

## **New Theoretical Approach of Flat Plate Solar Collector Considering the Glass Cover as a Participating Media Subjected to Solar and Thermal Radiations**

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### **ABSTRACT**

*A new theoretical approach of black flat-plate solar collector considering the glass cover as a participating media and 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 represented by Ray Emission Model. The optical constants of the complex refractive index, considering 160 values the pair of real part ( $n$ ) and imaginary part ( $k$ ), of a clear and low iron glasses reported 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 (SG) models have been proposed for rapid calculation. We should mention that the results presented here are related to the low-iron glass. However, the instantaneous efficiency of the solar collector with low iron glass cover was compared with that obtained with clear one using SG models. It has been shown that the effect of the non-linearity of the radiative heat exchange, between the black plate absorber and the surroundings on the shape of the instantaneous efficiency curve is important. Indeed, the thermal loss coefficient is not constant but is function of temperature; due primarily to the radiative transfer effect. Therefore, when the heat exchange by radiation is dominant compared with the convective mode, the profile of the efficiency curve is not linear. 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. It increases by approximately 8%.*

### **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, which is characterized by two bands of strong absorption around 9.5 and 21.5  $\mu\text{m}$ , and which affect seriously the temperature distribution and heat flux through the glass cover (Khoukhi et al., 2003).

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 (Duffie and Beckman, 1974) and (Howell et al., 1982). 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 (Khoukhi et al., 2003).

In the present work, a classical flat-plate solar collector with a black absorber 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 (Bird and Riordan, 1986), 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 glass covers are taken into account using 160 values of the real part  $n$  and imaginary part  $k$  of the complex refractive index. These optical constants have been reported by Rubin (Rubin, 1985) and cover the range of solar and thermal radiation (0.3 to 300  $\mu\text{m}$ ). 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<sup>2</sup>). REM<sup>2</sup> is a generalized method for calculation of radiation heat transfer between absorbing, emitting and scattering media (Maruyama and Aihara, 1997).

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  $k$  for both clear and low iron glass materials. Temperature distribution and steady heat flux through the glass covers have been obtained. Using non-gray models (NG) with 160 values of  $n$  and  $k$ , the CPU time consumed were found to be prohibitively long, around 17 hours on Personal Computer (VT-Alpha 600, 21164 A, 600 MHz) for both clear and low-iron glasses. Therefore, simplified semi-gray models (SG) have been proposed. Steady heat flux and temperature distribution have been obtained in case of SG models and compared with the NG ones. We should mention that the results presented here are related to the low-iron glass. However, the instantaneous efficiency of the solar collector with low iron glass cover was compared with that obtained with clear one using SG models.

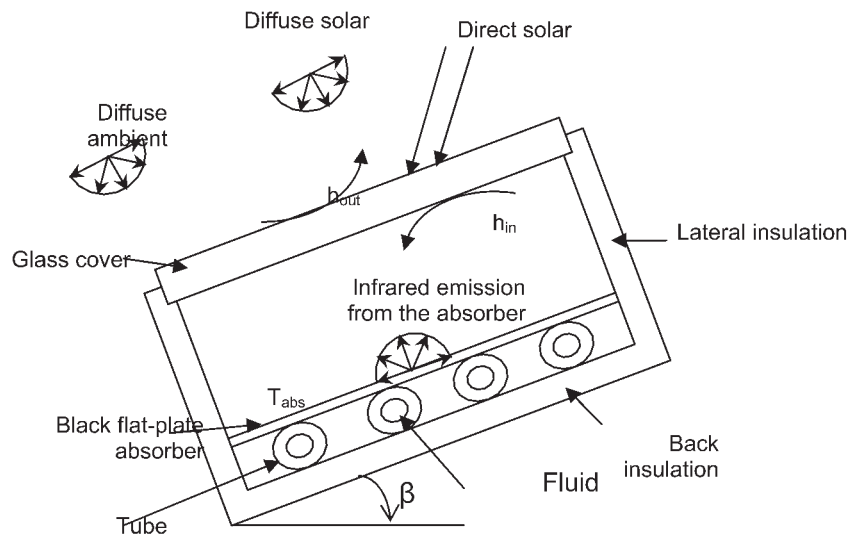


Figure 1. Flat-plate solar collector subjected to solar and thermal irradiations.

### ANALYSIS MODEL

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

### RADIATION TRANSFER THROUGH THE GLASS COVER

The glass cover is considered as a participating media subjected to collimated solar and diffuse solar and thermal irradiances (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.

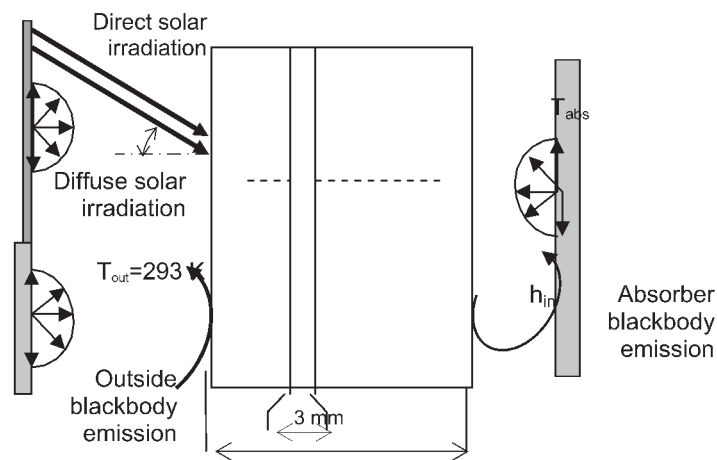


Figure 2. Analysis model of a solar collector glass cover

The heat transfer rate at which radiation energy is emitted by the radiation element is given by the following expression (Maruyama and Aihara, 1997) (MA)

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

where  $\varepsilon_i$ ,  $n$ ,  $\alpha$  and  $T_i$  are the glass emissivity, real part of the complex refractive index of the glass cover, Stefan-Boltzman constant and temperature, respectively.  $\Omega_i^D$  is the albedo of the volume element or diffuse of surface element as defined by (MA), and  $G_{i,\lambda}$  is the spectral irradiance on radiation element  $i$ .  $A_i^R$  is the effective radiation area (Maruyama and Aihara, 1997).

The net rate of heat generation can be derived from the heat balance on the radiation element

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

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

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

If the system is consisted of  $N$  volume and surface elements ( $N-2$  participating layers and 2 boundary surfaces), the equations (1) and (2) can be rewritten as (MA)

$$Q_{J,i,\lambda} = Q_{T,i,\lambda} \quad (4)$$

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

In which the absorption view factor,  $F_{j,i}^A$ , is introduced as defined by MA. 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 (MA and Maruyama, 1998)). The unknown  $Q_{T,i,\lambda}$  or  $Q_{X,i,\lambda}$  can be obtained by solving equation (4). The total net rate of heat generation is given by

$$Q_{X,i} = \int_0^{\infty} Q_{X,i,\lambda} d\lambda \quad (5)$$

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

$$q_{X,i} = Q_{X,i} / V_i \quad (6)$$

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:

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

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

### CONVECTIVE HEAT TRANSFER COEFFICIENTS

The convection is taken into account at both sides of the glass cover assuming the outside convective heat transfer coefficient  $h_{out}$  to be taken in term of wind speed velocity calculated using the empirical equation proposed by Watmuff and reported by Agarwal and Larson (1981), where

$$h_{out} = 2.8 + 3v \quad (8)$$

$v$  is the wind speed in  $m s^{-1}$ . The convective heat transfer coefficient between the glass and absorber,  $h_{in}$ , can be evaluated using the equations expressed by Duffie and Beckman (1974), assuming the natural convection of the air between two parallel planes

$$h_{in} = \frac{Nu \Lambda_{air}}{e_{air}} \quad (9)$$

$\Lambda_{air}$  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

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

$\beta$  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.

The *Grashoff* number is

$$Gr = \frac{g|T_{abs} - T_o(nl)|e^3}{v^2 T_{air}} \tag{11}$$

$T_{abs}$  and  $T_o(nl)$  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  $\rho$ ,  $c_p$ ,  $\Lambda_g$ ,  $t$  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.

**RESULTS AND DISCUSSION**

The calculation has been carried out at noon on the first of February in Sendai city (Japan). The site characteristics and other parameters used in numerical simulation are given in Table. The solar collector is simulated in steady state varying the mean absorber plate temperature.

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

<i>Parameter</i>	<i>Value</i>	<i>Unit</i>
Zenith angle ( $\zeta$ )	55.47	°
Latitude	38.16	°
Longitude	140.51	°
Altitude	45.0	m
Day of year	32	-
Wind speed velocity	1.5	m s <sup>-1</sup>
Ambient temperature	293	K

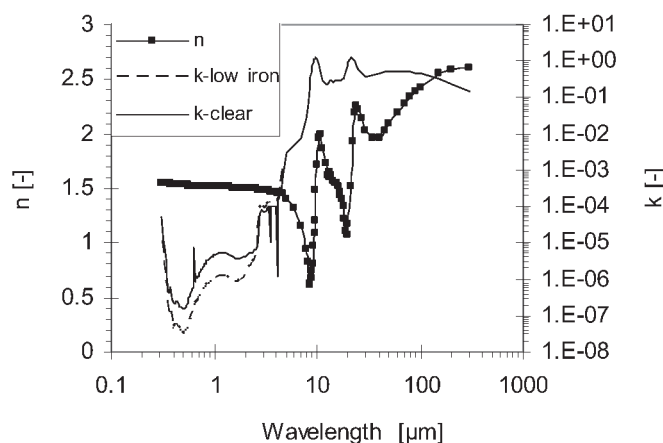


Figure 3. Real part ( $n$ ) and imaginary part ( $k$ ) of the complex refractive index of clear and low iron glasses, non-gray models

Fig. 3 shows the spectral variation of the optical constants  $n$  and  $k$  for clear and low iron glasses in case of nongray (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 to 5  $\mu\text{m}$ ). Indeed, the curve of  $k$  for low iron glass is smaller than that for clear glass in the range of 0.3 to 5  $\mu\text{m}$ . On the other hand,  $k$  values are the same for clear and low iron glasses in the infrared range.

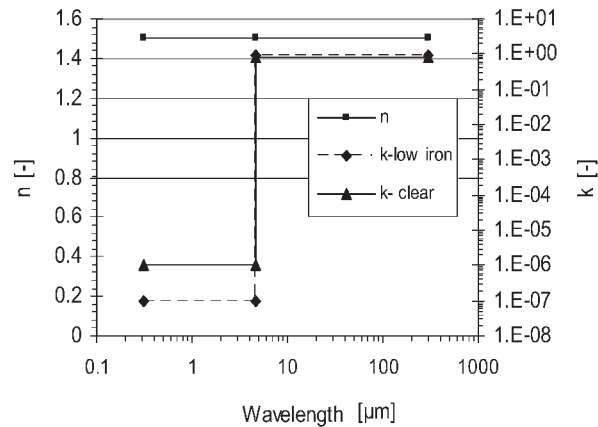


Figure 4. Real part ( $n$ ) and imaginary part ( $k$ ) of the complex refractive index of clear and low iron glasses, semi gray models.

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°C and 80°C of the mean absorber plate temperature ( $T_{\text{abs}}$ ). 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.

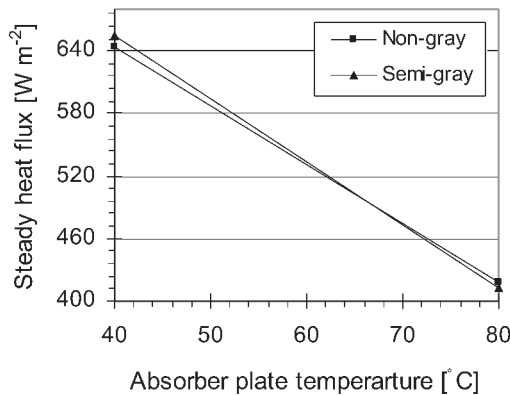


Figure 5. Steady heat fluxes through the glass cover using non-gray and semi-gray models for  $T_{\text{abs}}$  equal to 40°C and 80°C.

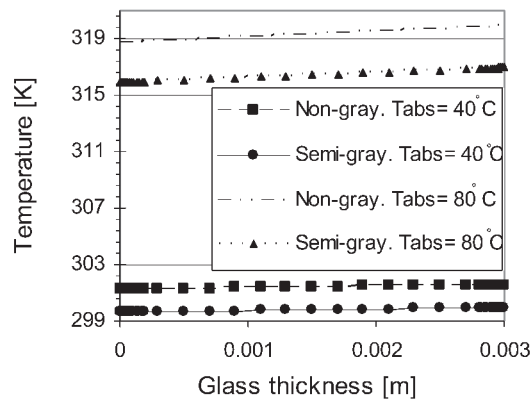


Figure 6. Temperature distributions within a glass cover layer using non-gray and semi- gray models for  $T_{abs}$  equal to 40°C and 80°C.

Fig. 6 shows the temperature distributions 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 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°C 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°C 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. 8 presents the instantaneous efficiencies of the solar collector with both clear and low iron glass covers. The efficiency curves were found to be not linear in shape, due to the non linearity of the radiative heat loss from the absorber. 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.

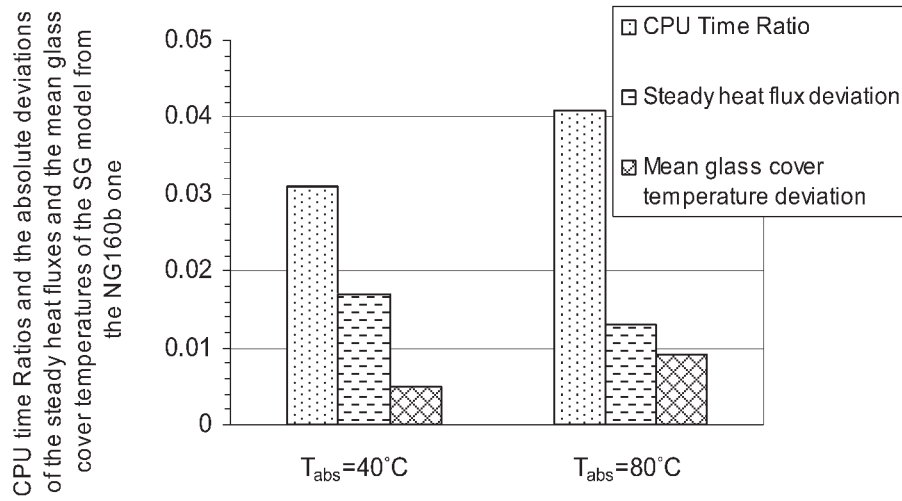


Figure 7. Comparison of CPU time ratios and absolute deviations of the steady heat flux and mean temperatures of glass cover calculated using SG model from NG one.

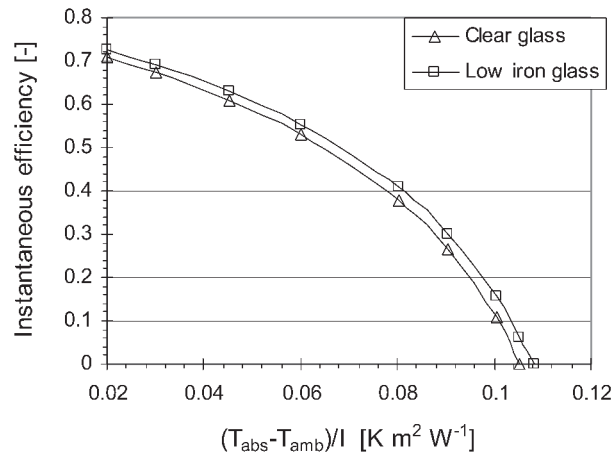


Figure 8. Instantaneous efficiencies of the solar collector using clear and low iron glass cover versus  $(T_{abs}-T_{amb})/I$ .



## CONCLUSION

A non-gray calculation procedure taking into account the absorption and emission within the solar collector with clear and 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 both glasses, covering the short and long wavelength.

The CPU times consumed in case of NG model were found to be prohibitively long for both glasses. Therefore, simplified SG models have been proposed and found to be suitable for rapid simulation with a very high level of accuracy.

It has been shown that the effect of the non-linearity of the radiative heat exchange between the black plate absorber and the surroundings on the shape of the instantaneous efficiency curve is important. Indeed, the thermal loss coefficient is not constant but is function of temperature; due primarily to the radiative transfer effect. Therefore, when the heat exchange by radiation is dominant compared with the convective mode, the profile of the efficiency curve is not linear in shape.

The instantaneous efficiency of the system is higher in case of low iron glass cover compared with clear one using SG models. It increases by approximately 8%.

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## دراسة جديدة للاقط مائي شمسي باعتبار الغطاء الزجاجي كوسط غير رمادي معرض للطاقة الشمسية والحرارية

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### ملخص

يتناول هذا البحث دراسة جديدة للاقط مائي شمسي أخذاً بعين الاعتبار الامتصاص والإشعاع داخل الغطاء الزجاجي. تمت المحاكاة للاقط الشمسي باستخدام نوعين من الزجاج، شفاف عادي وشفاف ذي نسبة منخفضة من الحديد. تم استعمال الثوابت البصرية (n) و (k) لمعامل الانكسار للنوعين. الوقت المستهلك لمحاكاة الجهاز كان طويلاً جداً. لذا تم إنشاء نماذج نصف رمادية لتسريع الحسابات. تم إثبات أن المردودية اللحظية للجهاز، إذا استخدمنا الزجاج ذا النسبة المنخفضة من الحديد، تكون أعلى مقارنة بالزجاج العادي.