



MODELING FENESTRATION WITH SHADING DEVICES IN BUILDING ENERGY SIMULATION: A PRACTICAL APPROACH

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ABSTRACT

The use of operable shading devices impacts building loads significantly. The need exists for an explicit treatment of window shading devices in the design of energy efficient buildings through simulation. A general framework for modeling complex fenestration systems has recently been implemented in ESP-r. The underlying models have been developed with emphasis on computational efficiency and straightforward input requirements. The capabilities, which currently include modeling of slat-type blinds in any arrangement between glazing layers, are summarized and an overview of the solar optical and thermal models is given. An analysis of slat-type blind models was carried out comparing the complex fenestration facility in ESP-r to slat-type blind models in EnergyPlus. Simulations were conducted for a test cell with a south facing window. The results show good agreement between the two simulation programs. Considering the complicated nature of shading layer modeling, the new complex fenestration facility in ESP-r yielded encouraging results in this preliminary study.

INTRODUCTION

Given the current architectural trend toward highly glazed facades in commercial buildings, the management of solar gain is an important consideration in energy efficient building design. Solar gain through windows represents the most variable and largest gain in a building. The appropriate use of shading devices saves cooling energy and reduces the peak cooling load. Shades with switchable properties such as slat-type venetian blinds can be optimized to balance solar gain with glare and daylight levels.

The case for improved solar gain control in buildings can be made from an economic standpoint by considering the effect of summertime peak loads on electricity distribution. In southern Ontario, Canada, for example, the biggest contribution to the peak electrical load comes from residential and commercial sector cooling on hot summer days. The cost to construct and maintain the power distribution grid is directly related to the peak demand. Thus, the potential reduction in peak cooling load through the effective use of shading devices in buildings can have a large impact on electricity demand profiles.

In addition, the shift toward better insulated building envelopes, reduced air-infiltration rates and

solar utilization via large south facing glazing is leading to indoor spaces that are more sensitive to solar gain. Without appropriate solar gain control strategies, building peak cooling loads and increased cooling energy can offset any benefit from thermally benign envelopes. Control of solar gain is thus not only necessary in current highly glazed, poorly insulated buildings, but is critical in the design of new energy efficient residential and commercial green buildings.

Shading devices such as operable louver blinds, roller blinds, drapes, overhangs, and retractable awnings are simple and effective devices, yet their impact on peak cooling loads and annual energy consumption is poorly understood. Until recently, the impact of shading devices has been generally neglected in envelope design and equipment sizing. Few tools exist that can aid the building designer in quantifying the impact of window shading on building loads. With the renewed impetus toward energy efficiency in building design, the potential benefits of automated switchable shades are significant, and the ability to appraise the impact of such technologies is in demand. There is a clear need for an explicit treatment of window shading layers in building energy simulation. Control schemes for automated shades can be readily integrated with simulation, achieving fine resolution of solar gain control to determine the resulting impact on thermal loads, electrical lighting power and luminance levels.

In order to bridge the gap between research and design practice, such models require practical, straightforward approaches to be successfully deployed, but need to adequately represent real-world complexity. This paper presents a simulation tool for the assessment of window shading strategies on building performance that attempts to adhere to these principles. A graphical interface is aimed at quick synthesis of complex fenestration assemblies. The underlying models, linked with ESP-r, resolve the complexities of energy transport interactions between glazing/shading systems and the building thermal domain.

BACKGROUND

Centre-of-Glass Analysis

The solar and thermal characteristics of glazing systems are well understood. The energy flowpaths through fenestration can be divided into three sections: centre-of-glass, edge-glass and frame. Of interest here is the centre-of-glass region, as it

typically accounts for the majority of heat transfer through windows. The centre-of-glass region is traditionally modeled as a one-dimensional heat transfer problem.

The flow of solar energy through fenestration elements in a building envelope is non-trivial due to the coupling of the three modes of heat transfer. Solar flux incident on a window is reflected, absorbed and transmitted at each glazing layer, resulting in many inter-reflections of solar rays in the glazing array. 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. The analysis can thus be carried out in two steps. First, a solar analysis determines the transmitted, reflected and absorbed solar fluxes at each glazing layer. Second, using the absorbed quantities as source terms, a heat transfer analysis is carried out to establish an energy balance at each layer considering convection and longwave radiation exchange. Figure 1 illustrates the centre-of-glass heat transfer model.

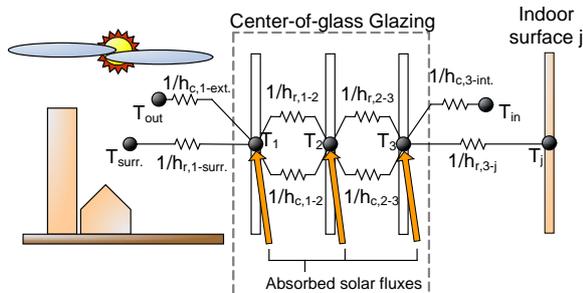


Figure 1: Centre-of-glass heat transfer model.

The conventional one-dimensional centre-of-glass glazing analysis can be extended to include shading layers such as slat-type blinds, roller blinds, drapes and insect screens. The analysis of shading layers can be simplified by treating the layer as a planar, homogenous layer that is included in the series of layers that make up the glazing/shading system. However, the presence of a shading layer adds significant complexity to the centre-of-glass glazing analysis. Solving for the solar fluxes is complicated by the scattering of solar beam energy due to the presence of non-specular shade materials. Shading devices such as slat-type blinds are also semi-transparent to longwave radiation (i.e., diathermanous). This results in ‘jump’ resistors (Figure 2) which account for non-adjacent layers in thermal communication with one another. The problem is even more complicated when a blind is present on the indoor or outdoor side.

The presence of shading devices also affects the convective air flow around the window. Figure 3 illustrates the additional jump resistors needed to describe the convective heat transfer situation for three shade configurations: outdoor, between glass panes and indoor.

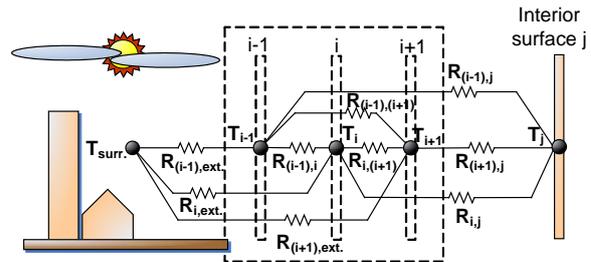


Figure 2: Longwave radiation network with jump resistors in which any layer can be diathermanous.

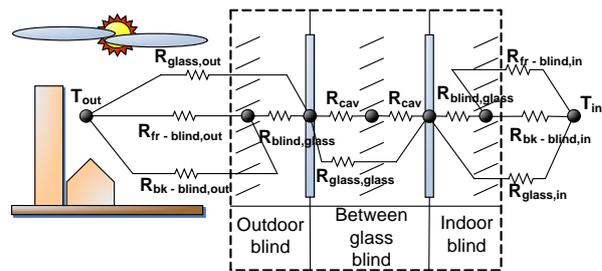


Figure 3: Convective resistance network for three shade configurations.

Underlying Shading Models

Recent efforts in window shading research at the University of Waterloo’s Advanced Glazing System Laboratory (AGSL) have produced a set of practical and flexible models that characterize shading layer properties and the interaction of such shading layers within a glazing system. The strategy is to separate the solar and thermal analysis, as in conventional glazing analysis, and to treat the shading layer as an equivalent homogeneous layer, suitable for one-dimensional centre-of-glass analysis. Completed to date are improved solar multi-layer methods for coping with scattering shading layers, a general treatment of longwave radiation exchange with diathermanous layers, the development of between glass slat blind convection models and approximate convection models for indoor/outdoor blinds. The models have been developed with emphasis on generality and computational efficiency, while retaining accuracy. These models are applied to the development of the complex fenestration facility in ESP-r.

It is worth noting that the only model component that relies heavily on empirical information is the convective heat exchange between glazing/shading layers. Solar and longwave radiation models that characterize glazing/shading layer interaction are based on fundamental heat transfer relations valid for any combination of glazing/shading layers.

Effective Solar-Optical and Longwave Radiative Properties for Slat Blinds

Based on previous work by Yahoda and Wright (2005), Kotey et al. (2008) have developed simplified effective solar optical property models for slat-type

blinds intended for building energy simulation. Kotey et al. (2008) assume that the slats reflect and transmit solar radiation diffusely. Slat material properties are assumed to be independent of the angle of incidence. A four or six surface radiosity enclosure flat slat model is used to account for beam-diffuse reflectance and transmittance, depending on slat illumination. Diffuse-diffuse solar properties and longwave radiative properties are calculated using a four surface flat slat model. A curvature correction is applied, as the flat-slat model over-predicts blind transmission when the solar profile and slat angles are aligned.

Solar Multi-Layer Model

Wright and Kotey (2006) have developed a method by which existing solar optical models for systems of 1-D centre-of-glass specular glazing layers can be extended to include the effect of scattering shading layers. The model is based on the assumption that only specular and/or isotropically diffuse components of solar radiation result from the interaction of insolation with any item in a glazing/shading layer array. An expanded set of solar optical properties is assigned to each layer accordingly to account for beam-beam, diffuse-diffuse and beam-diffuse (scattered) solar fluxes. Spatially averaged effective properties are used to characterize shading layers. The model provides significant detail concerning the quantities of reflected, transmitted and absorbed solar radiation. The method is general enough to allow for introduction of incident solar radiation both on the outdoor side and indoor side of the window. The resulting computer code is well suited for use within time-step simulation (Wright and Kotey 2006).

Longwave Radiation Exchange

The presence of diathermanous shading layers adds complexity to the thermal resistance network of the 1-D glazing/shading array. Standard methods for determining the radiant exchange, such as the net radiation method, are general enough to cope with jump resistors, and the temperature solution can still be resolved accurately. However, methods for calculating glazing system U-value and SHGC (e.g., Wright 1998) can be in error when a jump resistor is present. A new method for calculating the indices of merit of multi-layer systems has been developed by Wright (2008) extending earlier work by Collins and Wright (2006). This method is sufficiently general to handle any combination of diathermanous and opaque layers in the glazing/shading system.

Although the U-value and SHGC are not required to characterize complex fenestration elements for time-step building simulation, Wright's (2008) method is useful in determining the longwave radiant exchange. This method allows for the determination of individual radiant heat transfer coefficients between any pair of surfaces in an enclosure containing any combination of diathermanous and opaque surfaces. The ability to track individual

surface exchanges in a room enclosure containing diathermanous surfaces makes book keeping of radiant fluxes manageable.

Convection Models

Convective heat transfer in a sealed cavity with a large aspect ratio between two glass panes has been well characterized. Standard correlations exist (e.g., Shewen et al. 1996) and can be used for different fill gas types and mixtures. With the addition of a shading attachment, the nature of convective heat transfer is highly dependent on the position of the blind. Fill gas flow in a sealed cavity with an integral, or between-glass, slat-type blind behaves in a predictable manner. Placing a shading layer on the outdoor or indoor side roughly triples the area of convective heat transfer to the ambient or indoor air, respectively. Air flow around an outdoor blind is dictated by the outdoor conditions whereas for indoor blinds, ventilation and temperature conditions influence the flow. In the simplest case, isolated buoyancy flow is driven by indoor temperature differences. The prediction of convective heat transfer coefficients for outdoor and indoor blinds is non-trivial, however, even with approximate values for the coefficients, the sheer increase in convective heat transfer area results in large convective fluxes to the ambient and indoor air in the presence of outdoor and indoor blinds, respectively.

Between-the-Glass Slat Blind

The effect of a slat-type blind on the convective exchange within a glazing cavity is well understood. Huang, Wright and Collins (2006) conducted an experimental investigation into the effects of a slat-type blind on convective and radiative heat transfer inside a vertical window cavity. A simplified convective heat transfer model was developed that compared well with experimental results. The model essentially modifies any vertical cavity correlation (e.g., Shewen et al. 1996) to account for the presence of the blind by applying a modification factor to the slat width which effectively increases the cavity spacing.

Indoor Blind

The nature of natural convection flow around an indoor slat-type blind is a subject of ongoing research (e.g. Collins 2004, Shahid and Naylor 2005, Naylor et al. 2006). To date, a general correlation describing convective exchanges with an indoor slat-type blind does not exist. The problem is further complicated by the various flow and mixing conditions that may exist in practice and deviate from the steady laminar buoyancy flow assumption.

Shahid and Naylor (2005) have shown that the tip of the slat to glass spacing can significantly affect the energy performance of a window with an indoor venetian blind. As the blind is positioned closer to the window, the convective exchanges between the inner glass and blind surfaces to the indoor air are

diminished, while convective exchange between the inner glass and blind surface is increased. Given such a dependence on blind to glass spacing, an approximate convection model has been developed by Wright et al. (2008). The model predicts heat transfer coefficients for a shading layer that is exposed to an indoor environment, as a function of the distance from the tip of the blind slats to the glass surface. The model is an approximate method and does not account for various frame and window sill designs that may impede the flow. Further study of the general problem is recommended; specifically in regard to effects of imposed air flow types and window geometry, to provide insight on the validity of using this simplified model.

Outdoor Blind

An approximate convection model for an outdoor blind consists of applying a supplied external convective heat transfer coefficient to the front and back of the blind and outdoor glass surface. The convective heat transfer area is thus tripled. The outdoor convection coefficient may be determined within a building energy simulation based on wind speed and direction, surface orientation and temperature conditions. Since the outdoor blind is exposed to forced convection, the interaction between the blind and outermost glass surface is ignored. It is assumed that the blind has no influence on the air flow at the outdoor glass surface.

ESP-R IMPLEMENTATION

The Complex Fenestration Construction (CFC)

The fundamental strategy for the implementation of the AGSL shading models is the design of a new multi-layer construction within ESP-r, the Complex Fenestration Construction (CFC). Its design is an attempt to contain the glazing/shading system in a separate facility while preserving current ESP-r functionality. The CFC type utilizes the ESP-r multi-layer nodal scheme, with provisions to cope with shading layer complexities.

Only slat-type blind models are currently implemented in the CFC type, however, the framework is general enough for the addition of other types of shading layers. The CFC type can be applied to vertical external surfaces in ESP-r and can be used to model windows with or without shading devices.

Solar Processing

The main advantage of the CFC solar processing routines over the existing ESP-r transparent multi-layer construction (TMC) is in the way solar optical properties of glazing/shading layers are characterized. Each glazing/shading layer is treated explicitly in the CFC solar calculation. Off-normal solar optical properties for glazing/shading layers are calculated at each time-step based on their normal incidence input values. These input properties can be easily obtained from glazing manufacturer's data or

the International Glazing Database (IGDB) (LBNL 2008). A multilayer accounting technique (Wright and Kotey 2006), which copes with scattering layers, is then used to determine how much of the incident solar flux is absorbed at each layer, reflected or transmitted.

With such a framework in place, the control of individual layer properties (e.g., slat angle of a blind) at the time-step level becomes straight forward. The CFC thus introduces the ability for simulating dynamic control of solar gain through fenestration without cumbersome input requirements such as alternate optical property sets. Alternate property sets currently used for TMC control are difficult to establish, especially if the system includes a shading layer.

Thermal Processing

The absorbed fluxes obtained from the solar multi-layer calculation for each layer of the CFC are used as input to the nodal conservation equations in ESP-r's thermal calculation. The placement of the shading layer (e.g., indoor/outdoor/between-the-glass) has a significant impact on the distribution of absorbed solar fluxes, and thus affects considerably the portion of solar energy flowing inward to the zone.

In ESP-r, the radiant exchange within an air cavity of a multi-layer construction is currently lumped with the convective exchange into a constant gap resistance. Interior surface longwave radiation exchange is determined by an analytical method that generates a linearized longwave radiation coefficient between each pair of indoor surfaces (details in (Clarke, 2001)). Exterior surface longwave radiation exchange is determined by considering the difference between emitted and received fluxes from each surface node exposed to sky, ground and surrounding buildings portions of the exterior hemispherical envelope.

Longwave radiation exchange in a CFC type is represented by nodal flux injection/extraction terms. The method is generalized to allow for any number of diathermanous layers in any configuration, to communicate with intra-construction nodes as well as external surroundings and interior surface nodes. The method yields the heat flux between each pair of surfaces by determining an exchange factor that accounts for the direct view (shape) factor as well as all reflected fluxes in the enclosure.

The strategy for resolving convective exchange between CFC layers is to calculate gas gap resistances on a time-step basis and replace the existing constant gap resistances within ESP-r with these temperature/time-dependent resistances. For convective jump resistors, the strategy is the same as for longwave exchange, namely to resolve these by using convective flux nodal generation terms. The combination of convective resistances and convective generation terms account for the presence of indoor

or outdoor blinds and thus the resultant increase in convective heat transfer area.

Graphical Front End

To reduce the input burden on the user, a simple graphical user interface tool, the Glazing Shading Editor (GSLEdit), has been developed at the Advanced Glazing Systems Laboratory (Wright et al. 2009). The editor was designed for quick synthesis of a glazing product with or without shading components. The editor compiles system information into an organized output file. When a CFC is specified in ESP-r, the GSLEdit file is imported to automatically generate the inputs necessary to describe the CFC composition. System composition in GSLEdit is based on access to glazing and shading layer databases.

CFC MODEL COMPARISON

A preliminary study was conducted to compare slat-type blind models featured in EnergyPlus 2.0 with the Complex Fenestration Construction slat-type blind models in ESP-r. EnergyPlus shading models serve as a useful comparison, as they have been compared to experiments carried out by Loutzenhiser et al. (2008).

Simulation Methodology

The model geometry consisted of a room with a large south facing window such that solar gain through the window represents the largest heat gain to the interior. An insulated envelope ensures that absorbed solar radiation on opaque sections is mostly rejected to the environment. Table 1 summarizes the model parameters.

The thermal zone walls, window and roof were modeled with an exterior boundary condition, which includes exposure to wind, shortwave and longwave radiation. The floor was modeled with a ground boundary condition using a default monthly temperature profile. The Perez et al. (1990) model was used in both simulation programs to resolve the solar irradiance incident on external surfaces.

Test Cases

In comparing the shading models of the two simulation codes, of particular interest is the impact of the blind position relative to the glazing, and the impact of a shaded window compared to an unshaded window. Table 2 summarizes the test cases examined in the study.

Table 1: Simulation parameters.

Model Parameters	Description
Walls, floor, roof construction	Exterior layer: Brown brick – 10 cm Mid layer: Glasswool – 7.5 cm Interior layer: Breeze block – 10 cm
Climate data	CWEC Toronto, Canada
Simulation period	July 7, 0-24 h

Site exposure	Rural/country
Ground reflectivity	0.2
Ground temperature	22.3°C
Thermostatic control	Basic ideal thermostatic control with cooling setpoint at 25°C
Ventilation and infiltration	No ventilation / no infiltration Default ESP-r interior convection correlations.
Warm up days	4
Time steps per hour	6

Table 2: Simulation test cases.

Case 1: Double Glazing	Unshaded window – reference case 6mm clear glass with 12.7mm air gap
Case 2: DG with OUTDOOR slat blind.	Slat orientation: horizontal Slat angles: 0° (horizontal) and 45° Slat width: 0.0127 m Slat spacing: 0.01058 m
Case 3: DG with BETWEEN- GLASS slat blind	Slat thickness: 0.00033 m, flat slats Distance to glass (Case 2 & 4): 0.04 m Between-glass gap space (Case 3): 0.0254 m Slat reflectivity: 0.5
Case 4: DG with INDOOR slat blind	Slat emissivity: 0.85 Slat transmittance: 0 Opening multipliers for Case 4 (EnergyPlus only): 1

EnergyPlus Set-up

Solar optical property calculations in EnergyPlus 2.0 are based on WINDOW 5 algorithms (Finlayson et al. 1993). The flat horizontal slats are considered to be perfect diffusers in the EnergyPlus 2.0 blind model. The solar-optical model of slat-type blinds, which is dependent on the slat geometry (width, spacing, angle) and slat material optical properties, is based on (Simmler, Fischer and Winkelmann 1996). Ground and sky diffuse radiation components are treated separately for blind optical property calculations. Heat transfer between the window and shading device is calculated using ISO 15099 (2003). The thermal capacity of glazing/shading layers is neglected. More detail on EnergyPlus window shading models is provided in EnergyPlus documentation (EnergyPlus Engineering Reference 2008).

CFC Set-Up

The Complex Fenestration Construction (CFC) type was used in ESP-r to model the glazing/shading centre-of-glass system. Glazing/shading layers in the CFC type are treated explicitly within the nodal scheme of the thermal building domain. Thermal mass of the glazing/shading layers is not neglected and is assigned in the same manner as opaque envelope constructions. The calculation of the slat blind solar optical properties for incident diffuse radiation does not differentiate between sky-diffuse and ground-diffuse components.

In both EnergyPlus and ESP-r models, edge and frame effects of the window were not considered.

Results

Several comparisons were made to quantify the effect of shaded glazings on solar transmission and cooling load. All hourly simulation results are based on a 24 h simulation period for July 7 CWEC data for Toronto, Canada.

Solar transmission and cooling load results for Case 1 are shown in Figure 6. For each blind configuration, two slat angles, 0° (horizontal) and 45° (ccw, blocking the sun), were simulated. It was found that the solar transmission curves for Case 2-4 are almost identical hence only Case 2 solar transmission results are shown in Figure 7. Due to the high transmittance of clear glass, the position of the blind has little effect on the overall system transmittance. This would not be the case for other types of glazings with coatings and tints. Figures 8, 9, and 10 present the hourly cooling load results for Case 2, 3 and 4, respectively.

Discussion

Overall, the comparison of EnergyPlus 2.0 and ESP-r CFC slat blind model results are encouraging. Hourly cooling loads for the outdoor, between-glass and indoor blind cases are in good agreement, with differences in the same range as the reference double glazing case.

A consistent lag between ESP-r and EnergyPlus results occurring in the afternoon hours of the simulation period is observed in all cases except for the indoor blind case. The hourly beam and diffuse radiation values incident on the south window for both codes are in very good agreement, ruling out the resolution of global solar radiation as a source of discrepancy. The lag in cooling load curves is most likely attributed to different interior surface convection algorithms in the respective codes. A further investigation into the convection models revealed that employing the same natural buoyancy correlation in both codes reduced the discrepancy significantly, but not entirely. Thermal mass of the glass and shading layers in ESP-r had only a minor effect on the lag. A more thorough investigation into the heat balance approach of both codes could unearth more reasons for the observed differences, however, that investigation was not warranted within the scope of this preliminary study.

In examining the solar transmission curves of Figure 7, there is a discrepancy for slats angled at 45°. This is the result of different diffuse radiation treatments in the two codes. EnergyPlus considers sky-diffuse and ground-diffuse components separately whereas ESP-r lumps the two components and considers incident diffuse radiation to be uniform across the hemisphere seen by a vertical surface.

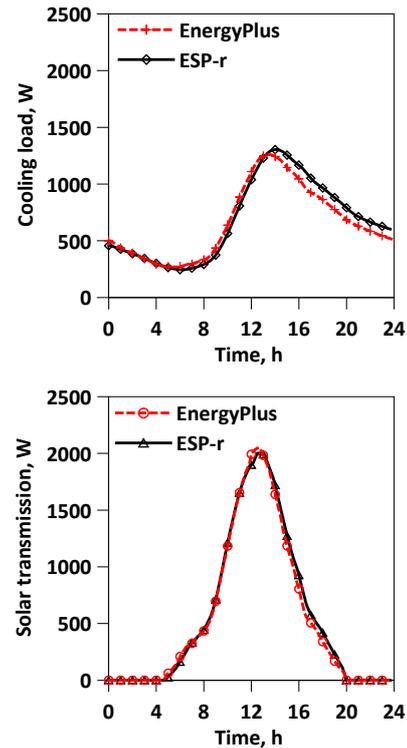


Figure 6: Results for Case 1 - Double Glazing.

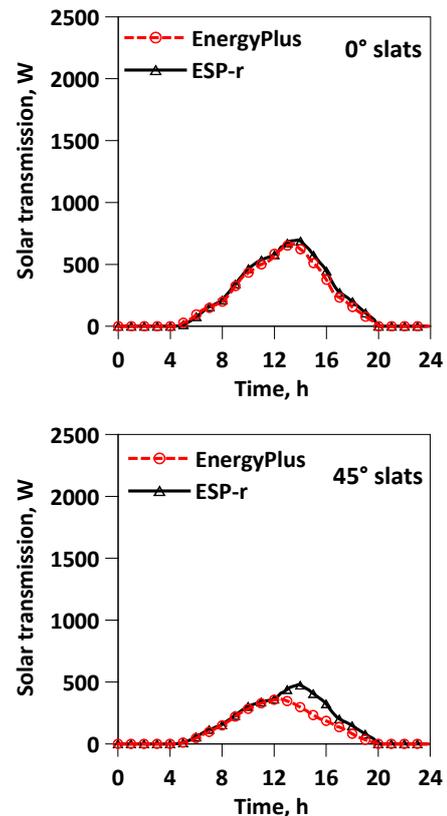


Figure 7: Solar transmission results for Case 2 – Outdoor Blind.

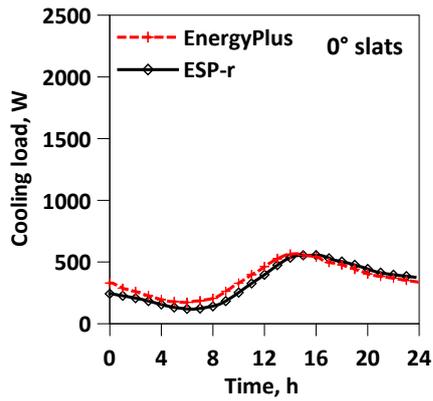


Figure 8: Cooling load results for Case 2 – Outdoor Blind.

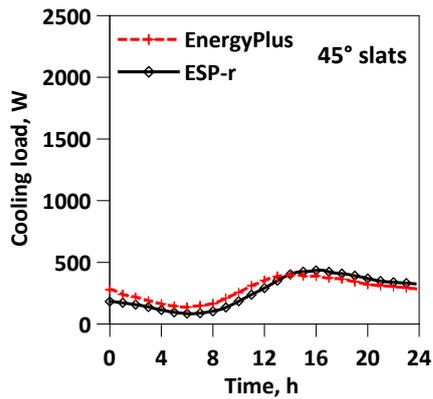


Figure 9: Cooling load results for Case 3 – Between Glass Blind.

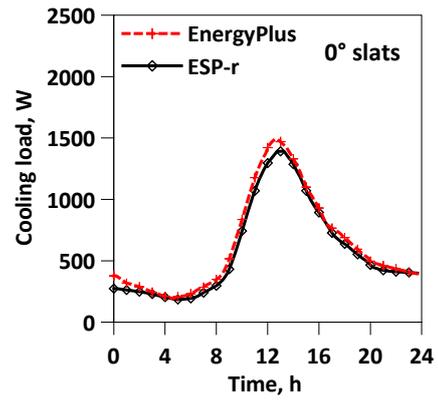


Figure 10: Cooling load result for Case 4 – Indoor Blind.

Of note are the relative cooling energy (area under cooling curve) and peak load reductions due to the presence of a slat blind when compared to the reference double glazing case. Both total cooling energy and peak loads are significantly reduced as the blind is placed toward the outdoors.

The presence of an outdoor blind is seen to reduce the total cooling energy by up to about 60% and peak cooling load by more than 65%. The between-glass blind case shows a reduction up to 30% in total cooling energy and about 27% in peak cooling load. Although the cooling load plots (Figure 10) for the indoor blind case are closely aligned with respect to each other, with respect to the reference double glazing the difference between EnergyPlus and ESP-r cooling energy and peak load reductions are as much as 11%. Both indicate a decrease in cooling energy (10-20%) but an increase in the cooling peak (5-15%). The indoor blind effectively acts as a solar absorber and readily converts much of the absorbed energy into convective cooling load. The peak cooling load for an indoor blind also occurs at the peak solar transmission, as the blind has little or no thermal capacity. The presence of an indoor blind can therefore cause the cooling peak to coincide with the solar peak, placing even more demand on the cooling system than in the double glazing case.

CONCLUSION

The successful implementation of the AGSL shading models into ESP-r in the form of the Complex Fenestration Construction has been demonstrated. The tool was developed with emphasis on glazing/shading system generality to allow for specification of any combination of shading/glazing layers. The generation of input files for CFC types relies on straightforward composition of input parameters via a graphical user interface, the Glazing Shading Layer editor GSLEdit.

It is anticipated that additional enhancements such as a front end shading control facility and coupling of the CFC framework with ESP-r's daylight routines are needed to gain acceptance amongst the users of ESP-r. Such a comprehensive tool will be of significant value to building design practitioners, promoting the straightforward analysis of window shading in buildings designed for energy efficiency.

ACKNOWLEDGEMENT

This research was supported by the Natural Sciences and Engineering Research Council of Canada.

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