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WINDOW 3.1: A COMPUTER TOOL FOR ANALYZING WINDOW THERMAL PERFORMANCE

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ABSTRACT

WINDOW 3.1 is a public-domain computer program developed by the Windows and Daylighting Group at Lawrence Berkeley Laboratory for analyzing heat transfer through window systems. The program uses an iterative technique to calculate the one-dimensional temperature profile across a user-defined window system. From this data, window system performance indices (e.g., U-value, shading coefficient) are calculated. WINDOW 3.1, a major update to WINDOW 2.0, incorporates several technical additions and many new user-friendly features, and provides a consistent and versatile means for heat transfer analysis as did WINDOW 2.0. WINDOW 3.1 can vary environmental conditions, window tilt, number of glazing layers, layer properties (thermal infrared, solar and visible optical properties, and thermal conductance), gap widths, composition of gap gas fill, and spacer and frame materials. This paper presents an overview of the computational methodology, describes the capabilities of the program, and discusses the applications of WINDOW 3.1 for standardizing window heat transfer calculations and in designing new insulating window systems.

1. INTRODUCTION

Window heat transfer is a combination of three modes of heat transfer: 1) conduction through glazing, frame elements, and air or other gas; 2) convection through air layers on the exterior and interior window surfaces and between glazing layers; and 3) radiative heat transfer between glazing layers or between glazing layers and interior or exterior spaces. These three modes of heat transfer are shown schematically in Figure 1.

Evolving window designs are reducing heat transfer but increasing the complexity of analysis and measurement. Low-emissivity coatings (which reduce radiative heat transfer) and low-conductivity gas fills (which replace the air between glazing layers to reduce conductive/conductive heat transfer) are designed into many state-of-the-art window products. A well-designed double-glazed window with low-emissivity coatings and a gas fill has a U-value of approximately 0.25 Btu/hr-ft², compared with a U-value of 0.5 Btu/hr-ft² for a standard double-glazed unit with an 0.5-inch air space. Furthermore, researchers and manufacturers are currently developing glazings with U-values as low as 0.1 Btu/hr-ft².

With these advances in window designs comes a need for accurate and consistent information about all aspects of the thermal performance of all window products. In many cases, results from experimental analysis are not available, are inconclusive, or are too expensive to obtain for all possible design options of interest. Computational models to analyze heat transfer rates and assess the comfort and condensation resistance of windows are an attractive alternative. Most large manufacturers have in fact developed proprietary window heat transfer models. However, these models are not available to the public, and the working assumptions and program capabilities often vary from one model to the next.

Figure 1. Modes of heat transfer through a window
The WINDOW program addresses these issues. Public accessibility to WINDOW and documentation of its algorithms allow the program to serve as a standard reference for designers, manufacturers, public officials, and consumers. Over 600 copies of WINDOW 2.0 have been distributed since its release to the window industry in 1986. The continuous inclusion of recent research results into the program ensures its capability of analyzing existing and developing products. The program is now used to design and develop new products, to assess and compare performance characteristics of all types of window products, to assist educators in teaching heat transfer through windows, and to help public officials in developing building energy codes.

WINDOW 3.1 runs interactively on an IBM PC and any of the compatibles (with DOS 2.1). Bostik Construction Products (Huntingdon Valley, PA) has distributed WINDOW 2.0 to the window and glass industry free of charge as a professional courtesy and is planning to distribute WINDOW 3.1 in the same manner.

2. COMPUTATIONAL METHOD

Heat transfer across a window is a function of both the temperature difference between the inside and outside and the incident solar radiation on the window. In order to evaluate heat transfer through a specific window, its configuration and physical dimensions must be specified. This includes the glazing properties (visible, total solar and infrared optical properties and thermal conductance), the gap gas (air or low-conductivity gas) thermophysical properties, spacer and frame characteristics, and environmental conditions. WINDOW 3.1 accepts inputs for each of these components, but in order to simplify the input process, the user has access to libraries of values for glazing, gas, spacer, and frame properties and defaults for environmental conditions. A single library number represents all the data associated with a specific glazing type, gas fill, or frame type. Defaults for the environmental conditions are the ASHRAE summer and winter design conditions.

To analyze window heat transfer, the window must be broken down into an assembly of nodes where the heat transfer between each node can be calculated. Under steady-state conditions, the temperatures of the nodes are such that the net energy flux entering each node is equal to that leaving each node. To perform such an energy balance, WINDOW models the user-defined glazing system as a one-dimensional steady state resistance network. This is illustrated in Figure 2 and described in the following paragraphs (3, 4). Resistances between nodes are simply the sum of the inverses of the radiative and conductive/convective heat transfer coefficients. Frame and edge effects are modeled separately. Three temperature nodes are assigned to each glazing layer (center and both surfaces), along with an outside and inside temperature node. Initially, a linear temperature distribution across the window system is assumed based on the specified outside and inside temperatures. A finite difference method is then used to converge upon the correct temperature distribution. From this temperature distribution, any desired performance index can be calculated.

The temperature-dependent conduction/convection and effective radiation heat transfer coefficients for
the outward-facing and inward-facing surfaces and for the gas filled gaps are calculated from the temperature distribution at each iteration. The heat transfer coefficients between the nodes within the solid materials simply depend on the conductivity of the materials.

Conductive/convective heat transfer coefficients are calculated based on empirical relationships. The outside film coefficient depends on the wind speed, the direction from which the wind is approaching, and the temperature difference between the outside and the outward-facing window surface. The inside film coefficient is a function of the difference between the inward-facing surface temperature and the inside temperature. Gap heat transfer coefficients are computed from empirical equations for the Nusselt number. The Nusselt number relates the temperature difference between the surfaces bounding the gap, the width of the gap, and the gas viscosity, density, conductivity and thermal diffusivity. Window tilt is also accounted for in all conductive/convective correlations.

The radiative energy flux leaving each surface is calculated from the Stephan-Boltzmann law using the surface infrared hemispherical emissivity and temperature. The net radiative flux between radiating nodes divided by the associated temperature difference gives an effective radiation heat transfer coefficient.

The contribution to the energy balance from absorbed solar radiation at each glazing layer depends on the absorbance of each layer. The optical properties of the total window system based on the individual layer properties can be determined using a ray-tracing method or a net-radiation method, both of which give the same results. WINDOW calculates the solar and visible transmittances \( T \) in Figure 2 and front and back reflectances, as well as the solar absorbance \( A \) in Figure 2) of each glazing layer from these results. The solar energy absorbed by each layer is assumed to be absorbed at the node at the center of the glazing layer.

In multiple-glazed window systems, the glazing layers are separated by spacers (typically metallic). This geometry is shown in Figure 3a. While the center-of-glass areas of such window systems may be good insulators, the edge area (glass-metal-glass contact) often acts as a thermal short circuit, degrading the thermal performance of the glass-edge area. Figure 3b, obtained through finite element modeling, shows the direction and magnitude of heat transfer through a window edge. Based on experimental and analytical work, correlations have been defined that give edge-of-glass U-values as a function of center-of-glass U-values for metallic and nonmetallic spacers. These correlations have been included in WINDOW 3. The edge area is defined as that within 2.5 inches of the spacer. Note that in a 2-foot by 4-foot window, the edge area encompasses approximately 30% of the entire glazed area; U-values for edge areas can be 50% higher than for the center-of-glass in a low-emissivity, argon-filled, double-glazed window.

Heat transfer through a window frame is a function of that frame's conductivity. While the choice of spacer type will influence edge-of-glass heat transfer, frame type does not significantly affect edge-of-glass or center-of-glass heat transfer. Frame U-values are measured or calculated separately and are included in WINDOW 3.

The model assumes that the solar-optical properties of the glazing layers are roughly constant over the solar spectrum. However, for window systems with multiple spectrally selective glazings (i.e., glazings with wavelength-selective solar-optical properties such as low-emissivity, blue or green glass), such an approach may induce small errors. In such cases, WINDOW 3.1 allows the user to input the system's overall solar optical properties determined using a multiband model [4]. The addition of a multiband model to WINDOW is planned.

Figure 3a. Cross section of window. Shown are two glazing layers, separated by a hollow metal spacer, sealed inside a clad sash.

Figure 3b. Vector plot of two-dimensional heat transfer through the window cross section of Figure 3b.
3. PROGRAM CAPABILITIES AND PERFORMANCE INDICES

The WINDOW user may design and analyze a window made up of any combinations of glazing layers, gas gaps, and frame and spacer types, for any environmental conditions. Four libraries containing the information on each of these components are accessible to the user. The user may specify a component by reference number or may input data for user-defined components. The window tilt may be varied between 0 and 90 degrees, and the user has a choice of working in English or SI units. The program cannot yet model non-glass shading systems directly.

The glazing library associates a reference number, name, thickness, solar transmittance, front and back side solar reflectance, visible transmittance, front and back side visible reflectance, long-wave infrared transmittance, front and back side hemispherical emissivity, and thermal conductivity with each glazing type (Figure 3), and includes most common glazing materials (6). The user may add or delete layers or search through the library for glazing layers with particular properties.

A gas library gives options for low-conductivity gas fills. The user can choose between air, argon, krypton or any combination of these three gases. User-defined gases may be input into the library by defining their conductivity, viscosity, density and Prandtl number.

The frame and spacer library includes choices for most common frame types (aluminum, aluminum with a thermal break, wood, wood with cladding, vinyl) and the choice of metallic or non-metallic spacers. A frame may be defined by specifying its U-value. The frame library contains two standard window frame sizes (one residential and one commercial) plus a user-defined frame size.

Standard ASHRAE winter (0 F and a 15 mph wind outside, 70 F inside, nighttime) and summer (85 F and 7.5 mph outside, 75 inside, 248 Btu/ft²-hr incident solar radiation) environmental conditions (7) are stored in the last library. User-defined environmental conditions may also be specified.

Based on the glazing layer and gap properties, WINDOW uses the iterative procedure described in the previous section to calculate center-of-glass steady state glazing layer and surface temperatures for three sets of environmental conditions. From each temperature distribution, the center-of-glass (i.e. glass only) U-value is calculated. Based on spacer type, a U-value for the insulated glass unit, Uig, can be calculated. If a frame type is specified, the complete window's U-value is calculated. For ASHRAE summer conditions, the window's shading coefficient is also calculated. Many manufacturers use the term "relative heat gain" to describe the net heat gain through the glazing system under conditions almost identical to ASHRAE summer conditions. This value is also calculated.

The shading coefficient (SC) is the ratio of solar heat gain through the window to the solar heat gain through a 1/8-inch single pane of clear glass under summer conditions. "Relative heat gain" is defined as SC = 100 (Btu/ft²-hr) / Uig, where Uig is the center-of-glass U-value.

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Figure 4. WINDOW 3 glazing library screen.
From the temperature of the inward-facing window surface and the indoor ambient temperature, the percent relative humidity at which condensation will occur is calculated (7). The interior surface temperature is also output as a comfort indicator.

The total solar and visible transmittances and reflectances for the prescribed window are also displayed. Visible reflectances are important in order to assess glare inside and outside, and solar reflectances can help examine possible adverse solar gains on neighboring buildings.

A sample WINDOW 3.1 input/output screen is given in Figure 5. The user builds a window system by specifying parameters from the library. Once a window system has been defined and results calculated, parameters on this screen such as the glazing reference number, gas type, or gap width may be changed and new results calculated. Results can be saved to a file for printing once a session is over.

4. CONCLUSIONS

WINDOW 3.1 is a state-of-the-art and user-friendly personal computer program that calculates all commonly used thermal performance indices for a user-defined window. This window may include glazings with or without low-emissivity, solar reflective, or other coatings, and low-conductivity gas fills. Gap widths, tilt, environmental conditions, and frame type may also be varied. Correlations for the two-dimensional edge heat transfer at a window's glass edge are included in order to calculate window U-values representative of actual performance. The user-friendly improvements in WINDOW 3.1 allow for the quick analysis of window configurations with minimal user input and learning time.

WINDOW and associated documentation is available to the public. The program has been used by local and national standards organizations, by manufacturers for designing new products and for reporting on existing ones, and by architects and engineers for product evaluation.

Typically, whole building energy simulation tools are limited in their ability to model window thermal performance. WINDOW results or algorithms have been and can be incorporated into such tools in order to improve their capabilities and accuracy.

Plans for the program's future include adding and refining algorithms for specific components (i.e., infrared-absorbing gasses, edge effects, spectrally selective glazings) and incorporating educational features. Future versions of the program will comment on user-defined window choices and offer suggestions on optimizing thermal performance.

5. ACKNOWLEDGEMENTS

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6. REFERENCES
