Effect of Realistic Boundary Conditions in Computer Modeling of Condensation Resistance for Fenestration Systems

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ABSTRACT

Condensation resistance of fenestration systems (windows and doors) is determined from the temperature distribution on indoor fenestration surfaces and the indoor air dew-point temperature. For many years, condensation resistance was determined from hot box measurements of indoor fenestration surface temperatures, but more recently, computer modeling of the temperature distributions has emerged and is currently being validated. Depending on the method used, the temperature considered is either the calculated coldest indoor fenestration surface temperature or a measured average temperature for several predetermined indoor fenestration surface locations. It is known from experience with U-factor determination that computer models lower the overall cost of determining thermal indices (e.g., U-factor, solar heat gain, condensation resistance) and provide more consistent results. Computer models capable of predicting temperature distributions on fenestration surfaces are more complex than models used only for the calculation of U-factors, which is the main reason that they did not appear until recently. An ASHRAE research project was initiated several years ago to validate existing computer models, and the first phase of the project included seven different insulated glazing units (IGU) for which computer modeling (using standardized overall surface heat transfer coefficients) and infrared thermography measurements were performed. The results of the research project indicated that computer models can offer a viable alternative to actual physical measurements.

This paper shows that further improvements in calculated indoor surface temperatures can be achieved if more realistic boundary conditions are used. Since IGUs are flat products, no significant improvement is achieved by including more accurate radiation models; however, for fenestration products with frames, improved radiation models are useful. The inclusion of local convective heat transfer coefficients, which are geometry as well as temperature dependent, provide more accurate boundary conditions for both IGUs and fenestration products. Local convective surface heat transfer coefficients were obtained from detailed numerical calculations and from detailed measurements. The agreement between measured and calculated results showed significant improvement over previous studies, indicating that future condensation resistance models need to incorporate improved boundary conditions. This can be done for many fenestration system geometries; however, for more complex geometries, additional detailed numerical computational fluid dynamic/heat transfer research efforts are required.

INTRODUCTION

Condensation resistance of fenestration products is currently being evaluated, when requested, using experimental procedures (AAMA 1997; CSA 1990). The National Fenestration Rating Council (NFRC) at this time does not require determination of the condensation resistance indices, but it is preparing standard procedure (NFRC 1998) that would include both computer modeling and testing. ASTM (1998) is also currently developing a standard method for measuring and calculating condensation index (CI), which is based on the best aspects of both the AAMA and CSA standards.

Recently, a new generation of computer tools has been developed that are capable of more accurate prediction of temperatures on the indoor or outdoor boundary of fenestration systems. The most recent version (2.0) of THERM (Arasteh et al. 1995; Finlayson et al. 1998) incorporates advanced radiation modeling and local convective heat trans-

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fer correlations in glazing cavities (Curcija et al. 1999). While the calculated temperatures show great improvement over the ones determined using "effective conductivity" approach (Jonnson 1985; ASHRAE 1998), there are still disagreements between calculated and measured results. It is believed that this disagreement is due to the use of average surface heat transfer coefficients on indoor and outdoor surfaces of fenestration system.

A limited amount of work was done in the past investigating local heat transfer effects on fenestration boundaries (Curcija and Goss 1993; Curcija and Goss 1995; Schrey et al. 1998). While the first two studies focused on modeling convective flows around the fenestration system, the third study used experimental results from IR thermographic temperature measurements and, using a computer model with fixed outdoor surface heat transfer coefficient and adjustable indoor surface heat transfer coefficient, tried to match measured temperature distribution on the indoor side. The disadvantage of this approach is its inability to determine the convective/radiative split of the surface heat transfer coefficient, which makes any effort to develop suitable correlation very difficult. Also, authors failed to recognize that the surface heat transfer coefficient varies on the outdoor side as well, in effect oversimplifying the problem from four unknowns to a single unknown. The authors are aware of a very recent experimental study that utilizes a hot wire anemometer and temperature probe mounted on a traversing system (Griffith et al. 1998) to determine the local convective heat transfer coefficient, but the results were not available in time to include them in this study.

The computer modeling in this study was done using the fenestration thermal performance modeling tool THERM (Finlayson et al. 1998). A newly released version of this program is capable of the application of complex boundary conditions, including gray body radiant heat transfer and view factor calculation (local radiant heat transfer), variable convective heat transfer, flux, and temperature boundary conditions. The program also incorporates local convective and local radiant heat transfer models in the glazing cavity and a local radiant heat transfer model in frame cavities. Results from the numerical work of Curcija and Goss (1993) and Branchaud (1997) were used to apply the local convective heat transfer coefficient on the indoor and outdoor sides of the fenestration system.

It should be noted, however, that the assumptions used in generating the computer model may not truly reflect actual conditions to which the fenestration system is exposed in the laboratory or in the field. For these reasons, computer simulation is still most effective when used to compare the performance of different products, like the procedures used in code compliance and certification/rating.

DESCRIPTION OF SPECIMENS AND MODELING ASSUMPTIONS

Two different types of fenestration system were used to examine the effects of locally varying boundary conditions. The first type is a flat insulating glazing unit (IGU), mounted flush with the warm side of the measurement apparatus. This product was the subject of study performed under the sponsorship of ASHRAE's Condensation Resistance Subcommittee (Sullivan et al. 1996; Zhao et al. 1996). The same set of units were tested in two different laboratories and modeled using two different computer programs. In this study, results from one of the IR thermographic laboratories (Griffith et al. 1996) were used to compare computer modeling results. The second type of fenestration system is a wood picture window, which was made by a major wood window manufacturer specifically for the purpose of computer program validations.

Two IGUs were studied, one with an insulating (foam) spacer (IGU1) and the second with an aluminum spacer (IGU2). Both units have the same outside dimensions of 508 mm (20 in.) × 460 mm (16 in.) and the same air gap spacing and both include double clear glass. Vertical cross sections of the two IGUs are shown in Figure 1. The wood picture window (PFM01) includes double clear glazing, an

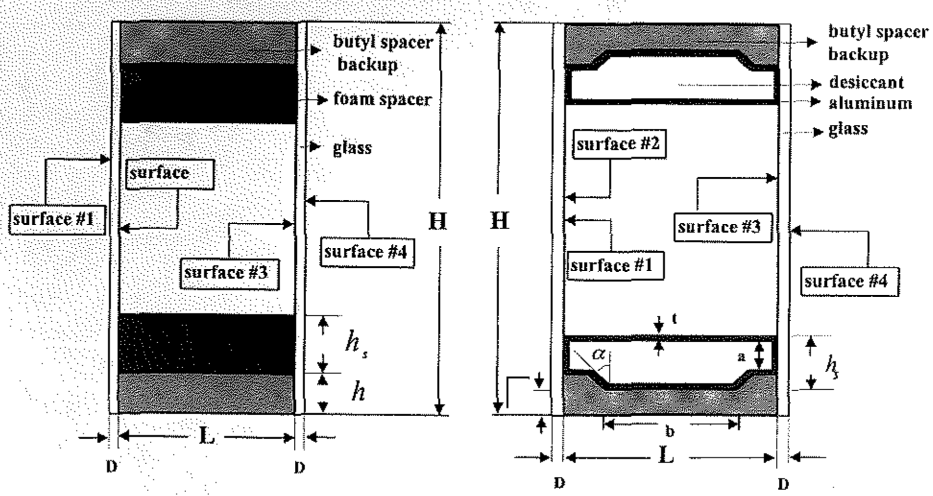

Figure 1 *Vertical cross sections for IGUs.*

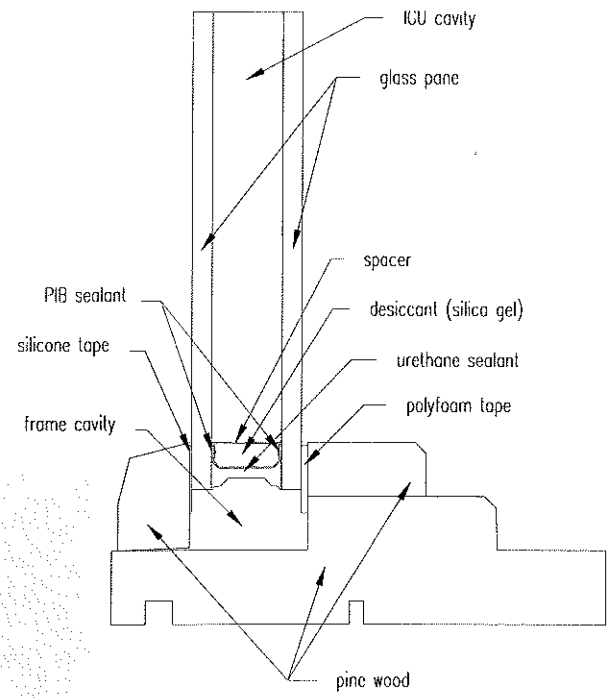

Figure 2 *Wood fixed window: two-dimensional cross section through frame and edge of glass.*

aluminum spacer, and a wider air gap than the IGUs. The outside dimensions are 914 mm (36 in.) × 610 mm (24 in.).

A two-dimensional cross section of the frame and edge-of-glass region of the wood picture window is given in Figure 2. Table 1 lists important dimensions for the three units studied.

The THERM 2.0 computer modeling tool (Finlayson et al.1998) had been used for all of the results generated in this study. Overall, four different sets of modeling scenarios were used:

1. Simple conduction model, also known as effective conductivity model, with constant boundary conditions. This simple model is currently in use for calculating U-factors for certification purpose (NFRC 1997).
2. "Variable h" model (Curcija et al. 1999) for modeling convective heat transfer in glazing cavities.
3. Advanced radiation modeling, utilizing element-to-element radiant heat transfer and view factor calculation (Curcija 1996) along with the "Variable h" model in the glazing cavity. This combination of two models is currently being used in THERM for the purpose of condensation resistance modeling (CI Model).
4. Locally varying convective heat transfer coefficients applied on indoor or outdoor or both boundary sides in addition to the modeling assumptions in the third scenario.

TABLE 1
Characteristic Dimensions

Product ID	H (m)	L (m)	D (m)	h_s (m)	h_b (m)	a (m)	b (m)	t (m)
IGU1	0.508	0.0127	0.003	0.00635	0.0047625	None	None	None
IGU2	0.508	0.0127	0.003	0.008	0.0047625	0.00508	0.01016	0.000762
PFM01	0.610	0.0165	0.0047	0.006096	0.005017	0.004115	0.012827	0.0003302

TABLE 2
Modeling Assumptions and Boundary Conditions

	h_{ic}	h_{ir}	h_{oc}	h_{or}	Model
Scenario 1	3.37	4.23	25.47	3.23	Conduction only
Scenario 2	3.37	4.23	25.47	3.23	Variable h model
Scenario 3	3.37	Advanced radiation (Curcija 1998)	25.47	Advanced radiation (Curcija 1998)	CI Model
Scenario 4a	Locally varying (Curcija and Goss 1993) [1]h_{ic}=3.34	Advanced radiation	25.47	Advanced Radiation	CI Model w/ variable convective bc's
Scenario 4b	3.37	Advanced radiation	Locally varying (Branchaud 1997) [1]h_{oc}=28.3	Advanced radiation	CI Model w/ variable convective bc's
Scenario 4c	Locally varying (Curcija and Goss 1993) [1]h_{ic}=3.34	Advanced radiation	Locally varying (Branchaud 1997) [1]h_{oc}=28.3	Advanced radiation	CI Model w/ variable convective bc's

[1] This value was obtained by integrating local values for flat surface.

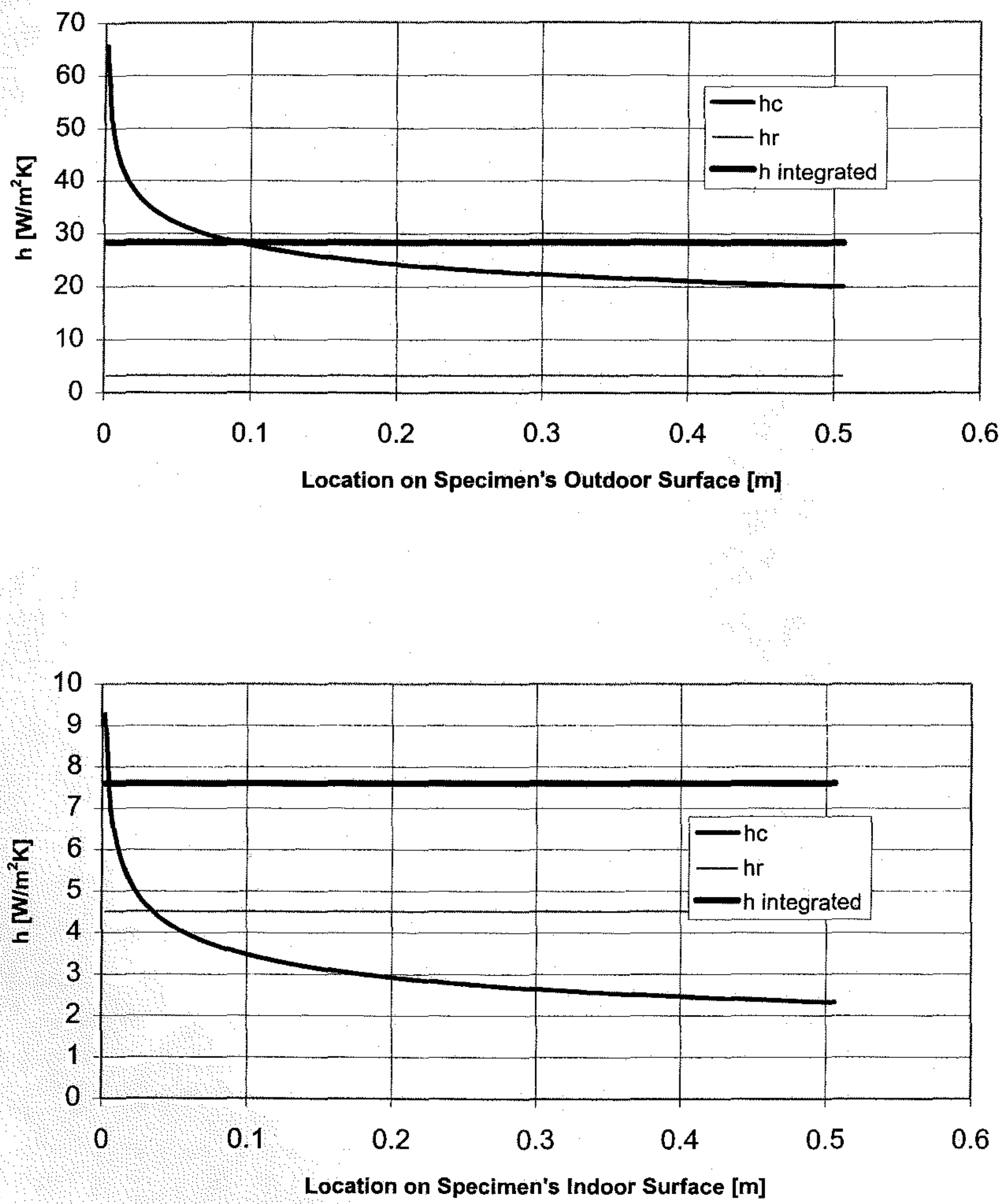

Figure 3 *Local convective heat transfer coefficient on indoor and outdoor boundaries of IGUs.*

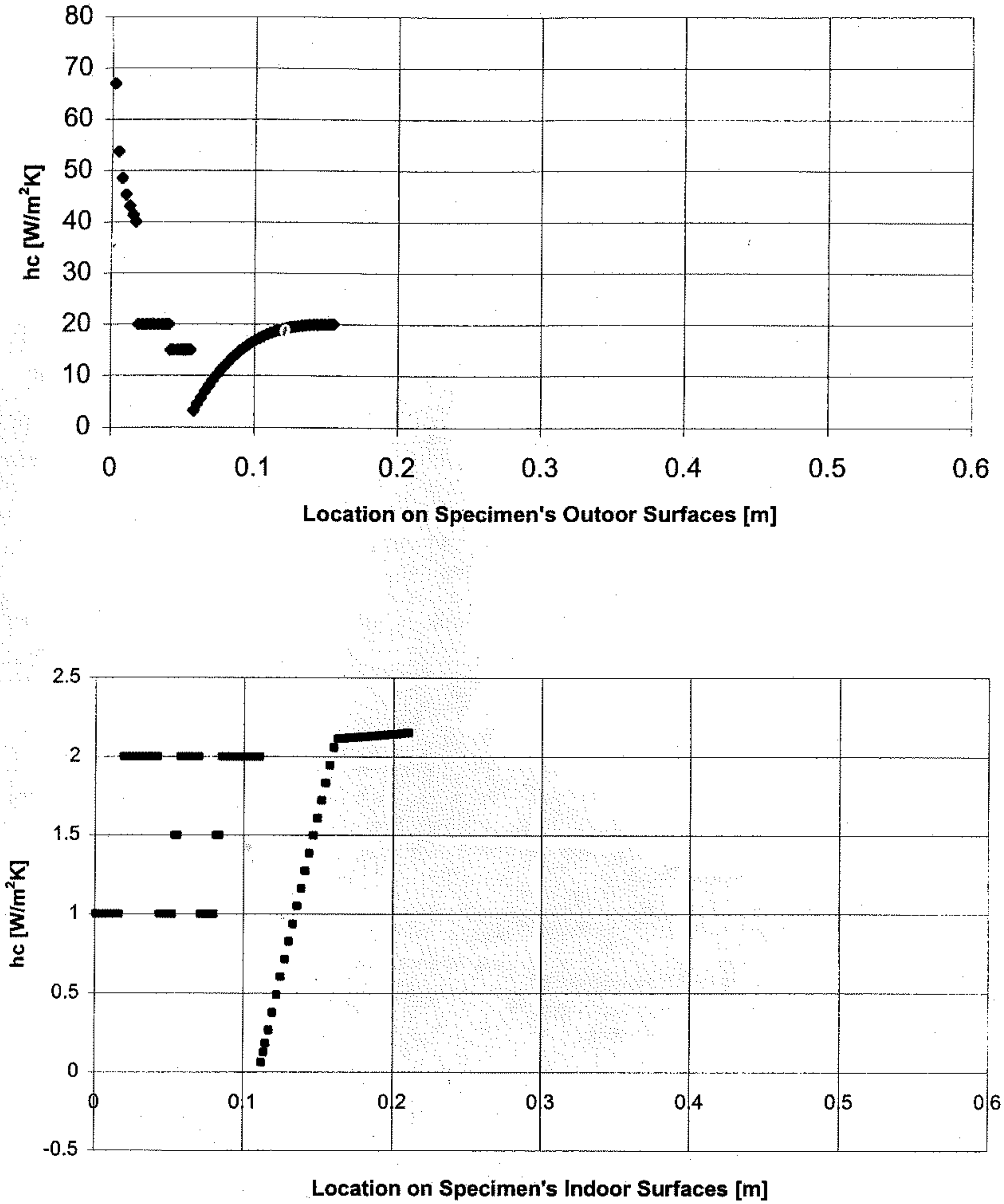

Figure 4 *Local convective heat transfer coefficient on indoor and outdoor boundaries of PGM01.*

This last scenario is the main subject of this study, and its results were compared to other computer modeling results and IR thermographic measurements. Table 2 lists modeling assumptions and boundary conditions used in all four scenarios.

It is interesting to note that experimentally determined average surface heat transfer coefficients, reported in Griffith et al. (1996), are very close to the values obtained by integrating theoretical and computer modeling results that were used in this study's scenario 4. Integrated values, used for constant convective surface heat transfer coefficients in scenarios 1 to 3 and 4, were applicable (i.e., when a constant surface heat transfer coefficient was used for one of the boundaries).

In the case of frame sections of the wood picture window, both continuously varying and step varying (i.e., each separate section, where the separate section was assumed to have any portion of the boundary with unchanging slope, was assigned an average value), convective heat transfer coefficients were used. There was no significant difference noted between these two approaches, so the step varying value was used for its simplicity. The glazing section of the boundary for the wood picture window had a continuously varying convective surface heat transfer coefficient, with the corner regions treated as recommended by Curcija and Goss (1993) for the indoor side and Branchaud (1997) for the outdoor side. Figure 3 shows the distribution of indoor (h_{icy}) and outdoor local convective heat transfer coefficient (h_{ocy}) for the two IGUs, while Figure 4 shows the distribution of h_{icy} and h_{ocy} for the wood picture window. Since the IGUs were flat specimens, and they were installed in an appropriately sized mask wall (e.g., with the overall thickness very close to the thickness of the IGUs) in order to avoid corners and dead spots, values of convective heat transfer coefficients are derived from the flat plate theory. The same applies to the radiant heat transfer, which is constant for a flat plate surrounded by surfaces at constant temperature. However, for the wood picture window, frame sections had formed several corners and dead spots, where the value of the convective heat transfer coefficient departs from the flat plate theory. A small sensitivity study had shown that for frame sections an average value of hc can be used in place of continuously varying hc. This effect enabled the use of a simpler way to assign boundary conditions on the frame.

IGU models were done for the entire vertical cross sections, using two models for each IGU, one for the "sill" part and one for the "head" part, where the height for each part was equal to one-half of the total height. For the wood picture window, only the sill part was modeled due to availability of experimental results.

RESULTS

Finite element meshes were generated using THERM's automated mesh generator and were further refined using the built-in error estimator. Examples of the final meshes are given in Figure 5.

The temperature distribution on the indoor side of the fenestration systems was plotted vs. distance from the bottom point on the indoor side, and results were compared for different scenarios. In Figures 6 and 7, all investigated scenarios are plotted against IR thermographic measurements for IGU1 and IGU2. It can be seen from the figures that IGU1 shows better agreement, particularly in the "sill" region. The agreement for the "head" region is excellent for both units.

As a part of this work, special attention is paid to isolating the effects of the local convective heat transfer coefficient on one of the sides (indoor or outdoor). This was accomplished by specifying the local convective heat transfer coefficient on one side while keeping the other constant. As might be expected, the effect of varying the indoor (warm) side convective heat transfer coefficient has a larger effect than variations on the outdoor side due to controlling resistance on the indoor side. However, it is important to note that for conducting spacer, ignoring the outdoor variations produced more than 2°C difference when compared to the case when this variation is accounted for. For condensation resistance calculations, this can be a significant effect. Another important observation can be made regarding the use of the CI model alone (scenario 2), which offers significant improvement over the effective conductivity model in predicting temperatures on indoor boundaries. However, near the head region, ignoring local variations in convective heat transfer on indoor and outdoor boundaries significantly lowers the accuracy and ability of the model to predict local temperatures.

The temperature distribution on the indoor side of the PFM01 (wood) window (see Figures 8 and 9) shows less overall agreement between the computer model and experimental results. This is due to more complex geometry (frame sections), which causes larger variations in airflow around the window and convective heat transfer coefficient. Research data used to generate local convective heat transfer coefficients (Curcija and Goss1993; Branchaud 1996) dealt with somewhat different geometries, so some extrapolation was

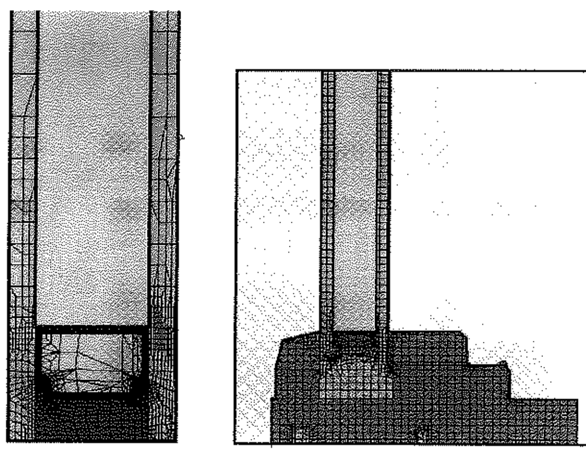

Figure 5 *Example of finite element meshes for studied specimens.*

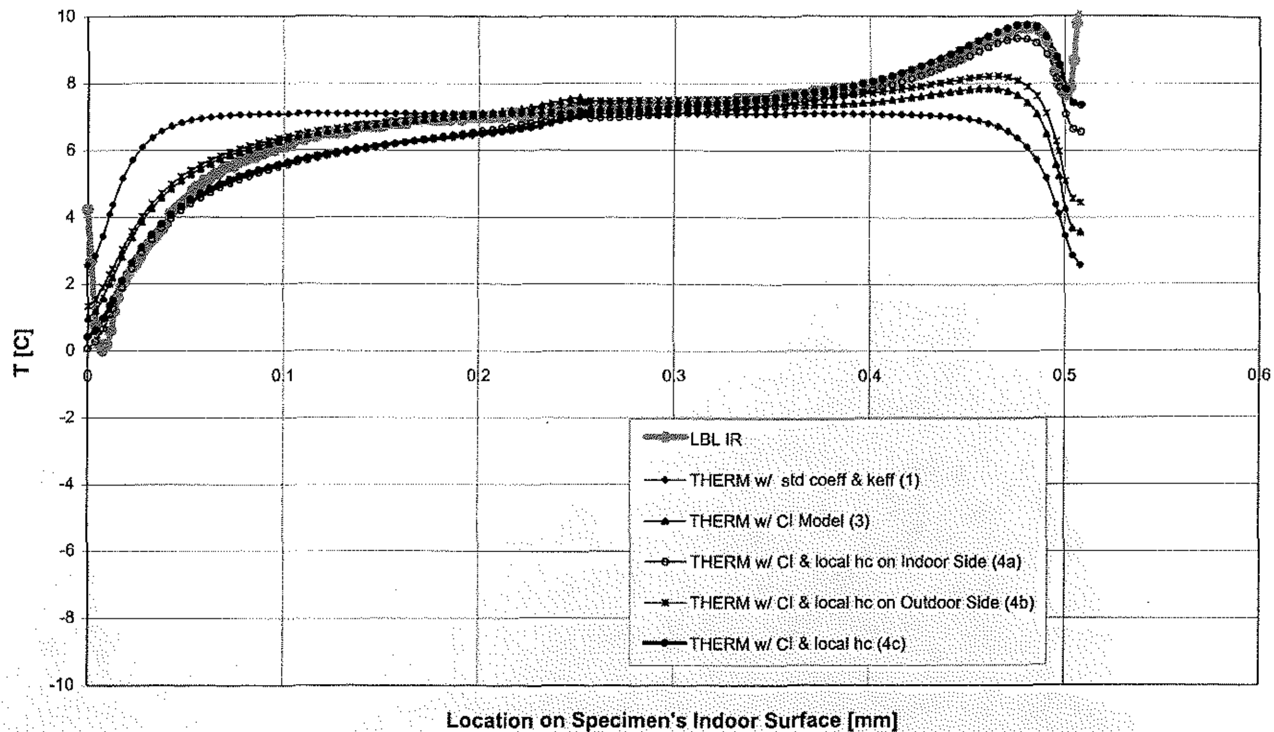

Figure 6 *Temperature distribution on indoor boundary of IGU1.*

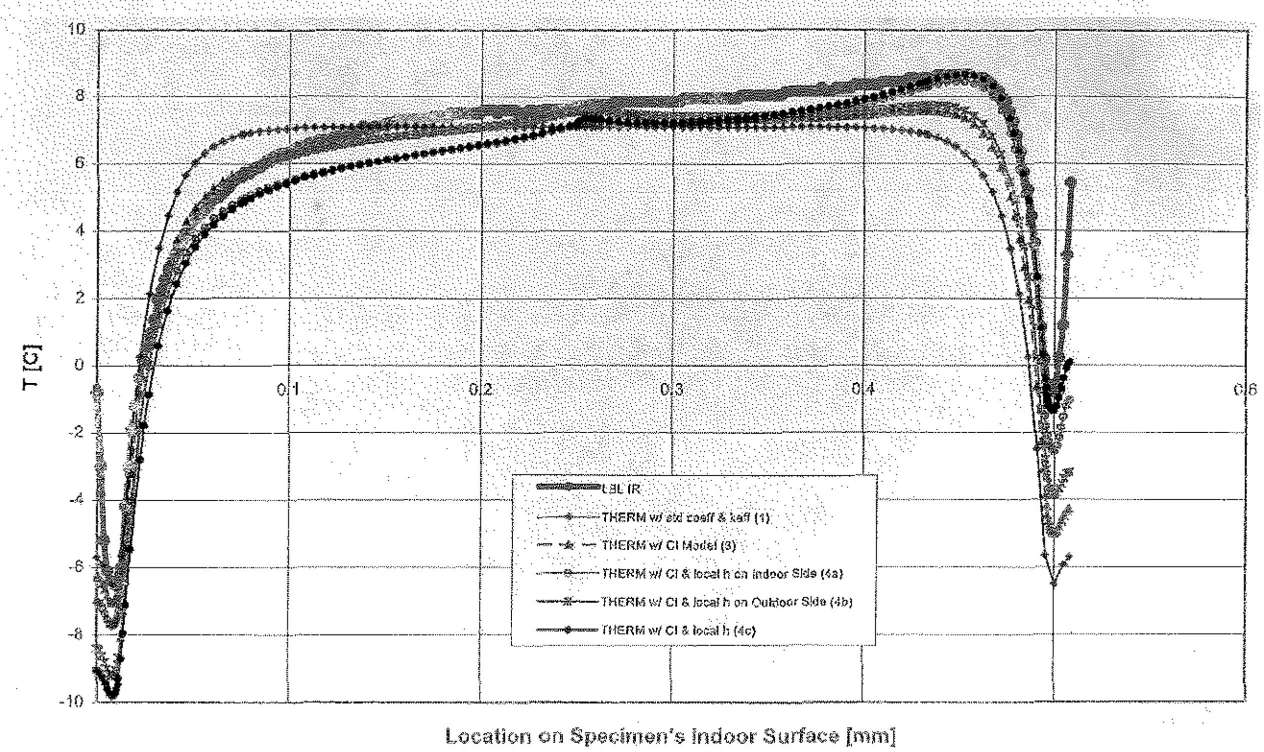

Figure 7 *Temperature distribution on indoor boundary of IGU2.*

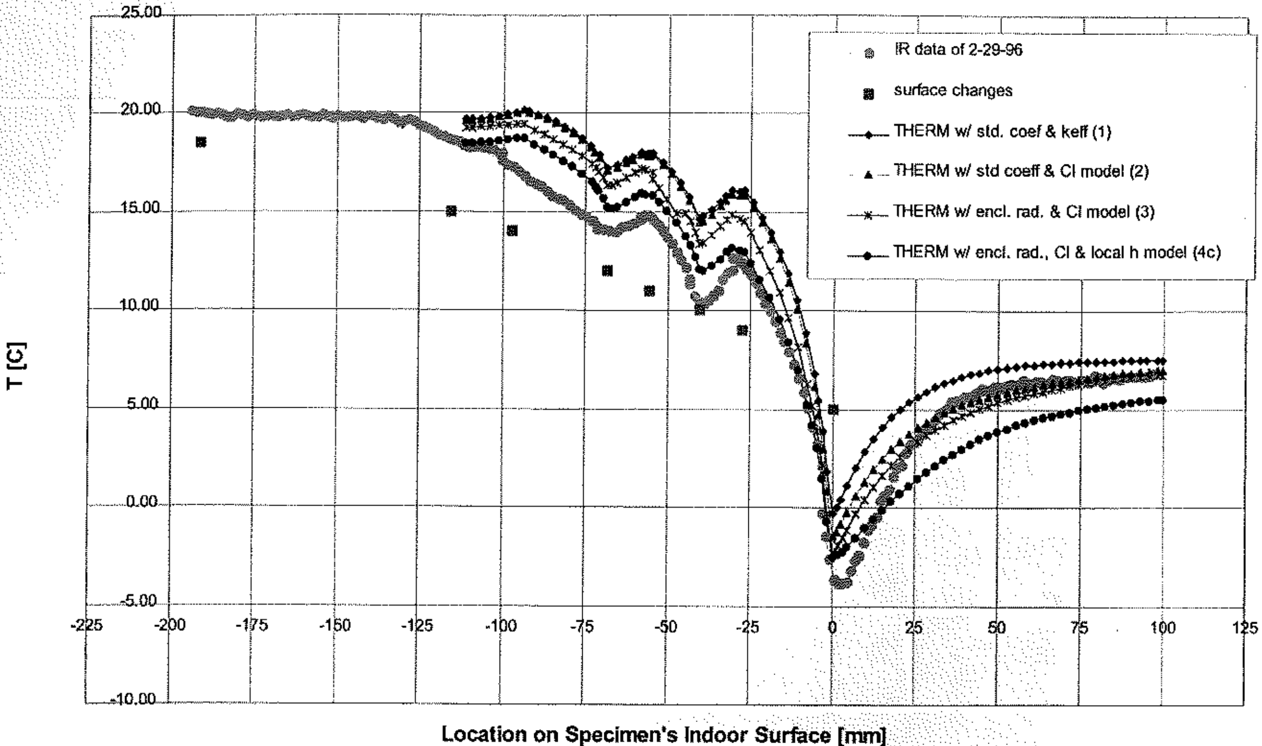

Figure 8 *Temperature distribution on indoor boundary of PFM01—scenarios 1, 2, 3, and 4c.*

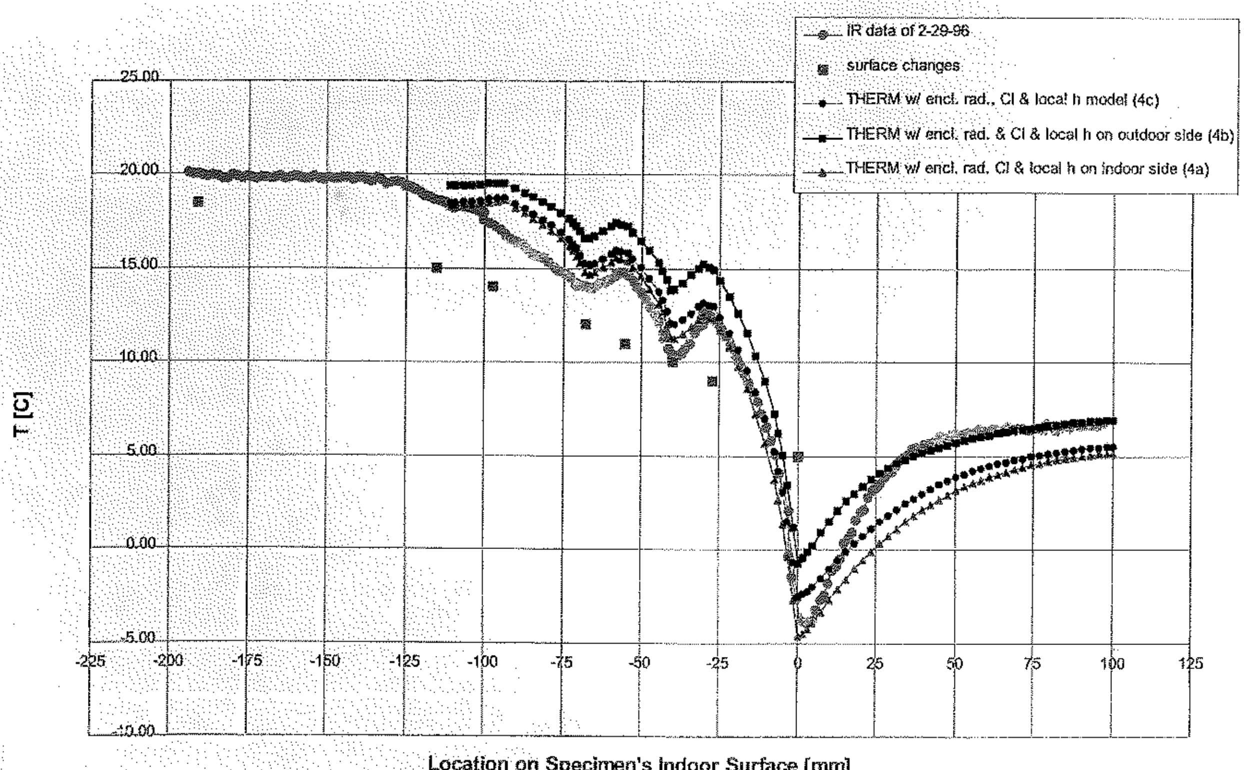

Figure 9 *Temperature distribution on indoor boundary of PFM01—scenarios 4a, 4b, and 4c.*

necessary to apply them to the boundaries of the PFM01 model.

Nevertheless, when compared to the commonly accepted effective conductivity modeling method (scenario 1), all other methodologies investigated here (i.e., scenarios 2 through 4) produce better agreement with measurement results. In terms of predicting temperature distribution on frame surfaces as well as the lowest temperature, which occurs at the sightline for this window, the CI model with the locally varying convective heat transfer boundary condition (Scenario 4c) gives the best results. It is interesting to note that the disagreement between this model and experimental results comes at the region closer to the center of glass, which is quite unexpected. Typically, the center-of-glass region shows good agreement even with the application of the simplest models (Scenario 1). This may indicate that the overall indoor side convective surface heat transfer coefficient is higher than reported in experimental results. A similar observation should apply to IGU2, with the exception that the difference for that unit is smaller.

Variation of the local convective heat transfer coefficient on one side, while keeping the other side constant, produced a pattern similar to those of the IGUs. The difference is not quite as large as with IGU2 (i.e., 2°C vs. 1°C), which is expected since the spacer is not exposed and local radiant heat transfer plays more a significant role for a wood fixed window. The head section for this window was not investigated, so it is not possible to draw any conclusions here.

CONCLUSIONS

The use of algorithms that account for local convective and radiant heat transfer in glazing cavities improves the ability of computer modeling tools to accurately predict temperature distribution on window boundaries (and elsewhere in the model).

The application of locally varying convective heat transfer coefficients on fenestration system boundaries, as well as local radiant heat transfer models, further improves the ability of computer tools to accurately predict the thermal performance of fenestration systems, including the calculation of the Condensation Index, which is based on surface temperatures and the relative humidity of the indoor air.

Individual surfaces on the frame sections, for insulating frames, can have average convective heat transfer coefficients without noticeable loss of accuracy. As the specimen becomes more conductive, there is more need for applying a continuously varying convective heat transfer coefficient. The edge-of-glass region of an IGU, being more conductive, requires the application of a continuously varying convective heat transfer coefficient. The same would apply for more conductive frames.

Modeling of the local radiant heat transfer on window boundaries is important for more projecting surfaces and was done without simplifying assumptions in the computer model used in this study. This should be a preferred method of modeling radiant heat transfer since the closed form solution to this problem is readily available.

Further research is needed in studying local convection heat transfer applicable for the specimen mounted in a typical hot box and/or IR thermographic facility so that assumptions used in a computer model of heat transfer in fenestration systems more closely resembles actual operating conditions.

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