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A Comparison of Calculated and Measured Indoor-Side Window Temperature Profiles

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ABSTRACT

Computer-generated surface temperature profiles are presented for the indoor side, vertical centerline of two windows and a calibration transfer standard (CTS). These specific configurations were chosen because they match test specimens used in a previous test program, and the resulting temperature profiles, measured using a thermographic camera, are available in the literature. Calculations were completed using the VISION4 program for one-dimensional center-glass analysis and the FRAME 4.0 program for two-dimensional analysis of the edge-glass and frame. Three different computational models were used: (1) the conventional procedure used widely to generate total-window solar gain and heat loss coefficients, (2) a procedure to account for fill-gas motion was added, and (3) the convective heat transfer coefficients were reduced near the recessed corners of the indoor surface. Profiles were scrutinized most closely at the bottom edge-glass section—where condensation most readily occurs. Simulation provides useful qualitative information, and each of the two features added to the model provides better agreement with measurement. It is concluded that simple, inexpensive, and easy-to-use computer software can offer reliable design guidance and performance verification regarding condensation resistance.

INTRODUCTION

Over the last three decades, the increased variability of energy prices, coupled with a variety of window design innovations (e.g., low-e coatings, substitute fill gases) and a continuing interest in efficient building design, has led to the development of more advanced models for characterizing the thermal performance of windows. More recently, the availability of inexpensive desktop computers has resulted in the creation of more intricate computer-based models. The state-of-the-art in the thermal analysis of windows entails a two-step process. First, a one-dimensional model is used to analyze the center-glass area, and then a two-dimensional numerical conduction analysis is used to characterize the remaining sections of the window. This approach is convenient because only a very small amount of data need to be passed from one program to the other, and each program is fast and easily managed as a result of a relatively small requirement for memory and CPU time. Various combinations of software have been developed in Canada, the United States, Europe, and elsewhere. Experience has been gained to the extent that U-factors and solar heat gain coefficients (SGHC) produced by computer simulation are felt to be as accurate as those produced by testing with hot box and/or solar calorimetry (e.g., EE 1990). Recognizing that simulation offers significant savings in time and expense, various standards have been put in place that take advantage of such window simulation software.

Still more recently, there has been significant interest in the temperature distributions of the indoor surfaces of windows that are subjected to winter nighttime conditions. The ability of a window to remain free of condensation—the window's "condensation resistance"—is important, not only because accumulated water (and possibly frost or ice) may cause damage, but also because the presence of condensation is visible evidence of poor thermal performance and it is natural for the homeowner to form the corresponding opinion regarding the quality of the product.

The measurement of window surface temperatures entails more effort, and expense, than the more common hot-box test-

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ing that is undertaken to measure a total-product U-factor. The usual approach is to place thermocouples on the window surface, but this must be done carefully to minimize the effect of the thermocouple on local surface temperature and heat transfer processes (see, e.g., NFRC 1997a). Questions arise regarding the most useful locations for thermocouples. Ideally, the thermocouple placement would ensure that localized thermal bridges are identified without overstating the effect of such bridging. It is difficult to establish the proper thermocouple location *a priori*. It is also important to have strict control of the humidity level in the warm-side chamber, and the surface heat transfer coefficients must be known.

Similarly, computer simulation for determining local surface temperatures requires more detailed modeling procedures than those that have been established for calculating total-product U-factor. The conventional simulation procedure for assessing thermal performance includes the effect of edge-seal conduction, which is often the one design detail that most strongly influences condensation resistance, but it neglects several phenomena that are known to cause a temperature minimum at the lower edge of the indoor glass surface. The missing factors include: the influence of fill-gas motion, the local reduction of indoor-side convective heat transfer coefficient at recessed corners, the decrease of indoor side convective heat transfer coefficient as the buoyancy-driven boundary layer develops from the top to the bottom of the window (henceforth denoted "meso-scale" variation), radiant clear-sky cooling of the outdoor sill surfaces, self-viewing of indoor surfaces, and possibly others.

More advanced numerical models have been developed that are capable of two-dimensional simulation of the full height of a window or even three-dimensional simulation of the entire window. Such simulations demand a significant investment of time and effort, more extensive and expensive computing equipment, and are rarely undertaken. However, examples of full-height, two-dimensional calculated temperature profiles can be found in the literature—the most notable being those generated for a blind, round-robin comparison of measured (Griffith et al. 1996;Elmahdy 1996) and calculated (Zhao et al. 1996; deAbreu et al. 1996) temperature profiles for a variety of flush-mounted insulated glazing units (IGUs) (Sullivan et al. 1996). Measurements were made using thermography.

The earlier comparison of flush-mounted IGUs generated enough interest that an effort has been made to repeat the exercise using complete windows (i.e., with frames and recessed surfaces, etc.). The thermographic measurement of temperature profiles across recessed surfaces, in contrast to flat surfaces, is significantly more difficult because of the variability of background radiation incident on the specimen resulting from the self-viewing nature of the specimen. Measurements of complete window specimens have been made, and the results have been published (Griffith et al. 2002). The goal of the current study is to present calculated temperature profiles that can be directly compared to the measurements of Griffith et al. (2002). Rather than undertake the complexity of a full-height two-dimensional simulation model, temperature profiles have been generated using the more conventional approach of dealing with center-glass and edge-glass/frame areas using separate pieces of software. Specifically, VISION4 (e.g., UW 1996) was used for center-glass analysis and FRAME 4.0 (e.g., EE 1995) was used for frame and edge-glass calculations. This methodology was briefly included in the Canadian national standard for determining condensation potential in windows (CSA 1998). In addition to providing convenience, this approach offers an opportunity to study the effectiveness of various extensions to the more conventional simulation model. In particular, two extensions were incorporated: one that accounts for fill-gas motion and the other to account for reduced convective heat transfer coefficient at the recessed corners of the indoor surface. These model extensions showed promise in a previous comparison by McGowan and Wright (1998), but the only data available for comparison in that instance were limited sets of thermocouple measurements.

TEST SPECIMENS

Three test specimens—a calibration transfer standard (CTS) and two windows—were examined by Griffith et al. (2002), and the same specimens were considered in this study.

The CTS consisted of two pieces of glass separated by 12.5 mm of insulating foam. Thermocouples were placed between the glass and foam surfaces and, knowing the thermal resistance of the foam, the temperature difference could be used as an accurate measure of heat flux through the assembly. In turn, the temperatures and heat flux values were used to measure the average indoor and outdoor surface heat transfer coefficients.

The second and third specimens were both double-glazed windows with a 16.5 mm air-filled glazing cavity. The edge-seals were of a dual-seal construction, built with an aluminum spacer bar (incorporating silica-gel desiccant) with a poly-isobutylene (PIB) primary seal and polysulphide secondary seal. Each glazing unit was installed in a wood, fixed-casement frame. The only difference between the two windows was that the third specimen included a low-emissivity (low-e) coating. The second specimen was built with uncoated clear glass.

The remaining discussion will refer to the three specimens as CTS, ClrClr, and ClrLowe for the purpose of convenience.

More details regarding the dimensions and geometry of the test specimens can be found in (Griffith et al. 2002). Dimensioned drawings have been made available on the internet (Griffith 2000). The FRAME 4.0 simulation models used to represent the CTS and window specimens are shown in Figures 1 and 2, respectively. The indoor frame surfaces consist largely of vertical and horizontal sections so, except for the omission of one small chamfer and one rounded corner, Figures 1 and 2 are accurate representations of the indoor surface geometry (the crosshair cursor indicates the location

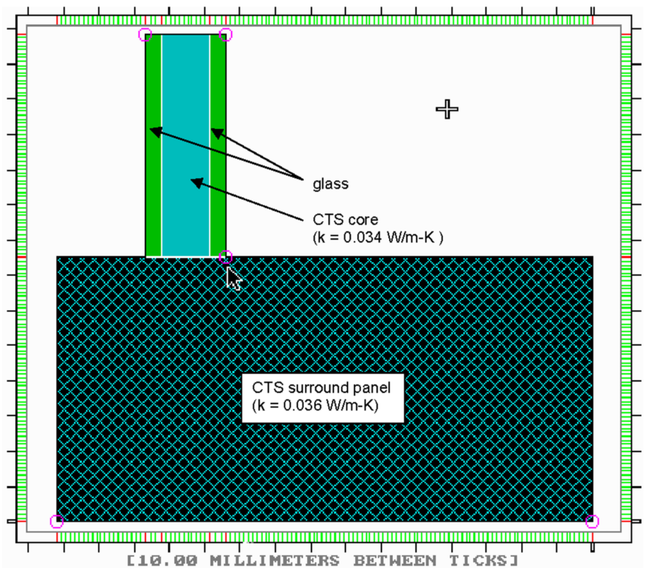

***Figure 1** FRAME representation of CTS.*

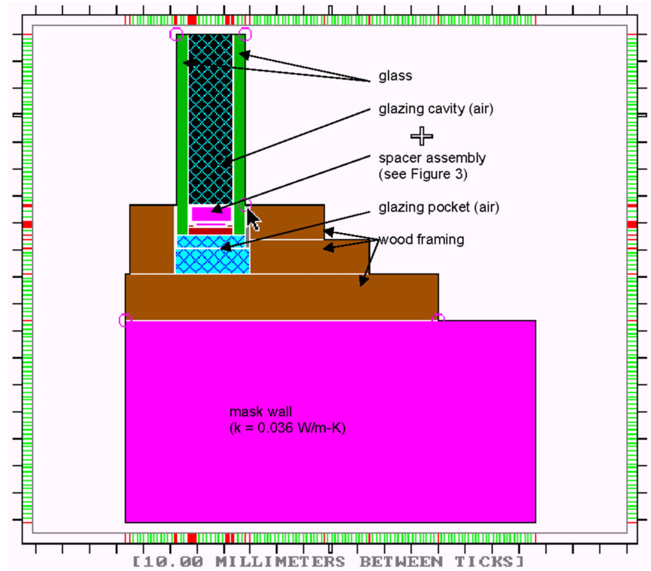

***Figure 2** FRAME representation of window cross sections: frame and edge-glass.*

of the indoor space). The outdoor frame surface includes two sloped sections that have been replaced with rectangular sections in accordance with established practice (e.g., NFRC 1997b), and it was determined that such details regarding the outdoor frame surface had virtually no influence on the temperature profile at the indoor surfaces. The FRAME 4.0 representation of the critical edge-seal section was created using information provided by Griffith (2000). Figure 3 shows the detail of the edge-seal representation used in FRAME 4.0. Thermal conductivity values and emissivities suggested by Griffith (2000) were assigned to the various CTS and window materials. These data are listed in Table 1.

SIMULATION PROCEDURES

Conventional Simulation

All computer simulations were undertaken using VISION4 (UW 1996) for center-glass analysis and FRAME 4.0 (EE 1995) for edge-glass and frame analysis. VISION4 incorporates a one-dimensional thermal resistance network model based almost entirely on fundamental principles (Wright 1998a). The only empirical component of the VISION4 model of interest in this study is the correlation for convective heat transfer across the glazing cavity (Wright 1996). The FRAME 4.0 program generates a numerical solution for the temperature field and heat transfer through a two-dimensional composite assembly of frame and edge-glass materials. Approximations are made in the event that the problem domain includes cavities. Known correlations are used to assign a fictitious, or "effective," conductivity to the gas contained in frame cavities to account for convective and radiant heat transfer. The gas is then treated as a solid. The frame

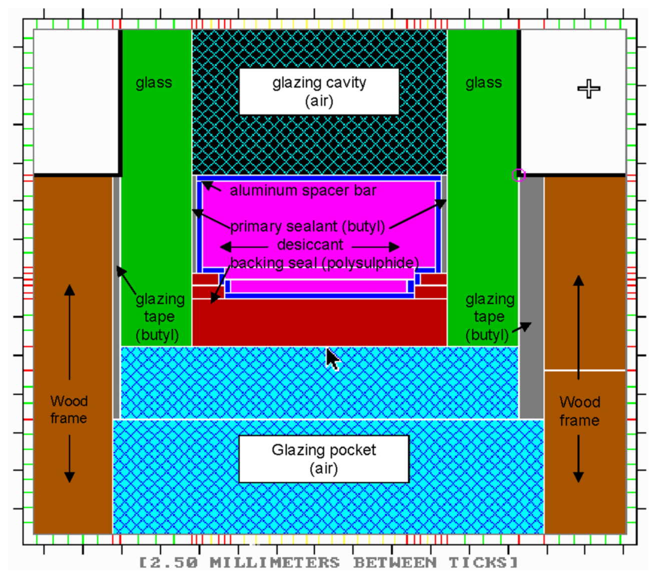

***Figure 3** FRAME representation of window edge-seals.*

assemblies examined in this particular study included only one small cavity near the edge-seal (i.e., the glazing pocket into which the IGU is installed). Similarly, the fill-gas contained in the glazing cavity is treated as a solid, and its effective conductivity is evaluated on the basis of results produced by the VISION4 calculation.

The initial set of simulations was completed using the VISION/FRAME software in its conventional configuration, as described above.

TABLE 1
Thermal Conductivity of Window Materials for FRAME Simulation

Material	Thermal Conductivity (W/m·K)	Emissivity
Glass	1.0	0.84
Low-E Coating	n/a	0.10
Wood	0.14	0.90
Butyl Rubber	0.24	0.90
Aluminum	160	0.2
PVC Flexible	0.12	0.9
EPS Foam, CTS Core	0.034	0.9
EPS Foam, Surround Panel	0.036	0.9
Silica Gel Desiccant	0.03	0.9

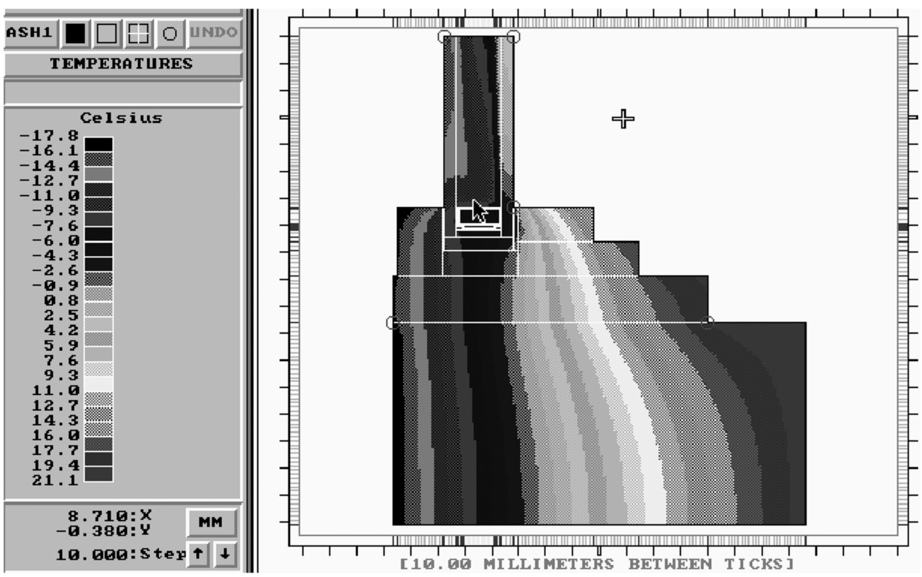

Figure 4 *FRAME representation of temperature profile in solution domain (for glazed window specimen).*

Fill-Gas Convection Model

It is known that fill-gas motion contributes to the presence of condensation along the bottom edge of the window view area. The fill-gas is progressively cooled as it descends adjacent to the outdoor glazing. Where the fill-gas turns at the bottom of the glazing cavity and begins its ascent, the coldest gas closely approaches the bottom of the indoor glazing (Wright and Sullivan 1994, 1995a; Sullivan et al. 1996), causing an area of increased heat flux and decreasing the temperature of the indoor glazing near the bottom sightline.

A simplified model has been devised that allows VISION4 and FRAME 4.0 to account for fill-gas motion (Wright and Sullivan 1995b; Wright 1998b). This procedure entails several steps. First, VISION4 executes a two-dimensional finite-volume, computational fluid dynamics (CFD) analysis of the buoyant fill-gas motion in the glazing cavity. This process is largely transparent to the user because the program already has access to the cavity geometry and the fluid properties, and the one-dimensional calculation provides the necessary wall temperatures. Second, VISION4 stores the fill-gas velocity field for the edge-glass section of the glazing cavity, along with the temperature of the fill-gas inflow at the edge-glass/center-glass interface, by writing to a disk file. Third, FRAME 4.0 reads this information and allows the user the make a "convection" run that uses the fill-gas velocity-field data to account for fill gas motion.

A second set of simulations was completed using the VISION/FRAME software with the fill-gas motion option activated. Figure 4 shows a graphical representation of the temperature distribution for a glazed window. The asymmetry of the temperature field is evidence of the left-to-right motion of the fill-gas in the bottom of the glazing cavity (in the area above the arrow cursor).

Reduction of Convective Heat Transfer at Recessed Corners

It is customary for window simulation software to estimate surface heat transfer coefficients as a function of wind speed at the outdoor surface and center-glass surface temperature at the indoor surface. However, it is unusual for surface heat transfer coefficients to be specified as a function of location. In other words, the prevalent approach is to use the same value of heat transfer coefficient across the entire glass and frame window surface. The local inaccuracies that arise from this simplification present no difficulty in the calculation of U-factor or solar gain, but improvements are available, and desirable, for the purpose of studying condensation resistance.

Curcija and Goss (1993) note that the heat transfer coefficient associated with natural convection on the indoor side, $h_{c,i}$, decreases near recessed corners. They suggest that $h_{c,i}$ varies linearly along the glass surface—starting from zero at the sightline and increasing to 100% of the center-glass value at a distance of two inches from the sightline. Therefore, the edge-glass portion of the glazing, which is 63.5 mm (2.5 in.) wide, was divided into five segments of 12.7 mm (0.5 in.) each. The heat transfer coefficient, $h_{c,i}$, was held constant over each individual segment. In the series of four segments starting at a point 50.8 mm (2 in.) from the sightline and working toward the sightline, $h_{c,i}$ was reduced by 1/8, 3/8, 5/8, and 7/8, respectively, in relation to the value of $h_{c,i}$ that was applied over the center-glass area.

A third simulation model was devised using the VISION/FRAME software with the fill-gas motion option and with $h_{c,i}$ reduced along the edge-glass surface.

ASHRAE and ISO Boundary Temperatures

Simulation runs were carried out using two indoor-outdoor temperature difference conditions corresponding to ASHRAE and ISO design conditions. Under the ASHRAE condition, the indoor and outdoor temperatures were set at 21.1°C (70°F) and –17.8°C (0°F), respectively. Under the ISO condition, the indoor and outdoor temperatures were set at 20°C and 0°C, respectively. These temperatures were chosen to facilitate comparison with results of Griffith et al. (2002) who used the same temperature settings in their apparatus.

As-Tested and NFRC Glazing Surface Heat Transfer Coefficients

Computer simulations were completed using two sets of indoor and outdoor (i.e., warm-side and cold-side, respectively) heat transfer coefficients.

First, and of primary interest, the heat transfer coefficients present during the experiments of Griffith et al. (2002) were applied. The indoor and outdoor heat transfer coefficients, including both convective and radiative heat transfer, were measured using the CTS and reported (Griffith et al. 2002) and are repeated in Table 2. It was assumed that these coefficients also pertain to the subsequent testing of the two window specimens. The split between convective and radiative portions of the indoor heat transfer coefficient, for the purpose of adjusting $h_{c,i}$ at recessed corners, was estimated by modeling the CTS "glazing" in VISION4 at the as-tested temperature conditions. It was found that $h_{c,i}$ comprised 40.5% of the total indoor heat transfer coefficient, h_i.

The National Fenestration Rating Council (NFRC) specifies (NFRC 1997b) a fixed set of surface heat transfer coefficients for simulating frame sections and specifies heat transfer coefficients for glazed sections based on algorithms coded in a center-glass analysis program, WINDOW 4.1 (Arasteh et al. 1994). As a matter of interest, simulations were repeated using these NFRC coefficients. The appropriate values were provided by Griffith (2000) and are listed in the first three rows of Table 3. Note that the split between convective and radiative portions of the indoor-side heat transfer coefficient are provided, allowing for the reduction of $h_{c,i}$ along the edge-glass surface. Also note that the convective/radiative split listed for glazing surfaces in Table 3 are very close to the 40.5% value given in the previous paragraph.

As-Tested and NFRC Frame Surface Heat Transfer Coefficients

In the absence of information regarding the local variation of room-side heat transfer coefficients, the coefficients applied over the center-glass area were also used at the frame surfaces when simulations of the "as-tested" condition were completed. It was assumed that the split between convective and radiative portions of the indoor heat transfer coefficient was also unchanged. In addition, $h_{c,i}$ was reduced at the recessed corners of the indoor frame surfaces in the same manner that $h_{c,i}$ was reduced at the edge-glass surface. Specifically, $h_{c,i}$ was taken as zero at the deepest point of the recessed corner, and increased in steps over 12.7-mm-wide areas. If a given frame surface was less than 50 mm wide, the progression was truncated at the intervening edge. Note that the "Redh" modification was applied to frame surfaces only when the same modification was being applied to the edge-glass area.

TABLE 2
Heat Transfer Coefficients—
Experiments of Griffith et al. (2002)

	Heat Transfer Coefficient (W/m^2K)	
	Indoor Side	Outdoor Side
ASHRAE Temperatures	8.0	30.0
ISO Temperatures	8.0	24.0

TABLE 3
Heat Transfer Coefficients—As Specified by NFRC

Specimen	Region	Heat Transfer Component	Indoor Side (W/m^2K)	Outdoor Side (W/m^2K)
CTS	Glazing	Convective	3.10	25.46
		Radiative	4.60	3.21
		Total	7.70	28.66
ClrClr	Glazing	Convective	3.40	25.46
		Radiative	4.52	3.57
		Total	7.92	29.03
ClrLowe	Glazing	Convective	3.08	25.46
		Radiative	4.63	3.21
		Total	7.71	28.67
All	Frame and Surround Panel	Convective	2.52	25.46
		Radiative	5.09	3.57
		Total	7.61	29.03

When simulations were completed using the NFRC heat transfer coefficients, the total frame surface coefficients listed in the final row of Table 3 were applied uniformly over the frame surfaces.

COMPARISON OF TEMPERATURE PROFILES

Calculated temperature profiles are presented in Figures 5 through 10. In each case, the vertical axis shows temperature and the horizontal axis shows accumulated surface-distance upward from the bottom sightline.[1] The profiles are labeled "Conv," "FGM," and "FGM/Redh," respectively, in reference to the three simulation models: (1) conventional, (2) conventional plus fill-gas motion, and (3) conventional plus fill-gas motion plus reduced $h_{c,i}$ at recessed corners. In the special case of the CTS, it is not appropriate to model fill-gas convection, so only two simulation models were used—the conventional simulation and a simulation with only the reduced $h_{c,i}$ modification, which is shown as "Redh" in the corresponding figures.

The first set of three figures—Figures 5, 6, and 7—shows results for the CTS, ClrClr, and ClrLowe specimens, respectively, simulated using the ASHRAE temperature settings and the "as-tested" heat transfer coefficients listed in Table 1. A curve showing the thermographic measurements of Griffith et al. (2002) is also included (labeled "IR sill" to denote infrared measurements of the sill section of the specimen). The second set of figures—Figures 8, 9, and 10—shows similar results with the temperature settings changed to the ISO values.

A comparison of heat transfer coefficients is presented in Figures 11 and 12. Figure 11 shows results generated using the "Conv" simulation model for the ClrClr test specimen subjected to both ASHRAE and ISO temperature conditions and simulated using both the "as-tested" and "NFRC" heat transfer coefficients. Figure 12 shows a similar comparison for the ClrLowe test specimen.

[1] Some imagination is needed to locate the sightline of the CTS.

DISCUSSION

General Observations

Several major observations can be made regarding Figures 5 through 10 as a set. Each simulation curve shows a minimum temperature at the sill sight-line. This was expected, and several reasons are known to cause this "cold spot." Examining the area of prime interest—the sill edge-glass area—it can be seen that the simulation results generally show the same trend or curve shape as the measured data. The conventional modeling technique clearly overpredicts the measured edge-glass temperature, but the two model refinements—the fill-gas motion and the reduced convective heat transfer at recessed indoor corners—predict successively lower edge-glass temperatures and display a much improved agreement. Noting that Griffith et al. (2002) report a variety of significant difficulties associated with their experimental work, it can be stated that the level of agreement between the FGM/Redh model and their measurements is well within the error band attached to the measured data. In fact, the level of experimental error makes it impossible to know with certainty whether additional model refinement will be fruitful, but clearly the features that have been incorporated at this stage are useful.

The frame surfaces are warmer than the glazing surfaces in all cases, as would be expected (the frames have more thermal resistance than the glazing systems for these specimens). In the case of the CTS specimen, the frame surface temperature is relatively constant and very nearly equal to the indoor air temperature for most of the frame height (see Figures 5 and 8), as the CTS "frame" is made of the same insulating material as the mask wall.

The window specimens are more irregularly shaped than the CTS specimens, and the frame surface temperature is seen to vary in direct proportion to the length of the conductive path from the indoor surface through the frame to the outdoor condition. Thus, the frame surface temperature is low where

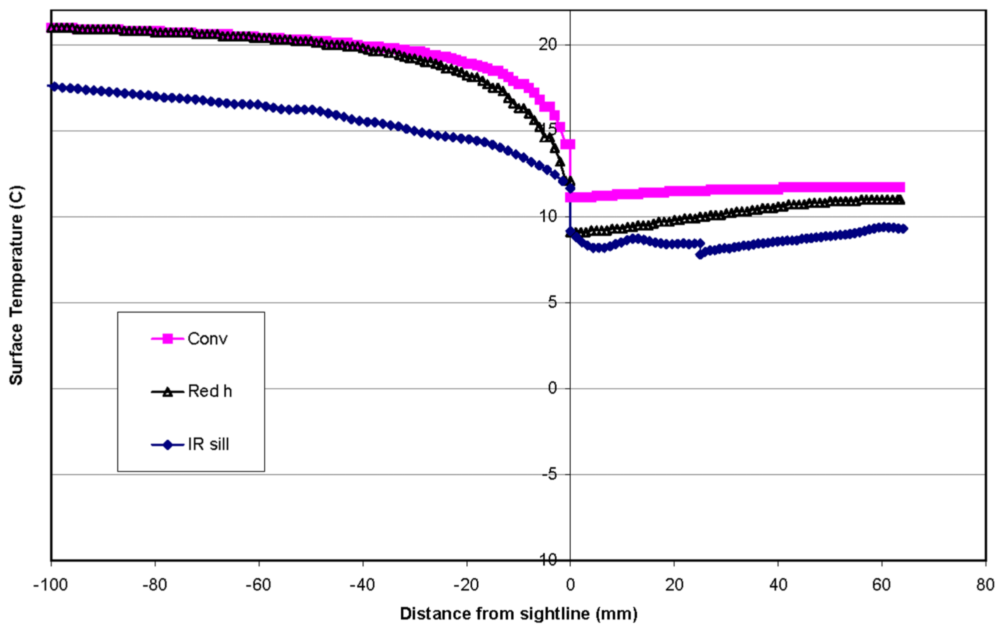

Figure 5 *CTS at ASHRAE conditions.*

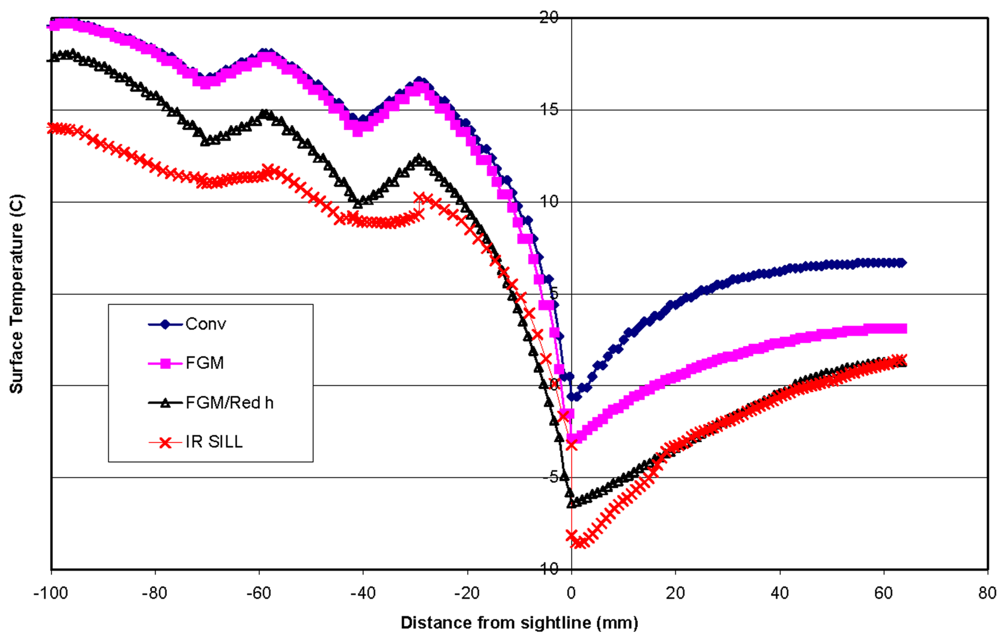

Figure 6 *ClrClr at ASHRAE conditions.*

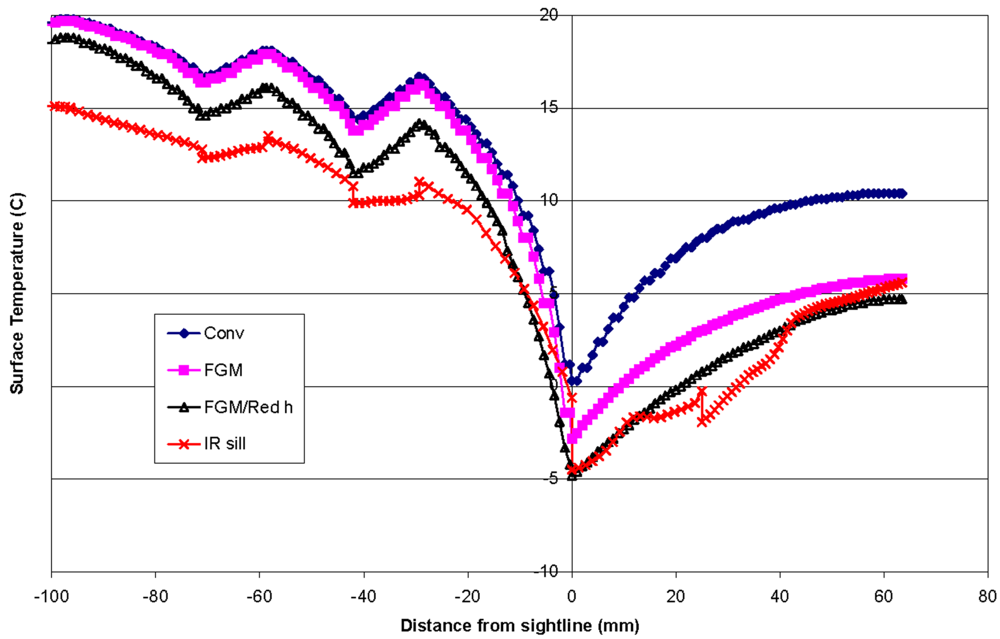

Figure 7 ClrLowe at ASHRAE conditions.

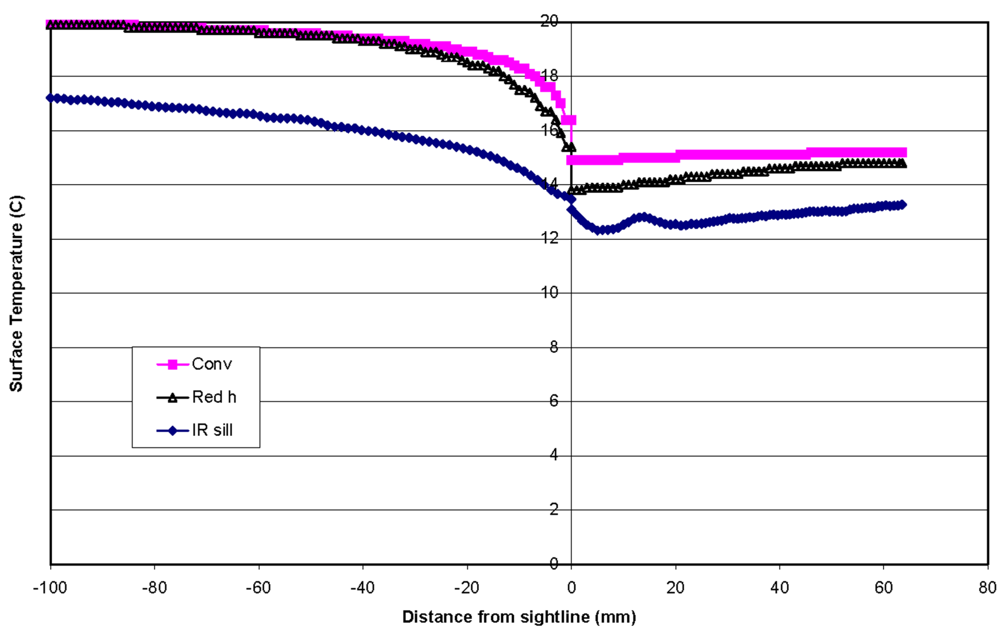

Figure 8 CTS at ISO conditions.

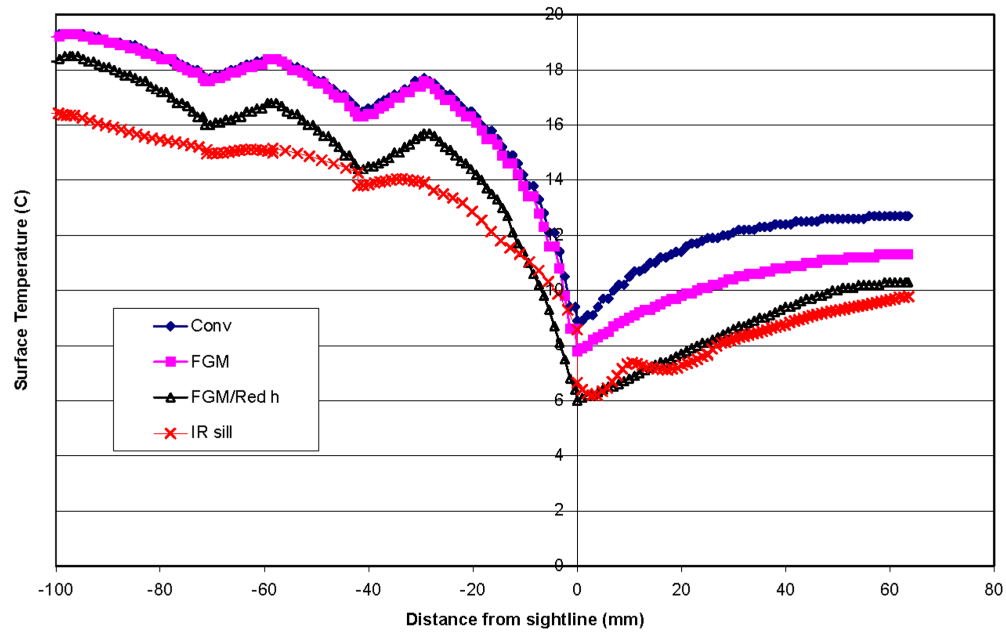

Figure 9 *ClrClr at ISO conditions.*

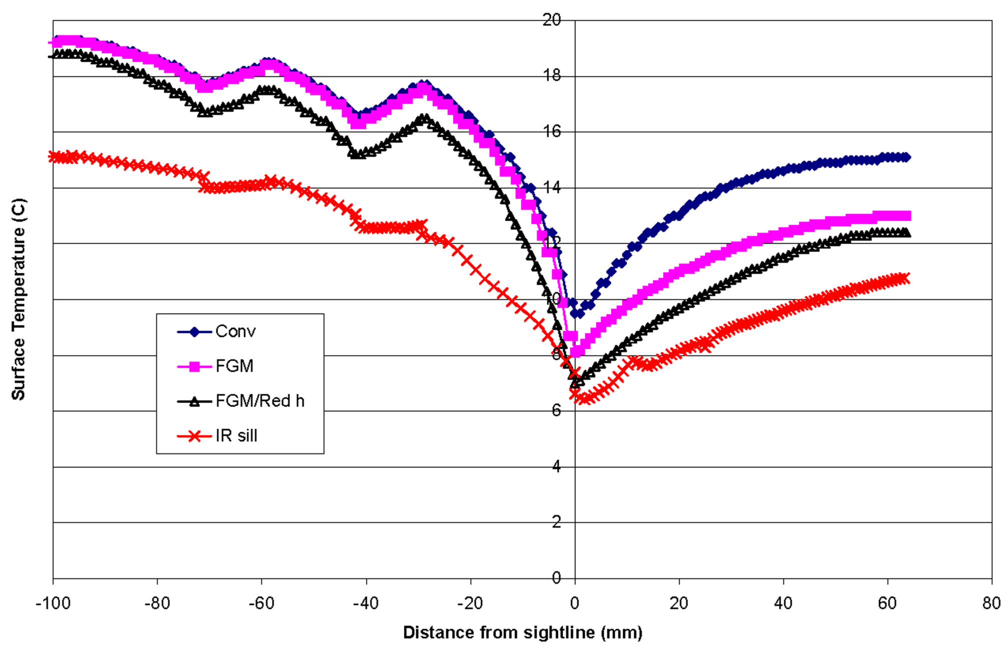

Figure 10 *ClrLowe at ISO conditions.*

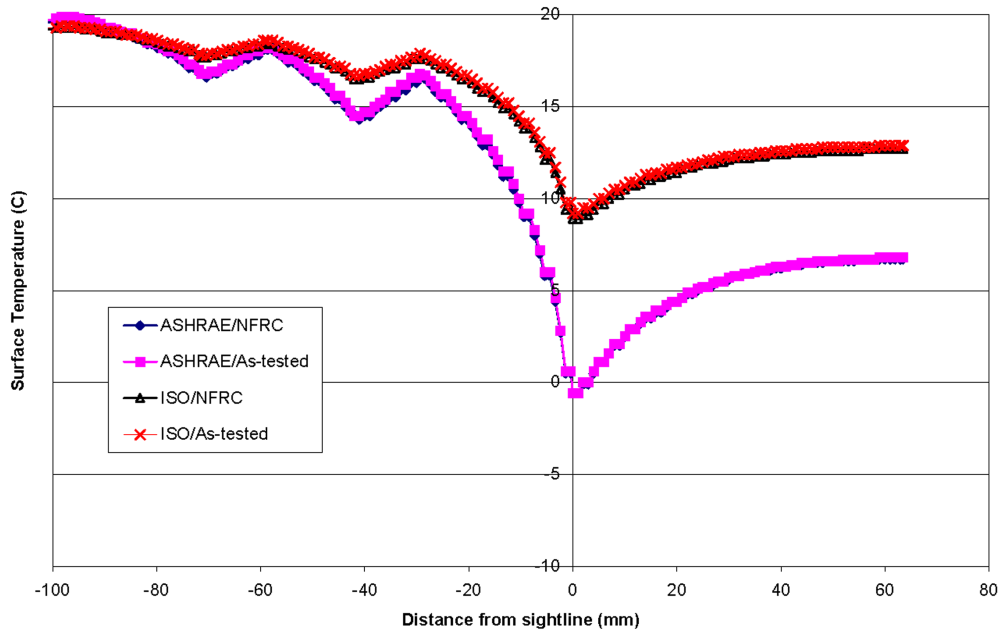

Figure 11 *ClrClr at various conditions.*

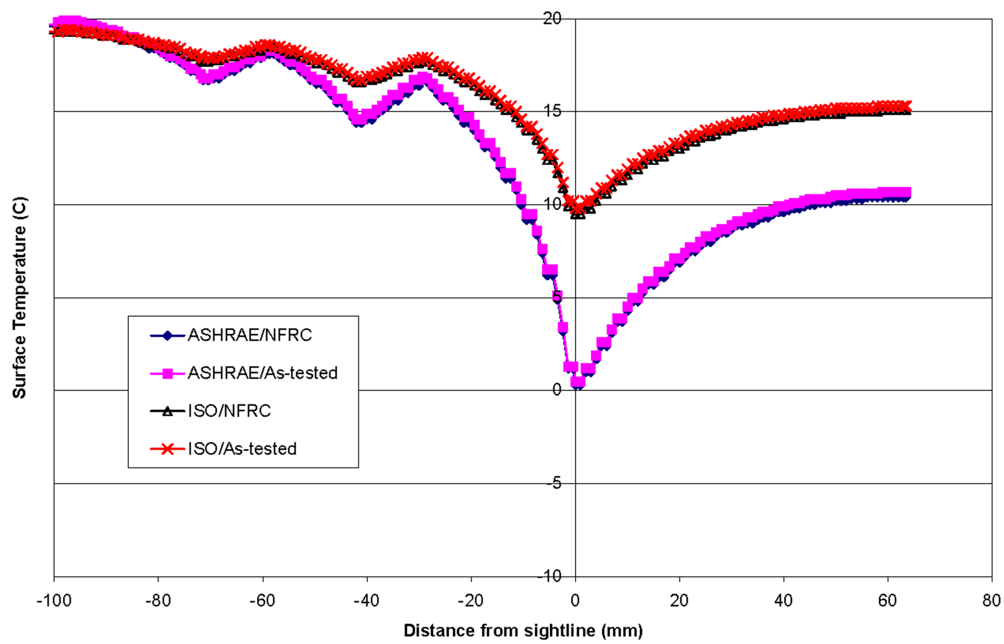

Figure 12 *ClrLowe at various conditions.*

the conductive path is short, particularly in the area near the sightline. Edge-seal conduction also reduces the surface temperature in this area. Away from the sightline, the frame surface temperature is higher at the projecting corners, where the conductive path is relatively long, and lower in recessed corners, where the conductive path is shorter.

Observations Regarding the Measured Temperature Profiles

Various anomalies can be seen in the measured temperature profiles. For example, Figure 5 shows a jump in the thermographic data (CTS specimen at "ASHRAE" temperatures) at 25 mm above the sightline. Thermographic scans were taken with four different camera positions to include the full height of each window. This temperature jump appears to be a junction between two scans, but it is not. In fact, the data shown fall fully within the scope of a single scan, and the reason for this discontinuity is not known.

A small fluctuation can be seen in each of the measured temperature profiles between 5 mm and 15 mm above the sightline. This is due to the presence of a thermocouple, which was taped to the surface of the glass 10 mm above the sightline. Griffith et al. (2002) point out that this error may have been caused by a mismatch between the emissivity of the tape and the emissivity of the glass. They also speculate that the contour of the protruding thermocouple may have altered the flow in that area, in turn causing a local change in $h_{c,i}$.

A more pronounced irregularity in the measured data can be seen in Figure 7 (low-e window at "ASHRAE" temperatures). Between 10 and 40 mm above the sightline, the temperature profile departs noticeably from the smooth curve typical of such situations. It is clear from the discontinuity alone that significant uncertainty must accompany the data. Outside of this region, the measured data agree remarkably well with the "FGM"/"Redh" simulation.

Calculation vs. Measurement: Sill Edge-Glass

Examining the edge-glass temperature profiles for only the window specimens (Figures 6, 7, 9, and 10) it can be seen that, with little exception, the measured temperature profiles agree well with the calculated "FGM"/"Redh" results. In Figure 6 (clrclr window at "ASHRAE" temperatures), the match between the curves at locations more than 20 mm from the sightline is exceptional. The trend in the thermographic data shifts at the 20 mm height, and the measurements below this point may have been influenced for the same unknown reason that is evident in Figure 7 and discussed in the previous paragraph. The measured data for the same window tested under ISO conditions (see Figure 9) do not show the same temperature depression within 20 mm of the sightline. In fact, Figure 9 shows a very good agreement between calculation and measurement over the full edge-glass area. Calculation and measurement show the same trend in Figure 10 (low-e window at "ISO" temperatures), but the measurement shows the edge-glass surface to be consistently colder than the results predicted by calculation. In this case, an explanation is available. Griffith et al. (2002) specifically mention this experiment and point out that, "the sill view of the low-E window under ISO conditions was taken during a period when the thermography chamber was not performing well." They go on to mention that, "when operating under these conditions, the vertical bulk air temperature gradient can be as high as 4°C." It is clear that, if the simulation had been carried out using the lower warm-side air temperature corresponding to the lower section of the test chamber, a lower edge-glass surface temperature would have been predicted.

Calculation vs. Measurement: Frame

Several observations can also be made regarding the comparison of calculated and measured frame surface temperatures at the sill. The calculated and measured frame temperature profiles display the same trend. Each profile rises from a minimum at the sightline and approaches a temperature near the indoor air temperature away from the sightline. However, the "conventional" and "FGM" simulation models predict frame surface temperatures that are noticeably higher than the measured values. These models both apply the average indoor heat transfer coefficient, as measured using the CTS, across the glass and frame surfaces of the window. In contrast, the "Redh" model refinement, which entails a reduction of the heat transfer coefficient at the recessed corners of both the edge-glass surface and the frame surface, removes about half of the noted discrepancy. Viewing the data of Figure 10 (low-e window at ISO temperatures), the improvement does not seem as dramatic, but temperature stratification of the environmental chamber was noted in this case and the measured data are known to be erroneously low.

Temperature jumps in the measured frame surface profiles serve as a reminder that it is difficult to make reliable thermographic measurements at irregular surfaces, and there is a significant level of uncertainty attached. Discontinuities can be expected at the corners of the frame surface, but only one temperature should be recorded for any given location.

Other reasons may be offered to explain the difference between calculated and measured frame surface temperatures. For example, the thermal conductivity used to characterize the wood composing the frames was not measured. The conductivity value listed in Table 1 is widely used as a generic value and it is certain that this value will be inaccurate, although it is not very useful to speculate on how great this inaccuracy may be.

Meso-Scale Variation of the Indoor Convective Heat Transfer Coefficients

It is interesting to speculate about the variation of the indoor convective heat transfer coefficient, $h_{c,i}$, associated with the development of the natural convection boundary layer along the height of the window. For convenience, this variation will be called "meso-scale" variation in contrast to the variation of $h_{c,i}$ that occurs at recessed corners on a much smaller scale or the variation that might occur over the extent of a much larger surface such as the wall in which the window is mounted.

It may be expected that $h_{c,i}$ will decrease from the top-to-bottom of the window as a consequence of the way in which the boundary layer develops—very much similar to the classic example of a boundary layer developing along the surface of a cooled vertical plate. This is closely connected to the idea that the convective heat transfer to the sill section of the frame is influenced not so much by the room air temperature but more by the cool air that flows downward from the glass surface. Recall that the glass surface is generally colder than the frame surfaces.

It can be argued that evidence of boundary layer development on the indoor side can be seen in the temperature profiles measured by Griffith et al. (2002). The center-glass portions of their measured temperature profiles (not reproduced here) consistently show a small vertical temperature gradient. This is true of both window and CTS specimens. Griffith et al. (2002) pointed this out and mentioned that:

> It is well known that window glazings under such conditions have a temperature gradient in the vertical direction; the usual explanation is that this gradient is a result of convective flows inside the glazing gap. The data for the CTS, however, show temperature gradients at the center of glass that are comparable to those of the glazing even though the CTS has closed-cell foam rather than an air gap.

In fact, research has shown that, except for variations confined to the edge-glass region at the head and sill, the heat transfer coefficient across the glazing cavity is essentially constant (e.g., Wright and Sullivan 1989, 1994, 1995a). The observations of Griffith et al. (2002), in particular their observation that the temperature gradients of the CTS and conventional windows were similar, support the idea that the heat transfer coefficient in the glazing cavity is constant, as well as the idea that the influence of meso-scale variation of $h_{c,i}$ can be seen in the measured data. Thermal stratification of the test chamber may have produced evidence of a vertical surface temperature gradient in the data of Griffith et al. (2002), but evidence of this stratification (e.g., temperature jumps at the junctions of thermographic scans) was present in only a few instances.

A reduced value of $h_{c,i}$ used at the sill area of the window can be expected to bring simulation and measurement into better agreement—not only for the frame but possibly for the edge-glass area as well. Calculated surface temperatures would be reduced at the sill, but the influence would be less pronounced if the "Redh" model, which has already been demonstrated to be useful and which is not related to meso-scale boundary layer development, has already been applied.

Research regarding the meso-scale variation of $h_{c,i}$ is underway and will be the topic of a follow-up publication.

Quantitative Comparison

For the cases shown in Figures 5 through 10, the temperature differences between simulation and test were computed. The averages of these differences were computed over the edge-glass and frame portions of the specimens for each case, and the results are summarized in Table 4.

Again, the results indicate that the proposed modifications to the "Conv" method of using computer software (i.e., the method used to obtain total-product U-factors) provide a marked improvement in the agreement between simulation and test. Edge-glass temperatures agree to within 0.5°C for the clear double-glazed specimen (ClrClr) and to within 1.4°C for the low-e window. Even the "edge-glass" portion of the CTS specimen shows reasonable agreement, with an averaged difference of 1.6°C between simulation and test. Frame temperatures do not show as good an agreement, however, and reasons for this have been discussed.

TABLE 4
Average Temperature Differences Between Simulation and Measurement

Specimen and Conditions	Surface Temperature Difference (Simulation minus IR), °C		
	Standard	FGM	FGM/Red h
CTS ASHRAE- edge-glass	2.9	N/A	1.6
- frame	2.5		2.4
CTS ISO- edge-glass	2.3	N/A	1.6
- frame	2.5		2.4
Clr_Clr ASH- edge-glass	7.2	3.6	0.5
- frame	5.7	5.4	2.3
Clr_Clr ISO- edge-glass	3.5	2.0	0.4
- frame	2.9	2.7	1.2
Clr_Lowe ASH- edge-glass	6.8	2.2	0.5
- frame	4.6	4.2	2.5
Clr_Lowe_ISO- edge-glass	4.4	2.4	1.4
- frame	4.1	4.0	3.1

Comparison of Surface Heat Transfer Coefficients

Simulation was used to explore the influence of changes made to the surface heat transfer coefficients. Specifically, the "as-tested" and the "NFRC" heat transfer coefficients were compared. Figures 11 and 12 show the results. Recall that the "conventional" model was used to generate the curves shown in Figures 11 and 12. The "FGM" and "Redh" models were not applied.

In each of Figures 11 and 12, the upper pair of temperature profiles corresponds to ISO temperatures, and the lower profiles correspond to the colder ASHRAE temperature condition. In each figure there appears to be only two temperature profiles, although four have been plotted. This illusion presents itself because the change between sets of heat transfer coefficients has virtually no effect on the indoor surface temperature. The difference in the temperature that results from using the two different conditions generally falls in the range of 0.1°C to 0.2°C when averaged over the edge-glass area and is never more than 0.3°C locally. The simulation reports temperatures to only the nearest 0.1°C, so some of this difference may be due to truncation; in any case, the observed differences are unimportant in relation to the uncertainty associated with any test result.

CONCLUSIONS

Computer simulation compares favorably to thermographic testing, and can provide a valuable tool in determining edge-glass surface temperatures (hence, condensation potential) in windows. The possibility exists for further refinement to the simulation methodology, but, in general, the accuracy of the computer model is good and within the range of uncertainty customarily attached to test results.

Some modifications are required to the "conventional" modeling protocols (in which simulation tools are used in the United States and Canada to determine total-product U-factors for windows) so that the tools can be used to predict local surface temperatures. These modifications are not complex and can easily be coded into the existing software tools so that the process becomes transparent to the user. In fact, the "FGM" model refinement has been available for more than seven years, and its use has been documented elsewhere (e.g., McGowan and Wright 1998; CSA 1998).

Useful modifications include explicit modeling of convective motion of the fill gas in the glazing cavity and local variation of the indoor heat transfer coefficient to account for reduced convective flow at recessed corners of window specimens (e.g., at the sightline).

Thermography also requires some refinement before it can be used reliably in evaluating window surface temperatures, as has been noted elsewhere (Griffith et al. 2002).

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DISCUSSION

Jeff Haberl, Associate Professor, Texas A&M, College Station, Tex.: (1) Have you calculated the annual energy impact/peak heat loss/gain of FGM/redh model versus the conventional model? (2) Have you considered performance measurements of screened windows (screen inside/outside)?

John L. Wright: The FGM/redh model was devised for the sole purpose of obtaining more accurate surface temperature predictions at the sill edge-glass area where condensation most readily occurs. The FGM model lowers the indoor surface temperature predicted at the sill edge-glass but the opposite effect takes place at the top of the window and the net effect on overall heat transfer can be shown to be virtually zero. The conventional model does account for fill-gas motion but does so on a spatially averaged basis. The "redh" model may have an influence on U-factor but because this model is applied over a small area and because it entails only the convective portion of the surface heat transfer and because the surface resistance is only one of a series of thermal resistances between the indoor and outdoor spaces, this influence can be expected to be very small. In summary, there may appear to be a conflict between the models used here for predicting surface temperature and the conventional models for predicting U-factor and solar gain but in fact there is no conflict.

We have not done any work related to insect screens but it is known on an anecdotal basis that an insect screen on the indoor side can significantly aggravate condensation problems but an insect screen on the outdoor side can significantly alleviate condensation problems.