Validating Wind-Driven Rain Module in HAM-Tools

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ABSTRACT

This paper is a continuation of previous research carried out to improve the hygrothermal analysis capabilities of the readily available HAM-Tools building simulation software. HAM-Tools is an open source library of Simulink models specifically constructed for thermal system analysis in building physics including one-dimensional heat, air, and moisture (HAM) analysis through building envelope components and ventilated spaces. The previous study was intended to improve the program by adding a wind-driven rain module using a semi-empirical model from ASHRAE 160P in the hygrothermal analysis. Comparison to WUFI simulation results was used to verify the wind-driven rain module in HAM-Tools. However, the previous study did not account for the difference in moisture transport mechanism and calculation between the two programs. HAM-Tools uses suction pressure differential as the driving force and the hydraulic conductivity while WUFI uses moisture content difference as the driving force and liquid diffusivity for liquid transports. In this study, the verification procedure for the wind-driven rain module was corrected. Simulation results using HAM-Tools were compared to results from WUFI simulation for different weather data and wall assemblies and to field measurements taken under coastal climate of British Columbia. The comparison with WUFI results and field measurements indicated that the newly designed HAM-Tools wind-driven rain module is performing properly.

INTRODUCTION

Wind-driven rain (WDR) is one of the most important boundary conditions and the main moisture source that affects the hygrothermal performance and durability of building envelopes (Kumaran and Sanders 2008). Wind-driven rain can penetrate through the building facade, which potentially damages the building envelope and reduces its performance and service life. Therefore, it is important to have a proper tool that takes into account heat, air, and moisture variations through the building envelope to be able to analyze the moisture that is being transported through the building envelope structures. This study is a continuation of the previous work that attempted to investigate the effect of microclimatic conditions on the hygrothermal performance of building envelopes using HAM-Tools, an open source one-dimensional hygrothermal performance analysis tool developed using Simulink. A wind-driven rain module was added into the program using a semi-empirical model from ASHRAE 160P 2009 (Wu, Ge, and Horvat 2012). From this model, the amount of rain is calculated using Equation 1.

$$R_{wdr} = F_E \cdot F_D \cdot F_L \cdot U \cdot \cos\theta \cdot r_h \tag{1}$$

where R_{wdr} is the wind-driven rain in mm/h, U is wind speed in m/s, r_h is the unobstructed horizontal rainfall intensity in mm/h, and θ is the angle between wind direction and perpendicular to façade. The exposure factor F_E is obtained based on the height of the building and the terrain surrounding it. The rain deposition factor F_D is based on the slope of the roof and if the wall material is subject to rain runoff. F_L is the empirical constant. To create the WDR module, Equation 1 was used to calculate the WDR intensity. The completed model is shown in Figure 1. Since HAM-Tools has defined south to be zero degrees and increase by moving counter clockwise, section A changes this to define north to be zero degree and counts

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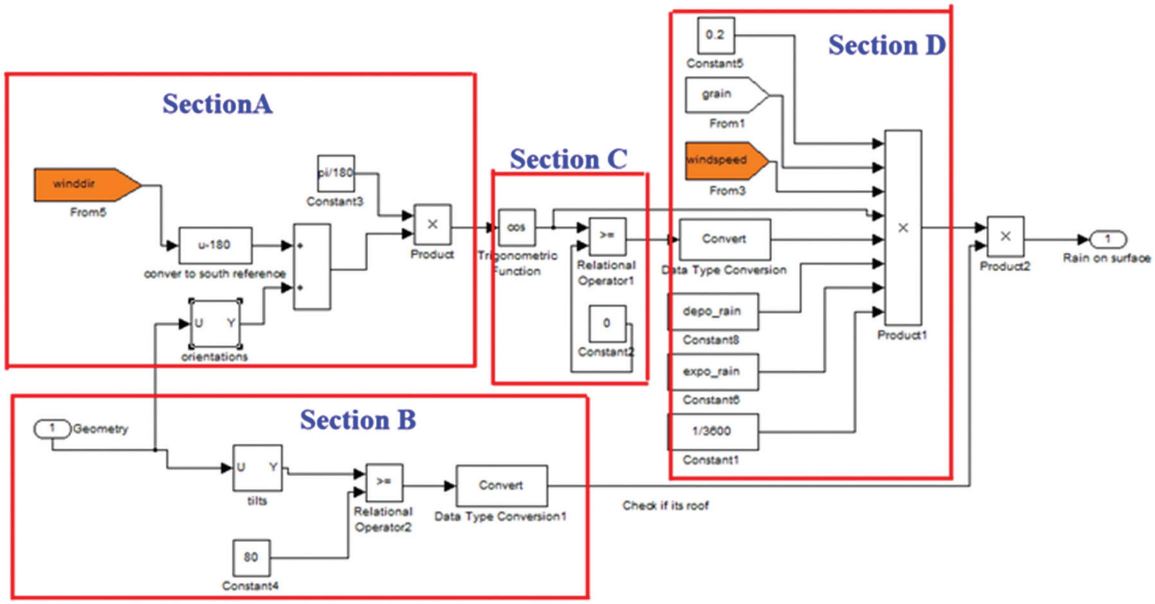


Figure 1 *Added WDR module to HAM-Tools (Wu, Ge, and Horvat 2012).*

clockwise. This ensures that the weather data that is input in HAM-Tools is consistent with the normal meteorological data. Section B verifies if the surface chosen in the geometry is a roof, while section C ensures that the wall orientation faces the direction of the wind blowing by setting the WDR intensity to zero if wind is not hitting the surface of the wall. Finally, section D is the multiplication of all these and the parameters defined in Equation 1. Since currently the time step used in HAM-Tool's calculations is in seconds, it is necessary to convert the result of the WDR module to be consistent with the software. For example, if the weather data is presented in hourly data, then a factor of 1/3600 is introduced.

The developed module was then verified by comparing the results with WUFI, a widely accepted, commercial hygrothermal simulation tool. However, HAM-Tools uses suction pressure differential as the driving force and the hydraulic conductivity while WUFI uses moisture content difference as the driving force and liquid diffusivity for liquid transports. Due to the difficulties in converting material properties from one program to the other, material with the closest property match was selected for the analysis in the previous study, which contributed to discrepancies in moisture content between these two programs. To further improve and verify the wind-driven rain module in HAM-Tools, materials with known retention curve, which allows the conversion from liquid diffusivity to hydraulic conductivity, were carefully selected for the analysis. Simulation results from HAM-Tools were compared to WUFI results using different wall constructions and weather data and to field measurements collected under the coastal climate of British Columbia, a climate with more instance of wind-driven rain and higher amount of rainfall. This paper presents the improvement and verification of the wind-driven rain module in HAM-Tools.

METHODOLOGY

Material Properties

To compare simulation results from HAM-tools to WUFI, the material properties of wall assemblies need to be consistent. Since HAM-Tools has a very limited material database, materials from WUFI's database are used to construct the simulations. Most of the material properties can either be directly input from one program to the other, or can be easily converted. Table 1 summarizes the necessary conversions.

The main difference between these two programs is the driving force and material properties to account for liquid transport. WUFI uses the gradient of water content and liquid diffusivity while HAM-Tools uses suction pressure difference across the material thickness and hydraulic conductivity. To convert liquid diffusivity for materials from WUFI's database to hydraulic conductivity required by HAM-Tools, the material's retention curve is needed.

Water Transport Conversion

The liquid diffusivity in WUFI is governed by Equation 2 (Fraunhofer IBP 2010).

$$g_w = D_W \cdot grad(w) \tag{2}$$

where g_w is the liquid moisture flux in kg/m^{2}s, D_w is liquid transport coefficient in m^2/s, and w is moisture content in kg/m^3. WUFI uses tabulated data to provide the transport coefficient as a function of water content in the material. It applies to two

Table 1. Material Property Conversions for HAM-Tools and WUFI

WUFI Input	Conversion from WUFI to HAM-Tools	Ham-Tools Input
Thermal conductivity	Same	Lambda_dry: Thermal conductivity of dry material
Water vapour diffusion resistance factor, $\mu_{(@RH)}$	Delta_p_RH = $\delta_0 / \mu_{(@RH)}$ where $\delta_0 = 2 \cdot 10^{-7} \cdot T^{0.81}/P$	Delta_p_RH: Vapor permeability
Temperature dependent thermal conductivity supplement	Same	Lambda_T: Thermal conductivity factor dependent on temperature
Water absorption coefficient	Same	WAC
Free water saturation	Same	W_capillary: Capillary moisture content by volume
Moisture storage function (@RH)	Slope_sorption_ksi = ∇(moisture storage function (@RH))	Slope_sorption_ksi: Slope of the sorption isotherm at specific RH
Liquid diffusion resistance factor	$K = \frac{\rho_{dry} \cdot D_y}{\frac{\partial P_{capillary}}{\partial w}}$ $P_{suc} = \frac{\ln(\mathrm{RH}) \cdot R \cdot T \cdot \rho_w}{M_w}$	Hyd_Cond_K = Hydraulic Conductivity
Thermal conductivity	Heat resistance = (1/thermal conductivity)·thickness	Heat resistance
μ	Vapour resistance = $1/(\delta_0 / \mu) \cdot$thickness	Vapour resistance

kinds of moisture transports: the suction, which is when free water is presented at the material surface (such as rain), and redistribution, which is the transport of moisture without the presence of free water. The transport redistribution coefficient is approximated one tenth of the suction coefficient.

In HAM-Tools, the liquid transport uses the water retention curve and is based on the suction pressure difference across the material thickness. It is governed by Darcy's law, shown in Equation 3.

$$g_w = K \cdot \frac{\partial P_{suc}}{\partial x} \tag{3}$$

where K is the hydraulic conductivity in kg/Pa·m·s, P_{suc} is the suction pressure in Pa, and $\partial/\partial x$ is the differentiation term in the x direction. The relationship between these two means of water transports can be calculated using Equation 4 (Carmeliet and Roels 2000).

$$K = -\frac{\rho_{dry} \cdot D_y}{\frac{\partial P_{capillary}}{\partial w}} \tag{4}$$

where ρ_{dry} is the density of the material in kg/m^3. The relationship between moisture content and suction pressure is known as the retention curve. Thus, the differentiating term is the differentiation of the retention curve that obtains the moisture storage capacity of the material. Finding the relationship between relative humidity and suction (at high RH) allows for calculating the retention curve. Equation 5 describes this relationship (ASTM-Standard 2009).

$$\ln(\varphi) = \frac{P_{suc} M_w}{R T \rho_w} \tag{5}$$

where M_w is the molar weight of water and R is the ideal gas constant. It is possible to find the suction pressure at a specific relative humidity from the Equation 5. By using sorption isotherm curve of a material, the calculated relative humidity can then be used to find the moisture content of a material at the specific suction pressure. Subsequently, the retention curve can be obtained by correlating the moisture content and the suction pressure. Finally, this retention curve is used in Equation 4 to obtain the relationship between hydraulic conductivity and liquid diffusivity of a material.

If the sorption isotherm of a material in WUFI's database has enough details (moisture content values at high relative humidity), then the retention curve can be calculated. The retention curve is normally obtained through laboratory measurements using pressure plate technique, which uses overpressure to force water out of a saturated specimen (Janz and Johannesson 2001).

BOUNDARY CONDITIONS AND WALL CONSTRUCTIONS

In order to verify and validate the model, the boundary conditions have to be defined. This includes outdoor weather data and indoor climate data. The wall constructions are described below as well.

Exterior Weather Data

The weather data collected from a weather station located in downtown Toronto is used for the verification process. Since the wind-driven rain module is heavily dependent on wind speed, wind direction, and rain (Kumaran and Sanders 2008), it is important to verify the wind-driven rain module under a different climate with higher rainfall. Moreover, if the temperatures reach below freezing point, ice can form at high moisture levels in the pores of building materials. This affects the liquid transport by limiting capillary suction in building materials (Künzel 1995). Thus, it is important to choose weather data that not only has a high amount of rain, but also temperatures that mostly do not fall below freezing point. Therefore, the second set of weather data is obtained from an on-site weather station in Burnaby, BC, Canada, where there is higher amount of rainfall and only a few days that the temperature reaches below freezing point (Environment Canada 2012). This is an ideal climate for verification purposes for the wind-driven rain module. The simulations are conducted on the walls facing the prevailing wind-driven rain, which is east and south-east for Toronto and Burnaby locations, respectively. The driving rain diagram is shown in Figure 2. It should be noted that the duration of the Toronto weather data is for the whole year of 1984, while Burnaby data is from Beginning of January till end of June of 2008.

Interior Climate Data

The interior climate is set according to EN 15026 standard from International Association for Science and Technology of Building Maintenance and Monument Preservation (WTA) Guideline 6-2-01/E. The moisture load is set to normal use and initial conditions of the wall assemblies are set at 20°C. Both HAM-Tools and WUFI have an option to select the EN 15026 standard for the indoor conditions.

Wall Construction

The first wall assembly constructed in both programs is chosen to be a typical North American wood frame residential wall construction. Detail of the wall assembly is shown in Table 2. This assembly is tested against Toronto weather data.

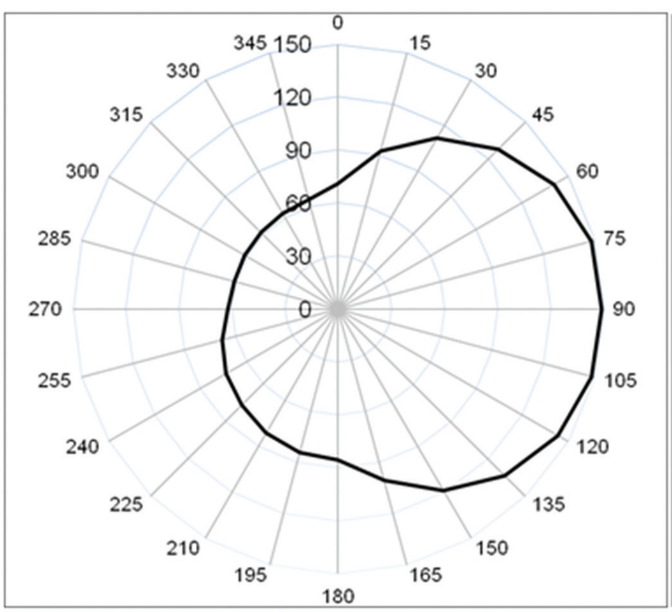
The second wall represents the wall assembly tested in the test facility in Burnaby. The details of the wall can be found in Table 3.

The wall construction in Table 3 is used with Burnaby weather for both verification and validation purposes.

RESULTS AND ANALYSIS

Verification Using Toronto Weather Data

First, the weather data from Toronto (January 1 to December 31, 1984) with the wall assembly described in Table 2 was used. In order to achieve a base comparison, the wind-driven rain module was turned off. The results are shown in Figure 3 with wind-driven rain module off. The figure also shows the relative difference with WUFI's results as the reference. It should be noted that in order to keep the simulations consistent between the two programs, the numerical mesh for HAM-Tools was changed to correspond to that used in WUFI for all the simulations.



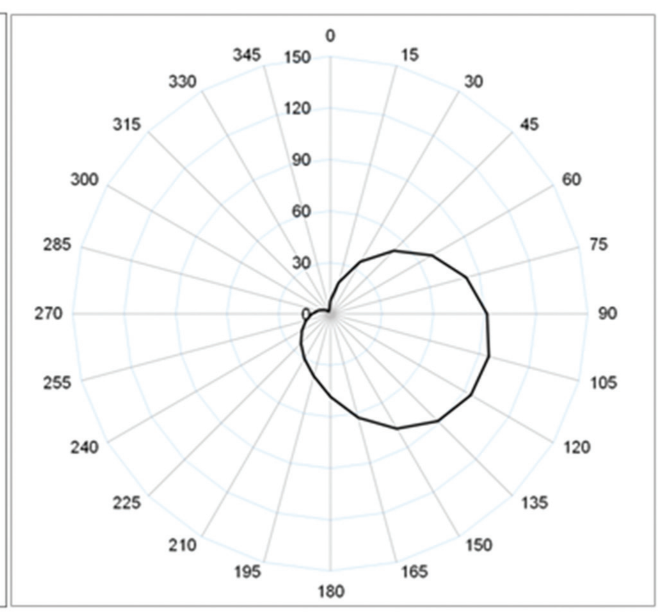


Figure 2 *(Left) Wind-driven rain rosette for Burnaby for four months from January to April 2008 (mm). (Right) Annual wind-driven rain rosette for Toronto using year 1984 weather data (mm).*

Table 2. Simulated Wall Construction

Material (Outdoor to Indoor)	Thickness, mm	Thickness, in.
Wood siding	20	0.787
Air space	19	0.984
60 minute building paper	0.1	0.00394
OSB sheathing	12.5	0.492
Fiberglass insulation	89	3.504
Polyethylene vapour retarder	0.15	0.00591
Gypsum board	12.5	0.492

Table 3. Field Experiment Wall Assembly

Material (Outdoor to Indoor)	Thickness, mm	Thickness, in.
Red matt clay brick	90	3.543
Air space	25	0.984
Spun bonded polyolefine (SBP) membrane	0.2	0.00787
Plywood	12.7	0.5
Low density fiberglass batt insulation	140	5.512
Polyethylene membrane	1	0.0393701
Gypsum board	12.5	0.492

The relative difference in moisture content is shown to be 10% or less between the two programs. This difference between the two programs should be considered when analyzing the results with the WDR module activated.

The simulation is then performed with the WDR module turned on. The result is shown in Figure 4.

When the wind-driven rain is on, the same difference can be observed when the module was off. However, just considering the spikes that show the presence of rain, it can be seen that the relative difference of these spikes is 10% or less. The reason for this effect is due to the difference in liquid diffusivity for suction and distribution that WUFI uses. When rain is present, the suction transport coefficient in WUFI is used in the calculation. This is the same value that is used to calculate the hydraulic conductivity for HAM-Tools. However, WUFI uses the redistribution transport coefficient when the rain stops and there is no presence of free water. The redistribution coefficient is generally one tenth of the suction coefficient. Therefore, HAM-Tools results tend to dry out faster during the rainy periods.

The same simulation is also performed with Burnaby weather data and wall construction described in Table 3. The moisture content of plywood, the fourth layer from exterior is used for this comparison. The result is shown in Figure 5.

The relative difference in the plywood between the two simulations is mostly around 2% to 4%, with the exception of the very end of the simulation that shows around 8% difference. Similar to previous comparison of wood siding, this difference can be explained from the slight variation in vapour diffusion and vapour permeability values between the two programs.

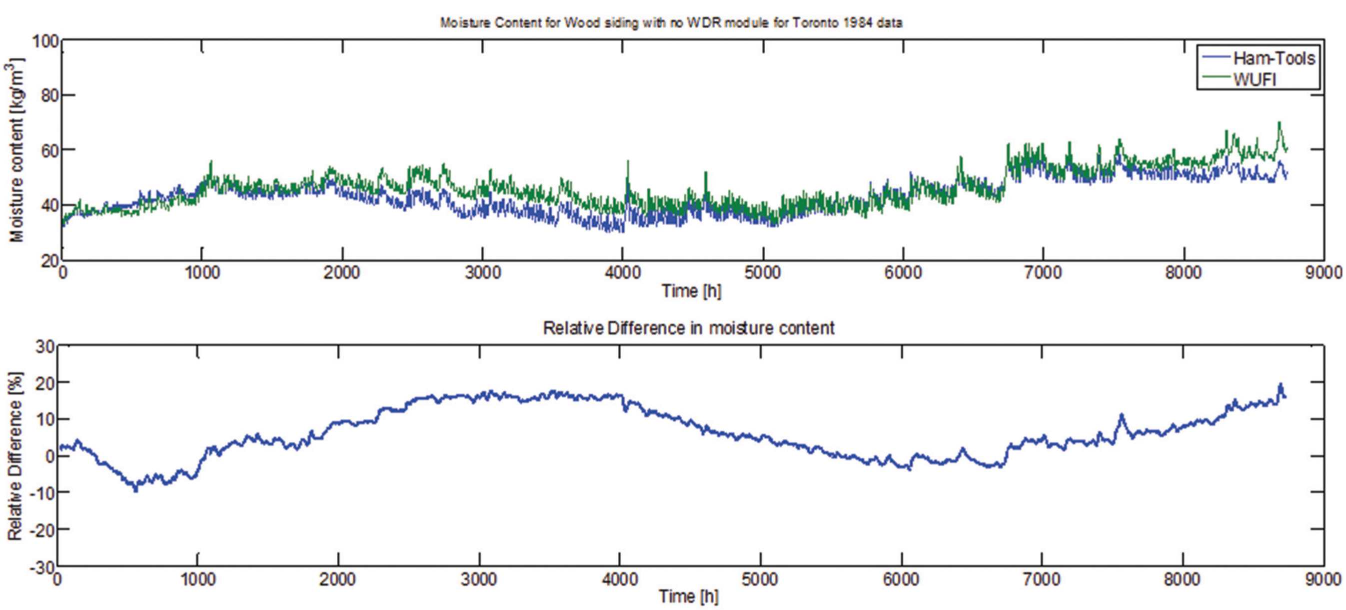


Figure 3 *(Top) Comparison of moisture content in wood siding between HAM-Tools and WUFI with wind-driven rain off. (Bottom) The resulting relative difference in % between these two programs. WUFI results are used as reference.*

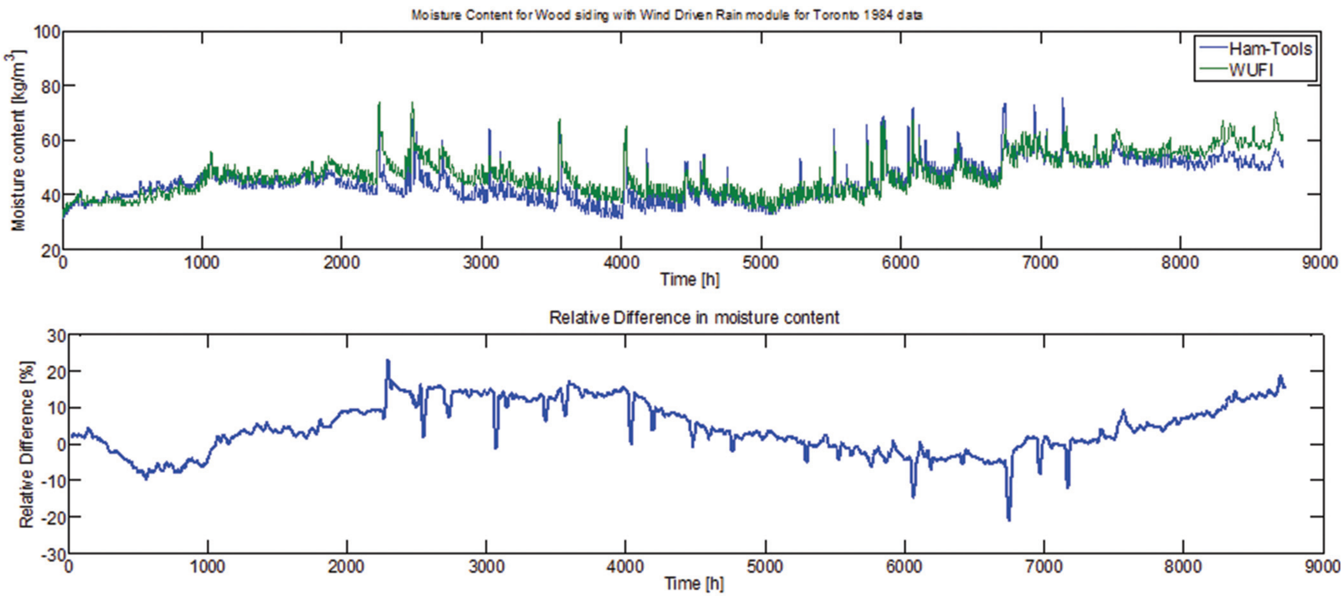


Figure 4 *(Top) Comparison of moisture content in wood siding between HAM-Tools and WUFI with the wind-driven rain module on. (Bottom) The resulting relative difference in % between these two programs. WUFI results are used as the reference.*

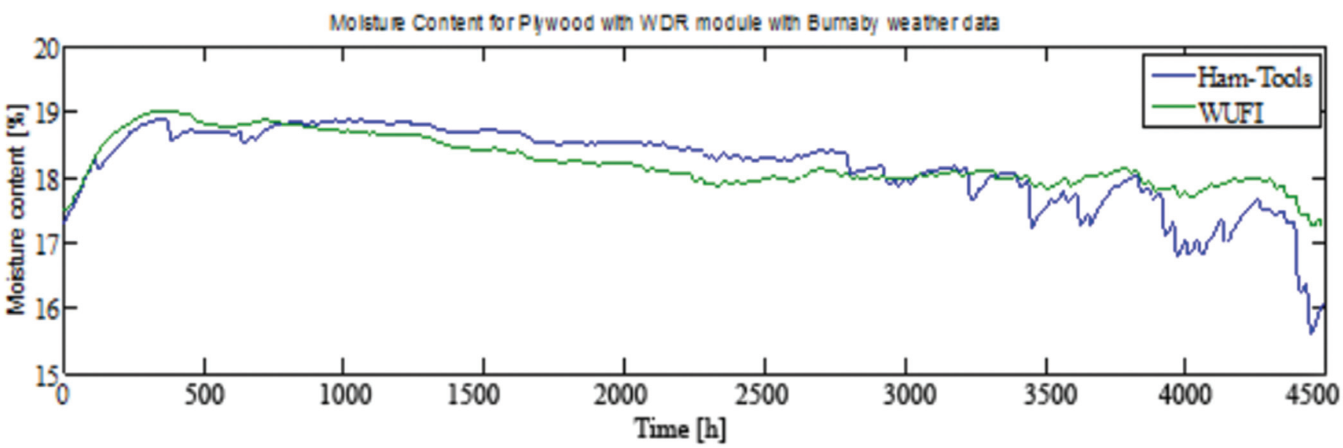


Figure 5 *Comparison of moisture content in plywood between HAM-Tools and WUFI with the wind-driven rain module on.*

MODEL VALIDATION

A field measurement experiment was conducted on the test facility in Burnaby using the wall assembly described in Table 3 and the Burnaby weather data in 2008 (Simpson and Ge 2010). The field measurements' initial moisture content of each layer is shown in Table 4.

It should be noted that there were no sensors present in the insulation and gypsum board to obtain initial relative humidity for those layers, and so they were assumed to have the same value as the interior conditions (Simpson and Ge 2010).

Table 4. Initial Relative Humidity of Wall Components in Burnaby Test Hut

Wall Component	Relative Humidity, %
Brick veneer	91.5
Plywood	87
Insulation	50
Gypsum board	50

One of HAM-Tools input data is initial relative humidity. This value controls the initial moisture content of all the layers in HAM-Tools. The influence of initial conditions will diminish for simulations over a long period, such as a couple of years. For verification section, the initial relative humidity of all materials in both WUFI and HAM-Tools were kept the same. However, for this particular case, only a few months' measurements and on-site weather data were collected. Therefore, it is important to set the accurate initial conditions. In order to demonstrate this effect, a simple comparison is performed on the plywood for half a year using WUFI. For the first setup, the initial moisture content of all the layers is set at 87% rh. In the second setup, the initial moisture content of plywood is kept at 87% while all the other layers are changed to be at 40% rh. The results are shown in Figure 6.

This result shows that having different initial moisture content in the surrounding layers directly affects the moisture content in the studied layer. This affects the result at the very beginning of the simulation by increasing or decreasing the moisture content of the surrounding layer. As a result, to better reflect the reality, different initial relative humidity inputs for each layer were added in HAM-Tools and the variable for every single node within the construction block was changed accordingly. The result was compared to WUFI and is shown in Figure 7.

With correct initial moisture content, HAM-Tools was then tested and compared with field measurements. Figure 8 shows the simulated and measured results.

The simulated result shows the same trend as the measured data with a relative difference of around 5% and a maximum difference of around 10%. The differences may be

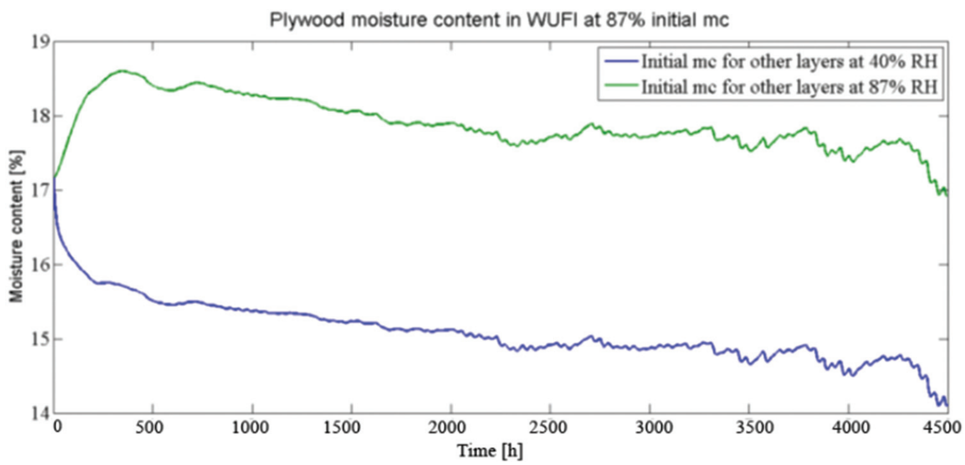


Figure 6 *Comparison of plywood's moisture content with different initial conditions.*

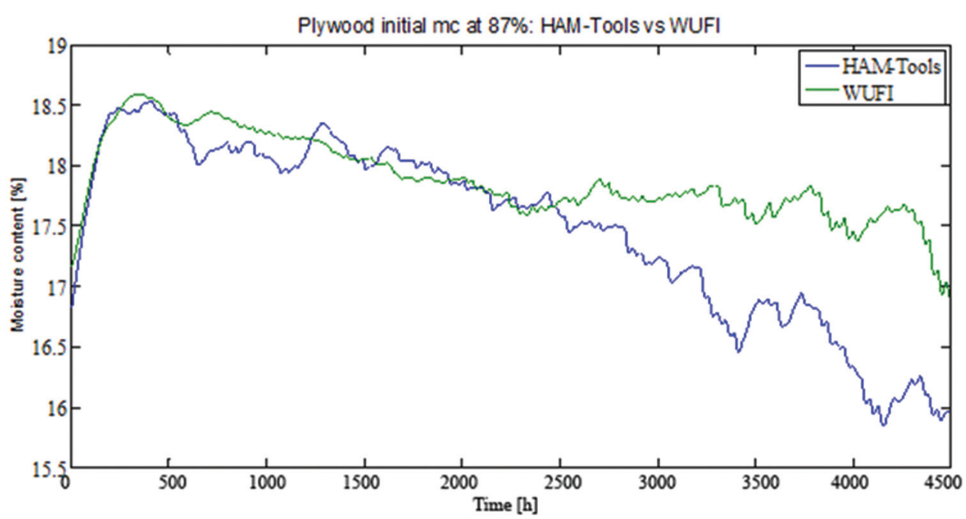


Figure 7 *Plywood's moisture content comparison between HAM-Tools vs WUFI with different initial moisture content at each layer.*

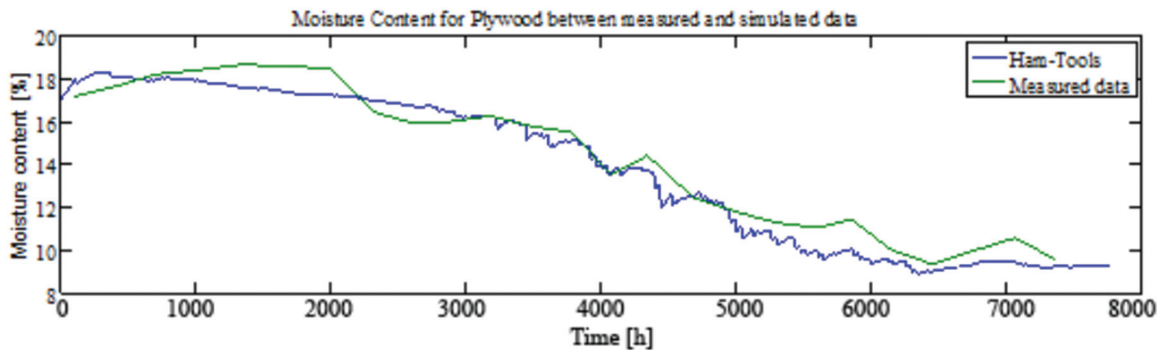


Figure 8 *Comparison of moisture content of plywood between simulated (HAM-Tools) and measured data.*

attributed to the initial moisture content of the materials, discrepancy in material properties, and measurement errors. Thus, with a more accurate measurements, the program may obtain better results in comparison with measured data. It should be noted that there were no sensors present to measure the moisture content in the layers behind the plywood (batt insulation and gypsum board) since it was not needed for the study (Simpson and Ge 2010). The assumed initial moisture content of the insulation slightly affects the outcome of the comparison. Similarly, the liquid and vapour diffusivity of each material were not directly measured. Instead, WUFI's material database was used to provide these values.

CONCLUSIONS

The previous study to create a wind-driven rain module for HAM-Tools required proper verification with other simulation programs and validation with measured data. A widely accepted commercial program, WUFI, is used for the verification. Because of the very limited material database in HAM-Tools, materials from WUFI's database were selected. Importance was placed on proper conversion of these material properties from WUFI to the HAM-Tools. The most significant one was the water transport properties, in which HAM-Tools uses hydraulic conductivity while WUFI uses liquid diffusivity. Moreover, the consistency for the weather data between each program and actual data had to be considered.

First, the conversion formula between hydraulic conductivity and liquid diffusivity was found. Then proper materials were chosen from WUFI's database that included enough information for the conversion to be applied. Using these materials, a wall assembly was chosen and used to validate the module by comparing the results with WUFI. The results showed a 10% relative difference in the exterior layer when the WDR module was off due to vapour diffusion. When the module was on, the relative difference for the spikes were less than 10% as well. This can be explained since HAM-Tools uses the same water transport coefficient (hydraulic conductivity) for both wetting and drying periods while WUFI has a smaller value for drying periods. The comparison between these two programs was also made for a wall assembly tested under Burnaby weather conditions. The result showed an average relative difference of 4% in the moisture content of plywood.

Finally, the module was compared with field measurements carried out on a building envelope test facility. The comparison showed a relative difference of around 5% and a maximum relative difference of around 10%. This difference can be due to the discrepancy in material properties, initial moisture content, effect of air movement presented in the air cavity, and measurement errors. In general, the simulation results from HAM-Tools agree well with simulation results from WUFI and field measurements. Thus, it can be concluded that the newly designed HAM-Tools wind-driven rain module is performing properly.

NOMENCLATURE

D_w	=	liquid transport coefficient, m^2/s
F_D	=	rain deposition factor
F_E	=	rain exposure factor
F_L	=	empirical constant (0.2), kg·s/(m^3·mm)
g_w	=	liquid moisture flux (or density of moisture flow rate), kg/m^{2}s
K	=	hydraulic conductivity, kg/Pa·m·s
M_w	=	molar weight of water (0.018, Kg/mol
P	=	atmospheric pressure, Pa
P_{suc}	=	suction pressure, Pa
R	=	ideal gas constant (8.314), j/(mol·k)
R_{wdr}	=	wind-driven rain intensity, mm/h
T	=	thermodynamic temperature, K
T'	=	absolute temperature, K
w	=	liquid moisture flux, kg/m^3
$\partial/\partial x$	=	differentiating in the x direction, m
$\frac{\partial P_{capillary}}{\partial w}$	=	suction isotherm or Hydraulic conductivity
θ	=	direction of wind, °
ρ_w	=	density of water (1,000), kg/m^3

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