RADIATIVE HEAT TRANSFER CONSIDERING THE EFFECT OF MULTIPLE REFLECTIONS IN GREENHOUSE STRUCTURES

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Abstract. *In greenhouse structures, given the major role played by glazing systems with regard to losing and gains of energy in the system, an accurate prediction of the radiative heat transfer through the glazing material and in the interface between cover and ground, it is of great importance in energy simulations involving solar radiation. Note that the solar radiation is not only a function of the extinction coefficient (consequently the transmission coefficient), but also depends on the multiple reflections inside the glazing and between the glazing and its neighborhood. Then the objective of this study is to incorporate multiple reflections in the glazing and its neighborhood analyzing its influence on radiative heat transfer. In this paper, results show that the methods available in literature that use only the multiple reflections on the glass cover can receive 13% less energy, while methods that consider only the transmission coefficient receives approximately 17.5 % more energy than the proposed method in this study, depending on the quality of the glass and the neighborhood reflectance.*

Keywords*: Solar radiation, Solar collector, Greenhouse, Multiple reflections, Glazing, Heat transfer.*

1. INTRODUCTION

Greenhouse structures can be found in many applications nowadays, among them in modern buildings where an assembly called trombe walls is used, to growing horticultural crops and in solar power plants that use collectors (water heating, thermal water pumps, solar thermal power plants, solar chimneys). Greenhouse structures are made with a glass cover and have a surround, where in some cases can be walls, objects, absorbers to collect heat and the ground. In any application, a surround is present, so the interactions between the glass cover and its surroundings must be considered.

The modeling thermal performance of glazing systems is directly related with the glazing properties and the external solicitations, such as the amount of solar radiation arriving at the glass system surface. Glass systems are usually thermally weak systems and are responsible for an important amount of heat losses and gains that can greatly affect the whole useful energy in the system. The accurate thermal analysis of glazing systems is still a challenge, even though the simplified theoretical methods have been available for many years, consisting in the assumption that such systems are transparent for the solar range and opaque for the infrared radiation [1, 2].

A bi-dimensional heat transfer model in a single glass system on a building was presented by Ismail and Henríquez [3], which included an unsteady state behavior (with incident angle and external temperature variable). The results shown the effects of glass thickness on the heat transfer, on the solar heat gain coefficient, and in the shadow coefficient. Khoukhi and Maruyama [4] studied the radiation in glazing systems for solar collectors, including the convective heat transfer between the glass cover and the absorber. It was taken in to account a non-gray surface for make possible the use of ray emission method, and external heat transfer and its influence was studied and compared with radiative heat transfer for different cases of incident radiation.

Various simplifications regarding the treatment of heat transfer through glazing systems are used in current glass energy simulations. In those codes, a resistance network of a small number of nodes is usually adopted and the heat capacity of the glazing is always neglected. For example, in the codes TRNSYS [5] and EnergyPlus [6], the heat transfer through the glazing it is performed using a two node model, i.e., one node per glazing surfaces and half the absorbed solar radiation is imposed at each glazing node.

Zhang et al. [7] studied experimentally and numerically the radiative heat transfer through the thin oxide coated glass, considering the multiple reflections on the surfaces of the glass and the coated layer. That approach generated results that have shown good agreement with experimental data, although they did not cover the interface glass-neighborhood reflections.

Analytical and numerical procedures for the treatment of heat transfer through glazing systems are extremely important on solar collectors. Lecouche and Lalot [8] applied an online identification neural technique to predict the in-situ daily performance of solar collectors using the Laplace transform, reaching an error of 0.5%. Kang et al. [9] studied experimentally the thermal performance of a large solar collector assembly, and the results shown that thermal efficiency of the collector assembly is mainly influenced by geometric and thermal parameters, reaching a difference in the range of 2.5% to 8% depending on the parameter tested. Rchinda and Ngos [10] studied thermal processes in a concentrated solar collector with a flat one-sided absorber. The results shown that the selectively coated collector with one side absorber is more efficient than the black painted absorber with the same conditions.

Kim et al. [11], Turgut and Onur [12] and Akpinar and Koçyiğit [13] performed numerical and experimental investigations of heat transfer in solar collectors with different parameters, but unfortunately, these authors did not consider the effects of multiple reflections in glass cover or between glass cover and the absorber.

A more accurate method for heat transfer in glazing systems was developed by Alvarez et al. [14] and more recently by Powles et al. [15] concerning the absorption of heat in thick and multilayered glass systems, since that in those systems the absorption coefficient was not a constant, like the most methods adopt. The authors concluded that there is a slightly difference between the proposed method and usual methods regarding temperature field and solar gain coefficient, which can be important depending of the application and of the error expected. This is one of the fewer works in literature that concernes about the multiple reflections on glazing materials. Besides a few authors in literacture use the multiple reflections in their studies, the influence of multiple reflections on the interface glass and ground was not taken into account. The impact of those decisions are analysed and discussed in this study.

Although some works presented in literature consider the effects of multiple reflections on the glass system, they not contemple the effects of multiple reflections on glass system and neighborhood. Consequently the main contribution of the present investigation is to report a more accurate method that consider these effects. The main objective of this study is the comparison of the use of multiple reflections on total system with multiple reflections only in the glass cover and without any multiple reflections, in order to evaluate the error induced by such approximation.

2. MATHEMATICAL MODEL

The angle between a solar beam and the vertical component is called zenith angle, θ, and in accordance with Hedderwick [16] can be expressed by:

$$\theta = acos[sen(\emptyset_d)sen(\emptyset_{lat}) + cos(\emptyset_d)\,cos(\emptyset_{lat})\,cos(w)] \tag{1}$$

where $\emptyset_{lat}$ is the latitude angle where the radiation is measured, w is the solar time, noon being zero and every hour is equivalent to 15° of longitude, mornings being positive and afternoons being negative, $\emptyset_d$ is the declination, i.e. the solar angle at noon with respect to equatorial plane (south hemisphere negative), and this declination, according to Hedderwick [16] is given by:

$$\emptyset_d = 23.45\,sen\left(360\,\frac{10+day}{365}\right) \tag{2}$$

where day is the number of days from January 1st.

The transmittance of the glass material is dependent of the extinction coefficient, a property of the glass quality. It also depends of the angle that crosses the glass material, which is function of the zenith angle and of the refraction index of the air and glass media, that in this case it is 1.526. The crossing angle is calculated by:

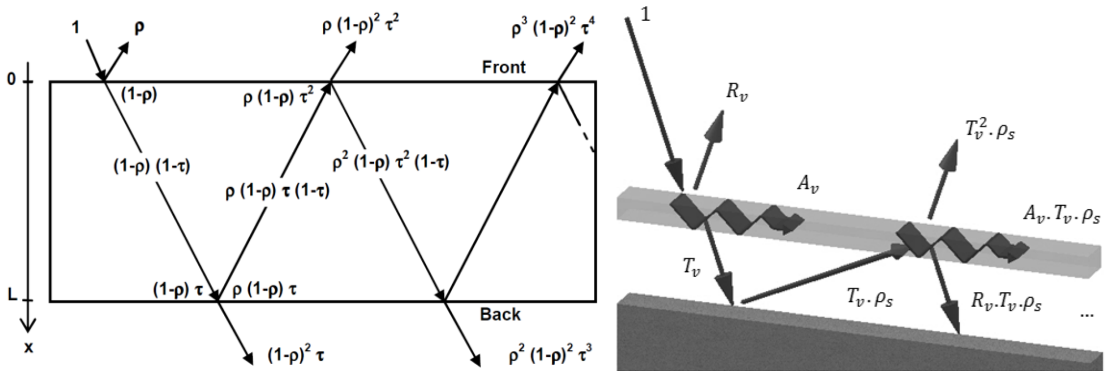
$$\theta_2 = asen\left(\frac{sen(\theta)}{1.526}\right) \tag{3}$$

and the transmittance is given by:

$$\tau = e^{-\frac{\varepsilon t}{cos(\theta_2)}} \tag{4}$$

where ε is the extinction coefficient (m^{-1}) and t is the thickness of the glass material (m). The extinction coefficient can vary from 12/m for high quality glasses (low absorption of heat and high transmission) to more than 75/m for low quality glasses (high absorption of heat due high iron oxide content meaning less transmission). The Eq. (4) results in a smaller transmittance when the sun is rising and setting, and higher values when the sun is approximately normal with the surface.

According to Siegel and Howell [17], it is possible to use the ray tracing method to calculate the reflection, transmission and absorption of heat in a glass system. If a unitary ray acts on a system, as illustrated in Figure 1, a fraction will be reflected, with intensity ρ and an amount of (1- ρ) enters inside the medium. Of this fraction that enters the material, (1- ρ)τ is transmitted for the other surface, and (1- ρ)(1-τ) it is absorbed by the material. In the other surface, from the fraction (1- ρ)τ that arrives, a part is reflected again for the first surface, and a fraction $(1-\rho)^2\tau$ is transmitted for the inner ambient. This process repeats itself until the infinite, by the multiple reflections inside the glazing material, with shorter intensities at each reflection, until extinction.



(a) (b)

Figure 1. Multiple reflections in (a) a translucent material and (b) on the glass cover and on the cover/ground interface.

As reported by Strobel et al. [18], a single panel of glass as collector presents a fraction reflected, transmitted and absorbed, respectively, according to:

$$R = \rho\left[1 + \frac{(1-\rho)^2\tau^2}{1-\rho^2\,\tau^2}\right] \tag{5}$$

$$T = \frac{\tau(1-\rho)^2}{1-\rho^2\,\tau^2} \tag{6}$$

$$A_v = (1-\rho\tau)\left[\frac{(1-\tau)(1-\rho)}{(1-\rho^2\,\tau^2)}\right] \tag{7}$$

As already commented, the previous equations are related to the model treated on scientific literature [3-7,14-15]. This approach does not consider the multiple reflections between the neighborhood and the glass cover. Since the ground reflects the radiation as well, multiple reflections must be considered. The Figure 1(b) shows the behavior of a solar beam when reach the glass roof above the ground.

When a solar beam is transmitted by the glass cover to the ground, part of this beam is absorbed by the ground or the absorber and a fraction of this is reflected again to the glass cover, and the process repeats. A smaller fraction is reflected again by the glass cover, and returns to the ground. The process is repeated until the total extinction of the beam or until that the fraction becomes insignificant. To find the total fraction of energy reflected, absorbed and transmitted of the entire system, is used the ray tracing method related in Siegel and Howell [17] using geometric series. Resulting in a fraction reflected for the total system:

$$\mathrm{R_{sys}} = \mathrm{R} + \left[\frac{\rho_s \mathrm{T}^2}{(1-\rho_s \mathrm{R})}\right] = \frac{\mathrm{R}(1-\rho_s\mathrm{R}) + \rho_s \mathrm{T}^2}{(1-\rho_s\mathrm{R})} \tag{8}$$

and a fraction absorbed in a total system is given by

$$A_{sys} = \mathrm{A} + \left[\frac{\rho_s \mathrm{T}\,A}{(1-\rho_s \mathrm{R})}\right] = \frac{\mathrm{A}(1-\rho_s\mathrm{R}) + \rho_s \mathrm{T\,A}}{(1-\rho_s\mathrm{R})} \tag{9}$$

and the fraction transmitted to the air and the neighborhood in the total system is:

$$\mathrm{T_{sys}} = \mathrm{T} + \left[\frac{\rho_s \mathrm{TR}}{(1-\rho_s \mathrm{R})}\right] = \frac{\mathrm{T}(1-\rho_s\mathrm{R}) + \rho_s \mathrm{TR}}{(1-\rho_s\mathrm{R})} \tag{10}$$

where R, A and T are repported by eqs. 5-7, respectively.

3. RESULTS AND DISCUSSIONS

The data set used in this study represents a typical summer day in the city of Curitiba, state of Paraná, Brazil, located at south latitude of 25.25º on the 1st day of summer. The data have a maximum global horizontal radiation of 800 W/m^2, that is adjusted with a sine function, with sunrise at 6 a.m. and sunset at 18 p.m., evaluated by Eq. (11).

$$G_h = 800 \sin\left(\frac{(t-6)\pi}{12}\right) \tag{11}$$

Besides this study check the influence of surround reflectance variation, the reflectance of the neighborhood was set in 0.4. Note that six glazing have been chosen from the International Glazing Database (IGDB, Anon A) [19], primarily to cover a wide range of glazing thicknesses and short-wave absorptions. Table 1 describes the single glazing properties.
In Figure 2 the simulation results shown that considering only the transmittance calculated by eq. 4, the heat transmitted to the system is super-estimated and under-estimated for low (ID #6) and high (ID#1) quality of the glasses, respectively. Considering multiple reflections only on a glass cover, can be seen that in both glasses the heat transfer is underestimated. Since that the multiple reflections between glass cover and the ground works trapping the heat that passes through the glass and reflect infinitely until its extinction, then the heat transfer is a bigger than the obtained with model that considers only the glass cover, as can be seen in Figure 2a for glass id #1, with better extinction coefficient, and in Figure 2b for glass id #6, with lower quality.
Figure 3 presents the percentage difference (values in modulus) of methods only with the transmission coefficient and of methods with multiple reflections only on glass cover compared to the proposed model this study, for each glass id chosen and for the parameters set by the simulation program. Note that, for the simulation parameters, the error between the use of only transmittance and the model presented can lead to an error about 11%, and in the use of multiple reflections only on glass cover this error drops for about 5%.
Figure 4 show the percentage difference (values in modulus) of methods that use only the transmission coefficient and methods that use multiple reflections only on glass cover compared to the proposed model for glass id #1, with better extinction coefficient, and for glass id #6, with lower quality related to the surrounding reflectance. Note that when the surrounding reflectance is negligible (zero), the use of multiple reflections only on glass cover can be used without any difference from the proposed model, since the radiation is not reflected from the surrounding surface, only in the glass cover. However, this percentage difference can rise linearly and reach values of 13% for better quality glass and 12% for low quality glass, for surrounding reflectance of 1,0. Only using the transmittance the percentage difference from the proposed model is 16.5% for lower quality glass and 17.5% for higher quality glass for surrounding reflectance equals to zero and drops linearly to about 2.5% for lower quality glass and 2% for higher quality glass.

These results show that for applications in which the absorber has higher values of reflectance, the error induced using only transmittance is lower, in order of 2% to 2.5%. On the other hand, in applications where the surrounding reflectance is next to zero, the use of multiple reflections only on glass results in lower error as well. It means that a previous study of the problem must be made in order to reduce the error involved applying a model that returns a lower error. The model proposed avoid such errors, which can reach 17.5% depending on the quality of the glass and the reflectance of the surroundings.

4. CONCLUSIONS

This paper studied the methods available in the literature for the treatment of the solar radiation in glazing panels found in greenhouse structures such as solar collectors, greenhouses and glazing facades. Three models were compared: transmittance only, multiple reflections only on glass cover and the proposed model that considers multiple reflections on total system (glass cover and the interface with the surrounding). In simulations that need a more accurate prediction of the heat transfer the incorrect treatment of the radiative behavior in the glazing system of the greenhouse structures can induce an error of up to 17% of this heat, that in the most cases is an incoming data, it is a significant difference. However, a sensitivity analysis of the problem must be set to evaluate the necessity to implement this proposed model. This divergence does not change for the heat flux applied, i. e., if the heat flux is low, this divergence will not impact significantly on the final results, but using higher values of heat flux, this divergence becomes considerable.

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4. RESPONSIBILITY NOTICE

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