

# Non-gray radiative and conductive heat transfer in single and double glazing solar collector glass covers

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## Abstract

A rigorous model for the radiative heat transfer combined with the conduction and the convection has been applied for a solar collector glazing. The glass cover is analysed as a non-gray plane-parallel medium subjected to solar and thermal irradiation in one-dimensional case, using the radiation element method by ray emission model. The model allows the calculation of the steady-state heat flux and the temperature distribution within the glass cover. The spectral dependence of the relevant radiation properties of glass (i.e. specular reflectivity, refraction angle and absorption coefficient) is taken into account. Both collimated and diffuse incident irradiances are applied at the boundary surfaces using the spectral solar model proposed by Bird and Riordan. Single and double glasses commonly used for the glass cover are considered. The optical constant of a commercial clear glass material have been used. These optical constants of real and imaginary parts of the complex refractive index of the glass, determined by the author from 0.19 to 5  $\mu\text{m}$  combined by those reported by Rubin from 6 to 300  $\mu\text{m}$  have been used. The calculation has been performed for both single and double glazing cover at low and high temperature of the absorber. The effect of the thickness of the single glass cover has been also discussed. The result shows that increasing the thickness of the single glass cover, the steady heat flux decreases at both low and high temperature of the absorber. It has been also shown that the double-glazing cover assembly is more suitable than the single one at high temperature of the absorber.

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*Keywords:* Solar collector glazing; Non-gray calculation; Radiative heat transfer; Optical constants glass material

## 1. Introduction

The accurate prediction of the thermal performance of a solar collector system depends strongly on how the transparent glass-cover material is analysed. In deed, the glass cover, which represents the most important component of the system, affects the thermal performance.

Almost all the classical studies assume that the solar collector glass-cover is transparent for the solar spectrum and opaque to radiation at infrared wavelengths. Under such assumptions the optical analysis of the transparent cover can be found in many references [1,2]. These assumptions may lead to considerable error in evaluating the thermal properties, heat flux and temperature distribution within the glass-cover. In reality, the transmittance, like reflectance and absorbance, is a function of

wavelength, angle of incidence of the incoming radiation, the real part  $n$  and the imaginary part  $k$  of the complex refractive index of the glass-cover. Moreover, the real and imaginary parts of the complex refractive index of glass are spectrally dependent. But for most solar energy applications they are assumed to be wavelength independent.

In the present work, the cover of the solar collector is considered to be a participating non-gray media subjected to solar irradiation (specified by the spectral solar model proposed by Bird and Riordan [3]) and thermal radiation (specified by black-body emission of the outside environment and infrared radiation of the black absorber). A more refined and rigorous approach is applied using the Radiation Element Method by Ray Emission Model (REM<sup>2</sup>). The REM<sup>2</sup> is a generalized method for calculating radiation heat transfer between absorbing, emitting and scattering media. The boundary surfaces of the glass are specular and the spectral dependence of radiation properties such as

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## Nomenclature

$A_i^R$	effective radiation area . . . . . m <sup>2</sup>	$T_0(nl)$	absorber side glass temperature . . . . . K
$c_p$	specific heat . . . . . J·kg <sup>-1</sup> ·K <sup>-1</sup>	$T_r$	measured transmittance through the glass sample
$F_{i,j}^A$	absorption view factor from element $i$ to $j$	$v$	wind speed velocity . . . . . m·s <sup>-1</sup>
$G_{i,\lambda}$	incident radiation . . . . . W·m <sup>-2</sup>	$V_i$	volume of the radiation element . . . . . m <sup>3</sup> , m <sup>2</sup>
$Gr$	Grashof number	$w$	solid angle
$h_{in}$	inside convective heat transfer coefficient . . . . . W·m <sup>-2</sup> ·K <sup>-1</sup>	$w_k$	weight of discretized angle
$h_{out}$	outside convective heat transfer coefficient . . . . . W·m <sup>-2</sup> ·K <sup>-1</sup>	$x$	position through the thickness of the glass-cover
$I_\lambda$	spectral radiation intensity . . . . . W·m <sup>-2</sup> ·μm <sup>-1</sup> ·sr <sup>-1</sup>	<i>Greek symbols</i>	
$I_{b,\lambda}$	spectral blackbody radiation intensity . . . . . W·m <sup>-2</sup> ·μm <sup>-1</sup> ·sr <sup>-1</sup>	$\beta$	slope . . . . . degree
$k$	imaginary part of the complex refractive index of element $i$ of glass	$\Delta x_i$	element thickness . . . . . m
$l_{air}$	thickness of the air layer between the glass and the absorber . . . . . m	$\varepsilon_i$	emissivity
$n$	real part of the complex refractive index of element $i$ of glass or of the glass	$\Lambda$	thermal conductivity . . . . . W·m <sup>-1</sup> ·K <sup>-1</sup>
$N$	number of volume and surface elements	$\mu$	direction cosine of polar angle
$Nu$	Nusselt number	$\mu_f$	viscosity of the fluid . . . . . kg·m <sup>-2</sup> ·s <sup>-1</sup>
$Pr$	Prandtl number	$\mu_k$	discretized angle
$Q_{J,i,\lambda}$	heat transfer rate of diffuse radiosity . . . . . W	$\nu$	kinematic viscosity . . . . . m <sup>2</sup> ·s <sup>-1</sup>
$Q_{T,i,\lambda}$	heat transfer rate of emissive power . . . . . W	$\rho_g$	density of the glass cover . . . . . kg·m <sup>-3</sup>
$Q_{X,i,\lambda}$	net heat transfer rate of heat generation . . . . . W	$\sigma$	Stefan–Boltzman constant . . . . . W·m <sup>-2</sup> ·K <sup>-4</sup>
$q_{r,\lambda}$	radiative heat flux . . . . . W·m <sup>-2</sup>	$\sigma_{s,\lambda}$	scattering coefficient
$q_{x,i}$	net rate of heat generation per unit volume or unit surface . . . . . W·m <sup>-3</sup> , W·m <sup>-2</sup>	$\theta_0$	incident angle of collimated solar irradiation degrees
$\vec{r}$	position vector	$\Omega_i^D$	albedo of volume element or diffusivity of surface element
$Ra$	Rayleigh number	<i>Subscripts</i>	
$Re$	Reynolds number	abs	absorber
$\hat{s}$	unit direction vector	air	air layer between the glass cover and the absorber
$S$	path length through element	$g$	glass
$S_h$	heat generation source . . . . . W·m <sup>-3</sup>	$s$	sky
$T$	temperature . . . . . K	$z$	zenith angle
		$i$	element $i$
		$j$	element $j$
		$\lambda$	spectral value

specular reflectivity, refraction angle and absorption coefficient are all taken into consideration.

The REM<sup>2</sup> method was proposed by Maruyama and Aihara [4] and can be applied for complicated three-dimensional shapes. Numerous researchers have studied heat transfer by combined conduction and radiation in glass medium. Khoukhi et al. [5] have analysed the combined non-gray radiative and conductive heat transfer in solar collector single glass cover using different model with regard to the optical constant of the glass material. Kong and Viskanta [6] have compared the diffusion approximation and Discrete Ordinate Method (DOM) for determining heat transfer in glass. The effect of the refractive index on radiative behaviour of heated absorbing-emitting layer has been reported by Spuckler and Siegel [7]. The combined conduction and radiation in two-layer planar medium with flux boundary conditions has been studied by Ho and Ozisik [8].

The work presented is here represents the extension of the previous paper reported by the author [5]. The effect of the

thickness of the glass cover at low and high temperature of the absorber, 40 °C and 80 °C, respectively, has been discussed in the present work.

Since the radiation loss from the absorber is the dominant heat transfer in the absence of the selective surface and for a small wind velocity, more than one glass cover can be used for a particular situation. In this paper, the effect of the double-glazing has been investigated at low and high temperature of the absorber, 40 °C and 80 °C, respectively.

The optical constant of a commercial clear glass material have been used. These optical constants of real and imaginary parts of the complex refractive index of the glass, determined by the Khoukhi et al. [9] from 0.19 to 5 μm, combined by those reported by Rubin [10] from 6 to 300 μm have been used. Using this data, the calculation has been performed for one position of the sun chosen at 11 a.m. on the fifth of July in Sendai city (Japan). The heat flux and temperature distribution within the glass layer have been obtained.

## 2. Analysis model and analytical condition

The glass material is almost transparent to the solar radiation, due to the small value of  $k$ . On the other hand, it is strongly absorbing in the infrared region. Therefore, the emission and absorption within a glass layer should be taken into account.

### 2.1. Analysis model

Figs. 1 and 2 show the model of solar collector single glass and double glass covers used in the present study, respectively. The solar collector glazing is subjected to collimated and diffuse solar and thermal irradiations. It is assumed that the glazing unit exists between two blackbodies which comprise the ambience of the surroundings and the plate black absorber. The analysis is carried out by dividing the glazing into a number of elements. Since the long-wavelength radiation from the ambient is mostly absorbed in the vicinity of the glass surface, the thickness of the element is thin ( $1 \mu\text{m}$ ) at the glass surface and thick ( $200 \mu\text{m}$ ) in the middle of the glass. The total number of element is set at 103 and 229 for single and double glazing,

respectively. The double glazing is constituted by two single glasses and we assume that between the two glasses a vacuum space of 3 mm exists. Therefore, the absorption and the convection are negligible in the vacuum space. The space between two glasses has been discretized into thin layers and the conduction is taken into account.

For the calculation presented here, it is assumed that the thickness of a single glass pane is 3 mm. The outside and absorber temperatures are 300 K and 343 K, respectively. The convection is taken into consideration as boundary conditions in both sides of the glass and the thermal conductivity of the glass material is assumed to be constant.

The solar collector glass-cover is transparent for the direct solar irradiation. However, no absorption occurs. The direct solar irradiation just passes through the glass-cover material. On the other hand, the diffuse solar irradiation and the thermal infrared radiation from the surroundings and the absorber are absorbed and emitted within the glass-cover material. Fig. 3 shows the real behaviour of the glass-cover of the solar collector subjected to solar and thermal irradiations.

### 2.2. Analytical assumptions

In the present study, the following assumptions are applied for the analysis.

- Since the thickness of the glass pane is much larger than the wavelength of the radiation, the coherence effects are neglected.
- The glass surfaces are optically smooth, and the incident radiation is specularly reflected.
- The scattering in the glass medium is neglected.
- The thermal conductivity of the glass material is assumed to be constant and independent of its temperature.
- The directional reflectivity has been computed from Fresnel equation as function of the complex refractive index of the cover and the incident angle.

### 2.3. Analytical conditions

The numerical simulation has been carried out for one location at 11 a.m. on the July 5, in Sendai city (Japan). Table 1

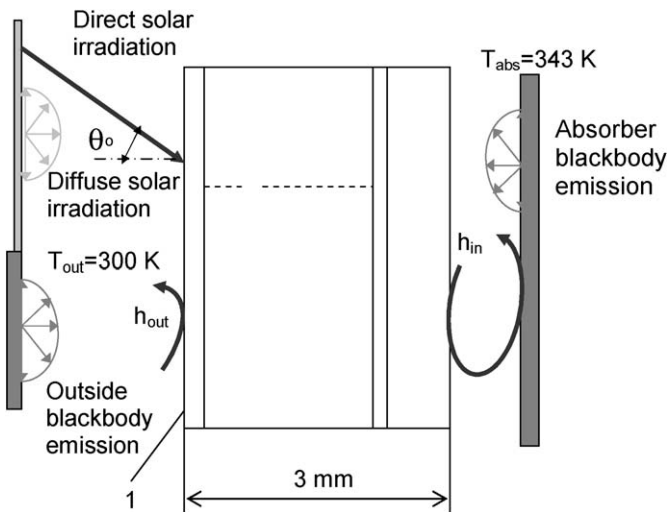


Fig. 1. Analysis model of solar collector glass-cover.

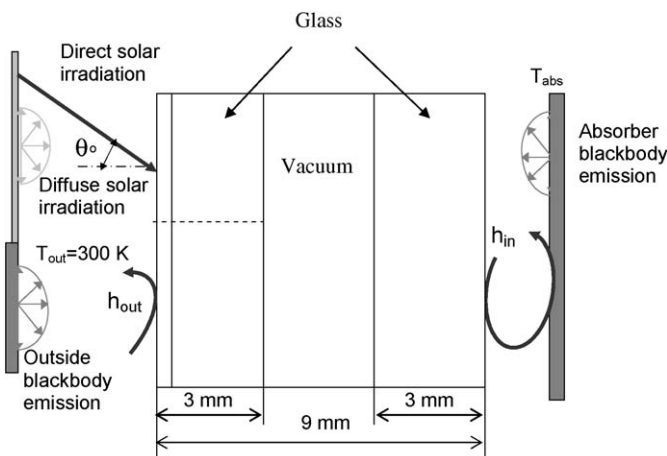


Fig. 2. Analysis model of solar collector double glazing.

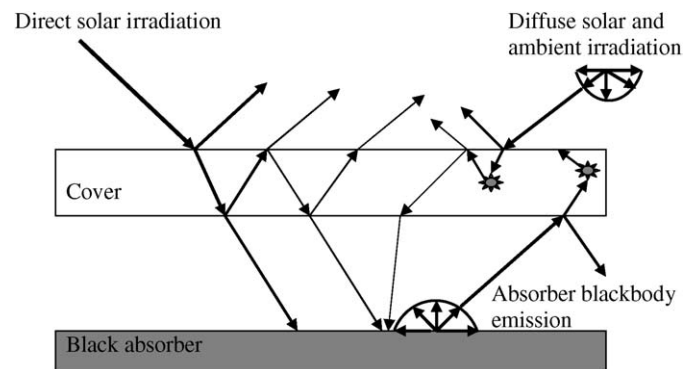


Fig. 3. Real behaviour of glass-cover material of the solar collector subjected to solar and thermal irradiations.

Table 1  
Characteristics of the site and other parameters used in numerical simulation (Sendai, Japan)

Parameter	Value	Unit
Zenith angle ( $\zeta$ )	19.92	[°]
Latitude	38.16	[°]
Longitude	140.51	[°]
Altitude	45.0	[m]
Day of year	186	[-]
Slope of the solar collector	40	[°]

Table 2  
Analytical conditions

Glass initial temperature [K]	310
Ambient temperature [K]	300
Absorber temperature [K]	343

Table 3  
Thermophysical properties of glass

Thermal conductivity $\Lambda$ [ $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ]	0.78
Density $\rho_g$ [ $\text{kg}\cdot\text{m}^{-3}$ ]	2700
Specific heat $c_p$ [ $\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ ]	0.84

shows the site characteristics and other parameters used in numerical simulation. The initial glass temperature, the outside ambient temperature and the absorber plate temperature are given by Table 2. Since the variation of the physical properties of the air and the glass material as a function of the temperature is small, it is assumed that their values are constants for a given initial values. The thermal conductivity, density and the specific heat of the glass and air are given by Table 3.

2.4. Spectral distribution of incident radiation

Fig. 4 shows the spectral distribution of direct solar irradiation on vertical surface, diffuse solar irradiation on horizontal surface and global solar irradiation on inclined surface (40°). Fig. 5 shows the spectral distribution of blackbody emissive power at 300 K and 343 K, and the spectral variation of the absorption coefficient of a clear glass material.

Figs. 5 and 6 reveal that at short-wavelength (visible and near infrared) the glass is almost transparent and hardly absorbing. However, the glass material is strongly adsorbing in long-wavelength (see also Fig. 5).

2.5. Radiative transfer

The general form of the radiation intensity in direction  $\hat{s}$  for a participating media is expressed from radiation energy balance as follows

$$\frac{dI_\lambda(\vec{r}, \hat{s})}{dS} = -(\kappa_\lambda + \sigma_{s,\lambda})I_\lambda(\vec{r}, \hat{s}) + \kappa_\lambda I_{b,\lambda}(T) + \frac{\sigma_{s,\lambda}}{4\pi} \int_{4\pi} I_\lambda(\vec{r}, \hat{s}') P_\lambda(\hat{s}' \rightarrow \hat{s}) d\omega \quad (1)$$

where  $I_\lambda$ ,  $\kappa_\lambda$ ,  $\sigma_{s,\lambda}$ ,  $d\omega$ ,  $I_{b,\lambda}$  and  $T$  are the radiation intensity, the spectral absorption, scattering coefficient, solid angle,

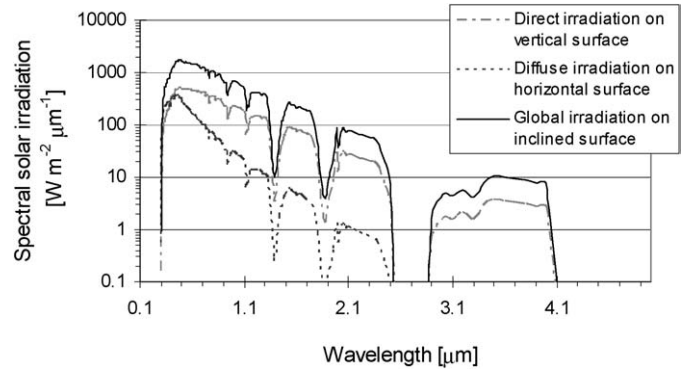


Fig. 4. Spectral distribution of incident solar irradiation.

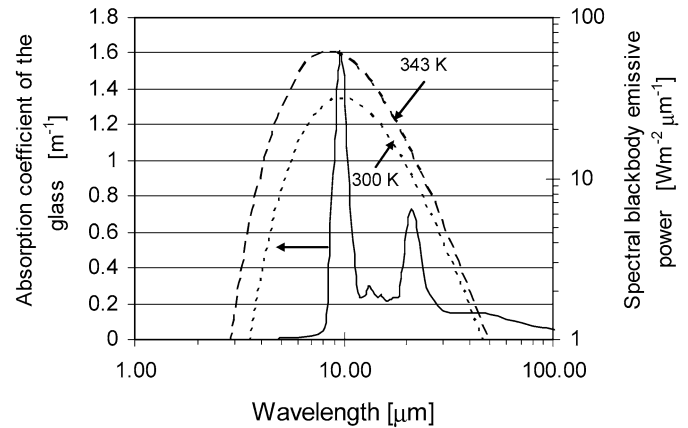


Fig. 5. Spectral distribution of incident blackbody radiation at 300 K and 343 K and absorption coefficient of a clear glass material.

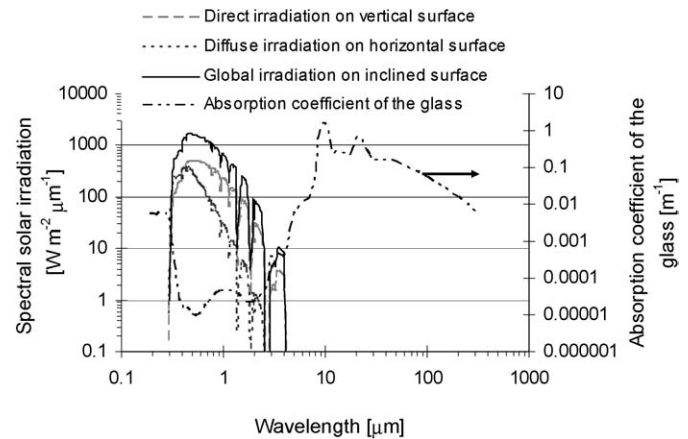


Fig. 6. Spectral distribution of incident solar irradiation and absorption coefficient of a clear glass.

blackbody radiation intensity and the temperature, respectively.  $P_\lambda(\hat{s}' \rightarrow \hat{s})$  is a phase function from the direction  $\hat{s}'$  to  $\hat{s}$ ,  $S$  is the path length in the direction  $\hat{s}$  and  $\vec{r}$  is the position vector (see Fig. 7).

A ray passing through the radiation element attenuates and separates into absorbed and transmitted fractions. The glass medium is discretized into thin element layer and considering the  $i$ th participating radiation element we introduce the following assumptions:

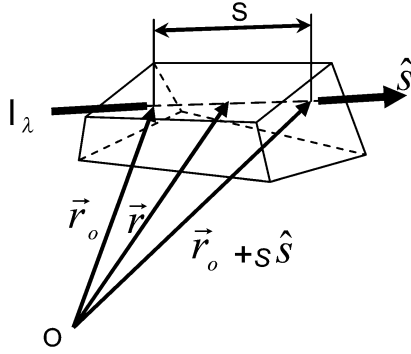


Fig. 7. Attenuation of the radiation ray along the direction  $\hat{s}$ .

- (1) Each element is at a constant temperature.
- (2) The refractive index and heat generation rate per unit volume are also constants over each radiation element.
- (3) Scattering within the glass media is neglected.

Under such considerations and using the direction cosine of each ray, Eq. (1) becomes [4]

$$\mu \frac{dI_\lambda(x, \mu)}{dx} = \kappa_\lambda [-I_\lambda(x, \mu) + I_{b,\lambda}(T)] \quad (2)$$

where  $\mu$  is the direction cosine and  $x$  is the position through the thickness of the glass-cover,  $\mu \equiv \cos\theta$  and  $\theta$  is the polar angle.

In case of no irradiation external to each radiation element, Eq. (2) is solved at each element as follows

$$I_\lambda(x + \Delta x_i, \mu) = I_{b,\lambda}(T) \left[ 1 - \exp\left(\frac{-\kappa_\lambda \Delta x_i}{\mu}\right) \right] \quad (3)$$

where  $\Delta x_i$  is the thickness of radiation element.

Eq. (3) is integrated for the whole projection area in the direction  $\mu$ , and radiant energy from element  $i$  in the direction  $\mu$  is given as follows

$$dQ_{J,i,\lambda} = I_{b,\lambda} \mu \left[ 1 - \exp\left(\frac{-\kappa_\lambda \Delta x_i}{\mu}\right) \right] dw \quad (4)$$

The total energy emitted from element  $i$  is given by integration of Eq. (4) for all directions. In the present study, the discretized direction cosine and weight functions given by Gaussian quadrature are used. Using those values, the spectral radiation energy emitted from element  $i$  is given as

$$Q_{J,i,\lambda} = I_{b,\lambda} \sum_{k=1}^K \mu_k \left[ 1 - \exp\left(\frac{-\kappa_\lambda \Delta x_i}{\mu_k}\right) \right] w_k \quad (5)$$

where  $\mu_k$ ,  $w_k$  and  $K$  are the discretized angle, the weight and the total number of discretized directions, respectively. In the present study,  $K$  is set at 200.

The effective radiation area  $A_i^R$  is given by the following expression

$$A_i^R = \frac{1}{\pi} \sum_{k=1}^K \mu_k \left[ 1 - \exp\left(\frac{-\kappa_\lambda \Delta x_i}{\mu_k}\right) \right] w_k \quad (6)$$

When the effective radiation area defined by Eq. (6) is applied to a solid surface with  $\kappa_\lambda \Delta x_i \gg 1$ , and if the backside is

not considered, the value agrees with the area of the solid surface. Then, the reflectivity of the solid surface is  $\Omega^s$ , and the emissivity is  $\varepsilon = 1 - \Omega^s$ , and finally, the total energy emitted from element  $i$  is represented for both surface and volume element as

$$Q_{J,i,\lambda} = A_i^R \varepsilon_{i,\lambda} n^2 \pi I_{b,i,\lambda} \quad (7)$$

where  $\varepsilon_{i,\lambda}$ ,  $n$  and  $\sigma$  are the emissivity of the glass, real part of the complex refractive index of the glass and Stefan–Boltzman constant.

For radiation elements  $i$  and  $j$ , the absorption view factor,  $F_{i,j}^A$ , is defined as a fraction of radiation energy emitted from element  $i$  and absorbed by element  $j$ .  $f_i^j(\mu_k)$  is the fraction of energy emitted from element  $i$  in the direction  $\mu_k$  which reaches element  $j$ . The absorption view factor,  $F_{i,j}^A$ , is given by

$$F_{i,j}^A = \frac{\sum_{k=1}^k \{ [f_i^j(\mu_k) dQ_{J,i,\lambda}(\mu_k)] [1 - \exp(\frac{-\kappa_\lambda \Delta x_j}{\mu_k})] \}}{Q_{J,i,\lambda}} \quad (8)$$

Once the absorption view factor is given by using the ray tracing method, the net rate of heat generation in element  $i$  is given by

$$Q_{X,i,\lambda} = Q_{T,i,\lambda} - \sum_{j=1}^N F_{j,i}^A Q_{J,j,\lambda} \quad (9)$$

where  $Q_{T,i,\lambda}$  is the radiation energy emitted by element  $i$  itself and equal to  $Q_{J,i,\lambda}$ . The heat transfer rate of the emissive power  $Q_{T,i,\lambda}$  or the net rate of heat generation  $Q_{X,i,\lambda}$  for each radiation element is given arbitrarily as a boundary condition. The unknown  $Q_{X,i,\lambda}$  and  $Q_{T,i,\lambda}$  can be obtained by solving Eq. (9) using the method described previously.  $Q_{J,i,\lambda}$  is eliminated from Eq. (9) and the relation between  $Q_{T,i}$  and  $Q_{X,i}$  is obtained

$$Q_X = Q_T - F^A Q_J \quad \text{with } Q_T = Q_J \quad (10)$$

Then

$$\begin{aligned} Q_X &= Q_T - F^A Q_T \\ Q_X &= Q_T [1 - F^A] \end{aligned} \quad (11)$$

The total net rate of heat generation is given by

$$Q_{X,i} = \int_0^\infty Q_{X,i,\lambda} d\lambda \quad (12)$$

The heat generation rate per unit volume is

$$q_{X,i} = Q_{X,i} / V_i \quad (13)$$

$V_i$  is the volume of the radiation element and  $V_i = A_i$  for a surface element.

Heat generation rate per unit volume by radiation means the divergence of radiative heat flux. Thereby, the radiative heat flux at position  $x_n$ , is calculated as

$$q_{X,\lambda} = \nabla \vec{q}_{r,\lambda} = \frac{\partial q_{r,\lambda}}{\partial x} \quad (14)$$

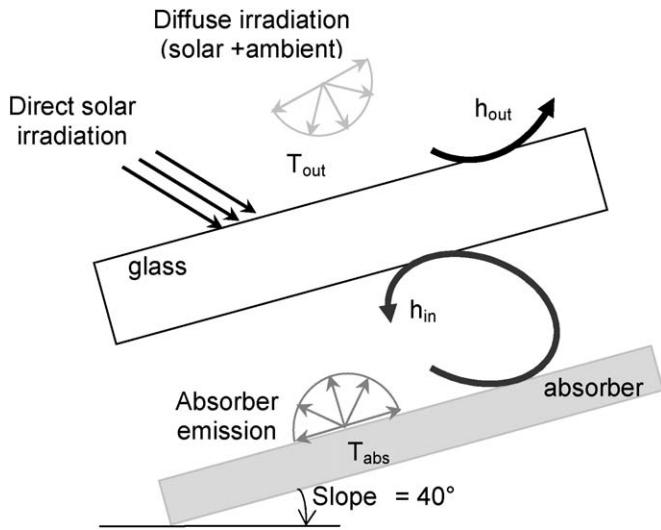


Fig. 8. Analysis model of solar collector subjected to solar and thermal irradiations.

The radiation heat flux through the layer is derived as

$$q_{r,\lambda}(x) = q_{X,1} + \sum_{i=2}^n (q_{X,\lambda,i} \Delta x_i) \quad (15)$$

$q_{X,1}$  includes the blackbody emission emanating from the ambient, and the diffuse and direct solar radiation components. In  $REM^2$ , diffuse or collimated irradiation at the boundary surface can be treated.

**Collimated irradiation.** When the participating medium is exposed to collimated irradiation flux,  $q_c$ , through boundary surface 1 with an incident angle  $\theta_0$ , the parameters in Eq. (5) are set as

$$\mu_1 = \cos \theta_0, \quad w_1 = \pi, \quad K = 1, \quad \varepsilon_1 = 1 \quad (16)$$

**Diffuse irradiation.** When the layer is subjected to diffuse heat flux,  $q_d$ , ray emission at surface boundary 1 is analyzed using the directions and weights given in discrete ordinate method as reported by Maruyama [11].

### 2.6. Conduction and convection heat transfer

Fig. 8 shows the solar collector system subjected to collimated and diffuse solar and thermal irradiation. The one-dimensional unsteady conductive heat transfer through the glass layer is given by

$$\rho_g c_p \frac{\partial T}{\partial t} = \Lambda_g \frac{\partial^2 T}{\partial x^2} + S_h \quad (17)$$

where  $\rho_g$ ,  $c_p$ ,  $\Lambda_g$ ,  $t$  and  $S_h$  are the density of the glass, specific heat of the glass, thermal conductivity of the glass, time and the heat generation source, respectively. The convection is taken into account as boundary conditions at both sides of the glass. The outside convective heat transfer coefficient  $h_{out}$  is calculated using the empirical equation proposed by Watmuff and reported by Agarwal and Larson [12]

$$h_{out} = 2.8 + 3v \quad (18)$$

Table 4  
Data used to compute  $h_{in}$

Parameter	Value	Unit
$Pr$	0.7	[-]
$th_{air}$	0.04	[m]
$A_{air}$	0.028	$[W \cdot m^{-1} \cdot K^{-1}]$
$\nu$	19.5e-6	$[m^2 \cdot s^{-1}]$
$\beta$	40	$[^\circ]$

where  $v$  is the wind velocity in the vicinity of the system.

The convective heat transfer coefficient between the glass and the absorber  $h_{in}$  is determined by the following equations, assuming the natural convection of the air between two parallel planes [2]

$$h_{in} = \frac{Nu \Lambda_{air}}{l_{air}} \quad (19)$$

where  $\Lambda_{air}$  and  $l_{air}$  are the thermal conductivity and the thickness of the air layer between the glass and the absorber, respectively. The *Nusselt* number,  $Nu$ , is given by the following relation [2]

$$Nu = [0.06 - 0.017(\beta/90)] Gr^{1/3} \quad (20)$$

where  $\beta$  is the slope.

The *Prandtl* number,  $Pr$ , is included in the above equation and assumed to be independent of temperature and taken equal to 0.7 [2].

The *Grashof* number is given as

$$Gr = \frac{g |T_{abs} - T_0(nl)| l_{air}^3}{\nu^2 T_{air}} \quad (21)$$

where  $g$ ,  $\nu$  and  $T_{air}$  are the acceleration due to the gravity, kinematic viscosity of the air between the absorber and the glass-cover and temperature of the air between the absorber and the glass-cover, respectively.  $T_{abs}$  and  $T_0(nl)$  are the absorber and the absorber side of glass temperatures, respectively. The data used in the present study to compute the inside convective heat transfer coefficient is given by Table 4.

In the combined radiative and conductive heat transfer analysis, Eq. (17) is discretized using the finite volume method [13]. At first, for a given initial temperature distribution, the radiation heat generation rate per unit volume and the convective heat flux from ambient air are calculated. Then, these values are substituted as the source term  $S_h$ , or considered as the boundary condition of Eq. (17). Next, the temperature distribution after some interval is obtained using the fully implicit method. The same calculation is carried out for the next temperature distribution until the steady-state condition is achieved.

### 3. Results and discussion

The effect of the thickness is clearly shown in Fig. 9. Increasing the thickness of the glass cover from 3 mm to 6 mm the steady heat flux through the cover decreases slightly at low and high temperature of the absorber. Even though, the differences are small, 3 mm is more suitable with regard to the cost and the weight of the solar collector system compared with 6 mm thickness.

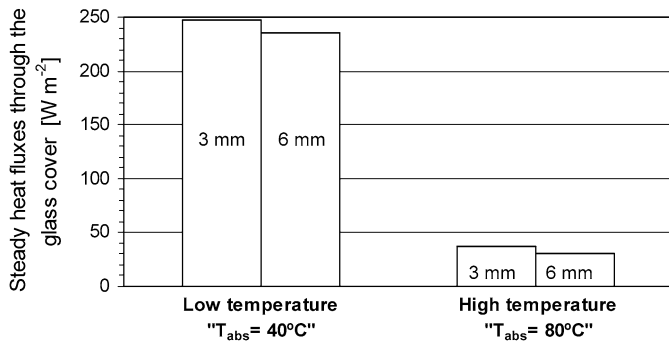


Fig. 9. Steady heat fluxes through the solar collector glass cover with 3 mm and 6 mm thickness.

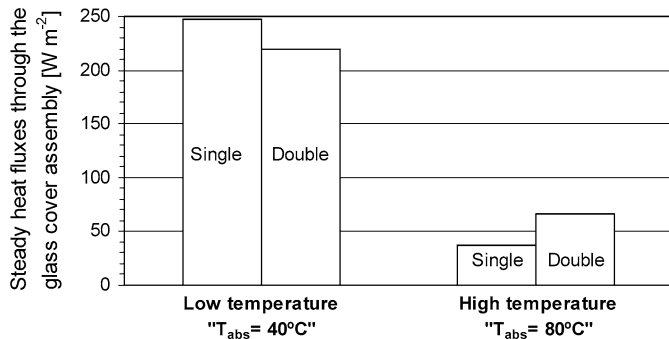


Fig. 10. Steady heat fluxes through the solar collector single and double glazing covers assembly.

Fig. 10 shows the steady heat fluxes through the single glass cover and the double-glazing covers assembly. At low temperature of the absorber, the steady heat flux through the single glass cover is higher than that obtained with double-glazing. At high temperature of the absorber, the double-glazing is more suitable rather than single glass. This result was expected since at high temperature of the absorber the emissive power emanating from the black absorber is too high. Therefore, the double-glazing prevents better the heat loss from the absorber to the surroundings than the single glass cover. Such configuration is more opaque for the infrared radiation rather than the single glazing.

#### 4. Concluding remarks

A more accurate modelling of a solar collector single and double glass cover system using rigorous radiative model has been presented. A non-gray computation procedure taking into account the absorption and emission within a glass layer is

proposed. Stead-state heat flux has been examined for a solar collector glass-cover subjected to solar and thermal radiation.

The thickness of the glass cover affects the heat flux through the cover. In fact, increasing the thickness of the glass cover the steady heat flux decreases.

It has been shown also that using double-glazing, the steady heat flux through the glass cover assembly is higher at high temperature of the absorber compared with single glass cover. However, at low temperature of the absorber the single glass cover is better.

#### References

- [1] J.R. Howell, B.B. Bannerot, G.C. Vliet, *Solar-Thermal Energy Systems. Analysis and Design*, McGraw-Hill, New York, 1982, pp. 122–129.
- [2] J.A. Duffie, W.A. Beckman, *Solar Energy Thermal Process*, John Wiley & Sons, New York, 1974, pp. 108–119.
- [3] R.E. Bird, C. Riordan, Simple solar spectral model for direct and diffuse irradiance on horizontal and tilted planes at the earth's surface for cloudless atmospheres, *J. Climate Appl. Meteorology* 25 (1986) 87–97.
- [4] S. Maruyama, T. Aihara, Radiation heat transfer of arbitrary three-dimensional absorbing, emitting and scattering media and specular and diffuse surfaces, *J. Heat Transfer* 119 (1997) 129–136.
- [5] M. Khoukhi, S. Maruyama, S. Sakai, M. Behnia, Combined non-gray radiative and conductive heat transfer in solar collector glass cover, *Solar Energy* 75 (2003) 285–293.
- [6] H.L. Kong, R. Viskanta, Comparison of the diffusion approximation and the discrete ordinates method for the investigation of heat transfer in glass, *Glastech. Ber. Glass Sci. Technol.* 72 (8) (1999) 254–265.
- [7] C.M. Spuckler, R. Siegel, Refractive index effects on radiation behaviour of heated absorbing-emitting layer, *J. Thermophys. Heat Transfer* 6 (4) (1992) 596–604.
- [8] C.H. Ho, N. Ozisik, Combined conduction and radiation in two-layer planar medium with flux boundary condition, *Numer. Heat Transfer* 11 (1987) 321–340.
- [9] M. Khoukhi, S. Maruyama, S. Bosi, A. Komiya, M. Behnia, A new simple approach for calculating the optical constants of a clear glass window from 0.19 to 5  $\mu\text{m}$ , in: *Official Proceedings of the 29th Annual National Conference of the Solar Energy Society of Canada Inc.*, August 21–25, University of Waterloo, Waterloo, ON, Canada, CD-ROM, WIN-05, 2004.
- [10] M. Rubin, Optical properties of soda lime silica glasses, *Solar Energy Materials* 12 (1985) 275–288.
- [11] S. Maruyama, Radiative heat transfer in a layer of anisotropic scattering fog subjected to collimated irradiation, in: *Radiative Transfer—II, Proceedings of the Second International Symposium on Radiation Transfer*, 1997, pp. 157–172.
- [12] V.K. Agarwal, D.C. Larson, Calculation of the top loss coefficient of a flat-plate collector, *Solar Energy* 27 (1981) 69–77.
- [13] S.V. Patankar, *Numerical Heat Transfer and Fluid Flow*, Hemisphere, Washington, DC, 1980, pp. 41–74.