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Laboratory Measurements and Benchmarking of an Advanced Hygrothermal Model

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Abstract

Recent research in the field of assessment of hygrothermal response has focused on either laboratory experimentation or hygrothermal modelling, but less work has been reported in which both aspects are combined. Such type of studies can potentially offer useful information regarding the benchmarking of models and related methods to assess hygrothermal performance of wall assemblies. This paper briefly presents an advanced hygrothermal computer model called hygIRC. The paper also reports the results of a series of experiments in which the drying rates of oriented strand board alone or in combination with several sheathing membranes were systematically measured. Results from these experiments are compared with those derived from hygIRC simulations and subsequently used to help benchmark the model. Preliminary results on the shape of the drying curves and the time taken to establish equilibrium moisture content show good agreement between the experiments and simulation. This was one of several steps undertaken in a broader benchmarking exercise to validate the model and its implementation.

Keywords: Air transport, Building System, Drying, Envelope, Heat Transfer, Mass Transfer, Modeling, Moisture, Experimental, Wood Product.

1. Introduction

Assessing the performance of new building materials, components or systems typically requires extensive laboratory testing or, in some instances, elaborate and time-consuming field trials. Thorough analyses of the hygrothermal behaviour of, for example, wall systems in response to different climatic loads is not usually part of the assessment process. Whereas laboratory and field experiments are often too selective and time consuming, assessing the response of wall systems to changing environmental loads is made easier through the use of hygrothermal simulation models. Simulation models can accommodate a variety of changing boundary conditions and as well, result in much faster analysis, given the recent advances in computer technology that have permitted ready access to enhanced computing performance. This in turn has brought about an increased emphasis on the use of numerical methods to solve the fundamental hygrothermal equations on which many computer models have been developed over the past decade. Depending upon the complexity of the problem under consideration, such models can be based on very simple, one-dimensional, steady state methods or on more complex, two and three-dimensional, transient methods. However, acceptance of results derived from simulation models is contingent upon acquiring evidence of a response comparable to that obtained from experimental work when the simulation is carried out under the same nominal environmental loads. Studies that incorporate both laboratory experimentation and simulation thus offer possibilities to compare results and hence 'benchmark' the response of the model to known conditions.

This paper presents the governing equations implemented in hygIRC and a series of drying experiments on oriented strand board (OSB) alone or in combination with different sheathing membranes designed to benchmark the model. It also presents preliminary results from a series of simulations in which the shape of the drying curve and the time taken to establish the equilibrium moisture content are determined and compared with the experimental results. This was one of several steps undertaken in a broader benchmarking exercise to validate the model and its implementation.

2. Hygrothermal simulation model

Researchers at the Institute for Research in Construction (IRC), jointly with those from the Technical Research Centre of Finland (VTT Finland), have been developing advanced hygrothermal models for the past fifteen years. Some of the joint activities were reported earlier [Ojanen et. al., 1994, Ojanen and Kumaran, 1995 & 1996, Karagiozis et. al. 1995, Salonvaara and Karagiozis 1998]. The current version of the hygrothermal model that is used at IRC is called hygIRC. It has a pre-processor that guides the user to correctly and easily capture the geometry of the building envelope assembly in the computational domain. It also gives various choices for the user to best define the boundary conditions. It mainly serves as a module that allows the user to correctly prepare inputs to the solver. Yet another module, called WeatherSmart (Djebbar et al, 2001), helps the user to analyze multi-year weather data and select representative environmental boundary conditions that best represent the problem under consideration. The user analyzes the long-term multi-year weather data to generate representative interior and exterior boundary conditions. A one-dimensional version of the main solver forms a part of this module to quickly assess the hygrothermal responses of the envelope assembly and leads the user to an appropriate selection of the boundary conditions. A third module is a recently updated database on all hygrothermal properties that correctly represent the building materials that are commonly used in North America. The dependencies of the properties on variables such as temperature, moisture content or relative humidity and at times on density are properly accounted for.

hygIRC is built around well-known heat, air and moisture transport equations (Fourier's, Fick's and Darcy's Laws as well as Navier-Stokes equations) and corresponding equations that define the conservation of energy, mass and momentum. The governing equations listed in Figure 1 shows that the approach adopted in hygIRC in deriving the balance equations from the phenomenological equations is evolved from the approaches used earlier by Kohonen in TRATMO I [Kohonen 1984] or by Ojanen in TCCC2D [Ojanen and Kumaran 1992, 1996]. The report of the International Energy Agency annex 24 [Hens, 1996] is also a useful source of information in which the equations used in hygIRC are explained. Several applications of the hygrothermal model, during its development, have been reported earlier [Salonvaara and Karagiozis, 1994, Karagiozis et al., 1995, Karagiozis and Kumaran, 1997]. hygIRC is used at IRC as the primary analytical tool to conduct parametric studies to assess the hygrothermal performance of various wall assemblies exposed to different climatic conditions in North America.

3. Experimental design

3.1. Scope of work

The primary focus in this benchmarking exercise was to evaluate the drying process of wood-based sheathing board in timber-frame constructions. Hence, the scope of this benchmarking exercise was limited to experimentally determining the drying processes of OSB sheathing board alone or wrapped in different sheathing membranes and comparing these to the drying response derived from simulation. Later experiments, not reported here, investigated the wood frame wall performance with greater levels of wall system complexity. Liquid and vapor transfers are included in the investigation. Hence the primary hygrothermal properties of interest are the vapor permeance and liquid diffusivity. Air movement is not explicitly considered in this benchmarking exercise with the exception of permeation of air through materials. The overall drying process was considered in terms of the shape of the drying curve and the time taken to establish equilibrium moisture content by the sheathing board.

3.2. Experimental approach

Experiments were carried out in controlled laboratory conditions on sheathing boards having nominal dimensions of 0.8-m x 1.0-m. This size had been deemed a reasonable compromise between small and full-scale experiments. This series of tests were conducted such that technical advantages gained from completing this series could subsequently be applied to subsequent full-scale experiments that were being planned as part of broader and more comprehensive benchmarking exercise (to be published). The present series consisted of collecting data on the drying characteristics of initially saturated OSB sheathing and various combinations of OSB in contact with different sheathing membranes.

3.3. Weighing system and load cells

Three weighing systems were fabricated, each one capable of accommodating three specimens. Specimens were attached to individual load cells (nominal capacity of 50 ± 0.02 kg) such that weight changes could be monitored over the course of the experiment. Weight changes of a total of nine different specimens could simultaneously be monitored from load cell measurements recorded on a data acquisition system. These weighing systems were placed in a climate control chamber (Maref et al. 2001) and the specimens were attached to the weighing system.

3.4. Initial and boundary conditions

The OSB specimens were immersed in water for up to 5 days and permitted to stabilise in a polyethylene wrap for 48 hours. Previous work had demonstrated that a stabilising period of such a length helped insure uniform moisture content throughout the OSB sheathing. Hence, the initial MC at the start of the experiment was assumed to be uniform throughout the thickness of the material for each test specimen. Boundary conditions for the experiment, provided in Figure 2, shows the recorded temperature (T) and relative humidity (RH) in the climatic chamber as a function of time conducted over a period of 21 days.

4. Model implementation and simulation assumptions

The sheathing board, flanked on either side with a "layer' of sheathing membrane (i.e. 3 layers: membrane, OSB, membrane), was represented in the model using a rectangular mesh approach. This mesh was comprised of 20 nodal points along the height of the specimen (y-direction) and 16 nodal points across the depth (x-direction) for a total number of 320 nodal points for the entire representation. Membranes, installed on either side of the OSB were each comprised of 3 equidistant nodes across their depth. The OSB (thickness 11.5-mm) had 10 equidistant nodes. In the case where the response of the OSB alone is simulated, the grid representation in this instance had an expanding mesh implying that grid density near the edges of the nodes across its depth was greater than that at the center.

The surface heat transfer coefficient was 10 $W/m^2 °C$ whereas the moisture transfer coefficient along the principal planar surfaces of the specimen was 4.6 x 10^{-7}kg/m•s•Pa and at the top and bottom of the specimen was 7.4 x 10^{-15} kg/m•s•Pa. Though the experimental data provide boundary conditions at every 2 minutes the time step used in the simulation was 60 minutes – this provided ample resolution in a drying process that generally took several weeks. The simulations were conducted under the following assumptions. Liquid transport through the membranes were not modelled, i.e., the membranes were represented as vapour diffusion control elements. The contact between the membranes and the OSB sheathing was assumed to be perfect (i.e. no interstitial airspace between components). The initial moisture content (MC) of the membrane was set to 0%.

5. Results and discussions

Simulations were performed using hygIRC to estimate the drying response of four specimens for which results are provided below in Figures 3-6. Results from simulation and experimental drying of an OSB sheathing alone exposed to the surrounding environmental conditions within the climatic chamber (provided in Figure 2) are plotted in Figure 3. In this experiment, the initial MC of the OSB was measured at 61% and this was set as an initial condition for the simulation. As can be observed in this figure, the equilibrium moisture content (EMC) is achieved after 21 days (5% MC); the simulation is nominally in good agreement with the experimental data. Noticeable differences exist during the first four days. However, it must be acknowledged that the overall agreement between the experimental and simulated drying curves is excellent in terms of the drying times as well as the shape of the drying curve derived from these experimental sets.

Figure 4 shows the results from simulated and measured drying response for the OSB sheathing wrapped on both sides by membranes II. The initial MC of the OSB wrapped with membranes II was 65%. In general, the simulation curve follows the shape of the experimental data, but there are some evident differences. Nonetheless, the overall simulation results provided in Figure 4 show good agreement in terms of overall drying time. The biggest difference in MC derived from these comparisons is around 6% MC. These relatively small differences are under investigation.

A comparison between simulated and experimental results for OSB wrapped with membrane VII is presented in Figure 5; the initial MC of the OSB is 63% and the EMC of 5%, is reached after 21 days. Once again, the shape of the simulated drying response is the same as that obtained from experiment and the time to reach EMC is similar to that of the experiment within an acceptable difference of ca. 2% MC. Finally, comparative results for OSB wrapped in membrane V are provided in Figure 6 and show excellent agreement between the simulated drying curve and the experimental results.

In general, the drying process is governed by the vapour permeability of the membrane. The higher the vapour permeability the faster the rate of drying in a given condition. For example membrane VII has higher vapour permeability than membrane II, as can be seen by comparing results in Figures 4 and 5.

6. Concluding remarks

Experimental work has been done to help benchmark an advanced hygrothermal model called hygIRC. Experiments were undertaken under symmetric drying conditions - i.e. both major surfaces of the test assembly were exposed to the same environmental conditions. The overall agreement between experimental and simulated results is good in terms of the shape of the drying curve and the time taken to reach equilibrium moisture content. The differences observed may be due to a number of reasons. The manifestation of discrepancies was case specific (one comparison showed a near perfect fit). This suggests that the algorithms of the model are functioning as expected, but the particular implementation or representation of each case may be responsible for some of the discrepancies. For example, subsequent investigation suggests that material properties can vary within a range, even for the same specimen, so that a sampling of various portions of a sheet of material may be needed to establish a more representative average. Other factors related to implementation of the model such as selection of the time step used in the simulation and the effect of selection of grid size need to be investigated as part of the ongoing benchmarking process.

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Moisture balance

$$\rho o \frac{\partial (u)}{\partial t} = -\nabla \left\{ \dot{m}_l + \dot{m}_v \right\} \quad (1)$$

$$\rho o \frac{\partial (u)}{\partial t} = -\nabla \left\{ \underbrace{- \underbrace{\rho_o D_w (u,T) \nabla u}_{Liquid\ diffusion} + \underbrace{k_w (u) \rho_w g}_{Liquid\ gravity\ flow}}_{\dot{m}_l} \underbrace{- \underbrace{\delta_p (u,T) \nabla P_v}_{Vapor\ diffusion} + \underbrace{\rho_v V_a}_{Vapor\ -\ airflow}}_{\dot{m}_v} \right\} \quad (2)$$

with $k_w = \rho_o \frac{D_w (u,T)}{\partial S / \partial u}$

Energy balance

$$\frac{\partial \left(\rho_T (u,T) C_p (u,T)\ T \right)}{\partial t} = \underbrace{-\nabla . \left(\rho_a (T) C_{p_a} (T) \vec{V}_a T \right)}_{Airflow\ convected\ heat} + \underbrace{\nabla \left(\lambda(u,T) \nabla T \right)}_{Heat\ conduction} + \underbrace{L_v \left(\nabla . \left(\rho_o \delta_p (u,T) \nabla P_v \right) \right)}_{\text{Evaporation / condensation heat}} - \underbrace{L_{ice} \left(\rho_o u \frac{\partial f_l}{\partial t} \right)}_{Freeze/thaw\ \text{heat}} \quad (3)$$

Figure 1 – Governing equations for moisture and energy balance

u	Moisture content kg (moisture)/kg (dry material) - (%)	ρ_w	Liquid moisture partial density (kg/m^3)
$\dot{m}_l$	Liquid moisture mass flow rate (kg/s)/m^2	D_w	Liquid moisture diffusivity (m^2/s)
$\dot{m}_v$	Vapor moisture mass flow rate (kg/s)/m^2	δ_p	Vapor water permeability (kg/ m s Pa)
k_w	Liquid moisture permeability (kg/m s Pa)	$\vec{g}$	Gravitational vector (m/s^2)
S	Capillary suction pressure (Pa)	C_p	Effective specific heat capacity (J/kg K)
P_v	Vapor moisture pressure (Pa)	C_{p_a}	Dry-air specific heat capacity (J/kg K)
T	Temperature (K)	f_l	Liquid fraction having a value from 0 to 1
t	Time (s)	λ	Effective thermal conductivity (W/m K)
$\vec{V}_a$	Air velocity vector (m/s)	L_v	Enthalpy of evaporation/condensation (J/kg)
ρo	Density of the dry porous material (kg/m^3)	L_{ice}	Enthalpy of freeze/thaw (J/kg)
ρv	Vapor moisture partial density (kg/m^3)	ρ_T	Actual total density of the material including moisture contribution (kg/m^3)

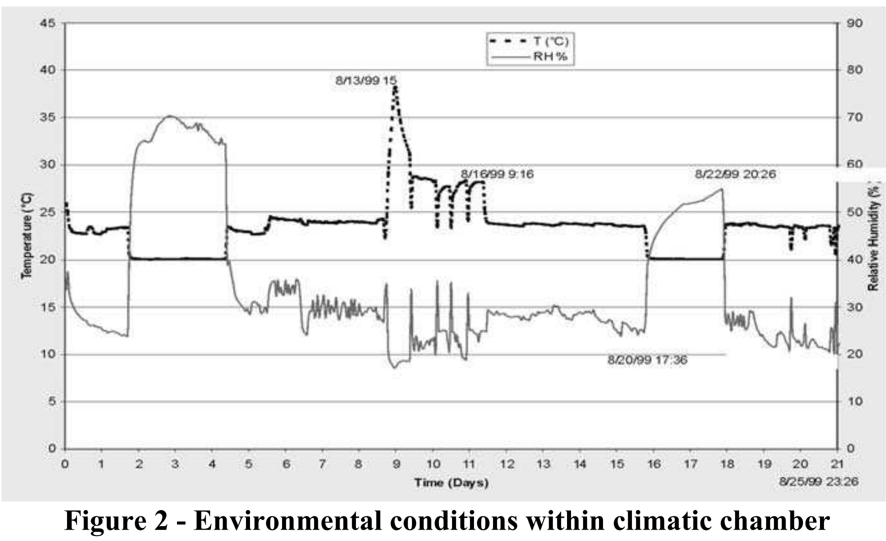

Figure 2 - Environmental conditions within climatic chamber

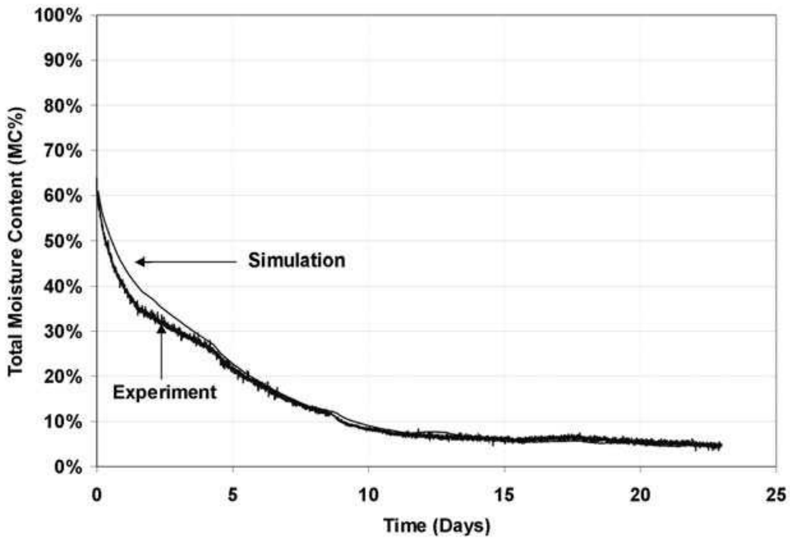

Figure 3 - Comparison of the simulated and measured drying results of OSB layer

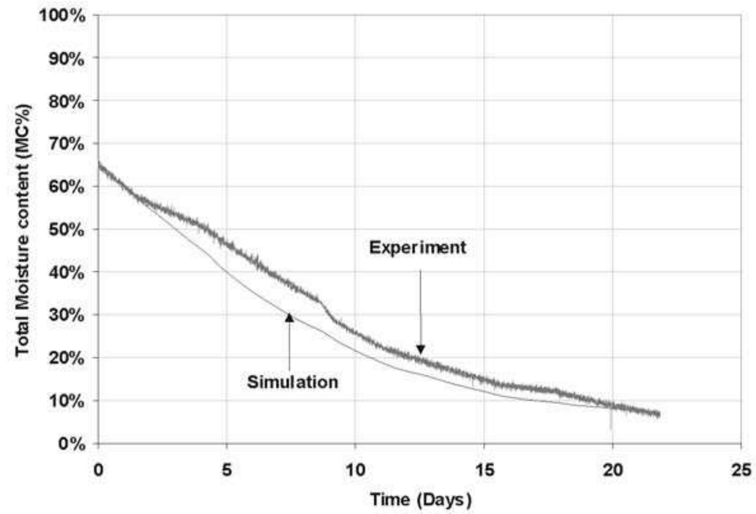

Figure 4 - Comparison of the simulated and measured drying results of OSB layer (The OSB was wrapped on both sides with membrane II)

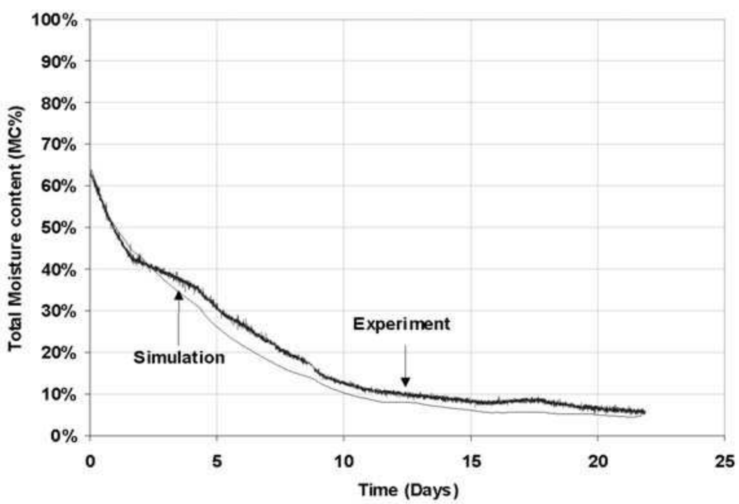

Figure 5 - Comparison of the simulated and measured drying results of OSB layer (The OSB was wrapped on both sides with membrane VII)

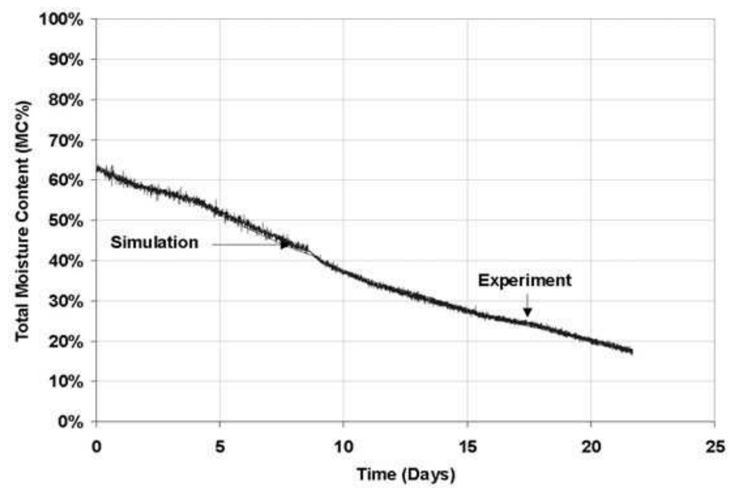

Figure 6 - Comparison of the simulated and measured drying results of OSB layer (The OSB was wrapped on both sides with membrane V)