Development of Wall Assembly System Properties Used to Model Performance of Various Wall Claddings

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ABSTRACT

Different cladding systems have inherently different hygrothermal performance characteristics. This paper looks at comparative test evaluation methods and tools applicable for various claddings and climatic loads. The hygrothermal performance of an EIF system is evaluated to demonstrate the methodology for total hygrothermal performance characterization and subsystem performance, such as drainage and ventilation drying. A series of laboratory tests have been performed to develop system characteristic performance data by employing a moisture engineering framework. Results were developed to characterize the drainage of EIFS clad wall systems under realistic loading. The drying performance of these walls was then investigated as a function of exterior loading employing advanced hygrothermal modeling. Results of the tests also provided validation data to computer modeling. Hygrothermal modeling was employed to develop the criteria required for moisture design and to perform relative performance ranking of various wall claddings in a wall cladding selection program as a function of both interior and exterior environmental loading.

INTRODUCTION

The hygrothermal performance of wall systems depends on both the material level performance and the system level performance. Designing wall systems requires an understanding of the total and part hygrothermal responses of the wall to heat, air, and moisture excitations. The hygrothermal response of a wall also depends on the interior and exterior loads. These loads are usually termed as environmental loads and can vary substantially from one location to another. Indeed, sometimes the environmental loads are geographically describable using a two-dimensional map and in some instances are not. For example, wind exposure is not only geographically distributed but is also dependent on the immediate topography, such as the location of the structure—whether it is on a hillside, plain, or valley. In a similar manner, if the structure is located on top of a mountain or on the seaside, the changes in wind pressures, saturation vapor pressure, and temperature must be properly accounted for.

Exterior cladding systems, defined in this paper as the element outboard of the structural sheathing, many times dictate the hygrothermal performance of the wall system. Essentially there are three general moisture classes of exterior claddings, the absorptive cladding system, the semi-absorptive system, and the non-absorptive system. Figure 1 shows an example of each. The absorptive cladding system stores a large quantity of moisture deposited by either by vapor diffusion or by wind-driven rain. For example, a brick veneer system is one such system where water can easily accumulate in the porous structure of the wall system, especially in the presence of high exterior vapor and liquid loads.

A stucco cladding system employing a continuous coating of exterior grade acrylic paint can be classified as a semi-absorptive or semi-reservoir cladding system. Some of the cementitious board systems also belong to this class, and, indeed, this class accommodates the majority of the systems. Finally, a non-absorptive exterior cladding is one that does not have the ability to store significant amounts of water in the

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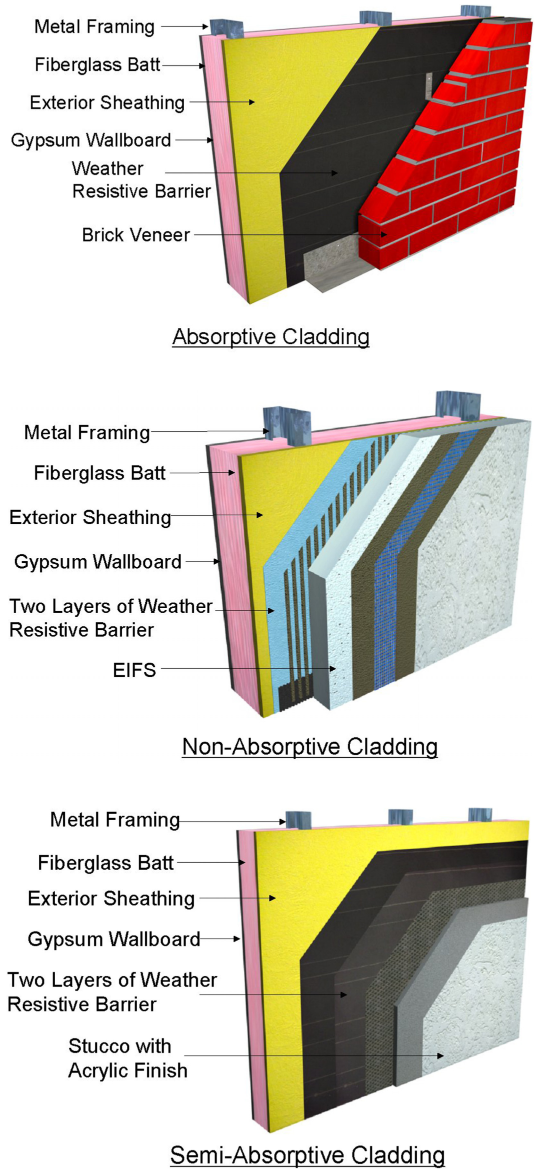

Figure 1 *Three types of exterior cladding systems (brick, stucco, EIFS).*

porous structure. Exterior insulation and Finish systems belong to this class of exterior claddings. Another such system is insulated metal panels used in high-end commercial buildings.

For each of these systems, there are many pros and cons with respect to water management. The difficulties usually arise by not specifically designing these systems for their respective hygrothermal loads. Every wall system must include certain moisture management capabilities. These moisture management capabilities should not compromise the thermal and air leakage counterparts but complement their optimum performance. Moisture management should be employed using moisture engineering principles. For example, for every specific wall system, one must explore the consequences of air barriers, vapor retarders, drainage planes, sheathing types, and framing appropriate for the exposure loads (interior and exterior hygrothermal loads). This type of moisture engineering is seldom performed, which is evident as moisture-induced failures are present in every climate type in the USA. Until recently, the tools to reasonably perform these analyses did not exist. With the advancement and development of better computer models, as noted below, and material property characterizations, a proper analysis can now be performed.

Recently major progress has been made in the advancement of hygrothermal analysis capability using computer modeling. Some of the most pioneering models have been authored by Künzel (WUFI, 1995), Künzel and Holm (WUFI-Plus, 2003), Salonvaara and Karagiozis (LATENITE, 1998), Salonvaara (TRATMO2, 1992), Grunewald (DIM, 1998) and Karagiozis (MOISTURE-EXPERT, 2001a). This new class of advanced hygrothermal models allows full-fledged moisture engineering analysis. Moisture engineering is performed by integrating field and real life performances with controlled, laboratory material level, system and subsystem performances, complemented with advanced modeling. Advanced hygrothermal modeling becomes a critical component in better understanding and interpreting the results from the material level response and system and subsystem performance with the ultimate objective of predicting real field performance. As with all field investigations, the number of sensors is limited and the placement of a sensor only millimeters away can substantially influence the conclusions generated by the study (Derome 1998). Modeling allows a much more refined spatial resolution that can be analyzed in terms of heat and mass fluxes and permits the characterization of the drying performance of the walls or envelope components examined.

Better understanding can be generated using these moisture engineering competencies, and this is currently being included in upcoming and current state-of-the-art moisture design tools, such as *ASTM MNL 40, Moisture Control and Condensation Analysis* (ASTM 2001). Design tools that exist today demand that the user be competent in the fundamental transport phenomena, and this level of competency is not that widely available. Having a tool available that could perform all the required analyses and present the data in a generic but useful decision-making tree structure is a much needed tool for engineers and architects alike. This new type of expert system software is needed and has been described in another paper by the authors (Karagiozis et al. 2004) that takes the inputs from advanced hygrothermal models such as WUFI-Plus and MOISTURE-EXPERT and allows designers to make decisions based on a wider range of parameters that includes economics, risk for potential durability problems, thermal performance, and moisture performance to list a few.

This paper will demonstrate the methodology employed for generating the technical and scientific inputs needed in the next generation of decision-making software tools. The authors provide an example of the methodology performed to characterize a wall system clad with EIFS. The approach followed allowed the full characterization of the hygrothermal performance of the EIFS wall system. Essentially a complete moisture analysis was performed, which allowed the engineering of all critical elements of the wall, optimizing their hygrothermal performance. The results that came about from this moisture engineering provided the scientific basis for the development of the WALL WIZARD™. This paper will present the engineering elements required for the hygrothermal performance characterization of any wall system.

MOISTURE ENGINEERING APPROACH

Moisture engineering analysis requires the integration of material performance, envelope-specific characteristics that include knowledge on how the wall is built, laws of physics, and the environmental loads. Walls will respond differently depending on the hygric loads, workmanship, material elements selected, and sequence of applications, environmental aging, and imbedded safety factors. This integrated approach is displayed in Figure 2 and is achievable when modeling is used as the vehicle for integration (laws of physics).

There are essentially two levels of laboratory tests performed during moisture engineering analysis, one at the material level and the other at the system level. Both require extensive testing and are time consuming; however, they are required if new innovations are introduced in wall system. Until now, the subsystem testing at the material level was performed in the field, and only after major failures appeared were measures taken. This time-tested approach is one of the least economical approaches.

MATERIAL LEVEL ANALYSIS

At the material level, several tests were performed to determine the hygrothermal performance of the various materials employed in the EIFS analysis. Material property tests were performed on several identified materials. Laboratory tests were performed and analyzed by Wilkes (2002), a researcher at ORNL, for all properties except the water uptake measurements. These tests were conducted at the Advanced Hygrothermal Property Laboratory within the Oak Ridge National Laboratory of the U.S. Department of Energy. The list of hygrothermal material properties is given below:

1. Density
2. Porosity
3. Water vapor permeance as a function of relative humidity
4. Sorption isotherm as a function of relative humidity and temperature
5. Suction isotherm as a function of capillary pressure

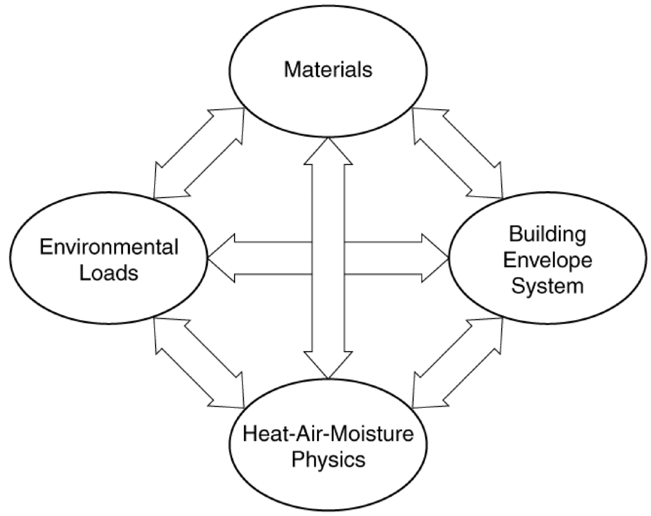

Figure 2 *Interactions that must be accounted for in advanced hygrothermal models.*

6. Thermal conductivity as a function of temperature and moisture content

For example, for the exterior coating Infinitex Quarzputz®, some of the measured hygrothermal material properties are given in Figure 3.

SUBSYSTEM LEVEL ANALYSIS

Laboratory Inputs

This part of moisture engineering analysis is the least understood part of moisture performance characterization. This activity is possibly the most difficult to perform and it can only provide useful data once it is integrated and critically analyzed with an advanced hygrothermal model (providing increased confidence in simulated results). In these tests, loading conditions are imposed based on field test scaling and are performed on "real" full-size geometric wall systems. One of the requirements of these tests is that they be conducted in laboratory controlled conditions providing prescribed boundary conditions. In these tests the system and subsystem responses are developed in a parametric manner to develop performance characteristic for elements of the wall that modeling cannot resolve—for example, the effects of mortar blocking can be examined for various levels of workmanship—or evaluating actual construction details, such as the presence of glue lines between the weather-resistive barrier and foam insulation, creating a cavity of perhaps only a few millimeters in size. These inputs provide invaluable data on how the specific wall assembly deals with water ingress, water drainage out of the wall system, air flow passage and resistance, vapor and liquid transport reduction due to the presence of glue attachments, and so on. Comprehensive data on the

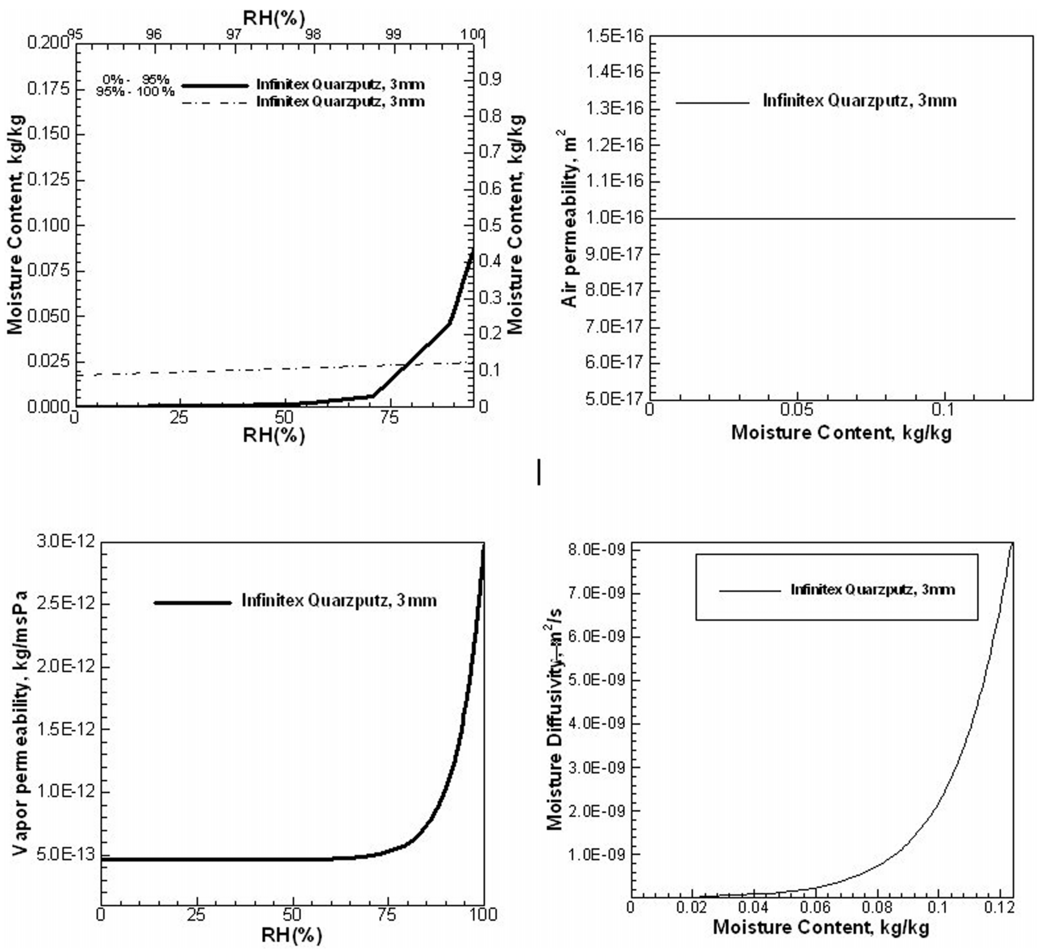

Figure 3 *Material properties (example case exterior finish: quarzputz).*

performance characteristics for any of these systems or subsystems are many times more critical than the inputs used by many designer hygrothermal tools.

For this particular EIFS example case, a series of tests were performed to develop the specific system and subsystem characterizations for inputs to the hygrothermal model. The following laboratory tests were conducted by Straube (2004) for this project:

a. Airflow resistance (see Figure 4, where the air cavity resistance is plotted out, as air flow versus pressure difference)
b. Drainage flow characterization of the EIFS cladding using a liquid applied weather resistive barrier (see Figure 5)
c. Drainage repeatability for the same weather resistive barrier (see Figure 4)
d. Quantity of water present on the drainage plane after a known quantity of water ingress
e. Natural drying of the drainage cavity under the influence of wind and stack effect conditions
f. The drying performance of the wall system from ingress of water in the insulation (stud) cavity (see Figure 6)

Tests (f) were performed only to calibrate and benchmark the advanced hygrothermal model under the most complex and difficult conditions. Currently, with the exception of this work, limited characterization exists on quantifying these subsystem performances in any wall system. Indeed, in many instances, any of the (a) to (e) characterizations may be more critical than diffusion drying, which is used exclusively today. ASHRAE's Standard Project Committee 160P has started working on developing consensus on design criteria inputs for some of the items listed above. ASTM has begun reworking and developing standards for the measurement and characterization of the critical subsystem performances.

ADVANCED HYGROTHERMAL MODELING

The hygrothermal model used in this paper is the MOISTURE-EXPERT model developed by Karagiozis (2001a). The model was initially developed to predict the one-dimensional and two-dimensional heat, air, and moisture transport in

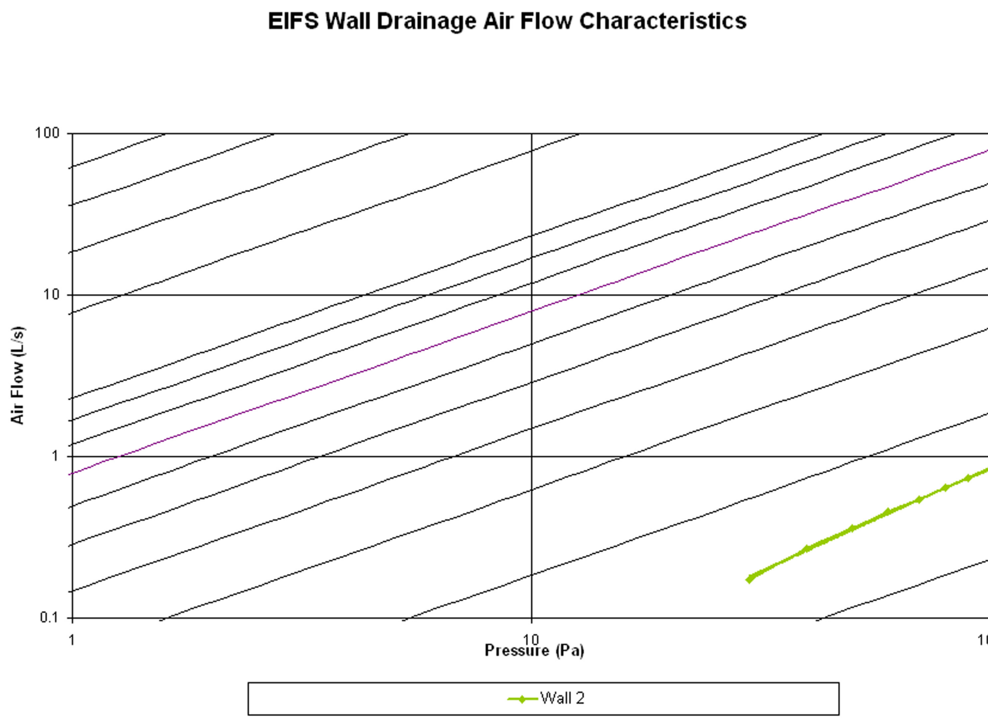

Figure 4 *Air cavity resistance measurements.*

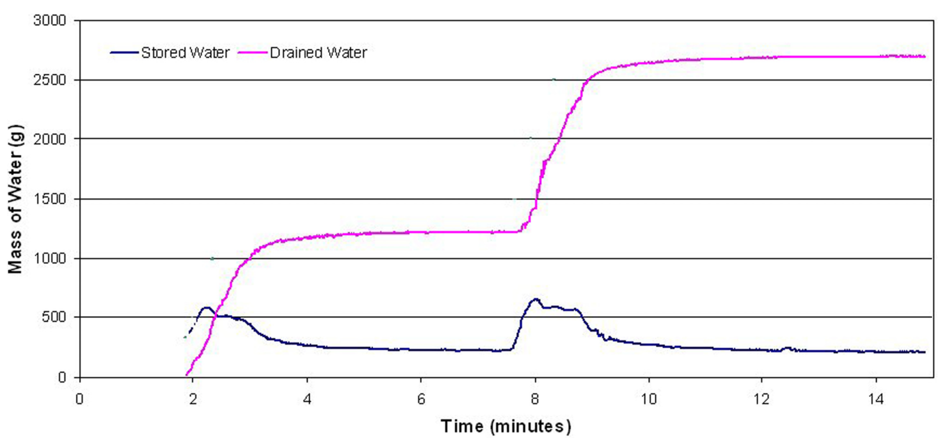

Figure 5 *Cumulative mass of water as a function of time for vertical drainage test of wall system.*

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. This model has been validated extensively against other models such as WUFI (Künzel 2001a) and laboratory data (Burnett et al. 2004) and field data (Straube 2004). MOISTURE-EXPERT includes the capability of handling temperature-dependent sorption isotherms and liquid transport properties as a function of drying or wetting processes and has been classified as robust in *ASTM Handbook 41, Moisture Control and Condensation Analysis in Buildings* (ASTM 2001).

The MOISTURE-EXPERT model includes the effects of porous air flow through the insulation and cracks by solving a subset of the Navier Stokes equations, Darcy's equations. Full treatment of the convection terms is also possible but dramat-

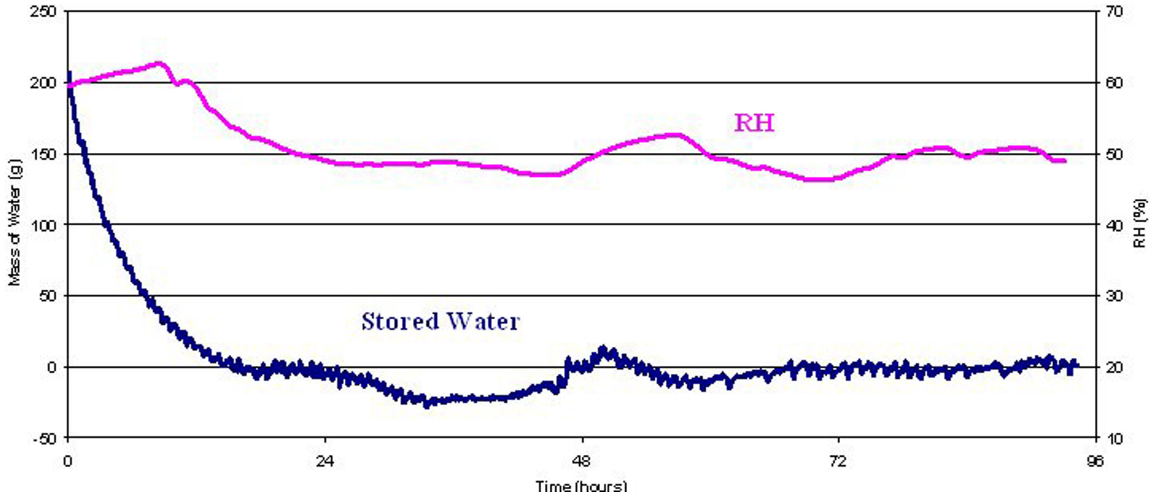

Figure 6 *Total wall system and subsystem wall drying and corresponding interior relative humidity (mass below zero indicates the initial conditions were higher than the final conditions).*

ically increases the computation time. The MOISTURE-EXPERT model accounts for the coupling between heat and moisture transport via diffusion, as well as natural and forced convective air transport. Phase-change mechanisms due to evaporation/condensation and freezing/thawing are also 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 subsystem performances and anomalies of the building envelope. One of the model's unique features is its capability to handle temperature-dependent sorption isotherms and directional and process-dependent liquid diffusivity.

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·s,
ρ_0	=	dry density of porous material, kg/m^3 ,
D_ϕ	=	liquid moisture transport coefficient, m^2/s,
u	=	moisture content, kg$_w$/kg$_d$,
T	=	temperature, °C,
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, and
g	=	acceleration due to gravity, m/s^2.

HYGROTHERMAL MODEL BENCHMARKING

One of the most critical elements for using advanced hygrothermal modeling is to validate the model with real exposure conditions, this being the ultimate test of any model. This element was identified as one of the most critical during this research project, as the MOISTURE-EXPERT model becomes the tool for developing the data in the WALL WIZARD™. MOISTURE-EXPERT has been extensively validated with IEA Annex 24 common exercises 2002, ORNL field data, and additional tests performed by Burnett et al. (2004). A series of field tests by Straube et al. (2004) has been employed to confirm the ability of the model to predict not only controlled laboratory tests but also uncontrollable field test with high accuracy. These series of tests were funded by ASHRAE Research Project TRP 1091, as presented in Burnett et al. (2004).

Three different wall wetting and drying experiments were performed at Penn State University and used in this model test exercise. Model results and experimental data showed remarkable agreement, capturing all critical hygrothermal phenomena. All the hygrothermal trends in the three benchmarks were correctly predicted by the MOISTURE-EXPERT model. The criticality of using measured material properties rather than generic data was also demonstrated. The model has been validated for the benchmark wall cases, as the weight loss due to ventilation drying was accurately predicted in all three cases.

The MOISTURE-EXPERT model clearly demonstrated its robustness by capturing all critical elements of the benchmark test. These were (a) the moisture storage present during the test because of the water injection (and associated time history effects), (b) the redistribution of water in the Homasote, (c) the moisture transport (vapor and liquid), and (d) the convective drying as a function of airflow.

Results from this benchmark test demonstrated the capability of the ORNL model to capture these phenomena, providing the TRP-1091 research team with a high level of confidence. We believe that the benchmark results presented in this report clearly show that we have met the objectives to permit the model to be incorporated in the WALL WIZARD™.

SYNTHESIS OF MOISTURE-ENGINEERING-MODELING COMPONENT

Analysis Inputs

There are four types of inputs required for the analysis of the hygrothermal performance of building envelope systems:

a. Exterior environmental loads (solar radiation, air water content, temperature, sky conditions, wind speed and orientation, and quantity of rain).
b. Interior environmental loads (inhabitant thermal and moisture production behavior and air pressures conditions).
c. Hygrothermal material properties that describe the transport coefficients of heat and moisture through each of the materials. These are transport coefficients that provide information on the thermal, vapor, and liquid transport and sorption/suction characteristics of construction materials.
d. Construction specific wall and wall subsystem performances. These inputs provide invaluable data on how the specific wall assembly deals with water ingress, water drainage of the wall system, air flow passage and resistance, vapor and liquid transport reduction due to the presence of glue attachments, and so on. Comprehensive data on the performance characteristics for any of these systems or subsystem is many times more critical than the inputs used by many designer hygrothermal tools.

Today, none of the above four types of inputs are standardized in a manner similar to other engineering applications. Currently, ASHRAE's Standard Project Committee 160P is working on developing consensus on design criteria inputs for (a) to (d) items listed above. ASTM has begun reworking and developing standards for the measurement of some of the activities for items in (c), while item (d) has only recently been developed in a qualitative manner (SPC 160P and ASTM) and only through the work reported by Karagiozis and Serino (2004), a more quantitative manner for these sub-system characteristics has been developed.

Hygrothermal Performance Results

An energy-efficient EIFS wall was simulated for a period of one year using the moisture engineering concepts outlined in this paper. All system and subsystem performances were embedded in the simulated wall system. The effects of the presence of a drainage layer, cladding attachment method, and overall assembly performance were obtained by an intensive experimental investigation. Figure 7 shows the temperature distribution in the wall system. Light gauge steel stud framing was employed in the model. The two-dimensional spatial snapshot for the 15th of January at 1:30 p.m. is shown. The influence of the thermal bridging is evident in Figure 7, where it is seen in both insulations (exterior foam and interior fiberglass insulation) as depression in temperatures. The velocity vectors are also plotted out in both insulation and drainage cavities. The influence of natural convection due to the presence of density gradients is shown. In Figure 8, the complex moisture transport is depicted in terms of the relative humidity

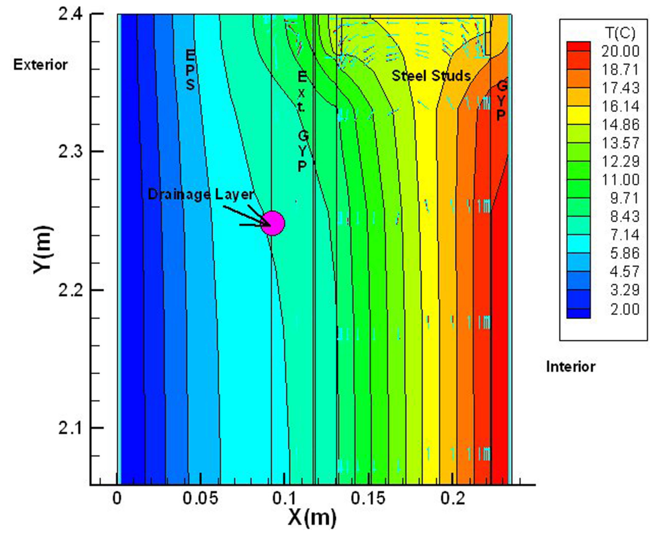

Figure 7 *EIFS wall system temperature distribution on January 15 in Charlotte.*

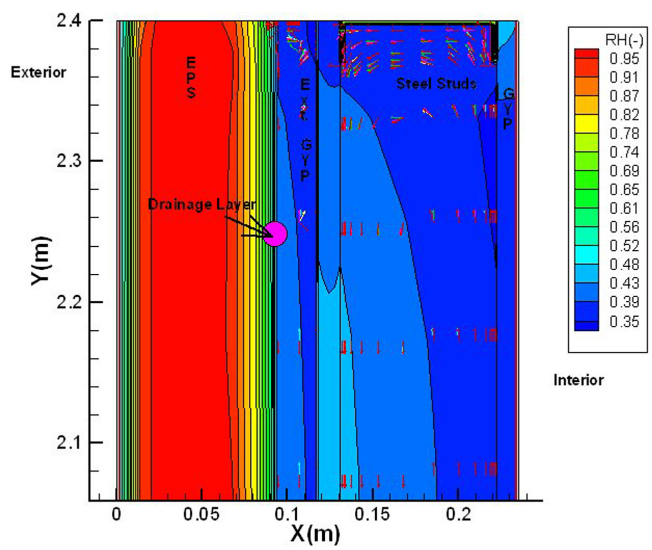

Figure 8 *EIFS wall system RH distribution on January 15 in Charlotte.*

distribution at the same time snapshot (15th of January). The influence of drainage is also shown, as water is drained from the higher elevations to lower ones. In this particular analysis, the wall system is successfully managing moisture transport, indicating good water management in the assembly.

As described in this paper, the same approach was followed for other wall systems, including stucco and brick veneer systems. These results will be reported in a future publication.

SUMMARY AND DISCUSSION

In this paper the authors have presented a methodology that employed moisture engineering principles to characterize the hygrothermal performance of a building envelope wall system. An example case of an EIFS wall system was employed to demonstrate the application of this methodology.

As highlighted in this paper, many of the system and subsystem performance characterizations presented do not exist at the present as standard tests. With the exception of this work on EIFS wall systems, data do not exist that can provide vital information that characterizes the "real" performance of other wall systems currently being used. Without data on the system characterization, any analysis performed is simply a parametric investigation for an ideal system. Ideal systems never fail or deteriorate with time. If they do fail, the wall has inherent design problems that violate the concepts of proper moisture design or when workmanship was not adequate. The concepts and procedures detailed in this paper provide an essential approach for characterizing and ranking a set of wall performances. Adopting such an approach allows the user to scientifically compare alternative designs, assessing and also quantifying how much better are particular design solutions. This level of assessment is quite unique and, as demonstrated in this paper, can be adopted for all systems.

Modeling, employing system and subsystems characterizations, can then be incorporated in the decision-making process. With the information provided by this integrated approach, a new class of building envelope design tools can be developed as semi-expert systems.

Representative replicas of the simulated walls were built, and a series of benchmark data was obtained. Measurements of the hygrothermal material properties were performed and included the simulation analysis. Subsystem testing on the ventilation flow, drainage flow, water storage, drainage layer drying, and wall cavity drying provided excellent correlation of the wall simulated and benchmarked. The results were then used in the subsequent hygrothermal simulation analysis for 20 locations in the USA. The results were processed to showcase various performance indexes, to allow the designer to evaluate the most appropriate wall for the location and constraints of the construction project in an easy-to-use application.

Architects and engineers are increasingly asked to design buildings that are both high-performance and cost-effective. They are also subject to increased liability when systems fail and have to provide documentation of due diligence to support their decisions. This approach will provide state-of-the-art analytical techniques incorporating site-specific environmental and building data to support and justify their cladding decisions.

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