Testing and Simulation of High-Performance Windows—Phase II of the Canadian/U.S. Joint Research Project on Window Performance

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ABSTRACT

The thermal performance of fenestration systems (windows and doors) has been the subject of investigation by a number of research organizations in the U.S., Canada, and Europe. In 1987, the U.S. Department of Energy (DOE) and the Canadian Energy Mines and Resources (EMR) formulated a Memorandum of Understanding (MOU) aimed at coordinating the research activities on fenestration systems in both countries. As a result, a Canadian/U.S. joint research project on window performance was initiated that is aimed at providing benefits to both countries from the results of the ongoing research work on fenestration and also to coordinate future activities in that area.

The results of Phase I of this project were published as an ASHRAE paper in 1990. This paper presents a summary of results of Phase II of the project.

One of the tasks in the joint research project is to ensure that the available tools to determine the thermal characteristics of fenestration systems produce comparable and accurate results. There exists a limited number of computer programs capable of analyzing the two-dimensional heat transfer through the center of glass, edge of glass, and frame of a window assembly. In addition, test procedures were used to assess the overall heat transfer through windows.

Nine high-performance windows were tested as a part of this phase, and the same units were also modeled using VISION 2, WINDOW 3.1, and FRAME 2.2 programs. This paper presents a comparison of the window R-value of the nine units as determined by testing and simulation.

The results of this round of testing and simulation of high-performance windows indicate some differences in the U-values determined from testing and modeling. These differences are due to a number of factors, including the uncertainty in calculating the overall U-values, air leakage through windows, inaccurate modeling of a window cross section, and insufficient information to model the window profile. The paper also provides an analysis of the differences between the results and the associated uncertainty in the reported U-values.

INTRODUCTION

In recent years, the research community and fenestration industry have witnessed the development of test procedures and calculation methods to assess the thermal performance of fenestration systems. The main goal is to make tools available to assist the fenestration industry in rating products with respect to energy and to facilitate window-labeling programs under way in Canada and the United States.

Computer models were developed for this purpose (Wright and Sullivan 1987; EMRC 1988; LBL 1988). It was felt, however, that without accurate laboratory test methods to verify the computer output, the level of confidence in the analytical results would not be satisfactory. To provide the required experimental data, test procedures were developed to determine the U-value of fenestration systems, using hot box measurements (Bowen 1985; Elmahdy 1988), solar calorimeters (Dubrous and Harrison 1988; Harrison and Dubrous 1990), or by means of a mobile test facility (Klems et al. 1982; Klems and Reilly 1990).

Efforts to develop analytical and experimental methods to determine the thermal characteristics of fenestration systems were under way in Canada, the U.S., and Europe. In an effort to coordinate the fenestration research activities in North America, the Department of Energy (U.S.) and Energy, Mines and Resources (Canada) reached an agreement, and the Canadian/U.S. Joint Research Project on Window Performance was initiated. More details about the project, its objectives, and its goals are documented in Elmahdy (1990).

Some of the results of Phase I of this project were reported in Elmahdy (1990). Phase II of the project focused on both testing and analytical evaluation of the U-values of high-performance windows. This paper presents a summary of the results on testing and modeling of nine high-performance window assemblies. Testing was performed at the Institute for Research in Construction (IRC), the National Research Council of Canada (NRCC), and the National Solar Test Facility, Toronto, Ontario, Canada. Three

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computer programs were used in modeling the windows. In addition, this paper discusses the differences in the U-values reported from testing and modeling of the window assemblies.

WINDOW DESCRIPTION

Nine high-performance window assemblies were included in this study. Some were prototypes and others were conventional windows with features to improve their thermal performance. The units were selected to address a number of issues:

- to provide test data on window types that were not covered in Phase I of the Canadian/U.S. joint research project, thus updating the data base of experimental and analytical data;
- to check on the validity of the developed test procedures and computer modeling in evaluating complex window designs (e.g., tilt and turn, units with internal grilles); and
- to compare test data with computer modeling using windows of different designs, including insulated spacer bars, different low-emissivity coatings on the glass, and gas-filled insulating glass units.

The selected units for this phase are coded Unit F143 to Unit F151, and a brief description of each follows.

Unit F143: Quad glazing (two sheets of glass and two thin mylar sheets in between), two low-emissivity coatings on the mylar sheets ($\varepsilon = 0.12$), two metal spacers, and one insulated spacer; the cavity is filled with 10% air and 90% krypton. The frame is custom built of polystyrene foam insulation.

Unit F144: The glazing is similar to that of Unit F143. The window is a fixed casement, wood frame with exterior vinyl cladding.

Unit F145: The glazing is similar to that of Unit F143. The window is a fixed casement, wood frame with exterior aluminum cladding.

Unit F146: A prototype of a high-performance window: triple glazed, a low-emissivity ($\varepsilon = 0.08$) coating on surfaces #2 and #5, 10% argon and 90% krypton, wood (casement) frame with exterior vinyl cladding, and a metal spacer.

Unit F147: Similar to Unit F146, but with an insulated (nonmetallic) spacer.

Unit F148: Triple glazing with a low-emissivity ($\varepsilon = 0.09$) coating on surfaces #2 and #5, a corrugated metal strip spacer, and an argon-filled cavity. The window is an awning type with a wood frame and sash.

Unit F149: Double-hung window, aluminum- and steel-reinforced vinyl frame, double glazed with one low-emissivity ($\varepsilon = 0.12$) coating on surface #3, an aluminum spacer, argon filled with an internal grille.

Unit F150: Wood frame with exterior aluminum nose cap wood frame, triple glazed with a low-emissivity ($\varepsilon = 0.1$) coating on surfaces #2 and #5, a metal spacer, and an argon-filled cavity.

Unit F151: Tilt-and-turn, steel-reinforced vinyl frame and sash, double glazed with a low-emissivity ($\varepsilon = 0.12$) coating on surface #3, and an air-filled cavity.

All windows were about 905 mm by 1,210 mm.

BRIEF DESCRIPTION OF TEST METHODS

IRC Test Method

Testing at the National Research Council of Canada was performed using the IRC test procedure, which is described in Bowen (1985) and Elmahdy (1988). The procedure is based on the use of a guarded hot box, a constant-temperature baffle, and a specially designed wind machine on the cold side (weather side) to provide a uniform film heat transfer coefficient on that side. The thermal resistance of the window assembly (surface to surface) is determined from the following expression:

$$R = (T_1 - T_2) \cdot A_w / Q_s \tag{1}$$

where

T_1, T_2 = average room-side and weather-side window surface temperature, K;
Q_s = heat transfer through the window, W;
A_w = projected area of the window assembly, m^2;
R = window thermal resistance (surface to surface), $m^2 \cdot K/W$.

The overall design thermal resistance (air to air) of the window assembly, R_d, is then determined from the following equation:

$$R_d = R_{fi} + R + R_{fo} \tag{2}$$

where

R_{fi}, R_{fo} = room-side and weather-side standard film coefficients, respectively ($R_{fi} = 0.12$ and $R_{fo} = 0.03$ $m^2 \cdot K/W$).

The average window surface temperature on the warm side, T_1, is determined by solving heat balance equations, not by direct measurements. This approach provides a better method to determine the surface temperature and was made possible by using the constant-temperature baffle in the guarded hot box. The main reasons for using this approach are

- to eliminate the potential for error due to attaching thermocouples to the window surfaces, which tends to disturb the boundary layer around the thermocouples;

- to enable the calculation of radiant heat exchange (and the radiant heat transfer coefficient) between the window and a surface of "known" temperature (the constant-temperature baffle); and
- to determine an average window surface temperature (by calculation) rather than using the area-weighted average temperature. The latter is commonly used and is known to introduce an error in the measured surface temperature, which is difficult to quantify.

The overall thermal resistance determined by the IRC method is accurate within $\pm 6\%$ under the worst conditions (i.e., when the heat transfer through the window is small, such as in the cases of high-performance windows). Details of the uncertainty and error analysis in the above hot box measurements and the overall procedure are documented in Elmahdy (1992).

Solar Calorimeter Method

Window testing at the National Solar Test Facility (NSTF) in Toronto is done using the test procedure described in Dubrous and Harrison (1988) and Harrison and Dubrous (1990). In summary, the net instantaneous heat gain, Q_{net}, through a fenestration system mounted in the calorimeter is calculated as the difference between the heat gain due to solar radiation, Q_{solar}, and the heat losses due to indoor/outdoor temperature difference, Q_{loss}:

$$Q_{net} = Q_{solar} - Q_{loss}. \tag{3}$$

Q_{solar} represents the fraction of incident energy transmitted through the fenestration system, W, and is given by

$$Q_{solar} = F \cdot G \cdot A_w \tag{4}$$

where F is the solar heat gain coefficient (SHGC), G is the irradiation level, W/m^2, and A_w is the area of the fenestration system, m^2.

The solar heat gain coefficient, F, is the product of the shading coefficient (SC) and the standard solar heat gain coefficient, F_{st}:

$$F = SC \cdot F_{st}. \tag{5}$$

F_{st} is equal to 0.87, and it represents the solar heat gain for a reference single pane of glass (ASHRAE 1985). It should be noted that all (area) normalized quantities are based on the total projected area of the window, A_w.

Q_{loss} is expressed in terms of the overall fenestration system U-value as follows:

$$Q_{loss} = U \cdot A_w \cdot \Delta T \tag{6}$$

where U is the overall thermal transmission coefficient (W/[m^2·K]) and ΔT is the indoor/outdoor temperature difference (K).

The net heat flow through the fenestration system per unit area, q_{net}, may be written as follows:

$$q_{net} = Q_{net}/A_w = F \cdot G - U \cdot \Delta T. \tag{7}$$

From Equation 7, the thermal performance factor, h, is written as follows:

$$h = \frac{q_{net}}{G} = F - U \cdot \frac{\Delta T}{G}. \tag{8}$$

Equation 8 is plotted (h vs. $\Delta T/G$) for each window and the solar heat gain coefficient (F) and the overall thermal transmission coefficient (U) are determined as the intercept and the slope of the line, respectively. Figure 1 shows a sample of h vs. $\Delta T/G$ as related to Unit F146.

When testing high-performance windows using the above procedure, the overall uncertainty in the U-value is about $\pm 8\%$ (this is equivalent to about ± 3 W/m^2 of heat flux). More details about error analysis of this test procedure are given in Harrison (1992).

Modeling

The U-value of the frame and edge-of-glass portions of the windows were determined using the LBL (1988) program. The center-of-glass U-value was determined using the computer programs described in Wright and Sullivan (1987) and LBL (1988). Another program (DeSolda and Gorman 1987) also was used.

RESULTS AND DISCUSSION

All the windows were tested at the IRC, six units (out of nine) were tested at the NSTF, and seven were modeled by the computer programs. Table 1 gives a summary of the fenestration system U-values determined by testing and modeling. The data are presented in graphical form in Figure 2.

As indicated earlier, the results of Phase I of the Canadian/U.S. joint research project showed reasonable agreement between hot box measurements (at the IRC) and computer modeling using combinations of four programs. Phase II of this project focused on high-performance windows, and the results show some differences in the U-values determined from testing and modeling. These differences may be attributed to one or more reasons related to accuracy of measurements, window installation, air leakage through the window, insufficient data for modeling, inaccurate modeling, or systematic errors in the calibration and measurements in the test facilities. The following are some observations and comments on the possible causes of these differences.

- The U-values of windows determined by modeling depend on the ability of the simulator to represent the correct window profile in the computer program. The availability of detailed shop drawings of windows is essential for obtaining the correct information for modeling. Past and present experiences in this regard

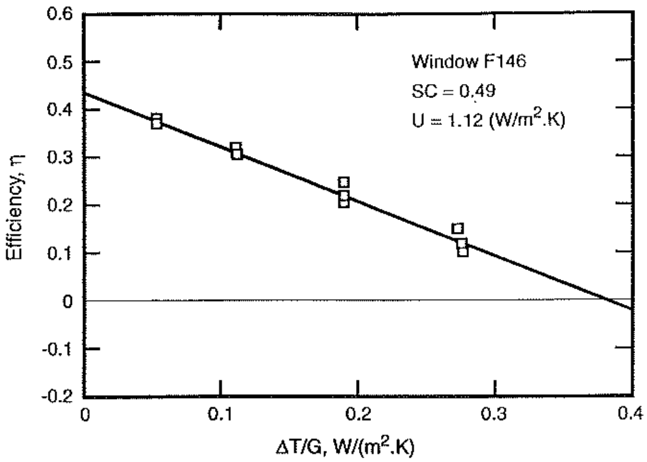

Figure 1 *Sample of the relationship between η and $\Delta T/G$ for unit 146.*

TABLE 1
Summary of the U-Value of High-Performance Windows

Unit #	NSTF	FRAME/VISION	IRC
F143	-	0.75	0.85
F144	-	1.08	1.20
F145	-	1.63	1.57
F146	1.02	-	1.22
F147	0.99	-	1.12
F148	0.90	1.12	1.24
F149	1.47	2.31	2.06
F150	1.36	1.77	1.82
F151	1.66	2.10	2.08

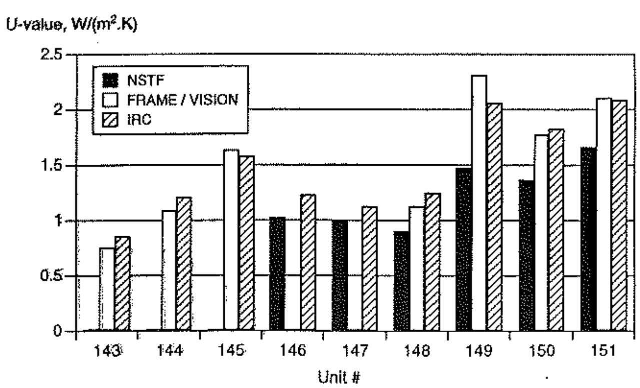

Figure 2 *Comparison between test and simulation results (U-values) of high-performance windows.*

proved that such information is very difficult to obtain. Consequently, the simulator has to rely on personal interpretation of the information available and the more complicated the window design, the higher the potential for errors. This may result in modeling windows that are not exactly the same as the tested windows.

- When windows were tested at the IRC, efforts were made to seal the perimeters and all the apparent cracks of the sash and frame. This is particularly important to eliminate any air leakage through the window assembly. In some cases, however, some cracks are not visible to the operator, which may result in undetected air leakage. It is imperative that all the leaks be sealed, and this practice should be followed by other testing laboratories to ensure that the results are comparable. This requirement is clearly stated in the new ASTM standards for the assessment of the thermal transmission of fenestration systems (ASTM E1423-91 [ASTM 1991a] and ASTM C1199-91 [ASTM 1991b]).
- The test results from the NSTF were adjusted for the standard ASHRAE film coefficients (on the room side and weather side). This adjustment was necessary to determine the U-value at the standard room-side/weather-side conditions, similar to all other reported data, so that comparison of the results would be done at the same boundary conditions. The results, however, showed a systematic difference in almost all the U-values reported. Although the heat loss through a window is within ± 4 W/m^2, there is additional systematic error due to air infiltration and the calorimeter flow loop stability that should be studied further (Harrison and van Worderen 1991). For that reason, the test data from the NSTF were, in some cases, considerably different from the IRC or computer modeling results. This does not contradict the claim that the method used in determining the U-value is about $\pm 8\%$. The latter is based on the absence of air leakage through the window (and its associated error).
- In the IRC hot box test facility, temperatures are measured within ± 0.1°C and the power input is accurate within ± 0.3 W. The uncertainty level in the calculated heat flow through the sample is $\pm 0.01\%$, and the thermal resistance of the mask wall is calculated within ± 0.011 m^2·K/W. The heat flow through the sample is accurate within ± 0.19 W/m^2. Finally, the overall uncertainty level associated with the hot box measurements is $\pm 6\%$ of the calculated overall U-value (Elmahdy 1992). This is the case under the worst testing conditions for high-performance windows. In that situation, a relatively small amount of heat flows through the window.
- The computer modeling of windows indicates that, for some windows, the calculated U-values are close to the IRC results. Some other data points, however, were about 15% different from the hot box results. There is a considerable uncertainty associated with modeling as a result of using material properties that may be

different from the actual properties. Window manufacturers often are the only source of such information. It is essential that efforts be made to provide accurate data to simulators so that the results can be comparable and accurate.

CONCLUSIONS

Testing and modeling of high-performance windows provided valuable information regarding the comparison between analytical and experimental results on the thermal characteristics of windows. The differences between test results and computer modeling varies, but it could be as high as 15% of the test results.

Some existing laboratory procedures to determine the thermal transmission (U-value) of windows require further refinements to reduce the degree of uncertainty in the measured and calculated quantities. Special attention should be given to the calibration of the test facility and proper installation of windows in the surrounding panel. Air leakage through windows should be eliminated so that the measured heat flow reflects the true thermal performance of the windows due to the defined boundary conditions.

Computer modeling of windows for the determination of U-values is a useful tool, providing the simulation is performed to represent the actual parameters and the correct data are used. Approximation in modeling window profiles should be improved to increase the accuracy of the computer output. In addition, window manufacturers should take the lead in compiling actual and accurate data about the thermal properties of all the materials used in making windows. This will have a positive impact on their product and will provide consumers with accurate results that will assist in product selection. This information is becoming increasingly important due to the widespread dependence on computer modeling of windows (instead of relatively expensive laboratory testing) for compliance with window labeling and certification programs.

Window testing in Phase II of the Canadian/U.S. joint research project included two more laboratories. However, due to the lack of documentation of some of the test procedures, uncertainty analysis, and calibration of the test facility, the test results were omitted from this paper and will be reported later when complete information is available.

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