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SOLAR ABSORPTION IN THICK AND MULTILAYERED GLAZINGS

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ABSTRACT

Thick and multilayered glazings generally have a nonuniform distribution of absorbed solar radiation which is not taken into account by current methods for calculating the center of glass solar gain and thermal performance of glazing systems. This paper presents a more accurate method for calculating the distribution of absorbed solar radiation inside thick and multilayered glazings and demonstrates that this can result in a small but significant difference in steady-state temperature profile and Solar Heat Gain Coefficient for some types of glazing systems when compared to the results of current methods. This indicates that a more detailed approach to calculating the distribution of absorbed solar radiation inside glazings and resulting thermal performance may be justified for certain applications.

INTRODUCTION

Current window simulation programs account for solar absorption inside glazing layers by assuming that an equal amount of radiation is absorbed at all points through the glazing [1], or that all the radiation is absorbed at the mid-point of the glazing [2,3]. It has been shown that these assumptions yield equivalent expressions for the surface temperatures and Solar Heat Gain Coefficient (SHGC or *g* factor) of the glazing system [4]. The assumption of uniform absorption throughout the glazing is a good approximation in the case of homogeneous glazings with very weak absorption. Uniform absorption is a poor approximation to the actual absorption profile for the thick or multilayered glazings commonly used in residential, commercial and automotive applications where the distribution of absorbed radiation inside the glazing is more complex. This paper presents a more accurate method for calculating the distribution of absorbed solar radiation inside thick and multilayered glazings. Our approach differs from previous work [5,6] in that it accounts for radiation transmitted, reflected and absorbed by other panes in the glazing system, and by coatings and layers within multilayer glazings, including inter-reflections between layers at all solar wavelengths. The distribution of absorbed solar radiation can be used to generate the resulting steady-state temperature profile inside the glazing and the SHGC of the glazing system, which are used in calculations of window and building energy performance, occupant comfort indicators and glazing thermal stress.

SOLAR ABSORPTION IN MULTILAYERED GLAZINGS

Absorption In Multilayered Glazing Layers

A glazing may consist of a number of elements including thick layers (glass, polycarbonate, interlayers and adhesive), interfaces and thin layers (uncoated interfaces between materials and thin film coatings). Here, `thick' and `thin' relate to the optical path length of radiation through

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the layers and its effect on coherence [7,8]. Solar radiation is incident on the exterior surface of the outermost glazing layer in a glazing system. As it propagates through each glazing layer it can be transmitted, reflected or absorbed by each element in each glazing layer. Flux can travel forwards (towards the interior) or backwards (towards the exterior) at all points in the system. The forward and backward traveling flux densities in the system are conveniently found numerically using a matrix method similar to that of Pfrommer et al. [8].

To obtain the distribution of absorbed radiation inside a glazing system, the structure of each glazing must be known in terms of the properties and position of the thick and thin elements that make up the glazing. Structural information can often be obtained from the manufacturer of the glazing, and the properties of each element in simple glazings can be obtained using the formulae of Rubin et al. [9]. Once the properties of a simple element (for example, a coating or a substrate layer) have been determined from a simple glazing, they can be re-used in more complex structures to calculate the distribution of solar radiation.

Absorption In Thick Elements

The distribution of absorbed radiation in a thick layer element of a glazing can be expressed as $dS_\lambda(x)$, the amount of radiation absorbed in a thin 'slice' of thickness dx at a distance x from the front of the layer:

$$dS_\lambda(x) = -I_\lambda^+ e^{-\alpha_\lambda x}(1-e^{-\alpha_\lambda dx}) + I_\lambda^- e^{-\alpha_\lambda d} e^{\alpha_\lambda x}(1-e^{\alpha_\lambda dx}) \quad (1)$$

where α_λ is the absorption coefficient of the thick layer material at wavelength λ, I_λ^+ is the forward traveling flux density entering the front of the layer, I_λ^- is the backward traveling flux density entering the back of the layer and d is the total thickness of the layer. The absorption coefficient of thick layer elements can be obtained from simple uncoated or laminated glazings [9].

Absorption In Coatings

There can be no absorption at an uncoated interface between materials, but a thin film coating generally absorbs some radiation, so an interface incorporating a thin film coating will have some absorption. The amount of radiation absorbed at a coated interface is given by:

$$S_c = I_\lambda^+ a_c^f + I_\lambda^- a_c^b \quad (2)$$

where $a_c^f = 1 - t_c - r_c^f$ and $a_c^b = 1 - t_c - r_c^b$ are the front and back side absorptances of the coated interface and I_λ^+ and I_λ^- are the forward and backward traveling flux densities entering the coating as before. The transmittance, t_c and front and back side reflectance, r_c^f, r_c^b, of the coated interface can be obtained from the measured properties of a simple coated glazing [9]. For thermal calculations, the absorption in coatings can be accounted for in the distribution of radiation within the glazing by assuming all the absorption occurs in an infinitely thin layer corresponding to the position of the coating in the glazing.

Optical Modeling Assumptions

In the numerical solutions of the distribution of absorbed solar radiation in various glazing systems presented here, each thick element in a glazing layer was divided into a fixed number of 'slices', and the radiation absorbed at coated interfaces was added to the amount of radiation absorbed in the adjacent 'slice'. The number of slices could be varied to ensure that the discretization of the distribution of absorbed radiation did not significantly affect the thermal results. The incident radiation was assumed to strike the glazing at normal incidence and to follow a standard air mass 1.5 solar spectral direct irradiance distribution [10]. The distribution of absorbed radiation was calculated for each wavelength in the solar spectrum, then solar averages were calculated from the resulting spectral system properties to obtain the distribution of absorbed solar radiation in the system.

THERMAL ANALYSIS

The temperature profile inside glazings and SHGC of glazing systems can be calculated using the methods of ISO 15099 [11], which normally uses the assumption that the distribution of absorbed solar radiation in each glazing is constant through its thickness. In order to account for a non-uniform distribution of absorbed solar radiation and the different thermal conductivity of materials in multilayer glazings, each glazing is divided into a number of 'slices' according to the calculation of solar absorption from the section above. In addition to the thermal analysis and boundary conditions in [11], the following conditions are set at each unexposed surface of a slice:

$$T_{b,j} = T_{f,j+1} \tag{3}$$

$$J_{f,j} = J_{b,j} = 0 \tag{4}$$

where J_f and J_b represent radiosities of the front and back unexposed surfaces of the slice. The modified system of equations is solved for temperatures and radiosities using standard methods for solving systems of non-linear equations

To generate the results presented below, the modified method for calculating the temperature profile and SHGC is applied with two distributions of absorbed solar radiation: the nonuniform distribution calculated using the method of the previous section and a distribution which represents the equivalent net absorption as a constant rate of absorption through the thickness of the glazing. In addition, the detailed model took account of the different thermal conductivity of each material in multilayer glazings for each slice, while the constant absorption model used the equivalent glazing thermal conductivity for each slice. The boundary conditions shown in Table1 were used for all calculations. These are similar to standard 'Summer' conditions commonly used for window simulations in North America.

Table 1. Boundary Conditions Used for Thermal Analysis

Outdoor Conditions	
Temperature	305.15 K
Wind Speed	2.75 ms^{-1}
Glazing Facing	Windward
Solar Irradiance	756.6 Wm^{-2}

Indoor Conditions	
Temperature	297.15 K
Forced Wind Speed	0.0 ms^{-1}
Mean radiant temperature	297.15 K

RESULTS

Single Glazing

Uncoated Glazings

Thick and heavily tinted single pane uncoated glazing is used in high-rise commercial construction where the glazing must provide solar control and withstand high wind and impact loads. The distribution of absorbed solar radiation in a thick absorbing layer is highly nonuniform due to the strong attenuation of the incident beam.

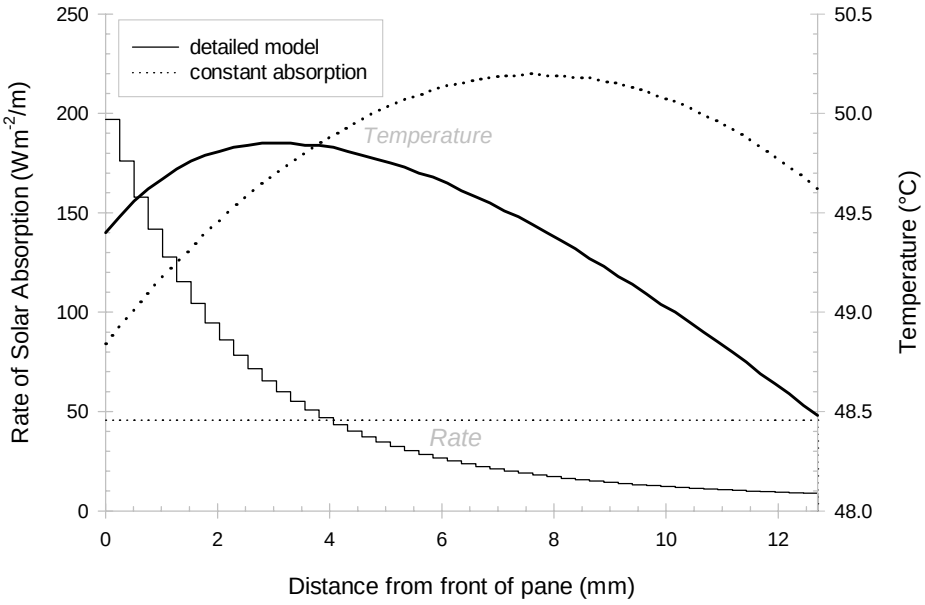

Figure 1. The local rate of solar absorption and temperature profile inside 12 mm (1/2") tinted glass using the absorption distribution predicted by the detailed model and the equivalent constant absorption rate.

Figure 1 shows 12 mm (1/2") tinted glass. The local rate of solar absorption is plotted against the distance from the front (exterior) surface of the glazing, calculated according to the detailed method presented above. Also shown is the constant rate of absorption which corresponds to the same net glazing absorption. The temperature profile inside the glazing layer is shown, as calculated using the two distributions of absorbed radiation. As mentioned above, it has been shown that thermal calculations assuming a constant rate of absorption are equivalent to models which assume that all radiation is absorbed at the midpoint of each glazing [4], however the latter models do not give a continuous expression for the temperature profile inside the pane.

The detailed model predicts a high rate of absorption in the outer part of the glazing, where a large part of the absorbed energy is lost to the exterior due to the high heat transfer coefficient at the outer glazing surface. The absorbed energy lost at the outer surface is not available to heat the pane or the interior space, so the interior surface temperature of the pane and SHGC (see Table 2) are both lowered relative to the prediction of the constant absorption model.

Table 2. Solar Heat Gain Coefficient (SHGC) of Glazings Calculated Using the Absorption Distribution Predicted By the Detailed Model and the Equivalent Constant Absorption Rate

Glazing System	SHGC	
	Detailed Model	Constant Absorption
12 mm uncoated tinted glass	0.4196	0.4351
10 mm tinted glass with reflective solar control coating on #1 surface	0.2714	0.2824
10 mm tinted glass with reflective solar control coating on #2 surface	0.3821	0.3835
Laminate consisting of 6 mm tinted glass outboard lite, 0.76 mm clear PVB interlayer and 3 mm clear glass inboard lite	0.4292	0.4403
Laminate consisting of 6 mm tinted glass outboard lite with a reflective solar control coating on #2 surface, 0.76 mm clear PVB interlayer and 3 mm clear glass inboard lite	0.3714	0.3883
Double glazed system consisting of 6mm tinted outboard lite and a 6mm clear inboard lite with a low-emittance coating on the #3 surface and 12.7 mm air gap	0.3205	0.3209

The difference in predicted interior surface temperature of more than 1°C and a difference in SHGC of more than 0.01 between the two models may be considered significant when these values are used as input to a window rating system, or for calculating the energy performance and thermal comfort indices of interior spaces. Thermal stress calculations are critical in assessing the suitability of various glazing systems for specific installation sites. Thermal stress in the glazing is related to the temperature gradient between the center of the pane and the edge, these calculations may also be sensitive to deviations of this magnitude in the center of glass temperature.

Coated Glazings

Coated glazings are used as single glazing in some commercial construction, usually to provide solar and glare control and a uniform exterior appearance for a building. The coating may be placed on the exterior (#1) or interior (#2) surface, depending on the desired performance and appearance of the glazing and the durability of the coating. Although most coatings used in this context have a high reflectance, they generally also have moderately strong solar absorptance. They are often combined with tinted substrates to modify the color of the glazing and to provide additional solar control. Both the coating and the tinted substrate contribute to nonuniform solar absorption distributions in this type of glazing. **Figure 2** and **Figure 3** show the absorption profiles and temperature distributions for a glazing consisting of a solar control coating on a tinted substrate where the coating is on the #1 and #2 surface respectively.

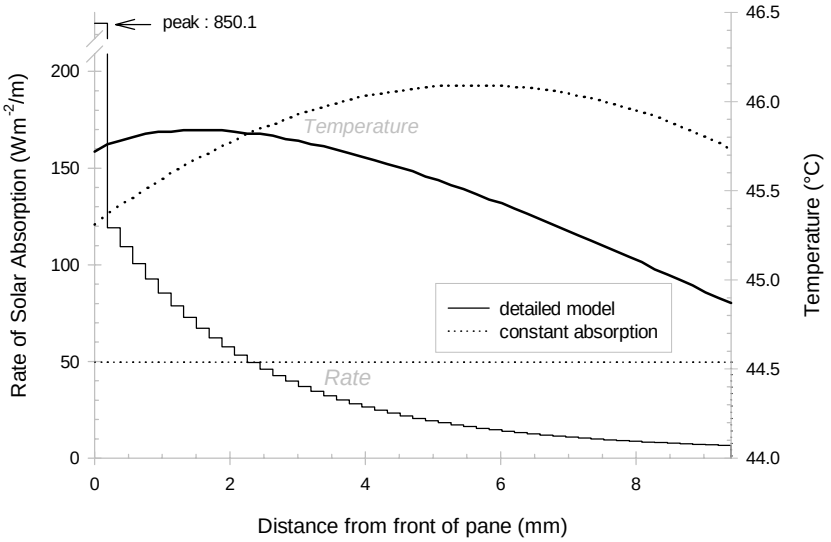

Figure 2. The local rate of solar absorption and temperature profile inside a glazing with a reflective solar control coating on the exterior (#1) surface of a 10 mm tinted substrate using the absorption distribution predicted by the detailed model and the equivalent constant absorption rate.

The SHGC values for these glazings are shown in Table 2. The greater the asymmetry in the distribution of absorbed radiation as calculated by the detailed model, the further it will deviate from the assumptions of the constant absorption model. The example with the coating on the #1 surface demonstrates a larger difference in the predicted interior surface temperatures and SHGC between the two models than when the coating is in the #2 position. This trend is consistent with other types of coated glass and also for glazings with retrofit polymer films (which may include metal layers or coatings) which are usually applied to the interior surface of glazings.

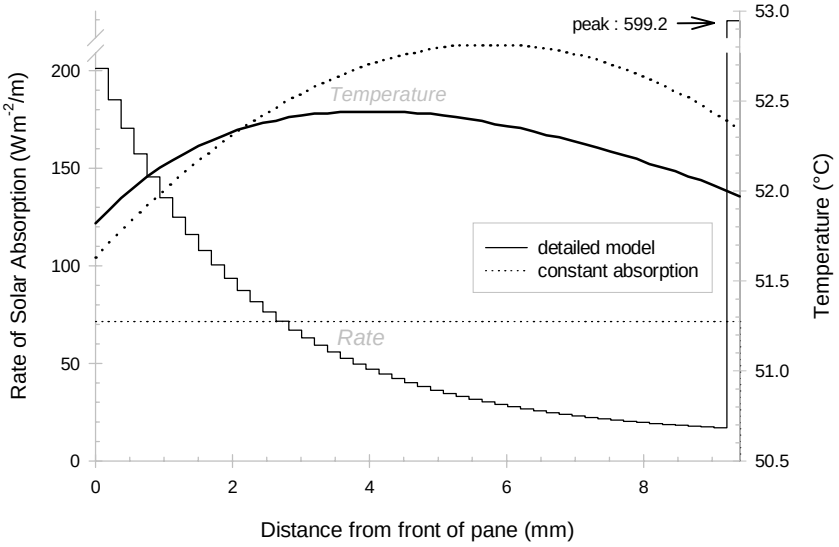

Figure 3. The local rate of solar absorption and temperature profile inside a glazing with a reflective solar control coating on the interior (#2) surface of a 10 mm tinted substrate using the absorption distribution predicted by the detailed model and the equivalent constant absorption rate.

Laminated glazings

Laminated glazings are often used where safety and security are important concerns in both commercial and residential construction. Laminated glazings may have particularly complex distributions of absorbed radiation inside the glazing due to their multilayer construction which may include several lites of glass, interlayers and coatings. This will produce the most noticeable effects on predicted temperature profiles and SHGCs in cases where the distribution of absorbed radiation is very nonuniform and where a large part of incident solar radiation is absorbed close to the outer surface of the glazing. This may occur where the outer layers of glass or interlayer are tinted, and where coatings are used inside the laminate.

Two examples are presented which represent laminates with a tinted outboard lite, a clear interlayer and a clear inboard lite, the results in **Figure 4** are when the outboard tinted lite is uncoated, in **Figure 5** the outboard tinted lite is coated with a solar control coating on the #2 surface. The SHGC values for these examples are presented in Table 2.

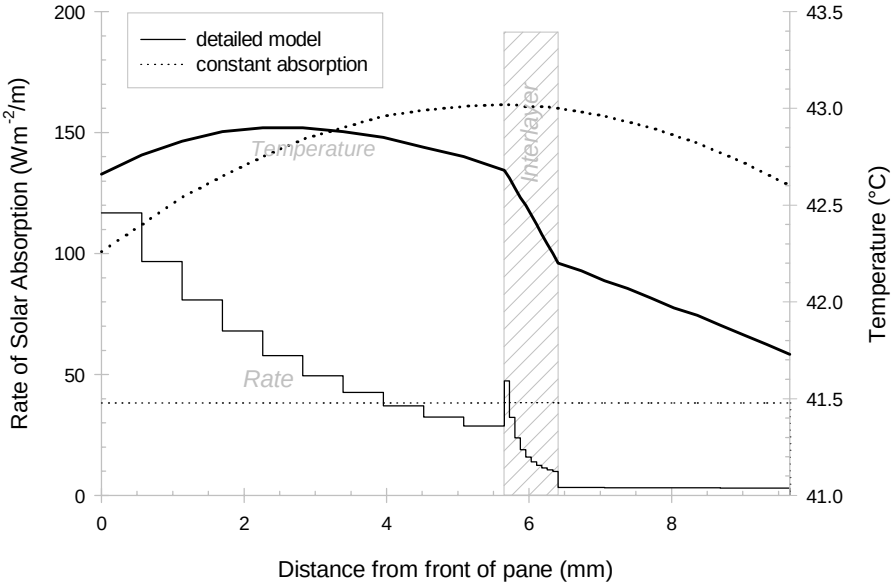

Figure 4. The local rate of solar absorption and temperature profile inside a laminate consisting of 6 mm tinted glass outboard lite, 0.76 mm clear PVB interlayer and 3 mm clear glass inboard lite. The position of the interlayer in the laminate is indicated by the shaded region.

The largest difference between predicted interior surface temperature and SHGC for the two models is displayed by the laminate with a coated outer lite (**Figure 5**), which has an extremely nonuniform distribution of absorbed radiation. The temperature profiles of both laminates also show the effect of accounting for the different thermal conductivities of the materials as well as the distribution of absorbed radiation in the multilayer structure of a laminate. The interlayer has a much lower thermal conductivity (0.212 $Wm^{-1}°C^{-1}$) than the glass (0.998 $Wm^{-1}°C^{-1}$), so it partly insulates the lites from one another, resulting in a large change in temperature across the interlayer. This further enhances the effects of the nonuniform distribution of absorbed radiation.

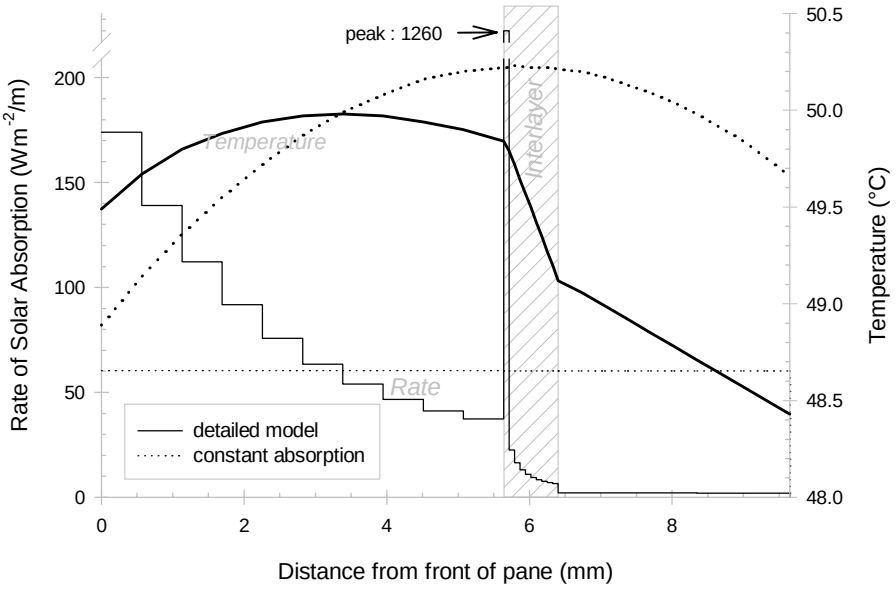

Figure 5. The local rate of solar absorption and temperature profile inside a laminate consisting of 6 mm tinted glass outboard lite with a reflective solar control coating on #2 surface, 0.76 mm clear PVB interlayer and 3 mm clear glass inboard lite The position of the interlayer in the laminate is indicated by the shaded region..

Multiple Glazing

Because of the large thermal resistance of the gas spaces between panes in multiple glazing, most of the radiation absorbed in the outer pane is lost to the exterior regardless of where inside the outer pane it was absorbed, similarly, most radiation absorbed in the inner pane is transferred to the interior. Although the distribution of absorbed radiation in multiple glazing is often nonuniform, the effect on the temperature profile inside each pane and the system SHGC is usually much smaller than for single pane systems.

The SHGC for a double glazed system consisting of 6 mm tinted outboard lite and a 6 mm clear inboard lite with a low-emittance coating on the #3 surface as calculated using the absorption distribution predicted by the detailed model and the equivalent constant absorption rate is shown in Table 2. Even though the distribution of absorbed solar radiation is nonuniform in this glazing system due to the tinted lite and the coating, the temperature profile and SHGC are predicted accurately by the constant absorption model in this case because of the dominant effect of the gap.

Environmental Conditions

The exterior and interior environmental conditions, particularly the incident solar irradiance and the exterior wind speed, control the resulting temperature profile inside the glazing and SHGC of the glazing system. The effect of nonuniform solar absorption on the temperature profile inside the glazing and SHGC is greater for larger incident irradiance and higher wind speeds.

CONCLUSIONS

Window simulations which assume that the absorbed solar radiation distribution inside glazing layers is constant or that all absorption occurs at the midpoint of glazing layers overestimate the interior surface temperature and SHGC for single glazings with highly nonuniform solar absorption distributions. This effect is largest for glazings where most solar absorption occurs near the exterior surface of the glazing and depends on the exterior environmental conditions. Applications which require particularly accurate simulated temperature or SHGC values for these types of glazings may benefit from using the method presented here to fully account for the distribution of absorbed radiation inside the glazing.

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