Advanced Hygrothermal Models and Design Models

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ABSTRACT

Moisture engineering is becoming an important task in the overall design of building enclosures in North America. Assessing the hygrothermal behavior of building components is important to avoid short term and long-term moisture induced damages or additional heat losses. Since experimental investigations are rather expensive and of limited transferability there is a need of heat and moisture calculations tools that give realistic results but that are also easy to use.

Several methods may be used to design wall systems, and modeling is definitively the most flexible approach. Engineers and Architects are commonly asked to perform thermal and moisture analysis of building envelopes. This is increasing the demand for calculation methods to assess the moisture behavior of building components. Modeling analyses are becoming increasingly important to investigate the interrelationships between envelope systems and subsystems and environmental loads.

Recently, the Oak Ridge National Laboratory (Building Technology Center) and the Fraunhofer Institute for Building Physics in an international collaboration developed WUFI-ORNL/IBP, a moisture engineering assessment model that predicts the transient transport of heat and moisture. The WUFI-ORNL/IBP model is an design tool for users in SI and IP units customized for both the USA and Canada.

On the other side, more advanced models such as MOISTURE-EXPERT, developed by the author at ORNL give researchers the capability to predict the behavior of complex multi-dimensional building envelope systems and sub-systems with a higher level of confidence. This hygrothermal model has been used successfully to develop design guidelines for both energy efficient and durable building envelope systems by manufacturers and state regulatory bodies.

In this paper the author will provide an overview of how important both hygrothermal models (design and advanced hygrothermal) are to building science envelope assessment. The limits, assumptions and differences between hygrothermal design tools and advanced modeling is discussed. Several example cases are given to demonstrate the suitability of each model.

INTRODUCTION

Consumers are expecting today a higher level of performance in every purchase they make. They expect products to be engineered. If performance failures occur in the products and systems, it is not generally presumed a normal aspect of consumer goods. Consumers also expect upfront service life data and ratings. This educated form of consumerism is slowly but steadily being requested by today's homebuyers. Home buyers expect a high level of aesthetic and comfort quality in a home that also has superior performance in terms of low yearly maintenance costs, and a high thermal and durability performance. Indoor air quality concerns in buildings are also becoming more important to consumers of new or recently retrofitted buildings.

In countries with cold climates, hot and humid climates, or even mild and mixed climates moisture is one of the most important agents leading to premature building envelope deterioration. Upscale and savvy buildings systems or building components are being introduced in the market place at a much faster rate than ever before. For example, within 1 year of the scientific discovery of the "SMART RETARDER" a vapor retarder that selectively changes it's vapor permeance at higher relative humidities, developed by [Kuenzel, 1998] at the Fraunhofer Institute in Bauphysics, has been installed in building envelopes for more than 3 million square meters. However, at the same time a plethora of building failures have sprouted all across North America and Europe. In Finland, mold and moisture problems have been studied and reviewed by examining the existing building stock. The Finnish National Institute of Public Health, based on the results of an extensive field survey, noted that roughly 50% of all the Finnish detached houses suffered from mold and moisture problems of varying degrees [Salonvaara, 2001]. In Vancouver Canada, a leaky condo crisis exists where many buildings are being repaired for the third time, each time with a different design (Barret Commission, 2000). This problem/crisis is becoming an emotional and scientifically embarrassing issue for both local and national code/research and training/consulting entities in Canada.

On the positive side, consumer awareness and media attention on these issues is providing a useful educational forum for prospective homebuyers. The issue of moisture control and in particular how well a home manages moisture is inevitably raised more often now than ever before.

Moisture may be transported by diffusion, capillary and convection processes, as well as unintended water penetration. Moisture can be present in any wall system in three thermodynamic physical states, the solid state being ice, the liquid state, and the vapor state. Indeed, all three may be present concurrently in a wall system. This makes the fundamental transport interactions within a construction material complex. Understanding the overall performance of building envelope systems with respect to heat, air and moisture (HAM) excluding durability, is a formidable task. During the transport of moisture, some materials may store and accumulate water in the porous structure. Depending on the amount of water stored, environmental conditions, history and intrinsic material properties of a material, mechanical, biological and chemical damage may occur. In any envelope, some construction materials may be more prone to ageing and damage due to moisture transport than others. Understanding and predicting moisture movement within and through the envelope is therefore of fundamental importance to predicting and improving performance, particularly durability.

Recently several models have appeared that predict the hygrothermal performance of building systems. These models vary significantly and can be ranked according to a new ASTM Manual of Moisture Analysis in Chapter 6 [Karagiozis, 2001], in terms of both mathematical sophistication and inclusions of building system and sub-system performances. This classification approach allows models to differentiate in terms of simplified, design and research tools. In the past few years, simplified models are being used less, especially with the introduction of user friendly hygrothermal design tools, such as the recent one released in North America, the WUFI-ORNL/IBP hygrothermal model [Karagiozis et al, 2001]. However, more sophisticated research models such as WUFI-2D [Holm and Kuenzel, 1999], MOISTURE-EXPERT [Karagiozis, 2001], TRAMO2 [Salonvaara, 2001], TCCC2D [Ojanen, 2001] and LATENITE [Salonvaara and Karagiozis, 1994] can be used to develop design guidelines for the long-term performance of building systems.

In this paper the author will present results from two different hygrothermal models; the WUFI-ORNL/IBP [Karagiozis, et al, 2001] hygrothermal design model and the advanced hygrothermal model, MOISTURE-EXPERT [Karagiozis, 2001]. Results will be presented from both of these models with selective applications to determine the importance of the use of these models to hygrothermally evaluate and design building systems.

BACKGROUND: 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 Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee, USA, and the Fraunhofer Institute for Building Physics (IBP) in Holzkirchen, Germany, both internationally established in the area of building energy performance and durability assessments. The joint effort of these two laboratories has created an easy-to-use and intuitively accessible building moisture engineering software. 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 moisture transfer model that can be used to assess the hygrothermal behavior for 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 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.

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 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);
- 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 1995) and has since been widely used by building envelope designers, architects, building physicists, consulting specialists, and universities in Europe. The model has been validated by Künzel (1995) using several field test. The WUFI ORNL/IBP model is an 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. WUFI-pro V3.0 mainly addresses users with some previous experience in the fields of hygrothermal analysis and moisture transport simulations.

MOISTURE-EXPERT:

Advanced Hygrothermal Model

This model was developed at the Oak Ridge National Laboratory by Dr. Karagiozis to predict the complex heat, air and moisture transport in building envelope systems. This research model incorporates the latest understandings of the physics of hygrothermal processes and to allow extension of this model to durability predictions. Each transport processes has been developed in an object-like representation, where specific indexes store the linkages of the process to other actions or performances. The type of representation allows direct interaction of the magnitude/strength, occurrence, and frequency of various hygrothermal potentials to durability processes. In this regard, this model is unique.

The model is capable in predicting the 1-D and 2-D heat, air and moisture transport in building envelope geometries. The model treats vapor and liquid transport separately. The moisture transport potentials are vapor pressure and relative humidity, and temperature for energy transport. The model includes the capability of handling temperature dependent sorption isotherms, and liquid transport properties as a function of drying or wetting processes.

MOISTURE-EXPERT model includes porous airflow through insulation by solving a subset of the Navier Stokes equations; the Darcy's equations. MOISTURE-EXPERT model accounts for the coupling between heat and moisture transport via diffusion and natural and forced convective air transport. Phase change mechanisms due to evaporation/condensation, freezing/thawing are incorporated in the model. The model includes the capability of handling internal heat and moisture sources, gravity driven liquid moisture, and surface drainage capabilities. The model also captures experimentally determined system and sub-system performances and anomalies of the building envelope. One of the model's unique features is its capability to include temperature dependent sorption isotherms, and directional and process dependent liquid diffusivity. Currently the model incorporates sub-system drainage performance from a field drainage study performed by Straube et al [2000].

The moisture transfer equation including contributions from liquid, vapor air flow and gravity assisted transfer is:

$$\dot{m}_M = -D_\phi(u,T,x,y)\nabla\phi - \delta_p(u,T)\nabla P_v + v_a\rho_v + K(u)\rho_w\vec{g}$$

Where:

$\dot{m}$ = Mass flux, $kg/m^2\cdot s$
D_ϕ = liquid moisture transport coefficient, m^2/s
u = moisture content, kg_w/kg_d
T= temperature, ^oC
δ_p = vapor permeability, kg/s·m·Pa
P_v = vapor pressure, Pa
v_a= velocity of air, m/s
ρ_v= density of vapor in the air, kg/m^3
K= moisture permeability, s
ρ_w= density of liquid water, kg/m^3
g= acceleration due to gravity, m/s^2.

MOISTURE-EXPERT is a state-of-the-art moisture engineering building envelope model that integrates experimental material and system and sub-system analysis coupled with advanced mathematical modeling that allows more accurate prediction of the hygrothermal performance of complex building envelope systems. This important development enables building engineers to couple the hygrothermal performance of an envelope to some engineering assessment on how good or bad the building envelope performs relative to new innovative assemblies or existing ones. The model may be inputted with system information about the wall systems as constructed, the aging characteristics and details (how the thermal-hygric-mechanical-chemical properties of a weather resistive barrier change with exposure and time for example).

This advanced moisture engineering analysis capability integrates experimental and analytical approaches to develop performance indexes of a building envelope system and sub-systems for specific interior and exterior loads. This analysis is needed to establish the design life span and durability requirements of a particular building envelope component.

Understanding and predicting moisture movement within and through the envelope is therefore of fundamental importance to predicting and improving performance, particularly durability. Figure 1 shows the transport of vapor and liquid transport of moisture. Since driving rain deposition on walls and roofs is often quantitatively the largest single source of moisture, controlling rain penetration is essential to a successful moisture control strategy. In fact, failure to control rain is likely the oldest and most common serious building enclosure problem.

Differences between design tools and advanced hygrothermal models

The development of an advanced moisture engineering model requires particular attention to:

- Heat and mass transfer physics (these changes as a function of various loads and time)
- Definition of the environmental loads, (now inputs such as fog, water penetration, sky temperature, etc)
- Definition of the construction entity (workmanship, defects, aging-degradation). Design tools do not have the capability to include these types of effects.
- Hygrothermal (structural-biological-mechanical) material properties. The design tools are not equipped with these features.

So far, we have discussed the individual elements that are required for developing an advanced hygrothermal model. An advanced hygrothermal model must also incorporate some key features that will allow the models higher level of confidence in simulations. Depending on the construction type, certain elements may be more important than others. For example airflow through masonry walls is not as important as through light weight wood frame constructions. Understanding the application limits of each model is an important part of applying advanced models to develop design guidelines.

As these two models present the state of the art in both design and advanced research tools, the differences between them are primarily due to:

a) Transient heat, air, and moisture transport formulation (as a minimum)
b) 2-dimensional spatial formulation (as a minimum)
c) Variable material properties; e.g., as functions of moisture content and temperature
d) Incorporating physics of:

- vapor transport
- liquid transport
- air flow
- hydraulic transport
- moisture capacity of the materials
- condensation and evaporation processes
- freezing and thawing processes

e) Incorporating boundary conditions

- incident solar radiation and sky radiation
- wind-driven rain at exterior surfaces
- wind pressure
- interior and exterior temperature and relative humidity
- interior moisture sources

f) Incorporate Building Systems and sub-system effects

- water penetration rates through sub-systems (joints, cracks, etc)
- air leakage (cracks, joints e.g. around a window)
- additional sources of moisture
- drainage and gravity effects

Assumptions

Several assumptions are necessary for the development of moisture engineering models and these must be acknowledged as the limitations of existing advanced models:

1. The material is macroscopically homogeneous
2. The solid phase is a rigid matrix, and thermophysical properties are constants with space
3. Enthalpy of each phase is a function of temperature and moisture
4. Compressional work and viscous dissipation are negligible for each phase
5. Diffusional body force work and kinetic energy are small
6. The gas phase is a binary mixture of ideal gases
7. The three phase system is in local thermodynamic equilibrium (solid-vapor-liquid)
8. Gravity terms are important for the liquid phase mass transfer but not the gas phase mass transfer
9. Fluids are Newtonian and inertial effects are small
10. The transport processes are modeled in a phenomenological way

Example Simulations

In this example, the WUFI-ORNL/IBP hygrothermal design tool was used. The performance of a stucco clad building envelope wall system was investigated as a function of the selection of the weather resistive barrier design. This example illustrates the use of design tools to assist in defining the level of water vapor performance of the weather resistive barrier in a climate as found in Seattle, WA. Figure 2 displays the wall assembly.

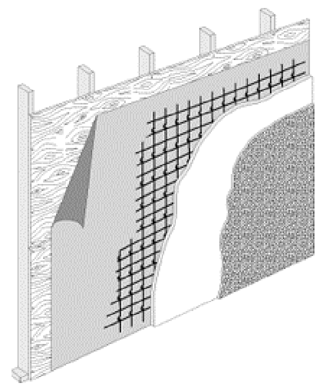

Figure 2: Conventional Stucco Wall

Simulations were performed using interior conditions that changed as a function of season. A three-year simulation with hourly environmental conditions was performed. The interior environmnetal values were obtained by measurements performed by Oak Ridge National Laboratory for the city of Seattle. The interior relative humidity fluctuated between 30 % to 60 % RH, and hourly values were used. For the exterior conditions hourly, exterior temperature, relative humidity, solar radiation, sky radiation, rain, cloud index, wind speed and orientation were used. Thirty years of data were analyzed to determine the 10 % cold year and 10 % hot year, respectively. These years were used in series.

In Figure 3, four simulations were performed for the stucco clad wall system, each characterizing the relative performance of the use of exterior weather resistive barriers. The four simulation cases were:

- No building paper
- 1 layer of Kraft paper
- 2 layers of Kraft paper
- 3 layers of Kraft paper

Wind-driven rain was also included in this analysis, and at present this is a unique feature of the WUFI-ORNL/IBP design model. The results show clearly the benefit of having at least two layers of building paper.

Use of additional layers did not improve the performance of the wall system. Currently design guidance on this issue is important in Vancouver, BC as up to three layers of building paper have been used to enhance the hygrothermal performance. This figure clearly shows the redundancy of using three building papers in a stucco wall system

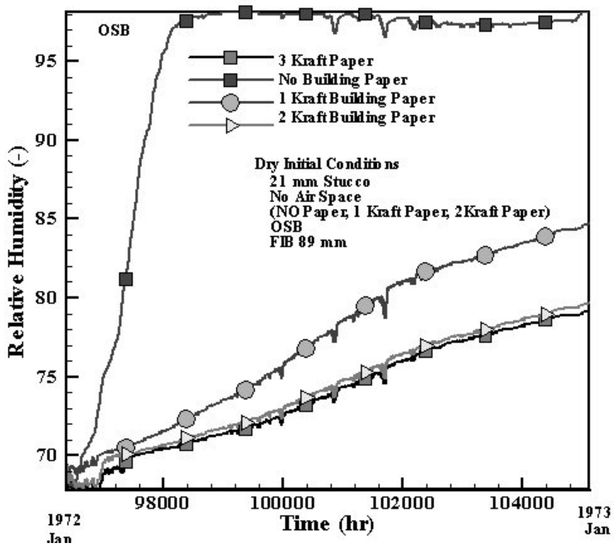

Figure 3: Effectiveness of Weather Resistive Membranes

In another example case, results in Figure 4 show the hygrothermal performance of a stucco clad wall as a function of foam insulation. A plywood sheathing board was used for this simulation. Here the hygrothermally positive influence of thermal insulation on the exterior side of the sheathing board is shown. The interior loads were increased to range between 50 and 70 % RH, and the design without the additional insulation failed. Here is clear the advantageous use of thermal insulation to enhance the durability performance of the wall.

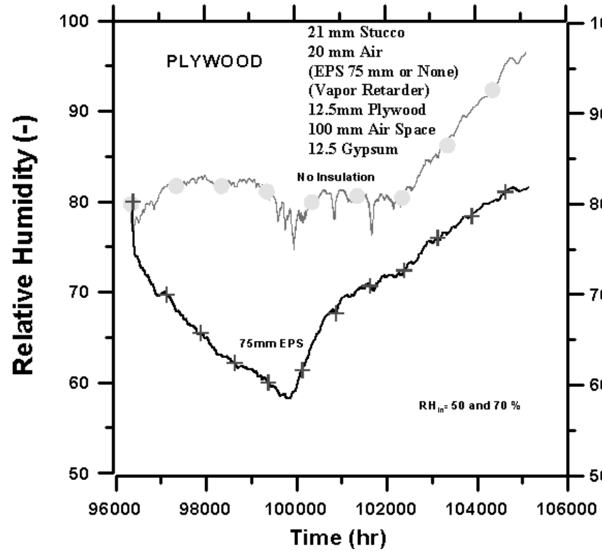

Figure 4:Effectivess of exterior insulation

EXAMPLE OF ADVANCED SIMULATION

A similar stucco clad wall system is investigated using the ORNL advanced hygrothermal MOISTURE-EXPERT. Figure 5 displays the wall assembly. The hygrothermal performance of the wall is investigated in terms of drainage and water management capability of the wall. In a recent publication by Straube, Lstiburek, Karagiozis and Shumacher [2001], the drainage of full wall systems were investigated experimentally for vinyl and stucco clad systems. These experiments allowed the development of sub-system performance data for the water penetration and drainage.

Figure 6 shows the hygrothermal performance of a leaky stucco clad wall system, and another wall positioned under a window. The total moisture content in the OSB sheathing board is shown as a function of time. Both walls were south facing and while the plain wall system did dry out, the one positioned underneath a window did not.

Figure 7 displays the spatial relative humidity distribution at one snap shot in time (Feb 1). The effect of air flow through the wall assembly is also depicted. Air flow can either increase or decrease the moisture accumulation potential in a wall system. From Figure 7 it is evident that moisture transport in building envelope systems is multidimensional for many cases.

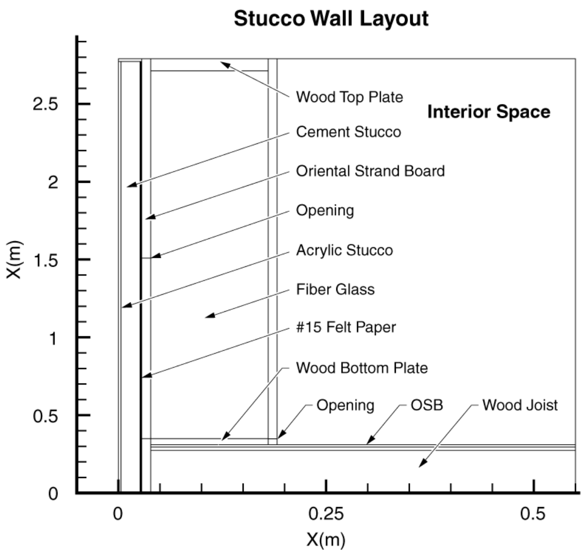

Figure 5: Stucco Clad Wall System

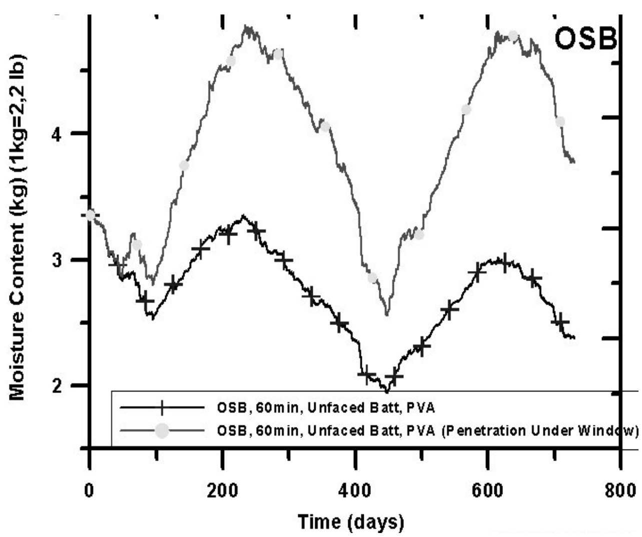

Figure 6: Effect of water penetration (Window/No Window)

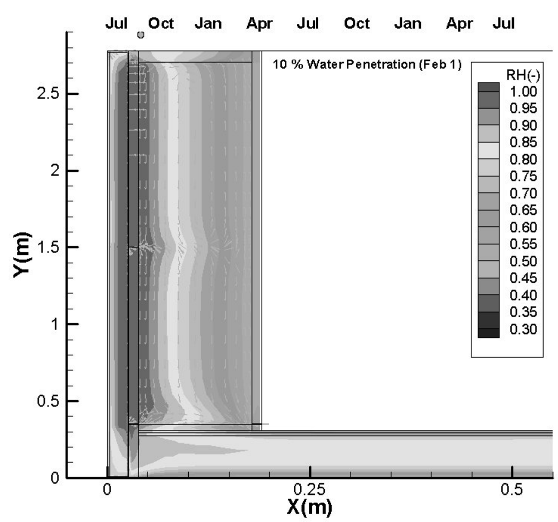

Figure 7: Relative Humidity Spatial Distribution

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different water penetration and drainage configurations. This example clearly shows the effect of proper drainage and design, as well as the sensitivity of this particular wall system to moisture penetration. This new approach to classifying the wall's sensitivity to moisture loads and drying potential can be used to develop design guidelines for building envelope practioners.

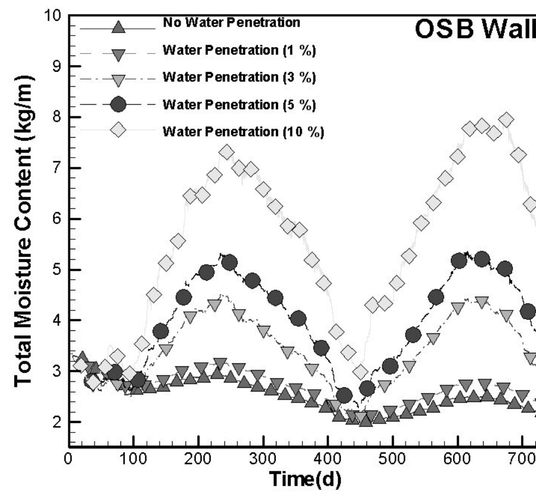

Figure 8: Moisture Acummulation as function of drainage and wetting potential

CONCLUSIONS

Two classes of hygrothermal models have been presented, one the moisture engineering design tools and the more advanced hygrothermal models.

Moisture design tools such as WUFI-ORNL/IBP can be used to evaluate in a comparative manner the hygrothermal performance of various design to a set of hygrothermal loads. Design models must provide the necessary inputs to the users, these being the interior amd exterior environmental conditions, and material properties and other loads. The model is easy to use and provides valuable information that assesses different design options.

The recently released public domain hygrothermal WUFI-ORNL/IBP model has become available to the building design community and can be downloaded at www.ornl.gov/btc/moisture. The WUFI-ORNL/IBP model can be used to assist building envelope designers to assess the relative performance of building systems to real environmental conditions.

Research tools such as MOISTURE-EXPERT not only can assist in evaluating the performance of various building envelope systems, but may optimize "real systems". In this model, building envelope systems may be optimized for better hygrothermal performance, and additional features such as water penetration, air flow and temperature dependent sorption may be included.

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