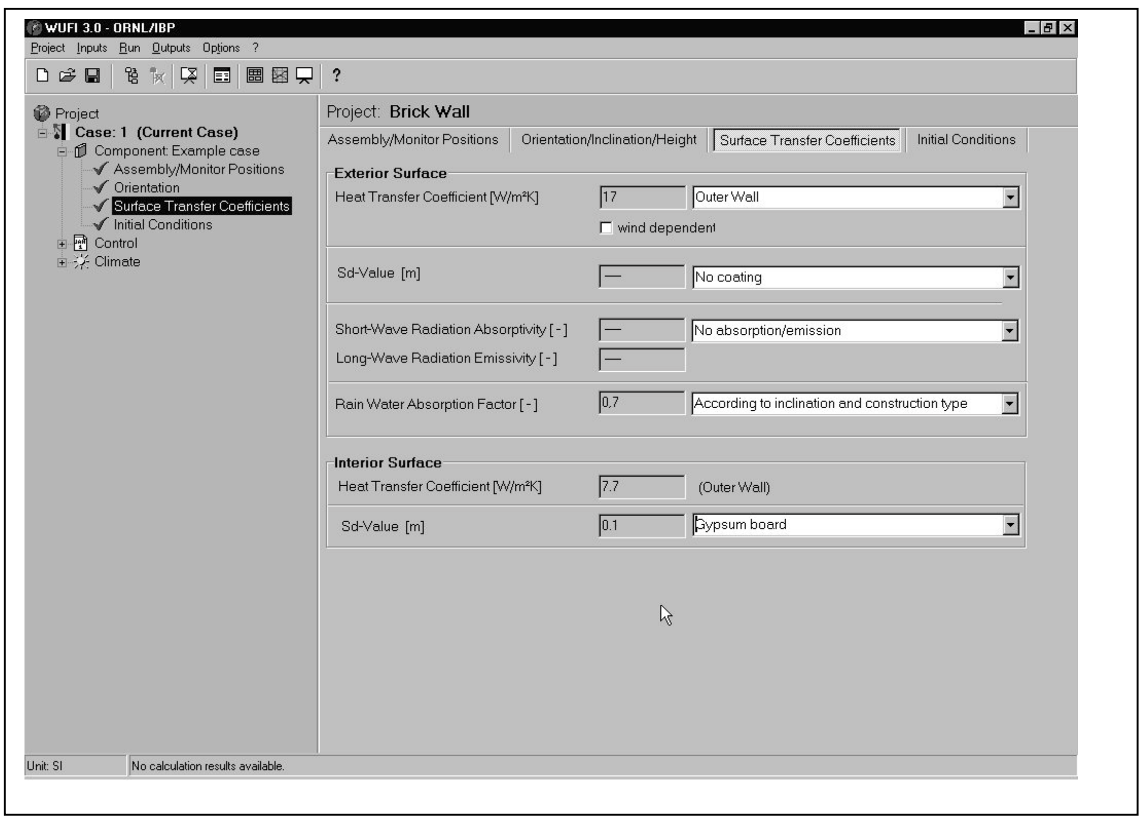

Fig. 9:

Surface Characteristic (thermal and moisture)

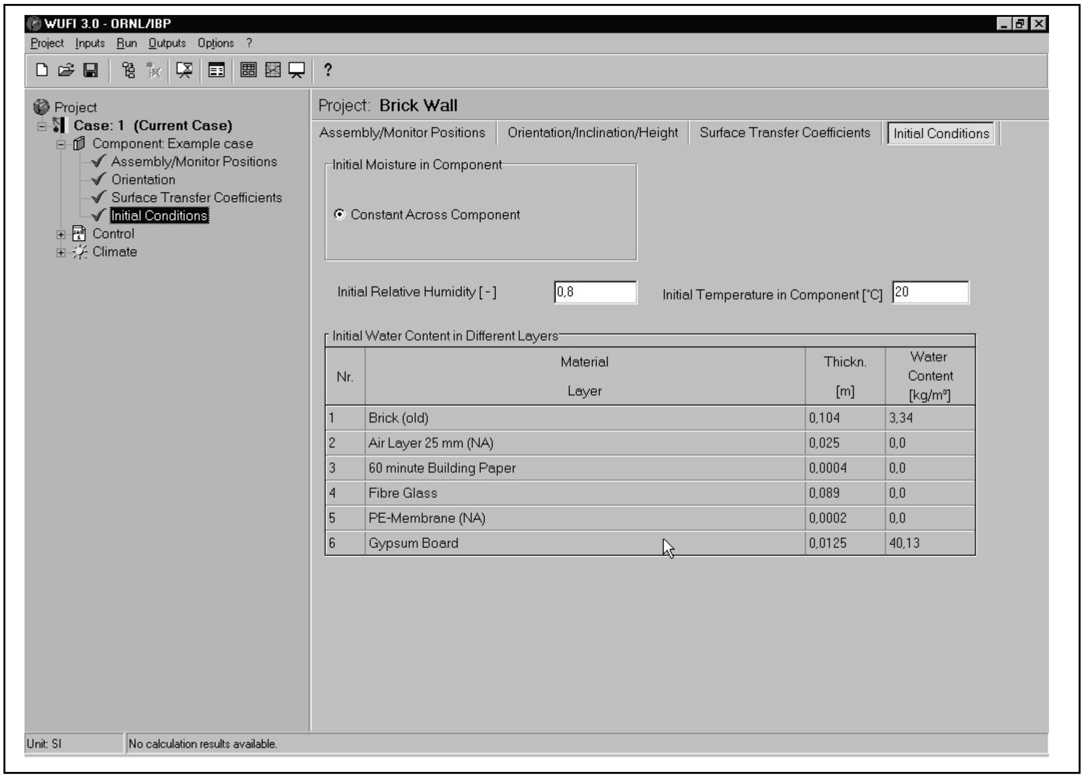

Fig. 10: Enter Initial Conditions

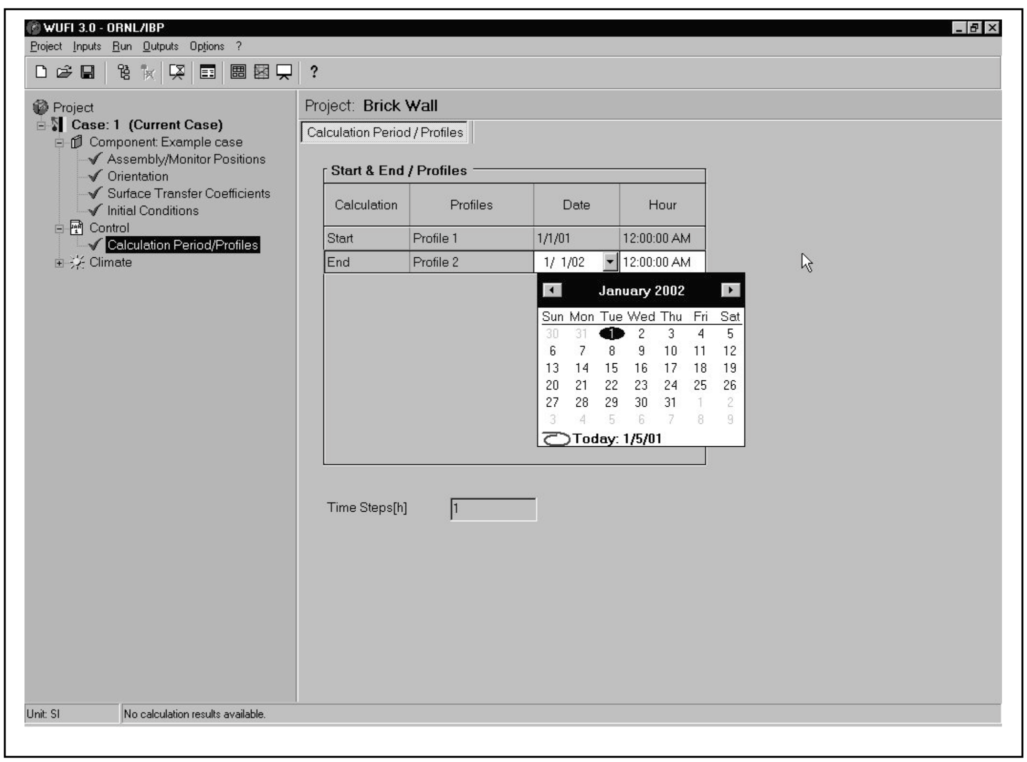

Fig. 11: Enter Simulation Time Period (Start-End)

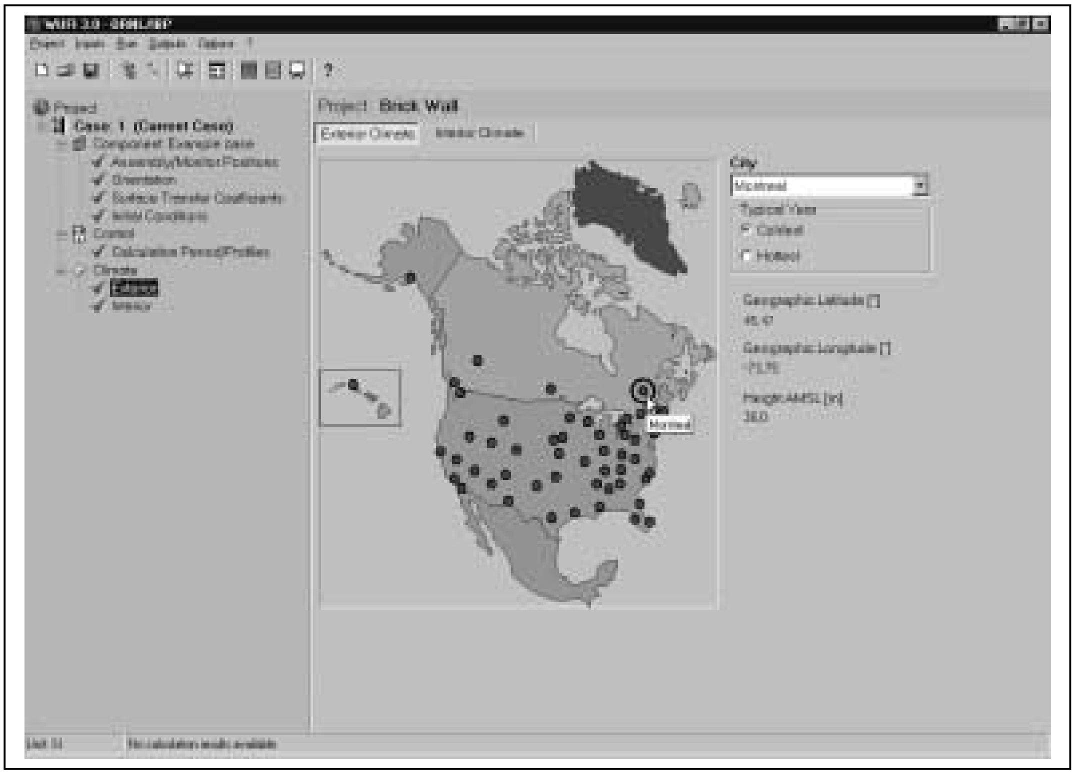

Fig. 12: Enter Exterior Climate Location (Hottest-Coldest)

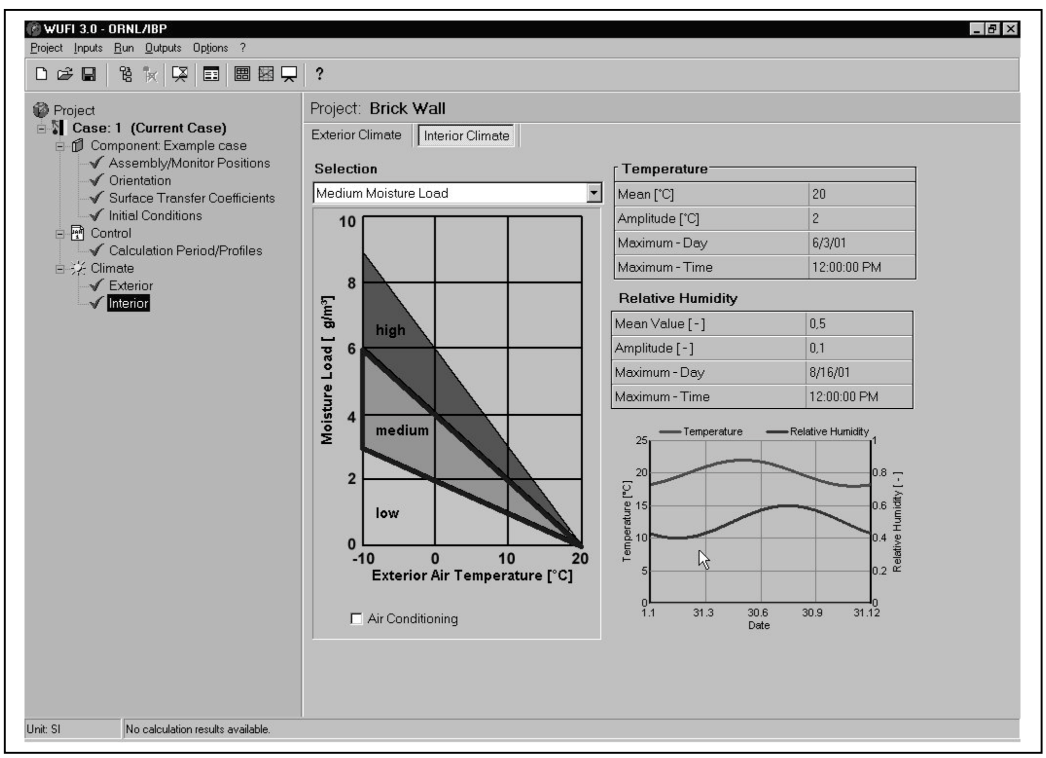

Fig. 13: Enter Interior Climate Type (Low-Medium-High Load, or Air Condition)

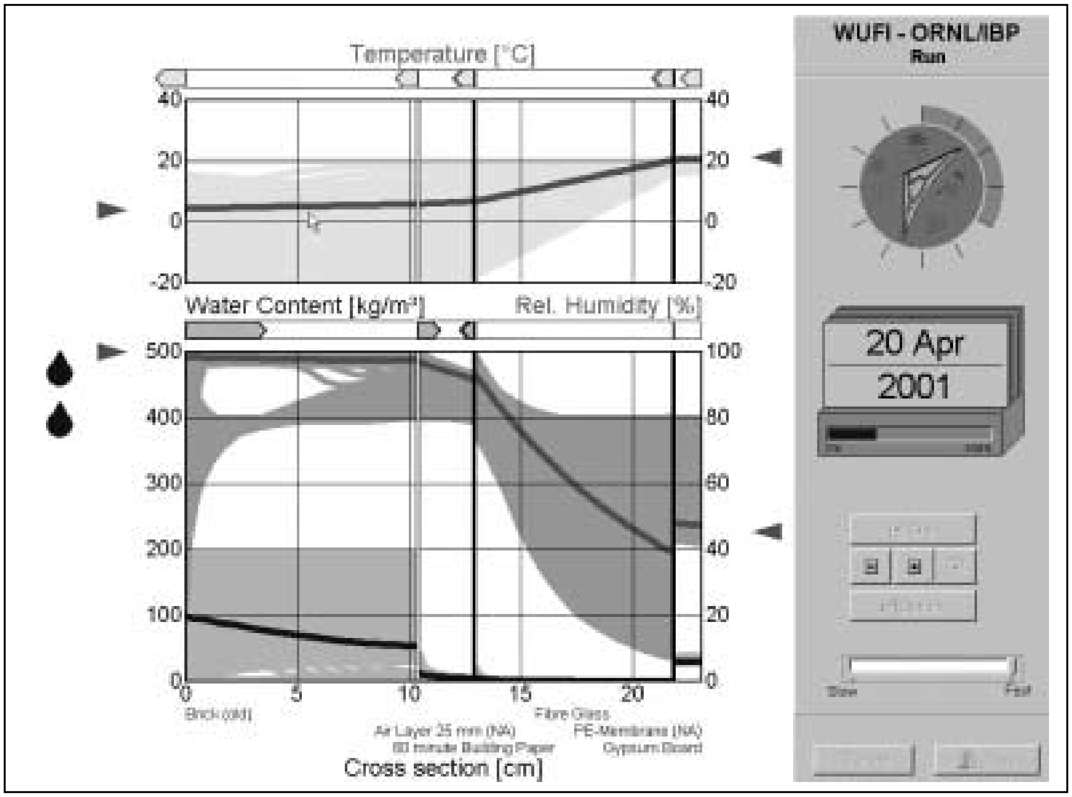

Fig. 14: Simulation Film Output (Graphical Simulation Results)

WUFI - ORNL/IBP

Material : Brick (old)

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	1670,0
Porosity	[m³/m³]	0,196
Specific Heat Capacity, Dry	[J/kg K]	840,0
Thermal Conductivity, Dry	[W/m K]	0,4
Water vapour diffusion resistance factor	[-]	16,0
Moisture-rel. Thermal Conductivity Supplement	[%/M.-%]	8,0

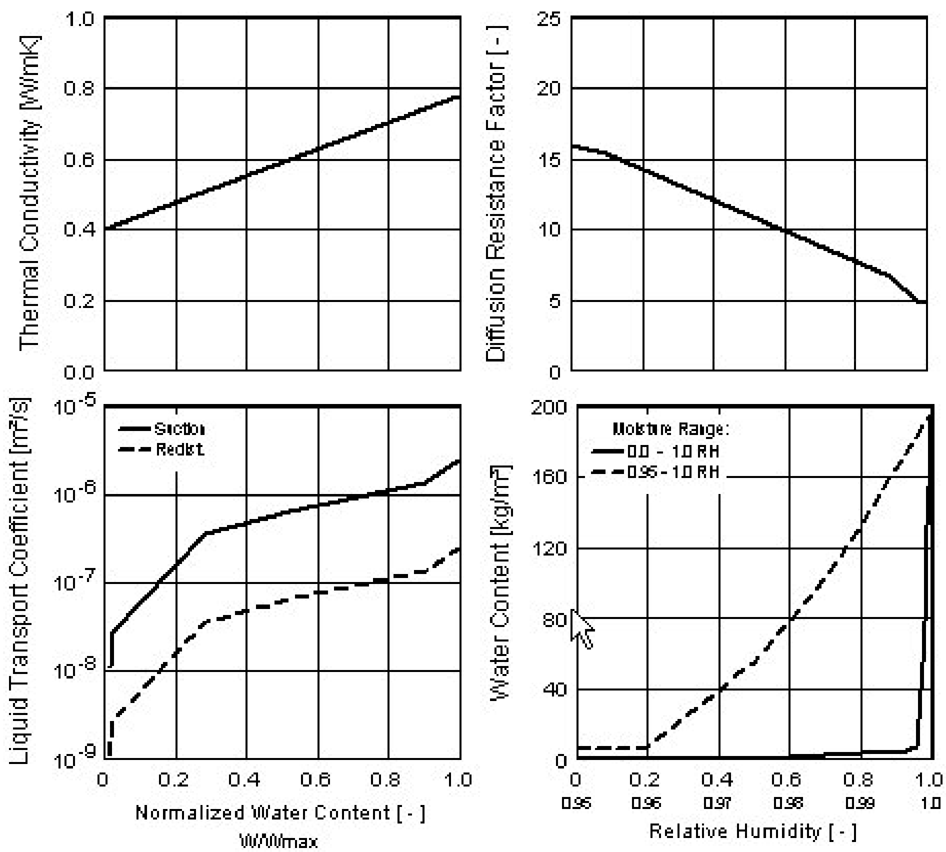

Fig. 15: Output of Complete Material, and Input Data Reference

WUFI - ORNL/IBP

Orientation

Orientation: South

Inclination: 90°

Surface Transfer Coefficients

Exterior

Name	Unit	Value	Description
Heat Transfer Coefficient	[W/m²K]	17	Outer Wall
Sd-Value	[m]	—	No coating
Short-Wave Radiation Absorptivity	[-]	—	No absorption/emission
Long-Wave Radiation Emissivity	[-]	—	No absorption/emission
Rain Water Absorption Factor	[-]	0,7	According to inclination and construction ty

Interior

Name	Unit	Value	Description
Heat Transfer Coefficient	[W/m²K]	7.7	Outer Wall
Sd-Value	[m]	0.1	Gypsum board

Fig. 16: Output of Complete Surface Characteristics Input

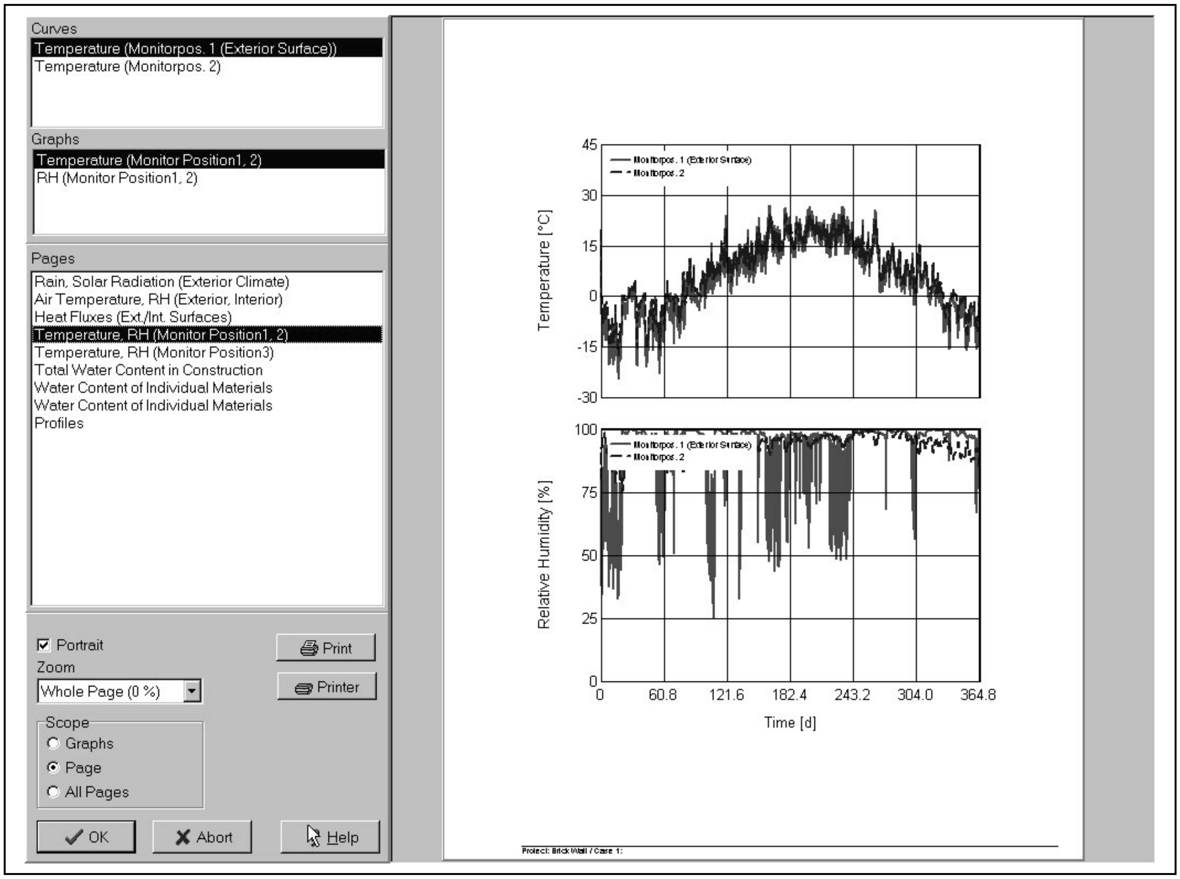

Fig. 17: Output for all T, RH , Moisture Content and Profile

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