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STATE OF THE INDUSTRY – COMPUTER-AIDED SIMULATION OF HIGH-PERFORMANCE BUILDING ENCLOSURES

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ABSTRACT

Computer-aided simulations are commonly used to predict building enclosure performance. Without informed guidance, however, they may produce inaccurate or misleading results that lead to performance failures. This paper explores common shortcomings and challenges associated with simulation of building enclosure assemblies through review of a broad range of software and simulation scenarios. Topics discussed include quantitative and qualitative simulation constraints, reliability of inputs, significance and integration of project-specific data, and interpretation of results.

INTRODUCTION

Design professionals increasingly rely on computer-aided simulation of building enclosures to evaluate compliance with energy codes and to predict thermal and hygrothermal performance. As energy codes become more stringent and enclosures become more efficient, margin for error decreases. Designers and building enclosure consultants (BECs) use computer models to assess the effects of thermal bridging and understand associated risks such as condensation. These analyses require that the modeler have a thorough understanding of the software and its limitations as well as project-specific details to obtain accurate results.

SIMULATION

Computer-aided simulation of building enclosures requires practical experience and knowledge of the software. This paper integrates shared modeling experience informed by investigation and testing of building enclosures as the basis of the discussion.

DISCUSSION

The following sections are intended to cover typical building enclosure modeling challenges innate to the construction industry. Each section gives a brief overview of the nature of the challenge, related modeling tools and their shortcomings, and common risks associated with reliance on computer-aided simulation. Table 1, below, provides a summary of contemporary modeling issues discussed in subsequent sections.

Table 1 – Outline of Contemporary Modeling Issues

Energy Code Compliance	- Level of Detail - Nonstandard Enclosure Systems - Accuracy of Model Inputs/Results - Design Team Coordination
Thermal Modeling	- Model Oversimplification - Representation of 3D Geometry - Quantifying Thermal Bridges
Condensation Risk Analysis	- Determination of Model Inputs - Defining Boundary Conditions - Defining Material Properties - Interpretation of Model Results

1. Energy Code Compliance

The International Energy Conservation Code (IECC) is a model building code, adopted in some form by most U.S. jurisdictions, that addresses the design of energy-efficient building envelopes and other building systems through prescriptive and performance-based requirements (IECC, 2015). Note that while some jurisdictions have local amendments or rely on independent code systems, this section focuses on the commercial building envelope section of the IECC, and by adoption through reference, ANSI/ASHRAE/IESNA 90.1 (ASHRAE 90.1) *Energy Standard for Buildings Except Low-Rise Residential Buildings*, which establishes minimum energy efficiency requirements for building systems, including the building enclosure, mechanical systems, service water heating systems, and lighting systems.

The IECC presents three possible paths to achieve code compliance for building enclosure systems – (1) conformance with ASHRAE 90.1, (2) prescriptive compliance, in which system performance characteristics are directly specified, or (3) total building performance provisions (i.e., whole building energy model) (Section C401.2). ASHRAE 90.1 allows the following compliance paths for the building enclosure (Section 5.2):

- Prescriptive Path
- Envelope (i.e., enclosure) Trade-Off
- Energy Cost Budget Method
- Appendix G – Performance Rating Method

The following sections focus on building enclosure trade-off analysis and whole building performance modeling.

1.1 Building Enclosure Trade-off Analysis

BECs rely on the enclosure trade-off approach when the proposed design does not meet prescriptive code requirements, for example, when the window-to-wall ratio (WWR) exceeds the code-prescribed 30% or 40% with daylight controls per IECC (ASHRAE prescribes a maximum WWR of 40%). As part of a building enclosure trade-off analysis, the designer must provide documentation to the Authority Having Jurisdiction (AHJ) to show that the proposed overall building enclosure thermal performance is better than that of a standard baseline building enclosure. The IECC and ASHRAE 90.1 include various methods for performing a building envelope trade-off analysis; however, most BECs rely on a U.S. Department of Energy software program called COMcheck, which is based on ASHRAE 90.1, Appendix C, to show percent improvement over a baseline code-compliant building enclosure. COMcheck is accepted by most U.S. jurisdictions to show compliance with the energy code.

AHJ Disputes

COMcheck requires significant knowledge of project-specific enclosure systems as well as the transitions between each system (e.g., locations of thermal bridges – see thermal performance section below). If a particular system does not match one of the preset assemblies in COMcheck, the user can input an average assembly U-factor (or other performance value) but must provide supporting documentation to the AHJ.

A common risk with COMcheck is that, at the time the drawings are sent to the AHJ for permit, the building enclosure consultant may not have enough detail to accurately input performance values into the software. If the COMcheck documentation provided is not consistent with the project drawings, the AHJ may object and delay the permitting process. Post-approval amendments are common as building enclosure detailing is refined; however, as the project proceeds from design into construction, if the COMcheck simulation is not updated or accurate based on contractor substitutions or field changes, the third-party inspector may find discrepancies (e.g., between the constructed enclosure systems and systems documented by the COMcheck). Under extreme circumstances, a building's certificate of occupancy may be delayed or endangered due to these discrepancies. Furthermore, an inspector from the AHJ may issue violations or fines if discrepancies are not corrected. As energy efficiency requirements increase, code officials are becoming more vigilant with regard to enforcement of energy code compliance.

Methodology of Trade-offs

Trade-offs allow enclosure systems that do not meet code-prescribed criteria to be offset by those that exceed the criteria (Bartlett et al., 2012). COMcheck uses area-weighted averages of the building enclosure systems and other weightings to calculate compliance; therefore, small areas that perform far better than code may offset larger areas that underperform the code. Alternatively, large areas that perform just slightly better than code may offset small areas that do not meet the code-prescribed criteria. Note, however, that COMcheck has built-in limits to prevent significant overcompensation between systems. In general, if these types of offsets are not achievable, it is prudent to pursue whole building performance modeling, in which the envelope can be counterbalanced by other energy-consuming systems (e.g., mechanical and electrical systems).

Before investing time and money into performing a building enclosure trade-off analysis, the building enclosure consultant should first predict the likely outcome. Since opaque wall assemblies can typically outperform code more easily and often for less cost than fenestration assemblies (e.g., upgrading insulation type is often easier than upgrading glazing), the WWR can be a good indicator to determine whether the trade-off approach will work. Enclosures with lower WWRs (e.g., less than 30% or 40%, depending on the code) are more likely to succeed in the trade-off approach, while for buildings with large WWRs (e.g., 50%), the design team should consider compliance via whole building performance modeling.

1.2 Whole Building Performance Modeling

When pursuing whole building performance compliance, the designer must submit a compliance report and documentation to show that the calculated energy cost of the proposed building is less than the standard reference building energy cost by a prescribed margin (IECC, 2015). This process involves developing a whole building energy model and optimizing performance trade-offs between the energy-consuming building systems listed in the code. Design teams use software programs such as eQuest or EnergyPlus to develop a whole building energy model, with thermal performance inputs for each building enclosure assembly provided by the BEC.

Representation of Enclosure Systems

Similar to the trade-off analysis, BECs may use a computer-based modeling tool, such as THERM (see thermal performance section below) to calculate enclosure system U-factors. The enclosure consultant must consider project-specific enclosure systems as well as the transitions between systems. Misrepresentation of systems will lead to errors in calculation of building energy efficiency. For example, manufacturer's reports on window thermal performance are typically based on adiabatic frame edge conditions; however, use of these values without considering project-specific surrounds will result in an underperforming enclosure, since consideration of surrounds typically worsens overall thermal performance.

Alternatively, many BECs are turning to estimations for linear and point thermal bridging effects at transitions between building enclosure systems rather than completing project-specific modeling. The Charles Pankow Foundation, ASHRAE, and the British Columbia Hydro and Power Authority (BC Hydro) have recently released publications that include results of two- and three-dimensional thermal modeling calculations for typical building enclosure transition details and thermal bridges (slab edges, building corners, parapets, etc.). Modelers can input these results directly into their energy models. Finite element thermal modeling is now typically reserved for building enclosure transition details that are not represented in published studies.

Design Team Coordination

As a caution, note that development of the whole building energy model is typically an iterative process. The model develops along with the building design, rather than being a standalone analysis that is created at a single point in time, and can be used to evaluate the cost-benefit trade-off of various energy-efficient design strategies (i.e., a parametric approach). As such, careful coordination between the building enclosure consultant, the energy modeler (if different from the enclosure consultant), and the rest of the Design Team is required at multiple stages of design.

2. Thermal Modeling

BECs rely on thermal modeling software to quantify the thermal performance of an assembly for input into energy code compliance software or to predict condensation potential. Thermal modeling can also be used to explore the effects of individual components on overall building performance, to analyze thermal bridging, and to inform design decisions (e.g., cost-benefit analysis).

2.1 Calculating Average Assembly U-factors in Complex Assemblies

Average assembly U-factors for opaque building enclosure systems can be determined using the tables in ASHRAE 90.1, Appendix A. If the assembly is not listed in Appendix A, designers must perform a laboratory test or calculate the U-factor by means of a hand calculation or computer-based modeling tool such as THERM (ASHRAE 90.1, 2016). Assembly U-factors for fenestration (barring minor exceptions such as glazed-in shadow boxes) are calculated in accordance with NFRC 100 *Procedure for Determining Fenestration Product U-factors*, published by the National Fenestration Rating Council (NFRC), which requires use of an additional program called WINDOW.

THERM and WINDOW, both developed by the Lawrence Berkeley National Laboratory (LBNL), are commonly used to quantify thermal performance of building enclosure components. THERM is a finite element simulator that calculates steady-state two-dimensional heat flow through materials, components, and systems based on a defined geometry and interior/exterior environmental conditions. WINDOW is a program that simulates heat transfer and solar heat gain through glazing assemblies, including the effects of convection and radiation within insulated glass units.

The general procedure to calculate an assembly U-factor using finite element software tools involves (1) dividing the assembly up into discrete, representative sub-areas, (2) defining interior and exterior boundary conditions based on requirements outlined in ASHRAE 90.1 for opaque enclosure assemblies and NFRC 100 for fenestration assemblies, (3) calculating sub-area U-factors, and, (4) calculating the assembly U-factor by area-weighted average of sub-area U-factors.

For opaque wall assemblies, representative sub-areas are determined based on assembly geometry. BECs rely on models to analyze unique and local conditions where the U-factor varies from the field of the wall (e.g., at thermal bridges). Figures 1 and 2 below show a graphic example of a thermal bridge (stone cladding attachment in this case) through a stone-clad curtainwall assembly (modeled as an opaque wall).

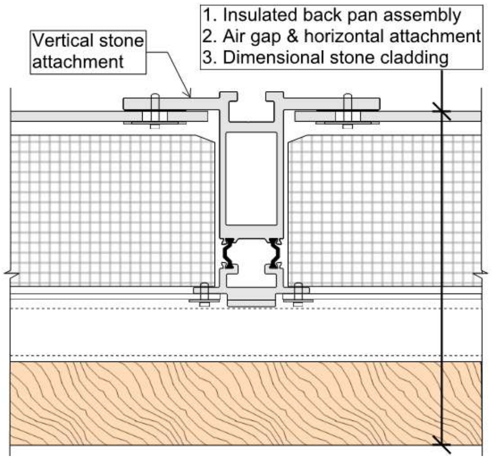

Figure 1 Plan Section at Stone Cladding Attachment

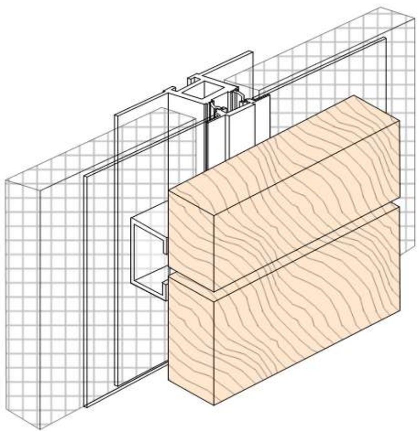

Figure 2 Isometric Detail at Cladding Attachment

For fenestration assemblies, NFRC 100 defines representative sub-areas as center-of-glazing, edge-of-glazing, frame, divider, and edge-of-divider (Section 4.8, Figure 4-1, NFRC 100).

As a general rule of thumb, the geometry of sub-area models should extend out to half the on-center spacing of the element being modeled. The model extents are reasonable if the temperature isotherms (lines of constant temperature displayed in the model results) are parallel to the interior and exterior boundaries, indicating minimal change in heat transfer across that boundary (Figure 3).

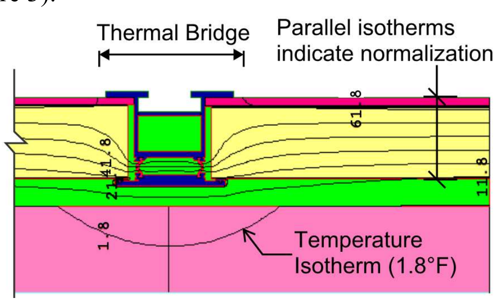

Figure 3 THERM Output with Temperature Isotherms

Model Oversimplification

Dividing an assembly into two-dimensional sub-areas becomes unrealistic when vertical and horizontal elements intersect or exist in different planes (see Figures 4 and 5 below). At these locations, the heat flow analysis must account for localized effects from each contributing element. Modelers sometimes use a series of two-dimensional models to analyze complex intersections of materials or determine the effective conductivity of a region. For instance, a modeler may derive the effective conductivity for part of an assembly in section where that element is visible (e.g., z-girts in Figure 4), and then input that value into a plan where the element is not visible (Figure 5).

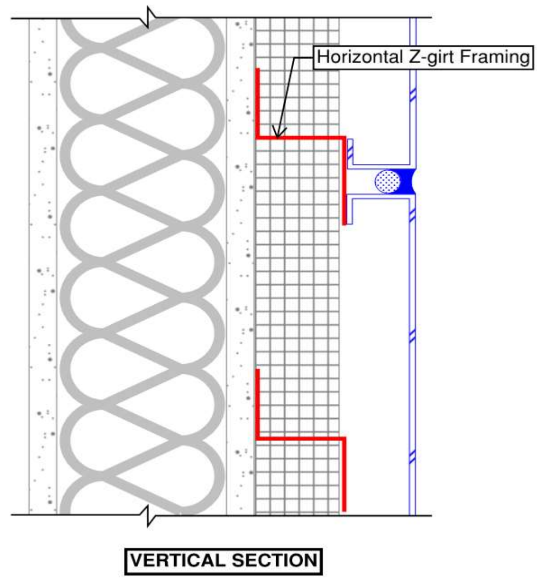

Figure 4 Section View of Exterior Wall Assembly

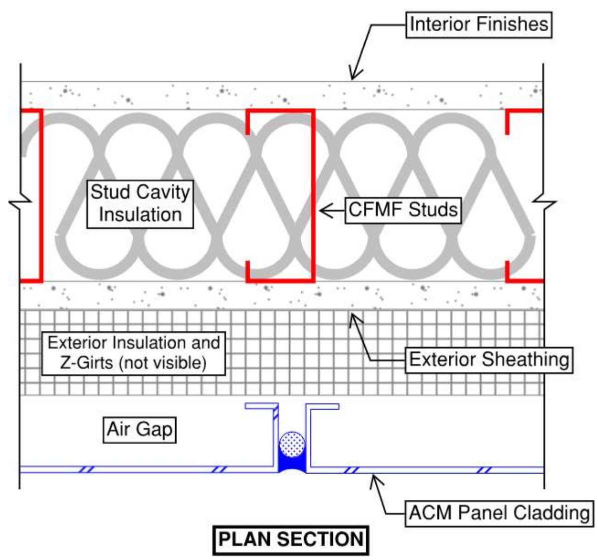

Figure 5 Plan View of Exterior Wall Assembly

This multistep process allows the entire calculation to be kept in the finite element software tool. In some cases, where complex shapes intersect, a more prudent approach is to use a three-dimensional heat transfer analysis program (see thermal bridging section below).

Margin of Error

Depending on the project design phase and the level of detail included in the model geometry, a designer may apply a safety factor to the assembly U-factor to reflect an amount of uncertainty. As an example, for fenestration assemblies in the design development phase, the BEC might evaluate an assembly with an assumed U-factor increase of 10% to account for changing material arrangements in the construction documents phase. Assigning a value to these increases requires experience and engineering judgment.

2.2 Accounting for Thermal Bridging

Thermal bridges are localized areas of increased heat flow through the building enclosure that are caused by conductive elements that bypass the thermal barrier of the building. Risks associated with thermal bridging include energy loss and related increases in annual energy cost, condensation near the thermal bridge, and occupant discomfort due to radiative or conductive effects (Blue et al., 2016).

In the past, designers could not easily account for complex interactions between thermal bridging elements and the enclosure as a whole. Today, however, the building enclosure industry has better-developed tools and greater processing power to evaluate potential consequences associated with thermal bridging and to quantify associated heat loss. BECs use two- and three-dimensional finite element tools to quantify thermal bridges, as these can analyze heat flow through continuous elements (Figure 6). The complexity of the detail and nature of the thermal bridge (e.g., continuous vs. discrete) dictate if two-dimensional analysis is sufficient or if three-dimensional heat transfer analysis is required to better understand or quantify the heat loss.

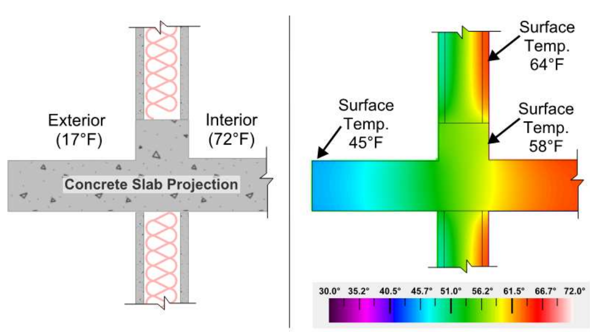

Figure 6 Side-by-Side of Slab Projection Detail and Color Infrared Analysis from THERM

BECs commonly use HEAT3 or ANSYS to perform three-dimensional heat transfer analysis. Finite difference simulators, such as HEAT3, calculate steady-state and/or transient three-dimensional heat flow through materials, components, and systems based on a defined geometry and interior/exterior environmental conditions.

Model Geometry

It is common in most heat transfer analysis programs to conservatively model surface areas of all components in direct contact with each other to account for thermal energy transmittance. This, however, eliminates a potentially beneficial air layer between materials and does not account for contact resistance. In reality, two components cannot contact fully due to porosity and surface roughness; therefore, modeling perfect contact between them represents a worst-case scenario (Peterman et al., 2017). With this approach, it is important to note that Heat3 allows two objects to occupy the same place if they are the same material, which can falsely affect results (Posey and Dalgliesh, 2005). Thus, it is important to use engineering judgment when analyzing model outputs to resolve potential discrepancies.

Simulation Mesh

For a three-dimensional model, the size of the simulation mesh is specified based on anticipated temperature gradients in the model. In some cases, expansive meshes may be used to concentrate the cells towards areas with large temperature gradients. The result is an array of small computational cells with short time steps, which increases the amount of required computing power. A poorly chosen computational mesh can increase the computation time dramatically, especially for transient analyses (Blomberg, 1999).

3. Condensation Risk Analysis

BECs are concerned with two types of condensation risk – surface condensation and condensation within an enclosure assembly (i.e., hygrothermal performance).

3.1 Analysis of Surface Condensation

Designers often rely on steady-state heat flow programs such as THERM to determine surface condensation risk given a set of static boundary conditions. Boundary conditions define the temperature and air film coefficient (film coefficient) directly adjacent to a surface. A more accurate approach to analyzing surface condensation risk is to perform a sensitivity analysis by manipulating boundary conditions in THERM to determine (A) interior mechanical setpoints required to preclude wintertime condensation on interior surfaces based on a predefined exterior temperature, or (B) at what exterior temperature interior condensation will occur given predefined interior conditions. In both cases, the dew point is calculated based on the interior temperature and relative humidity (RH); if the interior surface temperatures drop below the dew point, surface condensation will occur (Figure 8). In scenario A, the modeler must calculate a dew point for each interior temperature and RH combination based on project-specific information supplied by the mechanical engineer. In scenario B, one interior dew point temperature is calculated based on the predefined interior temperature and RH conditions.

When possible, BECs performing condensation analyses should obtain the conditions (temperature, RH, film coefficient) immediately adjacent to the detail being analyzed in lieu of using the mechanical engineer's interior design set point conditions. In the example in Figure 7, the air temperature and RH within approximately 3 in. to 6 in. of the IGU and mullion surfaces are required. The conditions in this near-wall zone may be influenced by radiators, diffusers, window shades, or other geometry, and therefore must be calculated to accurately assess risk. Some cases like large atria, tall windows, etc. might require computational fluid dynamics (CFD) to evaluate the near-component conditions (see film coefficient section below).

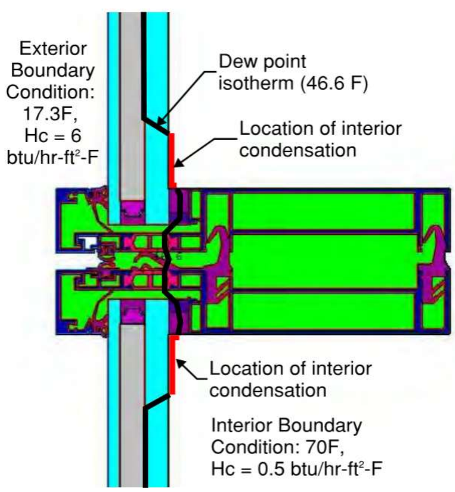

Figure 7 THERM Output Overlaid with Dew Point Isotherm and Locations of Interior Condensation

Temperature Boundary Conditions

In scenario A, the exterior temperature is set to the 99.6% heating design temperature specified in ASHRAE 90.1. Statistically, the 99.6% heating design temperature represents the lowest temperature a region will see for 99.6% of the year, and the exterior temperature to which most mechanical engineers design their heating systems. In this case, it is important for BECs to explain to clients that interior condensation may still occur when exterior temperatures drop below the 99.6% threshold. Depending on the allowable tolerance for condensation, the Design Team may prefer to use a more stringent temperature boundary condition, such as the absolute lowest temperature value based on available historical weather data.

In scenario B, the interior temperature is set to the air temperature within approximately 3 to 6 in. from the surface of the assembly. When the simulation yields an exterior temperature at which condensation occurs, the BEC must then compare that value to available historical weather data to determine anticipated hours of condensation per year.

Film Coefficient Boundary Conditions

The exterior and interior film coefficients typically default to those specified by ASHRAE 90.1 or NFRC 100; however, the modeler may choose to calculate these values or use engineering judgment to make an estimation. The film coefficient defines convective and radiative heat flow at the surface of the geometry and varies with adjacent fluid type (e.g., air) and velocity; therefore, it varies locally across the enclosure and can be difficult to calculate. At the interior, radiation is typically negligible and can be ignored; however, exterior radiation can be important, particularly for sky-facing elements or tall buildings that have a larger view factor to the sky. The exterior film coefficient can be calculated in accordance with ISO Standard 15099.

In cases where the interior air varies in velocity and temperature between its delivery point in the space and the interior surface of the modeled assembly, it is prudent to use a CFD model to calculate the interior film coefficient(s). In this case, the BEC must coordinate closely with the mechanical engineer, the Design Team, and the CFD modeler to obtain and communicate the level of detail required to input into the CFD model. The model must include the general interior layout of the building space and locations of mechanical diffusers, as well as detailed information on interior space conditions (mechanical and natural ventilation, space loads, etc.) and detailed geometry at the interior surface of the building enclosure assembly, among other items.

3.2 Hygrothermal Analysis

Designers rely on personal experience and engineering judgment to determine if hygrothermal analysis of an enclosure assembly is necessary. In doing so, they must consider the project-specific climate, requirements for interior conditions, and location of insulation and vapor barriers within the enclosure assembly, as these factors affect heat and moisture flow. Moisture buildup can lead to material degradation, increased risk of freeze-thaw damage, corrosion, and biological growth.

ASHRAE Standard 160-2016 Criteria for Moisture-Control Design Analysis in Buildings (ASHRAE 160) identifies performance-based criteria for predicting, mitigating, or reducing moisture-related damage to building enclosures. A number of analytic tools meet the procedural criteria within the standard, including a commonly used software program called WUFI. Developed by the Fraunhofer Institute, WUFI is a one-dimensional finite element simulator that calculates transient heat and moisture migration through building materials and assemblies. When using WUFI, the modeler inputs a series of hygrothermal loads, which include initial built-in moisture content of enclosure assembly materials, indoor mechanical conditions, and outdoor climate, among others (Glass et al., 2013).

Material Property Inputs

WUFI has an internally maintained database containing hygrothermal material data sets for a limited set of construction materials. Users can generate custom materials by copying an existing material in the database and inputting basic material data: bulk density, porosity, specific heat capacity, thermal conductivity, and water vapor diffusion resistance. Users can also input built-in moisture (pcf), if material-specific data is known. For absorptive materials (e.g., brick masonry) or variable permeance materials, it may be necessary to input hygrothermal functions in addition to the basic material data. Adjusting these values requires material-specific tabulated data; and in some cases, such as with existing building materials, lab testing is required to obtain accurate hygrothermal performance data to input into the model.

Interior Boundary Conditions

Interior conditions may vary considerably based on building zone (Glass et al., 2013), and more than one model may be required to accurately study a whole building. In buildings where indoor humidity and temperature are explicitly controlled, the WUFI model should reflect anticipated conditions to the extent possible. WUFI has several methods for approximating interior conditions. BECs commonly use either a simplified format that models the annual indoor temperature and humidity as sinusoidal curves, or the ASHRAE 160 format, which requires inputs based on temperature and relative humidity setpoints, moisture generation, and air leakage through the building enclosure. With both formats, issues can arise due to the assumption of constant moisture generation and air leakage. In space types with variable conditions and mechanical schedules (e.g., convention space or auditorium) it is prudent to import a climate file with project-specific schedules. In the case of existing buildings, the modeler can import actual measured data from the space.

If interior conditions are unknown, ASHRAE 160 provides default design loads and parameters. Additionally, the ASHRAE Handbook of HVAC Applications contains typical interior temperature and RH values for different space types, which can be modeled in WUFI as sinusoidal curves; however, the Design Team should be made aware, in these cases, that the model may lack accuracy. Additional models may be required further along in the design phase, when more detailed information is known about the mechanical schedules in the proposed space.

Exterior Boundary Conditions

ASHRAE 160 requires exterior conditions to be simulated based on either 10 years of consecutive weather data or the moisture design reference year for the project location (Section 4.5). WUFI has a built-in database of weather files for a limited number of cities in North America and Western Europe; however, a user may also upload a weather file (e.g., TMY3 file), if available.

Interpretation of Results

In order to determine the risk of moisture-related concerns such as mold growth and corrosion, numerical data must be exported directly from WUFI and post-processed. ASHRAE 160 specifies a criterion for determining the level of biological growth on material surfaces called the "Mold Index," based on the updated mold growth model developed by Ojanen and colleagues (Glass et al., 2017). The Mold Index integrates time-based surface temperature and relative humidity with the mold sensitivity of the building material being evaluated (Glass et al., 2017). According to ASHRAE 160, the Mold Index shall not exceed three (threshold for visible biological growth) regardless of the sensitivity class (Section 6.1). Modelers often determine the Mold Index at any surface considered moisture-sensitive and at locations where condensation potential is the highest. Previous versions of ASHRAE 160 relied on a thirty-day running average of RH and temperature at the surface being analyzed to determine risk of biological growth. Based on industry experience and research, this criterion was deemed to be inconsistent with field observations and predicted failure in enclosure assemblies in which visible mold growth did not occur (Glass et al., 2017).

The thirty-day running average RH is still referenced by ASHRAE 160 with regard to corrosion potential. According to the standard, corrosion potential should be determined based on the properties of the metals specific to the enclosure assembly; however, if no such information is available, the thirty-day running average RH at the surface of the metal should remain below 80%.

Corrosion risk can vary greatly based on metal type and project-specific conditions and exposures (e.g., sulfate exposure or air pollution). Much like for the mold index, industry research is required to determine the accuracy of the predictive capabilities of the thirty-day running average for corrosion risk.

CONCLUSION

Continued advancement of computer modeling technologies has allowed designers greater ability to analyze heat, air, and moisture issues in building enclosure assemblies. More powerful and adaptive tools increase design flexibility and allow designers to predict in-service performance of proposed assemblies. Determining the appropriateness of a particular tool, however, requires experience, caution, and diligent effort to avoid common mistakes. By examining inputs and outputs and studying the field performance of enclosure assemblies, the industry can continue to improve model reliability. Different tools have various pitfalls and avenues for misuse. Often, experience and an understanding of likely results can help manage risk for modeling errors.

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