HEAT TRANSFER ANALYSIS OF WINDOWS WITH VENETIAN BLINDS: A COMPARATIVE STUDY

B.A. Lomanowski and J.L. Wright
Department of Mechanical Engineering, University of Waterloo, 200 University Avenue West, Waterloo, ON, Canada, N2L 3G1
Phone: 519-888-4567 x33885, Fax: 519-885-5862, Email: blomanow@engmail.uwaterloo.ca

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ABSTRACT

The potential to reduce building load and annual energy consumption is widely recognized in the use of shading devices to control solar gain. Consequently, the ability to include and model shading layers in complex glazing systems is needed in evaluating the energy performance of a building envelope. In a previous study, solar-optical calculations were presented for a window with a light and dark coloured venetian blind using simplified models for three different glazing/shading configurations. Results were presented for the hourly transmitted, reflected and absorbed quantities of solar radiation for summer and winter conditions. In this study, a heat transfer analysis is presented to complement the previous study and provide all the relevant information required for building energy analysis. The individual contributions to the net heat gain consisting of total solar transmission, longwave radiant gain and convective gain are presented. The ability to quantify the relative importance of each heat gain component offers significant insight into the thermal characteristics of complex glazing/shading systems.

INTRODUCTION

The potential to reduce building cooling load and annual energy is widely recognized in the use of shading devices to control solar gain. The ability to fully describe a complex glazing/shading system in the context of building energy simulation tools is critical to accurately quantify this potential. Glazing/shading system analysis takes advantage of the fact that there is no appreciable overlap in wavelength between solar (short-wave) and thermal (long-wave) radiation. Energy transfer through a glazing/shading system can thus be characterized by first considering the distribution of incident solar radiation (transmission, reflection, absorption), followed by a heat transfer analysis using the absorbed quantities as source terms in each glazing/shading layer. The requirements for building energy simulation include coping with off-normal incidence angles as well as determination of all the components of heat gain into the indoor space, mainly the total transmission of solar radiation and the convective and radiative gains. The convective-radiative split is critical for any hour-by-hour building energy simulation, as only the convective gain represents immediate cooling load. The radiative fluxes (solar and longwave) impinging on an inner surface become cooling load only when the energy is transferred to the air by convection. Thermal mass of the indoor constructions thus introduces a time lag between impinging radiative fluxes and conversion of this energy to cooling load.

A recent study by Kotey and Wright (2006) presented a simplified solar optical model for windows with venetian blinds. Hourly values of solar absorption, transmission and reflection for three venetian blind and glazing configurations were calculated. The study was based on a multi-layer solar optical model developed by Wright and Kotey (2006) to generalize and simplify the computation procedure for complex fenestration systems of any configuration. Simplified procedures were established for determining spatially averaged or 'effective' venetian blind solar optical properties as functions of blind geometry and sun position. The simplified solar optical model treats blind slats as flat, perfect diffusers to eliminate the need for computationally intensive ray tracing techniques (e.g., Yahoda and Wright (2005)), thus putting a strong emphasis on fast run times. The model is well suited for building energy simulation, where the speed requirement is of critical importance and is valuable as a proof of concept for modeling complex venetian blind systems. However, only the solar radiation distribution is accounted for, and therefore the study does not present all the information that is needed for input into building energy simulation tools.

To complement the previous study, and thus provide the other pieces of information needed, the current study addresses the heat transfer problem. In order to fully describe the heat gain to the indoor space, the convective and long-wave radiative fluxes are required in addition to the transmitted solar flux. The ability to quantify both solar and thermal aspects of energy transfer in glazing/shading systems provides valuable insight into the effects of blind position and properties on the different components of heat gain. Several solution techniques exist for the center-glass heat transfer analysis of glazing systems based on performing an energy balance around each glazing layer (e.g. Hollands and Wright 1980; Rubin 1982; Finlayson et al 1993; Wright 1998). These methods are general enough to handle any number of diathermanous layers (semi transparent to long-wave radiation) and solve for the layer temperatures and fluxes, based on knowledge of absorbed source terms, long-wave radiative properties of each layer and convective coefficients. The addition of a diathermanous layer adds significant complexity to the determination of performance indices of a glazing/shading system such as U-value and SHGC. Recent work by Collins and Wright (2006) provides a method for calculating the U-value and SHGC of a glazing/shading system with a single diathermanous layer.

In order to incorporate shading layers into a center-glass analysis, various researchers (e.g. ISO 2000; Yahoda and Wright 2004) have developed effective longwave radiative property models for venetian blinds. The model of Yahoda and Wright (2004) is based on conventional grey enclosure analysis, treating slats as isothermal, uniformly irradiated diffuse reflectors/emitters. Effective longwave absorptance, reflectance, and transmittance are determined by introducing an external irradiance on a representative slat enclosure and solving for surface radiosities and irradiances.

The current study is intended as a proof of concept of hour-by-hour calculations based on existing solar and thermal models. Various venetian blind configurations are compared with a base case, a standard double glazed window, to provide insight into the thermal characteristics of complex glazing/shading systems.

METHODOLOGY

System Layout

The glazing/shading system considered in this study consists of three layers, two glazing layers and one venetian blind layer. The layers are numbered from 1 (indoor-side) to 3 (outdoor-side). Three glazing/blind configurations were analyzed: indoor-side blind, between-the-panes blind and outdoor-side blind. The indoor-side blind configuration is shown in Figure 1. The winter and summer conditions imposed on the system were taken from Kotey and Wright (2006). The indoor and outdoor environments are described as follows:

- Indoor space was treated as a black body with the indoor air and wall temperatures equal to T_{in}.
- T_{in} was set to 21˚C and 24˚C for the winter and summer condition respectively.
- Sky temperature was calculated using Swinbank's (1963) formula based on the hourly outdoor ambient temperature.
- Sky vault and ground were treated as a black body.
- Ground temperature was assumed equal T_{out}.
- Outdoor radiosity was the equally weighted average of the sky vault and ground radiosities.

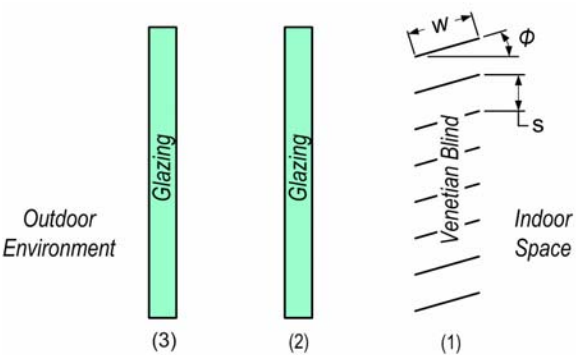


Figure 1. System layout: double-glazed window with indoor side venetian blind and blind dimensions.

The method of Yahoda and Wright (2004) was used to calculate the effective longwave radiative properties of the venetian blind, knowing the blind's geometry and slat emittance. The slats are assumed to be flat, uniformly irradiated diffuse reflector/emitters.

Multi-layer Heat Transfer Analysis

Having obtained the effective longwave properties of the blind layer and knowing the absorbed quantities of solar radiation in each layer from the simplified solar optical model (Kotey and Wright 2006), a one dimensional center-glass multi-layer heat transfer analysis was performed. Appropriate convection models were applied to each blind configuration. For the indoor blind case, natural convection takes place at both the indoor glazing and the blind. It is assumed that the venetian blind is positioned sufficiently far from the glazing for the convective interaction between the glazing and blind to be weak. This representation is shown in Figure 2 in the form of a convective resistance network. The channel temperature between the glazing and blind is assumed to be equal to the indoor air temperature T_{in}. However, this is not a realistic assumption if the blind is close to the glazing. In such an arrangement, the blind is submerged in the thermal boundary layer of the glazing and as a result the air channel and blind temperatures are shifted. An empirical correlation for free convection on a vertical surface (ISO 2000) was used to calculate the average Nusselt number on the inside glazing layer. The same correlation was applied to both sides of the blind layer. This is arguably a rather simplified assumption and in some situations may underestimate the convective coefficient to the indoor space. Ongoing research (e.g. Collins 2004, Roeleveld 2007) aims to develop a more sophisticated correlation for convective heat transfer in indoor venetian blind systems.

Tasnim et al (2007) have developed a convection correlation for the between-the-panes venetian blind that introduces a corrected cavity width, accounting for the presence of the blind, into a vertical cavity correlation by Shewan et al (1996).

For the outdoor blind case, convection on the outdoor glazing and blind has been modeled using a forced convection correlation (Incropera and DeWitt, 2002) for a vertical surface using wind speed data from the Waterloo weather station as the velocity input. The channel temperature between the outside blind and glazing is assumed to be the ambient air temperature T_{out}.

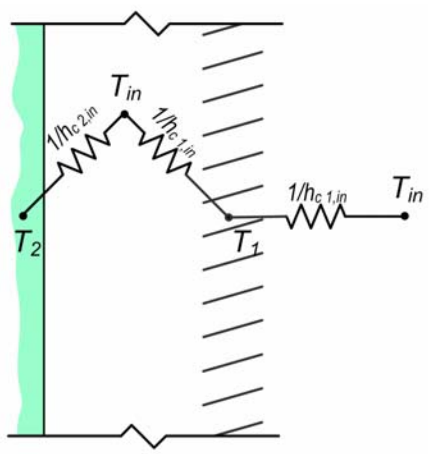


Figure 2. Convective heat transfer in an indoor side venetian blind.

Due to the coupled nature of the convective and radiative heat transfer in the glazing-shading system, an iterative method was used for solving the layer temperatures, longwave radiative and convective fluxes, by performing an energy balance on each layer with the absorbed quantities in each layer as source terms. The reader is referred to Wright (1998) for details of the heat transfer calculation.

Combining the results of the simplified solar-optical model with the heat transfer analysis gives a complete picture of the energy flowpaths through the center glass window model. The basis for comparison of each blind configuration is the net heat gain into the indoor space, which is comprised of the transmitted solar flux, the longwave radiative flux and the convective flux, as depicted in Figure 3. Table 1 summarizes the relevant output variables generated from the heat transfer analysis and the multi-layer calculation of Kotey and Wright (2006).

RESULTS AND DISCUSSION

Windows analyzed in this study are assumed to be located in Waterloo, Ontario (latitude 43.5˚ and longitude 80.6˚ west), southfacing and vertically mounted in a low rise structure.

The analysis considers winter and summer conditions defined by meteorological data taken from the University of Waterloo Weather Station files for January 01, 2004 and July 01, 2004, respectively. The data include hourly ambient temperature and wind speed, as shown in Figure 4. Data for the beam and diffuse irradiance on the south facing window were taken from Kotey and Wright (2006) and are also shown in Figure 4. The reader is referred to Kotey and Wright (2006) for details on hourly beam and diffuse irradiance data, as well as solar optical properties of the outdoor environment, glazing layers and blind slats.

The glazing layer longwave radiative properties are based on 3mm clear glass with an emissivity of 0.84. The glazings are treated as opaque, uniformly irradiated grey and diffuse reflectors/emitters of longwave radiation. Using Kirchhoff's law, the longwave reflectivity is 0.16.

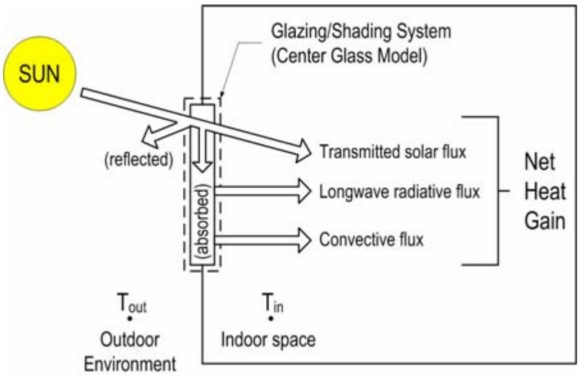


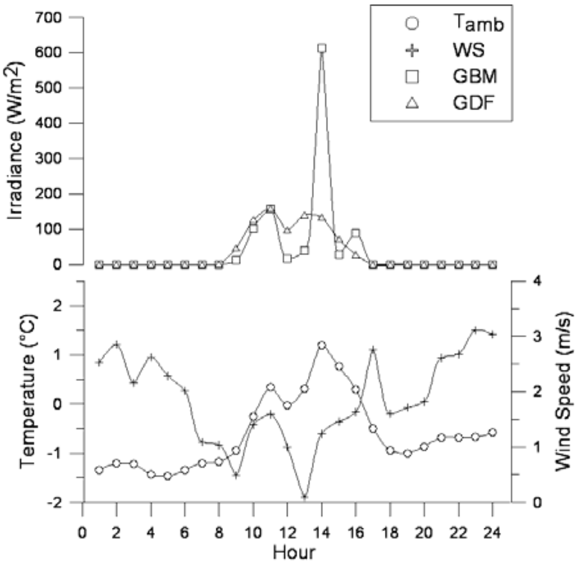
Figure 3. Net heat gain into the indoor space and its components.

Table 1: Relevant output variables

SYMBOL	DESCRIPTION
NtHtGain	Net heat gain to indoor space (W/m^2)
TransSys	Total (beam and diffuse) transmitted flux through the system (W/m^2) (Kotey and Wright (2006))
q_rad in	Longwave radiative flux to indoor space (W/m^2)
q_conv in	Convective flux to indoor space (W/m^2)
S(1)	Absorbed flux in layer 1 (W/m^2) (Kotey and Wright (2006))
S(2)	Absorbed flux in layer 2 (W/m^2) (Kotey and Wright (2006))
S(3)	Absorbed flux in layer 3 (W/m^2) (Kotey and Wright (2006))

The solar optical properties of the blind slats analyzed in the simplified solar analysis of Kotey and Wright (2006) are based on measurements by Jiang (2005). The long-wave emissivity of the slats used in the study is 0.85, a typical value for painted surfaces. The slat width, slat spacing and the slat angle of the venetian blind considered are w = 14.8 mm, s = 12.3 mm and Φ = 10˚ respectively. Using this geometry and slat longwave radiative emissivity, the effective longwave properties of the blind were calculated using the method of Yahoda and Wright (2004).

a)



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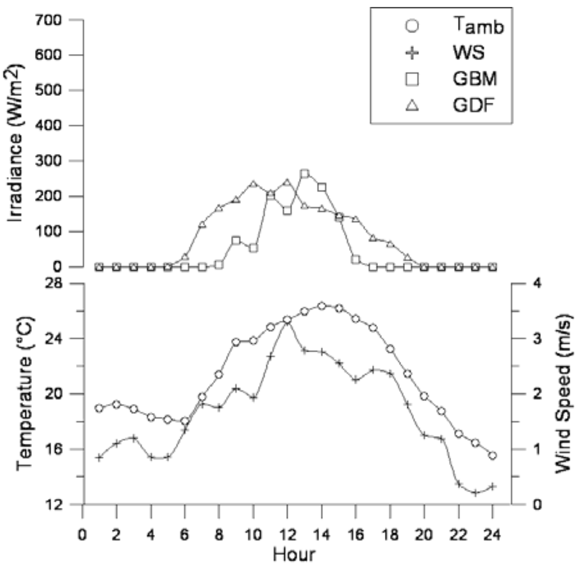

Figure 4. Hourly beam (GBM) and diffuse (GDF) irradiance (Kotey and Wright (2006)), ambient temperature (T_{amb}) and wind speed (WS) on a south facing window- a) winter day - Jan 01, 2004, b) summer day – July 01, 2004.

The gap spacings between layers (used in convective heat transfer correlations) for the three configurations are as follows:

- Indoor/Outdoor-side blind: blind to glazing spacing and double glazing gap spacing are 0.046 m and 0.0127 m respectively (blind spacing is measured from center of blind).
- Between-the-panes blind: center of blind is 0.012m from glazing on either side.

The height of the glazing and venetian blind layers is 1m.

Figures 5 and 6 show the absorbed quantities in each layer for the summer condition reproduced from Kotey and Wright (2006). The absorbed quantities are the source fluxes used in the heat transfer analysis, and serve as a reference for discussion of the heat transfer analysis results.

To gain an appreciation for the effects of different blind locations on energy transfer, a standard double glazed window (3 mm clear glass, 0.0127 m air gap) has been analyzed. Figure 7 shows the hourly net heat gain and its components for the double glazed window for the summer condition. During the sunlit hours (hour 6 to hour 19), the net heat gain to the indoor space is dominated by transmitted solar radiation, with a small contribution from the radiative and convective fluxes. This is the expected result for a non-shaded glazing which does little to block the solar radiation.

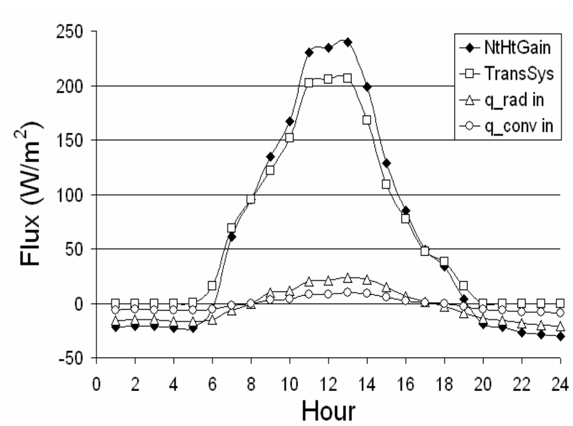

Figure 7. Hourly net heat gain and its component fluxes through a standard double-glazed window on a summer day (July 01, 2004).

Figures 8 and 9 compare hourly net heat gain and its components for the three venetian blind configurations in the summer condition for both dark and light blinds. Looking at Figure 8 a) in the sunlit period, the heat gain for an indoor dark blind is reduced only slightly from the double-glazed window case. However, the convective and radiative fluxes are quite significant, making up more than 75% of the heat gain.

For an indoor venetian blind, convective heat transfer between the window and indoor air takes place at the indoor glazing surface and both front and back surfaces of the blind (Figure 2), resulting in a relatively large convective gain to the indoor space.

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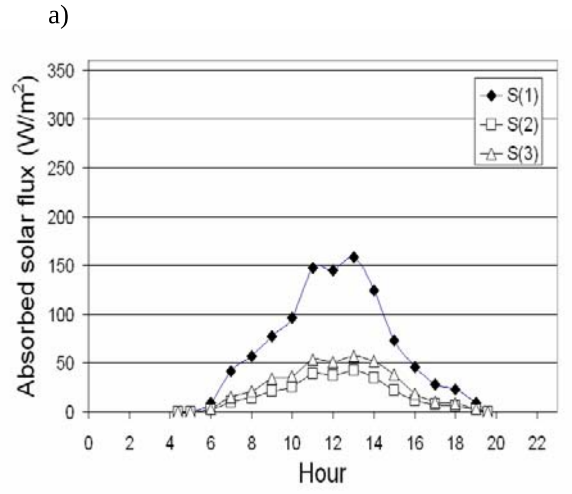

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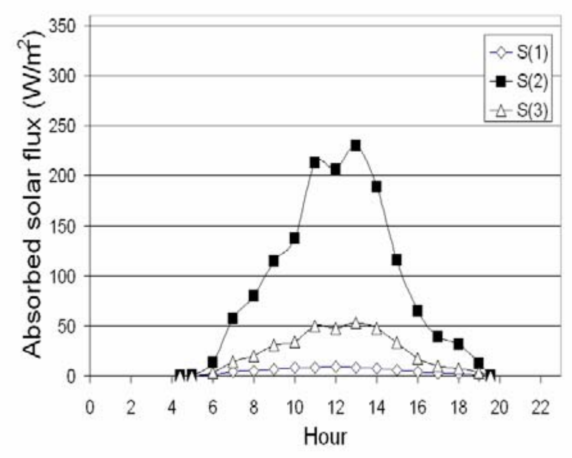

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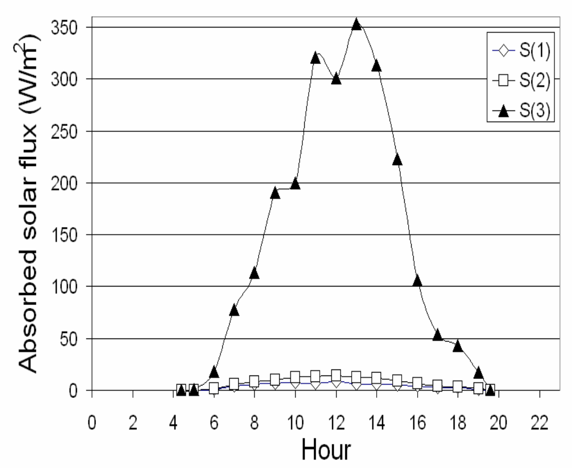
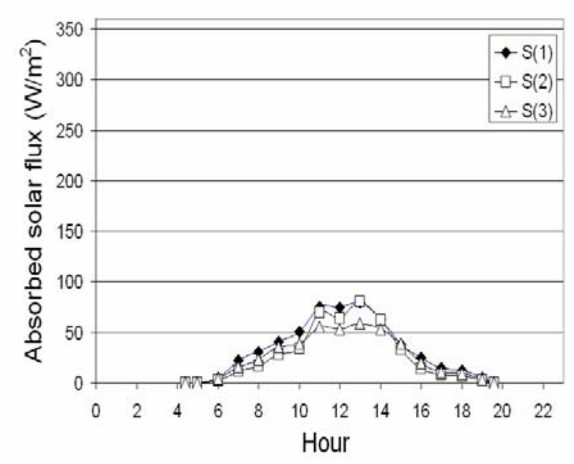


Figure 5. Hourly absorbed fluxes in each layer of the window with dark-coloured blind on a summer day (July 01, 2004) - a) Indoor-side blind b) Between-the-panes blind c) Outdoor-side blind. Reproduced from Kotey and Wright (2006).

a)



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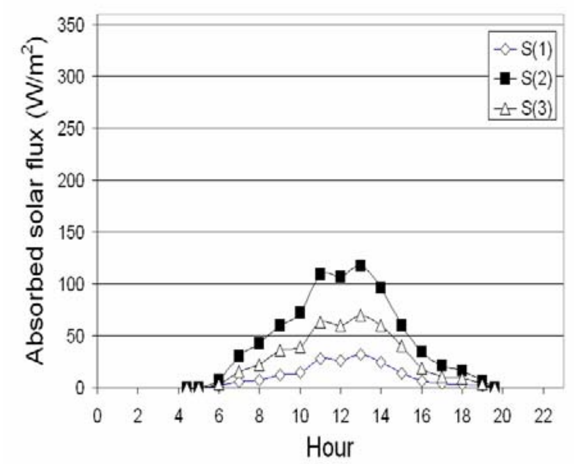

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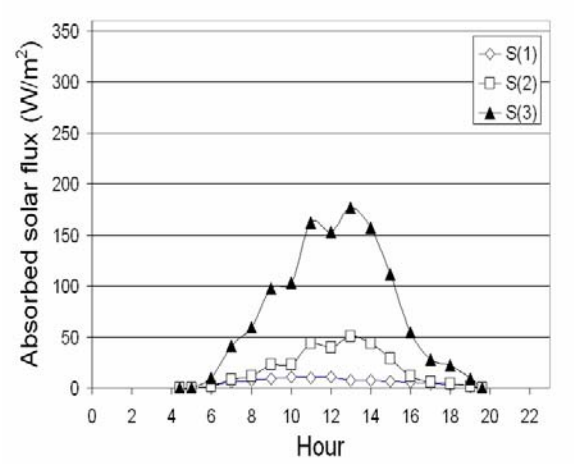

Figure 6. *Hourly absorbed fluxes in each layer of the window with light-coloured blind on a summer day (July 01, 2004) – a) Indoor-side blind b) Between-the-panes blind c) Outdoor-side blind. Reproduced from Kotey and Wright (2006).*

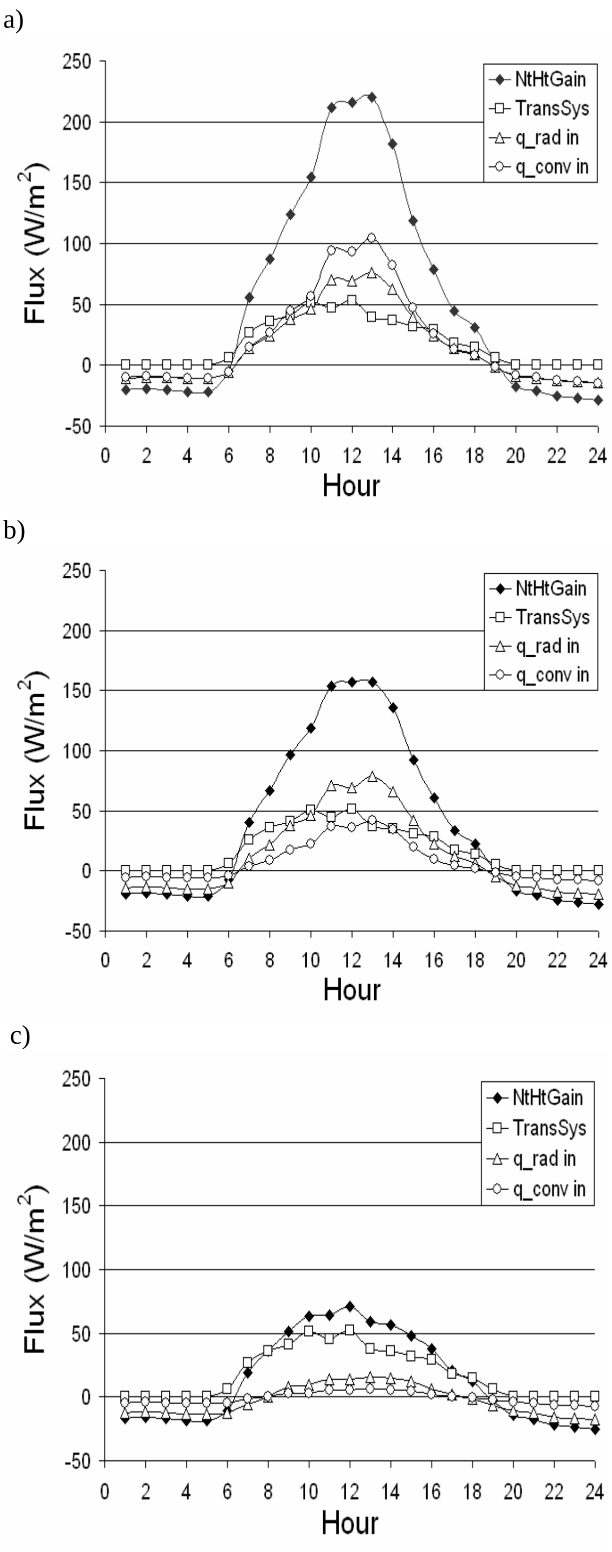

Figure 8. Hourly net heat gain and its component fluxes through a window with dark-coloured blind on a summer day (July 01, 2004) – a) Indoor-side blind b) Between-the-panes blind c) Outdoor-side blind.

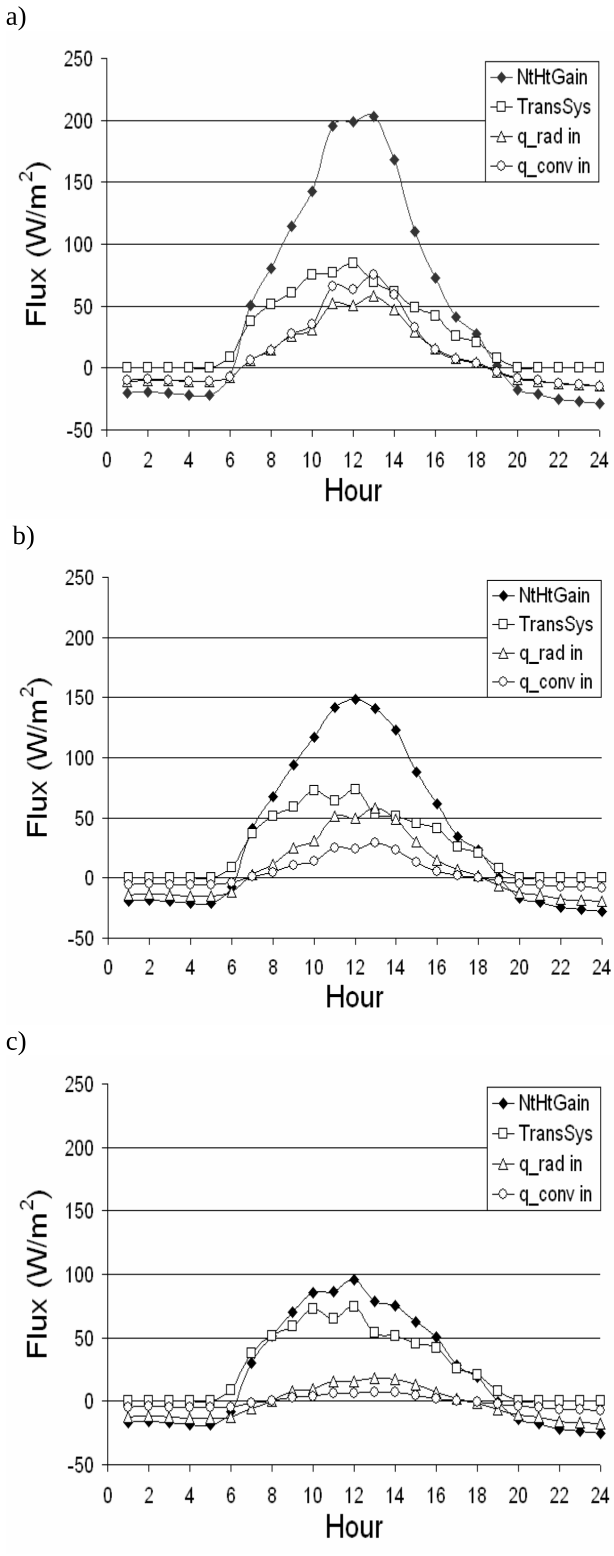

Figure 9. Hourly net heat gain and its component fluxes through a window with light-coloured blind on a summer day (July 01, 2004) – a) Indoor-side blind b) Between-the-panes blind c) Outdoor-side blind.

The hourly results for the between-the-panes blind configuration, as depicted by Figure 8 b), show a significant reduction in net heat gain. Compared to the indoor blind, it is evident that during the sunlit period the convective gain for a between-the-panes blind has been reduced considerably, while the radiative and transmitted solar fluxes are mostly unaffected. The reduction in the convective gain is accounted for by considering that only the inside face of the interior glazing communicates convectively with the indoor space, as opposed to both glazing and blind surfaces for an indoor blind configuration.

The outdoor blind results, shown in Figure 8 c) show a dramatic reduction in net heat gain to the indoor space, due to the very small radiative and convective components. The transmitted component, which remains effectively constant in all three configurations with dark blind, is now the dominant component. System transmission is almost entirely from diffuse irradiation as shown in Kotey and Wright (2006), because the orientation of the blind is such that for the summer condition, virtually all the beam radiation is blocked. As depicted in Figure 5 c), the outer blind solar absorption is very high, with the glazings absorbing very little solar radiation. Since virtually all of the absorbed solar energy is present in the outside blind layer, this energy is lost to the environment through forced convection, with very little of the energy ending up in the indoor space.

Similar trends can be seen for the light coloured blind. Solar transmission is higher due to the increased slat solar reflectance, with little variability between the three configurations. As shown in Figure 6, the absorbed quantities for the light blind are lower in comparison to the dark coloured blind, but follow the same trends. As a result, the radiative and convective gains to the indoor space are noticeably smaller. Looking at Figure 8 c) and 9 c), an interesting observation can be made; the heat gain for the light blind case is higher than for the black blind case, a result which may not be anticipated. In this case, because the radiative and convective gains are small, total transmission becomes the dominant component and therefore the controlling factor for net heat gain.

Looking at Figures 8 and 9 for the periods when solar irradiation is zero, it is interesting to note the relative magnitudes of the night time heat loss from the indoor space. Compared to the net heat gain during sunlit hours, the absolute value of the night time net heat loss is, depending on blind location, as much as an order of magnitude lower. These results demonstrate the variability of solar gain through glazing/shading systems imposed on an indoor space.

Figure 10 shows results for indoor and outdoor light blind configurations for the winter condition. Similar trends can be observed with respect to the effect of blind location on net heat gain components. The low solar altitude on the winter day provides a high beam component of solar radiation, resulting in a heat gain peak that is twice as high as in the summer condition.

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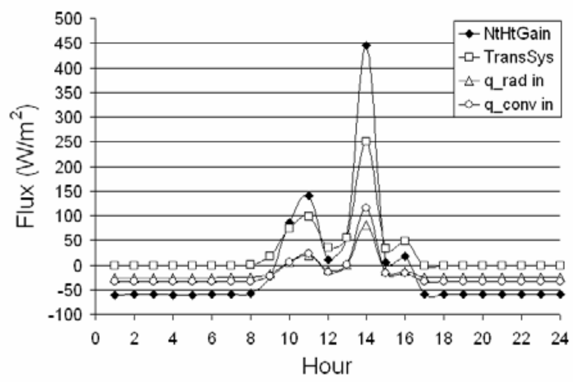

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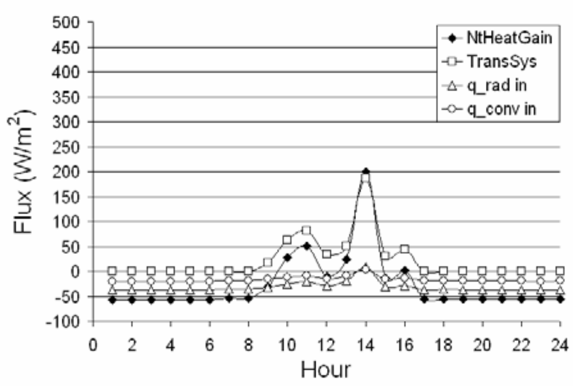

Figure 10. Hourly net heat gain and its component fluxes through a window with light-coloured blind on a winter day (January 01, 2004) - a) Indoor-side blind b) Outdoor-side blind

Results for the summer condition show that total solar transmission is relatively unaffected by the change in blind location for either dark or light blinds. However, when the beam component of solar irradiation is high, the scattering effect of the blind relative to its location in the glazing/shading array can become important. This is seen in the winter condition results, where total solar transmission is not constant with respect to blind location.

CONCLUSION

The need to fully describe the solar optical and thermal characteristics of complex glazing/shading systems is critical for providing the necessary inputs into building energy simulations to assess the potential in energy savings. A previous study analyzed the solar optical characteristics of three glazing/shading configurations using a simplified multi-layer solar optical model. The current study complements this work by addressing the heat transfer problem, and provides a comparative analysis of the net heat gain to an indoor space and the relative magnitudes of its components. The results are presented against a standard double-glazed window.

The results show that, in general, the net heat gain to the indoor space can be reduced considerably with a venetian blind in place, but the radiative and convective fluxes can be significant. In the case of a dark-coloured indoor-side blind, the radiative and convective gains can become large enough to offset the decrease in solar transmission, and have little effect on reducing solar gain. In fact, a dark indoor blind can increase the peak cooling load. In effect, the dark blind absorbs solar radiation and readily converts it into convective and longwave radiative energy without a time lag typically present with large thermal mass constructions. The optimum blind position, in terms of energy savings, is the outdoor-side blind, where dramatic decreases in net heat gain to the indoor space have been shown. Also, the night time heat loss is shown to be relatively small compared to the large variable load that solar gain imposes on the indoor space. The study, in combination with the previously developed solar-optical analysis, completes the required set of information needed to describe complex glazing/shading systems in the context of building energy analysis. In addition, the solar optical and thermal models used in the study have been developed with emphasis on computational speed. This is an important requirement in any building simulation sub-model.

ACKNOWLEDGMENTS

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