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THERM Simulations of Window Indoor Surface Temperatures for Predicting Condensation

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ABSTRACT

As part of a "round robin" project, the performance of two wood windows and a Calibrated Transfer Standard was modeled using the THERM heat-transfer simulation program. The resulting interior surface temperatures can be used as input to condensation resistance rating procedures. The Radiation and Condensation Index features within THERM were used to refine the accuracy of simulation results. Differences in surface temperatures between the "Basic" calculations and those incorporating the Radiation and/or Condensation Index features are demonstrated and explained.

INTRODUCTION

This paper reports results from window surface-temperature simulations performed with the two-dimensional finite-element heat-transfer simulation program THERM (Finlayson et al. 1998). These surface temperatures are simulated for use in predicting window condensation performance. The research is part of an American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) project to evaluate the accuracy of computer-simulated surface-temperature results for use in predicting window condensation resistance. The project is a "blind round robin" in which different research facilities measure actual window units while others use various computer simulation tools. None of the participants has access to the other researchers' data. An overview paper will bring together the various labs' results, assessing the effectiveness of the various simulation models in comparison to the actual measured data.

Condensation on a window results when the surface temperature on the window's interior side drops below the dew point of the room air. All methods that rate a window's condensation resistance depend heavily on accurate indoor side surface temperatures.[1] The work described in this paper uses a heat-transfer simulation program developed at Lawrence Berkeley National Laboratory (LBNL) to perform a "basic" simulation of window surface temperatures and to perform more refined simulations using two features of THERM: the radiation model and the condensation index model. results from the basic simulations are in relatively good agreement with tests for whole window heat-transfer numbers such as U-factors (Arasteh et al. 1993). However, the radiation and condensation index features enhance the program's ability to represent localized heat-transfer phenomena such as surface temperatures.

The project for which the research in this paper was performed is a follow-up to a 1996 ASHRAE study that compared indoor-side surface temperatures of glass only for seven insulated glazing units (IGUs) in order to validate computer models that simulate window performance (Sullivan et al. 1996). The research was performed at two test laboratories using infrared thermography and at two simulation laboratories using software simulation tools.

The current project examines whole window temperatures to assess the effects of interactions between the IGU (glass) and the window frame.

METHODS

The specimens for this project are a wood casement window (see Figure 1) with both a low-E and a clear IGU and

[1] Two common standards for rating condensation are the Canadian CSA standard (CSA 1998) and the draft NFRC 500 standard (NFRC 2001). Both standards use window surface temperatures to calculate a measure of condensation performance.

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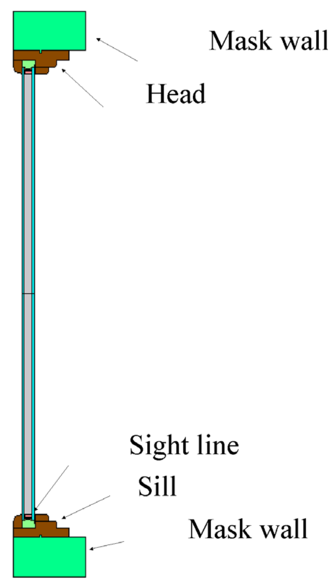

Figure 1 *Overview of full-height wood window.*

a calibrated transfer standard (CTS). The CTS is a panel that resembles an IGU (see Figure 2), but the air cavity between the glass panes has been replaced by foam. CTS panels are frequently used in thermal test facilities to determine heat-transfer film coefficients and to calibrate equipment. Because there is no air cavity in a CTS, there is only conductive heat transfer, which reduces the complexity and uncertainty of calculations. Results obtained with this panel will help to determine whether there are differences in heat-transfer film coefficients determined by the experiments and by the simulations performed for this project. Heat-transfer film coefficients directly influence the surface temperatures. Heat-transfer film coefficients from the experiments and simulations should be identical to permit meaningful comparison of surface temperatures.

The simulated models include a 75-mm-high section of surround panel, a foam mask wall (152 mm thick) that is used in testing laboratories to mount window specimens. This surround panel separates the cold and warm sides of the specimen in a thermal test facility.

The models were generated based on computer drawings (DXF) provided for the project. These drawings specified the geometry and dimensions of the window frame and glazing system and their overall relationship. The exact geometry specified in these files was modeled. Although the actual windows being measured for this project are full-height (830 mm) specimens, they were modeled as slightly more than half-height (500 mm) cross sections, which greatly reduces the complexity of the simulation. Dimensions slightly more than half-height were used because of an anomaly in the current version of the Condensation Index model that results in distorted temperatures across the center of the window if two exact halves are modeled. Modeling a top and bottom half that slightly overlap corrects this anomaly, which results in a continuous, smooth temperature profile.

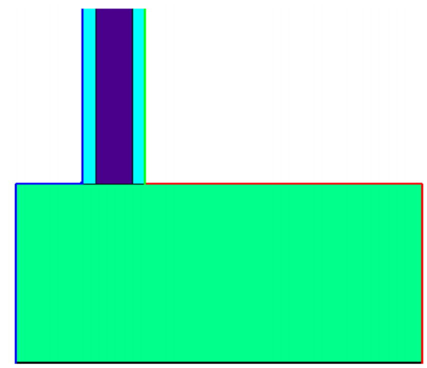

Figure 2 *Calibrated transfer standard sill section.*

As noted above, the cross sections were modeled using

- the basic model, which relies on a fixed heat-transfer coefficient for radiation and convection;
- the radiation model, which performs detailed calculations to determine the radiative heat-transfer coefficient on the window's interior surface;
- the condensation index (CI) model, which accounts for convective flow inside the glazing cavity, enabling THERM to more accurately simulate localized temperature variations.

Basic Model

In the basic model, typical boundary conditions (temperatures and heat-transfer coefficients) for fenestration system modeling are used, i.e., zero heat flux (adiabatic) at the top and bottom of the window unit. Interior and exterior boundary conditions have radiative and convective components; the basic model uses a fixed, combined surface heat-transfer coefficient for radiation and convection. A fixed radiative and convective heat-transfer coefficient is also used inside the glazing cavity. These values are calculated for the IGU using the software program WINDOW 4.1. The fixed combined coefficient for the frame cross section is based on ASHRAE/NFRC values for wood/vinyl frames. Results derived with fixed combined coefficients are labeled "BASIC" in the data presented below. The fixed radiative coefficient is calculated based on the radiative heat exchange of a surface at a standardized temperature and the large enclosure that stands for the room surfaces at the room bulk air temperature (21.1°C in this case). For window frames, the standardized temperature is based on the frame material. The wood frame modeled for this project is assumed to be at 17°C, which results in a radiative heat-transfer coefficient of 5.09 W/m^{2}K (equation 144 in ISO 15099).

TABLE 1
Heat-Transfer Film Coefficient Overview

	Exterior		Interior				
	Frame + Glass		Frame		Glass		
	H_{c+r} [W/m^{2}K]	T_e [°C]	H_c [W/m^{2}K]	H_{c+r} [W/m^{2}K]	H_c [W/m^{2}K]	H_{c+r} [W/m^{2}K]	T_i [°C]
Clear-Basic	29.0	–17.8		7.6		7.9	21.1
Clear-CI-Rad	29.0	–17.8	2.5		3.4		21.1
Low-E-Basic	29.0	–17.8		7.6		7.7	21.1
Low-E-CI-Rad	29.0	–17.8	2.5		3.1		21.1
CTS	29.0	–17.8		7.6		7.7	21.1
CTS-Rad	29.0	–17.8	2.5		3.1		21.1

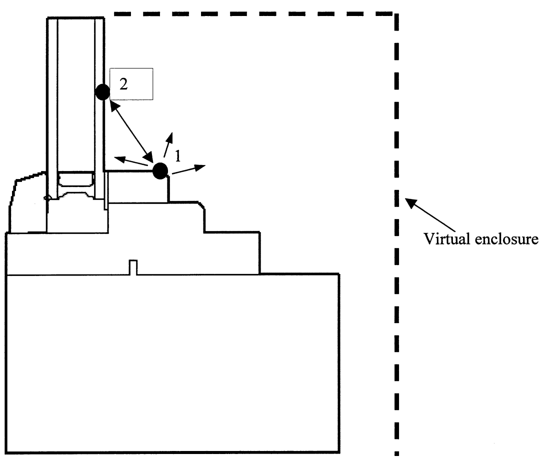

Figure 3 *Radiative exchange between glass and frame.*

Radiation Model

For most of the simulation results presented in this paper, the radiation model was enabled. This model calculates radiative heat transfer between all surface segments that can "see" each other. A surface segment sees another segment if there is a direct "line of sight" between the two. Figure 3 illustrates a line of sight between a segment on the window frame (#1) and a segment on the glass (#2); because these segments will most likely be at different temperatures, there will be radiative heat exchange between them. With the radiation model enabled, view factors are calculated from each defined segment of the window surface to each other segment. The size of the segments is determined by the grid that is generated by the software for the finite-element simulation. The view factor between two segments is the fraction that the second segment occupies in the field of view of the first segment. The program uses these view factors and the temperatures of each segment to calculate the amount of radiation that is exchanged between the segments. For the example in Figure 3, the frame not only exchanges radiation with the virtual enclosure that is at the room bulk air temperature but also with segments on the glass. The resulting surface temperature will be lower than would be calculated without the use of the radiation model because the radiation model accounts for the fact that there is less radiative exchange with the warm room and more from the cold glass.

Griffith et al. (1998) shows the increased accuracy in surface temperature prediction when using the radiation model. Results presented below from simulations with the radiation model enabled will be labeled with "RAD." For a detailed description of how the radiation model works, see Finlayson et al. (1998).

Condensation Index Model

The condensation index (CI) model was developed specifically to improve the accuracy of THERM's surface-temperature predictions of glazing units. The CI model varies convective and radiative heat-transfer coefficients inside the glazing cavity to account for convection effects. The convective heat-transfer coefficients are based on correlations derived from computational fluid dynamics (CFD) calculations for a number of different IGU configurations. The radiative heat-transfer coefficients are determined using the radiation model described above inside the glazing cavity. This approach is a major improvement over the traditional method of modeling glazing systems with the cavity as a rectangle that has an effective conductivity calculated by averaging convective and radiative effects over the whole cavity. The CI model will also result in U-factors different from those calculated without the CI model. Currently, no standard prescribes U-factors calculated with the CI model, so we are interested only in the temperature data.

The expected temperature profile for a glazing system is that the top portion will be warmer than the bottom because

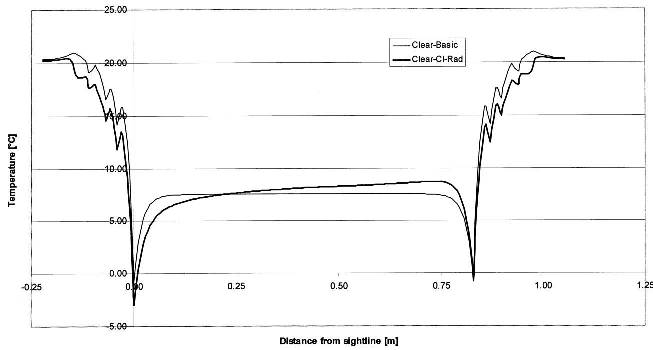

Figure 4 *Temperature as a function of distance along the center profile of the window for clear glazing in a wood window using Basic and CI-Rad models.*

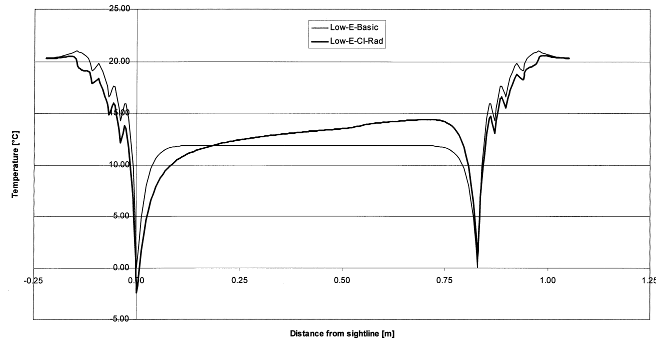

Figure 5 *Temperature as a function of distance along the center profile of the window for low-E-coated glazing in a wood window using Basic and CI-Rad models.*

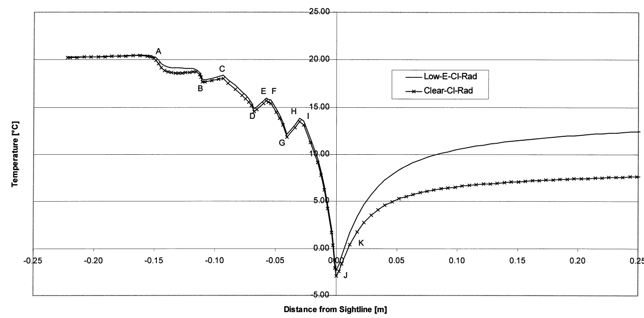

Figure 6 *Temperature as a function of distance along the sill profile of the window for low-E-coated and clear glazing in a wood window using the CI-Rad models.*

warm air rises to the top of the glazing cavity, and cold air falls to the bottom. This convective pattern is simulated by the CI model. In the cases where the CI model is not used, surface temperatures for head and sill cross sections will be identical, assuming the same frame cross sections for head and sill are used. Results from simulations using the CI model are labeled with "CI."

The glazing systems were constructed in WINDOW 4.1 according to the following specifications:

Clear IG: 4.7 mm clear glass + 16.5 mm air space + 4.7 mm clear glass

Low-E IG: 4.7 mm glass with emissivity = 0.10 on surface 2 + 16.5 mm air space + 4.7 mm clear glass.

Heat-Transfer Film Coefficients

All heat-transfer film coefficients that were used for the simulations are listed in Table 1. They are in accordance with the current NFRC procedures (Mitchell et al. 2000). H_c stands for the convective heat-transfer film coefficient and is only specified for the models that have the radiation model enabled. The radiative heat-transfer coefficient is different for each segment with the radiation model. H_{c+r} indicates a combined radiative and convective heat-transfer coefficient as used by the basic model.

RESULTS

Because we cannot compare our simulation results to measured data from other participants in this blind round robin project to assess THERM's accuracy, we only compare the Basic model simulation results with results from THERM with Radiation and CI models enabled. The curves labeled "[CI-Rad]" in Figures 4 through 8 should be used for comparison to the experimental data.

Results are plotted on a graph of distance vs. temperature. The X-axis represents the distance from the sight line of the window sill in meters. The sight line is the point where the window glass and the frame meet (the sill sight line is indicated in Figure 1; there is also a head sight line). The distance from the sight line is measured along the window surface. Negative sight line distance values are for points on the window frame below the sight line. Positive values are for points in the direction of the head of the cross section. The Y-axis represents surface temperatures in °C. Only surface temperatures along the vertical centerline of the glazing system are presented.

Figure 4 shows the results for a simulation performed on the uncoated clear glass IGU with and without use of the CI and radiation models; these results are labeled as "Clear-basic" and "Clear-CI-rad." The top part of the glazing system is clearly warmer than the bottom part in the CI-rad simulation, for reasons noted above in the "Condensation Index Model" section. The frame sections are colder in the CI-rad case because the radiation model accounts for the frame "seeing" the glass, which is colder then the room.

The results for the low-E IGU are shown in Figure 5. The differences in glass temperatures between the low-E-Basic and low-E-CI-Rad simulations are much larger in this case. The heat transfer in a low-E window is dominated by convective heat transfer because the low-E surface eliminates a large part of the radiative heat transfer. The CI model modifies the convective heat transfer in the cavity and therefore has a larger effect on a low-E IGU than on a clear glass IGU.

Figures 6 and 7 show data for the sill and head sections separately. The scale has been enlarged to show detail. The

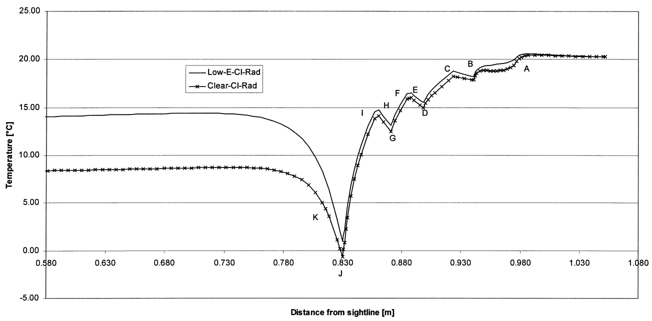

Figure 7 *Temperature as a function of distance along the head profile of the window for low-E-coated and clear glazing in a wood window using the CI-Rad models.*

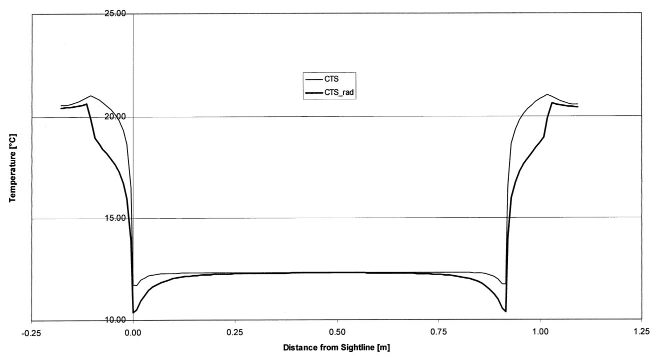

Figure 8 *Temperature as a function of distance along the center profile of the Calibrated Transfer Standard using the Basic and Rad models.*

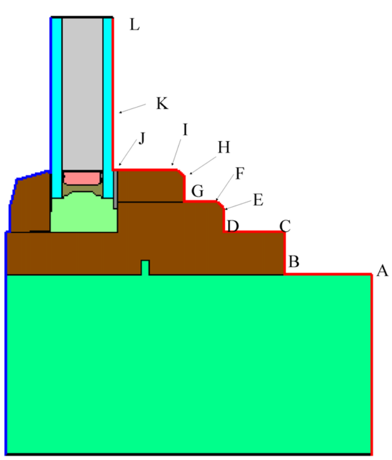

Figure 9 *Sill cross section of wood window, which shows the location of temperature points.*

results in both plots are calculated using the CI and radiation models.

Figure 8 shows the temperature profile for the Calibrated Transfer Standard (CTS). Because there is no cavity in the CTS, the CI model cannot be used. Temperature results from the Basic and Radiation models are presented.

TABLE 2
Location of Temperature Points [mm]

	X-coordinate		Y-coordinate		Accumulated distance	
	Head	**Sill**	**Head**	**Sill**	**Head**	**Sill**
A	108	108	873	–43	977	–147
B	71	71	873	–43	941	–111
C	71	71	855	–25	924	–94
D	46	46	855	–25	898	–68
E	46	46	845	–15	888	–58
F	43	43	843	–13	884	–54
G	29	29	843	–13	871	–41
H	29	29	833	–3	860	–30
I	27	27	830	0	857	–27
J	0	0	830	0	830	0
K	0	0	820	10	820	10
L	0	0	766.5	63.5	766.5	63.5
M	0	0	415	415	415	415

Figure 9 shows the locations of the temperature points that are listed in Tables 2 and 3. The locations are shown for the sill cross section; the same lettering is used for the head cross section. The points are located on the corners of the frame section and on three positions on the glass: 10, 63.5, and 415 mm above the sill sight line. Point J is the sight line.

DISCUSSION

We believe that window surface temperatures calculated using both the radiation and CI models will be the most accurate because these models permit THERM to account for localized heat-transfer effects and interactions that are not addressed in the basic model. We note below three specific details of our simulation procedure that should be taken into account.

1. Actual window surface temperatures are probably somewhat lower than the results from our THERM simulations because we relied on window center-of-glass conductivities generated by WINDOW 4.1, which does not incorporate changes to technical algorithms (e.g., interior film coefficients and gas mixture calculations) that are included in the ISO 15099 draft standard. ISO 15099's changes improve the accuracy of the calculation method and result in lower center-of-glass temperatures than those calculated by WINDOW 4.1. Use of these lower temperatures in condensation rating procedures (such as NFRC 500 and CSA-A440) would produce higher condensation predictions than would result from using the higher surface temperatures presented in this paper. Table 4 shows surface temperatures calculated using WINDOW 4.1 and ISO 15099. The next

TABLE 3
Temperatures at Specific Locations [°C]

Model	Clear-Basic	Clear-CI-Rad		Low-E-Basic	Low-E-CI-Rad	
Point		Sill	Head		Sill	Head
A	21.0	19.6	19.8	21.0	20	20.2
B	19.1	17.7	17.9	19.2	17.9	18.3
C	19.8	18.0	18.3	19.9	18.4	18.8
D	16.6	14.6	15.0	16.6	14.9	15.5
E	17.6	15.7	16.1	17.6	16	16.6
F	17.5	15.4	15.9	17.6	15.8	16.5
G	14.2	11.8	12.5	14.3	12.1	13.1
H	15.9	13.5	14.1	16.0	13.8	14.8
I	15.8	13.2	13.8	15.9	13.5	14.6
J	-0.8	-3.0	-0.6	0.0	-2.4	1.0
K	2.9	0.0	3.1	4.3	1.2	5.8
L	7.3	5.8	8.5	11.4	9.1	13.8
M	7.5	8.1	8.4	11.9	13.2	13.2

TABLE 4
Interior Surface Center-of-Glass Temperatures

	WINDOW 4.1	ISO 15099
Clear IG	7.6 °C	6.8 °C
Low-E IG	11.9 °C	11.2 °C

version of WINDOW, WINDOW 5, will incorporate ISO 15099 calculation methods.

2. Our initial basic model simulations used an edge-of-glass measurement of 63.5 mm (2.5 in.), which is standard modeling practice in NFRC and is sufficient for U-factor calculations. However, when the radiation model is enabled, this is too small a portion of the glass to produce accurate results because of the complexity of the effects of the portions of the window unit that “see” one another; when the glass area is small, many radiative exchanges are overlooked. Figure 10 compares the results of radiation (and CI) model simulations performed with a 63.5-mm edge of glass clear-CI-rad and a 500-mm edge of glass clear-CI-Rad-Extended glazing. Clear-CI shows the temperatures for a simulation without the radiation model enabled. Comparison of these results shows the difference in surface temperatures that result when the basic model is used in contrast to the radiation model and when the radiation model is used with a small glass area versus a half-height window with the extended glazing area. The more glass area included, the more accurate radiation model results will be because the complex heat-transfer interactions that the radiation model addresses take place over the entire surface of the window. The differences in surface temperatures among these various simulations is greatest for objects that are the farthest distances out of the plane of the glass (e.g., for the mask wall, which extends farthest beyond the surface of the glass). This difference in surface temperatures results because points that are farthest out of the glass plane “see” more of the glass when the height of the modeled glass region is extended and therefore their temperature is affected by interactions with more points on the rest of the window. We consequently modeled all windows with 500-mm edge of glass to facilitate the comparison of surface temperatures between the basic and radiation/condensation index models.

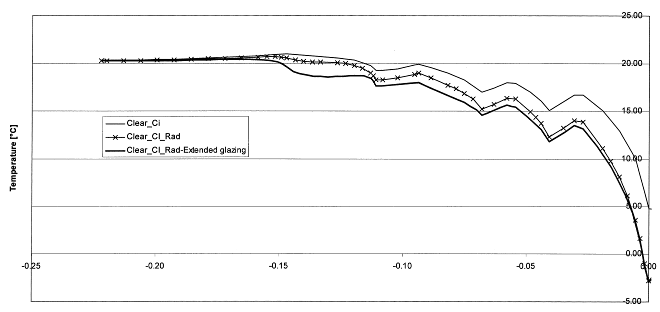

Figure 10 *Temperature as a function of distance along the head profile of the window for clear glazing in a wood window using the CI-Rad models, showing the effect of extended glazing area on frame temperatures.*

3. This study only looked at temperatures along the vertical centerline of the window. Temperatures in the corners of the

window are usually lower because the corners “see” the window jamb, which is colder than room temperature but not as cold as the glass temperature. These temperature differences affect radiative heat transfer. Convection and conduction are also affected (the convective heat-transfer coefficient is reduced because of the presence of the jamb). These lower corner temperatures will increase the potential for condensation. A future research project should look at increased condensation risks in window corners.

A separate paper that compares and summarizes the experimental and calculation results from all participants in this round robin project will be published by ASHRAE. That paper will provide valuable information about potential improvements in the simulation models evaluated. One improvement would be the use of variable convective heat-transfer coefficients for the window’s interior surface, in the same way that the CI model varies the convective heat-transfer coefficient in the glazing cavity. Currently, a fixed uniform convective heat-transfer coefficient is used for the frame and another for the glass. A variable convective heat-transfer coefficient for the window’s interior surface could improve the accuracy of surface-temperature predictions. The wide variety of geometries of frames and windows makes this a complicated effort, however.

ACKNOWLEDGMENTS

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