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Indoor-Side Convection Coefficients for Complex Fenestration Systems with Roller Blinds

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ABSTRACT

In order to characterize the resistor network that describes convective heat transfer on the indoor side of a complex fenestration system, three convection coefficients are needed. Although methods to obtain convection coefficients in glazing cavities are well established, the convection coefficients in the vicinity of an indoor-mounted attachment are not so readily available. In principle, convection coefficients of a three-resistor network cannot be obtained based on numerical solutions or measurement only. The ASHWAT models for simulating windows with attachments currently provide estimates of the three convection coefficients as functions of glass-to-shade spacing, based largely on known limits. Recently, a numerical technique, dubbed dQdT, was developed for evaluating the heat transfer coefficients of multi-temperature convection problems. This technique entails numerical solutions of the full set of governing equations and subsequent solutions of the energy equation with perturbed boundary conditions. In earlier work, dQdT was applied to a fenestration system with an indoor-mounted roller blind. To keep the flow laminar and the numerical solutions simple, a relatively short window was considered. Preliminary results suggested that ASHWAT gives good estimates of the convection coefficients and accurately predicts the general trends. Nevertheless, ASHWAT overestimated the glass-to-shade heat transfer coefficient for intermediate spacing, while underpredicting glass-to-air and shade-to-air heat transfer coefficients for larger spacings. The effect of spacing also seemed to be underestimated by ASHWAT. The present study was undertaken to further examine the accuracy of the ASHWAT estimates for windows with realistic dimensions, various glazing-attachment spacings and taking into account the transition of the flow to turbulence. Excellent agreement between the dQdT results and the ASHWAT predictions was obtained under summer design conditions, confirming the validity and utility of the current ASHWAT correlations. A minor adjustment to improve the accuracy of the current ASHWAT estimates is suggested.

INTRODUCTION

The ASHWAT Models

Energy-efficient glazing systems and shading attachments are now a key element in the design of green buildings. The ability to control solar gain through windows allows heating of the building with solar radiation when heating is needed and blocking solar gain when cooling is required. To achieve this level of control, models for the thermal performance of windows were needed for both rating/compliance purposes and whole-building simulation codes.

ASHRAE research project RP-1311 successfully concluded in 2009 with a comprehensive set of simulation models

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for glazing systems with attachments – slat-type shades, drapes, roller blinds and/or insect screens. The combination of glazing layers and shading attachments is known as a Complex Fenestration System (CFS). The models developed in RP-1311, known as the ASHWAT models, have been implemented in the ASHRAE Toolkit (HBX version) and other building energy simulation software (e.g., Wright et al. 2011). Using ASHWAT, tabulated shade performance data have been generated, now appearing in the ASHRAE Handbook of Fundamentals. ASHWAT solar transmission and SHGC results were compared with indoor solar simulator measurements and good agreement was obtained (Kotey et al. 2009). In addition, projects undertaken since the completion of RP-1311 demonstrate that the ASHWAT models can be used in time-step building energy simulation with very little added CPU time, while retaining full design flexibility and the possibility of real-time shade operation (e.g., Lomanowski and Wright 2011, Wright et al. 2011). For a full list of references on the ASHWAT models see the RP-1311 summary documents (Wright et al. 2009, Barnaby et al. 2009).

Driven by the significant and wide-spread use of the ASHWAT models, the present study was undertaken to enhance the fundamental grounding of the correlations currently used in ASHWAT to estimate the indoor-side convection coefficients of a CFS. A recently developed CFD-based technique is applied to demonstrate the validity of these correlations. To contextualize this study, a major part of the paper is dedicated to a summary of development of the resistor-network models used in ASHWAT for convective heat transfer on the indoor side of complex fenestration systems and the evaluation of the corresponding convection coefficients.

The Three-Resistor Network

A key element of ASHWAT is a very general resistor-network used to calculate U-factor and Solar Heat Gain Coefficient (SHGC) of CFS for 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). In a resistor-network, each layer is represented by a temperature node and is connected to other layers (nodes) though radiative and convective thermal resistances. The main advantage of this approach is that it allows heat transfer between any pair of layers, which may not necessarily be adjacent. The indoor portion of this resistor network is of interest to the present study.

In the presence of an indoor-mounted attachment there are complexities introduced in heat transfer around a window system which must be considered in modeling. Many attachments, e.g. Venetian blinds, drapery with open-weave fabric and insect screens, allow direct transmission of radiation, solar or longwave. Therefore, radiant exchange can take place directly between two layers that are not adjacent to each other, "bypassing" the layers in between. Likewise, air may flow through and around an attachment, allowing direct convective heat transfer between non-adjacent layers.

In Figure 1, the indoor portion of the resistor network of a CFS with an indoor-mounted attachment is shown. Note that each of the convective resistors shown in this figure exists in parallel with a radiative resistor. The present study pertains solely to the convective mode of heat transfer. In this delta network, convective heat transfer may occur through the resistor ("path") that bypasses or "jumps over" the intermediate shading layer. Furthermore, since any two of the three temperature nodes can communicate thermally, heat transfer at each node is in general influenced by all three nodes.

The delta network shown in Figure 1 is advantageous in that it reveals detailed information about the heat transfer phenomenon and provides the possibility of generating accurate solar-thermal performance data. Furthermore, the generic resistor-network formulation makes it possible to calculate SHGC and U-factor of a CFS for any combination of environment temperatures and any level of insolation. This is not possible using the traditional irradiance-radiosity approach for tracking longwave radiant exchange. The resistor-network formulation is computationally advantageous too, especially in the context of time-step building energy simulation. See (Wright 2008) and (Foroushani et al. 2015) for more detailed discussions of these advantages.

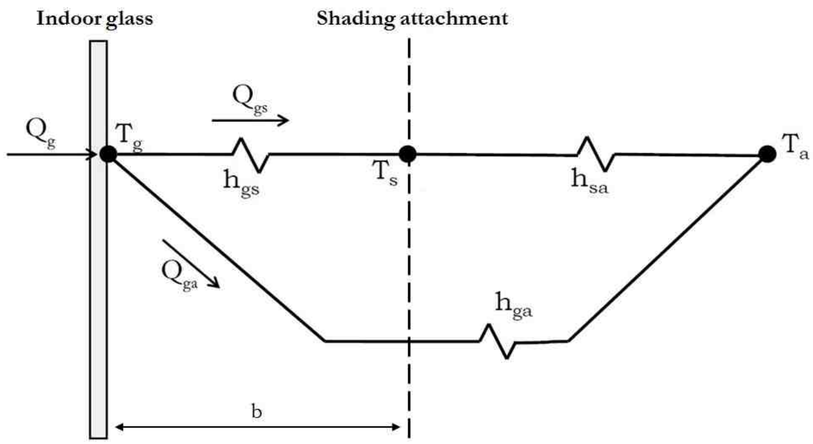

Figure 1 The resistor network of the indoor side of a glazing system at T_g, with a shading attachment at T_s, in indoor space at T_a

INDOOR-SIDE CONVECTION COEFFICIENTS

Current ASHWAT Estimates

Convective heat transfer in complex fenestration systems belongs to the broad class of multi-temperature convection problems: convective heat transfer problems involving two or more isothermal heat sources/sinks. The formulation of this class in terms of thermal-resistor networks has been shown to be advantageous (Foroushani et al 2016a,b). Nevertheless, it can be shown that in general, the paired convection coefficients that characterize the resistor network of a multi-temperature convection problem cannot be obtained based only on the knowledge of total heat transfer rates at the nodes, i.e. the information available from numerical or analytical solutions, or measurements. Modeling multi-temperature convection problems in terms of resistor networks and techniques for obtaining the corresponding convection coefficients is the subject of an ongoing research project.

Currently, approximate estimates of the three convection coefficients that characterize the delta network of Figure 1 are used in ASHWAT. Based on known limits and experience, empirical correlations have been developed that give indoor convection coefficients as functions of shade-to-glass spacing, b.

The glass-to-shade convection coefficient, h_{gs}, is estimated assuming laminar flow in the channel formed between the glass and attachment. Furthermore, assuming a relatively short thermal development length, heat transfer is assumed to be dominated by pure conduction across the vertical flow. Equation 1 is therefore taken as a reasonable estimate for h_{gs}. When the shading attachment is spaced well away from the window, h_{gs} will be small and its influence unimportant. Equation 1 is plotted in Figure 2.

$$h_{gs} = \frac{k}{b} \tag{1}$$

The convection coefficients pertaining to T_a, h_{sa} and h_{ga}, are evaluated based on a user-specified "run-off" value, h_c. This approach allows for the effects of different boundary conditions, e.g. forced versus natural convection, to be taken into account by adjusting h_c. To incorporate the effects of glass-shading spacing, b, two limiting cases were considered. When b is large the convective heat transfer at one layer, glass or shade, will not be influenced by the presence of the other layer and mimics convection at an isolated flat plate. Note that the attachment layer is exposed to air on both sides. When b approaches zero, on the other hand, the connection between the glass and the indoor air is blocked, while one side of the attachment layer remains exposed. An exponential function was introduced to represent this behaviour and make a smooth transition between the limits. This transition was scaled by assuming that the boundary layers at the glass and shading layer surfaces will not interfere for b>0.1 m (4 in). See Equations 2 and 3, and Figure 2 where these equations are plotted using h_c=3.5 W/m²K, a typical value for natural convection.

$$h_{ga} = h_c\left(1 - \exp\left(-4.6\frac{b}{0.1}\right)\right) \tag{2}$$

$$h_{sa} = h_{ga} + h_c = h_c\left(2 - \exp\left(-4.6\frac{b}{0.1}\right)\right) \tag{3}$$

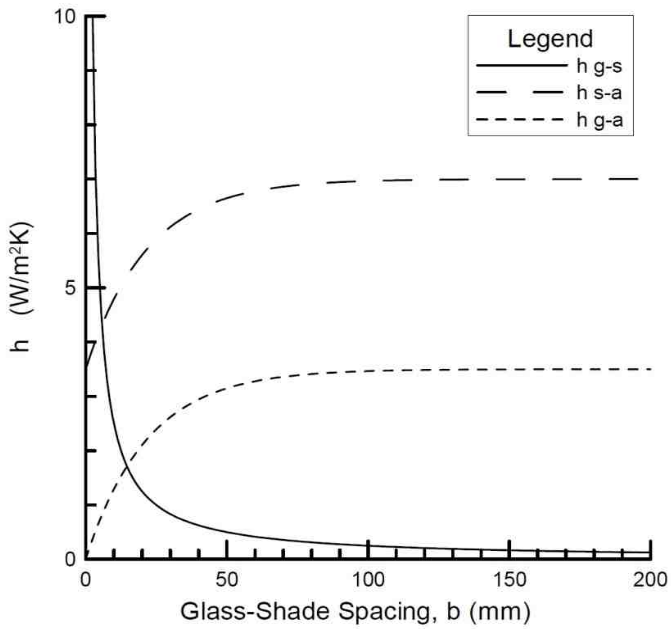

Figure 2 ASHWAT estimates for the indoor-side convection coefficients of a complex fenestration system (Barnaby et al. 2009) (h_c=3.5 W/m²K)

It is noteworthy that the indoor-side delta network is only a small part of the complex network of convective and radiative resistors that models heat transfer in a CFS. Moreover, heat transfer at the indoor side is in most cases dominated by radiant exchange. Therefore, the performance of the ASHWAT models and the whole-building energy simulations is unlikely to be sensitive to the indoor-side convection coefficients. This was demonstrated in a recent sensitivity analysis (Foroushani et al 2016c).

Nonetheless, the approximate models used in ASHWAT to evaluate h_{gs}, h_{sa} and h_{ga} do not enjoy the same level of fundamental grounding compared the other components of ASHWAT. The research on the thermal performance of window attachments is at a relatively early stage and the existing literature yields virtually no information about the resistor-network formulation and evaluating the corresponding resistances. As mentioned earlier, convection at the indoor side of a CFS is part of a broad class of heat transfer problems which has not been extensively studied.

dQdT: A New Technique for Characterizing Multi-Temperature Convection

In an ongoing research project, a technique dubbed dQdT has been developed for calculating the paired convection coefficients of multi-temperature convection coefficients. This technique entails a baseline solution to the full set of governing equations and subsequent solutions of the energy equation with perturbed boundary conditions. The development and application of this technique in the context of heat transfer in CFSs can be found in an earlier paper (Foroushani et al. 2015). Theoretical details of the dQdT technique can be found in (Foroushani et al. 2016b).

To obtain a convection coefficient using dQdT, e.g. h_{gs}, a baseline numerical solution is first obtained for the boundary temperatures of interest, $\{T_g,T_s,T_a\}$, and the heat transfer rate at the glass, Q_g, is obtained. Next, a new solution to the energy equation only is generated with the boundary temperature T_s perturbed to T_s^*, while the velocity field is not updated; the velocity field of the baseline solution is retained. Using the updated solution to the temperature field, the new heat transfer rate, Q_g^*, is calculated. Equation 4 is then used to evaluate h_{gs}.

$$h_{gs} = \frac{1}{A_g}\left(\frac{Q_g^* - Q_g}{T_s - T_s^*}\right) \tag{4}$$

Following the same procedure, h_{ga} and h_{sa} can be found using Equation 4 with a mere change of the subscripts.

Preliminary results of the dQdT technique were reported (Foroushani et al. 2015) for a CFS comprised of a flush-mounted glazing and an indoor-mounted opaque shading layer, e.g. a roller blind, for design summer and winter conditions and different values of glass-shading spacing. A relatively short height of H=0.5 m was chosen in order to keep the flow laminar and the computational cost low. Comparing the existing ASHWAT estimates with dQdT results, it was shown that ASHWAT gives a good estimate of the convection coefficients and predicts various trends with good accuracy. However, some shortcomings were noted. For this sample case, ASHWAT overestimates the glass-to-shade convection coefficient for intermediate spacing, while it underpredicts glass-to-air and shade-to-air convection coefficients for b>10 mm (0.39 in). The effect of spacing seems to be underestimated by ASHWAT. The present study was undertaken to further examine the observed discrepancies between ASHWAT and dQdT.

IMPROVED MODEL: SAMPLE RESULTS

A CFS configuration comprised of a flush-mounted glazing and an indoor-mounted roller blind was studied using the dQdT method. The glass and shading layers were modeled as impermeable, no-slip, isothermal surfaces with a height of H=1.65 m (H=65 in). Different glass-shading spacings were considered in the range 0.025 m (1 in)<b<0.15 m (5.9 in), i.e. 11<H/b<66. A commercial CFD solver was used to generate baseline solutions for six different spacings and perform the temperature perturbation involved in dQdT. In the numerical solutions, the Boussinesq approximation for density was invoked, while other thermophysical properties of air were assumed to be constant, evaluated at T_a (Pr=0.7). The Shear Stress Transformation (SST) k-ω model with low-Re correction was used for turbulence. Radiation was not modeled.

A schematic of the computational domain is shown in Figure 3. The domain was discretized into a non-uniform unstructured mesh of approximately 345,000 control volumes. Pressure, temperature, and turbulent parameters (kinetic energy and specific dissipation rate) were set at the far-field boundaries. The solver default values were used for the turbulence parameters (k=1 m^2/s^2, ω=1 s^{-1}). Since the effects of the shading attachment are mainly of interest in calculating cooling loads, results were generated for typical temperatures encountered under design summer conditions: T_g=35ºC (95ºF), T_s=28ºC (82.4ºF), and T_a=24ºC (75.2ºF). In this case, the Rayleigh number based on $(T_g+T_s)/2 - T_a$ and H is 3.9×10^9.

It must be noted that numerical modeling of natural convection in the transition regime, especially using RANS turbulence models such as SST k-ω, is one of the very difficult problems in CFD and there are considerable uncertainties arising specifically from the turbulence model and the far-field boundary conditions. Nevertheless, the results presented here are representative of typical engineering simulations using well-established models and commercial solvers.

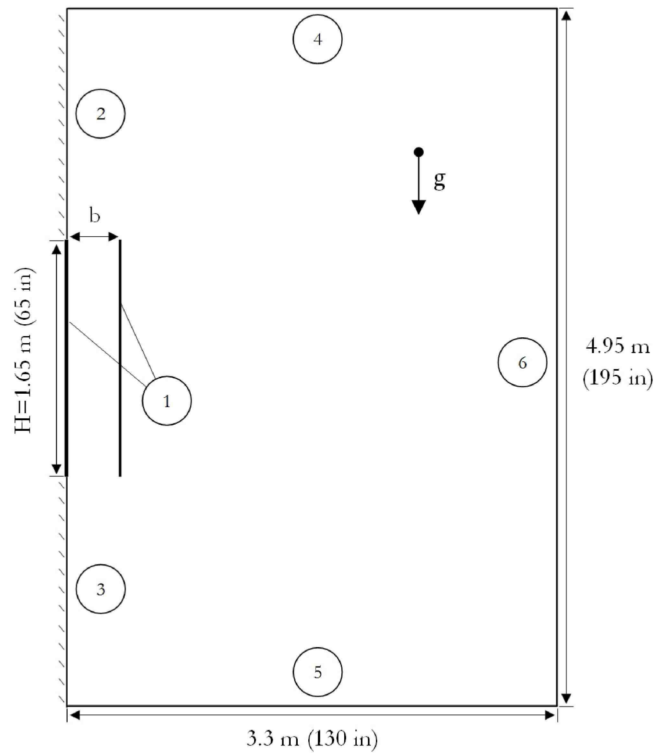

Figure 3 Schematic of computational domain. 1: Isothermal walls, 2-3: Adiabatic walls, 4-6: Pressure boundaries

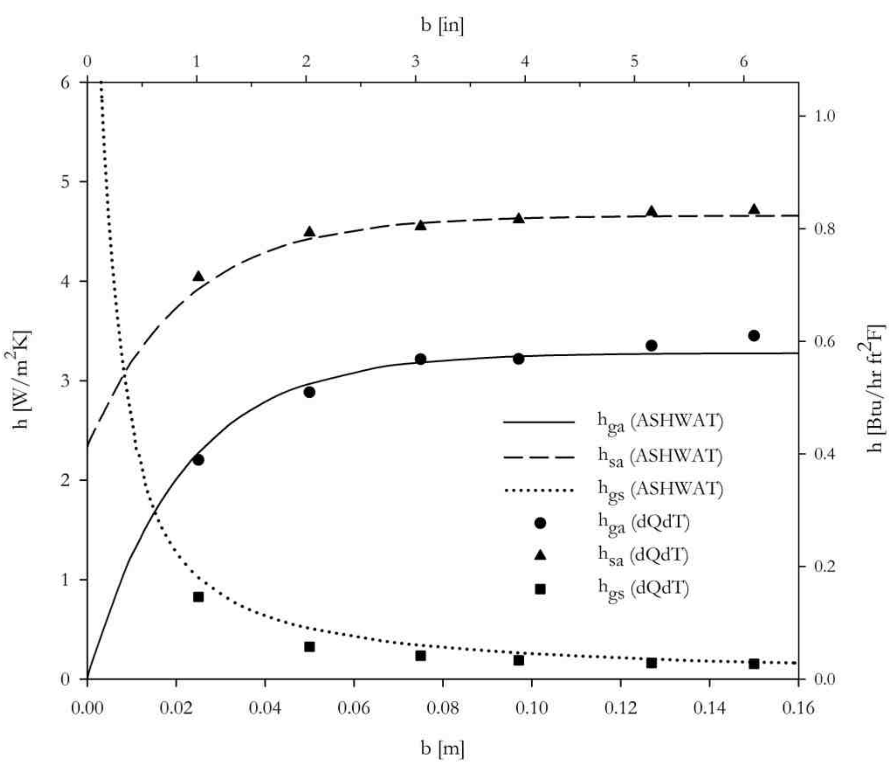

Figure 4 dQdT and ASHWAT results for the indoor-side convection coefficients of a complex fenestration system (H=1.65 m, T_g=35ºC, T_s=28ºC, and T_a=24ºC)

The dQdT results are shown in Figure 4 where the ASHWAT curves are also plotted for comparison. It can be seen that ASHWAT slightly overpredicts the glass-to-shade convection coefficient, h_{gs}. Note, however, that compared to the results for laminar flow (Foroushani et al. 2015), the dQdT results for h_{gs} in turbulent flow are reasonably close to the ASHWAT curve (Equation 1). This may be attributed to the enhancement of glass-to-shade heat transfer due to turbulent mixing and the increase in the effective conductivity of air. Recall that Equation 1 was developed assuming thermally-developed flow between glass and shade. The ASHWAT predictions for glass-to-air and shade-to-air coefficients, h_{ga} and h_{sa}, are in excellent agreement with the dQdT results. In the laminar-flow results (Foroushani et al. 2015), ASHWAT also underpredicted both h_{ga} and h_{sa}. But in the turbulent-flow results shown in Figure 4, ASHWAT predictions of h_{ga} and h_{sa} are both in very good agreement with the dQdT results.

Note that in Equations 2 and 3, the run-off value for h_{ga} and h_{sa} was assumed to be the same. Nevertheless, better accuracy is obtained by evaluating h_c for each layer separately using the respective surface-to-air temperature difference. The ASHWAT curves shown in Figure 4 were generated using run-off values of 3.29 W/m^{2}K (0.58 BTU/hr ft^2 F) and 2.33 W/m^{2}K (0.41 BTU/hr ft^2 F) for the glass and shade respectively, calculated using the empirical correlation by Churchill and Chu (1975). This is one possible modification to improve the accuracy of the ASHWAT correlations.

CONCLUDING REMARKS

Currently, the ASHAWT models use simple estimates for the indoor-side convection coefficients of a fenestration system with an indoor-mounted attachment. These estimates are based largely on two known limits and limited observation on the heat transfer performance of windows with shading attachments. It is known that the U-value and SHGC of a CFS have low sensitivity to the indoor-side convection coefficients. Nevertheless, the accuracy of the current estimates was further studied to reinforce the fundamental grounding of ASHWAT. In order to do this, a numerical technique, dQdT, was recently developed to calculate the paired convection coefficients that characterize the resistor network of a multi-temperature convection problem, including convection at the indoor side of a complex fenestration system. In the present paper, dQdT was applied to obtain the indoor-side convection coefficients of a window-roller blind configuration under design summer conditions. A commercial CFD solver was used to generate numerical solutions to turbulent heat and fluid flow around the fenestration system and implement the dQdT technique.

Earlier work, where only laminar flow was considered, had indicated a potential for improving ASHWAT using dQdT results. Although it was expected that the transition of the flow to turbulence introduces complexities to the heat transfer phenomenon and possibly reduce the accuracy of the ASHWAT estimates, the present study shows otherwise: even when the flow transitions to turbulence, ASHWAT estimates are in excellent agreement with the results of the more detailed dQdT technique. The close agreement between the results reported in this paper confirms the validity and utility of the current ASHWAT correlations. One possible modification in ASHWAT is to take into account the difference between the run-off values of glass-to-air and shade-to-air convection coefficients, caused by the difference in the driving temperature differences.

ACKNOWLEDGMENTS

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NOMENCLATURE

A	=	surface area
ASHWAT	=	ASHRAE Window ATtachment models
b	=	glass-shading spacing
CFS	=	Complex Fenestration System

h	=	convection coefficient
H	=	window height
k	=	thermal conductivity of air
Q	=	heat transfer rate
SHGC	=	Solar Heat Gain Coefficient
T	=	temperature

Subscripts

g	=	indoor glass surface
ga	=	glass to air
gs	=	glass to shade
s	=	shading layer
sa	=	shade to air
a	=	air

Superscripts

*	=	value associated with perturbation

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