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THE HEAT TRANSFER ASPECT OF UV ABSORBER COATING ON A GLASS PANE

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ABSTRACT Many people have deep concern about various undesirable effects the ultraviolet rays (UV) bring about. Thus a glass pane with UV absorber coating is coming into wide use. Besides the primary effect of shielding UV themselves, this coating secondarily induces a thermal shielding effect. From the commercial viewpoint, quantitative knowledge is necessary about it. Thus a drastic analytical model has already been developed and the reason for the thermal shielding effect was explained. In the present study we develop a more harmonious model and evaluate the extent of thermal shielding effect more accurately. It is found that the heat conducting through the pane into the room is highly reduced by UV absorber coating. However, under the condition of cooling the room, the amount of reduction is 40% less than the UV energy flux in the solar irradiation. Under the warming condition, the coating is not advantageous from the viewpoint of saving energy.

Keywords: solar irradiation, glass pane, UV absorber coating, energy transmission, thermal shielding effect

1. INTRODUCTION

Many people have deep concern about various undesirable effects the ultraviolet rays (UV) bring about. Thus a glass pane with UV absorber coating is coming into wide use. This coating is made, as a matter of course, for shielding UV themselves. Besides, however, it induces a secondary effect. That is, the energy flow containing the solar radiation through the pane into the room is somewhat reduced. From the commercial viewpoint (namely, for customers to be free from puffs), it is important to quantitatively know the extent of reduction even though its evaluation might be rough.

Mizukami and Aoyama [1] conducted an analysis on this problem with a highly simple model, and explained the reason why the energy flow into the room was reduced. They drastically assumed that the infrared rays (IR) were wholly absorbed on the outside surface of the pane and that the natural convection heat transfer coefficient on the room-side surface of the pane was merely a parameter. The value of the parameter was chosen to be 10 W/m^2K in numerical calculation. This choice may probably have led to overestimation of the energy inflow reduction. On the other hand, however, they elaborately obtained the radiation heat transfer coefficient by iteration.

In the present study the authors establish a more harmonious analytical model and evaluate the energy inflow reduction more reasonably.

2. PHYSICAL MODEL

The developed physical model is as follows:

(1) The absorber is a kind of resin. The absorber film coated on the pane glass is very thin (about 20 μm), but assumed to completely absorb UV. However it is transparent except for UV. The absorbed UV energy changes to heat. Therefore the absorber film can be regarded as a plane heat source when there is the solar irradiation I_s.
(2) Because the absorber film is very thin, its thermal resistance is ignored.
(3) The solar rays are vertically incident on the glass pane and penetrate it toward the room. As they penetrate, they attenuate due to partial absorption, which results in heat generation $G(x)$ in the glass, where x designates a position in the glass. Upon applying the Beer's law, the solar-ray energy flux in the glass can be written as

$$I(x) = I_s e^{-\alpha x}, \tag{1}$$

where α is the absorption coefficient of the glass. Then the heat generation is described as

$$G(x) = -\frac{dI}{dx} = \alpha I_s e^{-\alpha x}. \tag{2}$$

(4) Conduction of heat in the pane glass is described by

$$\lambda_g \frac{d^2T}{dx^2} + G(x) = 0, \tag{3}$$

where $T(x)$ is the temperature at position x in the glass and

λ_g is the thermal conductivity of the glass. Upon solving this equation under the boundary conditions of $T(0)=T_o$ and $T(d)=T_i$ and applying the solution, the conducting heat in the glass is obtained as

$$Q_d(x) = -\lambda_g \frac{dT}{dx} A = Q_d(0) + AF(x) \tag{4}$$

with

$$Q_d(0) = \frac{\lambda_g A}{d}(T_o - T_i) - \frac{A}{d}\int_0^d F(x)dx \tag{5}$$

$$F(x) = \int_0^x G(x)dx = I_s\left(1 - e^{-\alpha x}\right) \tag{6}$$

where T_i and T_r are the temperature of the room-side surface of the pane and the room temperature, respectively, and d is the thickness of the glass.

(5) The natural convection heat transfer coefficient on the room-side surface of the pane, h_{ic}, is evaluated with the correlation by Churchill and Chu [2]

$$Nu = \left\{0.825 + \frac{0.387 Ra^{1/6}}{\left[1 + (0.429/Pr)^{9/16}\right]^{8/27}}\right\}^2 \tag{7}$$

with

$$Ra = GrPr \tag{8}$$

$$Gr = \frac{g\beta|T_i - T_o|L^3}{\nu^2} \tag{9}$$

and accordingly

$$h_{ic} = \lambda_{air} Nu / L, \tag{10}$$

where λ_{air}, ν, β and Pr are the thermal conductivity, kinematic viscosity, volumetric thermal expansion coefficient and Prandtl number of air, respectively, Nu, Ra and Gr are the Nusselt number, Rayleigh number and Grashof number, respectively, L is the height of the pane, and g is the gravitational acceleration. It is noted that h_{ic} is almost independent of L.

(6) The radiation heat transfer to the wall of the room is approximated as that from a small surface to a completely surrounding large surface. Upon assuming that the wall temperature is equal to the room temperature, the radiation heat transfer coefficient is expressed as

$$h_{ir} = \varepsilon\sigma(T_i + T_r)(T_i^2 + T_r^2). \tag{11}$$

where ε is the emissivity of the room-side surface of the pane glass, and σ is the Stefan-Boltzmann constant, the value of which is 5.670×10^{-8} W/m^{2}K^4.

(7) The total heat transfer coefficient on the room-side surface of the pane can be written as

$$h_i = h_{ic} + h_{ir}. \tag{12}$$

The heat transfer coefficients, h_{ic}, h_{ir} and h_i, are evaluated for four room temperatures and shown in Fig.1 as a function of the room-side surface temperature of the glass. It is noted that the radiation heat transfer is significant.

(8) The heat transfer coefficient on the outdoor-side surface, h_o, is given as a parameter. Its value is chosen to be 20 W/m^{2}K, which is equal to the value under the

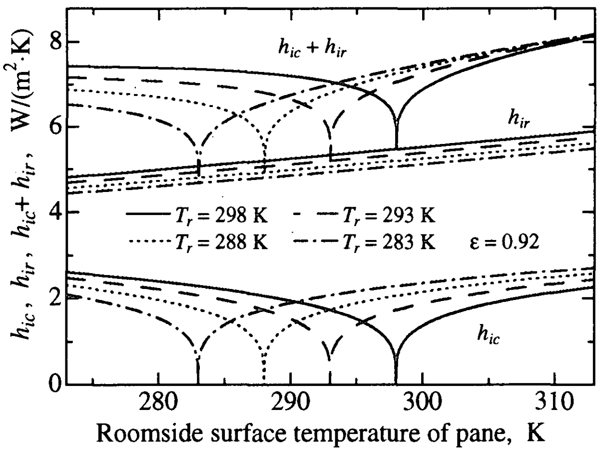

Fig. 1. Natural convection, radiation and total heat transfer coefficients on room-side surface of pane (L = 1 m).

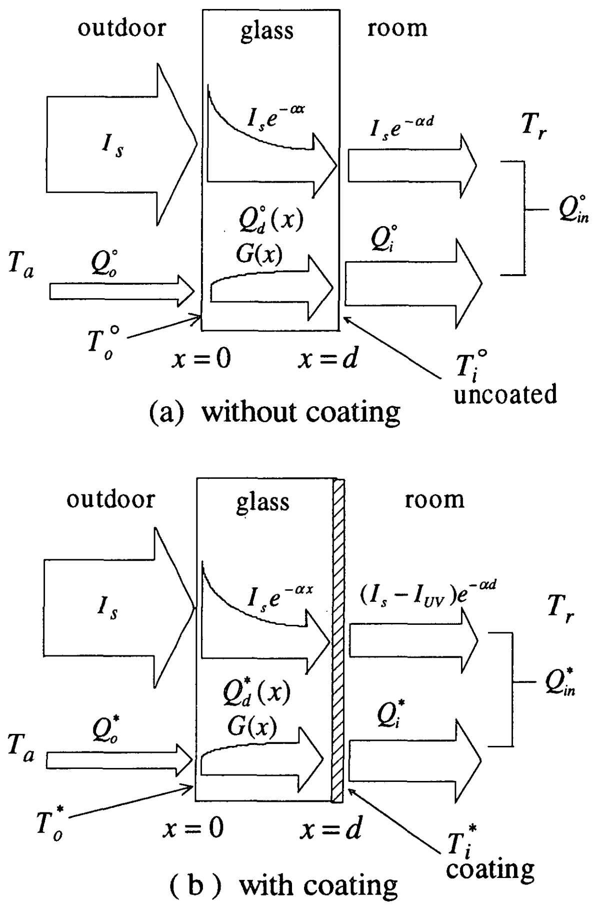

Fig. 2. Energy flow through single glass pane for cases (a) without UV absorber coating and (b) with it.

standard condition that is to be set in officially testing the thermal performance of the glass pane [3]. The standard outdoor temperatures are 303 K in summer and 273 K in winter. In passing, the standard room temperatures are 298 K in summer and 293 K in winter. Henceforth, however, we use "cooling" instead of "summer" and "warming" instead of "winter" because the room is cooled in summer and warmed in winter in Japan.
(7) The outdoor-side surface of the pane glass is not coated with UV absorber.

3. MATHEMATICAL FORMULATION

The physical model explained above is illustrated in Fig.2 for a single glass pane for cases (a) without UV absorber coating and (b) with it. The energy flow in Fig.1 consists of two kinds, namely, the solar-ray energy flow and the heat flow. The heat flow increases in the glass and the absorber film because the solar-ray energy partially changes to heat. The solar-ray energy that reaches the room-side surface of the glass is $I_s\exp(-\alpha d)$ regardless of absorber coating. However, as explained above, the solar-ray energy entering the room reduces by $I_{UV}\exp(-\alpha d)$ in case of coating, where I_{UV} is the UV energy flux in the solar irradiation. The quantities that differ between two cases are distinguished with superscripts ° and *, which designate no coating and coating, respectively.

In the following sections mathematical formulation is made based on the above physical model.

3.1 Energy Flow into Room through Uncoated Pane

If the pane glass is not coated with the UV absorber, the energy balances can be written at the boundaries as follows:
At the outdoor-side surface of the glass

$$Q_o^\circ = Q_d^\circ(0) \tag{13}$$

and at the room-side surface of the glass

$$Q_d^\circ(d) = Q_i^\circ \tag{14}$$

$$Q_d^\circ(d) = Q_d^\circ(0) + AF(d)\,. \tag{15}$$

The total energy entering the room is expressed as

$$Q_{in}^\circ = AI_s\exp(-\alpha d) + Q_i^\circ \tag{16}$$

with A as the surface area of the pane. In the above equations, Q_o° is the heat transferred from the outdoor to the glass pane, $Q_d^\circ(x)$ is the heat conducting in the glass, and Q_i° is the heat transferred from the pane into the room. Therefore the following equations hold:

$$Q_o^\circ = h_o^\circ A\left(T_a - T_o^\circ\right) \tag{17}$$

$$Q_i^\circ = h_i^\circ A\left(T_i^\circ - T_r\right). \tag{18}$$

Eliminating T_o° and T_i° from Eqs. (5), (17) and (18) (but keeping h_i° constant) and then Q_o° and Q_i° by the aid of Eqs. (13), (14) and (15) leads to

$$Q_d^\circ(0) = AK_{ar}^\circ\left\{T_a - T_r - \frac{F(d)}{h_i^\circ} - \frac{1}{\lambda_g}\int_0^d F(x)dx\right\} \tag{19}$$

where K_{ar}° is the heat transmission coefficient in the ordinary sense and therefore the following relation holds:

$$\frac{1}{K_{ar}^\circ} = \frac{1}{h_o^\circ} + \frac{d}{\lambda_g} + \frac{1}{h_i^\circ}\,. \tag{20}$$

Equation (19) indicates that heat transmission reduces due to the solar energy absorbed in the glass.

It is needless to say that we now can readily derive expressions for all other quantities about heat flow. Thus we can reevaluate the surface temperatures and then have new heat transfer coefficients. After repeating the above procedure a few times we can obtain the final numerical solution.

3.2 Energy Flow into Room through Coated Pane

For the case where the pane glass is coated with the UV absorber, almost all the above equations hold if superscripts are changed from ° to *. Exceptionally, Eqs. (14) and (16) must be replaced by

$$Q_d^*(d) + AI_{UV}\exp(-\alpha d) = Q_i^* \tag{21}$$

$$Q_{in}^* = A(I_s - I_{UV})\exp(-\alpha d) + Q_i^*\,, \tag{22}$$

respectively. However Eq. (22) has the same form as Eq. (16) if these equations are expressed in terms of $Q_d(d)$ instead of Q_i. As a result we have

$$Q_d^*(0) = AK_{ar}^*\left\{T_a - T_r - \frac{F(d)}{h_i^*} - \frac{1}{\lambda_g}\int_0^d F(x)dx - \frac{I_{UV}}{h_i^*}e^{-\alpha d}\right\} \tag{23}$$

with

$$\frac{1}{K_{ar}^*} = \frac{1}{h_o^*} + \frac{d}{\lambda_g} + \frac{1}{h_i^*}\,. \tag{24}$$

The final numerical solution is obtained after the same repeating procedure as explained in the previous section.

3.3 Energy Shielding Index and Thermal Shielding Index

Equation (23) superficially indicates that absorption of UV energy in the coated film also reduces heat transmission. Actually, however, the absorbed UV energy may partially flow toward the outdoor if it becomes large. Therefore we first introduce the energy shielding index

$$\eta_e = \left(Q_{in}^{\circ} - Q_{in}^{*}\right) / \left|Q_{in}^{\circ}\right| \qquad (25)$$

in order to evaluate the reduction effect on the total energy inflow. The total energy inflow can be negative when the room temperature is higher than the outdoor one (that is, the room is warmed) and further the solar irradiation is weak. It is noted that the energy shielding index is always positive. It diverges when the total energy inflow is equal to zero.

Then we define the thermal shielding index as

$$\eta_t = \left\{Q_d^{\circ}(d) - Q_d^{*}(d)\right\} / \left|Q_d^{\circ}(d)\right|, \qquad (26)$$

which indicates relative reduction of heat conducting through the pane glass due to the coating.

4. NUMERICAL RESULTS

Numerical calculations are conducted with the following values of parameters concerning the pane glass:

height; $L = 1$ m
thickness; $d = 3$ mm
thermal conductivity; $\lambda_g = 0.97$ W/(m·K)
absorption coefficient for solar rays; $\alpha = 74\,\mathrm{m}^{-1}$
emissivity of the room-side surface; $\varepsilon = 0.92$.

The above value of the emissivity is found in a figure of a textbook [4]. The ratio of UV energy flux in the solar irradiation, I_{UV}, to the solar irradiation, I_s, is taken to be 0.07.

4.1 Room-side Surface Temperature and Heat Transfer Coefficients

Figure 3 provides an example of variation of the room-side surface temperature with the solar irradiation. The room and outdoor temperatures are chosen to be the standard ones in warming the room. The effect of coating is not negligible. Figure 4 shows the corresponding variations of heat transfer coefficients on the room-side surface. The effect of coating is negligible in this figure. Further the heat transfer coefficients are almost independent of the solar irradiation.

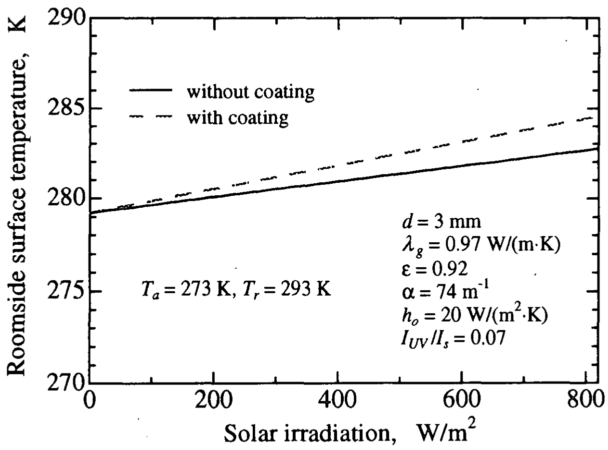

Fig. 3. An example of room-side surface temperature as a function of solar irradiation (for warming).

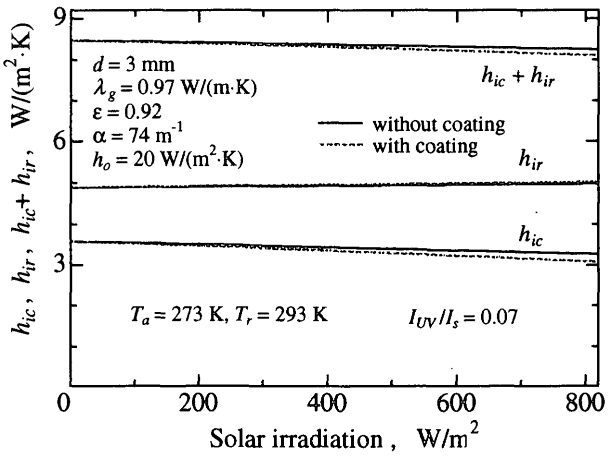

Fig. 4. Heat transfer coefficients on room-side surface under the same condition as that in Fig.3.

4.2 Thermal and Energy Shielding Effects

The total energy inflow under the standard cooling condition is compared in Fig. 5 between the case of no coating and the case of coating. It is found that it slightly reduces due to the coating. However the amount of reduction at the solar irradiation of 800 W/m^2 is as large as the heat transmitted from the outdoor at no solar irradiation.

In Fig. 6 the energy shielding indices are shown against the solar irradiation for three parametric outdoor temperatures. The chosen room temperature is the standard one in cooling the room. It is found in the figure that the energy shielding index increases from zero with increasing solar irradiation and seems to approach different constants depending on the outdoor temperature. The energy shielding indices evaluated in the present study are about 35% less than those evaluated by Mizukami and Aoyama.

As explained in section 4.1, the heat transfer coefficients on the room-side surface are little dependent on the solar irradiation. Further it can be seen in Fig. 5 that the solar-ray energy entering the room through the uncoated pane occupies a great part of the total energy inflow if the

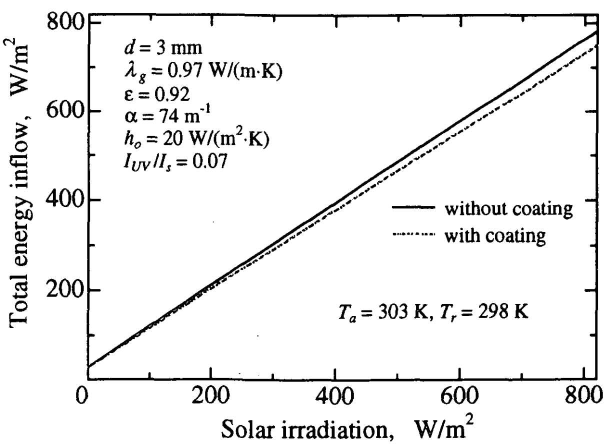

Fig. 5. Effect of coating on total energy inflow under standard cooling condition.

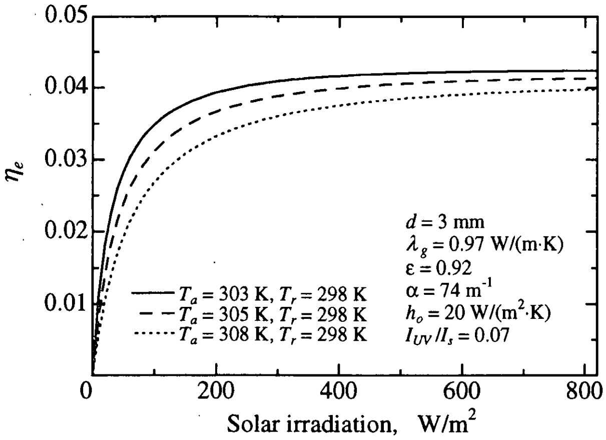

Fig. 6. Energy shielding effects under a few conditions (for cooling).

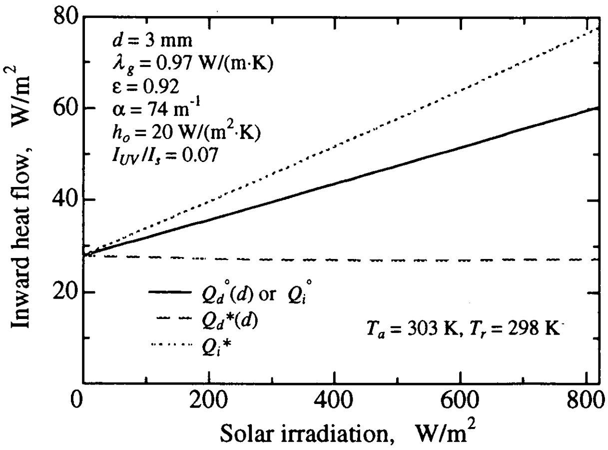

Fig. 7. Inward heat flow under standard cooling condition.

solar irradiation is large. Hence the following approximate expressions hold for large solar irradiations:

$$Q_{in}^{\circ} \cong AI_s \exp(-\alpha d) \tag{27}$$

$$Q_{in}^{\circ} - Q_{in}^{*} \cong \frac{K_{ar}^{*}}{h_i^{*}} AI_{UV} \exp(-\alpha d) . \tag{28}$$

Applying these equations to Eq. (25), we have

$$\eta_e \cong \frac{K_{ar}^{*}}{h_i^{*}} \left(\frac{I_{UV}}{I_s} \right) \tag{29}$$

for large solar irradiations. This equation indicates that the energy shielding index depends principally on the ratio I_{UV}/I_s and is less than the ratio because K_{ar}^{*} is less than h_i^{*}. Referring to Fig. 1, we can understand that h_i^{*} is less for lower outdoor temperatures under cooling conditions. Thus the energy shielding index shown in Fig. 6 is larger for lower outdoor temperatures.

The inward heat flows obtained under the same cooling condition as that in Fig. 5 are shown in Fig. 7 against the solar irradiation. The UV absorber coating brings about much reduction in heat conducting through the pane glass into the room. However it is noted that $Q_d^{*}(d)$ is kept constant independent of the amount of heat generated in the glass due to absorption of solar-ray energy. For smaller solar irradiations this is because transmission of heat from the outdoor into the room reduces by the same amount of heat as the heat generated in the glass. For larger solar irradiations the outdoor-side surface temperature rises above the outdoor one, and therefore the generated heat partially flows out toward the outdoor.

The thermal shielding indices obtained under the same cooling conditions as those in Fig. 6 are shown in Fig. 8 against the solar irradiation. They are much greater than the energy shielding indices. It will be needless to say that this is because heat conducting through the pane into the room is highly reduced by UV absorber coating but the amount of reduction is much less than the solar irradiation.

Figure 9 shows the total energy inflow under the

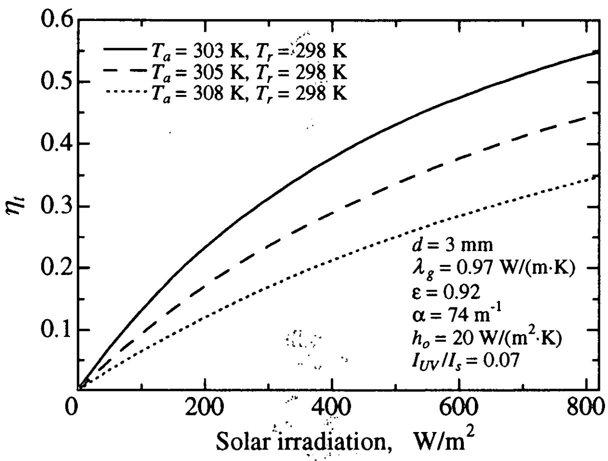

Fig. 8. Thermal shielding effects under the same cooling conditions as those in Fig. 6.

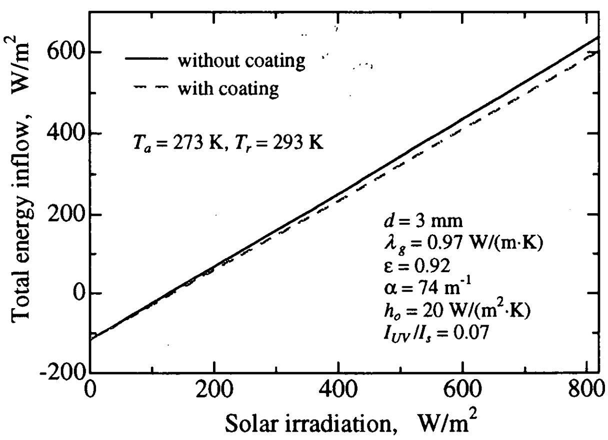

Fig. 9. Effect of coating on total energy inflow under standard warming condition.

standard warming condition. Naturally, its sign is negative if there is no solar irradiation. As the solar irradiation increases, it becomes larger, reaches zero and then changes the sign to positive. As a result, the energy shielding index

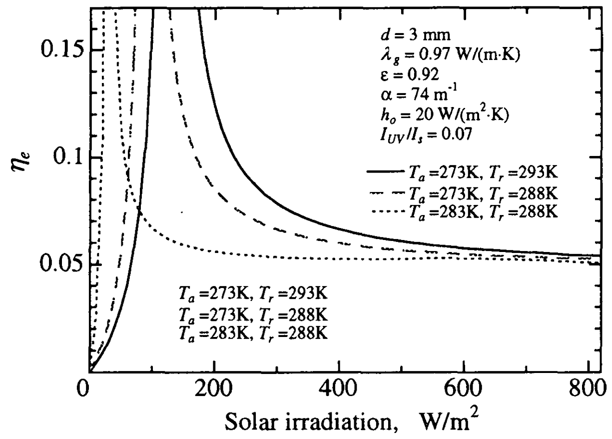

Fig. 10. Thermal shielding effects under a few conditions (for warming).

is very large and therefore may be meaningless for smaller solar irradiations. This fact can be assured in Fig. 10. It is sure that the total energy inflow reduces due to the UV absorber coating. From the viewpoint of saving energy, however, the reduction will not be advantageous under warming conditions.

5. CONCLUSION

The UV absorber coating on a glass pane secondarily induces a thermal shielding effect. The authors improved the analytical model of Mizukami and Aoyama, established a more harmonious model and evaluated the extent of thermal shielding effect more accurately.

The heat conducting through the pane into the room is highly reduced by the UV absorber coating. However, ordinarily, the amount of reduction is small compared with the solar irradiation. Under the condition of cooling the room, it is about 40% less than the UV energy flux in the solar irradiation. The energy shielding indices evaluated in this study are about 35% less than those evaluated by Mizukami and Aoyama. Under the condition of warming the room, the coating is not advantageous from the viewpoint of saving energy.

NOMENCLATURE

A,	surface area of pane, m^2;
d,	thickness of glass, m;
F	function defined by Eq. (6), W/m^2;
g,	gravitational acceleration, m/s^2;
G,	heat generation in glass, W/m^3;
Gr,	Grashof number, dimensionless;
h_i,	total heat transfer coefficient on room-side surface, W/m^{2}K;
h_{ic},	natural convection heat transfer coefficient on room-side surface, W/m^{2}K;
h_{ir},	radiation heat transfer coefficient on room-side surface, W/m^{2}K;
h_o,	heat transfer coefficient on outdoor-side surface, W/m^{2}K;
I,	solar-ray energy flux in glass, W/m^2;
I_s,	solar irradiation, W/m^2;
I_{UV},	UV energy flux in solar irradiation, W/m^2;
K_{ar},	heat transmission coefficient, W/m^{2}K;
L,	height of pane, m;
Nu,	Nusselt number, dimensionless;
Pr,	Prandtl number, dimensionless;
Q_d,	heat conducting in glass, W;
Q_i,	heat transferred from pane into room, W;
Q_{in},	total energy entering room, W;
Q_o,	heat transferred from outdoor to pane, W;
Ra,	Rayleigh number, dimensionless;
T,	temperature, K;
T_o,	temperature of outdoor-side surface of pane, K;
T_i,	temperature of room-side surface of pane, K;
T_r,	room temperature, K;
x,	position in glass, m;

Greek letters

α,	absorption coefficient of glass, m^{-1};
β,	volumetric thermal expansion coefficient, K^{-1};
ε,	emissivity, dimensionless;
η_e,	energy shielding index, dimensionless;
η_t,	thermal shielding index, dimensionless;
λ_g,	thermal conductivity of glass, W/m·K;
λ_{air},	thermal conductivity of air, W/m·K;
ν,	kinematic viscosity, m^2/s;
σ,	Stefan-Boltzmann constant, W/m^{2}K^4;

Subscripts

a,	outdoor;
air,	air;
ar,	from outdoor into room;
d,	thermal conduction;
g,	glass;
i,	room-side surface of pane;
ic,	natural convection near room-side surface;
in,	total inflow;
ir,	radiation from room-side surface;
o,	outdoor-side surface of pane;
r,	room;
s,	solar;
UV,	ultraviolet rays;

Superscripts

°,	without coating;
*,	with coating.

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