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State-of-the-Art for Hygrothermal Simulation Tools

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February 15, 2017

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Building Envelope & Urban Systems Research

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ACRONYMS

BTRIC	Building Technologies Research and Integration Center
DOE	Department of Energy
EMPD	Effective Moisture Penetration Depth
HAMT	Combined Heat and Moisture Transfer
HVAC	Heating, Ventilation and Air Conditioning
ORNL	Oak Ridge National Laboratory
WUFI	Wärme Und Feuchte Instationär

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ABSTRACT

The hygrothermal (heat and moisture) performance of buildings can be assessed by utilizing simulation tools. There are currently a number of available hygrothermal calculation tools available which vary in their degree of sophistication and runtime requirements. This report investigates three of the most commonly used models (WUFI, HAMT, and EMPD) to assess their limitations and potential to generate physically realistic results to prioritize improvements for EnergyPlus (which uses HAMT and EMPD). The outcome of the study shows that, out of these three tools, WUFI has the greatest hygrothermal capabilities. Limitations of these tools were also assessed including: WUFI's inability to properly account for air leakage and transfer at surface boundaries; HAMT's inability to handle air leakage, precipitation-related moisture problems, or condensation problems from high relative humidity; and multiple limitations for EMPD as a simplified method to estimate indoor temperature and humidity levels and generally not used to estimate the hygrothermal performance of the building envelope materials. In conclusion, out of the three investigated simulation tools, HAMT has the greatest modeling potential, is open source, and we have prioritized specific features that can enable EnergyPlus to model all relevant heat and moisture transfer mechanisms that impact the performance of building envelope components.

1. BACKGROUND

EnergyPlus is a powerful simulation tool capable of estimating energy performance of buildings and building components. Such a tool is essential for optimizing heating and cooling system by determining the indoor environmental conditions as a function of the outdoor environment, envelope performance, equipment, and more. In addition to making buildings more energy efficient, buildings also need to be durable and last for their expected service life. High levels of moisture inside the building envelope materials can reduce the service life of buildings by creating an unhealthy indoor environment due to microbiological growth (e.g., mold). Moisture can also cause structural damage to organic materials, such as wood, via decay (i.e., rot). In addition, high indoor moisture levels impact the operational efficiency of heating, ventilation and air conditioning (HVAC) systems; specifically, the more moisture, or latent load, the more energy will be used to dehumidify the air during cooling. As building envelopes become tighter to meet more energy-efficient building code requirements and preserve the conditioned indoor environment amidst the changing outdoor environment, less heat flow translates into less moisture transport across the envelope, which can result in moisture-related failures for buildings, "cities of tarps," and related litigation issues for buildings that would have functioned properly under older building codes where heat and moisture could more freely move between the layers of the building envelope.

Since moisture plays an important role in estimating both durability of the building envelope components and HVAC efficiency, properly simulating moisture transfer in EnergyPlus is highly relevant for ensuring accuracy of the simulation result. As of today, there are two main algorithms that account for moisture transfer mechanisms in EnergyPlus; the HAMT and the EMPD models. Despite being validated to account for transient heat and mass transfer, these models do not serve as the most frequently used tools to estimate the hygrothermal performance of a building envelope. Therefore, it is important to investigate why these models are not used more often and determine:

- can a user trust the simulation result generated by both HAMT and EMPD models,
- are both tools capturing all relevant moisture transfer mechanisms, and
- what can be done to improve calculation accuracy?

The HAMT and EMPD models will be compared with the most frequently used hygrothermal calculation tool, Wärme Und Feuchte Instationär (WUFI) (Künzel 1995). This tool has been validated (Kehrer and Schmidt 2008), and is useful for comparing hygrothermal features and simulation results.

2. MOISTURE TRANSFER ALGORITHMS IN ENERGYPLUS

There are two main algorithms that account for moisture transfer mechanisms in EnergyPlus - HAMT and the EMPD. We briefly summarize how these algorithms model hygrothermal performance and discuss possible improvements related to the computational efforts involved.

2.1 Combined Heat and Moisture Transfer (HAMT) Model

According to its developer, HAMT is a completely coupled, one-dimensional, finite element, heat and moisture transfer model, simulating the flux and storage of heat and moisture. The HAMT model description is given in the EnergyPlus documentation (DOE 2017). However, despite the claim that HAMT is a complete heat and moisture transfer model, and available at no charge, it's not as widely respected or used to assess hygrothermal performance of buildings and its components as tools like WUFI (Künzel 1995).

One reason why HAMT is not as frequently used is the computation effort required to complete the calculations. In HAMT the default temperature convergence limit is 0.002°C. We investigated how changing that number would affect the simulation result. By using a modified example file included with EnergyPlus 8.6, *HAMT_HourlyProfileReport.idf*, we evaluated the run time, temperature, relative humidity and water content in the center of the modeled roof. The roof assembly consists of plywood, cellulose and spruce materials (listed from outside to inside layers). We modified this input file to output the temperature, relative humidity and water content in layer 12 of the roof assembly (middle of cellulose layer), and then ran the simulation for one year using Baltimore Maryland TMY3 weather data.

To change the temperature convergence limit, EnergyPlus source code for version 8.6.0 was downloaded and line 144 of the HeatBalanceHAMTManager.cc file was modified. The default value is 0.002°C and in addition to this criterion we also tried, 0.05, 0.02, and 0.00001°C. Table 1 shows the simulation time for each of these temperature convergence limits.

Table 1: A relaxed temperature convergence criteria results in shorter run times. Run time of EnergyPlus 8.6.0 for different HAMT temperature convergence limits. Values are for simulations with 6 time steps per hour.

	Time (s)					
HAMT Temp Conv (°C)	Sim 1	Sim 2	Sim 3	Sim 4	Sim 5	Average
0.00001	862	920	890	902	875	889.8
0.002	216	210	215	210	209	212
0.02	132	127	128	127	129	128.6
0.05	124	118	120	118	116	119.2

We compared the change of the temperature, water content and relative humidity (for the different convergence limits) in one cell of the roof. Figure 1 shows the difference in temperature between the default convergence limit and for 0.05 and 0.02°C convergence limits. Notice that the difference is less than ±1°C for all cases, however the difference increases as the convergence limit relaxes.

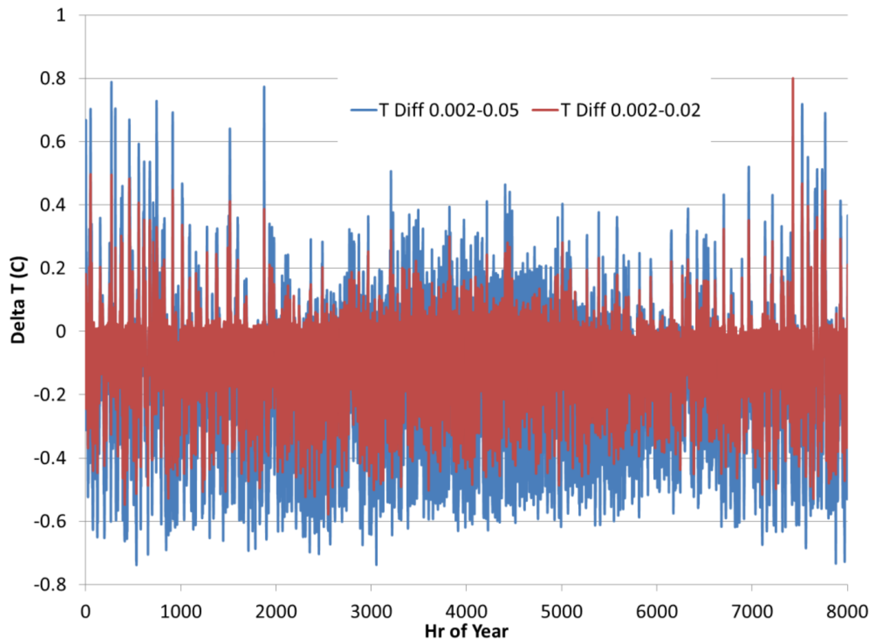

Figure 1: The temperature difference increases as the convergance limit relaxes. Figure shows the difference, in hourly temperature for the cellulose layer of a cathedral roof, between EnergyPlus' default convergence limit of 0.002°C for HAMT and other convergence limits.

Figure 2 shows the difference in water content between the default convergence limit and for 0.05 and 0.02°C convergence limits. The hourly difference is less than ±7 g H_2O per kg of cellulose out of an hourly average 114 g/kg of water content (output from EnergyPlus) for the year equates to a 6% maximum error.

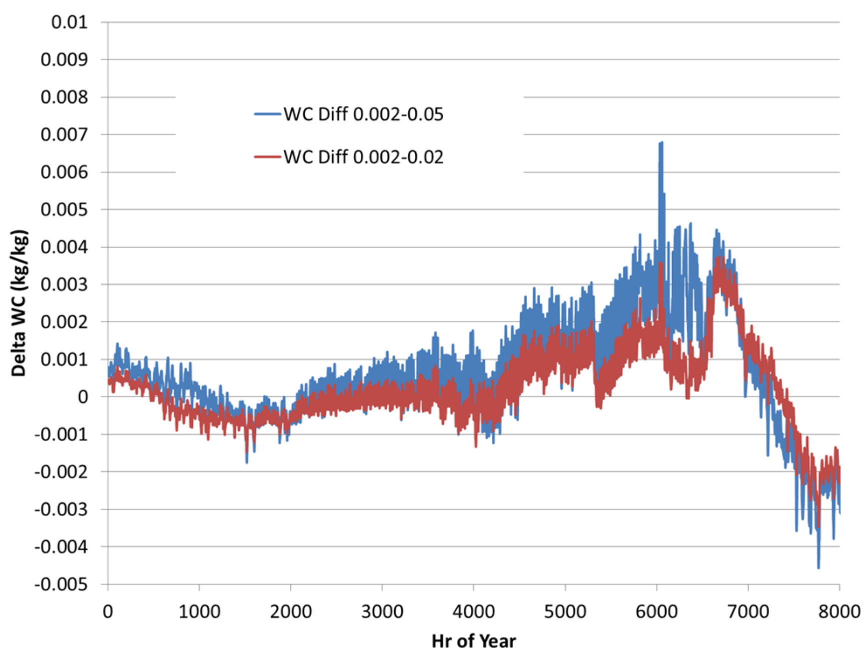

Figure 2: Difference in water content compared to default convergance limit is less than 6%. Plot shows difference in hourly water content for the cellulose layer of a cathedral roof, between EnergyPlus default convergence limit of 0.002°C for HAMT and other convergence limits.

Figure 3 shows the difference in relative humidity between the default convergence limit and for 0.05 and 0.02°C convergence limits. Notice that the difference is less than ±2.5% RH.

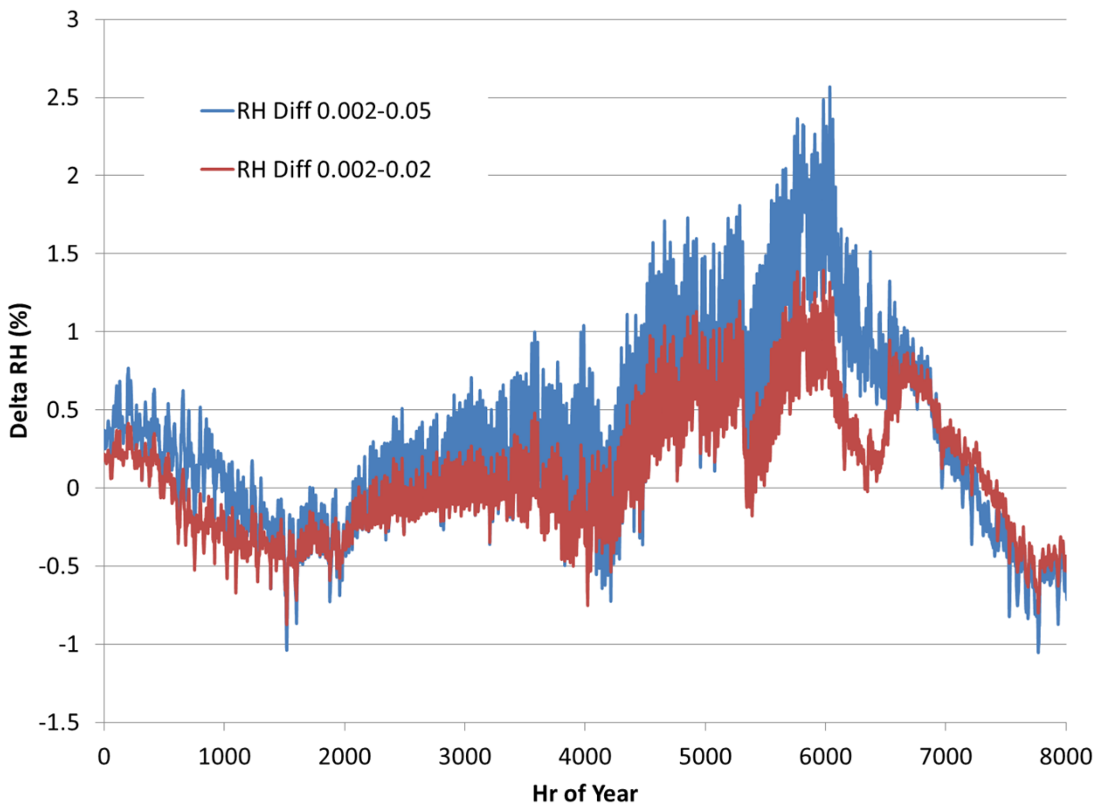

Figure 3: More relaxed convergance limits only cause a max difference in material RH of 2.5%. Plot shows difference in hourly relative humidity for the cellulose layer of a cathedral roof, between EnergyPlus' default convergence limit of 0.002°C for HAMT and other convergence limits.

2.2 Effective Moisture Penetration Depth (EMPD) Model

The Effective Moisture Penetration Depth (EMPD) model is a simplified approach to simulate surface moisture adsorption and desorption (DOE 2017). It estimates moisture adsorption and desorption from building surfaces and calculates the effect on the humidity in each thermal zone of the simulation model. There are two fictitious layers of material with uniform moisture content: (1) a surface layer, which accounts for short-term moisture buffering, and (2) a deep layer, which accounts for more slowly responding moisture buffering.

The EMPD algorithm is a simplified, lumped moisture model that simulates moisture storage and release from interior surfaces. Properties of multiple layers of various construction materials within a wall are lumped to create fictitious two layers; a surface layer and a deep layer. The properties that are lumped include water vapor diffusion resistance factor, and coefficients used to define the sorption isotherm curve. Similarly, moisture content is reported for the fictitious two layers.

The model calculates the moisture transfer between the air and the surface layer and between the surface layer and the deep layer. This moisture transfer impacts the indoor humidity, the indoor temperature through latent-to-sensible conversion from the heat of adsorption, and moisture in materials.

A major limitation of the EMPD model is that it ignores the moisture transfer between the exterior of the building envelope and the outdoors, and reports moisture content of the fictitious. A simple analysis was conducted to confirm that EMPD model used by EnergyPlus also does not account for moisture transfer between the exterior of the building envelope and the outdoor. EnergyPlus example file EMPD5ZoneWaterCooled_HighRHControl.idf was modified to eliminate infiltration and ventilation and simulated using a modified TMY3 weather file for Chicago. First outdoor air relativity humidity was fixed at 90% for the entire year (case 1) and then fixed at 10% (case 2). Figure 4 shows the percent difference in deep layer moisture content (DLMC) for the simulated wall

Where,

$$Percent\ difference\ in\ deep\ layer\ moisture\ content = \frac{DLMC\ for\ case\ 1 - DLMC\ for\ case\ 2}{DLMC\ for\ case\ 1} * 100$$

As seen in Figure 4, the initial difference is approximately 60% and gradually the difference decreases to zero over two months. After that, the DLMC is identical for both cases. No difference in DLME between the two cases with high difference in outdoor RH confirms that EMPD model does not account for moisture transfer between the exterior of the building envelope and the outdoor. How this issue can be resolved is discussed further in Section 4.

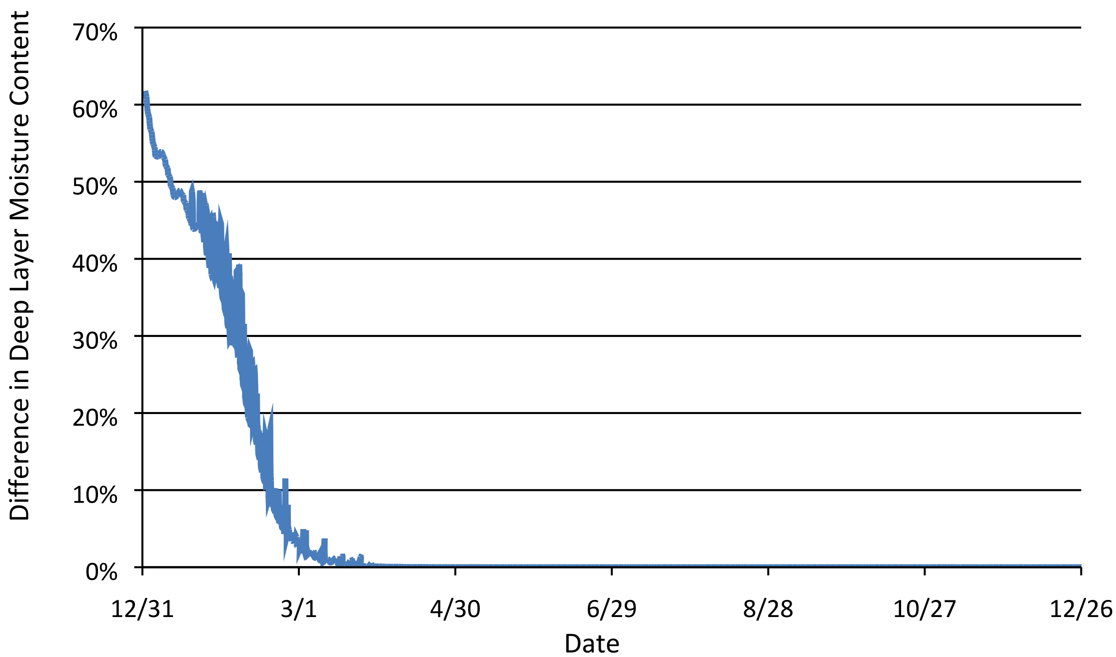

Figure 4 Percent difference in deep layer moisture content between the two simulated cases.

The EMPD model is derived by assuming cyclic variations in a thermal zone's humidity, and therefore in the humidity loads (Woods, Winkler et al. 2013). The surface layer's effective moisture penetration depth is based on the short-term fluctuations of humidity, typically on the order of a day. The deep layer effective moisture penetration depth is based on longer term humidity fluctuations, which may be from short-term changes in weather (~weeks) or seasonal variations (~months) (Woods, Winkler et al. 2013). To verify hourly variation in indoor and outdoor humidity ratio, EnergyPlus example file EMPD5ZoneWaterCooled_HighRHControl.idf was used with a TMY3 weather file for Chicago. Figure 5 shows the outdoor and indoor air humidity ratio for one week in winter and one week in summer. Clearly, there is a significant seasonal variation in outdoor air humidity ratio, but not as much in indoor humidity. Therefore, accounting for moisture transfer between the exterior of the building envelope and the outdoor is important for being able to realistically model moisture transfer through the walls and moisture content in building materials. This becomes even more important when the exterior envelope is constructed of hygroscopic materials such as brick, concrete, or any cementitious cladding.

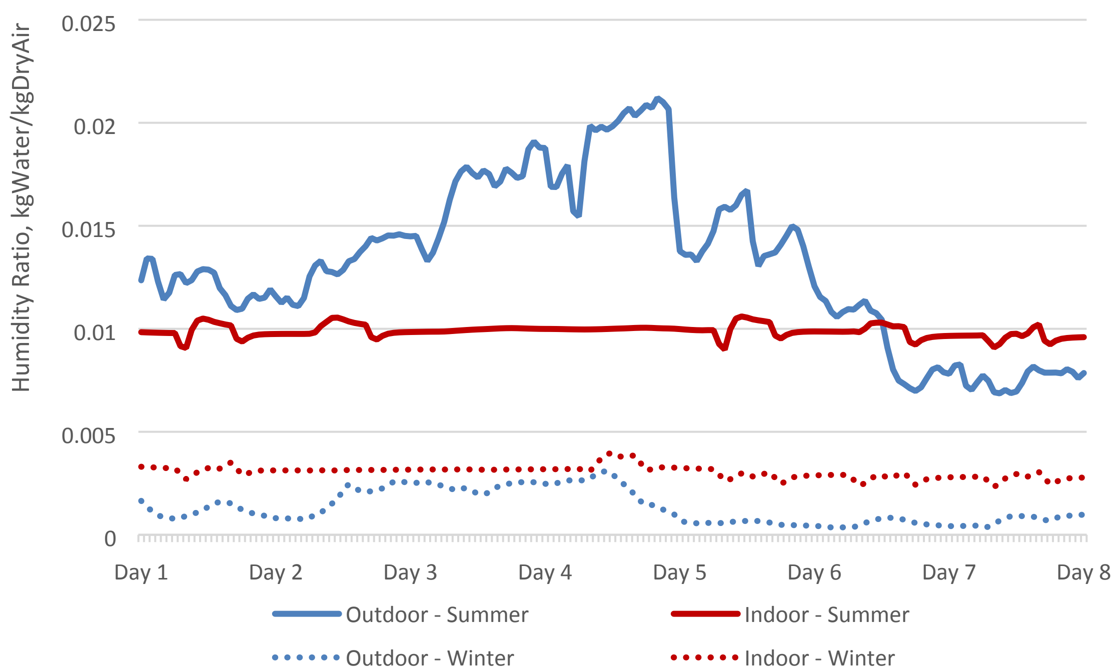

Figure 5 Comparison of outdoor and indoor humidity ratios using example file EMPD5ZoneWaterCooled_HighRHControl.idf and TMY3 file for Chicago.

As previously explained, EMPD is a simplified, lumped moisture model which includes two fictitious layers of material with uniform moisture content: a surface layer, which accounts for short-term moisture buffering, and a deep layer, which accounts for more slowly responding long term moisture buffering. It calculates the moisture content of the fictitious surface layer and deep layer. The surface layer and deep layer nodes are at the center of the fictitious layers, which assumes uniform moisture content within the layer. The EMPD outputs moisture content of the fictitious layers. Therefore, the values for moisture content have no direct physical meaning that can be used to predict either moisture content of individual building materials, or for the evaluation of potential moisture problems.

3. HYGROTHERMAL SIMULATION FEATURES

There are several natural phenomena that impact the heat and moisture performance of buildings that are not accounted for in WUFI, HAMT or EMPD. Table 2 depicts the available features from the major hygrothermal tools we analyze in this report. While WUFI has the most features, there are heat and moisture transfer mechanisms that are not accounted for and require more in-depth analysis.

Table 2. Feature Comparison Matrix of WUFI, HAMT and EMPD.

Natural phenomenon:	**WUFI Pro**	**HAM-T**	**EMPD**
Moisture storage capacity	x	x	x
- with temperature dependency			
- with relative humidity dependency	x	x	x
Water (liquid) transportation	x	x	
- capillary pressure driven	x	x	
- gravity driven			
Water (vapor) transportation	x	x	
- with relative humidity dependency	x	x	
Air leakage (Infiltration/Exfiltration) through materials	x		
- with temperature dependency			
- wind and ventilation driven			
Surface water absorption (capillary suction)	x		
Combined diffusion and capillary suction	x		
Precipitation	x		
Stagnant water on surface			
Exchange of moisture between model and interior conditions		x	x
Moisture effusivity, contact resistance between materials			
Intermediate condensation	x		
Thermal conductivity	x	x	x
- with temperature dependency	x		
- with relative humidity dependency	x	x	
Heat storage capacity	x	x	x
- with relative humidity dependency		x	
Radiation exchange at boundary surfaces	x (exterior)	x	
Intermediate radiation exchange inside air cavitities			
Exchange of heat between model and interior conditions		x	x
Thermal effusivity, contact resistance between materials			

3.1 LIMITATIONS IN WÄRME UND FEUCHTE INSTATIONÄR (WUFI)

The first missing feature of WUFI in Table 2 is the capability of defining the moisture storage capacity of any arbitrary material as a function of temperature. This natural phenomenon can typically be seen in organic materials and can have a significant impact on the performance of materials such as wood. As an example, the roof sheathing in unvented (sealed) attic constructions have shown to be at risk under certain climate and material conditions (Less, Walker et al. 2016). Moisture back-and-forth between the attic environment and the sheathing causes periodically high moisture contents of the wood large enough to result in wooden decay. This “ping-pong” effect is mainly a result of high temperature variations of the roof construction, the wood, and related moisture storage capacity. Since WUFI and EnergyPlus do not capture this phenomenon, the moisture performance failure of this roof construction cannot be foreseen.

WUFI has a built-in feature for handling convection. However, air leakage is not governed by boundary conditions, but instead by leakage rates a user defines manually. In reality, air leakage will be determined by two major factors; the air permeability of the building component and the air pressure gradient. Without taking into account wind loads, temperatures and possibly the characteristic of the ventilation system, it is difficult to estimate how much air will travel through the building element in question. Air leakage is also one of the major causes to moisture durability failure in buildings (Prowler and Trechsel 2008), which is why this feature ought to be included in a hygrothermal calculation tool.

Another missing feature in WUFI is the lack of heat and moisture exchange between the simulation model and boundary conditions. There exists a one-way exchange from the boundary conditions to the simulation model, but not vice-verse. For this reason, the indoor climate conditions will not change by how much heat and moisture is escaping from the interior surface, but instead fixed to standardized approaches that are used to estimate indoor climate conditions based on exterior conditions, such as ASHRAE 160, EN 13788, and EN 15026 (ISO 2001, EN 2007, ASHRAE 2016).

3.2 LIMITATIONS IN HAMT

HAMT is less feature-rich than WUFI. As part of EnergyPlus' algorithms, convection can be included in the simulations, but this only impacts the indoor temperature and moisture conditions, not a specific building envelope material. This means that in HAMT, and EMPD as well, air is "dumped" into the indoor environment without affecting the materials of the building envelope through which it travels. For example, HAMT cannot simulate a wall with a ventilated cladding, such as brick. Nor can it simulate humid air traveling through a building component and condensing at a material with a lower temperature inside the model. As has been discussed previously, air leakage is one of the main reasons for moisture durability failures in buildings and should be taken into account in a hygrothermal analysis.

HAMT does not take into account surface water absorption or precipitation. Obviously, rain water leakage is another major cause of moisture durability failures in building components. In addition, since precipitation is not taken into account, the natural phenomenon of solar driven moisture cannot be accounted for. This relatively quick moisture transfer mechanisms occurs when water absorptive cladding (brick, stone, stucco, etc.) is exposed to rain and how it reacts when being heated by solar radiation that follows a precipitation event. The temperature of the cladding will consequently rise by solar radiation exposure and drive moisture towards the interior of a wall assembly.

One heat and moisture transfer mechanism that HAMT is able to capture but WUFI is not, is the exchange of heat and moisture at interior and exterior boundary surfaces. Despite this interaction being accounted for in HAMT, there is currently no mechanism for outputting the heat and mass transfer at an interior or exterior surface. This feature allows the indoor environment to be fully coupled to the temperature and humidity conditions of the building envelope materials. This exchange of heat and moisture at a boundary surface is crucial to capture the impact of thermal inertia and moisture buffering capacity. Thermal inertia can have a big impact on temperature in buildings with materials such as concrete, stone or brick, and subsequently on the energy performance since these materials have high thermal storage capacity. The moisture buffering capacity will reflect on how much of the moisture content in the surrounding air is absorbed by the building, or the interior materials. This will impact indoor relative humidity levels with up to 10 percentage points (Pallin, Johansson et al. 2011).

EnergyPlus was recently modified to output the heat flux through different layers of the envelope construction (walls, roofs, floors); however, HAMT treats heat flux as steady-state with a constant of 0 for all envelope constructions. This appears to be an error in the code.

3.3 LIMITATIONS IN EMPD

The EMPD model is a simplified method to estimate indoor temperature and humidity conditions. Given the limitations defined in Table 2, particularly those relevant to moisture transfer mechanisms, we consider this model useless for full hygrothermal studies of the materials in a building envelope. However, it does estimate indoor humidity conditions by assuming that a building envelope has two different material layers in which moisture can be stored; one for short term changes in humidity indoor humidity conditions, and one for long term changes, as explained in Section 2.2. This approach has been successfully validated (Woods, Winkler et al. 2013), but to a limited extent since the study used a building envelope assembly which worked around EMPD's limitations. The validation study used an aluminum-faced polyisocyanurate foam board which largely prevents moisture transfer between the exterior of the building envelope and the outside. Since no moisture will travel through aluminum foil, any comparison with WUFI and HAMT has greater potential for a good agreement, but does not apply to building envelope assemblies where moisture can travel in both directions. Consequently, the EMPD model is not applicable for studying the moisture durability of building components.

4. DISCUSSION

EnergyPlus is a powerful tool for estimating the energy performance of buildings. Unfortunately, the embedded moisture transfer algorithms do not sufficiently account for moisture transfer mechanisms necessary to predict the moisture conditions of the indoor environment or the materials of the building envelope. The most-used hygrothermal tool, WUFI, is unable to capture all moisture transfer mechanisms for building and building envelope performance evaluation. WUFI's primary missing feature is air leakage which is difficult to simulate due to the constantly changing temperature and moisture conditions of the travelling air as it passes through the materials of the building envelope. Since air has relatively low volumetric heat and moisture buffering capacity, it will adapt towards the conditions of the materials through which it travels. Therefore, the air leakage path preferably needs to be known in order to estimate how much heat and moisture are released or gained by the air as it travels through a building envelope component, such as a wall or a roof. If that path is unknown, it is difficult to estimate the likelihood of moisture durability problems.

In WUFI, air leakage is treated one dimensionally; meaning, you can add air leakage as a source or sink at any location inside your simulation model. Unfortunately, the temperature and moisture conditions of the air that is being placed inside the simulation model, is either the same as conditions of the outside, or of the inside, depending on user selection. This means that the air is just "dumped" into the simulation model, with no consideration to how it got there in the first place. Obviously, this approach is not applicable to real conditions but an attempt from the developer of WUFI to account for air leakage through building envelope components. There are methods for simulating 2- and 3-D air leakage using a 1-D simulation model (Pallin, Hun et al. 2016). This approach can be implemented into EnergyPlus' HAMT to properly account for the hygrothermal impacts of air leakage.

As discussed in Section 3.1, the moisture storage function of materials is not temperature dependent in WUFI. Therefore, WUFI cannot accurately predict wooden decay as seen in several unvented roofs with open cell foam insulation. As for EnergyPlus HAMT, this phenomenon can be accounted for by making changes to the code so that the moisture storage function changes with varying temperature conditions.

Hygrothermal simulation tools must account for water surface exposure, absorption and intrusion in order to provide moisture-related impacts that effect building envelope failure and energy consumption. These three mechanisms can have a big impact on the moisture conditions of the building envelope materials, but also impact heat flux. Accounting for precipitation in a hygrothermal calculation tool is highly relevant, especially in cases where dew, rain, or snow impact the roof surface temperature.

While EnergyPlus' HAMT is more capable than EnergyPlus' EMPD, its simplified approach can be used to assess the impact of the heat and moisture buffering capacity of materials on the indoor climate. This model can be improved by adding one more surface layer that will actively exchange moisture between the outdoors and the other building layers. This would allow EnergyPlus to take into account moisture-based interaction with the outdoor climate.

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