Transmittance–absorptance product of solar glazing with transparent insulation materials

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Abstract

The transmittance–absorptance product of solar glazing containing the transparent insulation material (TIM) of square celled honeycomb is investigated. A method is developed for the determination of transmittance–absorptance product of beam, sky and ground diffuse solar radiations using the individual transmittances of cellular array and encapsulating covers; the internal reflections are taken into account. Three practical cases; cellular array, cellular array with top cover, and cellular array with top and bottom covers are considered. The results are presented for beam radiation as a function of angle of incidence and sky and ground diffuse radiation as a function of tilt angle. The predicted results are tested by measuring the global radiation transmittance of commercial TIM; the predicted results deviate from the measurements by an average of 2.0%.

Keywords: Transparent insulation materials; Solar glazing; Transmittance-absorptance product; Solar energy materials

1. Introduction

Transparent honeycomb insulation materials (TIM) represent a new class of thermal insulation used in glazing of solar thermal systems. TIM consists of a cellular structure immersed in an air layer. The glazing embodying the TIM holds great promise of increasing the efficiency of solar thermal systems. The solar transmittance–absorptance product $(\tau\alpha)$ of the glazing is an essential parameter to be considered for optimising its performance. Symons [1] presented the calculations of $(\tau\alpha)$ for the glazing containing the cellular array. These calculations considered only the solar beam radiation. However, in practice the solar radiation is composed of the beam and diffuse (sky and ground) components and under certain situations the magnitude of the diffuse component is significant. This paper presents a theoretical model for the determination of $(\tau\alpha)$ corresponding to global (beam + diffuse) radiations. It considers three configurations of the glazing;

1. cellular array without any covers
2. cellular array with top cover
3. cellular array with top and bottom covers

2. Model and analysis

The incidental solar radiation on the covers is partly reflected, absorbed and transmitted. The radiation falling on the cellular array undergoes reflection, refraction and absorption due to vertical walls while propagating through the cells. The propagation of radiation through the walls is due to internal reflections. A small portion of radiation reaching absorber is partly reflected and the rest is absorbed. The ray diagram of the radiation reaching the absorber plane directly as well as due to internal reflections between TIM, covers and absorber plane is shown in Fig. 1. The transmittance–absorptance product of the cover system involves the determination of beam and diffuse radiation transmittances of covers and honeycomb cellular matrix. The formulations for the determination of solar beam radiation transmittance of honeycomb array have been reported by Hollands et al. [2], Kaushika and Padmapriya [3], and Platzer [4] and are outlined in Appendix 1. The diffuse radiation transmittance of the honeycomb cellular matrix has been investigated by Arulanantham and Kaushika [5] by integrating the beam radiation transmittance over the appropriate range of angle of incidence. These formulations are adopted in the present work and are outlined in Appendix 2.

The present evaluation of $(\tau\alpha)$ involves the following assumptions:

1. the solar diffuse radiation is hemispherical isotropic in nature.
2. the radiation reflected back (scattered) by TIM as well as the covers is diffuse.
3. only one reflection of those rays which are reflected by the TIM is considered.

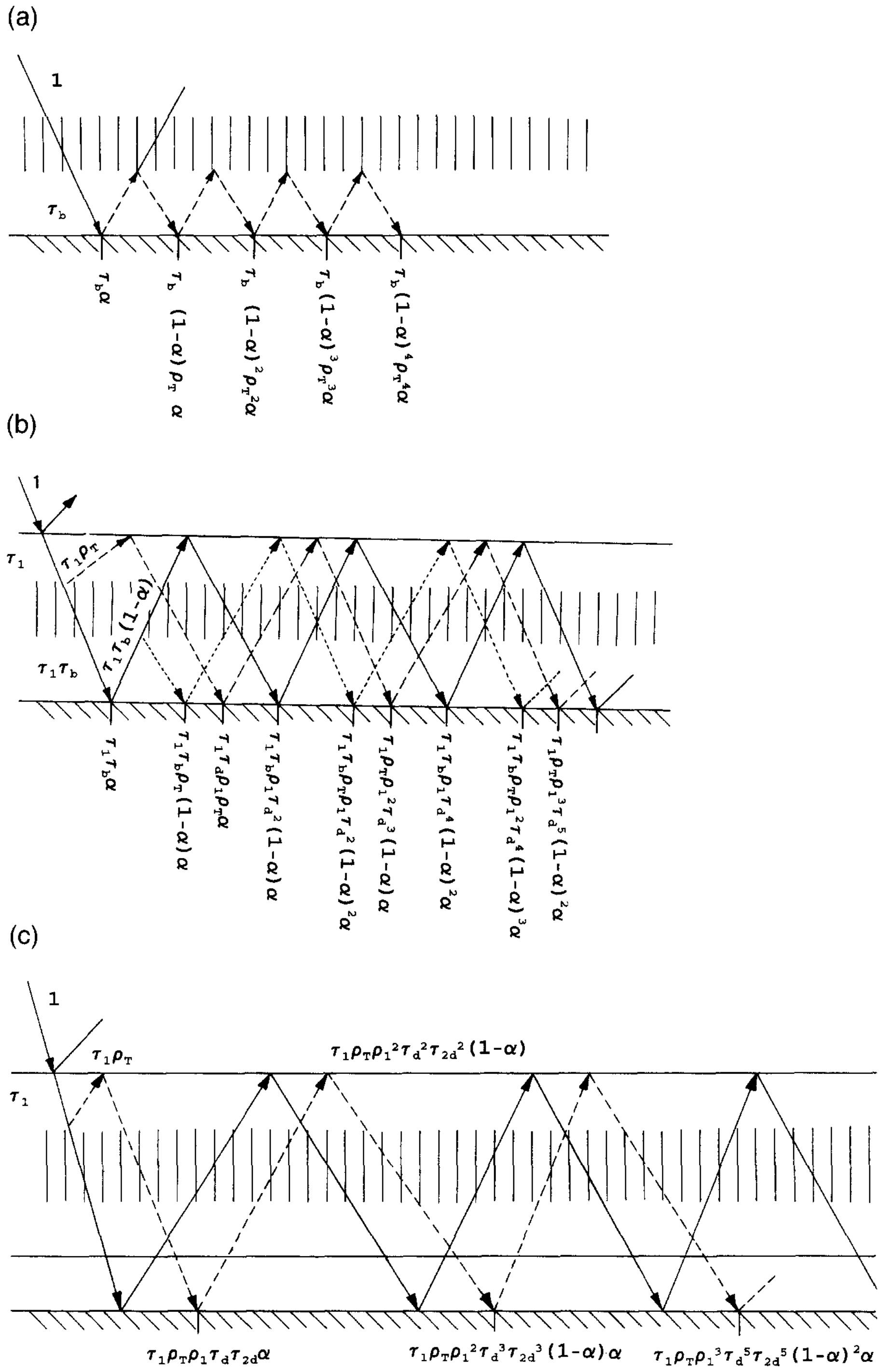
2.1. Cellular array without covers (configuration 1)

The solar beam radiation reaching the absorber plane consists of two set of rays (Fig. 1a);

1. radiation transmitted through cellular array
2. radiation reflected at the bottom of TIM.

The transmittance–absorptance product for the set 1 is

$$(\tau\alpha)_1 = \tau_b \alpha . \quad (1)$$


(a)
1
τ_b
$\tau_b\alpha$
$\tau_b(1-\alpha)\rho_T\alpha$
$\tau_b(1-\alpha)^2\rho_T^2\alpha$
$\tau_b(1-\alpha)^3\rho_T^3\alpha$
$\tau_b(1-\alpha)^4\rho_T^4\alpha$
(b)
1
τ_1
$\tau_1\rho_T$
$\tau_1\tau_b(1-\alpha)$
$\tau_1\tau_b$
$\tau_1\tau_b\alpha$
$\tau_1\tau_b\rho_T(1-\alpha)\alpha$
$\tau_1\tau_d\rho_1\rho_T\alpha$
$\tau_1\tau_b\rho_1\tau_d^2(1-\alpha)\alpha$
$\tau_1\tau_b\rho_T\rho_1\tau_d^2(1-\alpha)^2\alpha$
$\tau_1\rho_T\rho_1^2\tau_d^3(1-\alpha)\alpha$
$\tau_1\tau_b\rho_1\tau_d^4(1-\alpha)^2\alpha$
$\tau_1\tau_b\rho_T\rho_1^2\tau_d^4(1-\alpha)^3\alpha$
$\tau_1\rho_T\rho_1^3\tau_d^5(1-\alpha)^2\alpha$
(c)
1
$\tau_1\rho_T$
τ_1
$\tau_1\rho_T\rho_1^2\tau_d^2\tau_{2d}^2(1-\alpha)$
$\tau_1\rho_T\rho_1\tau_d\tau_{2d}\alpha$
$\tau_1\rho_T\rho_1^2\tau_d^3\tau_{2d}^3(1-\alpha)\alpha$
$\tau_1\rho_T\rho_1^3\tau_d^5\tau_{2d}^5(1-\alpha)^2\alpha$

The transmittance–absorptance product for the set 2 is

$$(\tau\alpha)_2 = \tau_b \rho_T (1-\alpha)\alpha. \tag{2}$$

The net transmittance–absorptance product

$$(\tau\alpha)_b = (\tau\alpha)_1 + (\tau\alpha)_2, \tag{3}$$

$$= \tau_b \alpha[1 + \rho_T(1-\alpha)]. \tag{4}$$

The above expression for $(\tau\alpha)_2$ considers only one reflection by TIM. The consideration of multiple reflection yields:

$$(\tau\alpha)_2 = \tau_b \rho_T (1-\alpha)\alpha + \tau_b \rho_T^2 (1-\alpha)^2 \alpha + \ldots, \tag{5}$$

and corresponding

$$(\tau\alpha)_b = \tau_b \alpha/[1 - \rho_T(1-\alpha)]. \tag{6}$$

Similarly the diffuse radiation transmittance–absorptance product for sky radiation is

$$(\tau\alpha)_s = \tau_{ds} \alpha[1 + \rho_T(1-\alpha)] \text{ or } \tau_{ds}\alpha/[1 - \rho_T(1-\alpha)], \tag{7}$$

and ground radiation is

$$(\tau\alpha)_g = \tau_{dg} \alpha[1 + \rho_T(1-\alpha)] \text{ or } \tau_{dg}\alpha/[1 - \rho_T(1-\alpha)]. \tag{8}$$

2.2. *Cellular array with top cover (configuration 2)*

The solar beam radiation reaching the absorber plane consists of the following three set of rays (Fig. 1b):

1. radiation transmitted through top cover and TIM
2. radiation reflected at the top of the TIM and transmitted further
3. radiation reflected from the absorber plane and transmitted further due to reflections at the bottom of the TIM

The transmittance–absorptance product for the set 1 is

$$(\tau\alpha)_1 = \tau_1 \tau_b \alpha\left[1 + (1-\alpha)\tau_d^2 \rho_1 + (1-\alpha)^2 \tau_d^4 \rho_1^2 + \ldots\right],$$

$$= \frac{\tau_1 \tau_b \alpha}{[1 - (1-\alpha)\tau_d^2 \rho_1]}. \tag{9}$$

The transmittance–absorptance product for the radiation $(\rho_T \tau_1 \rho_1)$ of the set 2 is

$$(\tau\alpha)_x = \tau_1 \rho_T \rho_1 \tau_d \alpha\left[1 + (1-\alpha)\rho_1 \tau_d^2 + (1-\alpha)^2 \rho_1^2 \tau_d^4 + \ldots\right],$$

$$= \frac{\tau_1 \rho_T \rho_1 \tau_d \alpha}{[1 - (1-\alpha)\rho_1 \tau_d^2]}. \tag{10}$$

The transmittance–absorptance product for the radiation $(\tau_1 \tau_b (1-\alpha)\rho_T)$ of the set 3 is

$$(\tau\alpha)_y = \tau_1 \tau_b \rho_T \alpha(1-\alpha)\left[1 + (1-\alpha)\tau_d^2 \rho_1 + (1-\alpha)^2 \tau_d^4 \rho_1^2 + \ldots\right],$$

$$= \frac{\tau_1 \tau_b \rho_T \alpha(1-\alpha)}{[1 - (1-\alpha)\tau_d^2 \rho_1]}. \tag{11}$$

The net amount of radiation of set 2, which is available at the top of the TIM is

$$
\begin{aligned}
&= \tau_1\,\rho_1\,\rho_T + \tau_1\tau_b\tau_d(1-\alpha)\rho_1^2\rho_T + \tau_1\tau_b(1-\alpha)^2\tau_d^3\rho_1^3\rho_T + \ldots,\\
&= \tau_1\,\rho_1\,\rho_T + \tau_1\tau_b\tau_d(1-\alpha)\rho_1^2\rho_T\left[1 + (1-\alpha)\tau_d^2\rho_1 + (1-\alpha)^2\tau_d^4\rho_1^2 + \ldots\right],\\
&= \tau_1\,\rho_1\,\rho_T + \frac{\tau_1\tau_b\tau_d(1-\alpha)\rho_1^2\rho_T}{\left[1-(1-\alpha)\tau_d^2\rho_1\right]}. \qquad (12)
\end{aligned}
$$

So the effective transmittance–absorptance product for the above set 2 from Eq. (10) is

$$
(\tau\alpha)_2 = \left[\tau_1\,\rho_1\,\rho_T + \frac{\tau_1\tau_b\tau_d(1-\alpha)\rho_1^2\rho_T}{\left[1-(1-\alpha)\tau_d^2\rho_1\right]}\right]\frac{\tau_d\,\alpha}{\left[1-(1-\alpha)\tau_d^2\rho_1\right]}. \qquad (13)
$$

The net amount of radiation of set 3, which is available at the bottom of the TIM is

$$
\begin{aligned}
&= \tau_1\tau_b(1-\alpha)\rho_T + \tau_1\tau_b(1-\alpha)^2\tau_d^2\rho_1\,\rho_T + \tau_1\tau_b(1-\alpha)^3\tau_d^4\rho_1^2\rho_T + \ldots,\\
&= \tau_1\tau_b(1-\alpha)\rho_T\left[1 + (1-\alpha)\tau_d^2\rho_1 + (1-\alpha)^2\tau_d^4\rho_1^2 + \ldots\right],\\
&= \frac{\tau_1\tau_b(1-\alpha)\rho_T}{\left[1-(1-\alpha)\tau_d^2\rho_1\right]}. \qquad (14)
\end{aligned}
$$

So the effective transmittance–absorptance product for the above set 3 from Eq. (11) is

$$
(\tau\alpha)_3 = \left[\frac{\tau_1\tau_b(1-\alpha)\rho_T}{\left[1-(1-\alpha)\tau_d^2\rho_1\right]}\right]\frac{\alpha}{\left[1-(1-\alpha)\tau_d^2\rho_1\right]}. \qquad (15)
$$

Beam radiation transmittance–absorptance for configuration 2 is therefore, given as

$$
(\tau\alpha)_b = (\tau\alpha)_1 + (\tau\alpha)_2 + (\tau\alpha)_3, \qquad (16)
$$

$$
(\tau\alpha)_b = \frac{\left[\tau_1\tau_b\,\alpha + \tau_1\,\rho_1\,\rho_T\tau_d\,\alpha\right] + \left[\left(\tau_1\tau_b(1-\alpha)\rho_T\,\alpha\right)\left(1+\tau_d^2\rho_1^2\right)/\left(1-(1-\alpha)\tau_d^2\rho_1\right)\right]}{\left(1-(1-\alpha)\tau_d^2\rho_1\right)}. \qquad (17)
$$

Similarly the sky and ground diffuse radiation transmittance–absorptance product for the configuration 2 is

$$
(\tau\alpha)_s = \frac{\left[\tau_{1ds}\tau_{ds}\,\alpha + \tau_{1ds}\,\rho_1\,\rho_T\tau_d\,\alpha\right] + \left[\left(\tau_{1ds}\tau_{ds}(1-\alpha)\rho_T\,\alpha\right)\left(1+\tau_d^2\rho_1^2\right)/\left(1-(1-\alpha)\tau_d^2\rho_1\right)\right]}{\left(1-(1-\alpha)\tau_d^2\rho_1\right)}, \qquad (18)
$$

$$
(\tau\alpha)_g = \frac{\left[\tau_{1dg}\tau_{dg}\,\alpha + \tau_{1dg}\,\rho_1\,\rho_T\tau_d\,\alpha\right] + \left[\left(\tau_{1dg}\tau_{dg}(1-\alpha)\rho_T\,\alpha\right)\left(1+\tau_d^2\rho_1^2\right)/\left(1-(1-\alpha)\tau_d^2\rho_1\right)\right]}{\left(1-(1-\alpha)\tau_d^2\rho_1\right)} \qquad (19)
$$

2.3. Cellular array with top and bottom covers (configuration 3)

If one considers only one reflection by the bottom cover the radiation reaching the absorber consists of the following five sets of ray (Fig. 1c);

1. radiation transmitted through TIM and two covers.
2. radiation reflected at the top of the TIM and transmitted further
3. radiation reflected at the bottom of the TIM and transmitted further
4. radiation reflected at the top of the bottom cover and transmitted further
5. radiation reflected at the bottom of the bottom cover and transmitted further.

Using the analysis similar to above the transmittance–absorptance product for beam, sky diffuse and ground diffuse radiations are given by;

$$\left[\tau_1\tau_b\tau_2\alpha + \tau_1\rho_1\rho_T\tau_d\tau_{2d}\alpha + \rho_{2b}\tau_1\tau_b^3\rho_{1b}\tau_{2d}\alpha\right] + \left[\left(\tau_1\tau_2\tau_b(1-\alpha)\alpha\right)\right] = \mathrm{AN}$$

$$(\tau\alpha)_b = \frac{\left[\mathrm{AN}\times\left(\rho_2+\rho_T\tau_{2d}^2+\rho_1^2\rho_T\tau_d^2\tau_{2d}^2+\rho_1\rho_2\tau_d^4\tau_{2d}^3\right)/\left(1-(1-\alpha)\tau_d^2\rho_1\tau_{2d}^2\right)\right]}{\left(1-(1-\alpha)\tau_d^2\rho_1\tau_{2d}^2\right)}, \tag{20}$$

$$\left[\tau_{1ds}\tau_{ds}\tau_{2ds}\alpha + \tau_{1ds}\rho_1\rho_T\tau_d\tau_{2d}\alpha + \rho_{2d}\tau_{1ds}\tau_{ds}^3\rho_{1d}\tau_{2d}\alpha\right] + \left[\left(\tau_{1ds}\tau_{2ds}\tau_{ds}(1-\alpha)\alpha\right)\right] = \mathrm{BN}$$

$$(\tau\alpha)_s = \frac{\left[\mathrm{BN}\times\left(\rho_2+\rho_T\tau_{2d}^2+\rho_1^2\rho_T\tau_d^2\tau_{2d}^2+\rho_1\rho_2\tau_d^4\tau_{2d}^3\right)/\left(1-(1-\alpha)\tau_d^2\rho_1\tau_{2d}^2\right)\right]}{\left(1-(1-\alpha)\tau_d^2\rho_1\tau_{2d}^2\right)}, \tag{21}$$

$$\left[\tau_{1dg}\tau_{dg}\tau_{2dg}\alpha + \tau_{1dg}\rho_1\rho_T\tau_d\tau_{2d}\alpha + \rho_{2d}\tau_{1dg}\tau_{dg}^3\rho_{1d}\tau_{2d}\alpha\right] + \left[\left(\tau_{1dg}\tau_{2dg}\tau_{dg}(1-\alpha)\alpha\right)\right] = \mathrm{CN}$$

$$(\tau\alpha)_g = \frac{\left[\mathrm{CN}\times\left(\rho_2+\rho_T\tau_{2d}^2+\rho_1^2\rho_T\tau_d^2\tau_{2d}^2+\rho_1\rho_2\tau_d^4\tau_{2d}^3\right)/\left(1-(1-\alpha)\tau_d^2\rho_1\tau_{2d}^2\right)\right]}{\left(1-(1-\alpha)\tau_d^2\rho_1\tau_{2d}^2\right)}. \tag{22}$$

2.4. Global radiation transmittance–absorptance product

For the TIM tilted at an angle, β, the global radiation falling on the top is given by [6],

$$I_{T\,top} = I_b R_b + I_d R_d + (I_b + I_d) R_r, \tag{23}$$

where

R_b – tilt factor for the beam radiation (I_b) and equal to $\cos\theta/\cos\theta_z$, where θ and θ_z are the angles of incidence of direct radiation and zenith angle, respectively.

R_d – tilt factor for the diffuse radiation (I_d) from the sky and equal to $(1 + \cos\beta)/2$

R_r – tilt factor for the ground reflected part of the diffuse radiation and equal to $\rho(1 - \cos\beta)/2$

The net amount of solar radiation, which is absorbed by the blackened plane is given by

$$I_{T\,bot} = I_b\, R_b(\tau\alpha)_b + I_d\, R_d(\tau\alpha)_s + (I_b + I_d)\, R_r(\tau\alpha)_g. \tag{24}$$

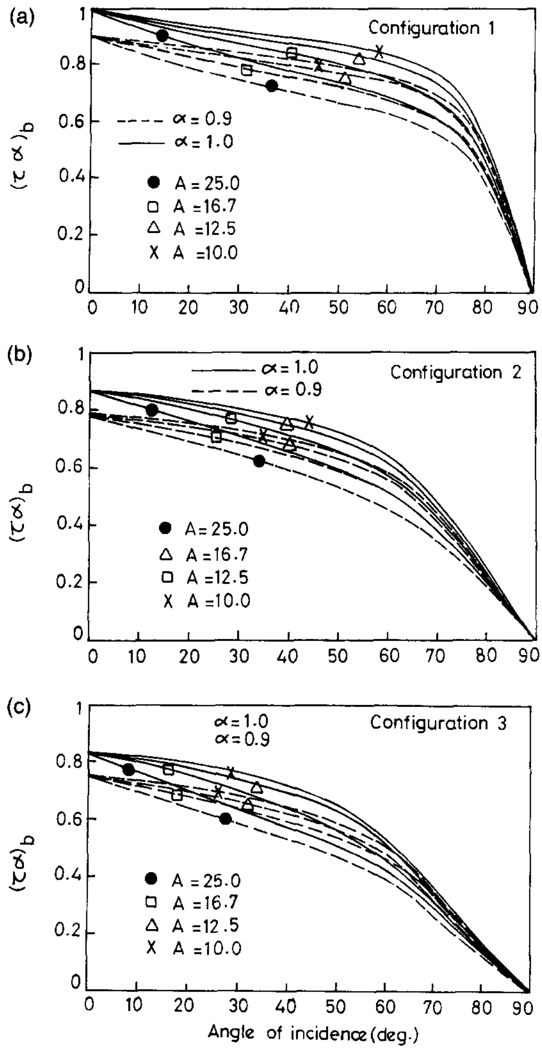


Fig. 2. Beam radiation transmittance absorptance product for glazing containing: (a) TIM only, (b) TIM and top cover, and (c) TIM with top and bottom covers.

So the global radiation transmittance–absorptance product for the TIM is

$$(\tau\alpha)_{glo} = \frac{I_b R_b(\tau\alpha)_b + I_d R_d(\tau\alpha)_s + (I_b + I_d) R_r(\tau\alpha)_g}{I_b R_b + I_d R_d + (I_b + I_d) R_r}. \quad (25)$$

3. Results and discussion

The beam radiation transmittance absorptance product for the configurations 1,2 and 3 as a function of angle of incidence for various aspect ratios is shown in Fig. 2. The

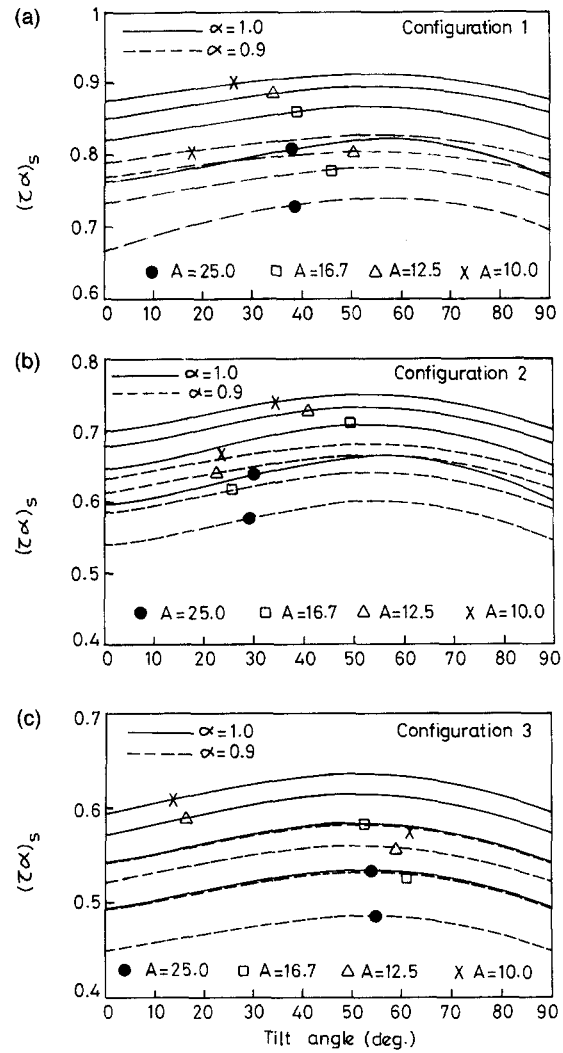


Fig. 3. Sky diffuse radiation transmittance absorptance product for glazing containing: (a) TIM only, (b) TIM and top cover, and (c) TIM with top and bottom covers.

reduction in transmittance due to two sets of covers is about 12% and 17%, respectively. Fig. 3 represent the sky diffuse radiation transmittance absorptance product for the configurations 1,2 and 3 and the reduction in transmittance due to covers is about 14% and 30%, respectively. The ground diffuse radiation transmittance is given in Fig. 4. It is reduced by about 14% and 32% for the two covers. The diffuse component of transmittance absorptance product seems to be very significant. The covers have considerable effect on the transmittance absorptance product and hence it should be of high quality (e.g., low iron content glass). As for as possible it is desirable to have single cover.

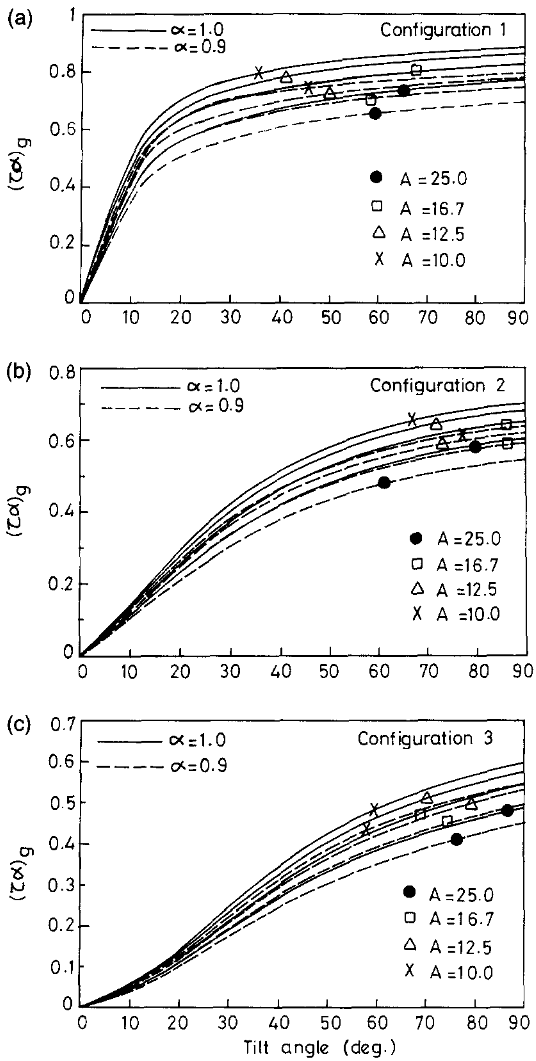


Fig. 4. Ground diffuse radiation transmittance absorptance product for glazing containing: (a) TIM only, (b) TIM and top cover, and (c) TIM with top and bottom covers.

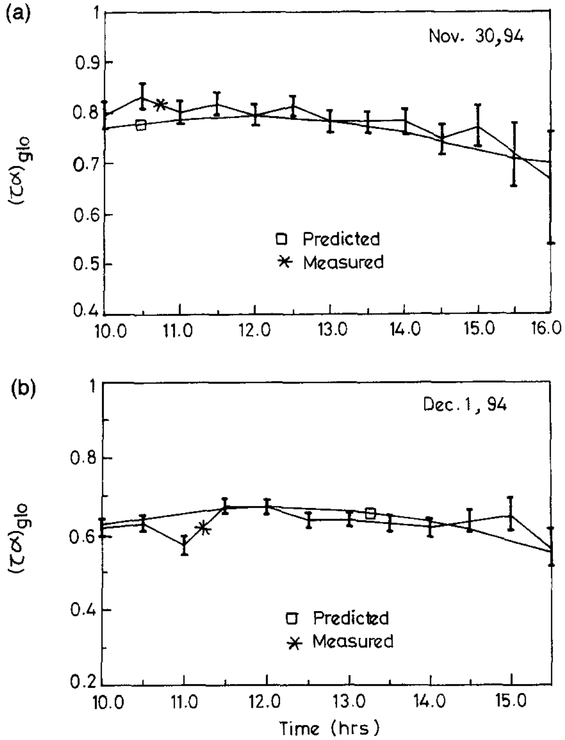


Fig. 5. Predicted and measured values of global radiation transmittance absorptance product for: (a) cellular matrix, and (b) cellular matrix with top cover.

To examine the validity of above formulations, field experiments for the measurement of global radiation transmittance–absorptance product were carried out. The cellular matrix was square honeycomb of polycarbonate supplied by ArEl Energy Ltd., Israel. The dimensions of the same are as follows; wall thickness 25 μm, cell depth 50 mm, cell size 2.5 mm × 2.5 mm and 4.5 mm × 4.5 mm. The global radiation measurements at bottom and top cover system were carried out with precision pyranometers. The transmittance absorptance product predictions are shown in Fig. 5 for configurations 1 and 2.; experimental observations along with possible error in measurements are also shown therein. In general the experimental observations deviate from the predictions by 0 to 6.4%. The results are good pointer to the validity of the above formulations which provide a convenient means of predicting the $(\tau\alpha)_{glo}$ of glazing embodying the cellular matrix.

4. Nomenclature

A	aspect ratio of TIM (L/d)
d	cell width

F	geometrical shape factor of diffuse radiation leaving vertical wall and reaching bottom of honeycomb directly as well as by all means
I_b	solar beam radiation
I_d	solar diffuse radiation
K_{a1}	absorption coefficient for wall material
K_{s1}	scattering coefficient of wall material
L	honeycomb cell depth
n_x	an integer representing the lower rounded value of N_x
N_x	number of walls intercepted by the solar ray in its propagation through the cellular array.
R_b, R_d, R_r	tilt factor for beam, sky and ground reflected radiation
α	absorptance
β	tilt angle
θ	angle of incidence
μ	refractive index of the TIM cell wall material
δ	thickness of honeycomb cell wall
ρ_1,ρ_2	reflectance of top and bottom cover to diffuse radiation
ρ_T	reflectance of TIM for solar radiation
ρ_{1b}, ρ_{2b}	reflectance of top and bottom cover to beam radiation
$\rho^s_{\gamma e}$	equivalent specular reflectivity at γ
$\rho^d_{\gamma e}$	equivalent diffuse reflectivity at γ
ρ_γ	hemispherical reflectivity
τ_b	beam radiation transmittance for TIM
$\tau c(\theta,\phi)$	transmittance (specular as well as diffuse) through the cell to beam radiation incident at an angle θ and azimuth angle ϕ
τ_{ds}	sky diffuse radiation transmittance for TIM
τ_{dg}	ground diffuse radiation transmittance for TIM
τ_d	diffuse radiation transmittance for TIM in horizontal plane
$\tau D(\theta,\phi)$	cell transmittance corresponding to specular reflection and refraction through the cells for beam radiation with incident angle θ and azimuth angle ϕ
$\tau E(\theta,\phi)$	transmittance through TIM walls
τ_1, τ_2	beam radiation transmittance of top and bottom covers
τ_{1ds}, τ_{2ds}	sky diffuse radiation transmittance of top and bottom covers
τ_{1d}, τ_{2d}	transmittance of top and bottom covers for diffuse radiation in horizontal plane
τ_{1dg}, τ_{2dg}	ground diffuse radiation transmittance of top and bottom covers
ϕ	azimuth angle

Appendix A. Solar beam radiation transmittance of honeycomb cellular matrix

The solar beam radiation falling on the top of the honeycomb matrix propagates through both cell and wall. The major portion propagating through the cells undergoes forward reflection towards absorber as well as refraction and absorption due to vertical walls. The radiation propagation through the walls is due to internal reflections. Following Hollands et al. [2] and Kaushika and Padmapriya [4], the beam radiation transmittance for honeycomb cellular matrix ($\tau_b(\theta,\phi)$) may be expressed as

$$\tau_b(\theta,\phi) = [\tau c(\theta,\phi) + \tau E(\theta,\phi)]\ E/(1+E). \tag{A1.1}$$

The fraction of cellular cross section occupied by wall material, E, for the square cell may be given by

$$E = \delta(\delta + 2d)/d^2, \tag{A1.2}$$

where δ is the wall thickness and d the wall spacing/cell width of the cellular array. $\tau c(\theta,\phi)$ is the specular as well as diffuse transmittance of solar beam radiation passing through the cells with walls of material having equivalent specular reflectivity $\rho^s_{\gamma e}$, diffuse reflectivity $\rho^d_{\gamma e}$ and absorptivity $\alpha_{\gamma e}$ is given by

$$\tau c(\theta,\phi) = \tau D(\theta,\phi) + \rho^d_{\gamma e} F[1 - \tau D(\theta,\phi)]/(\rho^d_{\gamma e} + \alpha_{\gamma e}), \tag{A1.3}$$

and

$$\tau D(\theta,\phi) = (\rho^s_{\gamma e})^{n_x}(n_x - N_x + 1) + (\rho^s_{\gamma e})^{n_x+1}(N_x - n_x), \tag{A1.4}$$

where N_x is number of walls intercepted by solar ray in it propagation through cellular array and n_x is lower rounded value of N_x.

For an incoming ray at an incident angle, θ, and azimuth angle, ϕ, N_x and γ may be expressed for square cell as follows

$$N_x = A \tan\theta, \tag{A1.5}$$

$$\gamma = \pi/2 - \theta. \tag{A1.6}$$

Above expression is an approximate form of the expression for $N_x(\theta,\phi)$ due to Symons [7] and Platzer [4]; it involves the assumption that Nx is a weak function of ϕ, which is quite valid for square cell configurations.

The transmittance through the cell wall, $\tau E(\theta,\phi)$, may be expressed as

$$\tau E(\theta,\phi) = (1 - R_\theta)^2 e^{-b\theta} + F(K_{s1}/(K_{s1} + K_{a1}))(1 - e^{-b\theta})(1 - R_\theta), \tag{A1.7}$$

where

$$b\theta = (K_{s1} + K_{a1})\mu L/(\mu^2 - \sin^2\theta)^{(1/2)}, \tag{A1.8}$$

$$K_{s1}/(K_{s1} + K_{a1}) = \rho^d_{\gamma e}/(\rho^d_{\gamma e} + \alpha_{\gamma e})(\text{at } \gamma = 0). \tag{A1.9}$$

The procedure for obtaining the optical properties and method of calculation is outlined in Hollands et al. [2] and Kaushika and Padmapriya [3].

Appendix B. Solar diffuse radiation transmittance of honeycomb cellular matrix

The transmittance for the hemishperical isotropic sky and ground diffuse radiation has been calculated by integrating the beam radiation over appropriate range of angle of incidence. Following Arulanantham and Kaushika [5] and Brandemuehl and Beckman [8] for the honeycomb matrix tilted at an angle β, the diffuse radiation from the ground, will have angle of incidence, θ, ranging from $\theta = \pi/2 - \beta$ to $\theta = \pi/2$. For a given value of θ, the azimuth angle, ϕ, will range from $\phi = \sin^{-1}(\cot\beta/\tan\theta)$ to $\phi = \pi - \sin^{-1}(\cot\beta/\tan\theta)$. Using these integration limits and due to axial symmetry, the transmittance for diffuse ground radiation, τ_{dg}, is

$$\tau_{dg} = \frac{\int_{\frac{\pi}{2}-\beta}^{\frac{\pi}{2}} \int_{\sin^{-1}\left(\frac{\cot\beta}{\tan\theta}\right)}^{\frac{\pi}{2}} \tau_b(\theta,\phi)\cos\theta\,\sin\theta\,d\phi\,d\theta}{\int_{\frac{\pi}{2}-\beta}^{\frac{\pi}{2}} \int_{\sin^{-1}\left(\frac{\cot\beta}{\tan\theta}\right)}^{\frac{\pi}{2}} \cos\theta\,\sin\theta\,d\phi\,d\theta}. \tag{A2.1}$$

Diffuse radiation from the sky will have angle of incidence ranging from $\theta = 0$ to $\theta = \pi/2$. For the incidence angle $\theta \leq \pi/2 - \beta$ the angle ϕ will vary from 0 to 2π and for the incidence angle $\theta \geq \pi/2 - \beta$ the angle ϕ will range from $\phi = \pi - \sin^{-1}(\cot\beta/\tan\theta)$ to $\phi = 2\pi + \sin^{-1}(\cot\beta/\tan\theta)$. By applying these integration limits and due to axial symmetry the transmittance for sky diffuse radiation, τ_{ds}, is

$$\tau_{ds} = \frac{\int_0^{\frac{\pi}{2}-\beta} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \tau_b(\theta,\phi)\cos\theta\,\sin\theta\,d\phi\,d\theta + \int_{\frac{\pi}{2}-\beta}^{\frac{\pi}{2}} \int_{-\frac{\pi}{2}}^{\sin^{-1}\left(\frac{\cot\beta}{\tan\theta}\right)} \tau_b(\theta,\phi)\cos\theta\,\sin\theta\,d\phi\,d\theta}{\int_0^{\frac{\pi}{2}-\beta} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \cos\theta\,\sin\theta\,d\phi\,d\theta + \int_{\frac{\pi}{2}-\beta}^{\frac{\pi}{2}} \int_{-\frac{\pi}{2}}^{\sin^{-1}\left(\frac{\cot\beta}{\tan\theta}\right)} \cos\theta\,\sin\theta\,d\phi\,d\theta}. \tag{A2.2}$$

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