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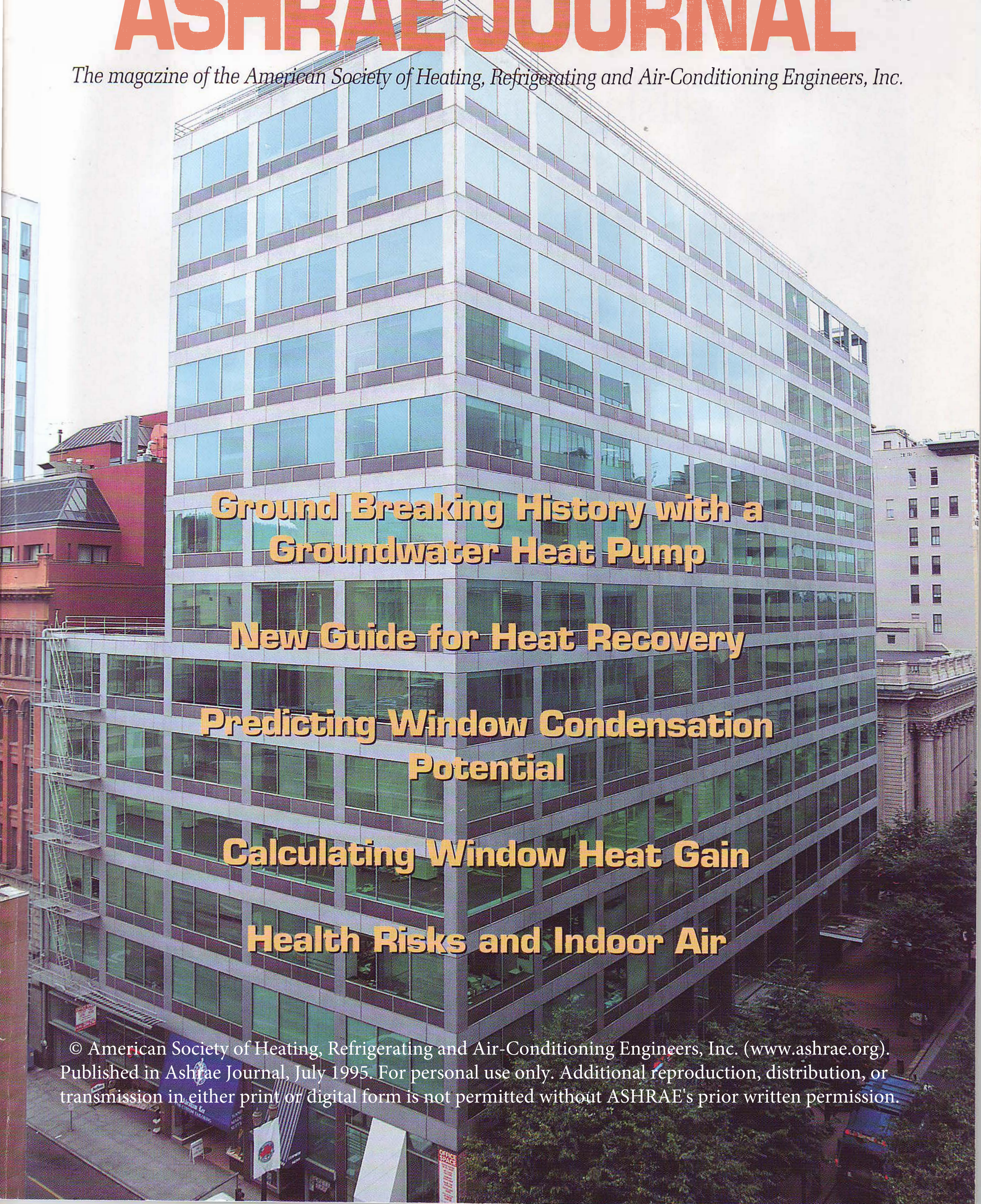

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Calculating Window Solar Heat Gain

The author examines several methods to accurately determine the amounts of solar gain provided by windows

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Window design has been revolutionized—largely by the introduction of low emissivity (low-e) coatings and substitute fill gases. The large number of design options necessitates the use of computer simulation for development and rating. Two window analysis programs, *VISION*[1] and *WINDOW*,[2] are widely used in North America. Both have been released in several versions—the most recent being *WINDOW 4.1* and *VISION3*. They differ in appearance because *WINDOW* is text based and *VISION3* incorporates a graphical user interface (GUI) but they perform similar solar optical and heat transfer calculations to arrive at center-glass U-factors and solar heat gain values. More detail can be found in Wright's "Summary and comparison of methods to calculate Solar heat gain."[3]

This article examines window solar heat gain—how it is calculated and what affects it. Solar heat gain is quantified by the Solar Heat Gain Coefficient (SHGC). SHGC is the fraction of incident solar radiation that reaches the conditioned space. It is customary to consider each of three areas: (1) the center-glass area, A_{cg}, (i.e., the glazed area more than 2.5 inches (63.5 mm) from any sight line), (2) the edge-glass area, A_{eg}, and (3) the frame area, A_{fr}. Component SHGC values are area-weighted to give a total window SHGC.

$$SHGC = \frac{A_{cg} \cdot SHGC_{cg} + A_{eg} \cdot SHGC_{eg} + A_{fr} \cdot SHGC_{fr}}{A_{cg} + A_{eg} + A_{fr}} \qquad (1)$$

Center-Glass and Edge-Glass Solar Heat Gain

Glazing system analysis takes advantage of the fact that there is no appreciable overlap between the band of solar wavelengths below about 3 μm and the band of longer wavelength radiation in which heat transfer takes place. This leads naturally to a two-step simulation process. First, an *optical analysis* determines how much solar radiation is transmitted or absorbed at each glazing. Second, a *heat transfer analysis* is used to impose an energy balance on each glazing. The net heat transfer from a glazing must equal the amount of absorbed solar radiation. The solar optical calculation requires no information regarding glazing temperatures or heat transfer. The only information from the solar optical step used in the heat transfer calculation is the amount of solar radiation absorbed at each glazing.

The solar heat gain of a glazing system consists of two components: (1) directly transmitted solar radiation, and (2) solar radiation absorbed within the glazing system and redirected to the indoor space by heat transfer. The size of this "inward flowing fraction" depends on how the thermal resistance of the glazing system is distributed. Therefore, the heat transfer analysis must be complete, yielding the required values of thermal resistance at each step through the glazing system, before $SHGC_{cg}$ can be quantified.

It is easy to recognize the dominant mechanism by which solar gain is supplied. If the solar gain results primarily from direct transmission $SHGC_{cg}$ will be only slightly greater than the solar transmittance (τ_s.). For example, a conventional single glazing delivers almost all of its solar gain by direct transmission ($SHGC_{cg} = 0.86$, $\tau_s = 0.84$). However, if absorption/redirection contributes heavily $SHGC_{cg}$ will be significantly greater than τ_s. A double glazed system with tinted indoor glazing might have $SHGC_{cg} = 0.62$, $\tau_s = 0.27$.

Solar Gain Through Frame and Dividers

Until recently it was common practice to neglect solar gain through the frame (i.e., set $SHGC_{fr} = 0$). However, Carpenter and Baker[4] estimated $SHGC_{fr}$ by using a two-dimensional (2-D) numerical analysis.[5] Pairs of simulations were run, with and without solar radiation, to determine the portion of the solar radiation incident on the frame that could be treated as solar gain. The solar absorptance of the frame surface was fixed at $\alpha^s{}_{fr} = 0.9$. They concluded that $SHGC_{fr} \approx 0.02$ for wood and vinyl frames and $SHGC_{fr} \approx 0.14$ for thermally unbroken aluminum frames. The corresponding increase in SHGC for the entire window is much less than 0.01 for wood/vinyl frames and 0.02 to 0.03 for windows with thermally unbroken aluminum frames.

A simple estimate of $SHGC_{fr}$ is incorporated in *WINDOW 4.1*. $\alpha^s{}_{fr}$ is used to calculate the amount of absorbed solar radiation. The ratio between the outdoor side convective heat transfer coefficient, h_{co}, and the frame U-factor, U_{fr}, is taken as the inward flowing fraction of absorbed solar radiation. This is similar to the way inward flowing fractions are calculated for glazings.

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$$SHGC_{fr} = \alpha^{s}{}_{fr} \cdot \frac{U_{fr}}{h_{co}} \quad (2)$$

Results generated using this approach contradict conclusions made by Carpenter and Baker[4]. When *WINDOW 4.1* was used to model a wood frame using $\alpha^{s}{}_{fr}$ = 0.01 and $\alpha^{s}{}_{fr}$ = 0.9 SHGC increased from 0.58 to 0.61. Similar calculations using a thermally unbroken aluminum frame changed SHGC from 0.62 to 0.74. In each case the increase in solar gain was about four times as great as expected. There are two reasons why these two methods gave such different results. (1) Outdoor film coefficient: The use of h_{co} in Equation 2 indicates that radiant heat transfer has been neglected. It is more accurate to use the outdoor film coefficient that also accounts for radiant heat transfer, h_o.

$$SHGC_{fr} = \alpha^{s}{}_{fr} \cdot \frac{U_{fr}}{h_o} \quad (3)$$

Carpenter and Baker used the ASHRAE winter design condition (h_o = 34.5 W/m^2°C). The *WINDOW 4.1* results were generated using the ASHRAE summer condition ($h_{co} \approx$ 16.8 W/m2°C). If the same outdoor film coefficient had been used the discrepancy between results would have been approximately halved. (2) Area Ratio: The frame U-factor, U_{fr}, shown in Equations 2 and 3 is based on the projected frame area, A_{fr}. However, the heat transfer coefficients, h_{co} and h_o, that appear in the same equations are based on outdoor surface area, A_{surf}. The outdoor film coefficient must be multiplied by the ratio of frame surface-to-projected area. Now the expression for $SHGC_{fr}$ becomes:

$$SHGC_{fr} = \alpha^{s}{}_{fr} \cdot \frac{U_{fr}}{\frac{A_{surf}}{A_{fr}} h_o} \quad (4)$$

It is common for A_{surf} to be about two times A_{fr}. A_{surf}/A_{fr} can never be less than unity. Thus, the calculations of *WINDOW 4.1* would have been in close agreement with those of Carpenter and Baker if they had been based on the same value of h_o and accounted for the surface-to-projected area ratio.

Carpenter and Baker also examined solar heat gain in the edge-glass area and concluded that the difference between $SHGC_{cg}$ and $SHGC_{eg}$ can be neglected. Near window dividers it is expected that $SHGC_{cg}$ can also be applied and that the overriding effect is the blockage of direct solar gain by the divider itself.

Spectral Selectivity

The solar optical analysis can be undertaken using band-averaged solar (i.e., total solar) optical properties in a single-band calculation or spectral optical data can be used to trace solar radiation in a series of wavelength bands with the amounts of energy absorbed, reflected and transmitted in each band being summed to determine the total fluxes of solar radiation. The difference in results produced by the two models can be explored by looking at some examples. $SHGC_{cg}$ results showed a difference of less than 0.01 in a double glazed unit with a 3 mm clear glass outdoor glazing plus a similar indoor glazing with a pyrolytic low-e (ϵ=0.197) coating. The multi-band model predicted $SHGC_{cg}$=0.718 while the single-band result was $SHGC_{cg}$=0.715. A similar glazing system with the same low-e coating on 6 mm clear glass and a 6 mm mild-green tinted glazing (solar transmittance=0.328) gives a difference of less than 0.01 ($SHGC_{cg}$=0.335 vs. 0.332). The difference between the two models can be greater in some instances but it is difficult to foresee how great the difference will be. Furthermore, it can be shown that results from the multi-band model will not be higher or lower, as a rule, than the corresponding quantities calculated with the single-band model. However, it is clear that the multi-band optical model will be consistently more accurate.

Note that fluxes of reflected, transmitted and absorbed solar energy will be a function of the spectral distribution of the incident radiation. Depending on the selectivity of the window glazings different results will be found if, for example, an air-mass 2 irradiance function is used instead of air-mass 1.5. The spectral irradiance function of an artificial source will also generate differences.[6] Increased accuracy can be obtained by using the known irradiance function. This is important if an attempt is being made to match calculated and measured results—especially if an artificial source is being used.[7]

Directional Properties

It is common for simulations to be performed using solar radiation incident normal to the glazing surface. SHGC values pertaining to normal insolation are useful when comparing design alternatives but are of limited value for building energy simulation. Solar radiation seldom reaches a window at near-normal incidence angles—especially in the southern U.S.

Simulations for off-normal incidence require the appropriate optical data. Fundamental relations can accurately predict the off-normal optical properties of uncoated glazings[8, 9] and more approximate methods can be coupled with measurements made at normal incidence to give data for coated glazings.[2, 10] $SHGC_{cg}$ is maximum at normal incidence, decreases by less than one or two percent when the solar radiation moves to 30° off-normal and then decreases sharply at higher incidence angles to the limit of zero at a 90° incidence angle.

It can be seen that the experimental determination of solar gain should not be carried out with solar radiation at high incidence angles because $SHGC_{cg}$ will be highly sensitive to incidence angle making test conditions and results difficult to reproduce. Difficulty can also be expected in reproducing measured SHGC values if the test involves both beam and diffuse insolation.

Heat Transfer

Heat flow through a glazing system can be quantified using a relatively simple 1-D analysis of coupled heat transfer. *VISION* and *WINDOW* incorporate a framework,[11, 12, 13] that sets them apart from conventional methods. They can deal with glazings that are partially transparent to thermal radiation (i.e., diathermanous) making it possible to quantify the performance of thin plastic films.[14] *VISION3* and *WINDOW 4.1* also offer the feature of accounting for the thermal resistance of the glazings themselves. The heat transfer models used in *VISION3* and *WINDOW 4.1* are based primarily on basic theory but they use empirical relations to quantify coefficients for convective heat transfer.

Indoor and Outdoor Convection

The correlations used by *VISION3* and *WINDOW 4.1* to evaluate indoor and outdoor side convective heat transfer coefficients represent natural convection on the indoor surface and forced convection on the outdoor surface. Some controversy exists concerning their validity[15] so it is likely that discrepancy between simulation and measured results will be reduced if measured indoor and outdoor convective heat transfer coefficients can be substituted in place of standard values. This effect will be most noticeable in glazing systems that both absorb a significant amount of solar radiation and also have low thermal resistance (e.g., tinted single glazed).

Uncertainty in estimating the indoor and outdoor convection coefficients leads to less error in calculating solar gain than might first be expected. There are several reasons for this. Very little thermal resistance exists between the outdoor glazing and the outdoor environment because the forced convection heat transfer coefficient is large. The outdoor convective coefficient must decrease appreciably before the indoor/outdoor thermal resistance distribution is altered enough to change the inward flowing fraction of absorbed solar radiation. On the indoor side more thermal resistance exists but most of the heat transfer takes place by radiant exchange. Again, the inward flowing fraction will be relatively insensitive to the indoor side convection coefficient. If a low-e coating were placed on the indoor facing surface the inward flowing fraction would be more sensitive to the indoor convection coefficient.

Simulations were run to examine the assertions made above. The indoor and outdoor convection coefficients were initially fixed at $h_{ci} = 3$ W/m2K and $h_{co} = 23$ W/m^{2}K, respectively. Two sets of simulations were completed—one with the h_{ci} increased by 50% and the other with hco increased by 50%. The resulting $SHGC_{cg}$ values are shown in *Table 1* for conventional single glazed (SG), conventional double glazed (DG), double glazed low-e (DGLE), double glazed low-e with argon (DGLEA) plus a tinted single glazed (SGT) and the same tinted single glazing with the emissivity of the indoor surface reduced to 0.1 (SLET).

The conventional single glazed window shows no sensitivity to changes in the indoor or outdoor convection coefficients because the amount of solar radiation absorbed is much smaller than the amount transmitted. Most of the amount absorbed is redirected to the outdoor space. The solar gain of the double glazed units is also very insensitive to changes in the indoor/outdoor convection coefficients.

The tinted single glazed system (SGT) absorbs more than 50% of the incident solar radiation making $SHGC_{cg}$ more sensitive to changes in the indoor and outdoor convection coefficients. However, 50% increases in these convection coefficients only changed $SHGC_{cg}$ by about 4%. It is also surprising that the reduction of indoor side emissivity on the tinted single glazed unit (SLET) increases this sensitivity only moderately. These results are encouraging. They show that inordinate effort and expense need not be devoted to tailoring highly repeatable convection coefficients in a test apparatus.

Natural Convection Between Glazings

Different correlations are used by *VISION3* and *WINDOW 4.1* to calculate the coefficient for convective heat transfer between vertical glazings, h. The correlation used in *WINDOW 4.1* is from "Heat transfer by natural convection across vertical and inclined air layers"[16] and *VISION3* uses a correlation developed by Wright in "A Correlation to Quantify Convective Heat Transfer Between Vertical Window Glazings"[17]. Under conditions most frequently of interest for window analysis the two differ by no more than 2%.

Table 1 holds a very important piece of information. The DGLE and the DGLEA glazing systems both contain a low-e coating so most of the heat transfer between the glazings takes place by convection. The DGLEA unit has argon fill gas instead of air. This makes a significant difference in the convective heat transfer coefficient between the glazings—primarily because the conductivity of argon is only about ⅔ the conductivity of air. The convective heat transfer coefficient in the argon filled unit is at least 25% lower than in the air-filled unit but the solar gain of the two units is almost identical. This is noteworthy. If a change that alters the interpane convection coefficient by 25% has little bearing on $SHGC_{cg}$ then much smaller uncertainties or variations in a other quantities will certainly be unimportant. Such quantities and their approximate uncertainties include fill gas properties (0.5% in curve fit), convective heat transfer coefficient (up to 5% in correlation), component fraction in fill gas mixtures (10% uncertainty in mole fractions yielding up to 2% uncertainty in gas properties) and pane spacing (3% due to moderate pane deflection).

Table 1. $SHGC_{cg}$ vs. Indoor/Outdoor Convection Coefficients*

	h_{ci} = 3.0, h_{co} = 23.0 W/m^{2}K	h_{ci} = 4.5, h_{co} = 23.0 W/m^{2}K	h_{ci} = 3.0, h_{co} = 34.5 W/m^{2}K
SG	0.86 / 0.86	0.86 / 0.86	0.85 / 0.85
DG	0.76 / 0.76	0.76 / 0.77	0.76 / 0.76
DGLE	0.64 / 0.64	0.65 / 0.64	0.64 / 0.64
DGLEA	0.65 / 0.64	0.65 / 0.65	0.64 / 0.64
SGT	0.48 / 0.47	0.50 / 0.49	0.45 / 0.44
SLET	0.41 / 0.41	0.43 / 0.44	0.39 / 0.39

*$SHGC_{cg}$ Listed for ASHRAE Summer/Winter Conditions

It can be seen why solar gain is not sensitive to changes in interpane convection. If the thermal resistance between two glazings is increased a larger portion of the solar energy absorbed at glazings between that cavity and the indoor side will flow to the indoor space. However, a smaller portion of the solar energy absorbed at glazings between that cavity and the outdoor side will reach the conditioned space. These two changes in solar gain will always cancel to some extent.

Weather Conditions

Optical properties are not affected by changes in temperature or insolation level. Thus, changing weather conditions can only alter solar gain by changing the temperature distribution through the glazing system which in turn changes the heat transfer coefficients within the glazing system.

Figures 1 and *2* show *VISION3* output plots for the DGLE glazing system simulated under the ASHRAE winter and summer conditions, respectively. Under the winter condition there is a large temperature drop across the cavity, ΔT, and h is 17% larger than it is under the summer condition. This difference is offset somewhat by a decrease in the radiative heat transfer coefficient which can be shown to vary approximately with the cube of the mean cavity temperature (absolute), (T_m). In this case T_m decreases by about 11% from the summer to the winter condition and the radiative coefficient decreases by almost 40%. However, the radiative coefficient is much smaller than the convective coefficient because a low-e coating is present and the change in heat transfer coefficient between the two glazings due to the combined effect is an increase of 8% which is insufficient to affect $SHGC_{cg}$. It might be argued that the solar gain of a conventional double glazed system (DG) will be sensitive to the change in weather conditions because the interpane heat transfer is dominated by radiant exchange. In this case the interpane heat transfer coefficient decreases by 21% from

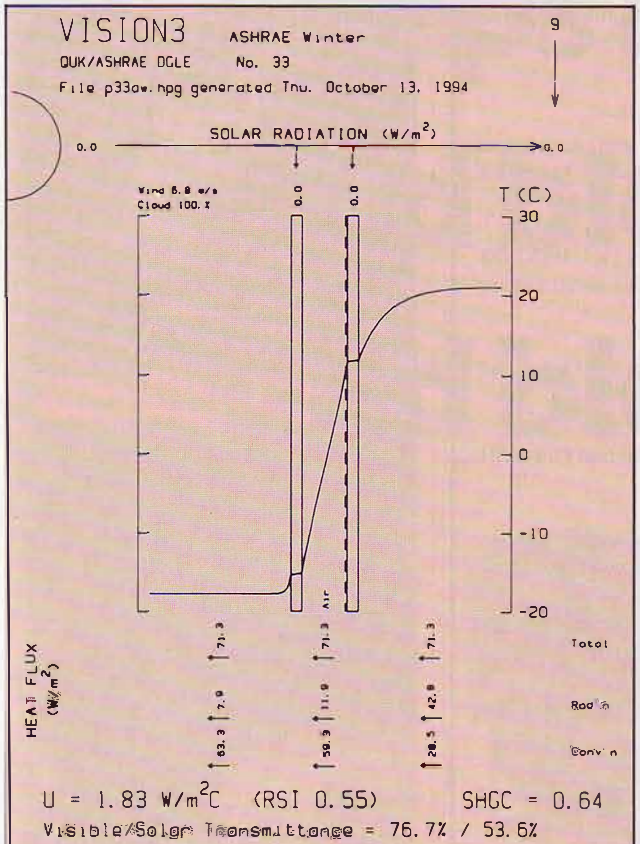

Figure 1. ASHRAE Winter.

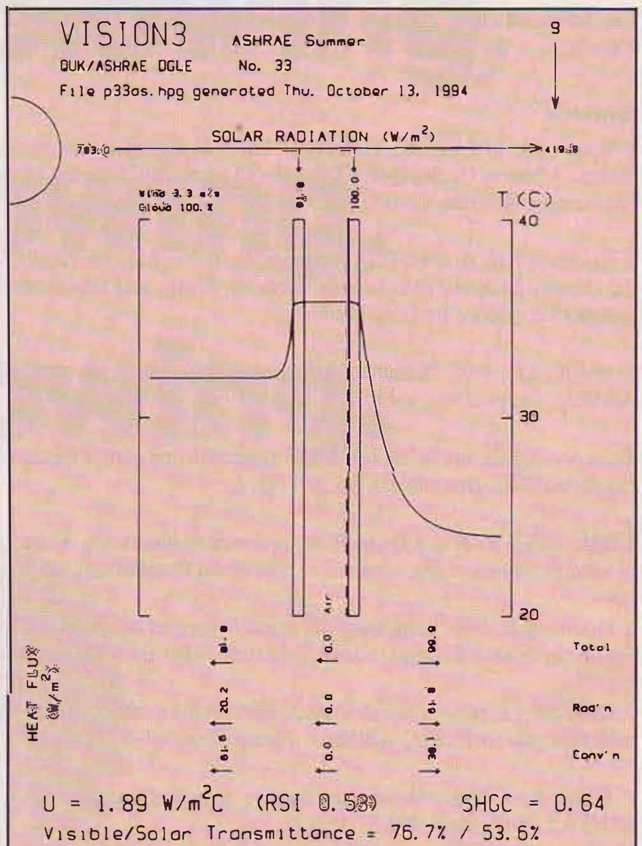

Figure 2. ASHRAE Summer.

summer to winter which is still not enough to appreciably alter $SHGC_{cg}$.

The combination of low ΔT and high T_m or high ΔT and low T_m tends to create changes in the interpane heat transfer components that are offsetting. This phenomenon can also be expected in glazing systems with more than two glazings.

More details can be found in "Summary and comparison of methods to calculate Solar heat gain,"[3] showing that $SHGC_{cg}$ is very insensitive to independently varied levels of solar radiation for all of the glazing systems listed in *Table 1.* This reference also provides details regarding clear sky conditions and shows that solar heat gain will not be significantly affected by changes in radiant exchange between the window and its environment because of changes in cloud cover.

Conclusions

When calculating solar gain the most important concern is to accurately determine the amounts of solar radiation directly transmitted and absorbed in the glazing system. The importance of accurate solar optical data must be emphasized. A spectral (i.e., multi-band) calculation is consistently more accurate. It is valid to apply center-glass $SHGC_{cg}$ to the full view area of the window. In many ways the inward flowing fraction is very insensitive to the details of the heat transfer models or variability in weather conditions.

Methods exist to calculate the solar heat gain of the frame. $SHGC_{fr}$ may be neglected if the thermal resistance of the frame is sufficiently high (i.e., wood, vinyl or better). $SHGC_{fr}$ can be reduced by using an outdoor surface with low solar absorptivity. It is more difficult to quantify solar gain for single glazing than any of the glazing systems with higher thermal resistance. The inward flowing fraction of the single glazing can be influenced appreciably by changes in the indoor and outdoor side convection coefficients. This effect leads to little uncertainty when dealing with a single clear glazing because most of the solar gain comes from direct transmission but a single tinted glazing presents greater difficulty. However, this variability of solar gain for the single glazing does not result from modeling difficulties. The solar gain can be expected to fluctuate under real conditions as the convection conditions change at the window surfaces. ■

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References

1. Wright, J.L. and Sullivan, H.F. 1992. *VISION3 glazing system thermal analysis:* reference manual, Advanced Glazing System Laboratory, University of Waterloo, Department of Mechanical Engineering, Waterloo, Canada.

2. Finlayson, E.U., Arasteh, D.K., Huizenga, C., Rubin, M.D., and Reilly, M.S. 1993. *WINDOW 4.0: documentation of calculation procedures*, Energy and Environment Division, Lawrence Berkeley Laboratory, Berkeley, California.

3. Wright, J.L., 1995. "Summary and comparison of methods to calculate Solar heat gain." ASHRAE *Transactions*, Vol 101, Pt. 1.

4. Carpenter, S.C., and Baker, J.A. 1992. "Determination of total window solar heat gain coefficient." ASHRAE *Transactions*, Vol. 98, Part 1.

5. EEL, 1989. *FRAME: A finite difference computer program to evaluate thermal performance of window frame systems, version 2.0*, Enermodal Engineering Ltd., Waterloo, Canada.

6. McCluney, R. 1993. "Sensitivity of Optical Properties and Solar Gain of Spectrally Selective Glazing Systems to Changes in Solar Spectrum," Solar '93 ASES Conference, 1993.

7. Harrison, S.J., and van Wonderen, S.J., 1994. "A test method for the determination of window solar heat gain coefficient," ASHRAE *Transactions*, Vol. 100, Part 1.

8. Furler, R.A., 1991. "Angular dependence of optical properties of homogeneous glasses." ASHRAE *Transactions*, Vol. 97, Part 2.

9. Milburn, D., 1994. Measurement of solar transmittance of advanced glazing materials, Ph.D. thesis, Department of Mechanical Engineering, University of Waterloo, Waterloo, Canada.

10. Ferguson, J.E. and Wright, J.L., 1984. *VISION: a computer program to evaluate the thermal performance of super windows*, National Research Council of Canada report no. Passive-10.

11. Wright, J.L. 1980. "Free convection in inclined air layers constrained by a v-corrugated Teflon film," M.A.Sc. thesis, University of Waterloo, Mechanical Engineering Department, Waterloo, Canada.

12. Hollands, K.G.T. and Wright, J.L. 1982. "Heat loss coefficients and effective $\alpha\tau$ products for flat plate collectors with diathermanous covers," *Solar Energy*, 30 (3), 211-216.

13. Arasteh, D., Reilly, S. and Rubin, M. 1989. "A versatile procedure for calculating heat transfer through windows." *ASHRAE Transactions, Vol. 95, Part 2.*

14. Wright, J.L. 1985. "The computer simulation of super window glazing systems which incorporate Teflon (FEP) inner glazings," proc. ISES/SESCI Intersol'85, Montreal, Canada, Vol. 1, pp. 267-271.

15. Yazdanian, M. and Klems, J.H., 1994. "Measurement of the exterior convective film coefficient for windows in low-rise buildings." ASHRAE *Transactions*, Vol. 100, Pt. 1.

16. ElSherbiny, S.M., Raithby, G.D. and Hollands, K.G.T. 1982. "Heat transfer by natural convection across vertical and inclined air layers," *Journal of Heat Transfer*, Vol. 104, pp. 96-102.

17. Wright, J.L. 1991. "Correlations for quantifying convective heat transfer between window glazings," note prepared for ASHRAE standards committee *SPC 142 (Standard Method for Determining and Expressing the Heat Transfer and Total Optical Properties of Fenestration Products)*. Symposium paper prepared for 1996 ASHRAE winter meeting (Atlanta), "A Correlation to Quantify Convective Heat Transfer Between Vertical Window Glazings."