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ABSTRACT

Hygrothermal analysis predicts the impact of transient heat and moisture transfer on building envelopes over time. Today, several computer modeling programs are available to designers. The specialized software helps the user visualize such factors as surface temperature differences, surface condensation potential, mold growth potential, building material moisture content, and moisture accumulation rates. In addition, the recently published ANSI/ASHRAE Standard 160-2009, Criteria for Moisture-Control Design Analysis in Buildings, now provides guidance on how to successfully conduct hygrothermal analyses.

The purpose of this paper is to present several illustrations of how to use the hygrothermal modeling techniques provided in ASHRAE Standard 160 to evaluate moisture-related problems in commercial roof and wall systems in various climates. Issues with cool roof surface temperatures, thermal bridging due to fasteners and metal framing, water vapor permeance of vapor retarders and water resistive barriers, as well as the influence of surface temperature on air leakage will be discussed.

SPEAKER

Stanley D. Gatland II is the manager of building science technology for CertainTeed Corporation. He is responsible for generating and providing technical information to architects, engineers, builders, trade contractors, building envelope consultants, building scientists, and building code officials on the system performance of new and existing building envelope materials, as well as building science educational training. Mr. Gatland has expertise in the areas of building science and architectural acoustics with an extensive national and international network of professional contacts in the fields of building science, energy efficiency, heat and moisture transfer, environmental acoustics, and fire performance.

Prior to joining CertainTeed, Gatland was a supervisor of materials testing for Celotex Corporation’s Technical Center in St. Petersburg, FL, and a thermal engineering research consultant for the Center for Applied Engineering in St. Petersburg, FL. Mr. Gatland is a graduate of the University of Massachusetts, Amherst, with both master’s and bachelor’s degrees in mechanical engineering. He is a member of ASHRAE, ASTM, ASME, and BETEC.

ABSTRACT

Hygrothermal analysis predicts the impact of transient heat and moisture transfer through building envelopes over time. Today, several computer-modeling programs are available to the designer. The specialized software helps the user visualize such factors as surface temperature differences, surface condensation potential, mold growth potential, building material moisture content, and moisture accumulation rates. In addition, the recently published ANSI/ASHRAE Standard 160-2009, Criteria for Moisture-Control Design Analysis in Buildings, now provides guidance for moisture-related problems in commercial roof and wall systems in various climates. Issues with cool roof surface temperatures, thermal bridging due to fasteners and metal framing, water vapor permeance of vapor retarders and water resistant barriers, as well as the influence of surface temperature on air leakage will be discussed. While the issues described are multidimensional in nature, simplified one-dimensional models can provide valuable information for the performance of the assembly.

INTRODUCTION TO HYGROTHERMAL ANALYSIS

When designing a building envelope, one of the best tools for predicting its moisture management performance is hygrothermal analysis. A large amount of research related to developing transient heat and moisture transfer (hygrothermal) analysis methods (Trechsel, 2001; Straube et al., 2001) and measuring the hygrothermal properties of building materials (Hens et al., 1996, Kumaran 2001, ASHRAE 2005) has been conducted and published in recent years.

Hygrothermal analysis predicts the impact of transient heat and moisture transfer through building envelopes over time. It may be used on construction projects in planning and on existing buildings with moisture problems. Specialized software helps the user visualize such factors as surface condensation and mold growth potential, the wetting and drying potential of the building envelope, and moisture content of building components. This analysis helps building designers evaluate potential preconstruction moisture risks and also helps analyze and solve moisture problems after construction.

OVERVIEW OF ASHRAE STANDARD 160

The recently published ASHRAE Standard 160-2009, Criteria for Moisture-Control Design Analysis in Buildings, has been under development for more than 10 years. The document provides guidance on how to conduct, evaluate, and report the results of one-dimensional hygrothermal analysis on new and existing building envelope systems. Three criteria are outlined and include design parameters, analytical procedure selection, and moisture-performance evaluation.

Section 4, Criteria for Design Parameters, provides guidance on how to select design values for initial moisture conditions of building materials, indoor temperatures, indoor relative humidity, building air pressure differentials, air speed and flow, weather data, and rain loads.

Ideally, the designer should measure the moisture content of all building materials in the assembly or be able to calculate values based on known conditions during the construction process. One good reference that describes moisture measurement techniques in building materials is Chapter 12, “Measurement Techniques and Instrumentation,” from Moisture Control in Buildings (Trechsel et al., 1994).

If the designer does not know the moisture content of the materials, ASHRAE Standard 160-2009 recommends that all building materials used in new construction, except concrete, have initial moisture contents of two times the equilibrium moisture content in air at 80% relative humidity at 20°C (68°F) or EMC80. Also, the standard recommends that any concrete’s initial moisture content should be two times EMC90. If the building is constructed using dry materials or...
procedures are in place to protect assemblies from getting wet during the construction process, the initial values for concrete and all other materials should be set at EMC90 and EMC80, respectively.

Indoor design conditions include air temperature and relative humidity. Tables 4.2 and 4.3.1 provide simplified indoor design temperature and relative humidity based on seasonal needs. In addition, indoor design humidity can be specified through an intermediate method that includes the effects of hourly weather data and the building's heating, cooling, and ventilation equipment, as well as moisture generation rates and controlled dehumidification. An even more complex method, using a full parametric calculation, is available to create the indoor humidity design conditions. In addition, the standard allows the designer to consider the effects of air pressure differentials and flows, which is optional.

Having accurate hourly weather is a very important part of any hygrothermal analysis. Section 4.5, Moisture Design Weather Data, requires a minimum of 10 years of historical weather data to create an average weather file for a geographic location. Data sets contain hourly measurements for dry-bulb air temperature, vapor pressure, dewpoint temperature, wet-bulb temperature, relative humidity, humidity ratio, total solar insolation on a horizontal surface (solar radiation), average wind speed and direction, rainfall amounts, and cloud indices. Fortunately, the need to conduct whole-building energy modeling in the past generated a library of historical weather data sets.

Many designers use the coldest or warmest 10th percentile hourly data set from 30 years of historical weather data as the weather file in order to compare extreme conditions. Tenth percentile data sets are determined by averaging the three coldest or warmest year data sets. For example, historical outdoor air temperature and relative humidity data for Chicago, IL, are graphically displayed in the top image of Figure 1. All simulations were conducted using WUFI Pro 4.2 software (2008).

Section 4.6, Design Rain Loads on Walls, describes how to determine a wall's exposure to rain. Loads are influenced by building height, the surrounding topography, wind direction, and roof slope, as well as wind speed, rainfall intensity on horizontal surfaces, and rain deposition on vertical surfaces. Again, many of the professional software packages can calculate rain loads based on weather data files, building envelope inclination (wall or roof), building envelope orientation (north, south, east, or west), and building height. Directional wind-driven rain data for Chicago, IL, are graphically displayed in the bottom image of Figure 1. Accurate estimates of wind-driven rain events are a very important part of hygrothermal analysis. ASHRAE Standard 160 recommends that 1% of the incident rainfall penetrate the exterior wall cladding or roofing system and be deposited over the exterior surface of the water-resistant barrier or roofing underlayment, respectively.

Section 5, Criteria for Selecting Analytical Procedures, sets minimum acceptable requirements for analytical tools capable of performing transient heat and moisture transfer calculations on building envelope assemblies. Transient heat-and-moisture transfer requires a lot of material data. Many building materials have been measured for hygrothermal properties, and several references have published data in recent years (Hens et al., 1996; Kumaran, 2001; ASHRAE, 2005). Building materials should be clearly defined by thick-
ness, density, porosity, specific heat, thermal conductivity, and water vapor diffusion resistance. In addition, moisture-dependent functions like moisture storage, liquid transport coefficients, and water vapor diffusion should be characterized across a range of conditions. Exposed surfaces should be characterized for convective and radiative heat transfer, as well as water vapor diffusion resistance.

Section 6, Moisture Performance Evaluation Criteria, provides guidance on how to recognize favorable surface conditions for mold growth and corrosion. Section 6.1 recommends meeting the following three conditions to minimize problems associated with mold growth.

a. Thirty-day running average surface RH <80% when the 30-day running average surface temperature is between 5°C (41°F) and 40°C (104°F).

b. Seven-day running average surface RH <98% when the 7-day average surface temperature is between 5°C (41°F) and 40°C (104°F).

c. Twenty-four-hour running average surface RH <100% when the 24-hour average surface temperature is between 5°C (41°F) and 40°C (104°F).

In addition, if no information exists regarding a material's resistance to corrosion, the standard recommends that metals used in construction should meet the 30-day criteria to avoid corrosion-related problems.

Hygrothermal analysis reports should include all of the details identified in Section 7. The standard requires that general and detailed information be provided about the building, the building envelope assembly, and component material data, as well as the method used to conduct the analysis and criteria used to determine the results. Fortunately, commercially available software packages allow the designer to generate most of the required information easily.

Several basic and comprehensive examples of hygrothermal analysis will be presented throughout the remainder of the paper. Issues to be examined are the effects of cold surfaces created by cool roofs on moisture accumulation in cold, humid climates, a visual inspection of thermal bridging, the impact of improperly located vapor retarders in warm-humid climates, the effect of different moisture intrusion rates on system moisture stability in mixed-humid climates, and the combined effect of low permeance vapor retarders and moisture-storage claddings in cold-humid climates.

**SIMPLE COOL ROOF ANALYSIS**

Cool roofs are becoming more popular, and many building codes are requiring new and existing constructions to incorporate surfaces with high solar reflectance and high thermal emittance in order to reduce a building's cooling load. Black roof surfaces can reach peak temperatures of 190°F on hot, sunny summer days (see Figure 2, left). Commercially available, highly reflective roof surfaces can reduce peak surface temperatures by as much as 70°F (see Figure 2, right). Lower surface temperature means the reduction of energy costs and peak energy loads, as well as reduction of the heat island effect in urban areas.

One of the side effects of a highly reflective roof is the fact that surfaces and materials in the assembly become much cooler. Surfaces with solar reflectances above 0.70 reflect solar radiation very effectively. Surfaces with thermal emittances above 0.75 radiate energy back to the atmosphere very quickly. The end results are that the cooler surfaces and materials become more susceptible to condensation, especially at night, which may lead to moisture accumulation.

The following example illustrates the phenomenon in a very simple way by comparing a traditional black roof with a cool roof. The insulation layer has been removed from the analysis to simulate any gaps that might exist in an older building retrofit in a cold and humid climate like Chicago, IL. Less energy is available to dry out building assemblies in colder climates.

The low-slope roof assembly consists of two layers: a roof membrane and plywood decking. One way to compare the moisture performance of an assembly is to look at the moisture content in building material layers that store moisture. The hygrothermal analysis was conducted over a three-year period using 10th percentile coldest-year weather data for Chicago. All conditions were the same between the two assemblies other than the radiative properties of the roofing membrane. The black roof's solar reflectance and thermal emittance coefficients were set at 0.10 and 0.90, respectively. The cool roof’s solar reflectance and thermal emittance coefficients were set at 0.70 and 0.75, respectively. The surface properties were assumed to not change over the three-year analysis.

![Figure 2 – Black roof surface (left); white reflective roof surface (right).](image-url)
Figure 3 graphically illustrates the moisture content of the plywood decking for each roofing system. The y-axis quantifies moisture content in terms of percent by weight. Values less than 20% are recommended for wood-based building materials. The black curve shows that the moisture content of the black roof's plywood decking peaks at approximately 20% during late winter. The white curve shows that the moisture content of the cool roof's plywood decking peaks at approximately 30% during the late winter. While a consistent wetting and drying cycle exists for both systems, the white roof is at a greater risk for moisture-related damage due to the high seasonal level. Incorporating continuous exterior insulation boards and interior airtightness is especially critical for cool roofs in cold climates due to the heightened potential for moisture accumulation due to colder surface temperatures.

IMPACT OF THERMAL BRIDGING

Many building envelope components are highly conductive and create thermal bridges. For example, metals conduct 300 to 1,000 times more heat than most building materials. The thermal impact of a metal stud in a framed cavity is greater than the actual surface area of the stud, so metal has an exaggerated effect on heat transfer out of proportion to its physical size. Figure 4 is a two-dimensional thermal image created using professionally available heat transfer-analysis software.

Not only does the thermal bridge impact the energy efficiency of the building envelope, but the hidden metal surfaces become condensing planes in insulated cavities or curtain wall façades. Hygrothermal analysis may be used to identify the impact of cold surfaces on moisture accumulation over time. Continuous exterior insulation boards are recommended in cold climates to improve energy efficiency and reduce cavity condensation potential. In addition, water vapor can condense on brick ties and fasteners that penetrate exterior sheathings (see Figure 5). The issue may become worse due to air leakage. Simplified one-dimensional hygrothermal analysis may be used to identify potential cold surfaces due to thermal bridging in multidimensional assemblies that may impact the building envelope's performance.

IMPACT OF INTERIOR VAPOR RETARDERS IN WARM, HUMID CLIMATES

Interior vapor retarders are not recommended in assemblies with fibrous cavity insulation in warm, humid climates under normal operating conditions. However, design conditions with high indoor humidity, such as swimming pools, may require the use of interior vapor control. Sometimes, an insulation product with a low-permeance facing, like foil-scrim-kraft (FSK), may inadvertently be specified with the vapor retarder installed between the framing and the interior gypsum board. Hygrothermal analysis may easily be used to illustrate the problems associated with incorrectly locating a vapor retarder in a traditional stucco-wall assembly in a warm, humid climate (see Figure 6).

A hygrothermal analysis was conducted on the wall assembly in Tampa, FL. Results were calculated on an hourly basis over a three-year period. Figure 7 graphically displays the surface temperature and relative

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**Figure 3 – Plywood decking moisture content comparison for a white and black roof.**

**Figure 4 – Heat transfer comparison between steel and wood framing.**

**Figure 5 – Gypsum sheathing with brick tie penetrations.**
humidity on the back side of the FSK facing. Curve “FSK” clearly shows that moisture builds up in the assembly from spring through the fall, causing condensation to occur on the back side of the FSK facing until winter. Removing the vapor-impermeable facing allows the assembly to dry to the inside seasonally and reinforces the fact that interior vapor retarders are only necessary in cold climates under normal operating conditions (see curve “No VR”). Visual interpretations of the results allow the designer to quickly make adjustments during the design process and avoid problems in the future.

INSULATED METAL BUILDING ROOFS IN MIXED-HUMID CLIMATES

More and more metal buildings are being constructed as a lower-cost alternative to light commercial buildings (see Figure 8). Many roofs and walls are insulated using fiberglass with vapor-impermeable fire-rated facings. Over time, insulation systems may accumulate moisture due to minor leaks in the roof or through air infiltration. This is especially problematic in mixed-humid climates that require some wintertime condensation control but also have long periods of warm, humid weather that reverse the moisture drive in the assembly.

A hygrothermal analysis was conducted through a one-dimensional cross section between purlins on a metal building roof assembly in Kansas City, KS. Results were calculated on an hourly basis over a three-year period. The metal roof system included a metal roof, 10 inches of fiberglass insulation (R30) and a polyethylene-scrim-kraft (PSK) facing. Figure 9 graphically illustrates the total water content of the insulated metal building roof assemblies under varying moisture intrusion rates. The y-axis quantifies total water content in terms of mass per unit area. The computer model was created with deficiencies to simulate moisture intrusion through the metal roof at very low levels (0.1%, 0.3%, and 0.5%), based on the incident rainfall.

Figure 9 displays the total water content of each assembly at 0.5%, 0.3%, and 0.1% moisture intrusion (MI) rates, respectively. Curve “0.5% MI” shows a dramatic increase in total water content with a moisture intrusion rate of 0.5%. The systems moisture balance is unstable. Curve “0.3% MI” shows a less dramatic increase in total water content with a moisture intrusion rate of 0.3%, but is considered unstable, as the amount continues to increase over time. Curve “0.1% MI” shows a stable moisture balance with the total water content cycling seasonally with a moisture intrusion rate of 0.1%. Vapor-tight assemblies are extremely sensi-

**Figure 6 – Traditional stucco-wall assembly.**

**Figure 7 – Traditional stucco-wall assembly with (FSK) and without (no VR) an interior vapor retarder in Tampa, FL.**

**Figure 8 – Fiberglass-insulated metal building.**
Hygrothermal analysis takes into consideration both the geographic location and the building orientation. For example, Figure 10 depicts a hypothetical east-facing brick veneer wall system located in Madison, Wisconsin, a city located in a cold and humid climate, with a 30-year average precipitation of 33 in. Modeling criteria provided in ASHRAE Standard 160 (2009) were followed with exception to the 1% moisture intrusion rate. The recommended moisture intrusion rate of 1% at the exterior sheathing surface was not possible due to the limitations of the software at the time of analysis. In addition, all materials started the simulation with an equivalent equilibrium moisture content at 80% relative humidity. Each hygrothermal analysis was conducted over a three-year period starting in October. Hourly heat and moisture transfer calculations were conducted with WUFI® Pro software (2008) using 30-year averaged historical weather for Madison, Wisconsin that includes, air temperature, relative humidity, atmospheric pressure, wind speed, wind direction, rain, solar radiation and cloud cover data.

Two interior vapor-control layers – a 6-mil polyethylene (6-mil PE) vapor retarder and a 2-mil polyamide (2-mil PA) “smart vapor retarder” (Künzel, 1998) – are compared in this example over a three-year period. In Figure 11, the solid line represents the moisture content of the oriented strand board (OSB) sheathing with the 2-mil polyamide film. The red line represents the moisture content when using the polyethylene film. The 2-mil polyamide vapor retarder is considered stable over the three years and the OSB layer with polyethylene exceeds 20% moisture content and continues to increase over time.

The reason for the polyethylene systems increase in OSB moisture content is illustrated in the surface condensation comparison chart, Figure 12. The graphical display shows that with the polyethylene wall system, condensation occurs as the relative humidity reaches 100%, and the OSB remains wet most of the time. The polyamide system shows no condensation forming and the system dries out seasonally.

Reports can be generated to compare any two materials in a building system for surface condensation and moisture content, combining the data to show sheathing mold growth risk. One can evaluate the risk for mold growth, as well as corrosion, by observing surface relative humidity averaged over time within a specific temperature range. Conditions that are ripe for mold and corrosion are: a surface relative humidity greater than 80% and temperatures ranging between 41°F and 104°F, monitored on a 30-day running average. Time above mold growth threshold...
CONCLUSION

Combined with recommendations from ASHRAE Standard 160, hygrothermal analysis is a powerful tool that allows the designer to predict a building envelope's performance over time. Visualization of moisture related phenomena greatly helps building designers evaluate potential preconstruction moisture risks and also helps analyze and solve moisture problems postconstruction. Specialized software helps the user visualize such factors as surface condensation and mold growth potential, the wetting and drying potential of the building envelope, and moisture content of building components.

REFERENCES


WUFI® Pro 4.2, a PC program for analyzing the onedimensional heat and moisture transport in building components, Fraunhofer Institute, Stuttgart – Holzkirchen, Germany, 2008.