PROCEEDINGS

EVALUATING CONDENSATION RESISTANCE FOR THE DESIGN OF WALL ASSEMBLIES

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ADDRESSING THE
BUILDING ENVELOPE

ABSTRACT

The energy efficiency aspirations of regulators necessitate innovations in many aspects of composite wall design. To meet energy standards in mild and cold climates, providing insulation in both interior and exterior wall cavities is increasingly becoming the norm. Designers' failure to understand the multidimensional nature of construction and to consider how buildings actually operate can unnecessarily restrain the condensation resistance and efficiency of wall systems. This presentation will explore how available resources can be leveraged by practitioners without specialized knowledge of heat-air-moisture computer models to evaluate condensation resistance of wall assemblies.

SPEAKER

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PATRICK ROPPEL, PENG, is a building science engineer in Morrison Hershfield, Ltd.'s (MH) Buildings, Technology, and Energy Division. He specializes in the analysis of building envelope performance through numerical methods. His mixture of field experience, investigations, computer modeling, and research is leveraged at MH to set realistic expectations for building envelope performance during design and evaluation of existing buildings. Roppel's research includes predicting indoor moisture levels for uncontrolled humidity, thermal performance of the building envelope, generic solutions for wall assemblies with low air- and vapor-permeance insulation, and attic ventilation.

EVALUATING CONDENSATION RESISTANCE FOR THE DESIGN OF WALL ASSEMBLIES

INTRODUCTION

In order to realize increased energy efficiency required by many building codes and energy standards, innovations in many aspects of wall design for residential buildings are necessary. Providing insulation in both interior and exterior wall cavities is becoming an increasingly common strategy to meet energy standards in mild and cold climates.[1] Innovative structural cladding attachments have been developed to accommodate different cladding types and varying levels of exterior insulation. Advanced evaluation techniques are necessary to determine the impact of thermal bridging on both the heat flow and structural capacity of complex wall designs. Additionally, in order to evaluate the condensation resistance of these designs, techniques are required that are more advanced than hand calculations based on conventional assumptions. Failure to consider multidimensional heat flow and how buildings actually operate when evaluating condensation resistance can unnecessarily restrain innovative and efficient wall systems in design practice.

This paper explores how practitioners can approximate the condensation resistance of wall assemblies for residential buildings during the design phase, allowing identification of details where more comprehensive analysis is warranted.

The focus of the paper is to outline a methodology that may be used to evaluate the condensation resistance of composite wall assemblies for any mild or cold climate. To achieve this, a method to determine appropriate indoor moisture levels (indoor humidity) must first be outlined, since assumptions about the indoor humidity are critical to the evaluation of condensation resistance. In practice, this can be as simple as specifying the same design criteria for all residential assemblies. Additional background information is presented to provide an appreciation of the concepts upon which these methods are based.

The remainder of the paper outlines a methodology to evaluate condensation resistance using the concept of a temperature index. Included in the discussion are examples that use these methodologies, as well as strategies for leveraging past research and case studies when designing wall assemblies.

DETERMINING INTERIOR MOISTURE LEVELS FOR DESIGN

Realistic assumptions of indoor humidity are critical when evaluating the condensation resistance of wall assemblies, since the indoor humidity contributes to the "load." However, indoor humidity is typically neither directly controlled nor constant in most residential buildings. The indoor humidity in residential buildings actually fluctuates with the outdoor temperature or, more accurately, by the moisture content of the outdoor air. The relationship between the outdoor air and the indoor humidity must be considered when determining appropriate assumptions for indoor humidity. If the appropriateness of the assumption of the indoor humidity for the climate is not verified, the assembly will likely be designed for unintentional loads. A discussion outlining how to determine climate-dependent indoor humidity levels for the heating season follows.

Uncontrolled indoor humidity is said to occur in buildings that do not directly control the indoor moisture levels by mechanical dehumidification. In these buildings, outdoor air is heated to the indoor operating temperature; and the primary mechanism for removing moisture generated indoors is ventilation (i.e., the exchange of indoor and outdoor air). This means that indoor moisture levels are governed by outdoor moisture levels; therefore, the indoor moisture levels are higher than the outdoor moisture levels for the entire heating season. How much higher the indoor air moisture levels are compared to the outdoor air is largely dependent on the ventilation rate relative to the rate that moisture is produced in the indoor space. This relationship leads to the following statement, which is the basis on which we advise indoor humidity be defined when evaluating the condensation resistance of wall assemblies:

> ***Residential buildings with similar average ventilation and moisture production rates will have a similar excess of moisture in the indoor air compared to the outdoor air, regardless of the climate.***

It is important to recognize that the previous statement is supported by physics and has been observed in numerous measurements in real buildings. Please note, however, that it is not the intent of this paper to provide a comprehensive assessment and foundation of an indoor moisture model. Research into indoor moisture models and measuring the indoor moisture levels compared to the outdoor moisture levels has a long history. Work related to establishing indoor moisture levels for design is reported to date back to the 1970s. Recent publications are included in the references to this paper (Roppel *et al.*, 2009; Sanders, 2009; Kalamees *et al.*, 2009; Kumaran *et al.*, 2008). The objective of this paper is to recognize that residential buildings with uncontrolled humidity can be categorized by the likely excess of moisture in the indoor air and to illustrate how convenient this information can be for defining indoor humidity.

Next, units are needed to define indoor humidity by the likely excess of moisture in the indoor air. There are many units that can be used to define the excess of moisture in the indoor air compared to the outdoor air, but there are advantages to the following approach:

> ***Define the excess of moisture in the indoor air compared to the outdoor air by vapor pressure difference (∆VP).***

Vapor pressure is a measure of the moisture in air, which can be calculated when the temperature and relative humidity (RH) are known. The difference in vapor pressure directly defines the "load" and indicates the overall vapor pressure gradient that drives vapor through the assembly.

Moreover, indoor humidity is dependent on ΔVP; therefore, it is highly desirable to define interior moisture levels by ΔVP directly. An example showing how the indoor air moisture levels are defined by ΔVP follows.

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This example demonstrates how the indoor humidity can be calculated for any climate using a single ΔVP value to account for the excess moisture in the indoor air. This example includes a comparison between two climates: Chicago, Illinois, as a cold climate; and Portland, Oregon, as a mild marine climate. The ΔVP value selected for this example is 800 Pa (pascal units of pressure, whose corresponding imperial unitl is pounds per square inch or psi). The significance of this value will be discussed later.

The ASHRAE Handbook – Fundamentals (2009) provides outdoor design conditions for these climates in Chapter 14, "Climatic Design Information." These values are listed as the 99% January humidification design conditions and the mean coincident dry-bulb temperature. The values relevant to this example are summarized in *Table 1*. These values provide a measure of the outdoor moisture content and temperature at January design conditions, and therefore we can determine the design outdoor vapor pressure (P_{out}). This can be calculated directly from the outdoor dewpoint temperature by the saturation vapor pressure at the dewpoint temperature using Table 3 or Equations 5 and 6, all of which are in Chapter 1 of *The ASHRAE Handbook – Fundamentals* (2009), "Psychrometrics." Outdoor temperature, RH, and outdoor moisture content are provided as reference values and to allow comparison with values determined by psychrometric charts.

The indoor vapor pressure (P_{in}) for a ΔVP equal to 0.123 psia (800 Pa) is calculated by adding the ΔVP to the outdoor vapor pressure (P_{out}): $P_{in} = P_{out} + \Delta VP$. *Table 2* summarizes the calculated indoor vapor pressure and RH at 70°F (21°C) for these two example climates.

The remaining step in establishing indoor humidity by the likely excess of moisture in the indoor air is to determine an appropriate value for ΔVP for design. The significance of a ΔVP equal to 0.116 psia (800 Pa) is now presented.

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Guidance on appropriate design ΔVP values for North American buildings for diverse occupancies, construction, operation, and climates is sparse. Sources of information on ΔVP limits appropriate for design are available, although this information is largely based on data from European buildings (Roppel *et al.*, 2009; Sanders, 2009; Kalamees *et al.*, 2009; Kumaran *et al.*, 2008; ISO standard 13788-01). However, it is possible to make reasonable assumptions for evaluating condensation resistance of wall assemblies for North American buildings.

A good starting point for finding guidance on appropriate design ΔVP values is the European Indoor Climate Class Model established by European statistical data (ISO standard 13788-01). The ΔVP limits are defined by a single parameter that represents the combined effects of moisture generation, moisture removal by ventilation, and secondary effects such as moisture buffering and window condensation.[2] This standard specifies 0.117 psia (810 Pa) as high indoor humidity for dwellings with high occupancy and/or moisture generation. These limits should be used with some caution, since the single parameter does not provide guidance with regard to their applicability to acceptable ranges of building construction (airtightness), ventilation, and climate type (heating degree days and outdoor moisture region). However, by making modest reality checks, one can overcome prudence regarding European ΔVP limits without unnecessarily restraining the design of innovative assemblies with overly cautious and unrealistic design assumptions. Reality checks can include: comparisons to traditional accepted RH levels for specific climate, accepted RH levels for health and occupant comfort, ΔVP limits compared to typical condensation resistance of windows, moisture balance equations, and measured data. A broad discussion of reality checks of ΔVP limits for mild and cold climates is available (Roppel *et al.*, 2009).

The European humidity classifications contained in ISO standard 13788-01 do not directly state whether the ΔVP limits are for average conditions (weekly, monthly, or seasonal intervals) or peak design conditions (hourly to daily intervals). The difference between average conditions and peak design conditions should be considered based on the type of condensation resistance evaluation being performed. This paper is focusing on quick analyses of condensation resistance of building envelope assemblies to target problematic details at steady-state design conditions.

In monitored buildings, ΔVP will fluctuate due to varying rates of moisture generation and removal over hourly and daily periods. The average ΔVP over the winter months is fairly constant. ΔVP values at design conditions should represent high moisture levels that are only occasionally exceeded in code-compliant buildings. In other words, an appropriate ΔVP value for peak design conditions should be a value that is not the highest ever recorded ΔVP, but should instead represent high moisture

Climate	Outdoor Dewpoint Temperature	Outdoor Temperature Humidity	Outdoor Relative Pressure	Outdoor Vapor
	ºF (ºC)	*ºF (ºC)*	*(%)*	*psia (Pa)*
Chicago	-8 (-22)	4 (-16)	56	0.012 (85)
Portland	16 (-9)	35 (2)	40	0.042 (284)

Table 1 – Outdoor design conditions for example climates determined by design tables in the – .

Climate	Outdoor Vapor Pressure, P_{out}	ΔVP	Indoor Vapor Pressure, P_{in}	Indoor Relative Humidity @ 70ºF (21ºC)
	psia (Pa)	*psia (Pa)*	*psia (Pa)*	*(%)*
Chicago	0.012 (85	0.116 (800)	0.128 (885)	36
Portland	0.042 (284)	0.116 (800)	0.158 (1084)	44

Table 2 – Calculated indoor design conditions for example climates.

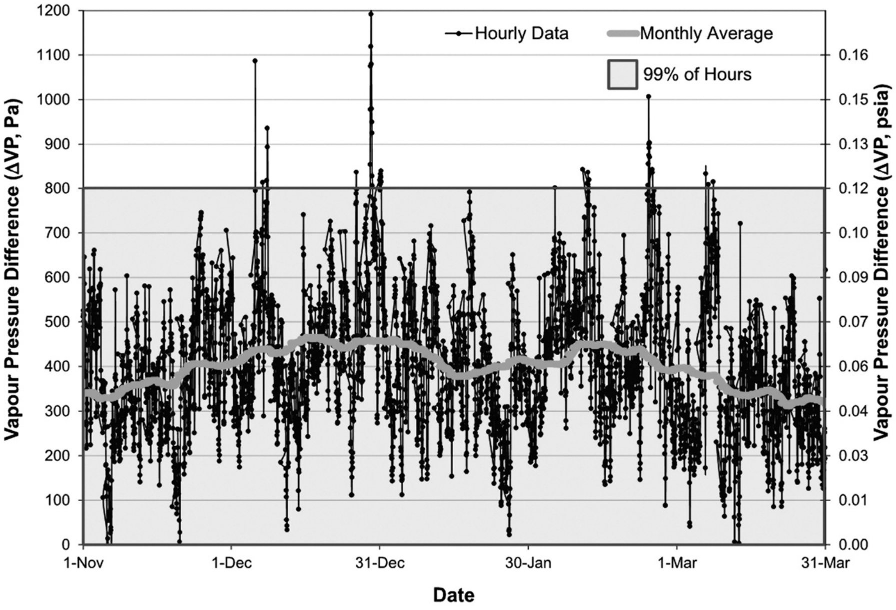

Figure 1 – Example of ΔVP distribution of a monitored building in Vancouver, Canada, during the heating season.

levels for most buildings the majority of the time. *Figure 1* illustrates this point for a monitored building in Vancouver, Canada, during the heating season.

A ΔVP value of approximately 0.116 psia (800 Pa) would appear to be appropriate for mild and cold climates for steady-state calculations for the following reasons:

1. An upper-bound ΔVP for cold weather can be determined by recognizing that humidification is typically necessary to maintain an RH of 35% in cold weather. Additionally, there is very little difference in moisture levels for temperatures less than -13°F (-25°C). Therefore, a reasonable upper bound is the vapor pressure of indoor air at 35% RH and 70°F (21°C) minus the small amount of moisture in the outdoor air for the cold-weather design temperatures. A value of 0.116 psia (800 Pa) is the ΔVP for saturated outdoor air (i.e., 100% RH) at -13°F (-25°C) and indoor air at 35% RH and 70°F (21°C).
2. The upper-bound ΔVP of 0.116 psia (800 Pa) can also be verified for mild weather by recognizing that ventilation rates in residential buildings should be set such that the indoor RH is maintained less than 60% RH for all seasons,[3] as per typical assumptions in ASHRAE standards and many building codes. This is dependent on occupant behavior—i.e., opening windows or turning on a fan when uncomfortable, but is the accepted upper limit for indoor humidity. Indoor air at 60% RH and 70°F (21°C) roughly translates to a ΔVP of 0.116 psia (800 Pa) for average winter outdoor temperatures in mild marine climates.
3. The typical thermal performance of windows can also provide a realistic upper bound of ΔVP because windows are typically the coldest interior surface exposed to interior air and, therefore, the location where condensation is most likely to occur. Indoor humidity should be controlled such that excessive condensation will not occur on commonly available good-quality windows.[4] Furthermore, window condensation can moderate the indoor vapor pressure by dehumidifying the indoor air by condensation. Evaluation of the condensation resistance of typical good-quality, double-glazed windows[5] available in cold climates supports an upper bound of ΔVP at 0.116 psia (800 Pa).

These reality checks provide an upper bound for a ΔVP value of approximately 0.116 psia (800 Pa) that seems appropriate for steady-state design conditions. Note that a lower ΔVP value is appropriate for both average conditions and analyses that consider varying outdoor conditions. This upper bound of ΔVP allows the indoor moisture level to be defined for any climate by utilizing the outdoor design conditions provided by building codes and standards, as shown in example calculations above for Chicago and Portland.

The remainder of the paper outlines a methodology to evaluate condensation resistance for indoor conditions defined by ΔVP.

EVALUATING CONDENSATION RESISTANCE

The basis of the methodology to evaluate condensation resistance is to determine the risk that interior surface temperatures and surface temperatures within the enclosure will be colder than the dew point of the air in contact with that surface. Predicting surface temperatures for wall assemblies can be extremely complex when considering heat-air-moisture transfer through three-dimensional wall assemblies. However, there are specialists in this type of analysis who can calculate these values. The methodology presented here leverages the work of others that has evaluated some of these complexities for generic assemblies and applies this information to the design of similar assemblies for specific climates. This can be accomplished through the use of temperature indices by comparing a temperature index for an assembly under consideration (assembly temperature index) to the minimum acceptable temperature index (design temperature index). In simpler terms, the following evaluation is done (see *Evaluation 1*).

Temperature index is explained below,

Is the temperature index of the assembly ($T_{assembly}$)

Greater Than

The minimum or design temperature index (T_{design})

Evaluation 1

$$T_i = \frac{T_{surface} - T_{outside}}{T_{inside} - T_{outside}}$$

Where
T_i is the temperature index (-)
$T_{surface}$ is the coldest temperature of the surface
$O_{outside}$ is the outdoor temperature
T_{inside} is the indoor temperature

Equation 1

followed by a discussion of the steps required to determine the values for each of the boxes in *Evaluation 1*.

A temperature index is a way to represent a surface temperature of interest (or concern) relative to a temperature difference. It allows a surface temperature to be extrapolated to any set of indoor and outdoor temperatures. Essentially, it is the temperature drop between the inside air and a surface, divided by the total temperature difference. Temperature indices for a surface are calculated as follows (see *Equation 1*).

A temperature index of zero is the outdoor air temperature, and a temperature index of one is the indoor air temperature.

There are many variations of this concept embodied in standards by various organizations. Most commonly, these methods are used by standards for fenestration products to compare the condensation resistance or to rate different products (AAMA 1503-09, NFRC 500-2010, CAN/CSA A440-00). However, these methods are sometimes also contained in standards for evaluating the condensation resistance of any building envelope component (ISO 13788:2001 [E]). The indices vary with respect to the way in which temperatures are averaged or the specific environmental conditions upon which they are based. The only indices relevant to wall assemblies are the I-value (CAN/CSA A440) and temperature factor, f_{Rsi} (ISO 13788:2001 (E)), each of which are nearly identical to the temperature index.

Predicting surface temperatures can be extremely complex when considering heat-air-moisture transfer through three-dimensional wall assemblies. However, there are reasonable estimates of the surface temperatures of common assemblies available that consider three-dimensional heat flow, either by lab measurement or computer modeling (Brown *et al.*, 1993; Kosny *et al.*, 1994; Roppel *et al.*, 2011).

Before discussing how to use these data, readers are alerted to the limitations of extrapolating temperature data (which has been determined for one set of conditions through either modeling or direct measurement) to other conditions through the use of temperature indices. Surface temperatures of building envelope components are affected by heat and moisture storage effects, air transport, and localized variations (for example, fastener locations, surface resistances, moisture levels, etc.), which may or may not be incorporated into the method of determining temperatures. Reported temperature indices are most commonly determined for conditions that are either controlled or set up to determine surface temperatures as a result of steady-state conduction and radiation. Accordingly, temperature indices should be used with attention to the limitations, and users should not perceive temperature indices as the absolute minimum temperatures that can be expected in practice. Nevertheless, temperature indices can be used to target areas where the risk of condensation does not appear to be effectively minimized.

Figure 2 illustrates the three-dimensional (3-D) temperature distribution of a steel stud wall assembly in which the exterior insulation is interrupted by horizontal Z-girts that support the cladding and interior insulation in the stud cavity. The temperature distribution of this wall assembly is dependent on the spacing, size, and orientation of the various thermal bridges. For comparison, if the insulation is continuous, then the coldest temperature on the exterior sheathing is between the steel studs. However, if the Z-girts are vertical and in

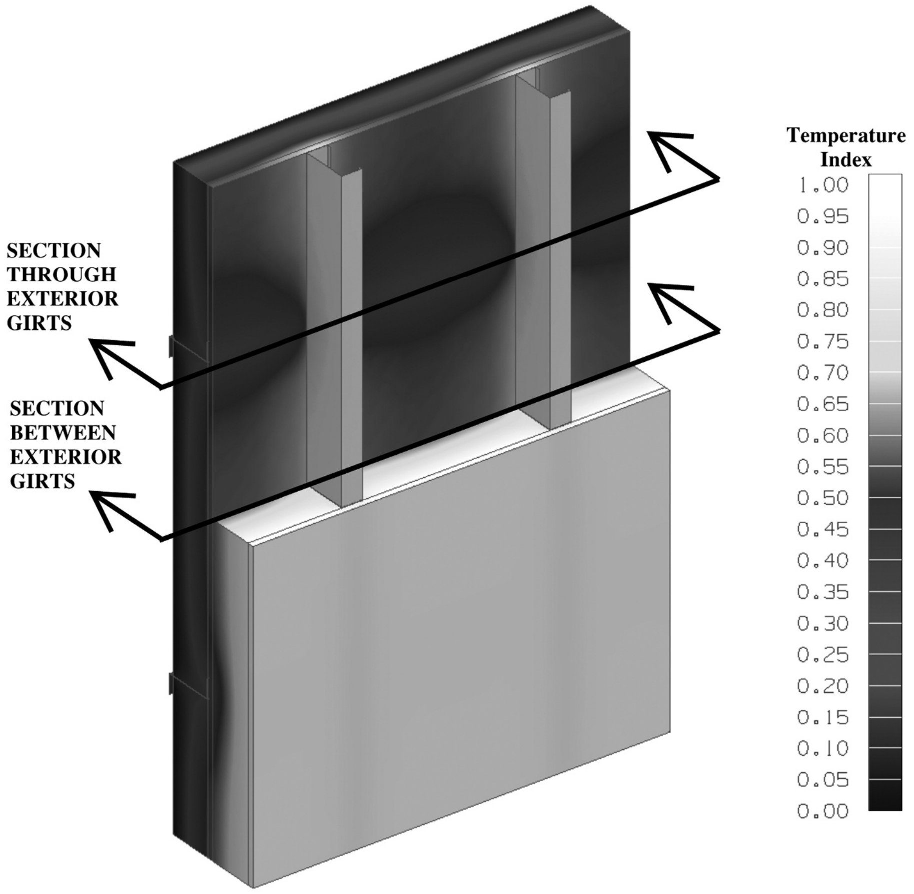

Figure 2 – Temperature distribution of a steel-stud assembly with 3-D heat flow paths.

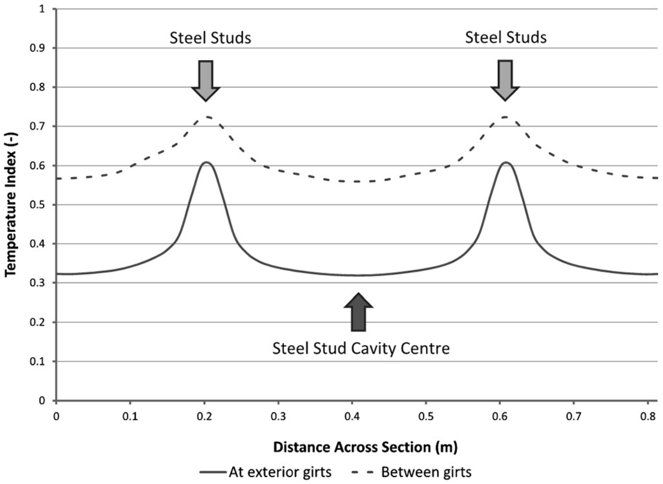

Figure 3 – Distribution of surface temperatures of exterior sheathing for an example steel-stud assembly with exterior Z-girts and insulation.

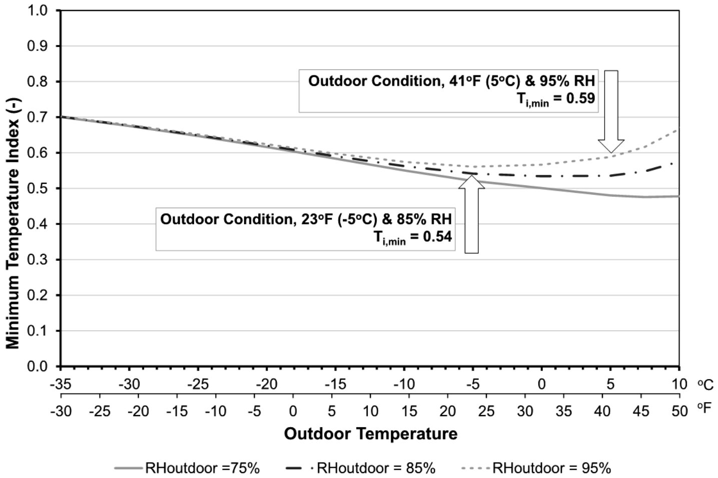

Figure 4 – Relationship of design temperature index to ΔVP.

line with the steel studs, then the coldest temperature will be at the intersection of the girts and studs. For the horizontal girt system shown in *Figure 2*, the coldest surface temperature of the sheathing occurs along the steel girts between the steel studs as shown by the ovals.

Figure 3 plots the temperature distribution of the interior surface of the exterior sheathing through horizontal sections at the Z-girts and between the Z-girts to show the range of surface temperatures on the exterior sheathing of the assembly illustrated in *Figure 2*.

In this example, the assembly temperature index ($T_{assembly}$) for evaluating the risk of condensation on the exterior sheathing is approximately 0.32 (i.e., the lowest index).[6] There are a couple of things worth noticing from this example. First, $T_{assembly}$ could have been determined for any surface–for example the interior surface–but one must remember that the design temperature index T_{design} must be evaluated at the same surface (this will be discussed in the next section). Secondly, for this example, 3-D heat flow must be considered to evaluate the surface temperatures. 3-D heat transfer calculation methods are not necessary if the heat flow through the section occurs only in one or two dimensions. However, consideration of the heat flow path, judging by the orientation of highly conductive components, is critical for evaluating surface temperature. It is important to recognize this when using temperature data for evaluating condensation resistance.

The design temperature index can be the interior air dew point temperature, the dew point of the air in contact with that surface, or minimum surface temperature based on an acceptable RH at that surface. Each of these values is determined by first establishing the indoor vapor pressure using the ΔVP methods presented in the first part of this paper. Where and how one can determine the design temperature index for these three conditions follows.

T_{design} values for surfaces in contact with the interior air are determined by first calculating the temperature index (T_i) using *Equation 1* above, and the interior air dew point. These steps are outlined in the following example.

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Using Chicago as an example again, the indoor vapor pressure of (P_{in}) of 0.128 psia (885 Pa) calculated in Example 1 is used to calculate the interior-air dew point. This can be done using a psychrometric chart or using Equation 39 or 40 in Chapter 1 of the *ASHRAE Handbook – Fundamentals* (2009), "Psychrometrics." For this example, the interior air dewpoint is 42°F (5°C). Using *Equation 1* above, the design temperature index can be calculated. See *Equation 2*.

A minor complication is that ΔVP has an exponential relationship with varying outdoor temperature, but temperature indices have a linear relationship with varying outdoor temperature. The significance of this relationship is that a design temperature index defined by the coldest outdoor conditions for a climate might not be good enough for milder weather for the same climate. This is something we observe in practice for mild marine climates. Window condensation will occur in mild, moist weather (i.e., 40° to 50°F [5° to 10°C]) during rain, but will not occur on the same windows during dry and cold weather (i.e., less than 32°F [0°C]). *Figure 4* illustrates this by plotting the minimum temperature index equal to ΔVP = 0.116 psia (800) for varying outdoor temperature.

As can be seen in *Figure 4*, between 32° and 40°F, for outdoor RH levels greater than 85%, the minimum temperature index

Where
$T_{surface}$ is the interior air dew point equal to 42ºF (5ºC)
$T_{outside}$ is the outdoor temperature equal to 4ºF (-16ºC)
T_{inside} is the indoor temperature equal to 70ºF (21ºC)
Therefore,

$$T_{design} = \frac{42 - 4}{70 - 4} = .058$$

Equation 2

increases with warmer temperatures. For this reason—especially for a mild marine climate—the design temperature index should be defined considering milder temperatures as well as the heating design outdoor temperature. However, it is only necessary to consider up to around 40ºF (5ºC) at 95% RH because ΔVP characteristically decreases in mild-to-warm weather (Roppel *et al.*, 2009; Sanders, 2009; Kalamees *et al.*, 2009; Kumaran *et al.*, 2008).

For designs with air-permeable insulations inboard of or within the building structure, the condensation resistance requires that a design temperature index be defined for surfaces within the enclosure.

A cautious assumption is to define the minimum temperature index by the indoor air dew point as per the previous section, based on the view that air leakage can bring moisture into the enclosure from the indoor air. However, this assumption will restrain the design of many wall assemblies with split insulation for noncombustible construction.

A Glaser or dew point calculation method can be used to determine the vapor pressure or dew point at a surface within an assembly. Add up all the vapor resistances (the inverse of vapor permeance) for each material, and determine the vapor pressure at the pertinent surface by the ratios of the resistances. An example follows.

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This example demonstrates how to evaluate the condensation resistance by calculating T_{design} at the interior surface of the exterior sheathing for Portland and Chicago climates using a Glaser or dew point calculation method and comparing to tabulated $T_{assembly}$ values. This example assumes minimal vapor control at the interior surface.

The vapor pressure at the inside surface of the exterior sheathing, $P_{surface}$, is

$$P_{surface} = P_{in} - R_{in}/R_{total}*\Delta VP,$$

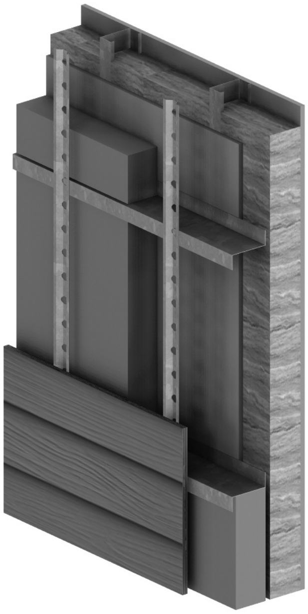
where R_{in} is the sum of the vapor resistances inboard of the surface being evaluated.

For Chicago, using the information in *Tables 2* and *3* and *Figure 5*, the vapor pressure at the inside surface of the exterior sheathing is

$$P_{in} = 0.128 - (0.006 + 0.2 + 0.03)/4.3*0.116 = 0.128 - 0.05*0.116 = 0.12 \text{ psia}$$

The dew point temperature can now be calculated using Equation 39 or 40 in Chapter 1 of the *ASHRAE Handbook – Fundamentals* (2009), "Psychrometrics." From this value, the T_{design} can be calculated as per Example 2. *Table 4* summarizes values that need to be determined to calculate T_{design} at a surface within the assembly using dew point calculation methods for Chicago and Portland.

The minimum temperature index for the interior surface of the exterior sheathing for the assembly shown in *Table 3* is $T_{assembly}$ = 0.32. The lowest temperature is located between the steel studs along the exterior girts as illustrated in *Figures 2* and *3*.



Component	Vapor Permeance (Perm)	Vapor Resistance (Perm-1)
Interior air film	160	0.006
½-in. (13-mm) drywall with primer and paint	5	0.2
R12 fiberglass batt	32	0.03
½-in. (13-mm) ext. sheathing	50	0.02
Sheathing membrane	7	0.14
3-in. (75-mm) XPS insulation	0.27	3.70
½-in. (13-mm) air space	240	0.01
Painted fiber cement siding	5	0.2
Exterior air film	1000	0
Total (R_{total})		4.3

Table 3 and Figure 5 – Vapor resistances of example steel-stud wall assembly with split insulation.

Climate	P_{out} psia (Pa)	P_{in} psia (Pa)	$P_{surface}$ psia (Pa)	Dew Point Temperature at Surface ºF (ºC)	Outdoor Temperature ºF (ºC)	Indoor Temperature ºF (ºC)	T_{design}
Chicago	0.012 (85)	0.128 (885)	0.12 (874)	40 (4.4)	4 (-16)	70 (21)	0.54
Portland	0.042 (284)	0.158 (1084)	0.15 (1073)	46 (7.6)	35 (2)	70 (21)	0.30

Table 4 – T_{design} at interior surface of exterior sheathing.

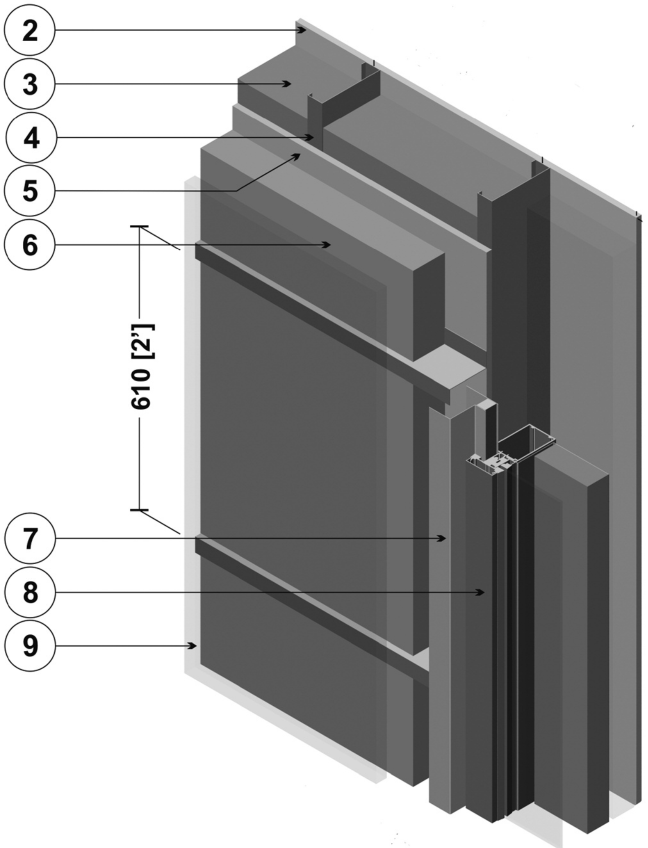


Figure 6 – Temperature index at curtain wall spandrel panel is lower than for clear field area of example steel-stud assembly.

Clearly, the condensation resistance of the wall design is not adequate for Chicago ($T_{assembly} << T_{design}$) but marginally adequate for Portland ($T_{assembly} \sim T_{design}$). However, closer attention to the details is warranted for this assembly in Portland (i.e., at transition details to other assemblies) because of the marginal adequateness of this assembly for the design conditions. For example, without modifications, the condensation resistance would not be sufficient at a transition to the curtain wall spandrel panel detail illustrated in *Figure 6*. The assembly temperature index is 0.26 along the exterior girts near the spandrel panel.

The condensation resistance of the wall assembly can be improved by providing a 1-perm vapor retarder (i.e., low-perm paint). This is still not good enough for Chicago, but it will provide an extra margin of safety for Portland. The T_{design} values decrease to 0.48 and 0.20 for Chicago and Portland, respectively, with the addition of a 1-perm vapor retarder. The Chicago T_{design} decreases to below 0.32 with the addition of a 0.2-perm vapor retarder. However, air leakage condensation must also be considered. Air leakage can both wet and dry-out assemblies, which depends on varying outdoor and indoor conditions specific to a climate. Luckily, there are solutions available that consider the complex heat-air-moisture transfer through stud cavities to help determine minimum insulation ratios for many climates. An example of leveraging these solutions is presented next.

Considering multi-dimensional heat flow and air leakage is important when evaluating the condensation resistance of many wall designs. There are solutions available that provide the minimum amount of outboard insulation for many climates and conditions. However, these solutions do not typically consider 3-D heat flow directly. This limitation can be overcome by utilizing the assembly temperature indices determined by 3-D heat-transfer modeling. The following examples show how this is done.

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Solutions to the minimum amount of outboard insulation required for stud walls with insulation in the stud cavity, considering the effects of air leakage, are available (Kumaran *et al.*, 2002, 2005, NBC; Brown et al., 2007; Craven *et al.*, 2010). However, these solutions typically assume continuous outboard insulation, and the assumed indoor moisture levels are not always defined by a constant ΔVP during the winter. This example shows how to use generic solutions for minimum insulation ratios and apply them to assemblies with thermal bridging through the exterior insulation.

Generic solutions suggest a minimum of 27% of the thermal resistance (sheathing, insulation, cladding) should be placed outboard of the studs to minimize[7] air leakage condensation for a ΔVP equal to 800 for heating degree days up to 12600 HDD 65°F (7000 HDD 18°C).[8] A more conservative solution, with stricter acceptance criteria, suggests that 50% of the insulation should be placed outboard of the studs to maintain the sheathing temperature above the interior-air dew point for a ΔVP equal to 800.

T_{design} can be established by the insulation ratio from recognizing that thermal resistance is directly proportional to the temperature distribution through an assembly for 1-D heat flow. Therefore, T_{design} is equal to the minimum thermal resistance required outboard of the studs.

For this example, the wall assembly is a steel-stud assembly that must comply with ANSI/ASHRAE/IESNA 90.1-2007 for non-residential buildings as outlined in *Table 5*. Different insulation strategies and methods to attach the cladding are being considered for Chicago.

U-values and $T_{assembly}$ values are tabulated in *Table 6* and *Figures 7*, *8* and *9* for three example assemblies.

The two assemblies with only exterior insulation exceed both the minimum requirement of 27% outboard thermal resistance and a more conservative design criterion of 50% outboard thermal resistance.

The split insulated assembly, on the other hand, can meet the minimum requirement of 27% outboard thermal resistance but cannot practically meet the 50% out-

Example Climates	Zone	Insulation	U-Value Btu/ft^2 hr °F (W/m^2 K)
Portland, Chicago, Toronto, Edmonton	4 to 7	R-13 cavity insulation + R-7.5 continuous outboard insulation	0.064 (0.36)

Table 5 – Insulation requirements for example climates per ASHRAE 90.1-2007.

Figure 7

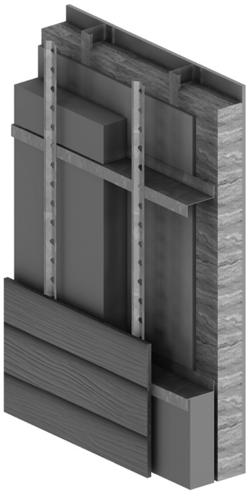

Figure 8

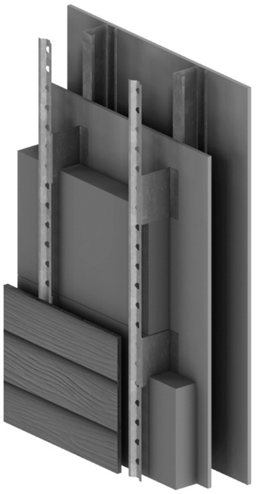

Figure 9

	Exterior Insulation	Exterior Insulated Horizontal Girts @ 24 in. o.c.	Split Insulated Horizontal Girts @ 24 in. o.c.	Exterior Insulated Intermittent Girts @ 36 in. o.c.
U-value Btu/ft^{2}hr°F (W/m^2 K)	R-5	0.146 (0.83)	0.075 (0.42)	0.132 (0.75)
	R-10	0.106 (0.60)	0.061 (0.35)	0.089 (0.50)
	R-15	0.088 (0.50)	0.054 (0.31)	0.068 (0.39)
	R-20	0.076 (0.43)	0.49 (0.28)	0.057 (0.32)
	R-25	0.069 (0.39)	0.045 (0.26)	0.049 (0.28)
$T_{assembly}$	R-5	0.63	0.21	0.63
	R-10	0.69	0.28	0.7
	R-15	0.72	0.32	0.73
	R-20	0.75	0.36	0.76
	R-25	0.76	0.38	0.78

Table 6 – U-values and temperature indices for example assemblies.

board thermal resistance design criterion. It is interesting to note that the energy requirements can be met with the intermittent girts assembly by providing around R-17 of insulation and has a very good condensation resistance. Conversely, the split-insulated assembly can meet the energy requirements with around R-10 exterior insulation and R-12 batt insulation, but has marginal condensation resistance.

CONCLUDING REMARKS

As energy-efficiency requirements tighten, providing insulation in both interior and exterior wall cavities is becoming the norm to meet energy standards in mild and cold climates. Not all assemblies are going to have the ideal of continuous insulation. The effects of 3-D heat flows on condensation resistance need to be evaluated during the design of some wall assemblies. However, considering the combined effects of heat-air-moisture transfer is often not practical in the middle of designing a building, and simple dew point methods will typically restrain innovative design because the duration of wetting and drying cannot be effectively evaluated.

This paper explored analysis methods that are available to practitioners to quickly evaluate the condensation resistance of wall assemblies for residential buildings during design by leveraging generic solutions. The key to leveraging generic solutions for evaluating condensation resistance is the ability to reasonably approximate indoor conditions and surface temperatures for a range of climates without detailed analysis. ΔVP limits and temperature indices provide the mechanism for quick analysis that is supported by more detailed analysis and measurement.

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FOOTNOTES

1. Climate Zones 4 to 8 as identified in 2006 IECC, ANSI/ASHRAE 169-06, and ANSI/ASHRAE/IESNA 90.1-07.
2. Typically, windows are the thermally weakest components of the building envelope and present the coldest interior surface temperature. Windows can therefore moderate the interior air moisture levels by removing moisture from the indoor air via condensation. Hygroscopic materials, such as wood, also have a moderating effect on indoor air moisture levels.
3. At winter operating temperatures between 68°F (20°C) and 74°F (23°C) and summer operating temperatures between 73°F (23°C) and 79°F (26°C), which represent human occupancy comfort for 80% of sedentary or slightly active persons in a thermally controlled environment (ASHRAE Standard 55).
4. If excessive condensation were to occur on typical windows, it would be necessary to increase ventilation effectiveness or dehumidify the indoor air.
5. A temperature index of 0.65 was used for this analysis. More about temperature index is presented later in the paper. Refer to the reference paper for more details on this point.
6. This temperature index value was determined for ASHRAE research project 1365-RP. A catalogue of thermal performance data, including temperature indices, for 40 common building envelope for mid- and high-rise construction is contained in the final report (Roppel *et al.*, 2011).
7. Condensation may occur under extreme conditions but occurs infrequently, and moisture does not accumulate.
8. Assuming an air barrier is provided that controls air movement through the assembly (assumed 0.1 $L/(s \cdot m^2)$ at 75 Pa maximum). Value determined by heat-air-moisture modeling (Brown *et al.*, 2007).