A SYSTEMATIC APPROACH TO HYGROTHERMAL MODELING AND COMPLIANCE WITH FAILURE CRITERIA USING WUFI

Pallavi Mantha[1] and Lois B. Arena[1]
[1]Steven Winter Associates Inc., Norwalk, CT

ABSTRACT

Simulating the prediction of moisture movement and related risk within building envelopes has gained momentum with the increased use of thicker walls, new materials and assemblies. One such simulation software used widely across North America for hygrothermal analysis is WUFI 5.1. As with any other simulator, WUFI 5.1 requires a few basic inputs such as location, orientation, climate and construction. But hygrothermal modeling is not a clear-cut task. The interactions between the macro level inputs and the dependency on molecular make-up and characteristics of materials makes prediction of hygrothermal performance very volatile. This volatility could lead to under or over predicting moisture related risk in building elements.

As a part of an ongoing research and monitoring project, the authors' team evaluated and intends to monitor several different configurations of wall assemblies in multiple climate and moisture zones to determine the accuracy of moisture modeling. The goal is to make recommendations to ensure durable, efficient assemblies. Based on this research, this paper presents a systematic approach to hygrothermal modeling with WUFI 5.1. Methods to determine compliance with existing failure criteria using results from WUFI 5.1 are discussed. General software observations and possible future improvements are suggested.

INTRODUCTION

The exterior building envelope is continuously subjected to outdoor climatic conditions that induce a dynamic air, heat and moisture gradient within the envelope. Compounding this dynamic is the increasing use of unconventional materials, construction techniques and new wall assemblies. Moisture finds its way into the envelope through various sources. Rainwater penetration, rising damp, bulk water intrusion from leaks, interstitial condensation due to air leakage, wetted building materials and high levels of interior humidity are some of the major sources.

Hygrothermal loads experienced by a building envelope vary with the temperature of the surfaces, permeability of the materials and boundary conditions. If moisture is trapped within the envelope, this could potentially lead to decay of the building materials and/or mold growth. Therefore, the design of the envelope for optimum thermal and hygric performance is crucial.

Transient mathematical models have been developed in an effort to provide a better understanding of the mechanisms and interactions of moisture and heat transfer in building envelopes. There has been a rapid improvement in the capabilities of computer-based moisture analysis tools that can predict the movement and accumulation of moisture in building components and materials. The tool discussed in this paper, WUFI 5.1, was created by the Fraunhofer Institute for Building Physics (IBP) and Oak Ridge National Laboratory (ORNL) WUFI 5.1 predicts moisture transfer by diffusion and capillary flow. It allows users to assess the effectiveness of the wall materials and constructions against moisture flow and indicates area where condensation can occur.

This paper draws on experience from performing approximately 500 residential wall simulations using WUFI 5.1, as a part of an ongoing research and monitoring project. The intention of this research study is to validate predictions from WUFI 5.1 for at least three different wall assemblies that are gaining popularity in the market, but have yet to be extensively monitored with respect to moisture and heat transfer. These assemblies include walls built to International Energy Conservation Code (IECC) using hybrid insulation strategies, high R-value walls, and brick masonry retrofits in climate zones 4 -7.

The following paper illustrates the process used to evaluate the compliance with various failure criteria applicable to hygrothermal performance of building envelope components.

HYGROTHERMAL MODELING

Predictions from hygrothermal computer simulations are very sensitive to the user inputs of the assumed boundary conditions and material properties. Inputs in WUFI 5.1 are organized into three basic categories: Component, Control and Climate.

Component

Construction assembly, orientation, surface transfer coefficients and initial conditions are input on this screen. Construction assemblies can be created using the materials in the material database. The user can insert monitoring positions at critical interfaces and within materials that are at an elevated moisture related risk. WUFI 5.1 calculates the temperature (T), relative humidity (RH), dew point and mold growth potential with limiting isopleths for each of the monitoring positions specified.

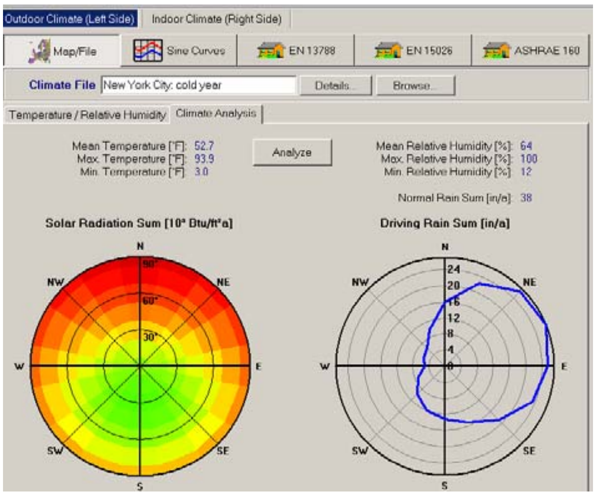

Figure 1 Screenshot showing climate analysis of the exterior climate for New York City, NY. North-East is the worst wind-driven orientation.

Orientation of the assembly dictates its interaction with the exposure to sun, wind and rain. Typically, a worst-case scenario is chosen for simulations; hence an orientation that receives the most wind-driven rain is selected. Solar vapor drive should also be accounted for while choosing a worst-case orientation. This information can be obtained from the 'Climate Analysis' tab on the 'Outdoor Climate' screen. *Figure 1* shows a screen shot of the solar radiation and wind driven rain wind roses for New York City, NY. North-East receives the most wind driven rain and hence chosen as the worst-case scenario orientation.

Inclination and building height is chosen as per the assembly being evaluated. For a project being evaluated for compliance with The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 160 "Criteria for Moisture – Control Design Analysis in Buildings", default driving rain coefficients specified by the Standard can be used. ASHRAE Standard 160 specifies a 1% rain exposure factor (FE) i.e. 1% of the water reaching the exterior surface will penetrate the exterior surface.

The surface transfer coefficients depend on the interior and exterior wall finishes. The user can specify heat resistance and permeance for the exterior and interior surfaces on this screen. Along with these, the user should also specify the radiation absorptivity, emissivity and adhering fraction of rain for the exterior surface. The initial conditions screen allows the user to input the initial relative humidity, temperature and water content in different layers of the assembly.

Control

The calculation period/profiles and numerics are input on this screen. Length of the calculation period (start and end dates) and time steps can be input on the calculation period/profiles screen. Simulation run time varies with assembly construction and analysis type. It is recommended that the simulation be run long enough to allow the wall to acclimatize. Typically, a hygrothermal simulation is modeled for a period of three consecutive years. This run time allows for the wall to acclimatize and reduce effects of assumed initial moisture content and temperature within the wall assembly.

Options that allow the user to control a calculation method are input on the numerics screen. For example, the user can choose to exclude moisture transport through capillary conduction from the calculation. This calculates the moisture transport only through vapor diffusion.

Climate

On this screen, the user defines the exterior and interior environmental exposure conditions of the construction. The external boundary condition is defined by selecting a weather file. WUFI 5.1 comes with a few built-in outdoor weather files in Hygrothermal Reference Years (HRY) format. HRY files contain radiation and rain loads that are crucial for moisture analysis. Along with these, HRY files contain cloud index, air temperature, relative humidity, wind speed and wind direction data.

Other weather file formats with rainfall data or custom weather files can also be used with WUFI 5.1.

WUFI 5.1 contains weather files for 55 North American cities. The user can select a representative warm year weather file or a representative cold year. These files are based on the years in the warmest and coldest 10th percentile of the 30 year weather data available.

The interior boundary conditions can be defined in several ways. The user can enter customized sine curves for the temperature and relative humidity or they can use various methods as defined in ASHRAE Standard 160.

COMPLAINCE WITH FAILURE CRITERIA

Moisture related damage within building envelope components could be attributed to various factors such as material properties, exterior and interior boundary conditions, and duration of exposure to moisture. The thresholds and/or considerations based on currently accepted failure criteria for moisture levels in building envelope components are: rot/decay in OSB/plywood, mold growth potential, condensation potential, assembly water content and frost damage in masonry walls.

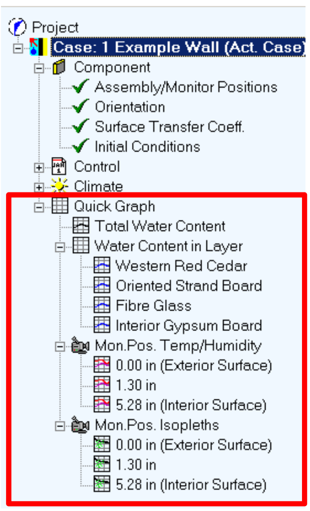

Figure 2: Screenshot of the output graphs from WUFI 5.1. These outputs are visible only after running a simulation

To comply with the failure criteria, post-processing of WUFI 5.1 outputs is required. Once a file is run, WUFI 5.1 creates the following graphs under the 'Quick Graph' menu item. (See highlighted portion in *Figure 2*).

- Total water content in lb/ft^2
- Water content in each layer of the envelope assembly in lb/ft^3
- Temperature in ^{o}F, relative humidity in % and dew point ^{o}F for exterior and interior surfaces (by default) and for every monitoring position inserted by the user.
- Mold growth isopleths for the exterior and interior surfaces (by default) and for every monitoring position inserted by the user

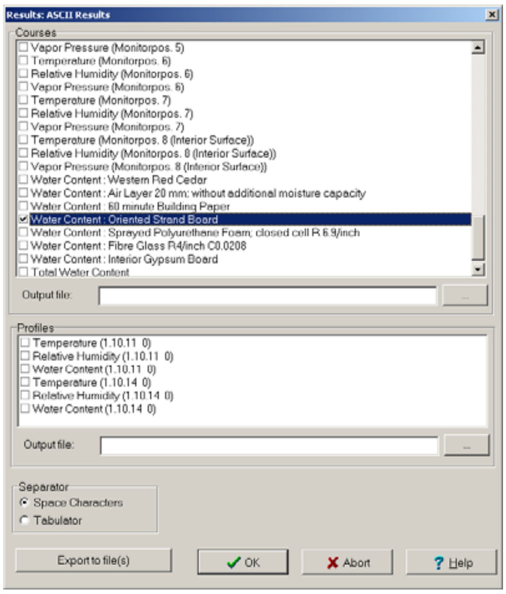

Figure 3: Screen shot of the ASCII -Export dialog box from WUFI 5.1

Data files can be exported from WUFI 5.1 in two ways:

1. Select a graph from the 'Quick graph' menu item as shown in *Figure 2*. Right click on the graph and export a file in the American Standard Code for Information Interchange (ASCII) format with the .ASC file extension.
2. The second option is to open the ASCII-Export dialog as shown in *Figure 3* from the 'Outputs' dropdown from the menu bar at the top. Select the required files to be exported and specify a folder for the output file.

The exported .ASC files can be processed using a standard spreadsheet tool. Note that each exported file will contain the number of data rows equivalent to user selection of simulation period and time steps. For example, an assembly simulated for three years with hourly time steps will have 26,280 data points.

Rot/Decay

It is often quoted that that the minimum water content requirement for the growth of fungi is about 20% in wood corresponding to about 80%- 90% relative humidity (Siau 1984). Decay generally occurs above 90-95% at 68°F (Viitanen et al. 2001).

Procedure:

File: Export the water content in the plywood/OSB layer in lb/ft^3.

- Step 1: Water content in lb/ft^3 has to be converted to Mass-Percent M- %.
- Step 2: Mass Percent calculation in IP:

$$M-\% = \frac{\text{Water content in layer in lb/ft}^3}{\text{Density of material in lb/ft}^3}$$

Where,

Density of the OSB/plywood can be acquired from the WUFI 5.1 material database.

- Step 3: The M-% value should not exceed the 20% threshold.

Mold Growth (ASHRAE Criteria)

The ASHRAE Standard 160 sets the performance criteria to minimize problems associated with moisture in building envelope assemblies. The Standard specifies that all three of the following conditions should be met:

- 30–day running average surface RH<80% when the 30-day running average surface temperature is between 41°F and 104°F[1];
- 7–day running average surface RH<98% when the 7-day running average surface temperature is between 41°F and 104°F
- 24-h running average surface RH< 100% when the 24-hour running average surface temperature is between 41°F and 104°F;

These criteria apply to all materials and surfaces in the building envelope except the exterior surface and materials that are naturally resistant to mold or have been chemically treated to resist mold growth. If any component within the assembly exceeds the RH limit for any of the three above criteria the assembly is considered as having failed the criteria. The number and year of failure occurrences should be evaluated for each wall.

[1] This approximately equates to moisture content of 14% for plywood and 13% for OSB (Richards, 1992).

Procedure

File: Export the temperature and relative humidity for monitoring positions inserted at the potential condensing plane/materials with high moisture related risk.

For 24- hour Running Average Criteria:

- Step 1: Calculate 24-hour running average of temperature and relative humidity from hourly raw data
- Step 2: Apply the 24-hour ASHRAE criteria to Step 1. 24-hour average running average surface RH < 100% when the 24-hour running average surface temperature is between 41°F and 104°F
- Count all instances that DO NOT MEET the above condition. This count indicates the number of 24-hour periods that fail the 24-hour ASHRAE criteria

The 24-hr running average temperature and relative humidity can be plotted as shown in *Figure 4*. Since the RH does not exceed the 100% limit anytime during the modeling period, this wall passes the 24-hr criteria.

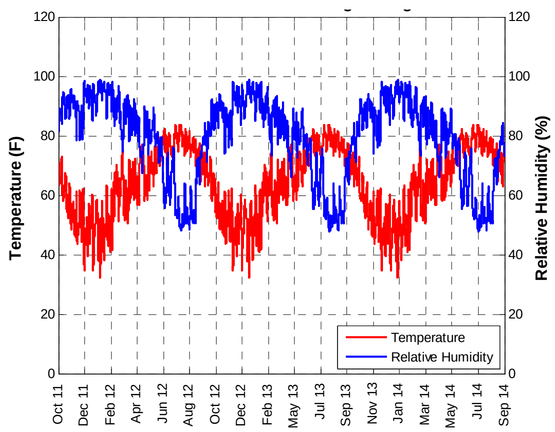

Figure 4: 24-hour moving average for temperature and humidity. Since the RH does not exceed 100 %, this wall passes the 24-hr criteria.

For 7-day Running Average Criteria:

- Step 1: Calculate daily average indoor air temperature °F and relative humidity from hourly raw data
- Step 2: Calculate 7-day running average of temperature and relative humidity based on the daily average data calculated in the above step

- Step 3: Apply the 7-day ASHRAE criteria to Step 2. 7-day average running average surface RH < 98% when the 7-day running average surface temperature is between 41°F and 104°F
- Count all instances that DO NOT MEET the above condition. This count indicates the number of 7-day averages that fail the 7-day ASHRAE criteria

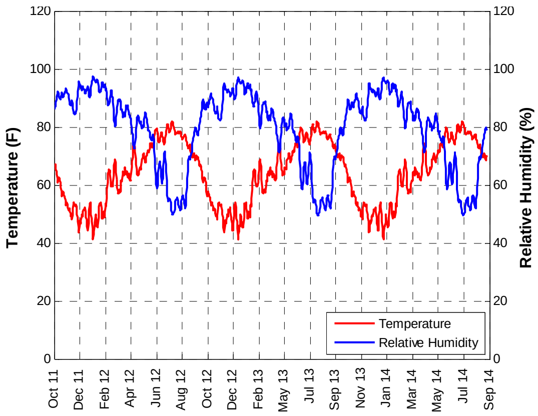

Figure 5: 7-day moving average for temperature and humidity. Since the RH exceeds 98 %, this wall demonstrates failure against the 7-day criteria.

The 7-day running average temperature and relative humidity can be plotted as shown in *Figure 5*. Since the RH exceeds the 98% limit during winter months, this wall is considered a failure against the 7-day criteria.

For 30-day Running Average Criteria:

- Step 1: Using the daily average indoor air temperature °F and relative humidity, calculate 30-day running average of temperature and relative humidity based on the daily average data calculated in the above step
- Step 2: Apply the 30-day ASHRAE criteria to Step 1. 30-day average running average surface RH < 80% when the 30-h running average surface temperature is between 41°F and 104°F
- Count all instances that DO NOT MEET the above condition. This count indicates the number of 30-day averages that fail the 30-day ASHRAE criteria

The 30-day running average temperature and relative humidity can be plotted as shown in *Figure 6*. Since the RH exceeds 80%, this wall is considered a failure against the 30-day criteria.

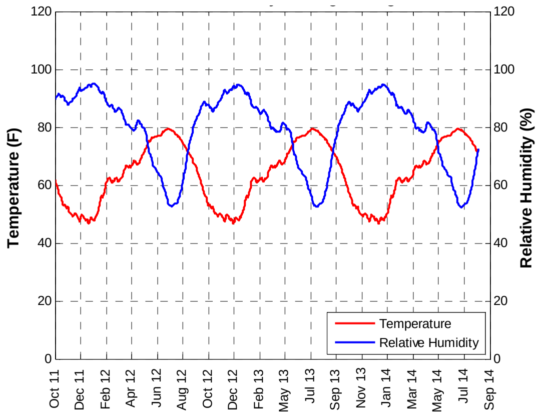

Figure 6: 30-day moving average for temperature and humidity. Since the RH exceeds 80 %, this wall demonstrates failure against the30-day criteria.

In many cases evaluated by the authors, failures happen at the beginning of the modeling period based on the initial conditions assumed, but do not occur again over the remaining three-year period. It is not clear from the Standard if an assembly should be allowed to acclimatize before calculating failures.

Mold Growth (Isopleths)

WUFI 5.1 plots graphs called isopleths to identify potential mold growth on the interior surface of the building assembly and the potential condensating surfaces. An isopleth system captures the germination time and growth rates of mold based on humidity and temperature (Sedlbauer 2002). WUFI 5.1 assigns a 'Lowest Isopleth for Mold' (LIM) which is the temperature dependent, lowest relative humidity under which no fungus activity is expected.

Figure 7 shows an example graph with limiting Isopleths. Each point in this graph represents the hygrothermal conditions at the interior surface of the assembly at a certain time. The color of the dots changes with time. For the isopleth shown in *Figure 7*, at the start of the calculation the dot color is red which turns to green and finally blue at the end of the three year calculation period.

LIM B I and LIM B II refer to limiting isopleth for building material specific fungi and substrate classes. If the conditions lie above the limiting isopleths, mold growth may be possible, but additional criteria evaluation is required for a firm assessment.

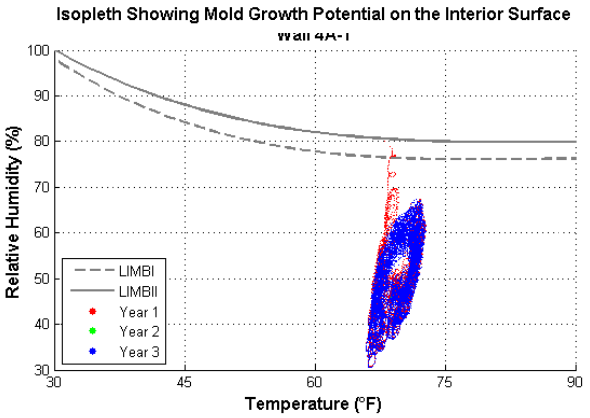

Figure 7 Isopleth graph predicting no potential for mold growth on the interior face of the drywall

Procedure:

Check the isopleth for dots crossing the LIM B I and LIM B II lines.

Mold Growth (Critical Water Content Method)

WUFI 5.1 comes with a post-processor named WUFI-Bio. WUFI-Bio compares the measured or simulated transient ambient conditions with the growth conditions needed by the fungi that are typical to buildings.

For a fungus spore to germinate, it requires certain water content. This water content is called the "critical water content" (Sedlbauer, 2002). WUFI-Bio calculates the critical water content as follows: depending on the temperature, the lowest relative humidity at which the spore germination takes place is calculated from the respective LIM curves in the isopleths. With the help of the moisture storage function for the spore, the corresponding critical moisture content can be calculated. This is a useful post-processor as one can quickly look for mold growth potential on any surface across the assembly.

Procedure:

This is a straightforward check. WUFI-Bio shows a graph similar to *Figure 8*. The red line indicates the critical water content and the blue line indicates the water content of the spore. The signal at the top left of the graph indicates a general assessment of mold growth risk and the severity of the infestation. A green light indicates that the mold growth is below 1.96 in/year: an acceptable performance level. A yellow light indicates that the mold growth potential is between 1.96 in/year and 7.87 in/year; additional criteria or investigations are needed for assessing acceptability.

A red light indicates that mold growth exceeds 7.87 in/year, which is usually not acceptable.

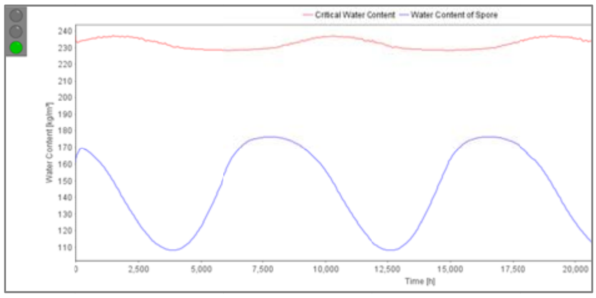

Figure 8 Critical water content and water content of spore. Since the water content of the spore does not exceed the critical water content, this wall shows acceptable performance.

Assembly Water Content

The total water content of the building envelope assembly is calculated over the simulation period. The desired result is that the assembly water content decreases over the modeling period indicating that the building component has the potential to dry out over time.

Procedure

File: Export the total water content in lb/ft^2 file.

- Step 1: To verify whether the wall is drying or accumulating moisture over time, compare the initial assembly water content (the first data point) to the final water content (the last data point)
- If the final assembly water content is less than the initial, the wall has the potential to dry out.

Condensation Potential

Condensation potential within the wall is evaluated by comparing the interior air dew point temperature to the surface temperature of the potential condensing layer(s) (Straube et. al. 2009). If the surface temperature of the material is lower than the dew point temperature of the air, condensation is likely to occur; the longer the period during which the surface temperature falls below the air dew point temperature, the greater the risk for damage. This criterion is generally applied to potential condensing surfaces within the assembly such as foam insulation and OSB.

Procedure

Files: Export the temperature and relative humidity for monitoring positions inserted at the potential condensing plane. Export the interior temperature and relative humidity from the ASCII-Export dialog.

- Step 1: Calculate the indoor air dew point temperature with a psychrometric function based on interior air temperature in °F and relative humidity %
- Step 2: Compare surface temperature to indoor air dew point temperature. If surface temperature is less than the dew point temperature, then condensation potential exists.
- Step 3: Count all instances where Step 3 occurs. This count gives the number of hours the potential for condensation exists over 3 years.

The condensation potential can be calculated more than one way. As was done in this paper, the dew point of the interior air was compared to the temperature of the condensing surface. This assumes that air leakage from the interior will be the driving force for condensation and will represent a worst-case scenario in absence of a bulk water leak or other major failure in the building. Condensation potential can also be evaluated from a diffusion perspective. Software like WUFI 5.1, predicts the dew point temperature of various surfaces in the wall based on diffusion. This analysis yields different, generally less severe results. Depending on construction quality, materials chosen, occupant behavior etc., the true answer will likely be somewhere in between these two methods. There is no recommended maximum threshold for condensation potential at this time. This value needs to be taken into account with all the other criteria and assessed on a climate-by-climate and building assembly by building assembly basis.

Frost Damage

Frost damage occurs mainly when damp masonry such as brick or concrete is exposed to frequent freeze thaw cycles. The two factors that influence frost damage the most are the moisture content on freezing and the number of freeze thaw cycles (Straube 2006).

The freezing temperature in brick is assumed to be lower than zero because of the dissolved salts in brick pores. (Said et al. 2003) A freezing temperature threshold of 23^{o}F and thawing threshold of 32^{o}F were used to estimate the number of freeze-thaw cycles within the brick wall. The critical moisture content is the level above which frost damage can occur. For brick, this is commonly assumed at 90% of free saturation (which is conservative). The exterior face brick and the interior 1st fill brick (in a multi-wythe construction) are evaluated for frost damage.

Typically, the number of zero crossings (times when the wall's temperature falls below or climbs above freezing) is calculated. This is usually at the external face of the brick: the higher the number of cycles, the more potential for freeze-thaw damage to occur (Sedlbauer, 2000).

Procedure

The surface temperature and relative humidity in the brick wythes is exported.

- Step 1: The surface temperature and water content in lb/ft^3 of the brick in question is exported
- Step 2: Identify the free saturation (water content at 100% RH) in lb/ft^3 of the brick used. This information can be obtained from the 'Moisture Storage Function' table in the material database. The water content in lb/ft^3 corresponding to RH of 1.0 is the free saturation of the brick in question.
- Step 3: Calculate critical saturation threshold for the brick material used. This is 90% of the free saturation (from Step 2).
- Step 4: Count Freeze–Thaw cycles. One freeze thaw cycle is observed when the temperature at hour [h] is equal to or below the freezing limit and temperature at hour [h+1] is equal to or above the thawing limit. Repeat this for all the data points.
- Step 5: Count number of instances when frost damage is likely to occur: Count freeze-thaw cycles from step 4 when water content in brick is above the critical saturation limit. Repeat for all data points.

In *Figure 9*, the blue line indicates the water content and the dotted black line indicates the critical saturation threshold of the brick. The red line indicates the temperature of the brick while the black solid and dashed lines indicate the freezing and thawing temperatures respectively. Though the temperatures fall below the freezing and thawing limits, the water content never exceeds the critical saturation level. Therefore, this wall has little potential for frost damage.

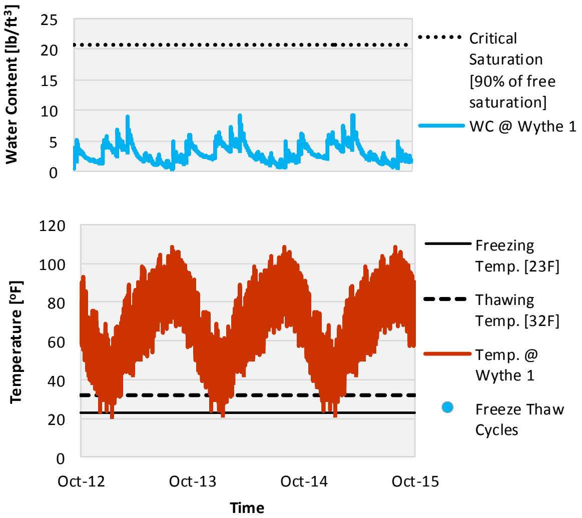

Figure 9 Example graph showing freeze-thaw cycles and water content in an exterior brick. The water content of the brick does not exceed the critical saturation threshold, hence there wall does not have potential for frost damage.

SOFTWARE OBSERVATIONS

WUFI 5.1 is stable with an intuitive user interface. It is available in both SI and IP unit systems. However, many times data exported through the ASCII export dialog is in SI units even though IP unit system is selected. For projects that include exporting huge amounts of data, it would be convenient to have an intuitive batch export option. Though WUFI 5.1 comes with a batch export option, it can only be accessed from the command line and requires selecting files to export with a bit mask (e.g. 0110001). This may not be a viable option for many.

CONCLUSION

This paper presents a comprehensive approach for assessing the hygrothermal performance and compliance with currently available failure criteria using WUFI 5.1. It is recommended that satisfactory performance be based on evaluating several of the following failure criteria simultaneously and not just a single threshold. These criteria include:

1. Water Content of exterior sheathing did not exceed 20% and did not increase over time;
2. ASHRAE 160 criteria for 24 hour, 7-day and 30-day running average surface temperatures and RH are met;
3. Isopleths generated in WUFI 5.1 do not indicate potential for mold growth;
4. Critical water content of fungi spore is not exceeded according to WUFI-Bio;
5. Final water content of the assembly (lb/ft^2) was lower than the initial level;
6. Freeze-thaw cycles do not occur when the water content within the brick exceeds the critical water content.

In addition to the above, criteria to evaluate the condensation potential was presented. Surface temperatures were compared to the interior air dew point temperature (Straube et. al. 2009). A step-by-step process of applying WUFI 5.1 results to evaluate compliance with the aforementioned failure criteria was presented.

ACKNOWLEDGEMENT

This paper is based on the research supported by the Department of Energy's Building America program.

REFERENCES

ASHRAE Standard 160-2009. "Criteria for Moisture-Control Design Analysis in Buildings." Atlanta, GA. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASTM MNL 40. (2001) "Moisture Analysis and Condensation Control in Building Envelopes." West Conshohocken, PA. ASTM.

Richards, R,; Burch, D.; Thomas, W.; 1992. "Water vapor sorption measurements of common building materials". ASHRAE Transactions 98(2).

Said, M.N.A.; Demers, R.G.; McSheffrey, L.L (2003). "Hygrothermal performance of a masonry wall retrofitted with interior insulation." NRCC-46109. 2nd International Building Physics Conference (Leuven, Belgium 2003-09-14) pp. 445-454. 2003-09-01

Sedlbauer, K., (2002), "Prediction of mould fungus formation on the surface of and inside building components", Doctoral Dissertation, Fraunhofer Institute for Building Physics.

Siau, J.F.; (1984)."Transport Processes in Wood". Springer-Verlag, Berlin Heidelberg New York.

Straube, J.F.; C. Schumacher. (2006) "Assessing the Durability Impacts of Energy Efficient Enclosure Upgrades using Hygrothermal Modeling." WTA – Journal 2/06, Accessed on May 31st, 2011 at http://www.hoki.ibp.fhg.de/download/WTA-Journal_2-06_Straube%20u%20Schumacher.pdf

Straube, J.; Smegal, J; (2009) "Building America Special Research Project: High-R Walls Case Study Analysis." Research Report – 0903. Somerville, MA. Building Science Corporation.

Viitanen, H., and. Salonvaara. M. 2001. Failure criteria. Moisture Analysis and Condensation Control, H. Trechsel, ed. ASTM Manual MNL 40, ASTM International, West Conshohocken, PA.