Application of Advanced Tools to Develop Energy Efficient Building Envelopes that are Durable

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ABSTRACT

In the recent past, building envelope designers and architects relied heavily on tradition to define and prescribe exterior envelope components of a building. Workmanship and understanding of the local materials were key to the success of the building project. Today, designers and architect frequently are asked to design buildings that are highly energy efficient. Sometimes this results in unexpected problems, as almost all current design guidelines do not specifically address moisture control. Established approaches exist to reduce thermal bridges in building envelopes; however, few guidelines exist to reduce moisture bridges. Major changes in the thermal, and moisture performance properties of key material components are being introduced into the building market. Designers are therefore required to analyze the heat and moisture transport of the envelope systems for the implemented climate.

Recently several advanced hygrothermal models have been developed and are widely available to the general public to assist in the design of both the thermal and moisture performance of building envelopes. In this paper, the application of ORNL's state-of the art hygrothermal model, MOISTURE-EXPERT, will be demonstrated using three different ventilation strategies on a wall envelope system. A moisture engineering approach is used. Results are presented to demonstrate how one could apply hygrothermal modeling tools to assist in both design objectives—energy efficiency and durability. Experimental data will be presented to benchmark the model. Finally, the paper will present a preliminary analysis to show the sensitivity of the hygrothermal results of cavity ventilation envelope on different exterior environmental loads.

INTRODUCTION

Consumers today expect a higher level of performance in every purchase they make. They inherently start out expecting products to be engineered. If the product or system experiences a performance failure, the product is either replaced or readily fixed. Consumers also expect up-front service life data and ratings. This educated form of consumerism is slowly but steadily being requested by today's home buyers. 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. It is the latter, "durability performance," that is most difficult to quantify.

Moisture is one of the most important agents leading to premature building envelope deterioration in any climate. Many times when a moisture problem is identified, a solution is not necessarily apparent. Quick fixes are almost never available. One of the more valuable forensic tools when investigating wood-frame housing, *the moisture content probe*, employs the principle that the electrical resistance of the material decreases with increasing moisture content, which is neither accurate nor spatially precise (large volume averaging). In a recent paper by Derome et al. (2001) the authors discussed the complex interaction and interference of dissolved ions and the reduction of the accuracy of the electrical resistance measurement with high moisture content (moisture level readings above the fiber saturation point of wood are of limited value).

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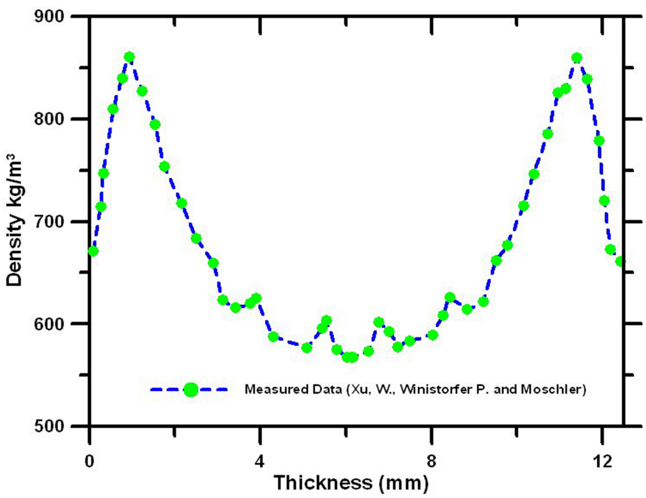

Figure 1 *OSB vertical density profile (Xu et al. 1996).*

Corrections to the moisture content measurements are needed for variables such as temperature, wood species, the presence of preservatives, and glues. These data are usually not available. In addition, if wood was exposed to moisture or temperatures that exceeded the limit for their respective dimensional stability, then past history needed to be accounted for. To make matters even more complicated, depending on the sheathing board, if density gradients in the material are present, as for example in oriented strand board sheathing (OSB) (see Figure 1), one needs to apply density corrections and sometimes species corrections for the different species layers that are apparently not available. Relying on experimental means to solve complex moisture control problems does not warrant a solution.

Moisture control problems can occur in dry climates such as Nevada. When abundance of moisture is present in schools, office buildings, and residences, there can be a variety of flourishing molds. Mold problems are not a U.S. construction issue; the problem exists in the international arena. Recently the Finnish National Institute of Public Health performed an extensive field survey and found that roughly 50% of all Finnish detached houses suffer from mold and moisture problems of varying degrees (Salonvaara et al. 2001). In Canada, the leaky condo crisis still exists in Vancouver, which was spotlighted eight years ago. Many buildings have been repaired for the third time, sometimes with a different design retrofit/repair strategy (Barret Commission 2000). The moisture control problem/crisis has become a scientific and political nightmare for local and national code/research and building envelope consulting experts in Canada.

Joining asbestos, lead, and PCBs, mold in buildings has captured the public's attention as a potential health hazard requiring special care. In 2003 more than 50 conferences/ seminars were organized in the USA that discussed and presented moisture and mold issues. On the positive side, consumer awareness and media attention on these issues is providing a useful educational forum to inform the public. The issue of moisture control and, in particular, how well a home manages moisture is inevitably raised more often now than ever before. Blame is usually cast against energy efficiency measures such as the code requirements for higher levels of airtightness and the increase in thermal efficiency by adding more insulation in all types of building envelopes (roofs, walls, and basements). Clearly, there is a need to develop sound moisture control/management designs for climate specific conditions.

Unlike thermal transport, moisture is complex to study and analyze. In all building applications, moisture seldom exits in isothermal conditions but occurs under both thermal and pressure gradients. This combined heat, air, and moisture transport (hygrothermal transport) is very challenging to accurately understand; one needs to resort to sophisticated transient hygrothermal models for assistance. Solving moisture problems that are not easily determined requires one to determine the sensitivity of a particular design to the various impacting environmental loads. In the last five years, several models have appeared that assist in the sensitivity analysis of the hygrothermal performance of building systems. These models vary significantly and have been ranked in a new *ASTM Manual of Moisture Analysis* (Treschel 1994) in terms of both mathematical sophistication and inclusion of building system and subsystem performances. This classification approach allows models to become differentiated in terms of their ability to solve real problems.

CURRENT UNRESOLVED MOISTURE MANAGEMENT ISSUES

There are many still unsolved problems that need to be addressed as we proceed in the development of highly energy efficient wall systems.

1. What are the performance requirements for interior vapor control strategies? How sensitive are the requirements in terms of climate (exterior environmental loads)? How critical are the interior loads?
2. Is ventilation beneficial in terms of moisture control? Can it be harmful? How can a designer optimize the design parameters?
3. How can different rain diversion technology be included in envelope designs? (How can one quantify and give credit in the design?)
4. What are the building envelope air leakage influences as a function of climatic region? How important or critical are they in terms of controlling thermal or moisture loads? Which envelopes are more sensitive to unintentional air leakage?
5. What are the interior hygrothermal loads of real people (in contrast to numerical ones)? How do moisture loads vary as a function of climatic location?

Figure 2 *Degradation of building paper in a flat roof after ten years of service.*

6. How do you add energy efficiency and increase the durability (moisture) performance at the same time?
7. What is the holistic influence of moisture in a home? What is the actual impact of the presence of moisture? How much energy does it cost? How can we take advantage of hygric buffering?
8. How can we optimize the moisture control designs in terms of whole buildings? What elements are critical? What are the guidelines to follow?

The above are some of fundamental questions for which only advanced hygrothermal modeling can provide the necessary insight. In the past few years, a few sophisticated research models, such as WUFI-2D (Holm and Kuenzel 1999), MOISTURE-EXPERT (Karagiozis 2001), TCCC2D (Ojanen 1994), and LATENITE (Salonvaara and Karagiozis 1994), have been developed to address some of the above issues.

This paper presents the recent shift in design approach that has occurred within the hygrothermal scientific community in analyzing real hygrothermal problems. A new approach, termed *moisture engineering*, is discussed, along with one example case used for demonstration purposes. The intention of this paper is to demonstrate that when experiments and advanced modeling are used hand in hand, a considerable amount of insight is gained. The author will employ the MOISTURE-EXPERT version 2 advanced hygrothermal model as the basis for the simulation work. This model is described in detail in Karagiozis (2001a, 2001b).

MOISTURE TRANSPORT DYNAMICS AND MOISTURE ENGINEERING

The solid matrix phase of the porous media may interact with one or more of the three phases of moisture, the vapor, liquid, and solid ice phases, if present. Phase-change phenomena, such as evaporation, condensation, heat of adsorption, heat of absorption, freezing, and thawing, are some of the physical phenomena that can occur during the transport of moisture. To complicate matters, construction materials have transport coefficients that are strong functions of the dependent variables. In many cases, materials may incorporate elements of memory (past history), and material properties may also change as a function of time (aging materials). In certain instances, as when moisture accumulation reaches a critical level, material dimensional and structural changes may occur that drastically alter the material performance. Figure 2 shows the degradation of building paper that has occurred in a flat roof in Seattle over a period of 10 years. Micro and macro accumulative damage may also occur within the structure of the material due to the presence of moisture, thermal, and pressure loads. Over the past 50 years, almost all construction materials have been evolving and improving. New manufacturing processes have been introduced. Different raw materials and additives have been employed. All of these have contributed to considerable changes in the heat, air, and moisture transport properties of construction materials.

Recently, the introduction of moisture engineering analysis in envelope design by integrating experimental material and system and subsystem analysis coupled with advanced mathematical modeling has given researchers the ability to predict the hygrothermal performance of complex building envelope systems with better confidence. Until recently, the largest source of moisture was not accounted for, this being wind-driven rain (water). Currently, a few models have incorporated this capability (WUFI-ORNL, WUFI-PRO, LATENITE, MOISTURE-EXPERT). This important development has enabled 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. This new approach to building envelope moisture assessment was first introduced in North America (Karagiozis and Salonvaara 1998; Karagiozis 2002) and was termed *moisture engineering*. It requires 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 approach allows one to apply a safety factor in the design by introducing a small amount of water ingress that is dependent on climate and load. Through advanced modeling, one may predict the long-term performance of building envelope systems (Karagiozis 2002) and compare the ranking of the various hygrothermal building envelope performances. Moisture engineering analysis essentially integrates experimental and analytical approaches to develop performance indexes of a building envelope system and subsystems for specific interior and exterior loads.

BUILDING ENVELOPE SYSTEM AND SUBSYSTEM EFFECTS

The hygrothermal performance of a building envelope depends on the integral performance of the building system under consideration and its subsystems. A building system consists of all one-dimensional, two-dimensional, and three-dimensional components, such as material layer systems, and includes all unintentional cracks and openings. Subsystems are defined by the close location and interactions of two material systems, such as a brick-mortar masonry interface, gluing of two materials together to form a substrate (EIFS board), stapling on a weather-resistive barrier, nailing a protective layer, coating on a surface, etc. To date, few analyses have been performed to understand these system and subsystem effects, while at the same time they are the predominant influence on the envelope. Water penetration into a wall cavity is extremely important, and the overall performance of the wall depends on the subsystem that allowed this transport of moisture. Similarly, air gaps can induce airflow through the system and cause higher than critical levels of moisture accumulation, resulting in damage. They are a result of cracks and imperfections in an envelope system, the way materials age, and the influence of interfaces. Unfortunately, information on these critical performance attributes is still not available, and there is a need, not only for identifying the performance characteristic, but also the development of methods to quantify the performance characteristic.

ADVANCED HYGROTHERMAL MODELING ASSUMPTIONS

Several assumptions are necessary for this development and must be acknowledged as the limitations of existing advanced hygrothermal models.

1. Porous construction materials are 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.

According to the manner the axioms of conservation for transport process, the rate of storage of any entity within a control volume at any given time equals the rate of this entity entering the control volume through the surrounding surfaces plus the rate of generation of the entity within the volume.

SHIFT IN MOISTURE CONTROL WALL DESIGN PARADIGM

Old Design Thinking (1950-2001)

It was not too long ago that the consensus among building officials, architects, and designers was that if building envelopes were built according to code specifications, water entry was never to happen. This wishful thinking was one of the many reasons why so many building envelopes have been damaged by moisture. Using this line of thinking, designs were developed that incorporated second lines of defense to make sure that water never entered the system. Many times these defense systems were made so complicated that it was inevitable that water readily entered into the wall system past these second-line defenses.

New Design Thinking (2001…)

Water as a liquid solvent will enter every building envelope at some point in time. Walls should shed as much water as possible and be capable of water management. Water management requires that water be drained, ventilated, evaporated, and transported to either the interior or the exterior environment. One should not only be concerned with shedding and restricting water accumulation in building envelopes, but one must design walls to withstand a minor water loading (wetting). If the wall system cannot handle this additional moisture source/loading, which is a function of the local climate, then an alternative wall design should be used. This additional moisture source, or imbedded safety factor in engineering design, is directly related to the exterior environment for which the wall is designed.

Currently this drastic shift in the moisture control design paradigm is currently being proposed by ASHRAE SPC 160P. The suggested moisture loads range between 1% and 5% of the exterior moisture load that strikes the wall cavity. An application of this new approach with an integrated moisture engineering analysis was performed by ORNL in conjunction with the City of Seattle and Washington State University, investigating the hygrothermal performance of stucco-clad wall systems (Karagiozis 2002).

To summarize the new approach to wall design:

- Incorporate vapor retarder (only when warranted by thorough analysis).
- Employ design overhangs (as large as possible).
- Design for drainage or even better source drainage.
- Use designer materials that work well in a wall assembly.
- Use a safety factor in wall design (withstanding real loads—thermal, moisture, and pressure).
- Test all your designs and theories using hygrothermal models (WUFI-ORNL, WUFI-Pro, and others software).

ADVANCED MODELING APPLICATION EXAMPLE

The application case chosen is one of the ventilation-assisted drying of a wetted wall system. This particular application is a challenge over many other benchmark examples because multiple physical phenomena occur, such as wetting the material, redistribution, and, finally, drying due to diffusion and convective mass transfer.

Ventilation Drying

The effect of wall drying is examined here in a research project sponsored by ASHRAE TRP 1091 (Burnett 2001). This project aims at determining the hygrothermal performance influence of ventilation cavities and sheathing membranes for a wide range of climatic conditions. Guidelines for the use of ventilation drying are limited and available for only cold climates. Indeed, the information even for cold climates is controversial: some recommend its use (Kuenzel 1995; Straube 1999), while others show no difference between ventilated and nonventilated walls (Hansen et al. 2002).

To accomplish the ASHRAE project objectives, a series of experiments were designed and performed at Penn State by Burnett et al. (2004) to examine the relationship between ventilation airflow and the drying of wetted wall systems in laboratory controlled environments. These series of tests were designed not only to provide performance data but to develop benchmark data for the ORNL modeling, MOISTURE-EXPERT (Karagiozis 2001) activity.

The study specifically set out to accomplish three tasks:

- Develop experimental data for ASHRAE TRP-1091 benchmarking of ORNL's hygrothermal model MOISTURE-EXPERT
- Develop performance data on convective airflow drying of wall systems at representative flow rates, especially at relatively low flow rates
- Provide insight on the drying rate and the ventilation flow rate

These tests were developed to reduce the number of boundary condition variables to three, namely, the convective airflow rate, environmental temperature, and relative humidity. A laboratory wall assembly of non-typical configuration, was designed with imbedded controls to inject water into the wall and to measure the drying performance. As this experiment did not provide tight control of the exterior environmental and initial conditions, the experimental results cannot lend themselves to generalization (extrapolations) in their existing form. The fluctuating temperatures and relative humidity were not identical for each of the different air cavity ventilation rates. These wall measurements are best suited for benchmarking and validation activity of the hygrothermal MOISTURE-EXPERT model, as identical conditions are not required. Only accurate measurements of all environmental loads and transient behavior of the walls is needed for model benchmarking, and that was achieved.

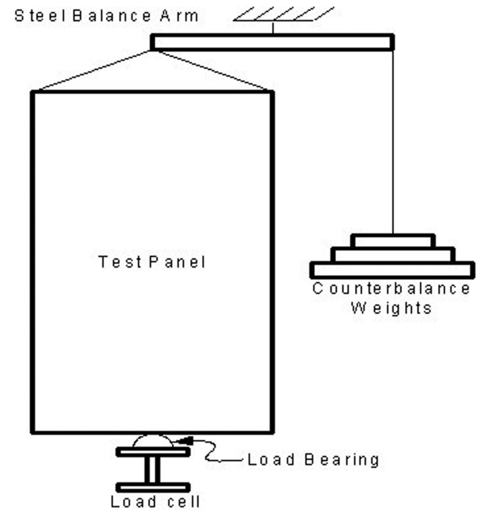

Figure 3 *Counterbalance system.*

Thermal gradients did exist across the assembly but were small. Water was injected and was uniformly spread throughout the interior surface of the sheathing board. This wetting approach was done by injecting a precise dosage of water, which was then repeated for all tests. The wall assembly had dimensions of 1.2 × 2.4 m (4 ft × 8 ft). Only a portion of this was wetting, accounting for approximately 78% of the wall. The experimental process involved injecting a predetermined quantity of water into the wall, and then the walls were monitored in terms of total weight, relative humidity distributions, temperatures, moisture contents in the sheathing board, and air cavity ventilation flow rate.

A detailed description of the assembly and the testing of the walls is reported by Burnett et al. (2004). The reader is referred to this work for much more in-depth experimental reporting. Below, only a brief outline of the tests will be presented.

Experimental Setup and Procedure

The benchmark experimental program involved five tests. One test was conducted for zero induced airflow, a datum test. Four wall panels were tested at flow rates that were measured: 1.6 L/s, 0.8 L/s, 0.4 L/s, and 0.2 L/s. Three were used for the model benchmark activity—the zero airflow, 1.6 L/s, and 0.4 L/s—as these were performed first. These relate the three flow rates to air change rates (ACH), for a 50 mm cavity depth, of 0.05, 19.4, and 38.8 ACH. The flow rates selected for this study result in velocities that are at the lower end of the range of measured values at the field testing facility at the University of Waterloo (Straube and Burnett 1998). These small flow rates were selected to show that the contribution of ventilation airflow to drying is apparent at even very low flow rates.

Simulated Wall Panel Assembly. The experimental setup, shown in Figure 3, was designed and built to idealize the outer

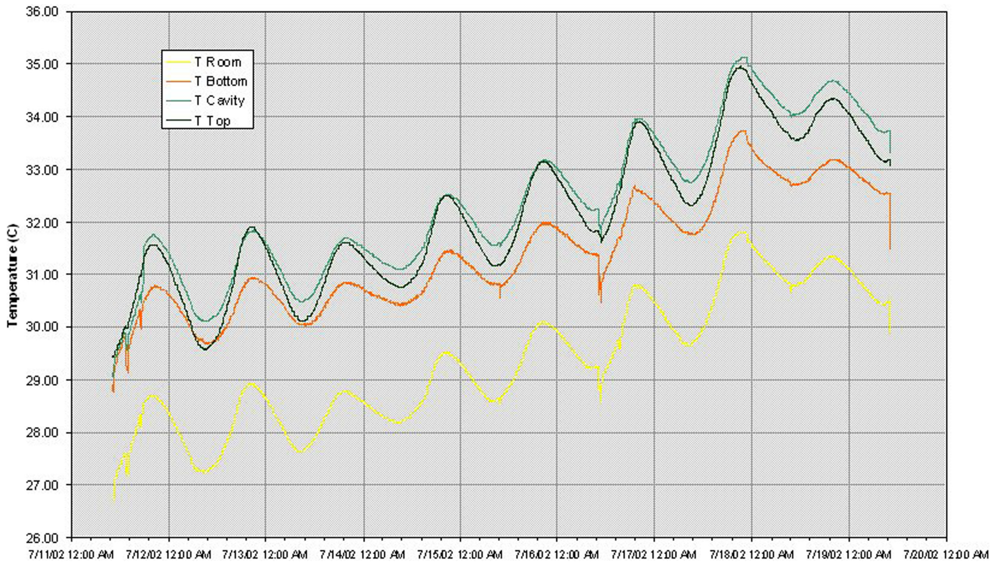

Figure 4 *Temperature distributions (0.8 L/s) (boundary conditions and results).*

portions of a typical wall system (i..e., those components that form and interact with the air space or chamber). The simulated test panel consists of seven layered components and

- a five-sided OSB box, lined with foil-faced polyisocyanurate; joints are carefully taped to form an insulated, airtight, vapor-tight container for the test panel;
- the wetting system, consisting of sheets of distribution paper;
- 12.5 mm of Homasote fiber sheathing;
- Tyvek housewrap;
- a 50 mm deep air space;
- Plexiglass cladding with 1100 mm wide × 19 mm high vent slots located 25 mm from the top and bottom of the panel;
- the top and bottom inlets.

Accurate measurement of the weight change of the test wall panel during the wetting and drying process is one of the keys to this experiment. A counterbalance weighing system was developed to measure with an accuracy of 5 grams or less. As shown in Figure 3, the system consists of a load cell, counterbalance weights, and a steel arm. Most of the panel weight is counterbalanced by the suspended weights, while only a small portion is carried by the load cell. Because of friction and panel movement, calibration of the counterbalance system was required at the start of each test. The calibration equation was then used to convert the measured weight change of the panel to the actual weight change.

Experimental Procedure. Each test was initiated by injecting the first 450 g of the 1350 g water to wet the Homasote sheathing. The weight change of the panel, along with other physical measurements, were monitored and saved using the data acquisition system. The data were then provided to ORNL for model benchmarking.

Initial Conditions. No special pretreatment was done to the material used in the tests. All of the tests were conducted in an enclosed building. Before the wetting (water injection) was initiated, the moisture content at all five locations (top-center, middle-left, middle-center, middle-right, and bottom-center) measured in the Homasote was within the range of 11% to 13%. At time equal zero, three 450 g doses of water were injected into the wall. However, the wetting system only covers 78% of the area of the sheathing. Taking account of the reduced area of contact and the fact that the transducers are located within the contact area, the measured moisture content increase could add 11% to the initial 11% to 13%.

Boundary Conditions. Figure 4 shows the ambient temperature in the building as well as the temperature evolution in the test wall that had 0.8 L/s airflow. It is evident that during the test period a considerable temperature variation existed, and transient daily temperatures of up to 1.5°C were present. The maximum variation between the lowest and highest room temperature was slightly over 5°C during the test period. Variations in relative humidity were also present over the testing period, and these are plotted out for case 9 in Figure 5. A variation of approximately 15% room relative humidity between the lowest and highest values occurred during the eight days of testing.

MOISTURE-EXPERT: ADVANCED HYGROTHERMAL SIMULATION MODEL

The MOISTURE-EXPERT model (Karagiozis 2001a) is one of the most comprehensive research hygrothermal

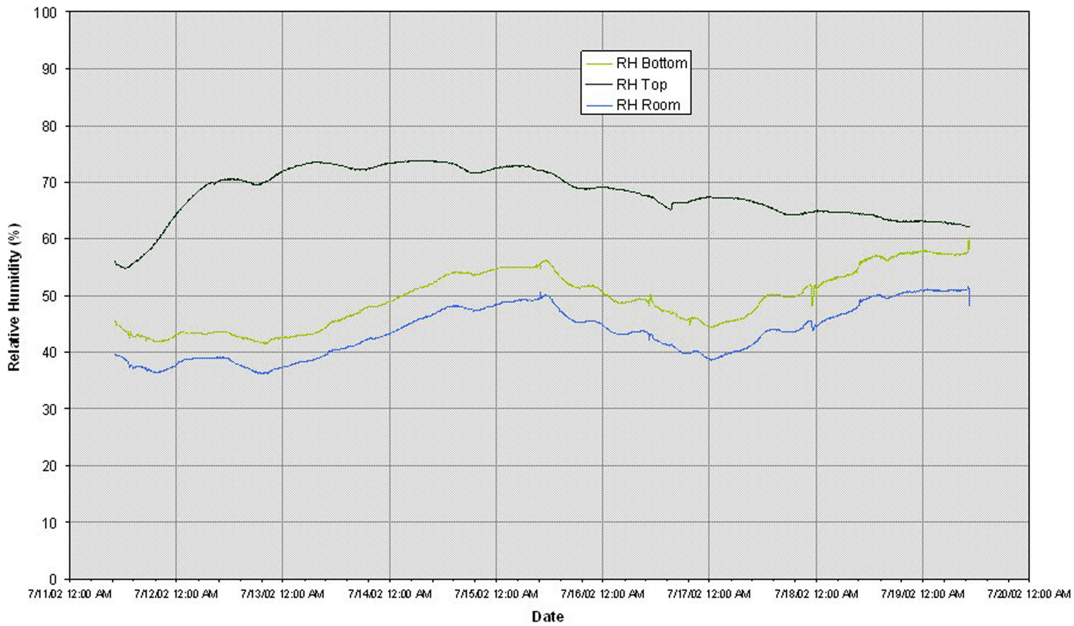

Figure 5 *RH distributions (0.8 L/s) (boundary conditions and results).*

models, as described in the recent *ASTM Manual on Moisture Analysis and Condensation Prediction* by Heinz Treschel (2001). Essentially, four sets of inputs are required to set up the model for hygrothermal analysis. Requirements include the exterior hygrothermal loads, interior hygrothermal loads, material properties, and building envelope system and subsystem characteristics. As the particular system and subsystem information is provided to the model, for example, cavity ventilation subsystem characteristics, then correspondingly more accurate predictions will result. Both influences—the level of effort in implementing the accuracy of the material property inputs (Homasote) and including specific information on the subsystem performance such as ventilation flow—will be demonstrated in this report. The moisture transport potentials used in the model are relative humidity (ϕ) and vapor pressure (Pv); for energy transfer, temperature is the driving force.

Simulation Details

In Figure 6 the grid distribution is given for the tested walls. Four different grid size distributions were initially used in the analysis. These were 18 × 13, 35 × 25, 70× 50, and 140 × 100. The purpose of parametric analysis was to obtain a minimum grid size distribution that provided numerical free error (grid size dependency) within a tolerance of ±0.01% of the dependent variable. The 35 × 25 grid size was found to satisfy this criterion and was used in the analysis of the test walls. The simulations were performed for a time step of one hour.

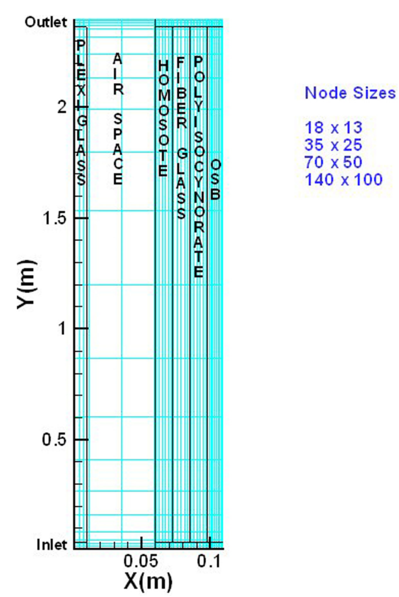

Figure 6 *Grid distribution analysis for two-dimensional hygrothermal simulations.*

Effect of Material Property Data

The issue of using appropriate material properties data is briefly described. In this section an example case is presented showing the effects of using measured sheathing board data versus using data measured by Kumaran (2001) that have been reported in the ASHRAE TRP-1018 project. Both are wood

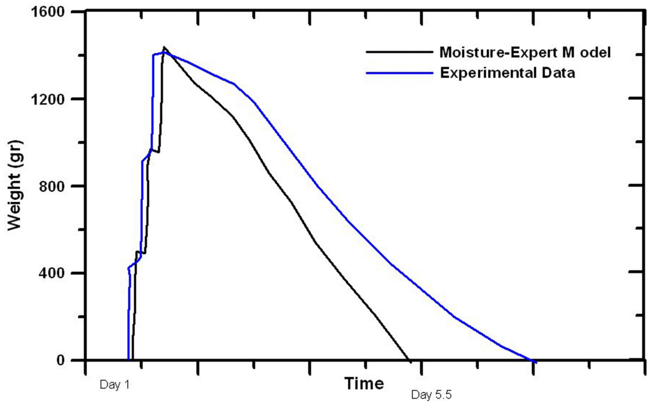

Figure 7 *Comparison between model simulation results using ASHRAE database.*

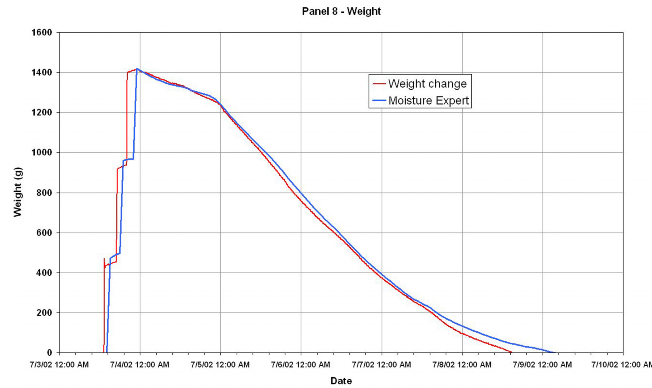

Figure 8 *Comparison between model simulation results using ORNL hygrothermal data.*

fiberboard material; the one measured at ORNL was the same as the material used in the wall.

A numerical model was developed for Case 8 (1.6 Lps of ventilation air). As in many simulation application cases, when the specific material data are not present in the database, generic data are used in the simulation. While for certain applications this may not result in substantial errors, this was not the case in this example.

In Figure 7, results are plotted out for the weight change of the wall as a function of time. Data measured at Penn State University are compared against predictions by MOISTURE-EXPERT using literature fiberboard material property data by Kumaran (2001). The agreement at the beginning of the simulation is rather good; the water injection is captured quite well. Comparing the weight change measurement and predictions, better agreement was found during the initial stage of the drying process where fast redistribution is occurring. Model predictions show that a much faster drying process is present, and drying to the original state (zero weight gain) occurred 1.5 days earlier than what the measurements indicate. While the agreement between experiment and model simulation was within 7% (percent error [Experiment-Model/Experiment] * 100) in the first day, the agreement quickly deteriorated to within 22% during the second day and 62% during the fourth day, as depicted in Figure 7. However, this kind of agreement/disagreement is quite prevalent for hygrothermal modeling benchmark cases that have even less complicated transport processes, i.e., with only the process of drying (not wetting + drying) with controlled interior boundary conditions (not varying) and no airflow ventilation present (IEA Annex 24; Maref et al. 2003).

Investigating the simulation data more carefully, it became obvious that the trend was correctly predicted at the beginning, but after a short time, the deviation between the model and the experiment agreement became larger. It was hypothesized that the source of this disagreement in the drying rate slope between experimental and simulation results could be the input material property data. Another consideration was also investigated, that possibly the chosen time step of one hour was too large, as the experimental data are reported each five minutes. However, that was quickly ruled out, as when a time step of five minutes was used in the model, exactly the same curve was generated.

As the most critical material layer element of this wall drying experiment is the sheathing board (Homasote) better data were needed. A material property activity had been underway at the Oak Ridge National Laboratory to develop a material property database system for MOISTURE-EXPERT Version 2.0. Material from the same batch of Homasote board material used in the walls at Penn State were already were measured by Dr. Wilkes at ORNL. Another simulation was then performed using the ORNL measured Homasote data.

Figure 8 shows the measured and simulated weight gains using ORNL material properties in the simulations. The results show remarkable agreement. This excellent agreement is evidence of the importance of correctly including the transport mechanisms as well as material and subsystem performance characteristics of the simulated model. The differences between experimental and numerical simulation are very small, approximately less than 5%. While the uncertainty in the weight measurement is on the order of ±5 g, the total uncertainty in the experiment, taking into account the uncertainties in all interior and exterior loads, could be estimated to be on the order of ±1% to 12.5%. Higher uncertainties are certainly present during the drier conditions/periods in the wall (end of the experiment). The agreement is remarkable though in that the model was able to correctly

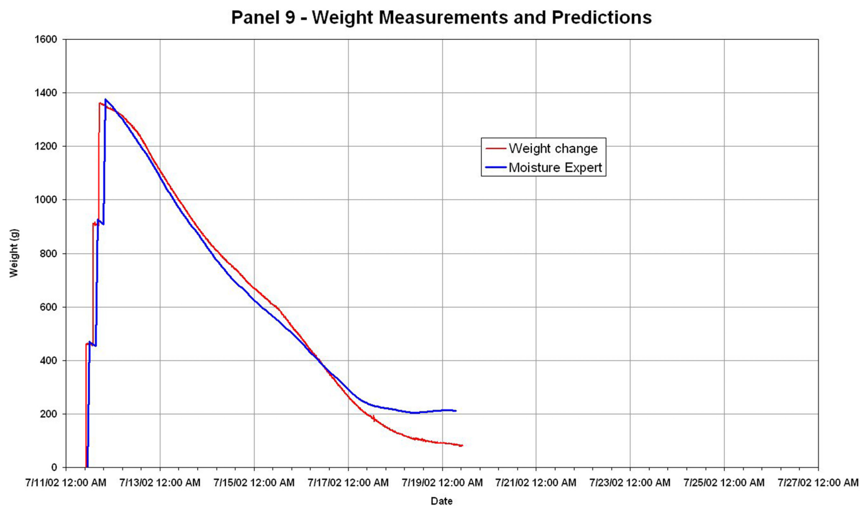

Figure 9 *Comparison between model simulation results and Penn State experimental data (1.6 Lps).*

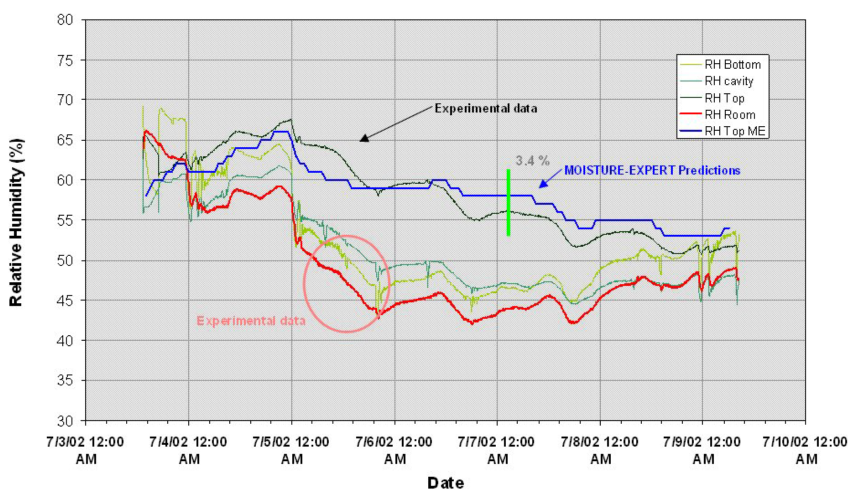

Figure 10 *Comparison between model simulation results and Penn State experimental data (1.6 Lps).*

follow the fluctuating excitations from the interior environment very closely. This agreement clearly depicts the importance of having better than representative material properties when benchmarking advanced hygrothermal models.

Simulation of the 1.6 Lps Case

In this particular wall wetting and drying test, the air cavity was 2 in. and at the bottom of the test, an airflow of 1.6 Lps was maintained at the bottom inlet region of the air cavity. In these tests, the pressure influence of the room unit heater was negligible, as the inlet and outlet region were protected. In Figure 9 the transient weight of the wall assembly is shown for the experiment and the simulation. Good agreement is found between the laboratory result and those simulated by MOISTURE-EXPERT. The simulation results lie within the total experimental uncertainty for more than 95% of the test period. The agreement in many ways is remarkable, as three modes of mass transfer are very well predicted: (a) water injection and storage, (b) initial redistribution, and (c) convective air drying.

Figure 10 displays the relative humidity as a function of time for several locations in the air cavity and in the room. Results are also displayed for the calculated relative humidity at the top location of the ventilation cavity. The agreement between the measured and calculated relative humidity results at the top location of the ventilation cavity is very good. It is important to note that the experimental results are in five-

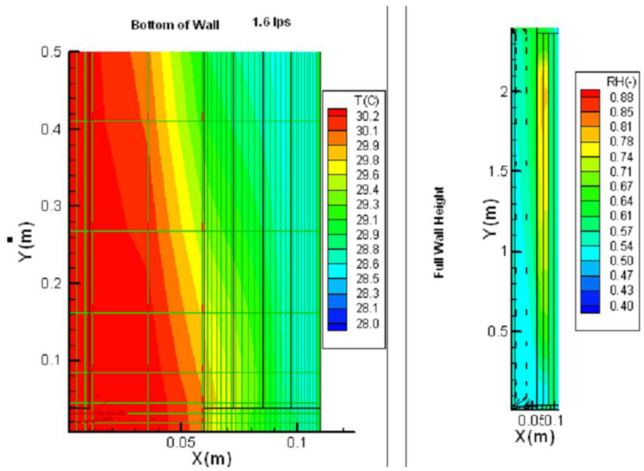

Figure 11 *Spatial temperature and RH distribution at 1.6 Lps at time = 5 days hr.*

minute increments, while the simulated results are in one-hour increments. A maximum difference in RH of 2.5% was found. Figure 11 displays a snapshot of the spatial relative humidity distribution and temperature distribution at five days after the initial wetting period. Warmer room air is heating the bottom of the test wall, allowing evaporation to occur, and slightly wetter conditions are observed at the top of the Homasote.

In summary, excellent agreement is found when comparing the MOISTURE-EXPERT simulation results with Penn State experiment data at a cavity ventilation rate of 1.6 Lps.

Parametric Analysis

Figure 12 shows a parametric analysis performed for the same ventilation cavity wall but with the exact exterior boundary conditions for the five different air ventilation rates. Three times similar to the experimental testing water injection times were employed in this numerical analysis. In this figure the weight of water stored in the wall is plotted out as a function of time in days. The simulations clearly depict the increased drying potential of ventilation. The higher the ventilation rates, the higher the drying potential of the wall. Indeed, the wall without any ventilation dried the slowest. The greatest increase in the rate of drying occurs between zero ventilation and 0.2 Lps. The rate of moisture removal drops as ventilation increases. These results provide some unique understanding of the potential for drying by including ventilation strategies in an existing wall system.

CONCLUDING REMARKS

Moisture engineering is a powerful new approach available to analyze, enhance understanding of, and develop solutions to difficult moisture control problems. The combination of system and subsystem characterization, detailed measurements, and advanced modeling permits the analysis of complex hygrothermal performances of building envelopes.

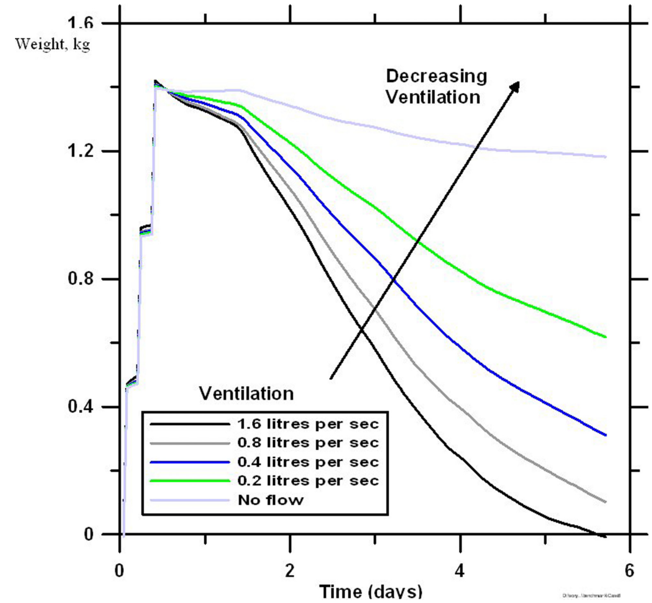

Figure 12 *Air cavity ventilation drying potential.*

As the results of this paper are the first series of results that will be generated in this project, they have been classified as preliminary, with the complete analysis to appear within a year. It is clear that even the small ventilation flow rates used in this project permitted very strong drying potentials. Under the current experimental conditions, it is evident that the wetted sheathing board can dry out by ventilation. Comparisons between the experimental data could not be conducted as the environmental boundary conditions were not maintained constant. For comparison purposes, the model is now able to provide these.

From the benchmark activity, good agreement was found between the experimental cases and model predictions. All of the wetting and drying trends were correctly predicted in the simulations. The criticality of using measured material properties rather than generic data was also demonstrated. This is especially true for benchmarking model results where one attempts to calibrate and imbed the correct system and subsystem features. The model has been validated for the benchmark cases as the weight loss due to ventilation drying was accurately predicted.

The MOISTURE-EXPERT model demonstrated its robustness to capture all critical elements of the benchmark test. These were:

(a) The moisture storage because of the water injection (and time history)

(b) The redistribution of water in the Homasote

(c) The moisture transport (vapor and liquid)

(d) The convective drying as a function of airflow

The results obtained comfirm the model's ability to capture these effects.The next level of validation will be performed using field data and will be reported in the near future.

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