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Non-gray calculation of plate solar collector with low iron glazing taking into account the absorption and emission with a glass cover

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Abstract

A new theoretical approach of black flat-plate solar collector considering the glass cover as a participating media taking into account the absorption and emission within a glass cover is presented. Two kinds of glasses commonly used as cover for such system, clear and low iron, have been studied. The glass material is analyzed as a non-gray plane parallel medium subjected to solar and thermal irradiations in one-dimensional case using the Radiation Element Method by Ray Emission Model. The optical constants of the complex refractive index, 160 values of real part (*n*) and imaginary part (*k*), of a clear and low iron glasses proposed by Rubin covering the range of interest for solar and thermal calculation have been used. The CPU times for predicting the thermal behavior of a solar collector using non-gray models were found to be prohibitively long. Therefore, suitable semi-gray models have been proposed for rapid calculation. In order to compare the thermal performance of solar collector having low iron glass as a cover with the solar collector having clear glazing, the previous result concerning the clear glass cover will be presented again. It has been also shown that the instantaneous efficiency of the solar collector with a low iron glass cover is higher than the efficiency of the system with clear glass cover.

Keywords: Plate solar collector; Glass cover

1. Introduction

Glass is considered quite interesting as a cover for solar thermal devices, particularly for a solar collector, because it absorbs almost all the infrared radiation re-emitted by the black absorber plate. Indeed, the glass material is strongly absorbing at long wavelength. However, the assumption that the glass is completely opaque for the infrared wavelength is still not exact due to the strong variation of the imaginary part of the complex refractive index of the glass,

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which is characterized by two bands of strong absorption around 9.5 and 21.5 μm, and which affect seriously the temperature distribution and heat flux through the glass cover [1].

On the other hand, almost all the classical studies assume that the solar collector glass cover is transparent for the visible and near infrared, and the thermal properties, such as reflectance and absorbance, are wavelength independent [2,3]. Actually, all the thermal properties are functions of wavelength and strongly depend on the optical constants of the complex refractive index *n* and *k* of the glass material. Moreover, *n* and *k* are spectrally dependent [1,4].

In the previous work, the authors presented a new theoretical approach of a flat-plate solar collector with a clear glass cover [4]. The work presented here is an extension of the previous one. In fact, nowadays, the clear glass is being replaced by the low iron one.

In the present work, a classical flat-plate solar collector with a black absorber having a low iron glass cover is considered. The glass cover is treated as a participating non-gray media subjected to solar radiation, specified by the spectral solar model for cloudless atmosphere presented by Bird and Riordan [5], and thermal radiation emanating from the black absorber and from the outside environment which is also considered to be black. The absorption and emission within the low iron glass cover are taken into account using 160 values of the real part *n* and imaginary part *k* of the complex refractive index. These optical constants are proposed by Rubin [6], and cover the range of solar and thermal radiation (0.3–300 μm). The boundary surfaces of the glass cover are specular, and the spectral dependence of the radiation properties is all taken into account. A more refined and rigorous approach is applied using Radiation Element Method by Ray Emission Model (REM^2). REM^2 is a generalized method for calculation of radiation heat transfer between absorbing, emitting and scattering media [7].

The calculation has been performed for one position of the sun chosen at noon on the first February in Sendai city (Japan). The back and lateral heat losses are assumed to be negligible.

The simulation has been carried out using 160 values of *n* and *k* of low iron glass material. Temperature distribution and steady heat flux through the glass cover have been obtained. Using non-gray model (NG) with 160 values of *n* and *k*, the CPU time consumed was found to be prohibitively long, around 17 h on personal computer (VT-Alpha 600, 21164 A, 600 MHz). Therefore, a simplified semi-gray model (SG) has been proposed. Steady heat flux and temperature distribution have been obtained in case of SG model and compared with the NG one. The steady heat flux, the mean glass cover temperature and the instantaneous efficiency of the solar collector with low iron glass cover were compared with those obtained with clear one.

2. Analysis model

The important parts of a typical flat plate solar collector as shown in Fig.1 are the black solar energy-absorbing surface, with means for transferring the absorbed energy to a fluid; a glass cover which reduce convection and radiation losses to the atmosphere; and back and lateral

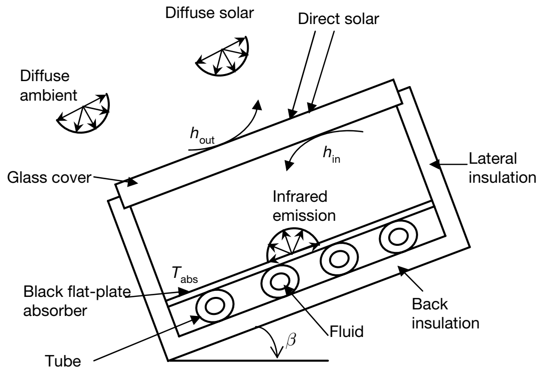

Fig. 1. Flat-plate solar collector subjected to solar and thermal irradiations.

insulation to reduce the conduction losses as the geometry of system permits. In the present study, the back and lateral conduction losses are assumed to be negligible.

3. Radiation transfer through the glass cover

The glass cover is considered as a participating media subjected to collimated solar and diffuse solar and thermal irradiations (see Fig. 2). The convection is taken into consideration at both sides of the glass. The cover is discretized to the thin radiation element, and we assume that each radiation element is at constant uniform temperature, and the real part of the complex refractive index n and heat generation rate per unit volume are also constant and uniform throughout the element. The scattering is neglected and the thermal conductivity of the glass is assumed to be constant.

The heat transfer rate at which radiation energy is emitted by the radiation element is given by the following expression [7]:

$$Q_{J,i,\lambda} = A_i^R \left(\varepsilon_i n^2 \sigma T_i^4 + \Omega_i^D G_{i,\lambda} \right) \tag{1}$$

where ε_i, n, s and T_i are the glass emissivity, real part of the complex refractive index of the glass cover, Stefan-Boltzman constant and temperature, respectively. Ω_i^D is the albedo of the volume element or diffuse of surface element as defined by the reference [7], and $G_{i,\lambda}$ is the spectral irradiance on radiation element i. A_i^R is the effective radiation area [7].

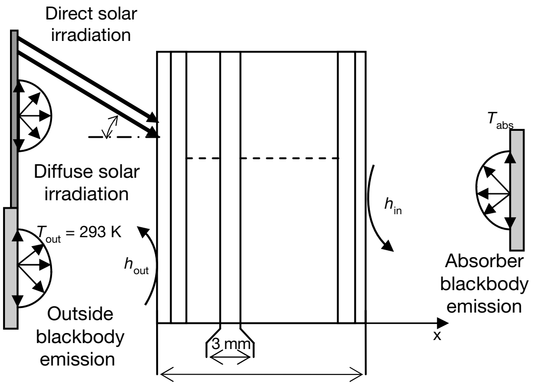

Fig. 2. Analysis model of a solar collector glass cover.

The net rate of heat generation can be derived from the heat balance on the radiation element [7]:

$$Q_{X,i,\lambda} = A_i^R \varepsilon_i \left(n^2 \sigma T_i^4 - G_{i,\lambda} \right) \tag{2}$$

As it was previously mentioned, the scattering is neglected, i.e. $\Omega_i^D = 0$. Therefore the heat transfer rate of diffuse radiosity, $Q_{J,i,\lambda}$, is equal to the heat transfer rate of emissive power, $Q_{T,i,\lambda}$, defined as follows [7]:

$$Q_{T,i,\lambda} = A_i^R \varepsilon_i n^2 \sigma T_i^4 \tag{3}$$

If the system is consisted of N volume and surface elements (N-2 participating layers and 2 boundary surfaces), the Eqs. (1) and (2) can be rewritten as [7]:

$$\begin{aligned} Q_{J,i,\lambda} &= Q_{T,i,\lambda} \\ Q_{X,i,\lambda} &= Q_{T,i,\lambda} - \sum_{j=1}^{N} F_{j,i}^A Q_{J,i,\lambda} \end{aligned} \tag{4}$$

in which the absorption view factor, $F_{j,i}^{\mathrm{A}}$, is introduced as defined by Maruyama and Aihara [7]. The heat transfer rate of spectral emissive power, $Q_{T,i,\lambda}$, or the net rate of heat generation, $Q_{x,i,\lambda}$, for each radiation element is given as a boundary condition [7,8]. The unknown $Q_{T,i,\lambda}$ or $Q_{x,i,\lambda}$ can be obtained by solving Eq. (4).

The total net rate of heat generation is given by:

$$Q_{X,i} = \int_0^\infty Q_{X,i,\lambda} \mathrm{d}\lambda \tag{5}$$

The heat generation rate of the radiation per unit volume or unit surface area is expressed as

$$q_{x,i} = Q_{X,i} / V_i \tag{6}$$

where V_i is the volume of volume element or the surface area of surface element.

The radiation heat flux through the layer is derived as [7]:

$$q_{r,\lambda}(x) = q_{X,1} + \sum_{i=2}^{n} \left(q_{X,\lambda,i} \Delta x_i \right) \tag{7}$$

$q_{x,1}$ includes the blackbody emission emanating from the ambient, and the diffuse and direct solar radiation components. Δx_i is the element thickness (see Fig. 2).

3.1. Convective heat transfer coefficients

The convection is taken into account at both sides of the glass cover assuming the outside convective heat transfer coefficient h_{out} in term of wind speed calculated using the empirical equation proposed by Watmuff et al. [9]:

$$h_{\text{out}} = 2.8 + 3v \tag{8}$$

where, v is the wind speed in ms^{-1}.

The convective heat transfer coefficient between the glass and absorber, h_{in}, is evaluated using the equations expressed by Duffie and Beckman [2], assuming the natural convection of the air between two parallel planes:

$$h_{\text{in}} = \frac{Nu \Lambda_{\text{air}}}{e_{\text{air}}} \tag{9}$$

Λ_{air} and e_{air} are the thermal conductivity and the thickness of the air layer between the glass and the absorber, respectively.

The *Nusselt* number is given by the following relation:

$$Nu = \left[0.06 - 0.017 \left(\beta / 90 \right) \right] Gr^{1/3} \tag{10}$$

β is the solar collector tilt angle in degrees.

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

The *Grashoff* number is:

$$Gr = \frac{g \left| T_{\text{abs}} - T_{\text{o}}(nl) \right| e_{\text{air}}^3}{\nu^2 T_{\text{air}}} \tag{11}$$

T_{abs} and $T_{\text{o}}(nl)$ are the absorber temperature and the absorber-side of glass temperature, respectively. T_{air} is assumed to be equal to the average temperature between the flat absorber and the absorber-side glass cover.

The one-dimensional unsteady conductive heat transfer through the glass layer is given by:

$$\rho c_p \frac{\partial T}{\partial t} = \Lambda_g \frac{\partial^2 T}{\partial x^2} + S_h \tag{12}$$

where ρ, c, Δ_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.

4. Results and discussion

The calculation has been carried out at noon on the first February in Sendai city (Japan). The site characteristics and other parameters used in

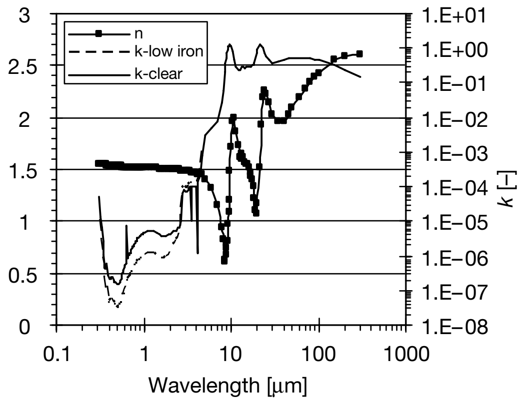

Fig. 3. Real part (n) and imaginary part (k) of the complex refractive index of clear and low iron glasses, non-gray models.

Table 1
Characteristics of the site and other parameters used in numerical simulation

Parameter	Value	Unit
Zenith angle (ζ)	55.47	°
Latitude	38.16	°
Longitude	140.51	°
Altitude	45.0	m
Day of year	32	–
Wind speed velocity	1.5	ms^{-1}
Ambient temperature	293	K

numerical simulation are given in Table 1. The solar collector is simulated in steady state varying the mean absorber plate temperature. In order to compare the thermal performance of solar collector having low iron glass cover with that having clear glass cover, the previous results of solar collector with clear glass cover have been presented again [4].

Fig. 3 shows the spectral variation of the optical constants *n* and *k* for clear and low iron glasses in case of NG models. The curve of the real part *n* of the complex refractive index is similar for both clear and low iron glasses. Low iron glass, which contains less iron oxides in the raw materials, produce less absorption in the visible and near infrared (0.3–5 µm). Indeed, the curve of *k* for low iron glass is smaller than that for clear glass in the range of 0.3–5 µm. On the other hand, *k* values are the same for clear and low iron glasses in the infrared range.

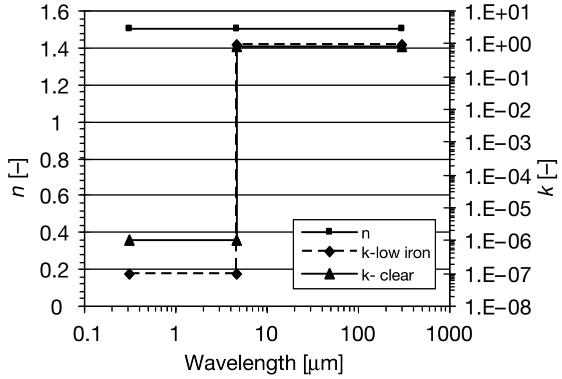

Fig. 4. Real part (*n*) and imaginary part (*k*) of the complex refractive index of clear and low iron glasses, semi gray models.

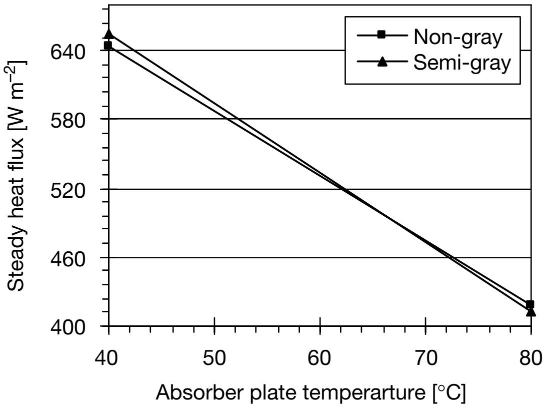

Fig. 5. Steady heat fluxes through the glass cover using non-gray and semi-gray models for T_{abs} equal to 40 and 80°C.

Fig. 4 shows the optical constants of clear and low iron glasses in case of SG models.

Fig. 5 shows the steady heat fluxes through the low iron glass cover obtained both with NG and SG models at 40 and 80°C of the mean absorber plate temperature (T_{abs}). At low temperature of the absorber (40°C), the steady heat flux obtained in case of SG model is higher than that obtained with NG one. At high temperature of the absorber (80°C), the steady heat flux obtained with NG model is slightly higher than that obtained with SG one.

Fig. 6 shows the temperature distributions of through the low iron glass cover. The result shows that the temperature distributions within the glass cover calculated by the NG model are higher than those obtained with SG one at low and high mean temperatures of the absorber. This is essentially due to the strong absorption (high value of *k*) within the glass layer when using NG model.

Fig. 7 shows the ratio *R*, which is defined as the rate of the CPU time consumed by the SG model to the CPU time consumed by NG one, and the absolute deviations of the steady heat fluxes

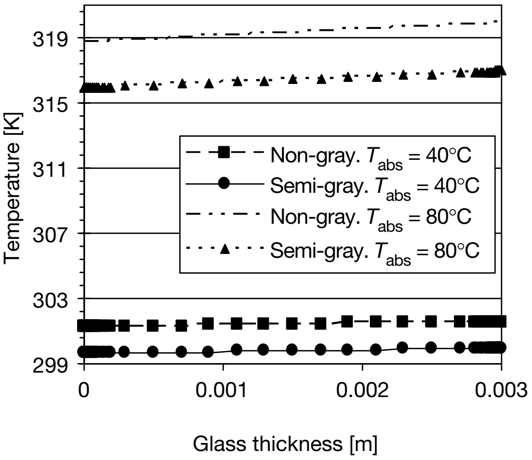

Fig. 6. Temperature distributions within a glass cover layer using non-gray and semi-gray models for T_{abs} equal to 40 and 80°C.

and the average glass cover temperatures in case of SG model from the NG one. The figure shows that the CPU times are considerably reduced to 3.1 and 4.1% for T_{abs} equals to 40°C and 80°C, respectively. The absolute deviation of the steady heat fluxes when using SG from the NG one are 1.7 and 1.3% for 40 and 80°C of T_{abs}, respectively. The absolute deviation of the average glass cover temperatures in case of SG model from the NG one are 0.5 and 0.9% for T_{abs} equals to 40 and 80°C, respectively. Therefore, it can be concluded that SG model is suitable for a rapid calculation with the accuracy still being satisfactory.

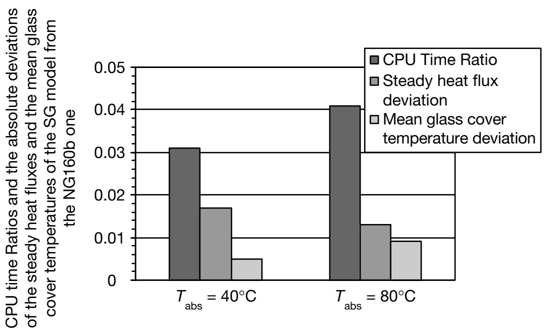

Fig. 7. Comparison of CPU time ratios and absolute deviations of the steady heat fluxes and mean temperatures of glass cover calculated using SG model from NG one.

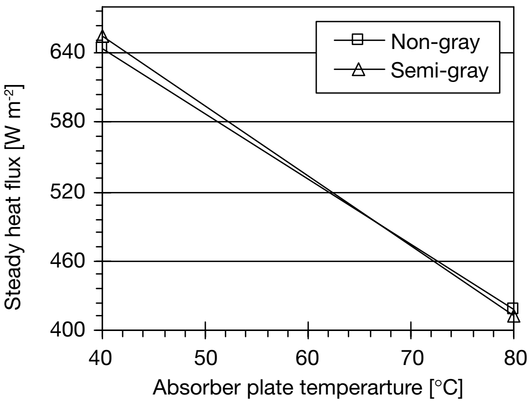

Fig. 8. Steady heat fluxes obtained with SG temperatures models for both clear and low iron glass cover and low as a function of the mean absorber temperature.

Fig. 8 shows the steady heat fluxes obtained with SG model for both clear and low iron glasses in term of the mean absorber temperature. In case of low iron glass, the steady heat fluxes are higher than those obtained with clear glass. This is due to the low value of k in short wavelength in case of low iron glass. Therefore, for strong absorption (case of clear glass), the amount of the heat flux through the glass is reduced.

Fig. 9 shows the mean glass cover temperature for both clear and low iron glasses as a

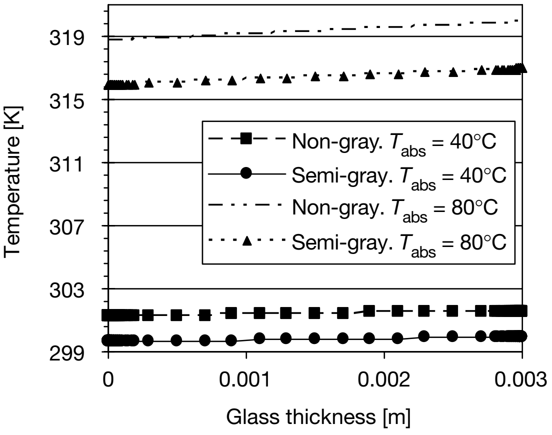

Fig. 9. Mean glass cover obtained with SG models for clear iron glass cover in term of mean plate absorber temperature.

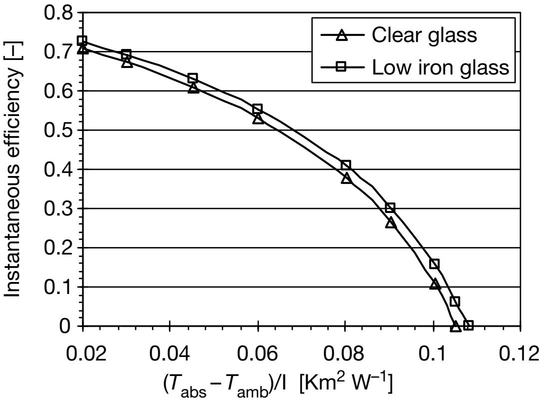

Fig. 10. Instantaneous efficiencies of the solar collector using clear and low iron glass cover versus $(T_{abs}–T_{amb})$/I.

function of T_{abs}. One can see that in case of clear glass the mean glass cover is higher than that obtained with low iron glass.

Fig. 10 presents the instantaneous efficiencies of the solar collector with both clear and low iron glass covers. It has been shown in the previous work [4] that the efficiency curve was found to be not linear in shape, due to the non linearity of the convective and radiative heat losses from the collector. The result shows that the solar collector with low iron glass has a higher efficiency, because the amount of the steady heat flux traveling through the glass cover is higher in case of low iron glass.

5. Conclusion

A non-gray calculation procedure taking into account the absorption and emission within the solar collector low iron glass cover using the radiation element method by ray emission model is proposed. Steady heat flux and temperature distribution have been obtained using 160 values of the optical constants of low iron glass material, covering the short and long wavelength.

The CPU time consumed in case of NG model was found to be prohibitively long. Therefore, a simplified SG model has been proposed and found to be suitable for rapid simulation with a very high level of accuracy. The mean clear glass temperatures were found to be higher than those obtained for the low iron glass. Using SG model for both clear and low iron glass covers, the steady heat fluxes, in case of low iron glass, were found to be higher than those obtained for clear glass cover. Consequently, the instantaneous efficiency of the system is higher in case of low iron glass cover.

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