LO-09-003 (RP-1311)

Improving Load Calculations for Fenestration with Shading Devices

Charles S. Barnaby
Member ASHRAE

John L. Wright, PhD, PEng
Member ASHRAE

Michael R. Collins, PhD, PEng
Associate Member ASHRAE

This paper is based on findings resulting from ASHRAE Research Project RP-1311.

ABSTRACT

Activities and findings arising from ASHRAE Research Project 1311-RP are summarized. This project included three main goals, (a) development of models for pleated drapes, venetian blinds, roller blinds and insect screens, (b) implementation of these models in the ASHRAE Loads Toolkit, and (c) compilation of results suitable for direct application in building cooling load methods such as Radiant Time Series (RTS). The solar and heat transfer interactions present in multilayer systems are complicated and the corresponding models entail significant complexity. This work produced the ASHRAE Window Attachment (ASHWAT) model that uses a simplified approach to the way in which radiation interacts with each glazing or shading layer. Each layer is assigned spatially-averaged "effective" optical properties so that glazing and shading layers can be arranged in any combination. ASHWAT offers wide scope in the design process, the possibility of active control (e.g., slat angle adjustment), fast computation, and facilitates the implementation of additional shading layer types. Very few input data are needed to model any layer. Measurement-based validation was undertaken at both the subcomponent level and at the complete system level with documentation in the technical literature. The ASHWAT model has been added to the ASHRAE Loads Toolkit and coupled to the heat-balance room model, supporting accurate calculation of cooling load impact of fenestration shading. Simplified correlation models were developed to allow shaded fenestration performance estimates via spreadsheet-tractable formulas. The model was also used to generate greatly expanded simplified data for inclusion in Fundamentals and suitable for direct use in widely-used engineering procedures.

INTRODUCTION

It is well understood that buildings account for a large portion of the greenhouse gas production and energy consumption in the developed world. Approximately 25% of this consumption can be attributed to windows. The potential for improvement in this sector is enormous. This becomes especially clear when it is recognized that buildings can be more than just energy efficient - they can be designed as net-zero or even net energy producers. Conservation is the key step in a shift to sustainability. Conserved energy is the greenest renewable resource.

The increased levels of insulation associated with green building design decrease heating loads but augment cooling loads. Well-insulated buildings can easily overheat. Solar gain is especially troublesome because it is often the largest and most variable heat gain. Fortunately, a properly designed and controlled shading device can be used to admit solar energy when and where heating is required, and reject it otherwise.

This paper summarizes ASHRAE research project 1311-RP, "Improving Load Calculations for Fenestration with Shading Devices." The purposes of this work were to

a. develop models for pleated drapes, venetian blinds, roller blinds and insect screens - the ASHRAE Window ATtachment (ASHWAT) models,
b. implement the ASHWAT models in the ASHRAE Loads Toolkit and

Charles Barnaby is the vice-president of research at Wrightsoft Corporation, Lexington, MA. **John Wright** is a professor and **Michael Collins** is an associate professor in the Department of Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, Ontario, Canada.

c. compile results suitable for simplified building analysis (e.g., the Radiant Time Series (RTS) method) and for rating the performance of various shading devices.

These goals have been achieved. The most visible evidence is in the Indoor Attenuation Coefficient (IAC) tables prepared for the 2009 ASHRAE Handbook - Fundamentals. However, the underlying research has generated benefits well beyond the original intent of the project - acting as a catalyst leading to new and more general ways of structuring the problem, new ways of making measurements, new data, new correlations, new ways to characterize components, new ways to assess the performance indices of multi-layer systems and new insight regarding the way in which the analysis of shaded windows can be efficiently coupled with heat-balance cooling load calculations and building energy simulation. This new information is well documented in the technical literature, including more than a dozen ASHRAE Transactions papers. A more thorough summary of the 1311-RP work can be found in (Wright et al. 2009).

THE ASHWAT MODELS

To retain generality and practicality while striking a balance between complexity and computational speed a simplified approach was taken regarding the way in which radiation interacts with a shading layer.

- Shading layers are represented by an equivalent homogenous layer that is assigned spatially-averaged "effective" optical properties. This approach has been used in a number of studies (e.g., Parmelee and Aubele 1952, Farber et al. 1963, Rheault and Bilgen 1989, Pfrommer et al. 1996, Rosenfeld et al. 2000, Yahoda and Wright 2004b, 2005) and has been shown to provide accurate characterization of venetian blinds (e.g., Huang et al. 2006, Wright et al. 2008, Kotey et al. 2008b).
- Some portion of the incident solar radiation passes undisturbed through openings in a shading layer and the remaining portion is intercepted by the structure - yarn, slats, or some other material. The portion of the intercepted radiation that is not absorbed is scattered and leaves the layer as an apparent reflection or transmission and these components are assumed to be uniformly diffuse. In addition, a shading layer will generally transmit longwave radiation (i.e., it is diathermanous) by virtue of its openness, and effective longwave properties are assigned accordingly.

Using effective optical properties and a beam/diffuse split of solar radiation, this framework provides freedom to consider many types of shading layers.

The ASHWAT models require very little input data because subcomponent models are used to calculate effective layer properties instead of relying on empirical information about the entire layer. For example, the effective solar optical properties of a venetian blind can be calculated as a function of slat geometry plus the solar and longwave properties of the slats. Effective properties of a pleated drape are calculated as a function of various fabric properties and a specified value of fullness.

Methods to obtain convective heat transfer coefficients for glazing cavities are well established. The convection coefficients for exposed glazing/shading layer surfaces cannot be predicted with the same accuracy. In the ASHWAT code these coefficients must be specified by the room model of the building simulation program. This approach provides the opportunity to differentiate between natural and forced convection and perhaps between different types of forced convection caused by different types of diffusers. Established values are available in the limiting cases where the shading layer is spaced well away from the window or where the spacing approaches zero. The method for specifying convection coefficients at an intermediate spacing is presented in (Wright et al. 2009) and Kotey et al. (2009b) mention this is a possible area of future research.

THE MULTI-LAYER ANALYSIS

Structure

Each glazing/shading layer system is treated as a series of parallel layers separated by gaps (Wright 2008, Wright et al. 2009). See Figure 1. First, the flux of absorbed solar radiation at each layer, S_i, is determined. Second, an energy balance is applied at each layer in order to obtain the set of layer temperatures, T_i , and the corresponding heat flux values. The longwave radiant exchange algorithm is noteworthy because it allows for the possibility of diathermanous layers and because the mean radiant temperature can differ from the air temperature on the indoor and/or outdoor side.

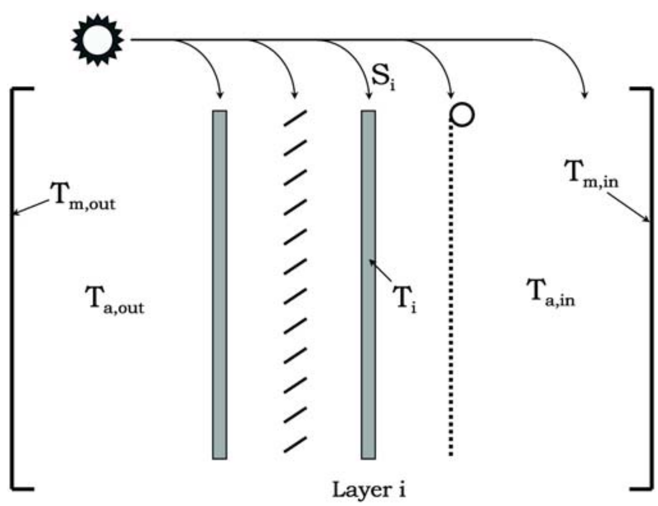

Figure 1 Glazing/shading multi-layer analysis structure.

Solar Analysis

An algorithm has been devised, extending the work of Edwards (1977) by which beam and diffuse components of solar radiation can be tracked as they interact with a multi-layer system of glazing and/or shading layers (Wright and Kotey 2006). The method is sufficiently general to include beam and diffuse insolation on the outdoor side as well as diffuse insolation on the indoor side.

Heat Balance

An energy balance is applied at each layer to obtain layer temperatures, radiosities and convective heat transfer rates. The known heat transfer coefficients are then used to construct a resistance network making it possible to calculate U-factor and SHGC for a system that includes one or more diatherma-nous layers. This hybrid calculation provides the opportunity to calculate U-factor, SHGC (Wright 2008, Collins and Wright 2006) and IAC under many different environmental conditions.

Glazing cavities are treated as sealed enclosures and the associated convective heat transfer coefficients are calculated using the correlation of (Wright 1996). Airflow between the first two layers, on the indoor side and/or the outdoor side, can be modeled in order to deal with unsealed shading attach-ments. Details regarding the way in which unsealed gaps are included in the heat balance can be found in (Wright 1986). The models for a glazing cavity with an enclosed venetian blind are documented in (Huang et al. 2006, Wright et al. 2008, Yahoda et al. 2004a).

Overview of the Layer Models and Input Requirements

Input data needed for each glazing layer include three solar properties (transmittance, front/back reflectance), eval-uated at normal incidence, plus three longwave properties (transmittance, front/back emissivity). These data are readily available (e.g., IGDB 2008). Off-normal solar properties of glazing layers are estimated according to the behavior of an uncoated reference glass (Wright et al. 2009).

The beam/diffuse characterization of solar radiation necessitates an expanded set of solar optical properties for shading layers (Wright and Kotey 2006). A portion of incident beam radiation will leave the layer without being scattered. The properties associated with this unscattered portion are called beam-beam properties. Beam-diffuse properties are needed to describe the scattered components of beam insola-tion. Despite this added complexity, the only input data needed to characterize drapery fabric, roller blinds and insect screens, including off-normal properties, are openness, total solar transmittance and total solar reflectance at normal incidence. These three properties are routinely used to specify drapery fabric (e.g., ASHRAE 2005, Keyes 1967) and can be measured with inexpensive instrumentation. ASHWAT models calculate the corresponding effective solar properties of pleated drapes and venetian blinds using information about geometry and the solar properties of the slats or fabric. The off-normal beam-beam and beam-diffuse properties of drapery fabric are used in the pleated drape model. Venetian blind slats are assumed to reflect and transmit in a purely diffuse manner. The ASHWAT code includes integration routines to obtain diffuse-diffuse properties of materials and layers.

A method has been devised to estimate longwave proper-ties of drapery fabric, roller blind material and common insect screens knowing only the openness of the material (Kotey et al. 2008a). These material properties are converted to effective longwave properties for pleated drapes (using the same net radiation balance used to obtain diffuse solar properties (Kotey et al. 2009a)) and venetian blinds (Yahoda and Wright 2004a, b).

Gaps can be specified as sealed or vented. Any gap thick-ness can be used. Any fill gas can be specified as long as prop-erty data (molecular mass, viscosity, specific heat and thermal conductivity) are available. These data are readily available for gases including air, argon, krypton and xenon. Properties can be calculated for fill gas mixtures (e.g., Rohsenow and Hartnett 1973).

Shading Layer Research

A new measurement technique was developed for this study. Special sample holders, small tubes with their end open-ings cut at various angles, were designed for use in the inte-grating sphere of a commercially produced spectrophotometer. These sample holders provide the unique capability of measuring beam and diffuse components of solar transmission and reflection with respect to beam radiation at various incidence angles. Semi-empirical models were formu-lated to evaluate the off-normal properties of drape, roller blind and insect screen materials (Kotey et al. 2009c, d, e). Effective layer properties of venetian blinds (Yahoda and Wright 2005, Kotey et al. 2008b) and the effect of pleating in drapes (Kotey et al. 2009a) are evaluated using a more funda-mental net radiation scheme.

The models formulated for the off-normal solar proper-ties of drape, roller blind and insect screen materials are based on measurements using samples with front/back symmetry. Drapery materials and roller blinds are generally symmetric. Insect screens are always symmetric. Exceptions include lined drapes and blackout roller blinds but these have zero openness (i.e., no beam-beam transmission) and little or no diffuse transmission. Under this circumstance the models for solar transmission become trivial and the models for reflection can be applied equally well to the individual sides of the fabric or roller blind material.

Energy Performance Indices

The ASHWAT heat balance includes a provision to calcu-late indices of merit for the multi-layer system. These include U-factor and SHGC. The code is based on the theory developed in (Wright 2008) and provides all of the generality of that theory except for two restrictions: (1) SHGC cannot be calculated for situations with zero solar radiation and (2) even though the system can include any combination of glazing and shading layers, indices of merit cannot be calculated for systems with more than one consecutive diathermanous layer.

Two additional indices of merit are calculated by the ASHWAT code, $F_{r,in}$ and $F_{r,out}$. The development of these parameters is also given in (Wright 2008). The values of $F_{r,in}$ and $F_{r,out}$ give a measure of the relative strength of radiative heat transfer, with respect to the total, between the multi-layer system and the indoor and outdoor environments, respectively. Typical values are $F_{r,\,out} \approx 0.1$ where forced convection is present and $F_{r,\,in} \approx 0.6$ where natural convection is present.

VALIDATION

Given that few publications have come from recent shading-related research, there are no clear benchmarks against which new shading models can be judged. In the current research, validation has been undertaken in two ways:

Component-Model Validation

The ASHWAT models were developed in small increments in order to validate at a detailed level. For example, the glazing system code was used to reproduce data found in the ASHRAE Handbook - Fundamentals. Solar transmission measurements were compared to the venetian blind model (Kotey et al. 2008b). The model for an enclosed venetian blind was formulated with guarded heater plate measurements and confirmed using computational fluid dynamics (CFD) (Huang et al. 2006, Wright et al. 2008). The optical property correlations for drapery fabric, roller blind material and insect screens were also based on theory and measurement (Kotey et al. 2009c, d, e).

System-Level Validation

Additional experiments were undertaken to test the complete simulation model (Kotey et al. 2009b). These experiments were completed using one glazing system in combination with various shading attachments using an indoor solar simulator - the National Solar Test Facility (NSTF) (Dubrous 1993, Harrison and Dubrous 1990, 1992, Brunger et al. 1999). ASHWAT simulations were completed for the same glazing/shading system configurations. The agreement between measured and calculated solar transmission results was very good. See Figure 2. The discrepancy between measured and calculated centre-glass SHGC values was also small, generally less than 0.05, and a mild sensitivity was noted with respect to surface convection heat transfer coefficients. Agreement was also very good when IAC results were compared. See Figure 3. It is worth noting that IAC was not found to be sensitive to the choice of surface convection coefficients.

The two-stage validation process was deemed to be successful, with NSTF measurements supporting the idea that the sub-models are correctly implemented and working well.

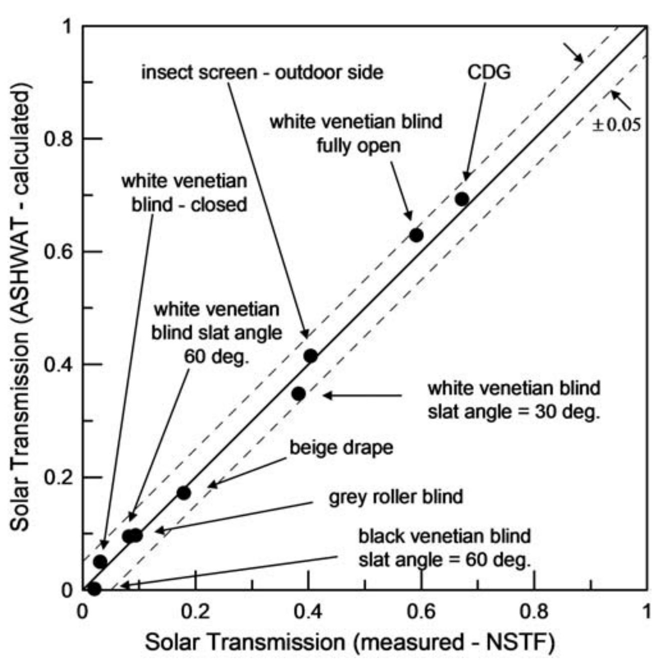

Figure 2 Comparison of center-glass solar transmittance, ASHWAT vs. NSTF.

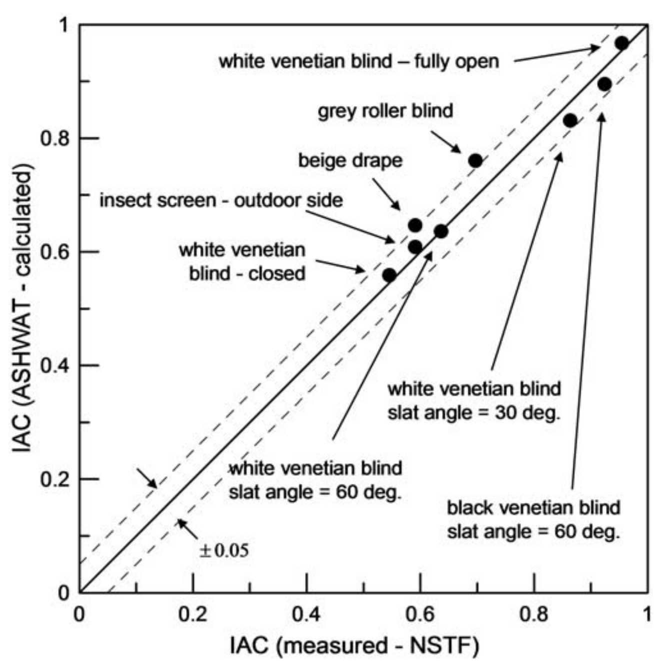

Figure 3 Comparison of center-glass IAC, ASHWAT vs. NSTF.

ASHRAE LOADS TOOLKIT INTEGRATION

The ASHWAT component models are implemented in FORTRAN-90 and have been added to the HBX (Heat Balance eXperimental) application. HBX performs peak cooling load analysis and is assembled from enhanced component models from the ASHRAE Loads Toolkit (Pedersen et al. 2001). The application was originally developed as part of 1199-RP (Barnaby et al. 2004) and has been further extended during the current work. HBX source code and documentation are available from ASHRAE in conjunction with the 1311-RP final report.

HBX is a batch application driven by a simple text input language. The language allows description of the geometry and construction of one or more rooms. Hourly cooling loads and room temperatures are calculated using a design-day temperature profile and the ASHRAE clear sky model. In prior versions, fenestration was described using SHGC, U-factor, IAC, and optional incident angle modifiers. In this work, additional input commands have been added that describe glazing layers, shade layers, inter-layer gaps, and multi-layer fenestration systems (assemblies of layers and gaps). Within a room description, reference can be made to either simplified or complex fenestration definitions. This allows direct comparison of ASHWAT results to those from prior calculation methods.

As is discussed above, ASHWAT performs solar and thermal calculations in separate steps. Given the assumption that layer optical properties are independent of temperature, the solar analysis depends only on fenestration system construction and relative sun position. Thus, solar calculations can be done once. In contrast, the thermal state of the system (layer temperatures) depends on indoor conditions, so thermal calculations must be repeated during the room heat balance iteration.

Solar

The solar analysis determines the fraction of incident solar (shortwave) radiation absorbed at each layer plus the fraction transmitted. The transmitted fraction is the amount absorbed in a fictitious indoor-side opaque black layer. Separate calculations are performed for beam, diffuse, and indoor-side diffuse radiation (indoor-side radiation sources include lighting and inter-reflected solar gain). The fractions for beam radiation depend on solar angles and must be derived for each hour of the design day. Diffuse radiation fractions are the same for all hours unless the shade characteristics are altered; for example, venetian blind slat angle can be changed over the day. In all cases, however, the fractions are constant for a given configuration and hour. Layer absorbed power is derived by multiplying the incident radiation components by the appropriate fractions and summing.

Since indoor-side intensity depends on total room gain that in turn depends on transmitted fraction(s), the analysis is performed in the following sequence. First, fractions are calculated for all fenestrations for beam, diffuse, and indoor-side diffuse. Second, outdoor-side insolation is applied and transmitted solar gain is totalled for the room. Third, the standard Toolkit solar targeting and inter-reflection methods are used to determine indoor-side solar diffuse intensity. Fourth, radiation from lighting is added to yield total indoor-side irradiation. Finally, total layer absorbed power is summed from the three components and stored for repeated use in the thermal calculations, discussed next.

Thermal

The HBX room model uses the successive substitution solution technique as described in section 2.2.2 of (Pedersen et al. 2001). A design day is repeatedly modeled to find the simultaneous conditions that produce heat balance at all room surfaces and at the room air node. During each hour, the procedure initially assumes that room air and mean radiant temperatures are known. These values are used to perform heat balances for the indoor (and implicitly the outdoor) face of each surface. Once indoor surface temperatures are known, the air temperature can be updated and cooling load derived. The ASHWAT thermal calculations fit directly into this structure with the exception that the indoor surfaces of shaded fenestration systems in general do not have single temperatures. Indoor-most shade layer longwave transmittance and shade gap convection complicate heat exchange with the room. The following procedures are used.

In the surface processing sequence, the performance of each complex fenestration surface is analysed using the ASHWAT thermal model, yielding total longwave radiant and convective gains to the room. Longwave transfer is recast as a composite surface temperature. During initialization, a composite emittance is derived for each fenestration system,

$$\varepsilon^* = \sum_{j=0}^{nl} \left[\varepsilon_j \cdot \prod_{k=j+1}^{nl+1} \tau_k \right] \tag{1}$$

where

ε^* = composite indoor (room-side) longwave emittance

ε_j = effective emittance of layer j ($\varepsilon_0 = 0.9$)

τ_k = effective longwave transmittance of layer k ($\tau_{nl+1} = 1$)

nl = number of layers in fenestration system (glazing and shade). Layers are numbered outside to inside (layer 1 is outermost, layer *nl* is innermost; fictitious layers 0 and *nl* + 1 represent outdoors and indoors).

The composite surface temperature is calculated from the ASHWAT longwave gain using the composite emittance.

$$T^* = \sqrt[4]{\frac{Q_{lw}}{\sigma\varepsilon^*} + T_0} \tag{2}$$

where

T^* = composite indoor surface temperature, °C (°F)

Q_{lw} = longwave radiant gain to room (from ASHWAT), W/m^2 (Btu/h-ft^2)

σ	=	Stefan-Boltzmann constant, W/m^2-K^4 (Btu/h-ft^2-R^4)
T_0	=	Temperature of absolute zero, -273.15°C (-459.67°F)

Next, an "extra" convective flux is computed; this is the gain in excess of that resulting from the standard HBX surface model.

$$QX = Q_{conv} - hc \cdot (T^* - T_a) \tag{3}$$

where

hc	=	unadjusted (default) convective coefficient at surface, W/m^2-K (Btu/h-ft^2-F)
Q_{conv}	=	total convective heat flux to room (from ASHWAT), W/m^2 (Btu/h-ft^2); includes open-channel gains and impact of inside surface convective coefficient adjustment (if any)
T_a	=	room air temperature, °C (°F)

Finally, the standard room air heat balance formulation is modified to include *QX,*

$$0 = q_{hvac} + q_{other} + \sum_{surfaces} A_i \cdot [QX_i + hc_i \cdot (T_i^* - T_a)] \tag{4}$$

where

q_{hvac}	=	heat gain from HVAC (air) transfer, W (Btu/h)
q_{other}	=	other sensible heat gain to room air (e.g., infiltration or ventilation), W (Btu/h)
A_i	=	area of surface i, m^2 (ft^2)

Eqn (4) is rearranged to find q_{hvac} if T_a is known (fixed room temperature) or to find T_a when q_{hvac} = 0 (floating temperature).

The above formulation was selected because it is has minimal impact on the standard heat balance calculation sequence. Other approaches are possible. For example, *hc* and *hr* (the linearized radiant transfer coefficient) could be adjusted so each transfer mode matches ASHWAT results. However, such changes would require more extensive modification to the HBX code and risk introduction of troublesome cases (e.g. negative coefficients) that could disrupt other aspects of the calculation.

CORRELATION MODELS

The scope of 1311-RP included development of methods suitable for use in spreadsheet or other simplified procedures. The goal was to find formulas that estimate properties of shaded glazing properties without use of the full ASHWAT model. This would allow, for example, improved accuracy in cooling loads calculated with ASHRAE Radiant Time Series (RTS) method.

Shading devices have two main effects on heat gain to building spaces: 1) reduction of total heat gain and 2) altering of the mix of radiant and convective gain. In addition, shading devices have a small to moderate effect on fenestration system conduction (U-factor).

Total heat gain through a fenestration system is characterized by the Solar Heat Gain Coefficient (SHGC). The effect of shading is conveniently represented by the Interior Attenuation Coefficient (IAC), defined as follows:

$$IAC = \frac{SHGC_{cfs}}{SHGC_{glz}} \tag{5}$$

Historically, IAC has been presented as a constant depending only on glazing and shade properties. For example, see Table 19 in Chapter 31, ASHRAE (2005). However, IAC also depends on solar incidence angle, especially for shades having non-uniform geometry (venetian blinds and pleated drapes).

The radiant fraction (FR) is the portion of total solar gain entering the space as radiation (as opposed to convection). FR can be strongly altered by indoor shading devices. In the extreme, a dark opaque shade absorbs solar radiation transmitted by the glazing and is heated, resulting in elevated convective gain to the space. Alternatively, a light color shade can reflect radiation back through the glazing without being heated; this can increase or decrease the radiant fraction. An important additional effect is the larger surface area that is active when room air circulates in the shade/glazing gap; the surface area available for convective heat transfer is approximately tripled when a shading layer is added to the indoor side of a window but radiant exchange is not augmented by this change. Shade type, solar angles, glazing characteristics, and room air motion all interplay to determine FR.

The RTS method directly uses IAC and FR in calculation of fenestration cooling loads, so correlation models were sought to predict these values for arbitrary shade / glazing configurations. Parametric ASHWAT runs were used to generate data sets over a range of solar angles, glazing systems, and shades as described in Wright et al. 2009. Table 1 shows the independent variables used to characterize the shades.

Table 1. Shade Property Definitions for Correlation Models

Shade	Symbol	
	T	R
Pleated drape	Fabric normal beam-total transmittance	Fabric normal beam-total reflectance
Roller blind	Normal beam-total transmittance	Normal beam-total reflectance
Insect screen	Normal beam-total transmittance	Normal beam-total reflectance
Venetian blind	— (Slat solar transmittance = 0 for all cases)	Reflectance of upward and downward facing slat surfaces.

Table 2. Roller Blind Correlation Model Coefficients

	C_0	C_1	C_2	C_3	C_4	C_5	C_6 SI (I-P)
IAC	1.00	-0.117	0.0148	-0.106	-0.654	0.169	-0.016 (-0.00282)
FR	0.335	-0.0391	0.255	0.112	0.258	0.489	-0.0051 (-0.000899)

The open-source package R (2008) was used for data manipulation, plotting, and regression of the ASHWAT data sets. Trial and error exploration of the data sets led to the selection of the following common model form:

$$X = MAX(0, C_0 + C_1 \cdot R + C_2 \cdot T + C_3 \cdot SHGC + C_4 \cdot R \cdot SHGC + C_5 \cdot T \cdot SHGC + C_6 \cdot U \tag{6}$$

where

X = value to be predicted (IAC or FR)

C_n = model coefficients; values depend on shade configuration. Note that the value of C_6 is unit-system dependent.

R, T = per Table 1

$SHGC$ = center-of-glass SHGC *without* shade

U = center-of-glass U-factor *without* shade, W/m^2-K (Btu/h-ft^2-F)

It was also found that solar angle significantly effects venetian blind performance, but is less important for the other shade types, since they are less "geometric." Thus angle-independent models were found for pleated drapes, roller blinds, and insect screens. Table 2 shows results for roller blinds. These coefficients are used for all solar angles, including diffuse. Figure 4 shows some example cases. Results for all shade types are found in (Wright et al. 2009).

The shading effect of venetian blinds depends on the sun-slat relative angle in addition to slat properties. For a given configuration, IAC correlates well with profile angle Ω_v as shown in Figure 5. The data scatter shown at some profile angles represents the variation due to different incident angles having the same profile angle. The figure also shows that the beam and diffuse IACs can differ significantly. FR (not shown) was found to vary strongly with slat angle but modestly with profile angle.

The ASHWAT results shown in Figure 5 offer some interesting insights regarding the operation of venetian blinds. The uppermost line represents a blind with slats continually adjusted to align with the sun (PRF). The slats block solar radiation only because of their curvature but the effect of this blockage increases slightly at high solar profile angle because, as the blind is closed, the width of the openings between slats becomes small. The lowest curve represents a fixed slat angle of 45 degrees (045). The slats intercept all beam insolation but as the solar profile angle increases (as the sun climbs higher in the sky) this irradiation illuminates only the outdoor tips of the slats, more of the reflected radiation escapes to the outdoor side and the IAC decreases. The second highest line represents

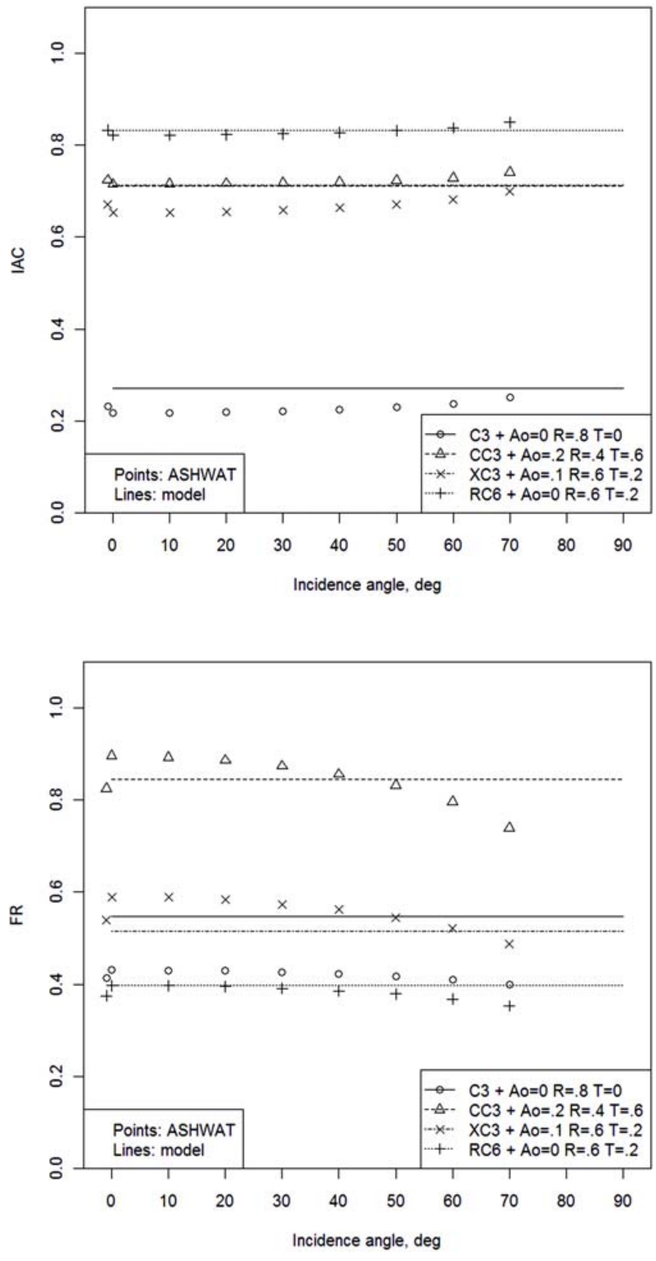

Figure 4 *Roller blind example model fits: IAC (upper) and FR (lower). Notes: Glazing -- C3: single clear 3 mm; CC3: double clear 3 mm; XC3: double selective low-e 3 mm; RC6: double reflective 6 mm. Ao = openness; R and T as defined in Table 1.*

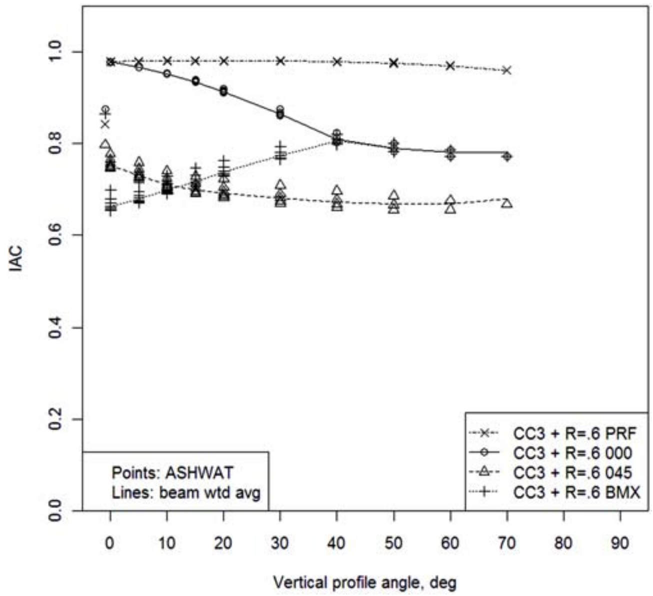

Figure 5 *IAC versus solar profile angle, indoor medium colored venetian blind, four types of slat-angle control. Note: Slat angle – PRF: follows profile angle (maximum gain); 000: horizontal; 045: 45 down; BMX: slat angle adjusted hourly to exclude beam (maximum slat angle = 0°, hence convergence with 000 curve).*

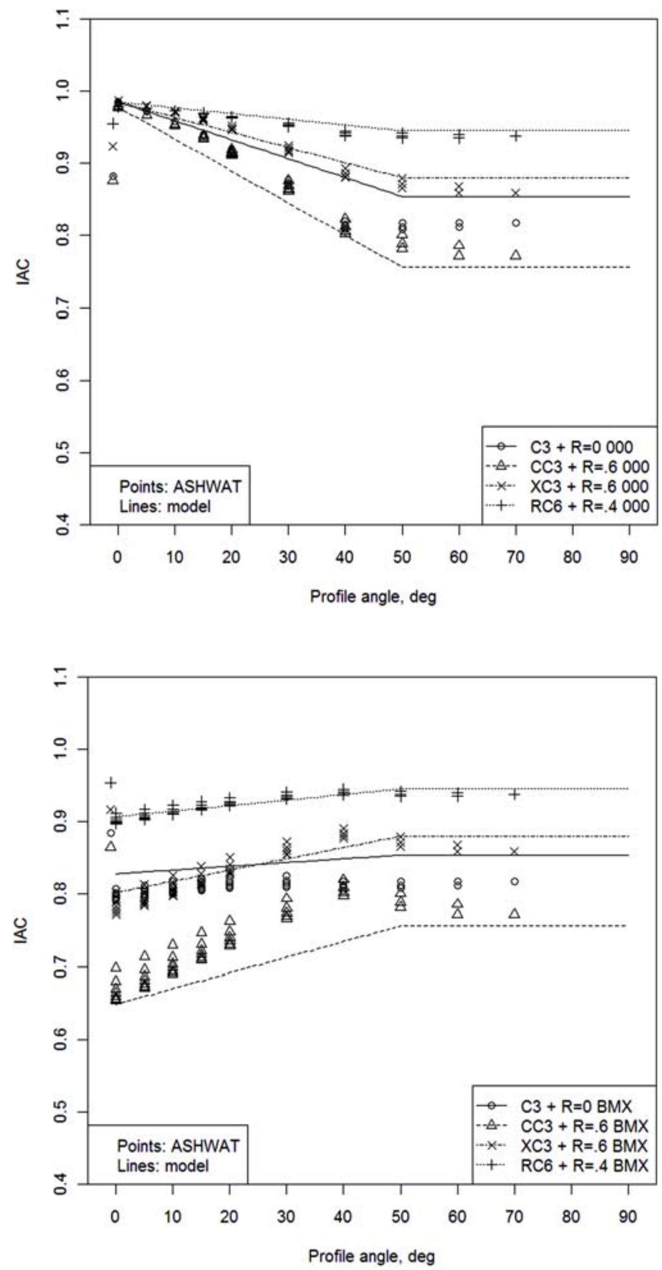

Figure 6 *IAC versus solar profile angle, indoor venetian blinds with glazing and slat reflectance as indicated; slat control 000 (upper) and BMX (lower).*

a constant slat angle of zero (000) – slats held fully open (horizontal). At a solar profile angle of zero the slats are aligned with the sun and the IAC coincides with the PRF case. As the profile angle increases the slats intercept more of the insolation and more radiation is reflected to the outdoor side. At a profile angle of about 40 degrees the horizontal slats intercept all of the incident radiation and at still higher profile angles, similar to the 045 case, the radiation is intercepted closer to the outdoor slat tips and more of the reflected radiation reaches the outdoor side. The fourth line represents a situation where the slat angle is continually adjusted and the blind is closed just to the extent that all beam insolation is blocked (BMX), but the slat angle is not allowed to exceed zero so that maximum view can be obtained. At low solar profile angle the blind is almost fully closed, reflecting a significant portion of the radiation – low IAC. As the profile angle increases each slat remains illuminated over its full width and more of the radiation from the slat surface can reach the indoor side. Eventually the slat angle increases to zero and the BMX case merges with the 000 case.

To model this variety of curves, separate correlations were generated for IAC_0 (IAC at $W_v = 0$), IAC_x ($IAC_{60} - IAC_0$), IAC_{dif} (diffuse IAC), and FR. The beam IAC is found as follows:

$$IAC = IAC_0 + IAC_x \cdot \min(1, 0.02 \cdot \Omega_v) \tag{7}$$

where Ω_v is in degrees. This form results in a "dog-leg" shape that matches the data, as shown in Figure 6.

As exemplified by Figure 4 and Figure 6, the quality of the correlations is not exceptional. Somewhat higher-quality models were found for some configurations. However, the advantages of using a common model format outweigh minor accuracy improvements.

HANDBOOK DATA

1311-RP work included application of ASHWAT to generate tabular data for the revised Fenestration chapter in the 2009 Handbook. IAC and FR values were calculated for a set of common glazing / shade combinations. This section documents the methods and assumptions used for those calculations.

For modelling purposes, 20 representative glazing materials were selected with a range of thickness (3 mm / 6 mm (1/8 in / ¼ in), color (clear, bronze, green, grey, blue-green, and reflective), surface longwave emittance (0.05 - 0.84), and solar selectivity. These materials were assembled into 56 single, double, and triple pane glazing systems representative of most commonly-used configurations. Material and system properties are documented in Wright et al. 2009.

A common procedure was used for all shade types except venetian blinds (see below). As is established above under Correlation Models, sun angles (i.e. incidence and profile angles) have only mild impact on IAC and FR of all shade types except venetian blinds, allowing representative values to be derived for each unique glazing/shade combination. Typical shade configurations were combined with the glazing systems and modelled with ASHWAT at several incidence angles (and, for pleated drapes only, profile angles), as shown in Table 3. Computed IAC and FR values for all angles

Table 3. Pleated Drape, Roller Blind, and Insect Screen Cases for Handbook Data

Shade	Cases	Incidence Angles	Profile Angles	Maximum Standard Deviation of Averaged Values	
				IAC	FR
Pleated drape	11 fabrics (Table 4), 100% fullness 100 mm (3.94 in) open gap	Diffuse, 0°, 15°, 30°, 45°	0°, 15°, 30°, 45° (<= IncA)	0.050	0.050
Roller blind	7 materials (Table 4) 100 mm (3.94 in) open gap		n/a	0.020	0.030
Insect screen (indoor)	1 material (Table 2) 25 mm (0.98 in) open gap			0.011	0.036
Insect screen (outdoor)				0.037	0.028

Table 4. Pleated Drape, Roller Blind, and Insect Screen Properties for Handbook Data

Case	Properties of...	Openness (A_o)	Beam-Total Transmittance	Beam-Total Reflectance
Pleated drape	Fabric			
Open weave light (fabric designator IL, see note)		0.35	0.58	0.36
Semi-open weave light (IIL)		0.15	0.41	0.48
Closed weave light (IIIL)		0.01	0.17	0.63
Open weave medium (IM)		0.35	0.49	0.25
Semi-open weave medium (IIM)		0.15	0.29	0.32
Closed weave medium (IIIM)		0.01	0.11	0.38
Open weave dark (ID)		0.35	0.39	0.07
Semi-open weave dark (IID)		0.15	0.18	0.10
Closed weave dark (IIID)		0.01	0.05	0.14
Cream sheer		0.45	0.74	0.23
Reflective white opaque		0.00	0.00	0.80
Roller blind	Shade			
Reflective white 7% open		0.07	0.16	0.75
White 14% open		0.14	0.25	0.60
Light grey 10% open		0.10	0.15	0.31
Dark grey 14% open		0.14	0.19	0.17
Reflective white opaque		0	0	0.80
White opaque		0	0	0.65
Dark opaque		0	0	0.20
Insect screen	Screen			
Typical		0.65	0.68	0.06

Note: Fabric designators are defined in Figure 31 and Table 22 of Fenestration chapter, ASHRAE 2005 (including diffuse) were averaged to yield mean values. The resulting values are tabulated in the 2009 Fenestration chapter and are not included in this paper due to space restrictions.

Due to the averaging process, some inaccuracy is introduced when mean IACs and FRs are used for specific solar angles. During data preparation, standard deviations of the mean values were computed. Table 3 shows the maximum standard deviations of IAC and FR for each shade type. While not negligible, these results indicate that the tabulated values are acceptable for typical engineering applications.

Venetian blind IAC values vary significantly with profile angle, due to the strong geometric nature of slat / solar interactions. Thus IACs were derived for profile angles of 0° and 60° and an interpolation procedure is used to obtain values for intermediate angles. As shown in Table 5, 3 blind positions, 3 slat reflectances, and 5 slat angles were included.

IMPACT ON COOLING LOADS

The implications of replacing the standard IAC model with ASHWAT are illustrated with a simple example. Sensible cooling loads were calculated for a test room with characteristics documented in Table 6. Several shade alternatives, listed in Table 7, were modelled with two methods, as follows.

Table 5. Venetian Blind Cases for Handbook Data

Shade Configuration	Slat Geometry	Slat Reflectances	Slat Angles
Indoor side, 100 mm open gap Between glazings 1 and 2, 12 mm (0.47 in) tip clearance Outdoor side, 100 mm (3.94 in) open gap	Width = 1.2 x spacing Crown = 0.06 x width	0.15, 0.5, 0.8	0° (horiz) 45° 75° (closed) PRF (see notes) BMX (see notes)

Notes: PRF: slat angle = profile angle (worst case, admits maximum solar); BMX: slat angle adjusts hourly to exclude beam solar

Table 6. Test Room Characteristics

Item	Value	Notes
Conditioned floor area	42.4 m^2 (456 ft^2)	
Dimensions	7.3 x 5.8 m (24 x 19 ft) Long axis N-S	
Height	2.44 m (8 ft)	Single story
Interior partition area	0	Single open space
Fenestration	4.09 m^2 (44 ft^2) west-facing window (23% of wall area) Double glazed 6 mm clear (12 mm air gap) U = 2.73 W/m^2-K (0.48 Btu/h-ft^2-F), SHGC = 0.70	
Fenestration variation	Shade alternatives per Table 7	
Internal mass	42.4 m^2 (456 ft^2) of 12 mm (0.5 in) wood	Typical default
Construction	Wood frame with fiberglass batt insulation Walls: U = 0.51 W/m^2-K (0.089 Btu/h-ft^2-F) Ceiling: U = 0.20 W/m^2-K (0.034 Btu/h-ft^2-F) Floor (crawlspace): U = 0.29 W/m^2-K (0.05 Btu/h-ft^2-F)	
Surface exterior (solar) absorptance	Walls: 0.6 Roof: 0.8	
Indoor design temperature	23.9 °C (75 °F)	
Indoor temperature swing	0	Non-residential default
Infiltration	0	
Internal gain	0	
Surface interior absorptance	Beam solar gain: floor: 0.6, internal mass: 0.3, other: 0 Diffuse solar gain: all surfaces: 0.6	
Outdoor design conditions	Atlanta, GA, Jul 21 T_{des} =32.6 °C (90.7 °F) Daily range = 9.6 °K (17.3 °F) Clearness = 0.92	

Table 7. Cooling Load Model Comparison

Case	Shade	Normal Incidence Properties				IAC	
		Properties of...	A_o (openness)	T[1]	R[2]	HOF 2005[3]	HOF 2009
None	--	--	--	--	--	1	1
RB light	Light roller blind translucent	Shade	0	0.25	0.60	0.46	0.58
RB dark	Dark roller blind opaque	Shade	0	0	0.20	0.81	0.77
VB light	Light venetian blind Slat width= 1.2 x spacing; 45° slat angle	Slat	--	0.05	0.55	0.66	0.75
PD beige	Beige pleated drape 100% fullness	Fabric	0.15	0.29	0.32	0.63	0.76

Notes: Table references refer to ASHRAE (2005) chapter 31 (Fenestration)
[1]Total transmittance, Table 21 (RB and VB) or Table 22 (PD)
[2]Total reflectance, Table 21 (RB and VB) or Table 22 (PD)
[3]Interior solar attenuation coefficient, Table 19

Table 8. Cooling Load Results

Case	Open/Sealed	Sensible Cooling Load, W (Btu/h)		
		IAC HOF 2005	IAC HOF 2009	ASHWAT
None	—	2587 (8829)	2587 (8829)	2603 (8884)
RB Light	S	1661 (5669)	1868 (6375)	1811 (6181)
	O			2005 (6843)
RB Dark	S	2263 (7724)	2195 (7492)	2154 (7352)
	O			2446 (8348)
VB Light	O	2006 (6846)	2160 (7372)	2322 (7925)
PD Beige	O	1954 (6669)	2177 (7430)	2356 (8041)

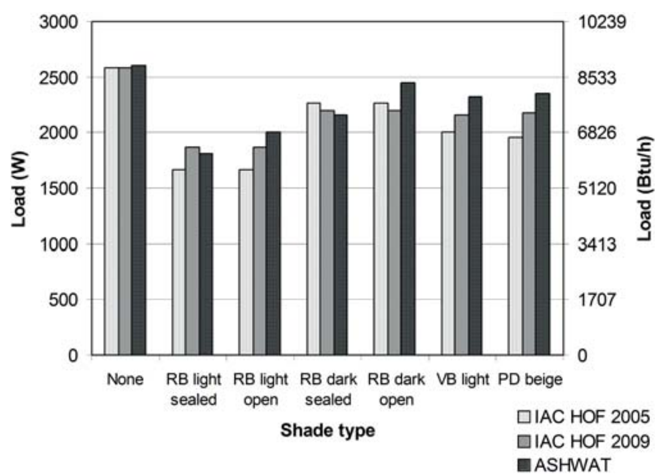

Figure 7 Comparison of sensible cooling loads calculated with IAC and ASHWAT models.

- Default HBX implementation using the IAC model as described in ASHRAE, 2005 p. 31.47 Equation (111), and
- ASHWAT with shade properties documented in Table 7.

Table 8 shows calculated sensible cooling loads for the shade and model alternatives. The same results are presented graphically in Figure 7, revealing a significant load impact, in some cases more than 10%.

Figure 8 compares HOF 2005 IAC and ASHWAT hourly heat gains for the pleated drape alternative. The ASHWAT results show proportionately more convective and longwave components and correspondingly less transmitted solar. This is not surprising, since the drape intercepts a significant fraction of the solar gain and is heated, resulting in convective and thermal radiant gain to the room. In addition, convective transfer occurs from both sides of the drape in addition to the indoor face of the glazing. Since convective gain is immediate cooling load, these effects contributes to the higher cooling loads predicted for the ASHWAT alternative. Note also that the peak gains calculated with ASHWAT are larger than IAC (417 vs. 336 W/m^2 (132 vs. 107 Btu/h-ft^2)).

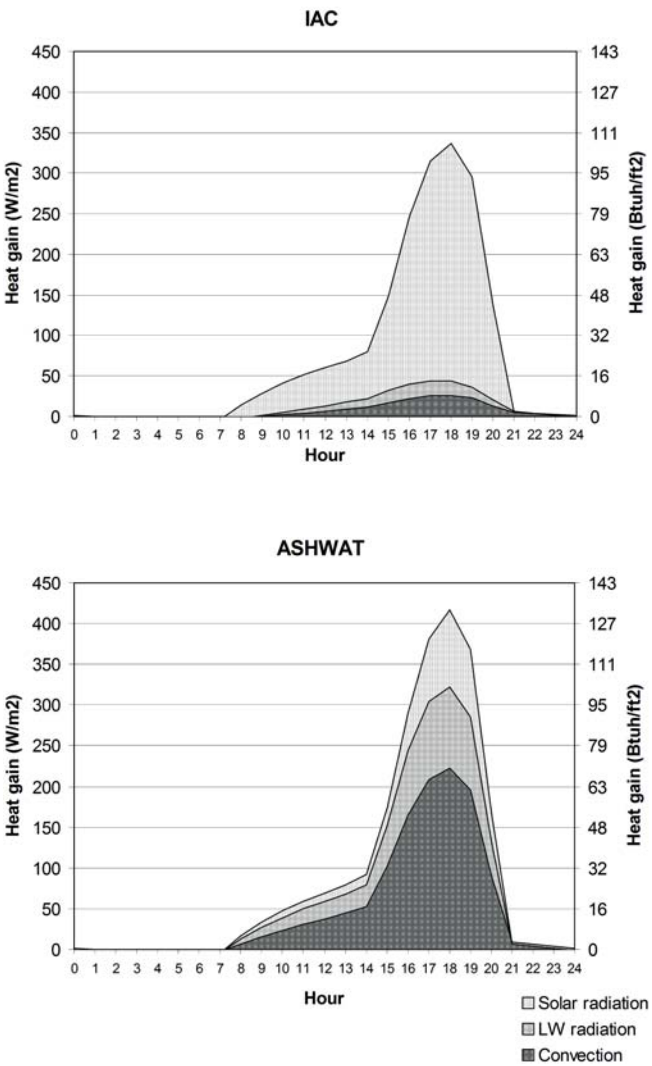

Figure 8 *Hourly heat gain components calculated with IAC model (upper) vs. ASHWAT (lower).*

DISCUSSION, CONCLUSIONS, AND FUTURE WORK

Significant progress has been achieved through the ASHRAE 1311-RP activity. The project moved through several stages including the formulation of a multilayer analysis framework using "effective" optical properties, the development of models for drapes, venetian blinds, roller blinds and insect screens, the demonstration of new models in the ASHRAE Toolkit, the production of summary data (IAC, FR) for the ASHRAE Handbook – Fundamentals. Byproducts of the work include input libraries for assembling multi-layer systems. All work has been extensively documented.

The need for more fundamental research arose at several stages. Progress in this category includes a multilayer solar analysis to track the beam and diffuse radiation, a method to measure off-normal, beam and diffuse components of solar reflection and transmission for shade materials, methods to calculate off-normal solar optical properties of shading materials, net radiation models for venetian blinds and pleated drapes, a simple method to estimate longwave properties of shading layer materials and the development of a new heat balance approach allowing (a) evaluation of U-factor and SHGC for any combination of opaque and diathermanous layers, exposed to any environment, and (b) a one-equation model offering the potential of on-the-fly heat balance calculations in the context of a time-step analysis.

The inherent value of the multilayer/effective-property approach should be emphasized. This framework entails a manageable level of complexity while delivering the power to analyze an almost limitless number of shading layer types and variations. In particular, the ability to adjust shading layer properties (e.g., slat angle) during the course of a simulation is valuable. The multilayer framework also offers the possibility for the development of additional shading layer models with relatively little effort.

A significant number of subcomponent models were validated. Many in-house measurements were performed. All of these measurements (Broad Area Illumination – Integrating Sphere (BAI-IS), guarded heater plate, spectrophotometer) are exceptionally accurate – of order 2%. A second level of validation was achieved with very good agreement between calculated and measured (NSTF) IAC and solar transmission values. This comparison included venetian blinds, a pleated drape, a roller blind and an insect screen.

In summary, it is worth noting that the 1311-RP research was undertaken with the specific aim of producing IAC and FR data for the ASHRAE Handbook - Fundamentals. The project was initiated when no comprehensive tool was available for modeling the complexities of a glazing/shading multilayer array. A small set of IAC and FR values were available. Now extensive sets of IAC and FR data have been compiled using a well-documented and consistent method. Few compromises have been made even though it might have been argued that the results need only be approximate because they will be used primarily for application in simplified building simulation models. The ASHWAT models exceed this level of utility. They offer a very wide range of design options that can readily be explored using rating tools or in the context of a more thorough building energy simulation.

Several suggestions for future research are offered.

- more accuracy regarding indoor and outdoor surface convective heat transfer coefficients
- explore the influence of forced convection and various types of diffusers on the convective heat transfer coefficients associated with an indoor shading attachment
- develop a more general theory regarding off-normal properties of drapery fabrics, roller blinds and perhaps insect screens

- link the ASHWAT models to design tools for "green" building design – a situation where extremely low loads and sensitivity to solar gain necessitate good simulation tools that include operable shades
- expand the set of shading layer models as demand arises - many innovative devices are being brought to market (e.g., sheer blinds)

The ASHWAT models can be used to answer many significant design and modeling questions

- investigate strategies for automated shading (mechachromic) control - most notably for venetian blinds because this is the most directionally-selective device
- investigate the influence of indoor-side forced convection - especially in the case of a shaded single glazing
- investigate the influence of different off-normal glazing and shading layer solar property models on performance results including IAC, Fraction-Radiant and peak cooling load
- examine the influence of shading attachment spacing on system performance

ACKNOWLEDGMENTS

We would like to thank ASHRAE, Natural Resources Canada (NRCan) and the Natural Sciences and Engineering Research Council (NSERC) for financial support as well as the Project Monitoring Subcommittee – Bob Hopper (original Chair, TC 4.1), Bob Doeffinger (TC 4.1), Chris Wilkins (TC 4.1), Dru Crawley (TC 4.7), and Ross McCluney (TC 4.5) – for their comments, guidance, and criticism throughout the project. In addition, many other TC members participated in project meetings and provided valuable feedback, including Steve Bruning, Christian Kohler, and Jeff Spitler.

REFERENCES

ASHRAE, 2005. ASHRAE Handbook – Fundamentals.

Barnaby, C. S., J. D. Spitler, and D. Xiao. 2004. Updating the ASHRAE/ACCA Residential Heating and Cooling Load Calculation Procedures and Data. 1199-RP Final Report. ASHRAE, Atlanta, GA.

Brunger, A., F. M. Dubrous, S. J. Harrison. 1999. "Measurement of the Solar Heat Gain Coefficient and U-values of Windows with Insect Screens," ASHRAE Transactions Vol. 105, Pt. 1.

Collins, M.R., J. L. Wright. 2006. "Calculating Centre-Glass Performance Indices of Windows with a Diathermanous Layer," ASHRAE Transactions, Vol. 112, Pt. 2. pp. 22-29.

Dubrous, F.M. 1993. "Development of a Solar Simulator Test Method for Evaluating the Thermal Performance of Windows," M.Sc. thesis, Department of Mechanical Engineering, Queen's University, Canada.

Edwards, D.K. 1977. Solar absorption by each element in an absorber-coverglass array, Technical Note, Solar Energy, Vol. 19, pp. 401-402.

Farber, E. A.; W. A. Smith, C.W. Pennington; J. C. Reed. 1963. Theoretical analysis of solar heat gain through insulating glass with inside shading. ASHRAE Transactions, Vol. 69, pp.393-405.

Harrison, S.J., F. M. Dubrous. 1990, "Determination of Window Thermal Characteristics Using a Solar Simulator Test Method," ASHRAE Transactions, Vol. 96, Pt. 1.

Harrison, S.J., F. M. Dubrous. 1992. "Uncertainties in Evaluation of Window SHGC and U-values Measured Using an Indoor Solar Simulator Facility," ASHRAE Transactions, Vol. 98, Pt. 2.

Huang, N.Y.T., J. L. Wright, M. R. Collins. 2006. "Thermal Resistance of a Window with an Enclosed Venetian Blind: Guarded Heater Plate Measurements," ASHRAE Transactions, Vol. 112, Pt. 2. pp. 13-21.

IGDB. 2008. International Glazing Database. http://windows.lbl.gov/materials/igdb/.

Keyes, M.W. 1967. Analysis and rating of drapery materials used for indoor shading. ASHRAE Transactions, 73, (1): 8.4.1.

Kotey, N.A., J. L. Wright, M. R. Collins. 2008a. "Determining Longwave Radiative Properties of Flat Shading Materials," 33rd Annual SESCI / 3rd CSBC Conference Proceedings, Fredericton, NB.

Kotey, N.A., Collins, M.R., Wright, J.L., and Jiang, T., 2008b, "A Simplified Method For Calculating The Effective Solar Optical Properties Of A Venetian Blind Layer For Building Energy Simulation," ASME Journal of Solar Energy Engineering, 131(2).

Kotey, N.A., J. L. Wright, M. R. Collins. 2009a. "A Detailed Model to Determine the Effective Solar Optical Properties of Draperies," ASHRAE Transactions, Vol. 115, Pt. 1.

Kotey, N.A., J. L. Wright, C. S. Barnaby, M. R. Collins. 2009b. "Solar Gain Through Windows with Shading Devices: Simulation versus Measurement. ASHRAE Transactions, 115(2).

Kotey, N.A., J. L. Wright, M. R. Collins. 2009c. "Determination of Angle-Dependent Solar Optical Properties of Drapery Fabrics," ASHRAE Transactions, Vol. 115, Pt. 2.

Kotey, N.A., J. L. Wright, M. R. Collins. 2009d. "Determination of Angle-Dependent Solar Optical Properties of Roller Blind Materials," ASHRAE Transactions, Vol. 115, Pt. 1.

Kotey, N.A., J. L. Wright, M. R. Collins. 2009e. "Determination of Angle-Dependent Solar Optical Properties of Insect Screens," ASHRAE Transactions, Vol. 115, Pt. 1.

Parmelee, G. V., W. W. Aubele. 1952. The shading of sunlit glass: an analysis of the effect of uniformly spaced flat opaque slats, ASHVE Transactions, Vol. 58, pp. 377-398.

Pedersen, C. O., R. J. Liesen, R. K. Strand, D. E. Fisher, L. Dong, and P. G. Ellis. 2001. A Toolkit for Building Load Calculations. ASHRAE, Atlanta, GA.

Pfrommer, P., K. J. Lomas, C. Kupke. 1996. "Solar Radiation Transport through Slat-Type Blinds: a New Model and its Application for Thermal Simulation of Buildings," Solar Energy, Vol. 57, No. 2, pp. 77-91.

R Development Core Team, 2008. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

Rheault, S., E. Bilgen. 1989. Heat transfer analysis in an automated venetian blind system, Journal of Solar Energy, Vol. 111 (Feb.), pp. 89-95.

Rohsenow, W.M., J. P. Hartnett (Editors). 1973. "Handbook of Heat Transfer," McGraw-Hill.

Rosenfeld, J.L.J., W. J. Platzer, H. Van Dijk, and A. Maccari. 2000. "Modelling the Optical and Thermal Properties of Complex Glazing: Overview of Recent Developments", Solar Energy, Vol. 69 Supplement, No. 1-6, pp.1-13.

Wright, J. L, C. S. Barnaby, M. R. Collins, and N. A. Kotey. 2009. "Improving Cooling Load Calculations for Fenestration with Shading Devices," final report, ASHRAE Research Project 1311-RP.

Wright, J.L. 2008. "Calculating Centre-Glass Performance Indices of Glazing Systems with Shading Devices," ASHRAE Transactions, Vol. 114, Pt. 2.

Wright, J.L., N. Y. T. Huang, and M. R. Collins. 2008. "Thermal Resistance of a Window with an Enclosed Venetian Blind: A Simplified Model," ASHRAE Transactions, Vol. 114, Pt. 1.

Wright, J.L. and N. A. Kotey. 2006. "Solar Absorption by Each Element in a Glazing/Shading Layer Array," ASHRAE Transactions, Vol. 112, Pt. 2. pp. 3-12.

Wright, J.L. 1996. "A Correlation to Quantify Convective Heat Transfer Between Vertical Window Glazings," ASHRAE Transactions, Vol 102, Pt. 1 pp. 940-946.

Wright, J.L. 1986. "Effective U-values and Shading Coefficients of Preheat/Supply Air Glazing Systems," Proc. Solar Energy Society of Canada, Winnipeg, pp 219-224.

Yahoda, D.S. and J. L. Wright. 2005. "Methods for Calculating the Effective Solar-Optical Properties of a Venetian Blind Layer," ASHRAE Transactions, Vol. 111, Pt. 1, pp. 572-586.

Yahoda, D.S., and J. L. Wright. 2004a. "Heat Transfer Analysis of a Between-Panes Venetian Blind Using Effective Longwave Radiative Properties," ASHRAE Transactions, Vol. 110, Pt. 1., pp. 455-462.

Yahoda, D. S. and J. L. Wright. 2004b. "Methods for Calculating the Effective Longwave Radiative Properties of a Venetian Blind Layer," ASHRAE Transactions, Vol. 110, Pt. 1., pp. 463-473.