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Assessing Convective Heat Transfer Coefficients Associated with Indoor Shading Attachments Using a New Technique Based on Computational Fluid Dynamics

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ABSTRACT

ASHRAE research project RP-1311 concluded with the creation of simulation models, the ASHWAT models, for glazing systems with shading attachments. Such assemblies are known as Complex Fenestration Systems (CFS). ASHWAT represents several key advances. An "equivalent layer" approach is used to track radiation at glazing layers, slat-type blinds, roller blinds, pleated drapes and insect screens. Longwave and off-normal solar optical properties are available for each of these shading layer types. A general thermal resistance framework allows for calculation of U-factor and Solar Heat Gain Coefficient (SHGC). Radiant flux, solar beam/diffuse or longwave, within the CFS multi-layer array is tracked by ASHWAT using an accounting system that is straightforward. To support this operation a large effort was devoted to the compilation of optical properties for shading layers - based on a significant level of measurement and analysis. It is also necessary to account for convective heat transfer between the various CFS layers. Methods to obtain convective heat transfer coefficients for glazing cavities are well established, even for a glazing cavity that includes a venetian blind. However, the convective heat transfer coefficients in the vicinity of a shading layer mounted next to a glazing system are not so readily obtained. Added complexity arises because each of three temperature nodes – indoor glazing surface, shading layer and room air – exchanges thermal energy with the other two nodes so three convective heat transfer coefficients are needed. No previous work provides an analysis of this three-resistor system. ASHWAT currently incorporates estimates of the three convective heat transfer coefficients, as functions of glass-to-shade spacing, based largely on known limiting cases and a limited amount of observation related to the behaviour of venetian blinds. Convective heat transfer coefficients can readily be evaluated in a two-resistor network. Quantification of the heat transfer between the nodes, for a given temperature difference, is sufficient. This is not the case for a three-node system. However, recent theoretical work shows that the three heat transfer coefficients can be obtained using a unique numerical perturbation procedure. Also, if this perturbation procedure is applied through Computational Fluid Dynamics (CFD) it is possible, using a specific sequence of steps, to escape the numerical error associated with small perturbations. The same approach cannot be applied to experimentation with natural convection. Theory is presented and sample results are compared to the ASHWAT estimates for a shading layer mounted adjacent to the indoor side of a window.

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INTRODUCTION

Background

It is widely recognized that buildings account for about half of the greenhouse gas production, more than half of the electricity consumption, and about 40% of the energy consumed in North America. Approximately 25% of this energy consumption is associated with windows. Good thermal design offers many possibilities for conservation and downsized mechanical equipment, and clearly the potential for energy savings is large. Consequently, the design of "green buildings" has become a topic of great interest and high activity. Skilled design of high performance glazing systems and shading attachments is a key component in successful green building design. The ability to control solar gain is especially important, allowing solar radiation to heat the building when heat is needed and being able to turn off the solar gain at other times.

In 2009 ASHRAE research project RP-1311 successfully concluded with the creation of a comprehensive set of simulation models for glazing systems coupled with slat-type shades, drapes, roller blinds and/or insect screens. The combination of glazing layers and shading attachments (or layers) has come to be known as a Complex Fenestration System (CFS). The models associated with RP-1311, known as the ASHWAT models, were implemented in the ASHRAE Toolkit (HBX version) and have since been incorporated in several significant building energy simulation software packages (e.g., Wright et al. 2011). ASHWAT has also been used to generate extensive tables of shade performance data that appear in the most recent ASHRAE Handbook of Fundamentals, Fenestration chapter. The ASHWAT models have been fully documented, almost exclusively in the ASHRAE Transactions. A full set of references can be found in the RP-1311 summary documents (Wright et al. 2009, Barnaby et al. 2009).

Four key components comprise the ASHWAT package. First, ASHWAT is based on an "equivalent layer" approach in which solar radiation scattered from any particular layer is assumed to be uniformly diffuse. This technique provides freedom regarding the way in which glazing and shading layers can be arranged and individual layers can be characterized by a relatively small amount of data (Wright and Kotey 2006). This technique also provides flexibility in design and in control of operable shading, and the opportunity to easily add new shading layer types. Currently ASHWAT includes models for slat-type shades, pleated drapes, roller blinds and insect screens. Second, a library of solar and longwave properties has been compiled for all of the shading layer materials included in ASHWAT. The properties of drapery fabric, roller blind material and insect screen are based on new measurements and newly developed techniques for measuring off-normal properties (Kotey et al. 2009a,b,c, Collins et al. 2011). Third, geometric layer models for slat-type shades and pleated drapes were formulated and tested (Yahoda and Wright 2004a,b, 2005, Kotey et al. 2009d, Collins and Jiang 2008, Kotey et al. 2009e, 2011). Fourth, a very general thermal resistance framework, a system that allows heat transfer between any pair of nodes, not just adjacent nodes, offers the possibility of calculating U-factor and Solar Heat Gain Coefficient (SHGC) for a CFS exposed to any combination of indoor/outdoor temperatures (air and mean radiant), and any level/direction of incident solar flux (beam and diffuse) (Collins and Wright 2006, Wright 2008). ASHWAT solar transmission and SHGC results were compared with indoor solar simulator measurements and good agreement was obtained (Kotey et al, 2009f). In addition, projects undertaken since the completion of RP-1311 demonstrate that the ASHWAT models can be used in the context of time-step building energy simulation with very little added CPU time – while retaining full design flexibility and the possibility of on-the-fly shade operation such as automated control of venetian blind slat angle (e.g., Lomanowski et al. 2009, Lomanowski and Wright 2009, 2011, Wright et al. 2011).

The Three-Resistor Network

The presence of a shading layer in a CFS, by design, has a direct influence on the way in which solar radiation interacts with each of the individual layers, with the CFS as a whole, and with the building. Similarly, a shading layer adds significant complexity to the mechanisms of heat transfer, and two additional details must be considered. First, many shading layers include open areas so they allow direct transmission of radiation, solar or longwave. Examples include venetian blinds, any drapery fabric with an open weave or the more modern, and popular, roller blind material that is fabricated with a uniform array of small holes. Second, in the case of an indoor shading attachment, air is usually able to flow through and around the shading layer. The connection between these two cases is that heat transfer can take place directly between two nodes that are not adjacent to each other. In the corresponding thermal network these additional heat transfer paths appear as resistors that bypass or "jump over" one or more intermediate layers. Figure 1 shows a shading attachment on the indoor side of a glazing system along with the indoor portion of the thermal network. The three-resistor network shown in Figure 1 clearly conveys the idea that each of the three temperature nodes communicates with the other two nodes by means of heat transfer. In other words, if one of T_g, T_s or T_a were altered independently a change in the rate of heat transfer would realistically be expected at both of the other nodes. Each of the three nodes exerts some influence on the other two. It is also worth noting that the network shown in Figure 1 could be used equally well to describe longwave radiant exchange or convective heat transfer.

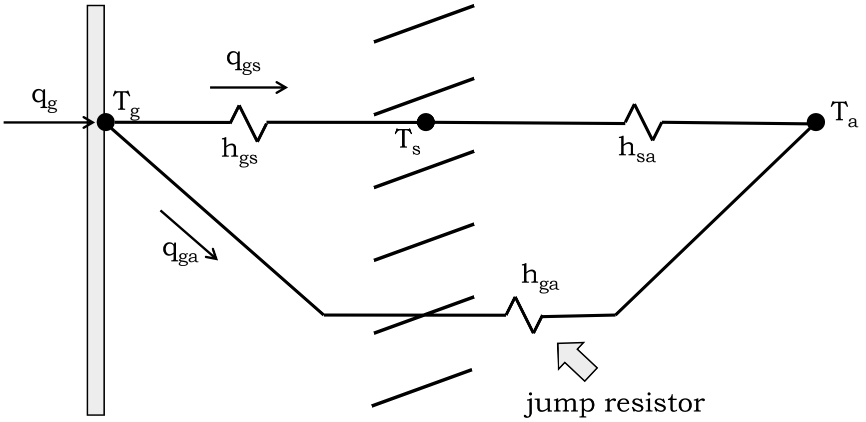

Figure 1: Three-node heat transfer network for the indoor surface of a glazing system, T_g, a shading attachment, T_s, and the indoor space, T_a

The network shown in Figure 1, complete with jump resistor, offers the opportunity to characterize the shading attachment more realistically, with the associated possibility of generating accurate solar-thermal performance results for the CFS. However, the three-resistor network brings two additional benefits that are highly important in the context of time-step building energy simulation. (1) When two three-resistor networks are employed in parallel, to characterize convective and longwave radiant heat transfer, simulation results include sufficient detail to calculate the ratio of radiant-to-total heat gain from the CFS to the conditioned space. This ratio, often called fraction-radiant, is a key piece of data needed to predict how and when heat gain is converted to cooling load; convective heat gain represents immediate cooling load but the conversion of radiant heat gain to cooling load entails a delay. The timing of the heat gain-to-cooling load conversion must be known to reliably predict peak equipment load. It is worth noting that the addition of an indoor shading attachment may not appreciably alter the radiant exchange between CFS and conditioned space but the presence of the shading layer roughly triples the area available for convective heat transfer. Therefore, an indoor shade generally causes the fraction-radiant of the heat gain to decrease, an influence that works to increase peak cooling load and to some extent negate the solar optical benefit of the shading attachment. (2) The three-resistor model lends stability to the iterative numerical operation used to solve the multi-layer CFS heat transfer problem. In an early version of ASHWAT the indoor side air flow was modelled by removing the resistor between glass and shading attachment (i.e., $h_{gs}=0$) while adding positive and negative energy sources at these two nodes to mimic heat transfer caused by the air flow. The same method was used, and is documented, in an older study of forced air flow between glazing layers (Wright 1986). But if, for convenience, the source term evaluation is lagged by one iteration the solution must be heavily over-relaxed to remain stable. In contrast, if the resistance network is kept intact and this aspect of the model becomes implicit, instead of explicit, the solution becomes stable and relaxation is unnecessary. When ASHWAT was upgraded to use the more general resistor network (Wright 2008), enabling the use of convective jump resistors and the use of the three-resistor network on the indoor side, the number of iterations required by the solver dropped by a factor of about 25. This high level of computation efficiency is one of the major reasons that ASHWAT is sufficiently fast to be embedded in building simulation software. It is also noteworthy that the general resistance network makes it possible to calculate SHGC and U-factor for a CFS exposed to any combination of environment temperatures and any level of insolation – something that can't be done using the more traditional irradiance-radiosity methods to track longwave radiant exchange.

Current ASHWAT Estimates of Convection Coefficients at the Indoor Shading Layer

Currently, ASHWAT provides an estimate of the three convective heat transfer coefficients shown in Figure 1, as a function of shade-to-glass spacing, based largely on known limiting cases. A small adjustment is also applied as a function of slat angle for venetian blinds, based on observations provided by interferometry and numerical analysis (Collins 2001, Collins et al. 2002a,b). The models, and relevant commentary, used to estimate h_{gs}, h_{sa} and h_{ga} are documented in Appendix C of the RP-1311 final report (Wright et al. 2009).

Although no difficulty has been reported regarding the application of a three-resistor network in the ASHWAT shading attachment model, it should be recognized that the models used to evaluate h_{gs}, h_{sa} and h_{ga} do not enjoy the same fundamental grounding or level of study that applies to all of the other ASHWAT components. The existing literature yields virtually no information about the use of three-resistor networks and the research of shading attachments is at an early stage. The current study was undertaken to develop a method by which the three individual convective heat transfer coefficients associated with an indoor shading attachment can be resolved and quantified.

PERTURBATION AND THE BIG FIX

Consider the thermal network shown in Figure 1. The radiant exchange version of this network can readily be characterized so attention is confined to convective heat transfer. Presuming that the glass, shade and room air temperatures, T_g, T_s and T_a, are fixed at known values, it is possible to study the resulting heat transfer by experiment or by means of Computational Fluid Dynamics (CFD). Either method will provide the corresponding heat transfer rates at the three nodes.

The heat flux from the glass surface, q_g, for example, is shown in Figure 1. The heat flux leaving each node splits into two legs of the circuit. See, for example, Equation 1.

$$q_g = q_{gs} + q_{ga} = h_{gs}\left(T_g - T_s\right) + h_{ga}\left(T_g - T_a\right) \tag{1}$$

Expressions similar to Equation 1 can be written for the T_s and T_a nodes but the resulting equations are not independent and are not sufficient to yield information about heat transfer rates or heat transfer coefficients in individual legs of the circuit. However, a solution is available through CFD-based perturbation.

If one of the node temperatures is perturbed, say by δT, the heat transfer rates will also be altered in two of the three legs of the circuit. Say T_s is perturbed as shown in Equation 2.

$$T_s^* = T_s + \delta T_s \tag{2}$$

Then Equation 1 can be re-written as Equation 3 while noting, for the moment, the assumption that h_{gs} is influenced by T_s but h_{ga} is not.

$$q_g^* = h_{gs}^*\left(T_g - T_s^*\right) + h_{ga}\left(T_g - T_a\right) \tag{3}$$

The change in heat flux at the glass surface, δq_g, caused by perturbing T_s, is found by subtracting Equation 1 from Equation 3. Equation 4 is obtained.

$$\delta q_g = q_g^* - q_g = T_g\left(h_{gs}^* - h_{gs}\right) - h_{gs}^* T_s^* + h_{gs} T_s \tag{4}$$

Equation 4 highlights the idea that δq_g is caused not just by δT_s, but also by any change in h_{gs} caused by δT_s. Given this added complication it appears that h_{gs} will be difficult to evaluate. The remedy is to hold h_{gs} constant; to fix h_{gs}. This cannot be done in a natural convection experiment but it *can* be done in the course of CFD simulation. Recognizing that, for a given geometry, h_{gs} is a function of only thermo-fluid properties (the properties of air in this case) and the flow field (i.e., the velocity vector field across the problem domain) it is apparent that h_{gs} can be fixed simply by holding the fluid properties and the flow field constant. So, with h_{gs} held constant, Equation 4 can be simplified and the result is Equation 5. Note that the same result would have been obtained even if it had been assumed that h_{ga} is influenced by T_s.

$$h_{gs} = -\frac{\delta q_g}{\delta T_s} \qquad (h_{gs} \text{ held constant}) \qquad (5)$$

Equation 5 is especially useful. The logic behind Equation 5 leads to a two step procedure. First, a CFD solution is generated for specific values of T_g, T_s and T_a , and the resulting temperature field is used to calculate q_g. Second, another solution is generated with a perturbation applied to T_s but in this case the CFD software is prevented from re-solving and updating the velocity field and fluid properties. In other words, only the energy balance portion of the CFD procedure is executed to generate a new temperature field that includes the effect of perturbation. Then, the new temperature field is used to calculate a new value of q_g and Equation 4 is used to evaluate δq_g and, to finish, Equation 5 gives h_{gs}.

Finally, two interesting observations can be made about the second simulation run, the perturbation run, because the energy balance becomes linear when the fluid properties and the flow field are fixed. As a result, (1) the perturbation does not need to be small and many difficulties associated with roundoff error can be avoided in the application of Equation 5, and (2) the energy balance can be solved with relatively little computational effort.

The method described above, leading to Equation 5, is presented and discussed in greater detail in (Mohaddes Foroushani et al 2015) where it is demonstrated with verification exercises and where complications associated with upwinding (outside the scope of this paper) are discussed and associated limitations documented. The method itself, perturbation with h constant with the use of Equation 5, is dubbed "dQdT" for convenience. Here, dQdT is demonstrated using a simple three-temperature problem that approximates a roller blind mounted on the indoor side of a window.

CASE STUDY – ROLLER BLIND COMPARISON

A CFS configuration comprised of a flush-mounted glazing and a flat indoor-mounted opaque shading layer, e.g. a roller blind, was studied using the dQdT method. The three heat transfer coefficients shown in Figure 1 were obtained for typical summer (T_g=35ºC, T_s=30 ºC, T_a=24 ºC (T_g=95ºF, T_s=86 ºF, T_a=75.2 ºF)) and winter (T_g=13ºC, T_s=18 ºC, T_a=21 ºC (T_g=55.4 ºF, T_s=64.4 ºF, T_a=69.8 ºF)) conditions and for different values of glass-shade spacing. The glass and shading layers were assigned a height of H=0.5 m (H=19.7 in). This relatively short height was chosen in order to avoid transition to turbulence. The thermophysical properties of air were simply held constant for all CFD runs, evaluated at 21ºC (69.8ºF), and the Boussinesq density approximation was invoked. A commercially produced CFD code was used.

Figure 2 shows the glass-to-shade heat transfer coefficient calculated using dQdT. Values of h_{gs}, are shown as a function of glass-shade-spacing, b. When b is small h_{gs}, is dominated by conduction, regardless of the node temperatures. This is in agreement with the ASHWAT model (Wright et al. 2009), $h_{gs}=k/b$. As b increases, for both winter and summer conditions, both h_{gs} and the conduction limit decrease but h_{gs} falls below the conduction limit and h_{gs} approaches zero at b=25 mm (b≈1 in). Two different h_{gs} values are obtained at b=12 mm (b=0.47 in) because of the slightly different flow fields obtained, for the winter and summer simulation temperatures.

Figure 3 shows dQdT results for h_{ga} and h_{as} with both compared to the ASHWAT model (Wright et al. 2009). The ASHWAT model requires a user-specified convective heat transfer coefficient, h_c, that applies at very large b, meant to make the distinction between forced and natural convection. In this study h_c was calculated using (Ostrach 1953) for a vertical flat plate at the given surface temperatures. The dQdT results are generally above the ASHWAT curves, except at low values of spacing (b≈6 mm (b≈0.24 in)). Moreover, h_{ga} approaches zero at a finite spacing, indicating that the glass will be isolated from the indoor air when the shade is closer than about 5 mm (b≈0.20 in). The ASHWAT model, on the other hand, is based on the assumption that h_{ga} reaches zero at b=0. The dQdT data follow trends similar to ASHWAT, but grow more steeply with respect to b toward the isolated flat plate limit. Another interesting observation is that both h_{ga} and

h_{sa} reach a peak near b=25 mm (b≈1 in), exceeding their isolated flat plate limits, indicating enhancement of heat transfer at each surface due the boundary layer developed along the other. As the spacing is further increased, both surface-to-air coefficients decrease and approach their respective isolated flat plate limits as given by Ostrach.

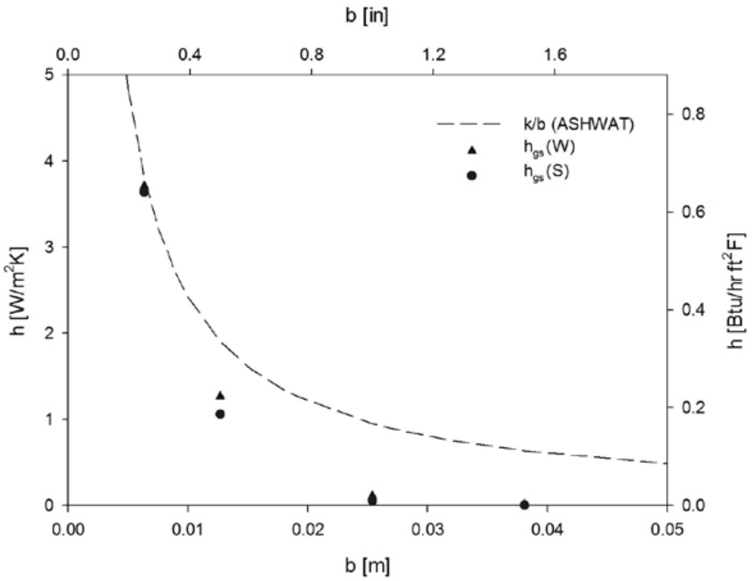

Figure 2: dQdT results for glass-to-shade heat transfer coefficeint, h_{gs}, versus spacing, b, with H=0.5 m (H=19.7 in), in summer (S) and winter (W), and comparison to ASHWAT model $h_{gs}=k/b$

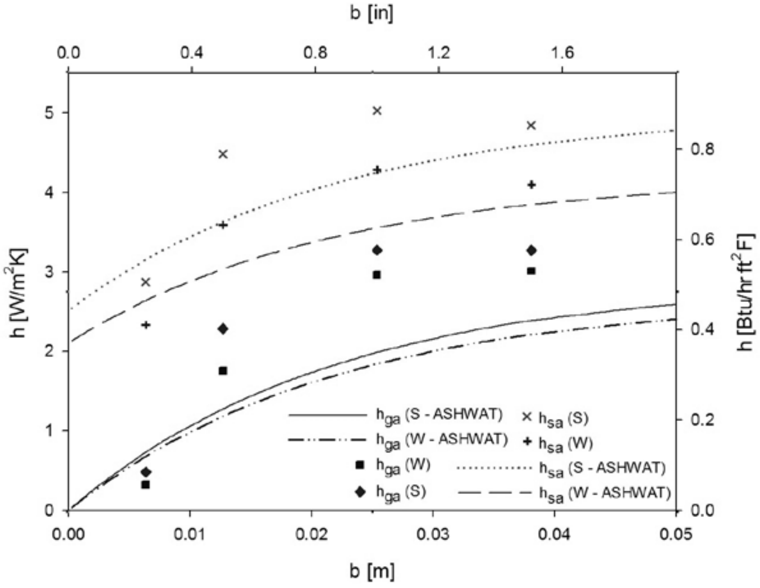

Figure 3: dQdT results showing h_{ga} and h_{sa} vs spacing, b, (H=0.5 m (H=19.7 in)) in summer (S) and winter (W), and comparison to ASHWAT model

CONCLUDING REMARKS

Sample results are presented for a shading layer attached to the indoor side of a window, and compared to the current ASHWAT characterization. In particular, the various convective heat transfer coefficients are examined as a function of spacing between glass and shading layer. While the ASHWAT model gives a good estimate of the heat transfer coefficients and accurately reflects various trends, it has shortcomings compared to dQdT, the new CFD-perturbation-constant-h technique. The ASHWAT model overestimates the glass-to-shade heat transfer coefficient for intermediate spacing but ASHWAT underpredicts glass-to-air and shade-to-air heat transfer coefficients for spacing beyond 10 mm (0.39 in). The effect of spacing seems to be underestimated by the ASHWAT model as the dQdT data points approach the flat plate limit at smaller spacing than ASHWAT predicts. Nonetheless, although it is clear that the ASHWAT models can be improved, it is worth remembering that the current research represents a preliminary investigation of a simple geometry. Also, it is not clear whether the noted discrepancies will strongly affect the overall performance of the CFS.

Further investigation of the three-resistor network of different CFS configurations, with more realistic geometries and a turbulence model when needed, will provide greater insight regarding the convective heat transfer coefficients that apply to indoor shading attachments. A sensitivity analysis could then quantify the level of improvement the dQdT results bring to the calculation of U-factor, SHGC, fraction-radiant and overall building energy performance.

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NOMENCLATURE

ASHWAT = ASHRAE Window ATtachment models
b = glass-shade spacing
CFS = Complex Fenestration System
h = convective heat transfer coefficient, based on glass area
H = window height
k = thermal conductivity of air
q = heat flux, based on glass area
SHGC = Solar Heat Gain Coefficient
T = temperature
δ = delta, indicating a small change

Subscripts

a, s, g = air, shade, glass nodes, respectively
xy = *x-to-y, where x and y = a, g, or s*

Superscripts

$*$ = variable or value associated with perturbation

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