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WINDOW (GLAZING AND FRAME) HEAT TRANSFER MODELING

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ABSTRACT

Seven windows were simulated using the VISION Glazing System Analysis Program and the FRAME Finite Difference Program. This work was part of a joint research effort involving research groups from Canada and the United States. Three research groups modeled the windows. The results were in agreement and agreed with laboratory test results for the windows.

The sensitivity of the simulations to the decisions made by the modeler was studied. A number of the model parameters were varied over a wide range. The results of this sensitivity analysis are presented and indicate that the model parameters need to be accurate in areas of high heat flux. A sensitivity analysis of the parameters in this region is a necessary part of the modeling procedure.

The proposed introduction of energy-labeling programs for windows will require manufacturers to determine the thermal performance of their products. In order to minimize the costs involved in testing the numerous window products and all their variations for such a window-labeling program, the good agreement of the modeling results and agreement with the test results indicate that testing a few products in a base case configuration and obtaining the thermal performance for the other variations of construction by detailed modeling could be a feasible approach.

INTRODUCTION

The heat flow in window systems involves the combined effect of convection, conduction, and radiation. The window system consists of one or more glazings, held in a frame. The frame cross section may be a very complex construction. In windows with two or more glazings, the glazings are separated by an edge spacer assembly. Many glass types, coatings, and fill gases are used in window systems. These variables make window heat flow modeling a complex process.

There is a movement toward the development of an energy-labeling program for windows in both Canada and the United States. With the introduction of window labeling, manufacturers will be required to establish the thermal characteristics of their products. The thermal characteristics of window systems can be determined by laboratory testing and computer simulation. Testing of all window types is a costly alternative for manufacturers. It would, perhaps, be desirable to establish the thermal perfor-

mance of one combination of glass, spacer, frame, gap, and fill gas by an appropriate test and then predict the effects of variations in a number of these parameters by an appropriate modeling procedure. What is currently needed is agreement on a test procedure, as well as a validation of the modeling procedure. This study looks at computer modeling of heat flow through window systems. The modeling was done using the VISION Glazing System Analysis Program (Wright and Sullivan 1987; Baker et al. 1988) and the FRAME Finite Difference Program (Ener
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modeal 1988). Part of this study involves the modeling of seven window systems as a contribution to a larger research project in window heat transfer (Elmady 1990). This study also looks at the sensitivity of the computer modeling to input parameters.

WINDOW MODELING

The research project in window heat transfer is a joint effort between researchers in Canada and in the United States. The first phase of the project involves testing and simulation of seven window systems. These windows had previously been tested in the Mobile Window Thermal Test Facility (MoWTT) (Klemens et al. 1990, 1984, 1982). The windows have since been tested in two other laboratories and modeled by a number of different researchers. This study presents the computer modeling done with the VISION and FRAME programs, on which the authors contributed to the research project.

A summary of the windows used in this study is listed in Table 1. The details of the frame cross sections are given in a paper by Elmady (1990). The seven windows cover a range of window types from a single glazing with an

<table>
<thead>
<tr>
<th>Window Number</th>
<th>Glazings</th>
<th>Frame Type</th>
<th>Major Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>F015</td>
<td>2</td>
<td>Aluminum</td>
<td>Thermally Broken Frame</td>
</tr>
<tr>
<td>F020</td>
<td>2</td>
<td>Wood</td>
<td></td>
</tr>
<tr>
<td>F022</td>
<td>2</td>
<td>Aluminum</td>
<td>Thermally Broken Frame</td>
</tr>
<tr>
<td>F024</td>
<td>2</td>
<td>Aluminum</td>
<td></td>
</tr>
<tr>
<td>F025</td>
<td>1</td>
<td>Aluminum</td>
<td></td>
</tr>
<tr>
<td>F062</td>
<td>2</td>
<td>Aluminum</td>
<td>Thermally Broken Frame, One Low-e Coating</td>
</tr>
<tr>
<td>Krypton</td>
<td>3</td>
<td>Wood</td>
<td>Two Low-e Coatings, Ar-Kr Fill Gas</td>
</tr>
</tbody>
</table>

*For more details on the windows see Elmady (1990).

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HEAT FLOW PLOT
Heat Flow—Total: 20.6 (W/m²·°C) Step: 0.82

Figure 1  Aluminum frame (F015) heat flow plot

aluminum frame to a triple-glazed unit with low-emissivity (low-E) coatings, gas fill, and a wood frame.

Heat flow through the window system was subdivided into three components: center-glass, edge-glass, and frame heat transfer. The edge-glass area was defined as the area around the perimeter of the glazing 2.5 in. (63.5 mm) from the sight line of the window (Peterson 1987). The center-glass area is the remainder of the glazing area. The U-values for each of these components were determined based on a projected area of the components on a plane parallel to the plane of the window.

The center-glass heat transfer was calculated using the VISION program. VISION uses a one-dimensional heat transfer analysis to model the heat flow through the center-glass region. The FRAME program was used to calculate edge-glass and frame heat transfer. FRAME uses a two-dimensional finite difference heat transfer analysis.

The VISION program gives the center-glass heat flux and U-values directly. The edge-glass and frame heat flux must be extracted from the FRAME results. The split between edge-glass and frame heat flow is determined graphically from a heat flow plot generated by FRAME. Figure 1 shows a heat flow plot with 26 flow lines. Equal amounts of heat transfer take place between each pair of flow lines, each of which forms a flow path. In this case there are 25 flow paths. Fifteen of the paths flow through the edge-glass and 10 through the frame. The FRAME heat flow is then split 60% through the edge-glass and 40% through the frame. The edge-glass and frame U-values are then calculated based on their projected areas. The center-glass, edge-glass, and frame heat flow results are used to calculate the overall window U-values based on the method outlined in the FRAME user manual (Enermodal 1988). The calculated U-values for the seven windows are included in Table 2.

The same set of windows was modeled independently by two other research groups. One of the research groups used the same two programs, namely VISION/FRAME, and the other used WINDOW 3.1 (LBL 1985, 1988) and ANSYS (DeSalvo 1987), a finite element program. The results from the three research groups, as presented in Elmahdy (1990), are in good agreement. The overall window U-value results were within 5% of the average of the simulations for each window. The simulation results also are in good agreement with the tested results from the National Research Council of Canada (Elmahdy 1990).

The consistency shown by the results from the three independent researchers with two different sets of programs, and their agreement with the tested results indicates that there can be a reasonable confidence in computer modeling of the thermal characteristics of window systems. In order to determine whether the simulation results are sensitive to the decisions made by the modeler in creating the simulation model, a number of simulations were made in which the values of the various input parameters were varied over reasonably broad ranges, as well as modifying other modeling details.

**MODELING SENSITIVITY**

The sensitivity of the computer programs to the modeling detail and the input parameters is an important issue. If the programs are sensitive to the modeler's decisions, computer modeling would not be acceptable for establishing the thermal characteristics of window systems. This analysis focused on the sensitivity of the FRAME program to the following parameters:

- Model detail
- Grid size
- Material conductivities
- Film coefficient

**Modeling Detail**

The FRAME program models the frame assembly as a series of rectangles. The current version of the program allows for 40 rectangular elements. A modified version of the program was developed for this research project, which allows for 55 elements. The 55-element version of the program is capable of modeling very complex window geometries.

### TABLE 2

<table>
<thead>
<tr>
<th>Window Number</th>
<th>Center-Glass (W/m²·°C)</th>
<th>Edge-Glass (W/m²·°C)</th>
<th>Frame (W/m²·°C)</th>
<th>Edge/Frame (W/m²·°C)</th>
<th>Overall (W/m²·°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F015</td>
<td>2.94</td>
<td>3.59</td>
<td>6.60</td>
<td>4.66</td>
<td>3.52</td>
</tr>
<tr>
<td>F020</td>
<td>2.94</td>
<td>3.44</td>
<td>2.47</td>
<td>2.91</td>
<td>2.93</td>
</tr>
<tr>
<td>F022</td>
<td>2.96</td>
<td>3.31</td>
<td>7.42</td>
<td>4.78</td>
<td>3.57</td>
</tr>
<tr>
<td>F024</td>
<td>2.96</td>
<td>3.17</td>
<td>8.35</td>
<td>5.02</td>
<td>3.65</td>
</tr>
<tr>
<td>F025</td>
<td>6.50</td>
<td>6.44</td>
<td>8.44</td>
<td>7.15</td>
<td>6.72</td>
</tr>
<tr>
<td>F026</td>
<td>2.41</td>
<td>3.09</td>
<td>7.32</td>
<td>4.60</td>
<td>3.14</td>
</tr>
<tr>
<td>Krypton</td>
<td>0.95</td>
<td>1.23</td>
<td>2.81</td>
<td>2.13</td>
<td>1.49</td>
</tr>
</tbody>
</table>
Two of the windows were analyzed to study the effect of the modeling detail on the program results. The first was the F020 wood frame window, and the second was the F015 aluminum frame window. The wood frame window was originally modeled based on drawings that did not show the complete detail of the window. It was then modeled in steps of increasing detail based on better drawings. The aluminum frame window was originally modeled in great detail, then some of the detail was removed in steps to simplify the analysis.

The wood frame window was originally modeled based on the drawing in Figure 2a. Later, the more detailed drawing of Figure 2b was available. The new drawing revealed two important features of the window frame that had not been included in the model. First, two PVC blocks in the wood frame were missing, and second, sealant isolating the glazing from the wood frame was also missing. Three more simulations of the wood frame window were made, two including each of the features independently and a third that included the combined effect of both the additional features.

The four models of the F020 frame showed virtually no change in the overall window U-value. The heat flow plot for the wood frame window in Figure 3 indicates that the area of highest high flux is through the glazing spacer. The addition of the sealant to isolate the glazing would be expected to make a difference in the heat flow, but since the conductivity of the sealant (0.21 W/mK) was on the same order as that of wood (0.14 W/mK), it actually made a negligible difference. The addition of the PVC and air cavities in the frame was in an area of lower heat flux, so they would be expected to make little difference to the heat flow. Also, since the conductivity of the PVC had the same value as the wood, it made no difference to the heat flow.

The aluminum frame window was initially modeled to include a great deal of the aluminum frame extrusion detail. Three more models of the aluminum frame window were developed. The three models each removed one piece of detail of the aluminum extrusion. Figure 4 shows a cross section of the window for each of the models. Figure 4a shows the detailed model of the window. Figure 4b shows the model with the two internal aluminum fins removed.

<table>
<thead>
<tr>
<th>FRAME RUN</th>
<th>Frame/Edge Heat Flow (W/m)</th>
<th>Overall U-value (W/m²·K)</th>
<th>Comments:</th>
</tr>
</thead>
<tbody>
<tr>
<td>F015</td>
<td>20.59</td>
<td>3.52</td>
<td>Original Case</td>
</tr>
<tr>
<td>F015B</td>
<td>20.58</td>
<td>3.52</td>
<td>Aluminum Fins Removed</td>
</tr>
<tr>
<td>F015E</td>
<td>20.12</td>
<td>3.48</td>
<td>Aluminum Flange Removed</td>
</tr>
<tr>
<td>F015C</td>
<td>20.39</td>
<td>3.50</td>
<td>Thermal Break Grip Removed</td>
</tr>
</tbody>
</table>
from the extrusion. Figure 4c shows the model with an aluminum mounting flange removed. Figure 4d shows the model with the grip into the thermal break removed. Table 3 gives the FRAME heat flow and overall window U-value results for these models.

The internal aluminum fins are in an area of low heat flux, which can be seen in the heat flow plot in Figure 1, and removing them made no difference to the heat flow. The mounting flange is in an area of slightly higher heat flux: removing the flange decreased the frame and edge-glass heat flow by about 1% and the overall window U-value by 0.6%. The thermal break is in an area of high heat flux: removing the grip into the thermal break decreased the frame and edge-glass heat flow by 2.2% and the overall U-value by 1.1%.

The simulation results of the above windows show that a model needs to be detailed in areas of high heat flux to accurately analyze the heat flow, but that simplification can be introduced into the model in areas of low heat flux to reduce the complexity of the model.

**Grid Size**

The dependence of a numerical solution on the grid size used is an important issue. The grid must be fine enough that the solution is independent of the grid, but no finer than necessary in order to keep the computer run time as low as possible.

FRAME simulations of the same window were made with progressively decreasing grid sizes. The grid size was decreased from a coarse grid with no extra grid lines to a very fine grid with many extra grid lines. Four runs were required until the results showed to be grid independent. The results of these runs are included in Table 4. The third and fourth runs show no change in the FRAME heat flow; thus, the third run is grid independent. The first and second runs are 5% and 3% lower, respectively, than the final run.
TABLE 4
Grid Dependence Results

<table>
<thead>
<tr>
<th>FRAME RUN</th>
<th>Frame/Edge Heat Flow (W/m)</th>
<th>Overall U-value (W/m²°C)</th>
<th>Comments:</th>
</tr>
</thead>
<tbody>
<tr>
<td>F015L</td>
<td>19.60</td>
<td>3.43</td>
<td>Coarse grid</td>
</tr>
<tr>
<td>F015M</td>
<td>20.07</td>
<td>3.47</td>
<td></td>
</tr>
<tr>
<td>F015N</td>
<td>20.59</td>
<td>3.52</td>
<td></td>
</tr>
<tr>
<td>F015O</td>
<td>20.65</td>
<td>3.52</td>
<td>Finest grid</td>
</tr>
</tbody>
</table>

These results indicate that the program may or may not achieve a grid-independent solution. It is the modeler's responsibility to verify that the solution is grid independent, and this may require a number of runs on a single window.

Computer Run Time
Computational time is influenced by both the model detail and the grid size. High model detail and small grid size both increase the run time. All seven windows were simulated on three computer systems, all of which had a math coprocessor. The results for the F015 window were as follows: an 8088 system ran at 4.7 MHz and took 62 minutes, a 286 system ran at 10 MHz and took 24 minutes, and a 386 system ran at 20 MHz and took 8 minutes.

Material Conductivities
The sensitivity of the FRAME program to the conductivities of the rectangles that form the window model is another important issue. Often the conductivities of certain elements in a window are uncertain. An example is the F015 aluminum frame window, in which there was a frame spacer between the glazing and the frame with an unknown conductivity. Also, the conductivity of the thermal break material was specified as 0.14 W/m-K, and it was difficult to determine who had specified this value. The F015 window was used to study the sensitivity of the program to the material conductivities.

The F015 window was modeled with variation in the conductivities of the aluminum, the foam spacer, and the thermal break material. The nominal value of the conductivity of the aluminum would be 160 W/m-K, a number representative of an aluminum alloy. Simulations were performed at this value, as well as values 30% higher and 30% lower. The conductivity of the foam spacer was unknown for this window. A value of 0.24 W/m-K was taken as an average value for a number of types of foam listed in a materials properties table of the CRC handbook (CRC 1978-79). The window was modeled with a foam conductivity of 0.24 W/m-K, as well as at values 50% higher and lower. The conductivity of the thermal break material was specified at 0.14 W/m-K. The window was also modeled with the thermal break conductivity of 0.14 W/m-K and at values 50% higher and lower. Finally, the window was simulated with all three of the above conductivities set at the higher value and with all three set at the lower value. The results of these runs are shown in Table 5.

The simulations for both the foam spacer and the thermal break material with the conductivities set to the higher and lower values gave frame and edge-glass heat flow results 3% higher and 2% lower than those at the suggested conductivity values. The models with the aluminum conductivity set to the higher and lower values gave frame and edge-glass heat flow results 0.8% higher and 0.4% lower than that for the 160 W/m-K conductivity. The model with all three conductivities set to the higher value gave frame and edge-glass heat flow results 7% higher than that with the values set to the suggested conductivities. The simulation with all the conductivities set to the lower values yielded results 5% lower than that with the conductivities set at suggested values. When the two extreme cases were combined with the center-glass heat flow, they resulted in U-values 3.5% higher and 2.5% lower than that for the overall window U-values with the conductivities set to the suggested values.

The conductivities of the thermal break material and the foam spacer had a significant effect on the heat flow results because both of these materials are in areas of high heat flux. The aluminum conductivity had less of an effect on the heat flow results. The aluminum has such a high conductivity relative to the other elements in the window it is virtually isothermal. Therefore, changing the conductivity will not affect the heat flow significantly. The extreme case results show that for this window, with the conductivities set to extremes, the overall window U-values vary by less than 3.5% in both directions. The results indicate that the window heat transfer model is relatively insensitive to the material conductivities.

Film Coefficient
The question of what is the most appropriate outside film coefficient with which to model windows has been an ongoing issue for many years. The answer to this question is not the focus of this work, but the sensitivity of the overall U-value to the outside film coefficient is. The inside film coefficient, including both convection and radiation, was assumed constant at 8.3 W/m²°C, a value representative of still air.

The outside film coefficient for ASHRAE winter design conditions is specified at a wind speed of 15 mph. This is an extreme condition that rarely occurs at the window surface in actual applications. Field measurements have shown that actual wind speeds at the window surface for a residential type of application are on the order of 4 and 5 mph. The outside film coefficients used for this study represented the extremes of 15 mph wind speed and still air, as well as an intermediate wind speed of 5 mph. The coefficients used included both convection and radiation.

Three windows representing low, average, and high thermal performance systems were each modeled with an outside film coefficient of 30 W/m²K (15 mph wind speed), 15.4 W/m²K (5 mph wind speed), and 8.3 W/m²K (still air). These coefficients were taken from ASHRAE (1969). The
three windows modeled were single-glazed (F025), double-glazed (F015), and triple-glazed (KRY) systems.

The results for these windows have been included in Table 6 and are also presented in Figure 5. The results show that the outside film coefficient has a dominant effect on single-glazed windows and a moderate effect on standard double-glazed windows and must be properly evaluated when modeling these window types. When modeling window systems with a higher thermal resistance, the choice of outside film coefficient has little effect on the results.

**CONCLUSIONS**

This paper describes a detailed set of window simulations. A comparison of these results with the results from other researchers showed good agreement, as well as agreement with tested results.

Modeling the details of very complex window systems is possible, but with experience the simulation can be simplified to reduce the complexity of the model. The modeler must be careful to achieve grid independence with each simulation. The areas of the window systems where the modeling detail, the grid size, and the input parameters are important are the areas where a high heat flux occurs.

Window simulation can be done on microcomputers; there is no need for a mainframe. Patient researchers can get results with a slow machine. With a faster machine, determining the sensitivity to various parameters is not difficult and should always be part of the modeling procedure.

The outside film coefficient only has a major effect on single-glazed systems and a slight effect on conventional double-glazed systems. For systems of even better thermal performance, the effect is negligible.

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**REFERENCES**


