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Heat Transfer Analysis of a Between-Panes Venetian Blind Using Effective Longwave Radiative Properties

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ABSTRACT

Center-glass thermal analysis programs based on one-dimensional models have proved to be exceptionally useful. Recently efforts have been made to extend the analysis to include venetian blinds. It is convenient to model the venetian blind as a planar, homogeneous layer that is characterized by spatially averaged, or "effective," optical properties. The blind is then included in a series of planar glazing layers. Thermal resistance values were calculated for a window with two layers of uncoated glass and a venetian blind in an air-filled glazing cavity. Three pane spacings and a wide range of slat angles were examined. The longwave effective properties for the blind were obtained using the analysis presented by Yahoda and Wright in a companion paper. The simulation model was completed with one of two simple models dealing with convective heat transfer in the glazing cavity. Calculated results were compared with earlier guarded heater plate measurements, and the agreement was encouraging in spite of the crude convection models used.

INTRODUCTION

Center-glass thermal analysis programs based on one-dimensional models have proved to be exceptionally useful (e.g., Wright and Sullivan 1995a; Finlayson et al. 1993). The models underlying these programs rely on the ideas that each glazing layer is flat and that each surface is a diffuse emitter/reflector in the longwave band (i.e., far infrared wavelengths), although each layer can be treated as specular with respect to shorter wavelength radiation (i.e., solar/visible wavelengths).

Recently, efforts have been made to extend the conventional one-dimensional analysis to include venetian blinds. The energy flow analysis of a glazing system with shading, such as venetian blinds, can be simplified by modeling the shading device as a planar, homogeneous "black-box" layer included in a series of planar glazing layers. The front and back surfaces of the shading layer are assigned spatially averaged optical properties, referred to as "effective" optical properties, which describe the performance of the shading device with respect to the way in which it interacts with radiation. In particular, the glazing system, including the environment, can be treated as an n-node array consisting of n–3 glazing layers, one shading layer, together with the indoor (i = 1) and outdoor (i = n) nodes, as shown in Figure 1.

The goal of the current study was to develop a model able to calculate thermal resistance values for a glazing system that includes a between-the-panes venetian blind and then compare these values with data produced by Garnet et al. (1995) and Garnet (1999), who made measurements using a

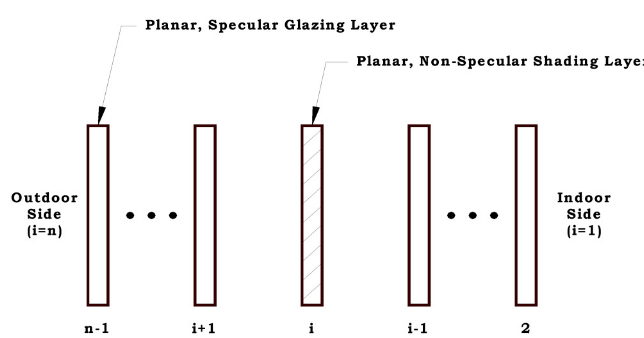

Figure 1 *Layer representation of glazing system with venetian blind.*

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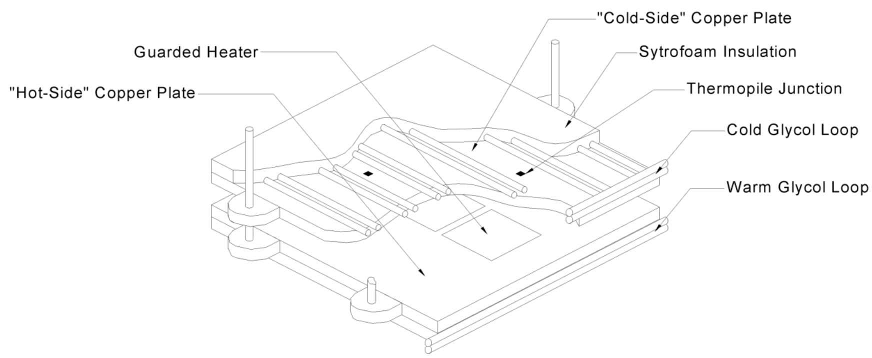

Figure 2 *Guarded heater plate apparatus.*

guarded heater plate apparatus. Both calculations and measurements were made for windows with two layers of uncoated glass separated by a venetian blind in an air-filled glazing cavity. The venetian blind examined by Garnet was a commercially available unit composed of painted aluminum slats. Three pane spacings and a wide range of slat angles were examined. The longwave effective properties for the blind were obtained using the analysis presented by Yahoda and Wright in a companion paper (Yahoda and Wright 2004). The simulation model was completed with one of two simple models dealing with convective heat transfer in the glazing cavity. Details regarding these convection models are presented in a subsequent section of this paper.

THE GUARDED HEATER PLATE APPARATUS

The center-glass thermal resistance measurements of Garnet et al. (1995) and Garnet (1999) were obtained using a guarded heater plate apparatus (GHP). The GHP consists of "hot-side" and "cold-side" copper plates, each being isothermal, and each maintained at a desired temperature by a water/glycol solution circulated by a constant-temperature bath. The GHP is depicted in Figure 2. The hot-side copper plate has three recessed electric resistance heater plates, each made of copper. The center heater plate is used to make center-glass measurements. A heat flux meter is located between each heater plate and the hot-side plate, as shown in Figure 3. The electrical power supplied to the nichrome wire in the heater plate is adjusted until a null reading is obtained from the heat flux meter. Under this condition, there is zero temperature difference and, thus, zero heat transfer between the hot-side plate and the embedded heater plate, and it must be concluded that all the energy supplied to the resistance heater is transferred across the test sample to the cold-side plate. Additional information about this particular apparatus can be found in the literature (e.g., ElSherbiny 1980; ElSherbiny et al. 1982, 1983).

In the case of glazing system measurements, thin sheets of neoprene were placed between the copper plates and the exposed glass surfaces of the glazing units to eliminate thermal contact resistance. A fully detailed description of glazing system center-glass U-factor measurements using the GHP is given by Wright and Sullivan (1988), and various measurement results can be found in the literature (e.g., Wright and Sullivan 1987, 1995b).

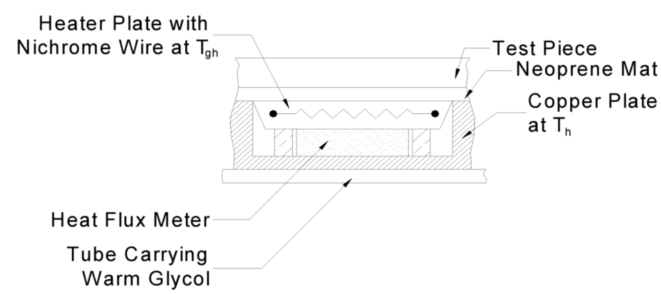

Figure 3 *Detail of guarded heater.*

Knowing the measured rate of electrical energy input to the center heater plate, the heat flux coming from the plate and going through the test sample, q'', can be very accurately determined. Then, knowing the temperature difference across the test sample, ΔT, the R-value of the sample is

$$R_{gg} = \frac{\Delta T}{q''} . \tag{1}$$

It should be noted that ΔT is not measured directly. Instead, the temperature difference between the two large copper plates, ΔT_{pp}, is measured. It is then possible to determine ΔT by making the following adjustment:

$$\Delta T = \Delta T_{pp} - 2R_n \cdot q'' \tag{2}$$

where $2R_n$ is the combined thermal resistance of the two neoprene mats.

Note also that the subscript gg is a reminder that R_{gg} includes only the thermal resistance "from-glass-to-glass." The resistances associated with the indoor and outdoor film coefficients, h_{in} and h_{out}, respectively, must be added in order to obtain the result in the more customary form of a U-factor. Equation 3 shows the procedure.

$$U = (h_{in}^{-1} + R_{gg} + h_{out}^{-1})^{-1} \quad (3)$$

U-factors reported by Garnet (1995, 1999) were based on GHP measurements with the resistances of the neoprene sheets replaced with resistances based on indoor and outdoor film coefficients of $h_{in} = 8\ \mathrm{W/m^2K}$ and $h_{out} = 23\ \mathrm{W/m^2K}$.

THE TEST SAMPLES

Garnet's experiments (1995, 1999) were conducted on glazing system test samples consisting of two 635 mm × 635 mm (25 in. × 25 in.) sheets of uncoated glass encasing a venetian blind. The fill-gas was air. Three different pane spacings were used: 17.78 mm, 20.32 mm, and 25.40 mm. The same venetian blind was used in each experiment. The width of the blind slats, w, was 14.79 mm, with a slat spacing, s, of 11.84 mm. The hemispheric longwave emissivity of the slat surfaces was measured as ε_{slat}=0.792 by Garnet using a Gier-Dunkel DB-100 infrared reflectometer. Garnet made thermal resistance measurements on each sample using slat angles (angle of tilt from the horizontal position) ranging from –75° to 75° in 15° increments.

THE HEAT TRANSFER MODEL

For the purpose of the current study, a heat transfer model was developed specifically to simulate the glazing system samples tested earlier by Garnet (1995, 1999). Specifically, this model can be applied to a venetian blind between two sheets of glass. The analysis can easily be modified and applied in a more general way to other shading/glazing configurations. Since the experiments did not involve solar radiation, the heat transfer model does not account for absorbed solar radiation.

System Temperatures

The model of the between-panes venetian blind glazing system consists of five layers in total: two layers of neoprene, two sheets of glass, and a shading layer, as shown in Figure 4. Five temperatures are used to describe the system:

1. The temperature of the indoor-facing surface of the hot side neoprene sheet, T_{in}.
2. The temperature of the indoor-side glazing, $T_{gl,in}$.
3. The temperature of the venetian blind layer, T_{shade}.
4. The temperature of the outdoor-side glazing, $T_{gl,out}$.
5. The temperature of the outdoor-facing surface of the cold side neoprene sheet, T_{out}.

The two glazing layers are treated as isothermal at temperatures $T_{gl,in}$ and $T_{gl,out}$. The shading layer is assigned an average layer temperature, T_{shade}. The temperatures of the indoor-facing and outdoor-facing neoprene sheet surfaces, T_{in} and T_{out}, are equal to the GHP hot and cold plate temperatures and were fixed at the nominal values used in the experiments of Garnet (1995, 1999) of 20° and 0°, respectively. The three system temperatures, $T_{gl,in}$, $T_{gl,out}$, and T_{shade} remain as unknowns.

Knowing T_{in} and T_{out}, the two glazing layer temperatures, can be determined from the temperature drop through the neoprene sheets as a function of q'' and R_n. Using expressions similar to Equation 2:

$$T_{gl,in} = T_{in} - R_n q'' \quad (4)$$

$$T_{gl,out} = T_{out} + R_n q'' \quad (5)$$

The resistance of the neoprene sheet, R_n, was obtained by direct measurement using the GHP apparatus. However, it is convenient to conceptualize the neoprene mat resistance in terms of its thickness, t_n, and its thermal conductivity, k_n. The relation between the three quantities is given by Equation 6.

$$R_n = \frac{t_n}{k_n} \quad (6)$$

Garnet (1999) reported values of $k_n = 0.17\ \mathrm{W/m \cdot K}$, $t_n = 1.524\ \mathrm{mm}$. These values correspond to $R_n = 0.009\ \mathrm{m^2K/W}$.

To determine the shading layer temperature, T_{shade}, it is necessary to model the heat transfer in the cavities between the glazing layers and the shading layer.

The Radiant Exchange Model

The radiant exchange is most readily modeled in terms of the flux of radiant energy incident at each surface, the irradiance, and the flux of radiant energy leaving each surface (including emitted, reflected, and transmitted components), the radiosity. The irradiance and radiosity are assigned the symbols G and J, respectively, and each is assigned a subscript to specify one particular surface (see Figure 5).

Figure 6 shows more detailed expressions for surface radiosities. Each radiosity consists of a combination of emit-

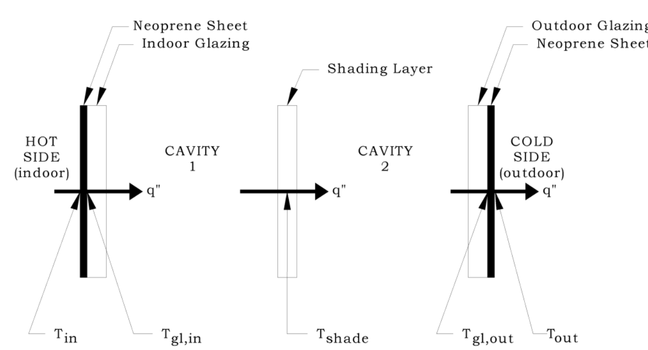

Figure 4 *Heat transfer analysis model of between-panes venetian blind.*

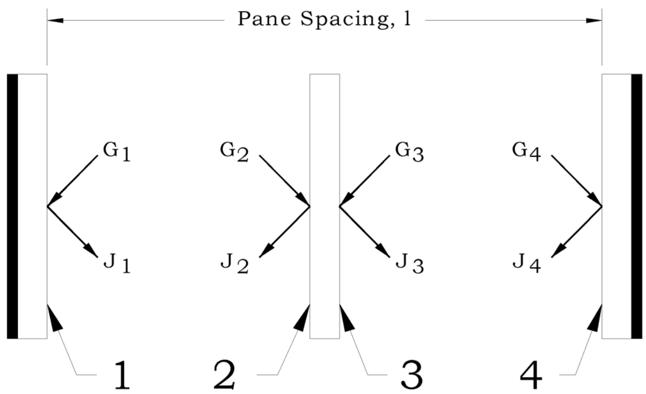

Figure 5 *Longwave radiation exchange between surfaces.*

ted and reflected flux components and, because the shading layer is partially transparent to longwave radiation, J_2 and J_3 also include transmitted flux components. Note that because the fill-gas (air) is nonparticipating, the irradiance at each surface has now been replaced by the radiosity of the opposite side of the cavity. The radiation balances shown in Figure 6 are given more formally in Equations 7 through 10.

$$J_1 = \varepsilon_1 \sigma T_1^4 + \rho_1 J_2 \tag{7}$$

$$J_2 = \varepsilon_2 \sigma T_2^4 + \rho_2 J_1 + \tau_3 J_4 \tag{8}$$

$$J_3 = \varepsilon_3 \sigma T_3^4 + \rho_3 J_4 + \tau_2 J_1 \tag{9}$$

$$J_4 = \varepsilon_4 \sigma T_4^4 + \rho_4 J_3 \tag{10}$$

Equations 7 through 10 include various optical properties. At the glass surfaces, the hemispheric emissivity values are denoted ε_1 and ε_4 ($\varepsilon_1 = \varepsilon_4 = 0.84$ for uncoated glass). Noting that glass is opaque with respect to longwave radiation, and invoking Kirchoff's law, it is apparent that $\varepsilon_1 + \rho_1 = 1$ and $\varepsilon_4 + \rho_4 = 1$. The effective longwave radiative properties for the venetian blind (ε_2, ρ_2, τ_2, ε_3, ρ_3, τ_3) were calculated using the techniques described by Yahoda and Wright (2004). Each of the blind layer effective optical properties is a function of slat width, slat spacing, slat angle, and the emissivity of the slat surfaces. Note that, on the basis of second law arguments, the front and back transmittance values of the venetian blind, τ_2 and τ_3, must be equal.

Energy Balances

Two more governing equations are obtained by writing an energy balance at each of the two glazing surfaces. For surface 1,

$$q'' = J_1 - J_2 + h_{cav1}(T_{gl,in} - T_{shade}) . \tag{11}$$

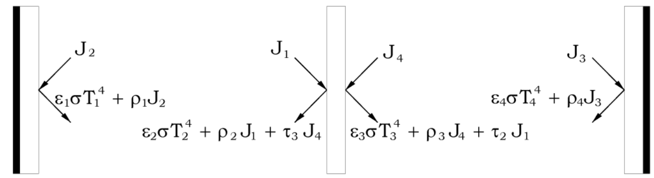

Figure 6 *Expanded surface radiosities and irradiances.*

For surface 4,

$$q'' = J_3 - J_4 + h_{cav2}(T_{shade} - T_{gl,out}) . \tag{12}$$

Convective Heat Transfer Coefficients

Equations 11 and 12 contain the convective heat transfer coefficients h_{cav1} and h_{cav2} used to describe natural convection in the tall, vertical, air-filled cavities between the shading layer surfaces and the glazing surfaces. Two simple models were devised to estimate h_{cav1} and h_{cav2}. Both of these models were based on the well-established procedure used to determine the heat transfer coefficient, say, h_{cav}, associated with heat transfer by natural convection across a tall, vertical, rectangular gas-filled cavity. Summarizing, h_{cav} can be expressed in terms of the Nusselt number, Nu, the conductivity of the gas, k, and the distance between the vertical walls, L, as shown in Equation 13.

$$h_{cav} = \mathrm{Nu}\frac{k}{L} \tag{13}$$

Various correlations are available to calculate Nu as a function of Rayleigh number, Ra. The correlation used in this study was developed by Wright (1996) and is shown in Equations 14 through 16.

$$\mathrm{Nu} = 0.0673838 \cdot \mathrm{Ra}^{1/3} \qquad \mathrm{Ra} > 5 \cdot 10^4 \tag{14}$$

$$\mathrm{Nu} = 0.028154 \cdot \mathrm{Ra}^{0.4134} \qquad 10^4 < \mathrm{Ra} \le 5 \cdot 10^4 \tag{15}$$

$$\mathrm{Nu} = 1 + 1.75967 \cdot 10^{-10} \cdot \mathrm{Ra}^{2.2984755} \qquad \mathrm{Ra} \le 10^4 \tag{16}$$

The Rayleigh number is given by

$$\mathrm{Ra} = \frac{\rho^2 L^3 g C_p \Delta T}{\mu k T_m} . \tag{17}$$

where ρ is the gas density, C_p is the gas specific heat, and μ is the fill gas viscosity. These properties are evaluated at T_m—the mean temperature of the fill gas. The temperature difference between the vertical walls of the cavity is denoted ΔT. The remaining item, g, is the acceleration due to gravity.

It is convenient to express h_{cav} as an R-value, R_{cav}, as shown in Equation 18.

$$R_{cav} = \frac{1}{h_{cav}} \tag{18}$$

Table 1. Effective Longwave Radiative Property Values

ϕ	$\varepsilon_{eff,LW} = \alpha_{eff,LW}$	$\rho_{eff,LW}$	$\tau_{eff,LW}$
0°	0.571	0.042	0.387
±15°	0.581	0.047	0.372
±30°	0.610	0.061	0.329
±45°	0.655	0.086	0.259
±60°	0.713	0.120	0.167
±75°	0.775	0.161	0.064
±90°	0.792	0.208	0

Natural Convection—Model One

The values of h_{cav} and R_{cav} were assessed by ignoring the presence of the venetian blind in the glazing cavity. That is, L was set equal to the distance between the two sheets of glass and $\Delta T = T_{gl,in} - T_{gl,out}$. Half of R_{cav} was assigned to cavity 1 and half to cavity 2. Then, in keeping with Equation 18,

$$h_{cav1} = h_{cav2} = 2h_{cav} \tag{19}$$

Natural Convection—Model Two

A second convection model was devised in a very simple attempt to mimic the way in which the venetian blind might divide the convective flow of the fill-gas as if it were separated into two cavities. The heat transfer coefficients, h_{cav1} and h_{cav2}, were approximated using Nusselt numbers determined separately for cavity 1 and cavity 2. In each case, L was set equal to half of the distance between the two sheets of glass and in each case $\Delta T = (T_{gl,in} - T_{gl,out}) / 2$.

Solution Algorithm

Equations 7 through 12 constitute a system that can be solved for six unknowns: J_1, J_2, J_3, J_4, q'', and T_{shade}. Once q'' is known, it can be used to obtain the R_{gg} and the U-factor of the glazing system.

Difficulties arise in generating the solution because the governing equation set is nonlinear, and also because the fill-gas properties vary with temperature. Two actions were taken to overcome these difficulties. First, the equation set was linearized by replacing the convection terms, which are routinely based on temperature difference, by similar terms based on black emissive power. More specifically, the conversion of the convection terms was accomplished by modifying the convective heat transfer coefficients so that they can be applied to differences in black emissive power rather than temperature differences. These modified coefficients are somewhat more sensitive to changes in temperature but do, nonetheless, facilitate the solution of the equation set from an overall perspective. Second, following an initial guess for q'', successive solutions were generated in order to update fill-gas properties and convective heat transfer coefficients as the temperature solution converged. Air properties were taken from Table A.4 of Incropera and deWitt (1996). Details regarding this solution technique can be found in the literature (e.g., Hollands and Wright [1983], Wright [1998], Hollands et al. [2001]). Finally, the solution results were used to determined R_{gg}, and Equation 3 was used to calculate the U-factor using the same values of h_{in} and h_{out} that were used by Garnet (1995, 1999).

RESULTS AND COMPARISON: SIMULATION VERSUS EXPERIMENT

The effective longwave radiative properties of the venetian blind were required before U-factors could be calculated for the glazing system. These effective properties were calculated using the models of Yahoda and Wright (2004) for the blind slat geometry and slat emissivity that coincide with the measurements of Garnet (1995, 1999). The resulting values of the venetian blind's effective longwave radiative properties are presented in Table 1. These results are presented as a function of the slat angle, ϕ. The value of $\phi = 0$ corresponds to a fully open venetian blind. Since both the top and bottom surfaces of the blind slats have the same emissivity, and because the models of Yahoda and Wright (2004) treat the slats as if they were flat, the effective properties are symmetric about $\phi = 0$.

The experimentally determined U-factors reported by Garnet (1995, 1999) were compared with the U-factors determined from the heat transfer analysis. As stated in the heat transfer analysis description, the effect of the shading layer on the convective heat transfer was treated in a simplified manner using one of two different approximations. In the first, the influence of the venetian blind on convection was ignored. In the second, the convective flow is treated as if the blind divides it fully into two separate flows.

The U-factor comparisons are presented in Figures 7, 8, and 9 for the three different pane spacings, 17.78 mm, 20.32 mm, and 25.40 mm, respectively. The presence of a (1) or a (2) in the legend indicates the U-factors were computed using the first or second convective heat transfer approximations. The "radiation only" values correspond to U-factors based on longwave radiation exchange between surfaces only. These "radiation only" U-factors will not correspond exactly to the radiation portion of the U-factors predicted with convective heat transfer because the two modes of heat transfer are coupled, but they do give an approximate indication of the significance of convective heat transfer in the overall U-factor. If a low-e coating had been present, the radiative heat transfer would have been significantly reduced.

The predicted U-factors for all three pane spacings generally fall within fifteen percent of the measured values, with most values within ten percent. Regarding the effect of fill-gas convection, the performance of the first approximation, on average, is slightly better than the second approximation. Garnet's measurements are not symmetric about the $\phi = 0$ (fully open) slat angle position. Garnet (1999) speculated that the asymmetry was present because of slats with positive tilt being able to deflect more of the primary flow (around the

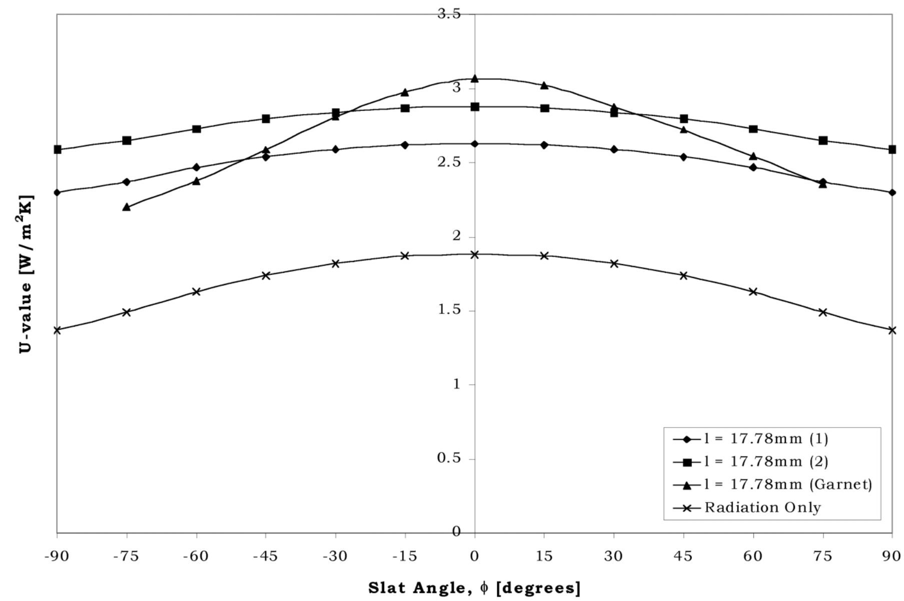

Figure 7 *Comparison of experimental (Garnet) and calculated (1, 2, no convection) U-factors as a function of slat angle for a pane-spacing, 1, of 17.78 mm.*

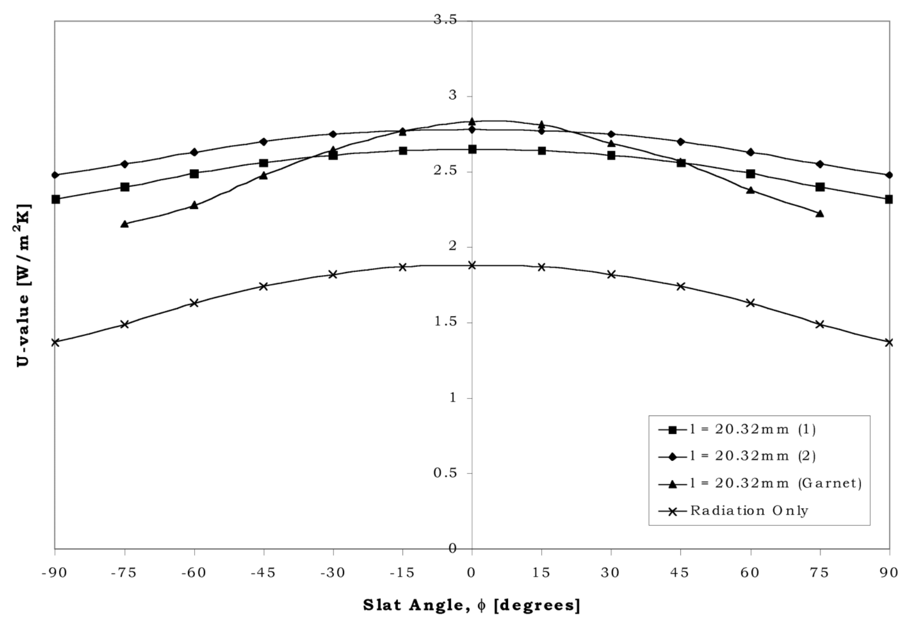

Figure 8 *Comparison of experimental (Garnet) and calculated (1, 2, no convection) U-factors as a function of slat angle for a pane-spacing, 1, of 20.32 mm.*

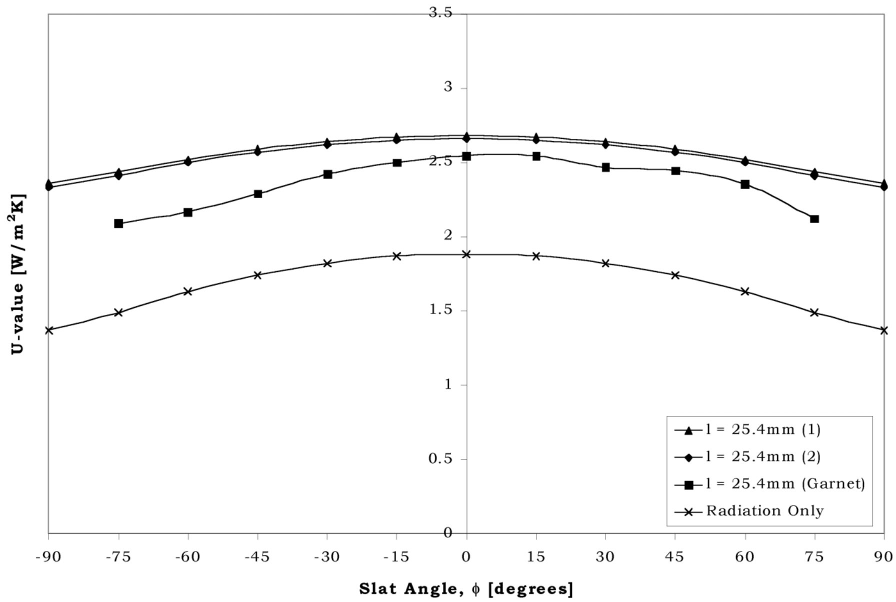

Figure 9 *Comparison of experimental (Garnet) and calculated (1, 2, no convection) U-factors as a function of slat angle for a pane spacing, 1, of 25.40 mm.*

entire blind) into the secondary flow (between slats) than slats with negative tilt. This asymmetry and the higher degree of sensitivity to slat angle are not present in the calculated U-factors because the convective heat transfer models do not include any means to include the effect of slat angle. Asymmetry is also not present in the calculated results because the top and bottom slat surface properties are identical.

A convective model that accounts for the effects of the blind on the cavity flow could improve the prediction of heat transfer. Nonetheless, the current results, given the crude nature of the convection model, are very encouraging.

CONCLUSIONS

The U-factors for three different pane spacings of between-panes venetian blinds were determined from a heat transfer analysis that combined the use of effective longwave radiative properties of the venetian blind and simple approximations for the convective heat transfer in the glazing cavity.

The calculated U-factors for the between-pane venetian blinds were compared with corresponding U-factors based on the experimental work of Garnet (1995, 1999). The comparisons show encouraging results, with most U-factor results agreeing to within 10%, despite the crude convection models. This may be taken as an indication that there is little value in the development of highly sophisticated models to deal with the detail of interaction between a between-pane venetian blind and the convective flow in the same cavity. Further study will be needed to see whether this conclusion fully applies to glazing systems that incorporate low-emissivity coating(s) and whether the conductivity of the slats plays a discernable role.

ACKNOWLEDGMENTS

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DISCUSSION

Ross McCluney, Florida Solar Energy Center, Cocoa, Fla.: Verified that radiation and scattering models were both Combustion?

Tom McHugh, HMG, Fair Oaks, Calif.: Need for division of slat angle sunlight conditions?