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ABSTRACT

This paper presents results of a parametric study of the energy performance of a prototypical single-family ranch-style house. The DOE-2.1B computer program was used to analyze the variation in heating, cooling, and total energy requirements due to changes in the following fenestration characteristics: orientation, size, conductance, and shading coefficient. These parameters allow us to estimate the performance of hypothetical fenestration systems using advanced aperture materials as well as commercially available products. The work represents the initial phase of a study in which the influence of other residential parameters such as internal loads, infiltration levels, natural ventilation, use of night insulation, shade management, and overhangs will also be investigated. Climate sensitivity was established by considering results from Madison, Wisconsin, and Lake Charles, Louisiana. To simplify the analysis, multiple regression techniques were used to generate a simplified algebraic expression that relates energy use to the parameters varied. This representation could form the technical basis for simplified design tools for selecting optimal fenestration parameters.

1. INTRODUCTION

Many studies have been performed in recent years documenting the effect of window characteristics on residential energy use. The usual objective has been to attain a better understanding of window systems and their interaction with a building. Whereas, at one time, windows were considered detrimental to the goal of reduced energy use, with the advantageous use of non-renewable sources, improved design strategies, and the advent of new window technologies, this is no longer the case. Of particular usefulness has been an adequate tool for analyzing window and building energy performance. Building energy simulation computer programs such as DOE-2 have meant that many different aspects of building energy use can be confidently investigated with relative ease.

Windows influence the thermal environment of buildings in a manner that is unusual among the major elements of the building envelope. Windows are characterized by convective/conductive heat transfer, radiant transfer, and mass transfer. Research in new window systems has concerned itself with changes to one or more of these properties. The introduction of double- and triple-pane glazing is an example in which both the conductive and radiant characteristics are affected. Recent studies (Refs. 1,2,3) indicate other, more complicated/multidisciplined approaches to the same objective of improved performance. Windows having extremely low U-values (on the order of 0.6 $W/m^{2\,o}C$) plus high solar and visual transmission have been produced (Ref. 1). In this system, a double-pane glass is used with low-emittance coatings on plastic interlayers and different gas mixtures in the air gap. Low emissivity coatings are also being used to reduce the radiative component of thermal losses while maintaining high solar transmission. Control of optical and thermal characteristics and mass transfer (infiltration/air leakage) can be provided by insulating shutters/movable insulation.

Systems such as these have added to the complexity of analyzing window performance. One way of circumventing the specific nature of many window system improvements is to perform a parametric analysis that encompasses many of the characteristics. The work reported in this document represents such an approach. It is part of an on-going study being conducted by the Windows and Daylighting Group of the Applied Science Division at Lawrence Berkeley Laboratory. A prototypical single-family, ranch-style house was selected for analysis using the DOE-2.1B energy analysis program (Ref. 4). The initial intent was to investigate effects arising from variations in orientation, size, conductance, and shading coefficient of the fenestration. Selection of an appropriate range for each variable insured coverage of most window systems. This allows us to determine the potential value of conceptual window systems having hypothetical performance characteristics.

Follow-up analyses will be concerned with the use of night insulation, shade management, overhangs, and other aspects of residential energy use such internal heat gains, infiltration levels, envelope conductance, and size and type of building.

Multiple regression techniques were used to analyze the data from the parametric runs. The work reported in Ref. 5 shows the versatility of using such procedures to analyze large amounts of data resulting from studies of this kind. Multiple regression is a statistical analysis procedure in which relationships between variables are established mathematically using a least squares method. Generally, sets of independent variables (e.g., U-value) are defined, from which a dependent variable (e.g., energy) is predicted. Once an equation for energy performance has been defined, it is possible to manipulate the equation to directly determine optimal performance values. Upon completion of the model description below, a more detailed discussion of the regression procedure and sample results is given.

2. MODEL DESCRIPTION

The building modeled in the DOE-2.1B program is presented in Fig. 1. It corresponds, with certain modifications, to the slab-on-grade ranch-style house reported on in 1983 (Ref. 6). The configuration is a 16.76 m by 8.53 m, one-zone structure with window sizes fixed on three sides at 15% of the wall area. The size of the fourth or primary side window varies from 0 to 60% of the wall area (0 to 17.1% of floor area). Single, double, triple, and high-resistive ($U = 0.534\ W/m^2\,^oC$) conductive values as well as shading coefficients of 0.4, 0.7, and 1.0 were used.

Wood frame construction was used, and the wall framing corresponds to 5.1 cm x 10.2-cm wood studs on 40.6-cm centers which occupy 25% of the wall area and has a U-value of $0.824\ W/m^2\,^oC$. The roof stud U-value is $0.227\ W/m^2\,^oC$ and occupies 10% of the roof area. Insulation levels of the non-stud portions of the wall and roof were set at R = 1.76 and R = 5.28. The slab-on-grade floor consisted of a carpet covered 10.2-cm concrete slab with insulation resting on a gravel bed. A U-value of $0.415\ W/m^2\,^oC$ was used for the floor, which had an effective area equal to $67.6\ m^2$. The effective area was derived from a two-dimensional, finite-element representation of the slab model, which yielded equivalent values of conduction gain/loss.

Scheduling for occupants, lights, and appliances was modified from Ref. 6. In that study, a composite process heat gain input was defined for all three internal loads. Saturation levels of 3.2 occupants per household and 28 W/m^2 for lighting and appliances were used. This corresponds to a maximum heat gain input of 10,721 KJ/hr, which equals a heat input of 56,931 KJ/day sensible and 12,825 KJ/day latent.

Infiltration levels were defined using an algorithm based on the work reported in Coblentz and Achenbach (Ref. 7). The method accounts for changes to a base level of infiltration due to variations in hourly wind speed and temperature difference between the outside air and room air. An average winter rate of 0.7 air changes per hour (ach) for window sizes equal to 15% of the wall area was used in the study.

Natural ventilation of 10 ach was implemented by simulating openable windows when all of the following conditions occurred: a. the windows were opened if opening the windows provided more cooling than would be provided by the mechanical system with the windows closed; b. the enthalpy of the outside air was less than that of the inside air; c. the outdoor air temperature was less than 25.5°C for October through May and 21.1°C for June through September.

A dual-setpoint thermostat was used to control the space conditioning. Heating was set at 21.1°C from 7am to 11pm with a night setback to 15.6°C. Cooling was set at 25.5°C at all hours. A direct-expansion, air-cooled air conditioning unit was used for cooling and a forced-air gas furnace for heating. Cooling system coefficient of performance was 2.174 and furnace steady-state efficiency was 0.74. System equipment was sized based on a design cooling temperature of 25.5°C and heating temperature of 21.1°C.

3. DISCUSSION

Multiple regression techniques were used to generate a simplified algebraic expression relating residential window parameters (independent variables) to annual energy use (dependent variable). Regression analysis uses the method of least squares to characterize the relationship between variables. Energy use for the model can be predicted for each orientation by explicitly defining the conductive and solar radiation effects of the fenestration system, as shown below:

$$E = \beta_1(U_g A_g) + \beta_2(\sum U_{go} A_{go}) + \qquad \text{conductance}$$

$$\beta_3(SC\ \ A_g)^2 + \beta_4(SC\ \ A_g) + \beta_5(\sum SC_o A_{go}) \qquad \text{solar}$$

$$+ \beta_6 \qquad \text{other}$$

where :

β = regression coefficients
U_g = primary glazing U-value
A_g = primary glazing area
SC_g = primary glazing shading coefficient
U_{go} = off-primary glazing U-value
A_{go} = off-primary glazing area
SC_o = off-primary shading coefficient

The conductance is linear with respect to U and A and is represented by the β_1 and β_2 coefficients. The solar influence is quadratic with respect to SC and A and is defined by the β_3, β_4, and β_5 coefficients. Coefficient β_6 contains the other load components: the wall, roof, and floor conductance; infiltration; interior loads; and natural ventilation. Follow-up studies will attempt to separate the β_6 values into these parts. Also of importance, but not treated in this paper, is the distinct separation of the above components into heating and cooling energy requirements and the introduction of different energy costs related to such a separation, i.e., gas versus electric. The development of a nomograph-type device is planned to permit the calculation of costs based on configuration changes as well as type of energy used.

The regression fits for both climates were extremely good. The squared multiple correlation coefficient, r^2, the proportion of variation explained by the independent variables, was 0.998 for Madison and 0.995 for Lake Charles (a value of 1.0 would mean perfect correlation). The standard error of the estimate, which can be interpreted as the standard deviation of the residuals (the difference between the actual and predicted values) was on the order of 1% for both climates. Figure 2 shows the numerical values of the coefficients as a function of orientation for the Madison WI data. Similar curves were also generated for Lake Charles. Immediately apparent is the amount of symmetry with respect to orientation. Also obvious is the sign difference between the conductance and solar terms, indicating the ability to trade off the two window properties. Madison and other heating-dominated climates yield such results, whereas Lake Charles, being cooling-dominated, yields coefficients that are all the same sign. The β_6 coefficient was independent of orientation at values of 113.45 for Madison and 59.97 for Lake Charles. Although one may be tempted to attach specific physical significance to the regression coefficients (i.e., the β_1 and β_2 could be interpreted as temperatures), a note of caution is warranted because a climatic correlation was not carried out. Further studies will enable a more precise definition of the physical significance of the results.

In the case of Madison, it is a easy to define optimum window size using the above expression. Taking the derivative with respect to primary window area and setting the equation to zero yields:

$$A_g = 1./(2.* \beta_3)\ [-\beta_4-\beta_1*(U_g/SC)] \quad (1)$$

The optimum size of course varies with orientation through the regression coefficients, but is also a function of the ratio of glass conductance to shading coefficient. This simple example indicates the versatility of regression approach. It should be mentioned that the methodology is valid only for the configuration under study; however, the general trends should also apply to other residential models. We will briefly discuss particular characteristics associated with some of the parametric runs.

Figure 3 presents typical results for the configuration in Madison WI. Total energy use versus primary window area is presented for a south orientation. The figure shows four distinct data groupings as a function of window conductance, and within each grouping are the data for varying shading coefficient. As expected for this heating-dominated climate, it is possible to reduce energy use by increasing the window size, provided the resistance and solar gain are large enough. In this example, conductance values less than U = 1.7 W/m^2°C yield essentially no change in energy use regardless of the size of the window. For primary orientations of north, east, and west, this value changes to high-resistance glazing (U = 0.534 W/m^2°C). Figures 4a and 4b show the component breakdown for the two extreme configurations on Fig. 3. The lighting, appliance, and fan energy are the same for each case. Cooling increases with size and with increased shading coefficient. The reduced conductance does not affect cooling appreciably, but a change in the shading coefficient yields approximately a three-fold increase in cooling. However, cooling levels in Madison are low and therefore do not change the overall energy use picture. Heating is the major contributor and is affected dramatically by window size and conductance. A zero window size energy use value of 113 GJ/yr rises to 145 GJ/yr at the largest size for the single-pane or high-conductance glass in Fig. 4a. This represents a 27% increase in total energy use. The high-resistive glazing zero level is about 72 GJ/yr, which decreases to 50 GJ/yr at the large size (Fig. 4b). This amounts to a 15% decrease in total energy use (the zero levels for the two figures are different because the off-primary glass properties have also changed).

A different perspective on window performance is presented in Fig. 5, which shows the net annual useful flux (e.g., the solar gain that contributes to a reduction in heating load) in Madison for a south orientation. This plot shows the effect only of heating energy; results are shown for the largest primary window area ($24.5m^2$). Positive flux values are obtained for U-values less than 3.0 $W/m^{2\circ}C$ at shading coefficients of 1.0, and less than 1.7 $W/m^{2\circ}C$ for shading coefficients of 0.4. The curves tend to shift left for smaller window areas. For example, for an area of 6.13 m^2, the 3.0 and 1.7 values change to 4.4 and 2.0, respectively. This implies that, per square meter, the smaller window is more effective; however, the amount of useful flux is greater for the larger window. Also shown are values typical of current glazing products, extracted from Ref. 9.

Plots comparable to Figs. 3 and 4 for Lake Charles cannot be presented within the scope of this paper; however, the data indicate a reversal of the influence of shading coefficient. Energy use decreases with decreasing shading coefficient, which results from the increased cooling associated with Lake Charles. Also, the grouping of the data as a function of conductance is not as straightforward as in Madison. Solar effects dominate and the changes caused by shading coefficient are more relevant than conductance variations. No optimum primary area is definable other than the smallest area.

4. CONCLUSIONS

This paper has discussed results of an ongoing study whose objective is to analyze the effects of fenestration on residential energy use. The work was undertaken as a parametric study covering a range of window properties: orientation, size, conductance, and shading coefficient. The intent has been to bracket each variable so that current and/or future glazing characteristics can be conveniently analyzed. Several conclusions can be ascertained from the work accomplished thus far:

a. Results clearly indicate the viability of using regression-derived equations to perform such analysis. In this study, a simple algebraic expression was defined that predicted energy use as a function of the abovementioned window properties.

b. The regression coefficients (in addition to the window properties) also give insight into the window performance associated with specific geographic locations. For example, in Madison, the energy reduction associated with increased solar gain is apparent in a negative sign attached to the solar radiation coefficient; in Lake Charles, the signs of all regression coefficient are positive.

c. The magnitude of the regression coefficient arising from other residential characteristics such as internal loads, infiltration, etc., is of sufficient magnitude to warrant further breakdown of the governing equation into such components. This procedure will increase the understanding of all aspects of residential energy use.

d. A substantial reduction in energy use in both Madison and Lake Charles for a residence using single-pane glazing can be achieved for all orientations by using increased window area and reduced conductance. The reduction in Madison can be as great as 50% when using high-resistive, high solar transmittance glazing, and as much as 16% in Lake Charles.

e. The impact of window orientation on total energy is much less than the effects arising from the other window parameters. Also, these orientation influences are reduced still further by decreased window conductance and shading coefficient.

f. Further studies will concentrate on the heating/cooling energy components in addition to the total energy. This is particularly important when dealing with climate extremes such as Madison and Lake Charles as was done herein. The energy costs associated with such a breakdown could alter conclusions regarding specific fenestration products.

5. ACKNOWLEDGEMENT

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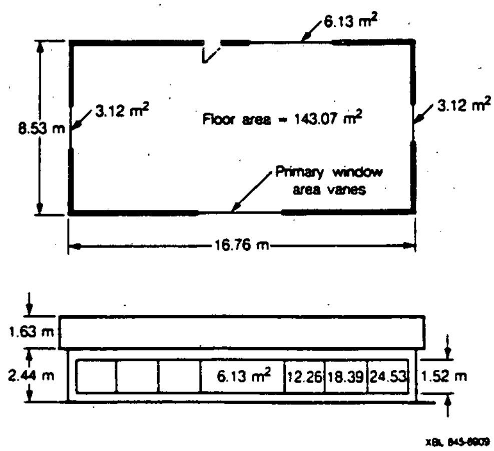

Figure 1. Residential model description.

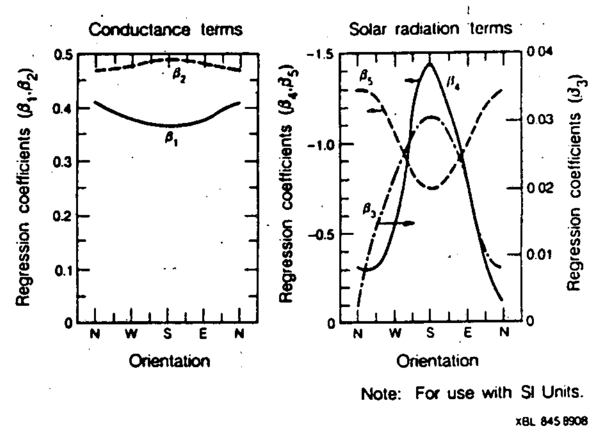

Figure 2. Annual residential energy use regression coefficients for Madison WI, as a function of primary window orientation.

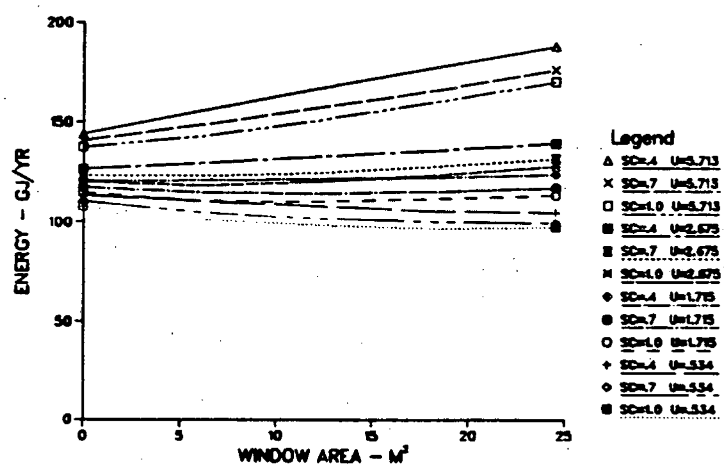

Figure 3. Annual residential energy use in Madison WI, for a primary window orientation due south as a function of window area.

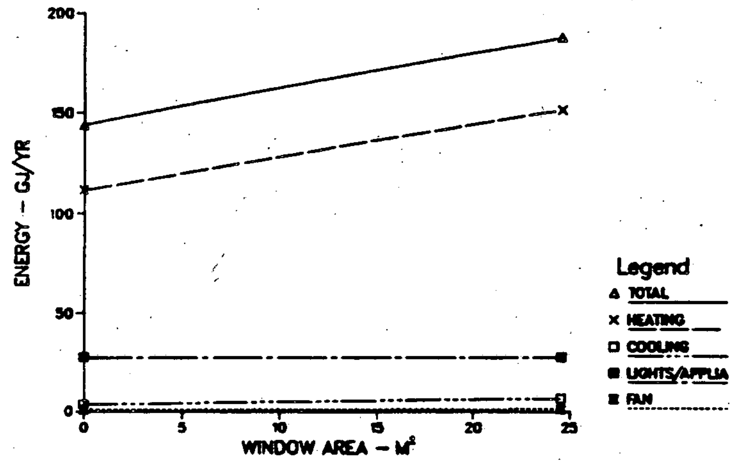

Figure 4a. Annual residential energy use components in Madison WI, for a primary window orientation due south as a function of window area. (SC = 0.4 UG = 5.713 $W/m^2{}^\circ C$).

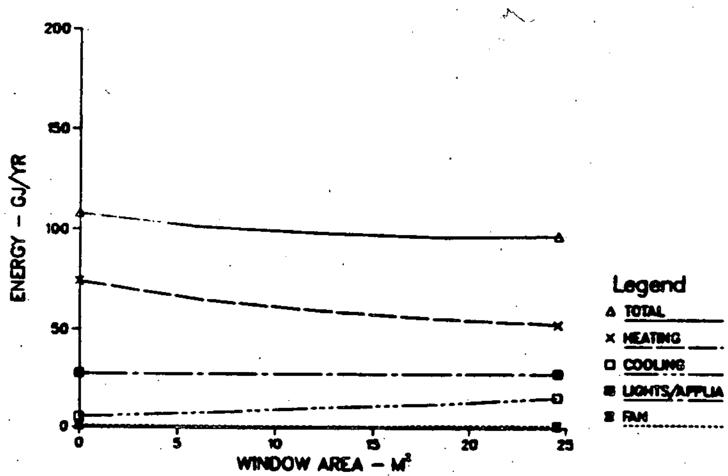

Figure 4b. Annual residential energy use components in Madison WI, for a primary window orientation due south as a function of window area. (SC = 1.0 UG = 0.534 $W/m^2{}^\circ C$).

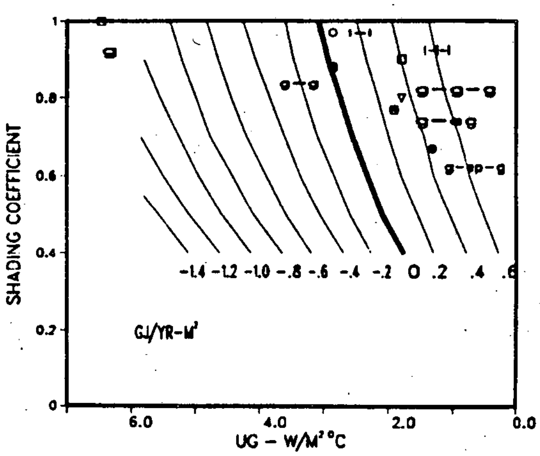

Figure 5. Net annual useful flux in Madison WI, for a primary window area of 24.53 m^2 for an orientation due south. The performance of typical glazing systems is indicated for glazing properties shown below.

	U ($W/m^2{}^\circ C$)	SC
g	6.46	1.0
g-g	2.87	0.88
g-g-g	1.8	0.8
g-eg	1.92	0.77
g-ep-g	1.32	0.67
l-l	2.87	0.97
l-l-l	1.80	0.9

g: 1/8" DS float glass
l: 1/8" low-iron sheet glass
e: low-emittance coating, e = 0.15
p: 4-mil polyester
All air gaps are 12.7 mm (1/2")
U-value: Standard ASHRAE winter conditions
SC: Standard ASHRAE summer conditions