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AN-92-6-1

USING INFRARED THERMOGRAPHY FOR THE STUDY OF HEAT TRANSFER THROUGH BUILDING ENVELOPE COMPONENTS

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ABSTRACT

Heat transfer through building envelope components is typically characterized by one number, the conductance. Such a characterization is best suited for homogeneous samples since it does not quantify or illustrate spatial variations within a sample. However, the growing use of advanced wall and window insulations with existing framing materials has increased the importance of understanding spatial heat transfer effects within building envelope components. An infrared thermography laboratory has been established to provide detailed quantitative and qualitative information on the spatial heat transfer effects of building envelope materials. The use of this facility for more effective product development and more accurate product characterization is discussed.

INTRODUCTION

Heat transfer through building envelope components is typically measured as being one-dimensional. However, the use of existing framing and structural materials with advanced window and wall subcomponents (i.e., highly insulating glazing systems, super-insulations) significantly increases the effects of existing thermal bridges and may create new ones (ORNL 1988; Arasteh and Selkowitz 1989). Unfortunately, conventional hot-box or hot-plate thermal tests only quantify a building envelope component's thermal performance with one number, the conductance. This number is the spatially averaged heat flux (per unit area, per unit temperature difference) for the measured sample; for nonhomogeneous samples, it is difficult to back out the relative performance of subcomponents.

Recent efforts to understand two-dimensional heat transfer effects in window and wall systems have focused on the use of an infrared thermography system to supply detailed quantitative and qualitative spatially dependent information. The primary components of an infrared thermography laboratory include an infrared scanner, hardware/software for post-processing, and a cold chamber. Figure 1 illustrates the physical setup of the infrared thermography laboratory. A specimen is placed in the opening of a cold chamber. One side of the specimen is exposed to the interior of the cold chamber, while the other side is exposed to an ambient temperature of approximately 70°F (21°C). The cold side of the chamber is set at between −20 and 32°F (−30 and 0°C), depending on the specimen under analysis. A temperature image or thermogram of the specimen's surface (typically the warm side) is then captured using an infrared scanner. The image can be post-processed using associated com-

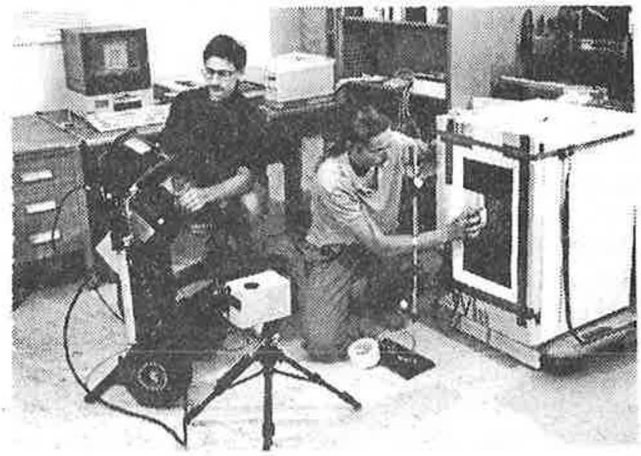

Figure 1 *Photograph of the infrared thermography laboratory (August 1990). An infrared scanner (on the tripod) records the warm-side temperature distribution of a sample placed between the interior of the cold box (on right) and ambient. The infrared scanner's controls are on the vertical cart. The closer the sample's, or part of the sample's, warm-side temperature is to ambient, the better an insulator it is. A computer (on the table at the back), attached to the infrared detector's control hardware, allows for quick and versatile post-processing.*

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puter hardware and software. Heat transfer rates can be correlated with surface temperatures; the better a material's insulating qualities, the closer its surface temperature will be to the surrounding air temperature. A sample post-processed thermogram is shown in Figure 2.

The infrared scanner or imaging radiometer infers spatial temperature data by measuring the relative amounts of infrared radiation between 8 and 12 microns emitted by a surface. The unit is internally calibrated to produce temperature data as a function of the surface emittance and background temperature. Multiple images are sampled and averaged by the computer processor to increase resolution. Relative temperatures for surfaces with the same orientation and equal emittances for a given thermogram are accurate to about 0.2°F (0.1°C). Absolute temperatures are not as accurate. The system's specified absolute temperature accuracy is 3.6°F (2.0°C). Additional uncertainty can arise due to emissivity and background temperature uncertainties. However, we have found that our thermogram data match thermistor data to within 1.5°F (0.8°C). The thermistor network's specified accuracy is 0.3°F (0.15°C). Because of the limitations in absolute temperature measurements, relative temperature measurements are the most reliable. Temperature-controlled blackbodies and extended area surfaces of known emissivity, employed within the infrared image, can be used to facilitate surface temperature comparison between different thermographic images with an accuracy approaching that of the relative temperature measurements. This method is a subject of ongoing research.

The infrared thermography laboratory is being used for three primary purposes:

1. to validate finite-element and finite-difference modeling (FEM/FD);
2. to aid in the development of highly insulating glazings, glazing edges, window frames, wall insulations, and wall-framing designs and materials; and
3. to explore the possibility of using such a laboratory for developing a thermography-based condensation resistance test (of particular interest to the window industry).

USING INFRARED THERMOGRAPHY TO VALIDATE TWO-DIMENSIONAL HEAT TRANSFER MODELING

Finite-element method and finite-difference computer modeling programs (FEM/FD) have recently begun to be used within the window and building envelope industries to evaluate two-dimensional heat transfer effects (ORNL 1988; Arasteh 1989; EE 1990). Many of these tools have been validated for other applications (aerospace, automotive); our purpose is to provide information that will validate these tools for use by building component manufacturers.

Both FEM/FD and infrared thermography provide surface temperature profiles of the object under study. Window surface temperatures calculated by FEM/FD programs (which are directly linked to heat transfer rates) can be validated with infrared thermography. U-values currently cannot be calculated directly from thermographic data, as the exterior and interior film coefficients are hard to quantify precisely. In addition, the thermographic scanning currently cannot take into account heat transfer in the

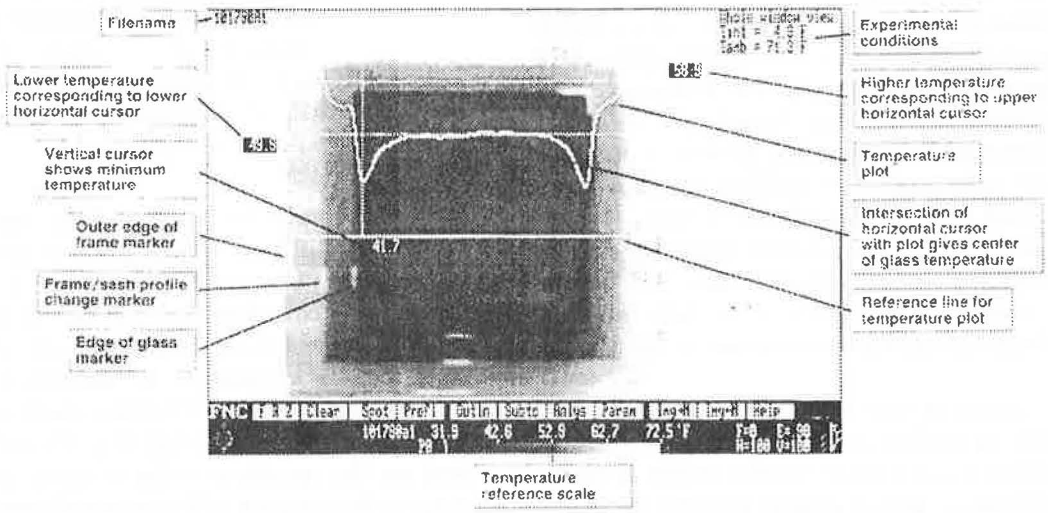

Figure 2 *Sample post-processed thermogram of the warm side of a wood-framed, double-glazed window. The better insulating frame (light) is warmer than the glass (dark). The outer edge of the frame, the glass/frame boundary, and profile changes along the frame are delineated by "hot" markers. These markers show up as light rectangles. Relative temperatures along a reference line (solid white line) are identified by the temperature plot above it. Absolute temperatures on the plot are identified by dotted cursor lines.*

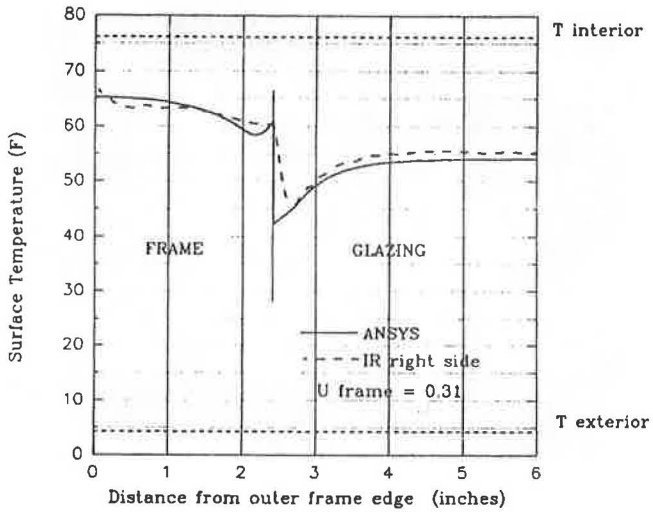

Figure 3 *Warm-side surface temperatures for the left side of the frame and edge of a solid wood-framed double-glazed picture computed using an FEM computer program and measured at the infrared thermography laboratory (IR). The window was subjected to a temperature difference of approximately 70°F. The cold-side wind speed is estimated at 7 mph parallel to the glazing surface (h_0 = 2.0 Btu/h·ft^2·°F). The only significant difference between computed and measured temperatures is seen at the wood/glass interface and is most likely due to the use of convective film coefficients in the model, which do not adequately represent edge conditions; unfortunately, more appropriate film coefficients do not exist. The frame U-value is calculated to be 0.31 Btu/h·ft^2·°F using the FEM computer program.*

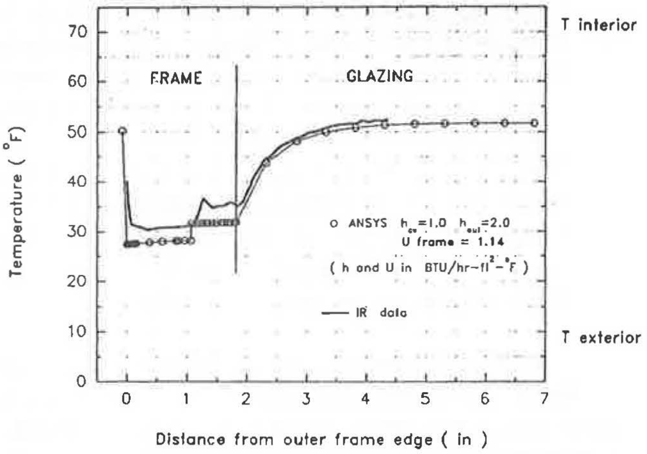

Figure 4 *Warm-side surface temperatures for the fixed side of the frame and edge of an aluminum double-glazed sliding window computed using the FEM computer program and measured at the infrared thermography laboratory (IR). The window was subjected to a temperature difference of approximately 70°F. The cold-side wind speed on all exposed surface areas is estimated at 7 mph parallel to the glazing surface (h_0 = 2.0 Btu/h·ft^2·°F); still air is assumed within the sliding track on the cold side (h_0 = 1.0 Btu/h·ft^2·°F). Differences between computed and measured temperatures of 4 to 5°F are consistently seen along the frame area; these are due to the uncertainties in estimating the film coefficients over the frame and the importance of the film coefficients in determining heat transfer in an aluminum frame; unfortunately, more appropriate film coefficients do not exist.*

third dimension (i.e., windows with deep sills). Future research will examine possible techniques to calculate U-values directly from infrared temperature data.

Our efforts have been directed at comparing temperature profiles from four windows generated from an FEM program (DeSalvo and Gorman 1989) with those from infrared thermography. Figure 3, which shows the warm-side temperature gradient from the frame and edge-of-glass of a conventional double-glazed wood window, is an example of such a comparison. Figure 4, which shows the warm-side temperature gradient from the frame and edge-of-glass of a typical aluminum-framed window, is another example. The agreements and differences between these and other windows studied point to the following conclusions:

1. Modeling of center-of-glass areas is accurate provided that the interior and exterior film coefficients, coating emissivities, and gas fill percentages are known. Note that conventional hot box testing does not need to know the coating emissivities or the type of gas fill.
2. Modeling of solid materials with known conductivities can be very accurate, as shown by the good agreement between modeling and testing for the wood-framed window.
3. Differences between modeling and testing can be seen where surface or between-glass film coefficients deviate significantly from average values assumed for the whole window. Figure 3 shows the difference in modeled and measured temperatures at the frame/glass interface with a wood frame. This difference is presumably due to a change in the interior film coefficient, which we cannot quantify. Another example of this phenomenon would be the slight disagreement we have seen between the top and bottom surface temperatures (due to convective looping effects), which are not predicted in the current two-dimensional model.
4. The greatest differences between modeling and testing arise in cases where the surface film coefficients are not well known and where they are the primary resistances to heat transfer (i.e., along the frame and

sash of an aluminum-framed window as in Figure 4).

5. Differences between modeling and testing arise in the case of larger hollow frames and sashes where convective and radiative effects are not well known and/or very difficult to model.
6. Differences between modeling and testing also arise where rounded or triangular framing elements have been squared off to simplify modeling. The magnitude of the difference depends on the simplifications made. In general, these are small differences.

Overall, the agreement between modeling and testing for the four windows examined to date is very good. In some cases, at a few locations (see Figure 4), modeled temperatures differ from measured temperatures over a discernible distance by up to 7°F (over a total temperature difference of 70°F). However, in all cases, the trends shown by modeling are the same as those shown by testing. The differences are almost always due to the approximations input into the FEM/FD program by the user to describe localized heat transfer conditions (i.e., film coefficients over complex frame/edge geometries, effective conductivities for hollow cavities with complex geometries). Future work will focus on using the infrared camera system to develop more accurate heat transfer correlations and improving the capabilities of these simulations to model these complex heat transfer mechanisms directly.

USING INFRARED THERMOGRAPHY FOR THE DEVELOPMENT OF ADVANCED INSULATING PRODUCTS

Super-insulating glazings, window frames, wall insulations, and structural systems are the subjects of current research. The successful development of such products is often an iterative process consisting of product design, testing, analysis, and redesign. Infrared thermography is a quick and efficient means to accomplish the testing and analysis phases of product development. The following two examples illustrate this.

Figure 5 is a thermogram of a sample of a new insulating material (argon-gas-filled panel) under development (Arasteh et al. 1990) within a mask of recognized resistance (CFC-blown foam). The thermogram shows that the argon-gas-filled panel's warm-side temperature is approximately 0.7°F warmer than that of the reference CFC-blown foam. From this thermogram, we know that the argon-gas-filled panel is definitely a better insulator than the CFC-blown foam; its R-value is estimated at R 8 h·ft^2·°F/Btu vs. the literature value of R 7.2 h·ft^2·°F/Btu for CFC-blown foam. Once this sample was prepared for testing and the cold chamber was allowed to come to equilibrium, the generation of this image was instantaneous. For the purposes of product development, where visual and relative performance data are valuable, infrared thermography can be extremely useful. Conventional hot-box or hot-plate measurements would have involved measuring the heat flow through the sample, which is a much more time-consuming process often requiring day-long test sequences.

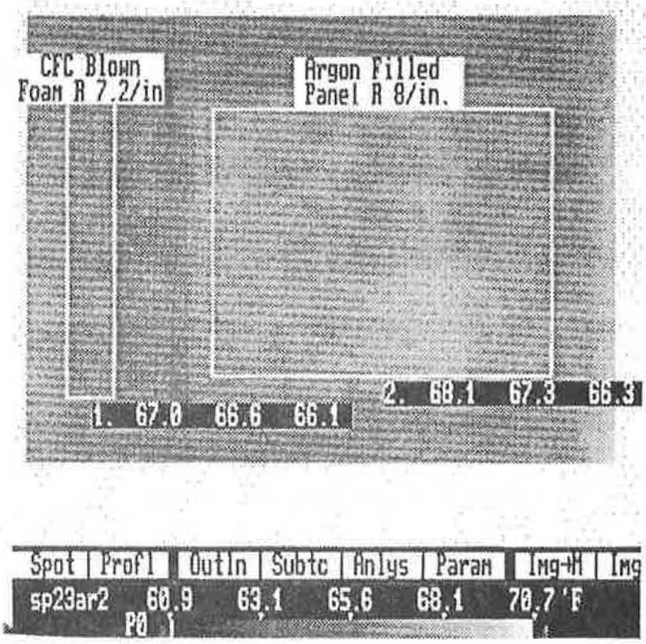

Figure 5 *Infrared photo of the warm side of a 1-in.-thick sample of CFC-blown foam with an insert containing a 1-in.-thick sample of argon-filled panels. The back of this panel faces a cold box at approximately −1.5°F; the ambient temperature is approximately 71.6°F. The warm-side temperature of the CFC-blown foam averages 66.6°F (max 67.0°F, min 66.1°F) and the warm side of the insulation averages 67.3°F (max 68.1°F, min 66.3°F). In this figure, warmer areas are lighter and colder areas are darker. A temperature grey-scale is shown at the bottom of the figure. Since surface temperatures correspond to heat loss rates, a higher warm-side temperature implies a lower heat loss rate. The R-value of the panels shown here is estimated at R8/in.; that of the CFC-blown foam is R7.2/in. Refer to Figure 2 for identification of thermogram features.*

In another experiment, an advanced R 8 h·ft^2·°F/Btu super-glazing with a minimally insulating edge was placed in a relatively well-insulated frame. As shown in the thermogram of Figure 6, the glazing's solid edge is a significant thermal bridge and the frame is not as good an insulator as the glazing. Figure 7 shows the same glazing and edge in an improved insulating frame. The difference in frame temperatures indicates the effectiveness of the new frame design. The expected difference between the overall conductance of these two products is approxi-

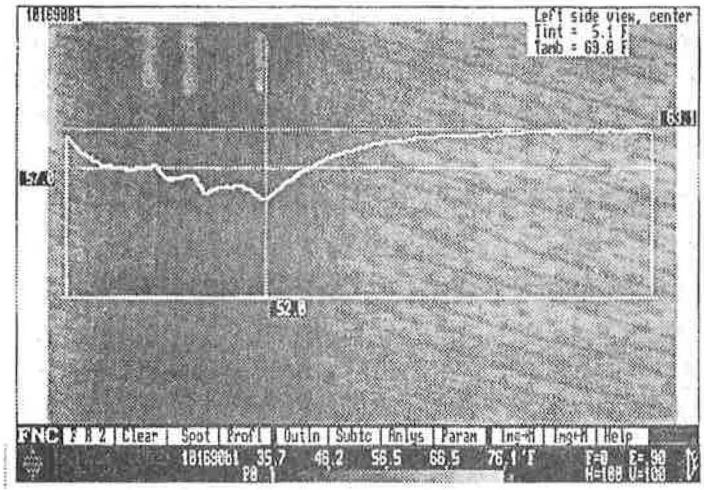

Figure 6 *Warm-side surface temperatures for the left side of a vinyl casement window measured at the infrared thermography laboratory (IR). The window was subjected to a temperature difference of approximately 70°F. Since temperatures correlate to resistances, we conclude that the frame area (on the left of the thermogram) is not as good an insulator as the center-of-glass area (right side). Refer to Figure 2 for identification of thermogram features.*

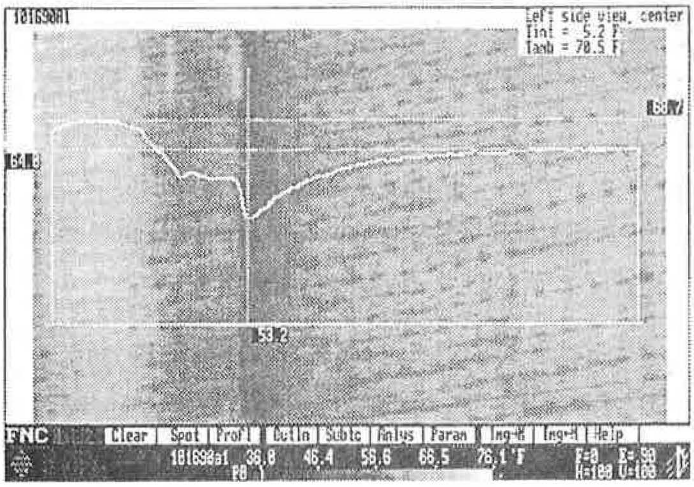

Figure 7 *Warm-side surface temperatures for the left side of a foam-filled vinyl casement window (identical to the window of Figure 6 in all ways except for the foam filling and the use of insulating clip on strips). The window was subjected to a temperature difference of approximately 70°F. Some parts of the frame are warmer than the center-of-glass, indicating that these parts of the frame are a better insulator than the center-of-glass. Comparing this figure with Figure 6 shows that foam filling can significantly reduce frame heat transfer. The spacer is still a thermal short circuit. Refer to Figure 2 for identification of thermogram features.*

mately the same as the expected uncertainty of many test laboratories; thus, conductance testing on the whole window would produce inconclusive results.

We are using this facility to test building and appliance insulations as well as advanced window products under development. Thermograms of prototypes tested have already helped to guide product manufacturers toward developing better products. It should be noted here that thermograms can be output as color images, which give much more visual information than do the grey-scale images reproduced in this article.

CONDENSATION RESISTANCE

The formation of condensation on the interior of building envelopes (primarily windows) is one of the largest sources of occupant complaints in residential buildings in moderate and cold climates. Existing condensation resistance tests are based on the use of a limited number of thermistors or thermocouples strategically placed on a sample. The limitations of such tests include obtaining a limited number of temperature points and the interference of the thermistors and their lead wires with the thermal environment being studied; these limitations are easily overcome with infrared thermography. The development of an infrared-thermography-based test for condensation resistance is the subject of ongoing collaborative U.S. and Canadian research.

CONCLUSIONS

The emergence of compact and highly accurate infrared thermography systems coupled to powerful post-processing software and PC-based computer graphics has opened up new possibilities for the detailed analysis of building component products and for more effective development of advanced products. A building envelope infrared thermography laboratory with these capabilities has been established and is operating, and is being used to validate thermal analysis models, giving a basic understanding of complex heat flow phenomena and to assist industry in the development of new energy-efficient products.

ACKNOWLEDGMENTS

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Technologies, Building Systems and Materials Division, U.S. Department of Energy, under Contract No. DE-AC03-76SF00098. Additional support was provided by the Residential Technology Section of the Bonneville Power Administration of the U.S. Department of Energy under Contract No. DE-AI79-86BP63401.

The authors wish to thank Steve Selkowitz at Lawrence Berkeley Laboratory and Sam Taylor at the Department of Energy for their guidance and support of this research project.

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