WUFI-ORNL/IBP—A North American Hygrothermal Model

Achilles Karagiozis, Ph.D. **Hartwig Künzel** **Andreas Holm**

ABSTRACT

Building envelope designers and architects provide expert advice during the selection of building envelope systems. Until recently, a limited hygrothermal engineering analysis was performed to determine performance of a selected wall system other than review the details of wall systems and subsystems. Infrequently, a glaser or dew point method analysis may have also been performed, but this kind of analysis is only steady state in nature and ignores the hygroscopic effects, such as nonlinear dependencies of hygroscopic material properties, moisture storage, freeze-thawing mechanisms, liquid transport, latent heat, and transient nature of moisture loads at the boundaries. The main reason for not performing a thorough moisture engineering analysis was the lack of an easy-to-use hygrothermal model that integrated the physics and that was accompanied by a material property database and a set of realistic hygrothermal environmental loads for both the interior and exterior of the envelope.

Recently, the increasing demand for better performing calculation methods to assess the moisture behavior of building components prompted an international collaboration between the Oak Ridge National Laboratory (USA) and the Fraunhofer Institute in Bauphysics (Germany) to develop a hygrothermal design tool named WUFI-ORNL/IBP. This hygrothermal design model can assess the response of building envelope systems in terms of heat and moisture loads and can also provide a very useful and fair method for evaluating and optimizing building envelope designs. This state-of-the-art model is discussed in detail in this paper and is also available in North America free of charge at www.ornl.gov/btc/moisture.

INTRODUCTION

In civil and architectural engineering, there is an increasing demand for calculative methods to assess and predict the long-term heat, air, and moisture (hygrothermal) performance of building envelope systems. Assessing the particular performance of a complete envelope system or a subsystem is a critical task for an architect or building envelope designer. This need for better tools to assess the hygrothermal performance of designed systems has been necessitated by numerous catastrophic moisture-related failures, by codes, and by 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.

However, recent advancements by Künzel (1995), Salonvaara and Karagiozis (1998), Karagiozis (1997, 2000), and IEA Annex 24, reported in Hens (1996), in fundamental understanding of 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, *Moisture Analysis and Condensation Control in Building Envelopes* (Karagiozis 2001). At present, only a limited number of these models have been termed as "moisture engineering models."

Karagiozis Achilles is senior research engineer and hygrothermal project manager at Oak Ridge National Laboratory, Oak Ridge, Tenn. **Künzel Hartwig** is director of hygrothermics and **Holm Andreas** is senior researcher and hygrothermal modeling manager, Fraunhofer Institute of Building Physics, Holzkirchen, Germany.

Essentially, moisture engineering models deal with the characterization of the complex hygrothermal 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) manage 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, 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 retrofits to the building durability (hygrothermal performance) can be predicted. 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, rather, 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 40 years, moisture engineering heavily relied on experimental approaches to resolve moisture performances of building envelopes. Hundreds of research investigations employing laboratory and field monitoring have been performed in both North America and Europe on specific building envelope case studies (Hens 1996; Trechsel 1994). A disproportionate 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 invaluable results in some case, but more questions than answers in others. During the same period (1960 to 1990), moisture modeling of building envelope systems was not developed to the same level of expertise as that provided by experimental approaches.

A review of the state-of-the-art model by Karagiozis (1997) 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 objective 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.

In this paper, a brief description of that model is given.

BACKGROUND ON WUFI-ORNL/IBP

The WUFI-ORNL/IBP hygrothermal model is an operating-system-based personal computer program for the hygrothermal (heat and moisture) analysis of building envelope constructions. WUFI-ORNL/IBP is an advanced hygrothermal model that was specifically tailored to the needs of architects and building envelope designers. The 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 easy-to-use and intuitively accessible building moisture engineering software on the market. This model is also an 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 and Condensation Control in Building Envelopes*, MNL 40 (Trechsel 2001).

The model is a transient, one-dimensional heat and moisture transfer model that can be used to assess the hygrothermal behavior of a wide range of building material classes under 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 model can be used to estimate the drying times of masonry, solid concrete, 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 a 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 simulations led to the development of the smart vapor retarder (Künzel 1998), a successful application of a software tool to a practical moisture control problem.

Once the user supplies the model 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 distribution results that describe the temporal evolution of certain quantities taken at specified locations or as mean values over specified layers.

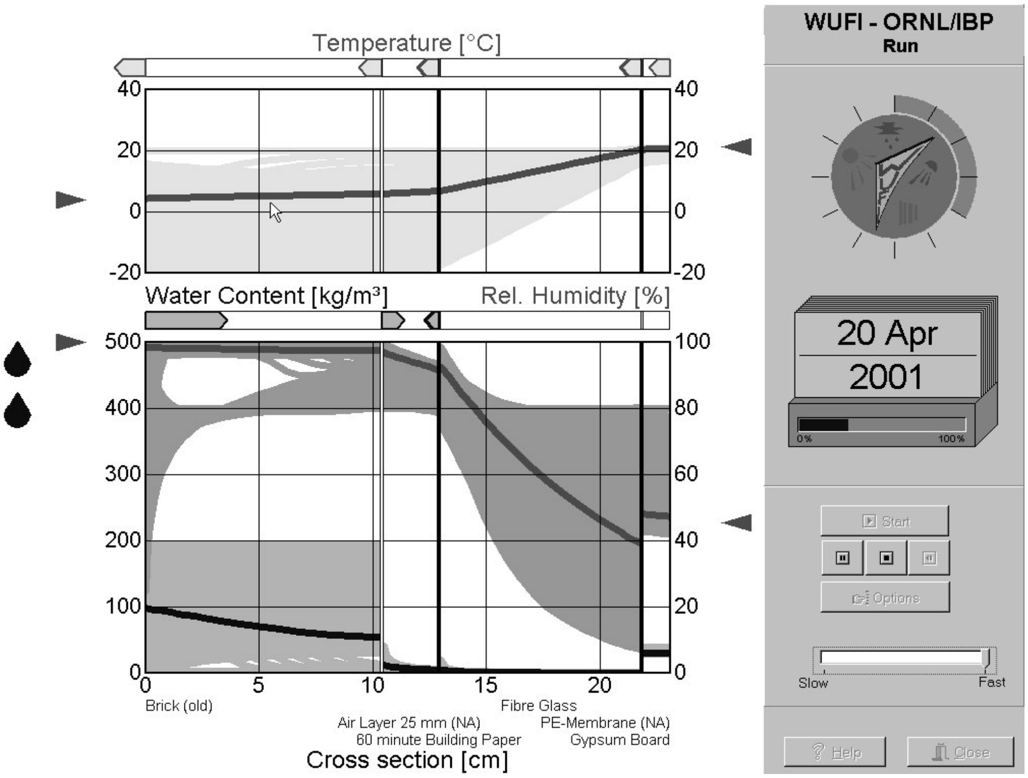


Figure 1 *Film display of the cross section distributions of temperature, relative humidity, and moisture content and heat and moisture fluxes.*

The following parameters are given as courses:

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

Additionally, the following 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, and
- the moisture content across the assembly.

A film file, which contains the transient profiles over all time steps, allows the display of the thermal and hygric processes in the building component as an animation. Figure 1 shows an example of a film file displayed as the model performs a simulation. A recently added feature is the way the moisture and thermal fluxes are displayed at the interface of each material interface.

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. The model 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 1995) 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 educational tool for understanding the basic principles and interactions present during moisture transport.

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 (1995) are discussed. For more details on the theory, consult the corresponding chapter 40 in the new ASTM manual, *Moisture Analysis and Condensation Control in Building Envelopes* (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% RH. For some materials, the equilibrium water content is not very sensitive to changes in temperature—these sorption curves are also called sorption isotherms. The capillary water range stretches from 95% RH up to capillary saturation at 100% RH. 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. Figure 2 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 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.

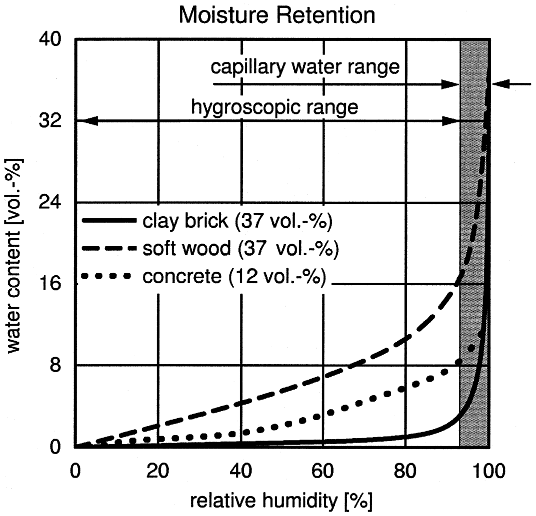


Figure 2 *Moisture retention curve for three typical building materials. Shaded area is the part the capillary water range determined with pressure plate apparatus.*

Moisture Transport

The moisture transport in porous materials is largely due to vapor diffusion, surface diffusion, and capillary conduction. The coincidence of these transport phenomena in practice will be explained by Figure 3. 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 outward 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 that is opposed to the vapor pressure gradient. By molecular motion in the surface, film moisture is thus transported inward. Vapor and surface diffusion can counterbalance each other to such an extent that the overall moisture transport and, therefore, the amount of condensation are

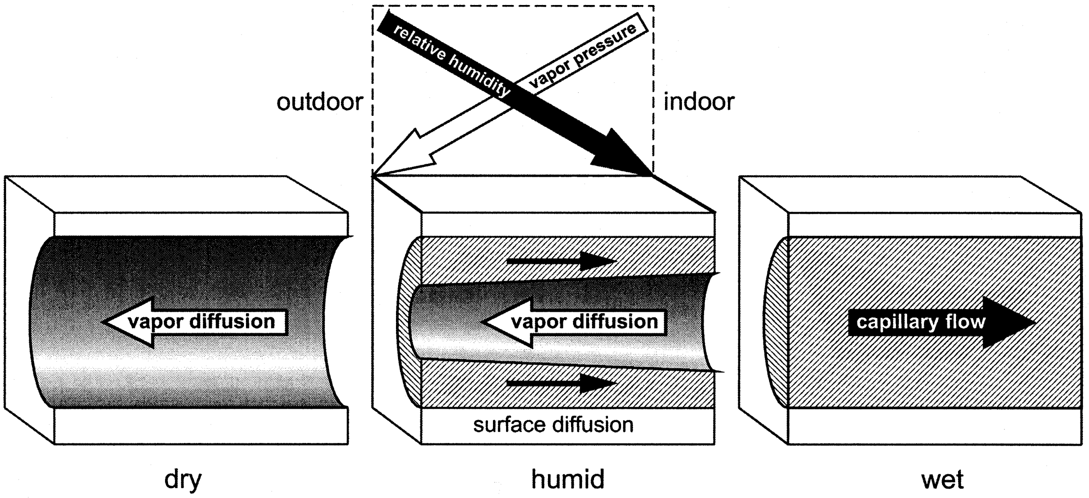


Figure 3 *Moisture transport mechanism.*

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 a driving force for capillary flow.

Governing Transport Equations

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

Moisture transfer

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

Energy transfer

$$\frac{\partial H}{\partial T} \cdot \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + h_v \nabla \cdot (\delta_p \nabla(\phi p_{sat}))$$

where

c = specific heat, J/kgK

D_{ϕ} = liquid conduction coefficient, kg/ms

H = total enthalpy, J/m³

h_v = latent heat of phase change, J/kg

k = thermal conductivity, W/(mK)

p_{sat} = saturation vapor pressure, Pa

t = time, s

T = temperature, K

w = moisture content, kg/m³

δ_p = vapor permeability, kg/(msPa)

ϕ = relative humidity

The storage terms are on the left-hand side of Equations 1 and 2. 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 D_{ϕ}. 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 nonlinearity 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 the program. The minimum parameters required for each material are specific heat capacity c, thermal conductivity λ, 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 Figure 2) 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 climatic 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 is included in the model. Bill Seaton from ASHRAE is gratefully acknowledged for his assistance.

Calculation Procedure

The transient calculation procedure of the model is outlined by the flow chart in Figure 4. 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 climatic conditions can be selected from the attached database. 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 and 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.

WUFI-ORNL/IBP HYGROTHERMAL MODEL FEATURES

The model is one of the most advanced hygrothermal models for building envelope analysis for architects, engineers, and consultants. It is based on a state-of-the-art understanding of building physics with regard to sorption and

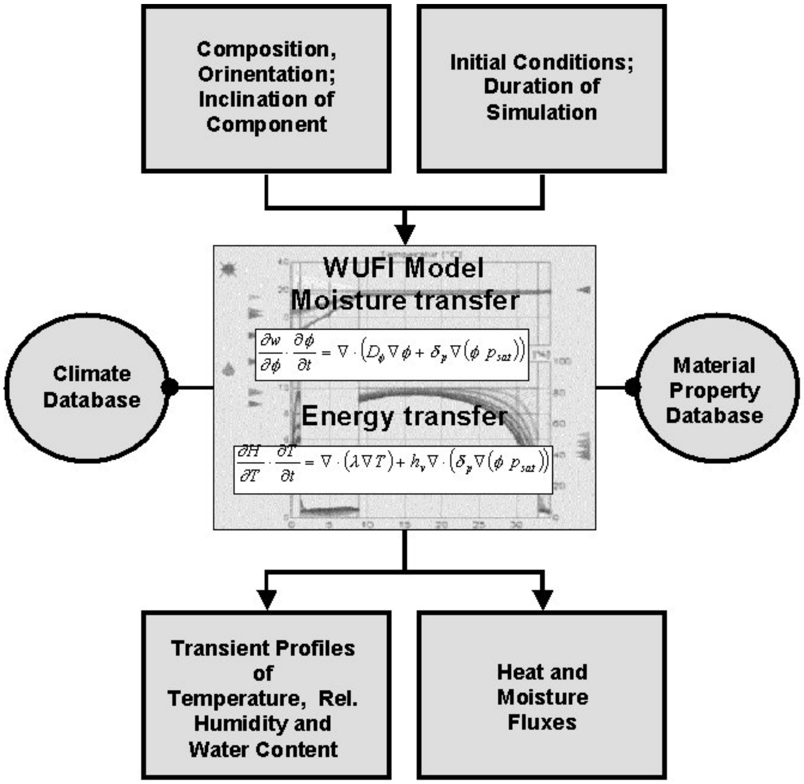


Figure 4 *Flow chart of WUFI-ORNL/IBP.*

suction isotherms, vapor diffusion, liquid transport, and phase changes. The model is also well documented and has been validated by many comparisons between calculated and field performance data (Künzel et al. 1995; Künzel and Keiβl 1996; Holm and Künzel 1999).

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 at Oak Ridge in the near future. This database will also be published on the Internet and registered users can download it for free. As material properties that pass the high-quality assurance required to be included in the database are not readily available, this is a limitation for all hygrothermal models.

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

- The model is an excellent 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 nonlinear material properties play in the transport of moisture.
- The model may be used to understand the transient heat and moisture diffusion and capillarity in any one-dimensional wall geometry.
- The 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 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 cit-

ies, one weather data set is included. The WYEC2 files are used for Canadian cities as full weather data, including rain, are not available to the public at present.) This new feature allows the user to compare the effect of climate on the performance of the structure.

- Interior conditions are set conditions and vary depending on time of year.

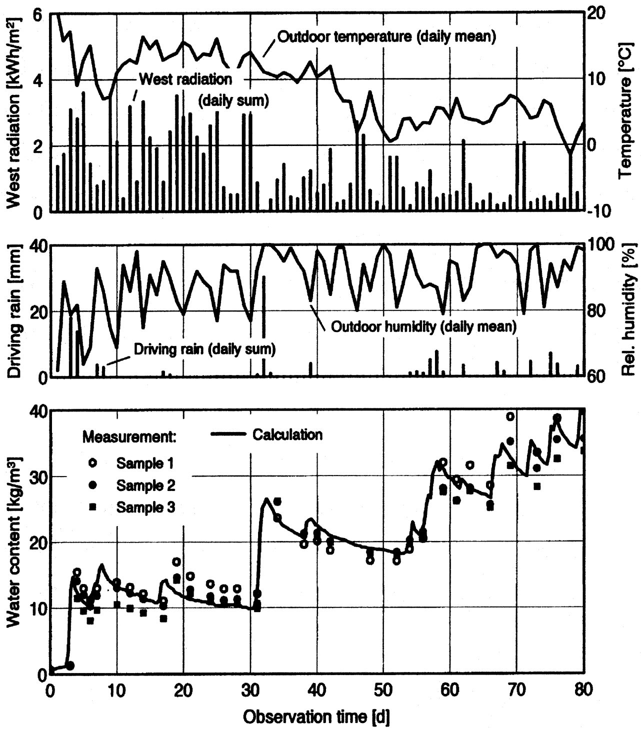


Figure 5 *Transient behavior of a stone facade. The output is the measured and calculated mean water content evolving with time. The actual weather input conditions are shown in the two figures above. The output is shown in the figures below (Künzel 1995).*

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

EXPERIMENTAL VALIDATION

The model is most likely the most validated and benchmarked model for hygrothermal applications. The validation of a numerical model requires reliable experimental investigations with well-documented initial and boundary conditions, as well as accurate material properties. The following three examples were chosen because they meet these criteria:

- *Moisture behavior of an exposed natural stone facade.* The degradation of natural stone facades is mainly due to moisture-induced weathering or damaging processes. Therefore, these facades are often treated with water repellent or reinforcing chemicals that may not always be beneficial. Such a treatment not only reduces the water absorption but also the drying rate. In order to investigate the hygrothermal behavior and the durability implications of natural stone facades, sandstone samples were thoroughly examined in the laboratory to obtain reliable material parameters for the simulations. Afterward, the samples were dried and exposed to the natural climate in a field test. During this test, the exact climatic conditions were recorded and the moisture behavior of the samples was determined by weighing and NMR-profile measurements. The material parameters and the recorded weather data (hourly values of indoor and outdoor temperature, relative humidity, driving rain, and solar radiation) served as input for the calculations. Figure 5 shows a comparison of the calculated and the recorded water content of the facade samples as well as the climatic conditions during the observation period.

This excellent agreement in total water content between experiment and calculation can be confirmed by examining the moisture profiles at certain time intervals in Figure 6.

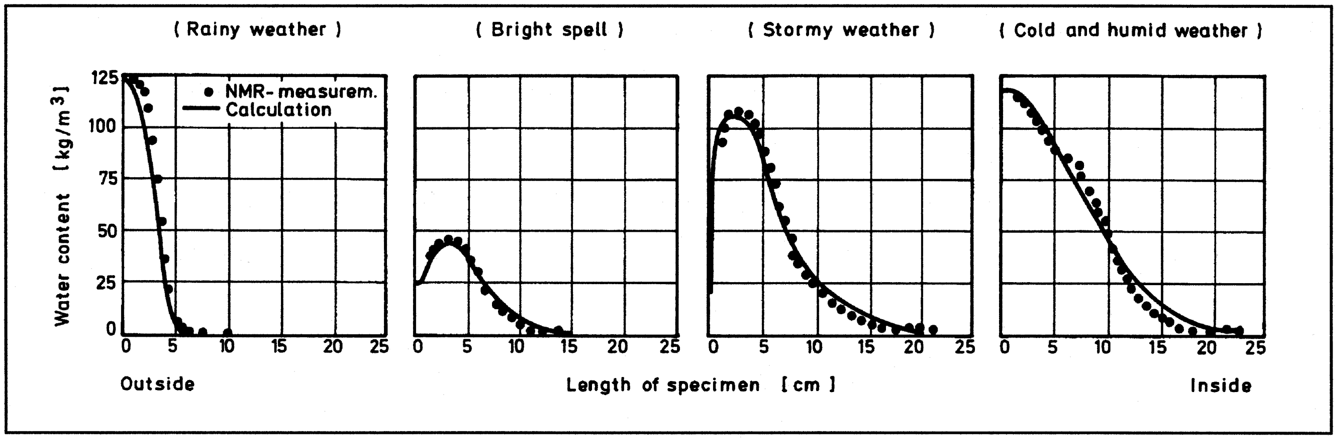


Figure 6 *Transient behavior of a stone facade. Measured and calculated moisture content profiles for four subsequent time periods (Künzel 1995).*

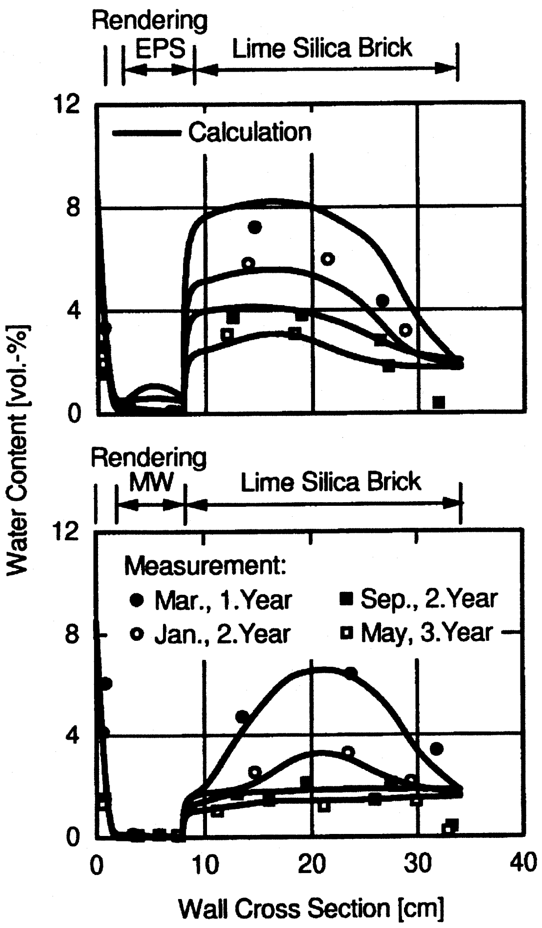


Figure 7 *Measured and calculated moisture content profiles at different time periods after finishing the construction for an EIFS with EPS insulation (top) and mineral wool (bottom) (Künzel 1995).*

- *Drying of masonry with exterior insulation.* Exterior insulation finish systems (EIFS) applied on masonry can prolong its dry-out time. In severe cases, the construction moisture in the masonry can severely damage the stucco of the EIFS if moisture is accumulating beneath it through vapor diffusion. Therefore, a test house was erected with calcium silica brick masonry and insulated with two types of EIFS. The insulation layers were 80 mm thick and consisted of expanded polystyrene slabs (EPS) or high-density mineral fiber. Mineral-fiber insulation is mainly used for fire protection or sound insulation purposes.

The drying process of the walls was monitored by drill probing the walls several times after completion of the house. Figure 7 depicts the measured and calculated moisture profiles over the cross section of the walls at subsequent time intervals. The results correspond well and they show a great influence of the insulation material on the drying behavior of the wall. Due to the rather low water vapor permeance of the EPS, the masonry in the top graph dries mainly to the interior of the building, which prolongs the drying-out process compared to the wall in the bottom graph. The high vapor permeability of the mineral-fiber insulation results in an effective dry-out to both sides. However, in this case, the stucco must also have high permeability in order to avoid excessive condensation beneath its surface, which can cause frost damage.

WUFI-ORNL/IBP MODEL INTERFACE/APPLICATION CASE

To demonstrate the user-friendly capabilities of the model, an example case was developed. A snapshot of the master screen for the WUFI-ORNL/IBP model is displayed in Figure 8. The user can return to this screen after inputting all needed parameters. The following simple steps are required to set up a wall system:

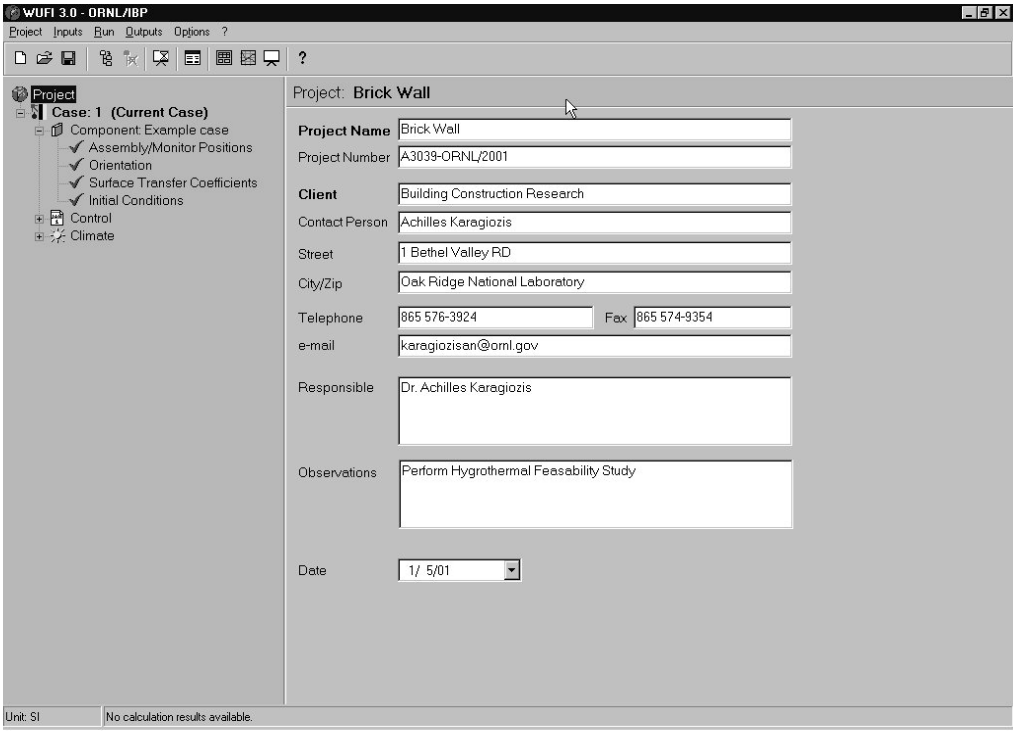
1. *The user develops a project.* Within each project, the user may introduce up to two separate sets of modeling cases. The interface functions for data input are organized in the following three groups:

- Component: The user specifies the modeling scenario and details of the envelope system of the modeling, such as geometrical makeup, the material parameters, orientation, rain parameters, surface characteristics, and initial conditions.
- Control: The user defines the time period for which the simulation is to be carried out as shown.
- Climate: The user defines the exterior and interior environmental exposure conditions of the construction.

2. *Run.* The user starts the simulation. During the calculation, WUFI-ORNL/IBP displays the computed thermal and hygric profiles as an animation.
3. *Output.* The user can display and print out the input data summary, check the status of the simulation, and view and print the results.
4. *Options.* The user can define the unit system (either IP or SI units), 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.

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 all the important quantities as a function of time while the simulation is being performed is of excellent educational value. One of the main objectives during the development of the WUFI-ORNL/IBP model was 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



Project: Brick Wall

Project Name Brick Wall
Project Number A3039-ORNL/2001

Client Building Construction Research
Contact Person Achilles Karagiozis
Street 1 Bethel Valley RD
City/Zip Oak Ridge National Laboratory
Telephone 865 576-3924 Fax 865 574-9354
e-mail karagiozisan@ornl.gov

Responsible Dr. Achilles Karagiozis

Observations Perform Hygrothermal Feasability Study

Date 1/ 5/01

Figure 8 *Enter project account details.*

menus where 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 model will aim at providing a greater selection of construction materials.

CONCLUSIONS

Major progress has been achieved in the last few years in the development of advanced hygrothermal models. An easy-to-use moisture engineering model is available to the 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. The additional degree of accountability also reduces the possibility of input errors.

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

Currently the WUFI-ORNL/IBP educational version is freely available to North America from the ORNL website, and the professional version from the Fraunhofer website, to the architectural and building envelope community.

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