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Guidelines for Modeling Projecting Fenestration Products

Dariush K. Arasteh, P.E.
Member ASHRAE

Elizabeth Finlayson

Dragan Curcija, Ph.D.
Member ASHRAE

Jeff Baker, P.Eng.

Charlie Huizenga

ABSTRACT

Heat transfer patterns in projecting fenestration products (greenhouse windows, skylights, etc.) are different from those in typical planar window products. The projecting surfaces often radiate to each other, thereby invalidating the commonly used assumption that fenestration product interior surfaces radiate to a uniform room air temperature. The convective portion of the surface heat transfer coefficient also is significantly different from the one used with planar geometries and is even more dependent on geometry and location. Projecting fenestration product profiles must, therefore, be modeled in their entirety. This paper presents the results of complete cross-sectional, variable film coefficient, two-dimensional heat transfer modeling of two greenhouse windows using the next generation of window-specific heat transfer modeling tools. The use of variable film coefficient models is shown to increase the accuracy with which simulation tools can compute U-factors. Simulated U-factors also are determined using conventional constant film coefficient algorithms. The results from both sets of simulations are compared with measured values.

INTRODUCTION AND DEFINITION OF THE PROBLEM

Heat transfer simulation software programs are used extensively in the United States and Canada to determine the thermal transmittance (U-factor in W/m^2°C) of fenestration products for both standardized ratings and product development (NFRC 1991; CSA 1993). The tools referenced in these procedures have simplified the costs associated with rating and product development tremendously, as they have been shown to be much cheaper, as accurate, and more consistent than physical laboratory testing (Arasteh et al. 1994).

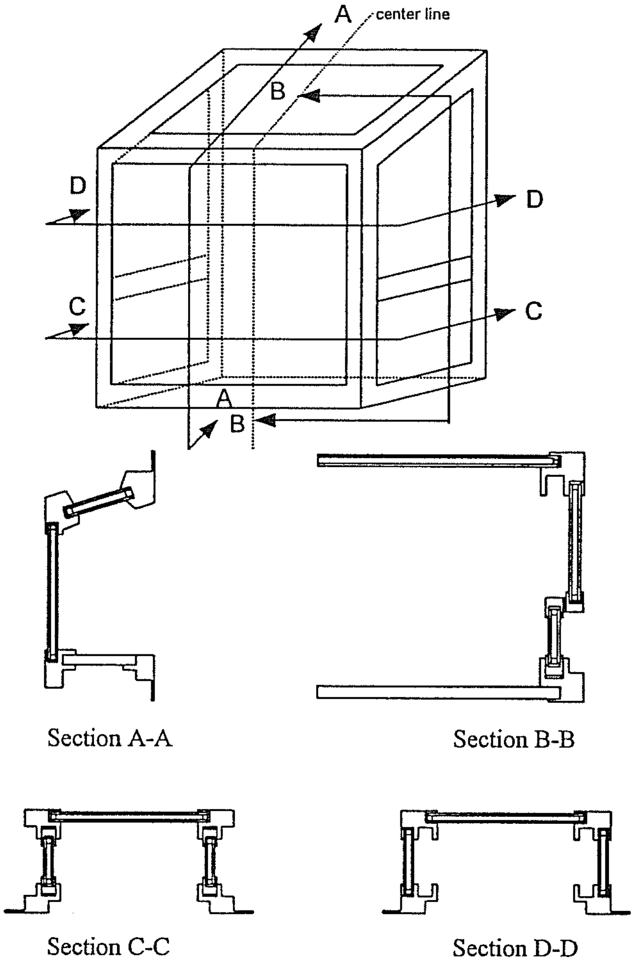
The simulation tools referenced in these procedures were developed to model planar or two-dimensional window products—those products typically thought of as residential windows. However, if one takes a look at the assumptions buried in the current simulation process, one would expect that these programs would not accurately predict the heat transfer through products that project out of the wall or roof into the third dimension. Recent research (Carpenter and Elmahdy 1994) confirms this, showing significant differences between as-tested and simulated U-factors for projecting products. Such products include greenhouse or garden windows, bay/bow windows, and skylights. In such cases, the assumption of constant interior surface radiative and convective heat transfer coefficients breaks down. Depending on local geometry, the interior surfaces of three-dimensional products radiate to themselves (at surface temperatures different from the interior air temperature) as much or more than they radiate to room surfaces at interior air temperatures. Because of the much greater depth of projecting products (150 mm to 500 mm), local air velocities will vary significantly, leading to geometrically dependent convective heat transfer coefficients.

IMPROVED MODELING PROCEDURES

There is no fundamental limitation on using two-dimensional finite element or finite difference techniques to determine projecting product U-factors with improved interior surface radiative and convective models. To do so requires the following:

1. Modeling horizontal or vertical sections in their entirety (see Figure 1).
2. Adding an element-to-element radiation view factor algorithm (Sparrow and Cess 1978; Hottel and Sarofim 1967; Shapiro 1983, 1986) so that the radiation exchange between each pair of elements on the interior surface can be properly accounted for.
3. Accounting for the convective effects through a variable film coefficient model or by incorporating a CFD model.

Dariush Arasteh is a staff scientist and **Elizabeth Finlayson** is a principal research associate in the Building Technologies Program, Lawrence Berkeley National Laboratory, Berkeley, Calif. **Dragan Curcija** is president of Carli Inc., Amherst, Mass. **Jeff Baker** is with WESTLab, Waterloo, Ontario, Canada. **Charlie Huizenga** is a research specialist at the University of California at Berkeley.



Section A-A

Section B-B

Section C-C

Section D-D

Figure 1 *Three-dimensional schematic and the four full cross sections used to model it.*

Since CFD models require a sophisticated user, a variable film coefficient model (with the film coefficients determined experimentally or based on CFD results) would be most appropriate if the tool is expected to be used outside of the research world.

There are several commercially available codes that include the technical capabilities mentioned above (e.g., FDI 1997; FC 1996; AR 1996). However, these codes have been developed as general purpose codes and do not lend themselves to efficient use by the fenestration industry. THERM 2.0 is an FEA tool with these capabilities (Arasteh 1997) developed explicitly to model such fenestration products (and simpler products).

This paper presents results for two greenhouse windows modeled with THERM 2.0. While THERM 2.0 has the capability to account for convective effects through the use of variable film coefficients, this capability was not used because the choice of the proper film coefficients is the subject of ongoing research (Griffith et al. 1997). Modeled data from THERM 2.0 are compared to data from THERM 1.02 (Finlayson 1996), which does not incorporate these advanced features, and to test data. While skylight models are not presented at this time, skylight modeling issues (variable radiative and convective heat transfer coefficients) are expected to be similar to greenhouse window products. Skylights will be the subject of a future paper.

Table 1 lists the properties of the two products modeled.

TOTAL PRODUCT U-FACTORS

Total product U-factors were determined by first modeling each unique vertical and horizontal cross section. For example, Figure 1 shows a three-dimensional schematic of GHWindow 2 and the four unique full cross sections used to model the window. Figure 2 shows the center vertical cross section (Section A-A) in detail.

Once each unique cross section is modeled in total, the results for each component (frame, edge, center glass) are isolated. For example, as shown in Figure 2, five frame areas are defined, three edge-of-glass areas are defined, and two center-of-glass areas are defined. These component U-factors are then mapped onto a diagram of the window where the window is opened up to define the projected area for each plane of the window (see Figure 3). A summed U*A can then be determined for each plane of the window and then for the total product. (In cases where a given component's U-factor is determined from two or more different full height or full width cross sections, the component U-factor is taken as the average

TABLE 1
Window Descriptions

Product	Glass System	Spacer System	Frame Material	Rough Opening Dimensions W × H (mm) and Area (m^2)	Total Projected Area[a] (m^2)
GHWindow 1	3 mm Clear-6.7 mm Air- 3 mm Clear	Butyl Rubber/ Alum. Strip	Aluminum - no thermal break	954 × 1662 1.52	3.21
GHWindow 2	3 mm Low-e (0.04)- 13 mm Argon- 3 mm Clear	Dual-Seal Aluminum	PVC	959 × 1600 1.53	2.80

a. The total projected area represents the sum of the inside projected area for each plane of the window.

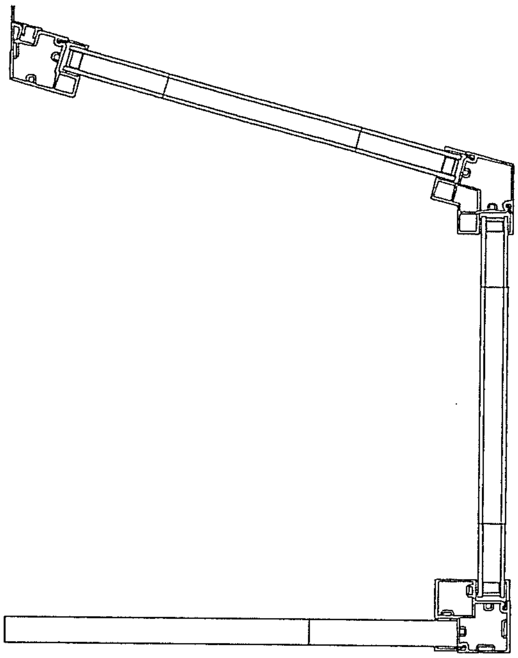


Figure 2 *Center vertical cross section.*

of the these numbers.) The U*A for the entire product is divided by the exterior frame dimensions (without the nailing flange) to produce the total product U-factor.

CONCLUSIONS

Table 2 summarizes available simulated and tested U-factors for these two products at ASHRAE winter conditions (no solar radiation, 21°C and 8.3 W/m^2 °C interior, and −17.8°C and 29 W/m^2°C exterior). Simulated data using THERM 1.02 produces a result based on simply extrapolating existing NFRC and CSA procedures. Data from THERM 2.0 make use of the radiation view factor improvement. MoWiTT data are based on field testing under a range of ambient temperature conditions and are given at a film coefficient approximately equal to ASHRAE winter conditions (Klems 1997). Other data (FRAME/VISION and hot box tests) are taken from Carpenter and Elmahdy (1994).

It is surprising that the FRAME/VISION simulation data and the THERM 1.02 results for GHWindow #1 are as far off from each other as they are (10%). More controlled "round-robins" (Baker 1996) have shown these two programs to agree with each other to within a few percent. Without comparing the specifics of each simulation, it is impossible to speculate on these differences. These two simulation numbers are consistent with the hotbox test information after it was recomputed to include a "standard" window interior film coefficient (8.3 W/m^2°C).

However, the use of a standard planar window interior film coefficient for the reporting of projecting window U-factors is unrealistic since projecting products will never see such film coefficients. More realistic greenhouse window U-factors can be determined through the use of simulation programs that include element-to-element radiation view factor algorithms, as shown by the comparison of the THERM 2.0 data with the as-tested hotbox data and the MoWiTT data.

As previously mentioned, the THERM 2.0 data assume a constant convective (but variable radiative) film coefficient. Based on research in progress (Griffith et al. 1997), we expect the use of variable convective film coefficients will further

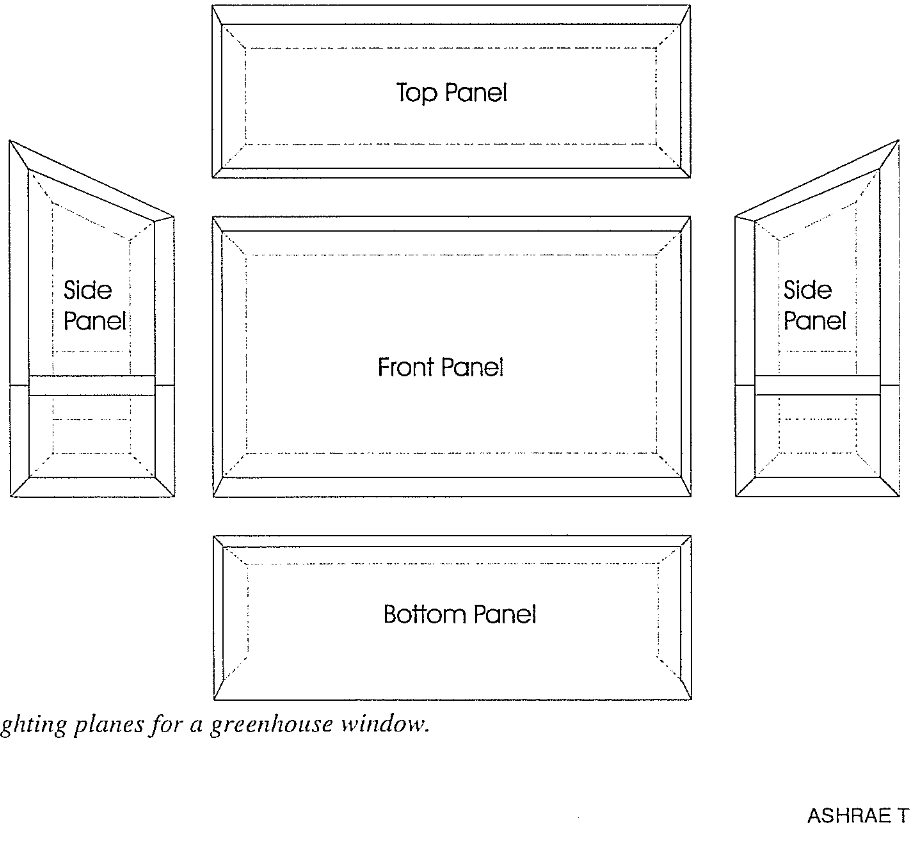


Figure 3 *Area weighting planes for a greenhouse window.*

reduce the simulated U-factors for such products. This would tend to bring the simulated numbers closer to the hot box data and MoWiTT Field Test data.

The differences between the THERM 1.02 and the THERM 2.0 cases for GHWindow#2 (14%) are less than for GHWindow#1 (24%), as expected, since this window utilizes more insulating frame and center-of-glass components. In this case, the impact of the interior film coefficient is not as great.

TABLE 2
Simulated and Tested U-Factors (W/m^2°C) for Projecting Fenestration Products

	GHWindow #1	GHWindow #2
Hot Box Test Data[a] with Standard Planar Window Interior Film Coefficient	9.91	N/A
Hotbox Test Data[a] as Tested	7.65	N/A
FRAME/VISION Simulation Data[a]	11.15	N/A
THERM 1.02 Simulation Data	10.11	4.32[b]
THERM 2.0 Simulation Data	7.95	3.75[b]
MoWiTT Data[c]	6.09 ±0.13	3.30 ±0.22

[a] Carpenter and Elmahdy 1994.
[b] Preliminary.
[c] MoWiTT test data uncertainty is experimental data uncertainty in measurements of total flux only. Estimating the additional uncertainties associated with measurements quoted for specific film coefficients is the subject of future research.

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REFERENCES

AR. 1996. *CFD2000: Finite element method analysis code.* Adaptive Research, Santa Monica, Calif.

Arasteh, D., F.A. Beck, N.I. Stone, W.C. duPont, R.C. Mathis, and M.J. Koenig. 1994. Phase I results of the NFRC U-value procedure validation project. *ASHRAE Transactions* 100(1): 1724-1734.

Arasteh, D. 1997. THERM 2.0—Internal Beta Version. Lawrence Berkeley National Laboratory, Windows and Daylighting Group.

Baker, J. 1996. Letter dated November 5, 1996, to NFRC Software Approval Task Group.

Carpenter, S.C., and A.H. Elmahdy. 1994. Thermal performance of complex fenestration systems. *ASHRAE Transactions* 100(2): 1179-1186.

CSA. 1993. *A440.2-93, Energy performance of windows and sliding glass doors.* Rexdale, Ont., Canada: Canadian Standards Association.

FDI. 1996. *FIDAP 7.6—User's and reference manual.* Evanston, Ill.: Fluid Dynamics International.

Finlayson, E.U, D. Arasteh, C. Huizenga, D. Curcija, M. Beall, and R. Mitchell. 1996. THERM 1.0., LBL-37371 Rev. Lawrence Berkeley National Laboratory, Berkeley, Calif.

FC. 1996. *FLUENT: Finite volume method analysis code.* Fluent Corp., Lebanon, NH.

Griffith, B.T., D. Curcija, D. Türler, and D. Arasteh. 1997. Improving computer simulations of heat transfer for projecting products using radiation view-factor models. *ASHRAE Transactions* 104(1).

Hottel, H.C., and A.F. Sarofim. 1967. *Radiative transfer.* New York: McGraw-Hill.

Klems, J.H. 1997. Greenhouse window U-factors under field conditions. *ASHRAE Transactions* 104(1).

NFRC. 1991. *NFRC 100-91, Procedure for determining fenestration product thermal properties (currently limited to U-values).* Silver Spring, Md.: National Fenestration Rating Council.

Shapiro, A.B. 1983. FACET—A radiation view factor computer code for axisymetric, @D Planar, and three-dimensional geometries with shadowing. Lawrence Livermore National Laboratory, Rept. UCID-19887.

Shapiro, A.B. 1986. TOPAZ2D—A two-dimensional finite element code for heat transfer analysis, electrostatic, and magnetostatic problems. Lawrence Livermore National Laboratory, Rept. UCID-20824, July.

Sparrow, E.M., and R.D. Cess. 1978. *Radiation heat transfer.* New York.: McGraw-Hill.

DISCUSSION

Ross McCluney, Principal Research Scientist, Research Institute: Florida Solar Energy Center, Cocoa, Fla.: Have the simulations accounted for possible "stratification" or "celling" of the air mass inside the projected window, i.e., increased residence times of this air mass, and hence, (winter) cooling or (summer) heating of it below or above the ambient room temperature? These alterations of the air temperature will directly affect the magnitude of the heat transfer, if they do indeed happen.

Dariush Arasteh: No they have not. The improvements to the modeling process focused on improving radiative heat transfer effects. However, the model used can use variable convective film coefficients to model this effect. Unfortunately no one currently has information on what these variable film coefficients should be.

Roger Henry, CANMET, Ottawa, Canada: This subject was introduced as important for rating products. The work described may be helpful to compare similar fenestration, but assumptions may limit effective comparison between projecting and planar windows.

Dariush Arasteh: The work was performed to allow a more reasonable comparison between projecting and planar products. Until this work, projecting products were penalized by the use of planar radiative film coefficients.

Michael Glover, Principal, Bowmead Technology Ltd., Ottawa, Ontario: Was the impact of curtains and other "real life" window attachments taken into account when developing the guidelines for modeling projecting fenestration products?

Dariush Arasteh: No, the effects of shading systems were not considered.