Computer Simulation of Window Condensation Potential

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ABSTRACT

Condensation on windows creates obscured view, can cause building damage, and may lead to mold growth and poor indoor air quality. The Canadian Standards Association (CSA) has developed new procedures to evaluate window condensation potential, using a combination of computer simulation and testing. This paper summarizes results of a study into various aspects of computer simulation related to the evaluation of condensation potential. These findings were used to assist in the development of the CSA procedures.

INTRODUCTION

For several years, standards organizations and window manufacturers have been looking for an inexpensive method of evaluating condensation potential to augment the existing test procedures. The intention is to simplify the process of evaluating products for condensation potential, increase the number of products evaluated, and improve the process of designing products to reduce condensation potential.

Computer simulation techniques have been developed that were shown to be reasonably accurate, although there was room for improvement. One of the issues raised in previous research (Curcija and Goss 1993; McGowan 1995) is that the assumption of a uniform room-side film coefficient is incorrect and may result in errors in the numerical prediction of surface temperatures. With this in mind, simulations were performed for several different specimens, using a uniform film coefficient for the entire room-side surface, as well as modeling local variation of the film coefficient.

PROCEDURE

The simulation procedure followed the methodology outlined by McGowan (1995) using FRAME (EE 1996) and VISION (UW 1996). These programs model the convective fill-gas motion in the glazing cavity, as described in Wright (1998) and allow local variation of the heat transfer coefficient (although the latter was not done in previous research).

The room-side heat transfer coefficient was modified by separating its mean value (i.e., the center-glass value) into radiative and convective components, h_r and h_c. The edge-glass portion of the glazing surface is considered to extend 63.5 mm (2.5 in.) from the sightline, and Curcija and Goss (1993) suggest that the convective coefficient, h_c, varies linearly between zero at the sightline and the center-glass value at 50 mm (2 in.) from the sightline on the glass. Therefore, the edge-glass portion of the glazing was divided into five segments of 12.7 mm (½ in.) each. It was assumed that the heat transfer coefficient is constant over each segment (using the value at the midpoint of the segment). Thus, the convective portion of the heat transfer coefficient in the four segments between y = 50 mm (2 in.) and y = 0 (i.e., the sightline) is reduced by 1/8, 3/8, 5/8, and 7/8, respectively, of the center-glass value. The radiative portion of the heat transfer coefficient, h_r, was modified to account for radiative interaction with the frame.

Figure 1 shows an example of the modified film coefficients used for the glazing in a fixed window with a thermally broken aluminum frame. The first term shows the modification to the convective coefficient, and the second shows the modification to the radiative term (as a first approximation, the modifier for the radiative term is the view factor from the surface to the indoor space). There are two sets of modifications: those labeled "a" simply reduce the radiative portion of the film coefficient on the glass by the view factor from the glass to the indoor space. The set labeled "b" includes radia-

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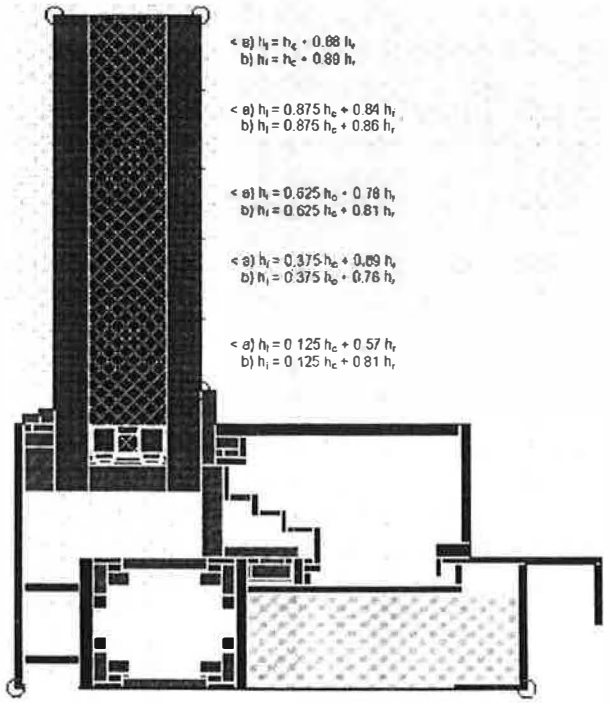

Figure 1 Local variation in room-side film coefficient.

tive heat transfer between the indoor space and the glazing reflected off the frame (the amount reflected increases at lower incident angles near the sightline). Data set "b" was determined by including the portion of radiative heat transfer incident on the frame, multiplied by the angle-dependent reflectance of the frame surface evaluated at the mean angle between the frame/sash surface and each boundary segment on the glass.

RESULTS

The intent was to compare existing test data against computer simulations. A great deal of data from AAMA (1988) and CSA (1990) tests were available. Almost none of the data were useful for comparison, however; the AAMA testing does not allow direct comparison (simulation predicts

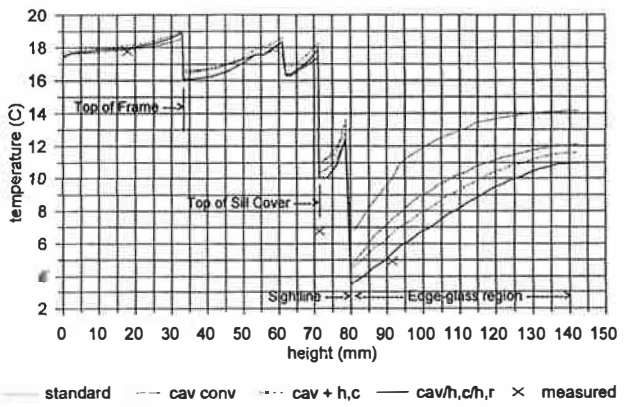

Figure 2 Specimen MI sill temperatures wood frame, DS alum spacer.

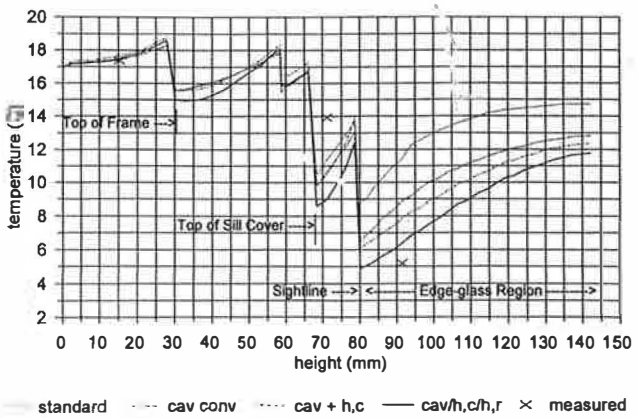

Figure 3 Specimen M6 sill temperatures Al-clad wood frame, foam spacer.

temperatures along the centerline of the glass, and the AAMA test measures temperatures near the corners of the glazing), and the CSA method does not report film coefficients (so test conditions cannot be reproduced in the simulation). Some tests were done following the CSA standard but with film coefficients measured specifically for comparison with simulation. The limited available test data were compared to simulation, as shown in Figures 2 through 7.

The change in simulated surface temperatures (at thermocouple locations) resulting from local variation in room-side film coefficient (rather than using a uniform value for h_i) is shown in Table 1. Only some of the data in Table 1 are represented in Figures 2 through 7; the rest are provided for information and can be found in EE (1997).

In all cases, simulations were done according to the CSA A440.2 (CSA 1993) method for determining U-factors, in which edge-glass convection is not included and the mean room-side film coefficient is uniformly distributed (labeled "standard"). Convective motion in the edge-glass portion of the glazing cavity is then included in the model ("cav conv"). Local variation in the convective component of the room-side film coefficient is included ("cav + h,c"), and, finally, the radiative component is also allowed to vary locally ("cav/h,c/h,r"). Where available, test values are provided ("measured").

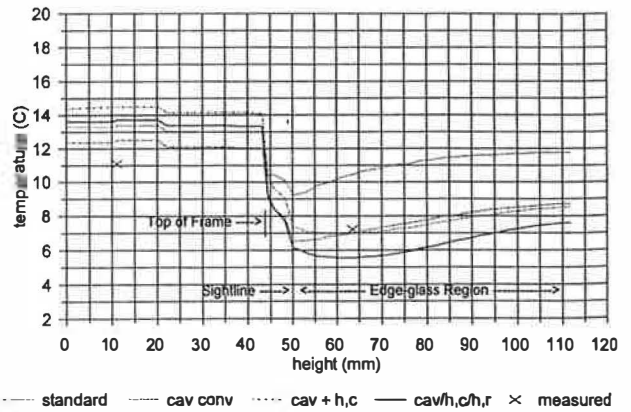

Figure 4 Specimen K5 sill temperatures TB alum fixed frame - TB alum spacer.

TABLE 1
Change in Surface Temperature Due to Local Variation in h_i, °C (°F)*

ID	Description of Specimen	Frame	Glass
M1	Wood casement frame, DS alum. spacer	−0.02 (−0.04)	−1.7 (−3.1)
M4	Alum-clad wood casement frame, DS alum. spacer	−0.5 (−0.8)	−2.2 (−4.0)
M5	Wood casement frame, silicone foam spacer	−0.3 (−0.5)	−1.7 (−3.0)
M6	Alum-clad wood casement frame, silicone foam spacer	−0.3 (−0.6)	−1.8 (−3.3)
M7	Wood casement frame, TB alum. spacer	−0.3 (−0.6)	−1.8 (−3.2)
M8	Alum-clad wood casement frame, TB alum. spacer	−0.4 (−0.7)	−1.9 (−3.4)
M9	Wood casement frame, vinyl spacer	−0.2 (−0.4)	−1.6 (−2.9)
K5	TB aluminum fixed frame, TB alum. spacer	+0.9 (+1.6)	−1.3 (−2.4)
K6	TB aluminum operable frame, TB alum. spacer	+0.2 (+0.3)	−0.9 (−1.6)
K7	TB aluminum fixed frame, silicone foam spacer	+1.2 (+2.2)	−4.2 (−7.5)

* EE (1997)

In all cases shown in Figures 2 through 7, an explicit model of the convective motion in the cavity produces colder surface temperatures on the sill sections. Including local variation of the room-side film coefficient produces still colder temperatures. In most cases, these changes produce more accurate results (relative to test). It also appears that the magnitude of the changes is roughly equally attributable to the effects of convection in the glazing cavity and local variation in the room-side film coefficient.

The measured values should be viewed with caution, however; thermocouple placement on the frames is not reported in the tests, so their location is not certain. For example, the thermocouple on the sash in Figure 2 was assumed to be on the vertical surface of the sash (at y = 71 mm or 2.8 in.). If it was actually on the horizontal surface of the sash (at y = 79.5 mm or 3.1 in.), the simulation would be as accurate in predicting the sash temperature as it is for the frame temperature (at y = 18 mm or 0.7 in.).

Also, the measured glass temperatures shown in Figures 2 through 5 were recorded at 50 mm (2 in.) from the corner of the window, whereas simulation applies to the centerline of the window. The measured temperature at the centerline could be as much as 2°C or 3.6°F warmer (EE 1997). Still, it appears that the changes resulting from including cavity convection and local variation in room-side film coefficient produce results closer to the test results.

In Figure 5, the modified simulation procedure produces temperatures that are closer to the measured values but are still 2°C to 3°C (3.6°F to 5.4°F) warmer than the test results. It may be that this specimen, an operable casement window, was affected by "wind-washing" during the test. This occurs when the specimen experiences air leakage into weepholes, thus bringing cold air into interior cavities of the specimen, possibly bypassing the thermal break in the frame (but not leaking cold air into the room side of the specimen). This effect was investigated by introducing the weather-side conditions into the interior of the specimen during a simulation, bypassing the thermal break (the line labeled "windwash" in Figure 5) to represent a worst-case situation. Figure 5 shows the test values lie between the case of no wind-washing and maximum wind-washing.

There is no way of predicting how much wind-washing will occur in a given test (and no way of determining the response of the specimen to wind-washing). Separate from the effects of air leakage, then, wind-washing poses some difficulty for the simulation procedure. It should be noted, however, that the specimen shown in Figure 5 has a relatively large thermal break and could be more sensitive to the effects of wind-washing than many thermally broken metal-frame windows. Given that this is close to a worst-case situation, the difference between simulation and test results (2°C to 3°C or 3.6°F to 5.4°F) is not excessive. Also, the effect of wind-wash-

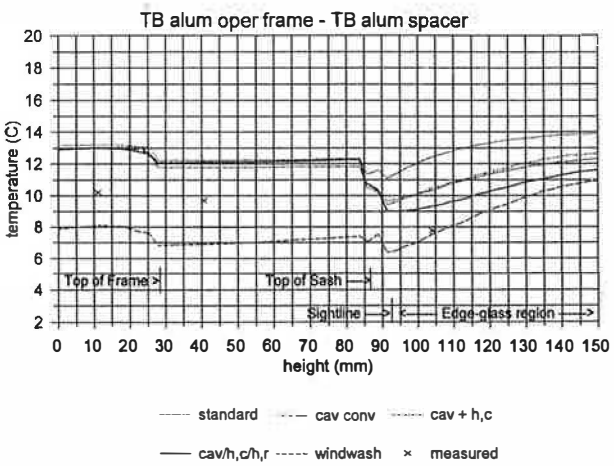

Figure 5 *Specimen K6 sill temperatures TB alum oper frame - TB alum spacer.*

ing on the glass temperature (which is the colder temperature and therefore defines the rated condensation potential of the window) is less than that of the frame, and the simulation is only 1°C to 2°C (1.8°F to 3.6°F) off the test value in this region.

The results for the thermally broken aluminum window are shown in Figures 6 and 7. This is a fixed window, shown in cross section in Figure 1. The glass temperature prediction for the "cavity convection model" is very close to the measured result and underpredicted by 3.3°C (5.9°F) degrees for the "cavity convection and hc adjusted model" when compared to the test (Figure 6). The simulation with the film coefficient adjusted for radiative effects produces a glass temperature more than 6°C (10.8°F) lower than the test value. In the test where the frame temperature was measured (see Figure 7), the glass temperature from simulation is still colder than the test result, but the simulated frame temperature is 5°C (9°F) warmer. A 5°C (9°F) difference in measured temperatures for the sill and the head has been observed in these types of specimens (EE 1997). Thus, the FRAME program temperature predictions are representative of the head (and upper jamb) portions of the window but are too high for the sill and lower jamb portions. Recent research (EE 1998) has identified several possible reasons for differences between measured and simulated temperatures for thermally broken products:

- temperature stratification in the warm-side test chamber;
- convection within the large aluminum channels of the frame;
- differences between the product drawings and the actual specimen (due to normal variations associated with manufacturing tolerances or assembly procedures);
- high flanking losses in the test, due to the manner in which the specimen is installed in the mask wall (the test procedure will account for these flanking losses, but the simulation procedure does not, unless the installation detail is known and included in the model); and
- the presence of wind-washing or air leakage in the test situation, which is not included in the model.

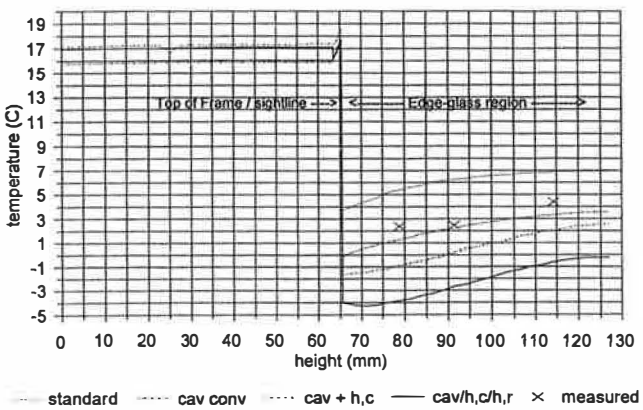

Figure 6 *Specimen K7a sill temperature TB alum fixed frame - foam spacer.*

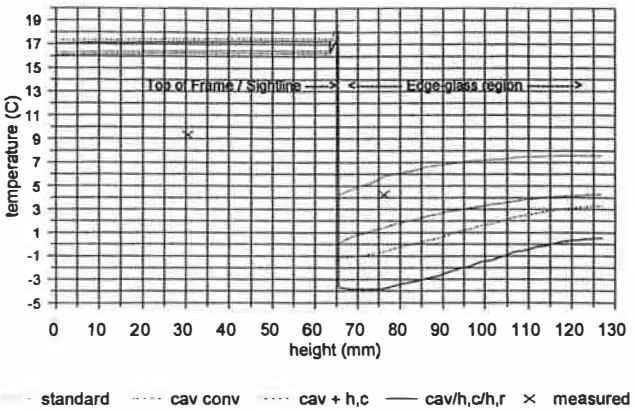

Figure 7 *Specimen K7b sill temperatures TB alum fixed frame - foam spacer.*

It is not known which (if any) of these reasons might account for the discrepancies in the results shown in Figures 6 and 7, but it seems to be related to the fact that these are metal-framed windows. These differences should be viewed in the proper context, however; discrepancies of similar magnitude have been observed in test results from different laboratories (EE 1997), and the reasons for these discrepancies are not clear. There is a need for further investigation into these issues, and it is expected that many of these discrepancies can be resolved through a combination of refinements to the test and simulation procedures.

Table 1 shows that improving the simulation methods changes predicted frame surface temperature by less than 1°C or 1.8°F in most cases (and the temperatures are already accurate relative to test values). The improvements (i.e., modeling fill-gas motion, local variation of h_i, etc.) have a large effect on glass temperatures, however, and appear to bring those values much closer to the measured glass surface temperatures.

The simulations with no local variation in the radiative component of the film coefficient (labeled "cav + h,c") are closer to the test values for the metal-frame specimens (Figures 4 through 7) than are the simulations with the radiative modification. It is possible that radiative heat transfer between the indoor space and the room-side surface of the specimen includes reflections off the frame surfaces; see equations "b" in Figure 1.

If this is the case (and Figures 4 through 7 suggest that it is), then modifications to the radiative component of the film coefficient should go beyond a simple enclosure to include surface reflection. This is somewhat involved—the diffuse/specular enclosure model would need to be extended to modify the diffuse/specular split to account for directional effects of reflection, and directional optical properties for various surfaces would be required.

The results in this study suggest that satisfactory results can be obtained without modifying the radiative component, although it should be noted that there is some uncertainty in the test data, and that these specimens did not have significant

self-viewing (relative to a garden window or projecting skylight, for example). It is expected that the radiative component would be more important in specimens with significant self-viewing, although frame reflection (and the angular dependence of optical properties for framing surfaces) should be considered in those cases.

EFFECT OF AIR LEAKAGE

Some concern has been expressed that air leakage can affect the condensation potential in a given window design. Air leakage (where outdoor air leaks completely through the specimen and enters the room side of the specimen) can reduce room-side surface temperatures in much the same way as wind-washing (in which cold air enters the specimen but does not penetrate to the room side). In some cases, the introduction of cold, dry, weather-side air may reduce the tendency for condensation to form.

Studies of the effects of pressure cycles (CANMET 1993) and operational cycles (CANMET 1991) showed a general increase in air leakage in windows after 2000 pressure cycles or 2000 motion cycles. The studies showed a reduction in rated condensation potential values for many of the specimens, but there was no correlation between increased air leakage and the reduction in condensation potential for the specimens evaluated. In some cases, although the air leakage of the windows generally increased after pressure cycling, the condensation resistance also improved. The results of both studies showed that the effect of increased condensation potential is mainly limited to the frame and that condensation on the glass is not affected by increased air leakage.

In a more recent study (EE 1997), the frame type in simulations had little effect on the rated condensation resistance of the glass. Thus, air leakage may affect condensation potential somewhat, but it does not appear to substantially change the performance of the glass. As the glass performance defines the rated condensation potential for most windows with nonmetal frames, air leakage may not have a substantial effect on condensation potential in these cases. Further research would be required, however, before categorically stating that air leakage is only important for metal-framed windows.

DEVELOPMENT OF A NEW PROCEDURE

An effective simulation procedure for condensation potential must be both simple and accurate. The proposed methodology is indeed quite simple, but its accuracy is difficult to determine due to the variation in results between test labs and the limited amount of data available for comparison. Simulated conditions are at least consistent compared with test results, which is a useful feature in national rating standards.

It is important to recognize the limitations of simulation. If air leakage has a significant effect on condensation potential, products that are found to have a significant amount of air leakage should be tested for condensation potential. Further study is needed to determine the exact level of leakiness at which this effect becomes important.

Also, two-dimensional simulation reflects temperature profiles at or near the centerline of the product. Although local effects of hardware (e.g., hinges, sash locks, operator mechanisms) can be modeled, it is difficult to assess the magnitude of corner effects or to attempt to develop a correlation between centerline and corner temperatures, as there are insufficient data to do so. Thermographic testing would be useful in this regard but only if the room-side film coefficient can be measured, to allow accurate comparison with simulation.

When these issues have been resolved, however, the procedure for simulating condensation potential will be relatively simple:

1. Except in the case of sliding windows, only sill sections need be analyzed. The other sections of a window do not contribute to the condensation potential. For sliding windows, the interlock should also be analyzed.
2. The convective cavity model in Wright (1998) should be used to characterize the contribution of fill-gas motion to condensation potential.
3. Local variation of the room-side film coefficient has a small effect on frame and sash temperatures; it is not worth the additional effort to modify the film coefficient on the frame and sash. The nominal center-glass film coefficient can be used on the frame and modified on the glass to account for the reduction in the convective film coefficient near the sightline. The method outlined in this paper is suggested for modifying the convective component of the room-side film coefficient. The radiative component can be modified, but the method appears to provide satisfactory results without this modification.
4. Temperature locations recommended in the test procedure should be used to define frame and glass surface temperatures and nondimensionalized in accordance with the appropriate standard to determine a temperature factor (TF, in accord with CSA 1998) or a condensation resistance factor (CRF, in accord with AAMA 1988) for the glass and for the frame. The value for the frame may only be achievable via physical testing for very leaky windows, but the value for the glass can always be obtained via simulation.
5. If simulation is to be compared against testing, the average room-side film coefficient must be known (and used in place of the center-glass value in Step 3). Thermocouple locations must be known for precise comparison. Room-side and weather-side air temperatures are also important inputs to the simulation procedure, and the test values must also be known prior to simulation.

CONCLUSIONS

- Computer simulation of condensation resistance offers low cost, repeatability, and a permanent record of the evaluation procedure and appears to be reasonably accu-

rate compared to test results, although there are not sufficient data to make a categorical statement regarding the accuracy of simulation (particularly in the case of metal-frame windows).

- Computer-based evaluation can be a useful complement to current North American rating methods, which use spot temperatures from testing to predict condensation potential. The simulated test procedure is not accurate for thermally broken frames or for cases where air leakage significantly affects window performance, however; further research involving more controlled conditions and thermography would be useful in improving the procedure.
- A two-dimensional simulation model does not include corner effects, although local effects of hardware can be considered. A three-dimensional model would address this problem but would be as expensive as testing in many cases, and the complexity of the data input required presents the possibility of introducing more errors. In many cases, the magnitude of corner effects is small, so it may be unnecessary to develop a correlation between centerline and corner temperatures, but there are insufficient physical test data to state this conclusively. Thermographic testing would be useful in this regard.
- Differences between test and simulation are equal to or less than the variability seen between laboratories (for the same specimen). The difference between test and simulation for the lower glass temperature is typically in the order of 1°C to 2°C (1.8°F to 3.6°F), with a worst case of 3.3°C (5.9°F) when compared to test results. There appears to be slightly poorer agreement between test and simulation for frame and sill temperatures. Simulation is typically 3°C higher than test and, in the worst case, 5°C for thermally broken aluminum frames.
- The larger difference for the framing system may be due to wind-washing, air leakage, or convection in large aluminum channels. Simulation does not currently address the influence of air leakage on condensation; indeed, the effect has not been quantified (although it may be significant). Also, wind-washing (partial air leakage) may increase condensation potential; this effect is also not quantified and may depend in part on the specific frame and weatherstripping design. Wind-washing is not specifically addressed by the proposed simulation procedure.
- Frame temperature is largely independent of the glazing system; sash temperature is only moderately independent of the glazing system for nonmetal frames. Also, the sash temperature is affected by spacer type, but the frame temperature is not (in the case of nonmetal frames or where the sash is insulated from the frame).
- The glass temperature at 50 mm (2 in.) above the sightline is almost fully independent of spacer type, but the glass temperature at 13 mm (½ in.) above the sightline is not. Also, the glass temperature is generally not affected by the frame type but is somewhat dependent on the glazing-in system (i.e., the weatherstripping and sealants used to secure the glazing system into the sash).
- Local variation in room-side film coefficient and fill-gas convection have equal effect on room-side surface temperature. Altogether, the glass temperature is reduced by about 2°C (3.6°F) and frame temperature by 0.3°C or 0.5°F (except in metal frames where temperatures increased by about 1°C or 1.8°F with local variation in h_i).

RECOMMENDATIONS

- The effects of wind-washing and air leakage on condensation potential should be further investigated. This would require testing of several specimens, sealed and unsealed to permit partial or complete air leakage, with thermography used to assess room-side temperature distribution. Also, measurement of room-side film coefficients would be required for comparison to simulation.
- In the absence of a clear understanding of the air leakage effects on condensation, simulation should not be used to assess condensation potential in the case of specimens that exhibit air leakage above some threshold (yet to be determined). Such products would require condensation evaluation to be done by testing.
- Thermography should be used to develop a correlation between centerline and corner temperatures, as there are insufficient data to do so. The room-side film coefficient should be measured at the same time to allow accurate comparison between simulation and thermographic results.
- A method for simulating condensation resistance is proposed. This procedure should be validated against tests, partly to assess its accuracy and fine-tune the simulation method, but also to determine when air leakage effects prevent the specimen from being simulated for condensation resistance, and require testing.

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