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On the Use of Neural Network for the Evaluation of Total Absorptivity of Glass in a Non-gray Absorbing/Emitting $N_2/CO_2/H_2O$ Mixture Environment

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Abstract: Total absorptivity of glass in the presence of a $N_2/CO_2/H_2O$ is determined numerically using the glass spectral optical properties and the spectroscopic data from RADCAL. Results show that mixture properties (surface temperature, mixture temperature, and species concentration) have significant effects on the glass total absorptivity. The commonly used approach of using a gray emitter in the evaluation of the glass total absorptivity is shown to be inaccurate. For a specific glass, a neural network, RADNNET-GL, is generated to correlate the glass total absorptivity and the neural network can be readily applied to practical engineering applications (e.g., fire simulations) to determine the glass thermal behavior efficiently.

Keywords: Radiative heat transfer, Non-gray, Glass, Absorptivity

1. Introduction

The thermal behavior of glass in the presence of a non-gray absorbing/emitting gas is an important problem for many practical engineering applications such as fire simulations. For example, the catastrophic window failure in a compartment fire is generally attributed to the induced thermal stress within the glass pane due to direct heating from fire gases [1]. Over the years, a great deal of work has been reported on the determination of optical constants of window glasses [2]. Based on these optical constants, the total absorptivity and transmissivity of glasses are generated by numerical integration. The computed glass absorptivity/transmissivity is then used to evaluate the thermal performance of windows. However, in nearly all of the existing analyses of thermal performance on windows for applications such as fire simulation [3] and fire safety analysis [4], a gray emitter is assumed to be the source of radiation in the determination of the glass total absorptivity. Since H_2O and CO_2 are non-gray, the accuracy of these existing models on the thermal performance of windows is highly uncertain. Therefore, the objective of the present work is to assess the effect of the emitting mixture properties (temperatures and species concentration) on the glass total absorptivity.

2. Mathematical Formulation

The reflection and transmission of radiation through a glass is a complicated process because of the multiple reflections that occur at the glass/air interface. The reflectivity at the glass/air interface, for example, is a function of both the optical properties of glass and the angle of incidence. Analytical expressions can be derived theoretically and they can be obtained from standard references [5]. But for the purpose of illustrating the effect of non-gray emission source on the glass absorptivity, the present work will primarily focus on the glass absorptivity for radiation incident in the normal direction relative to the window glass. The glass absorption behavior for radiation incident in other angular directions is expected to be qualitatively similar and will be considered in future works.

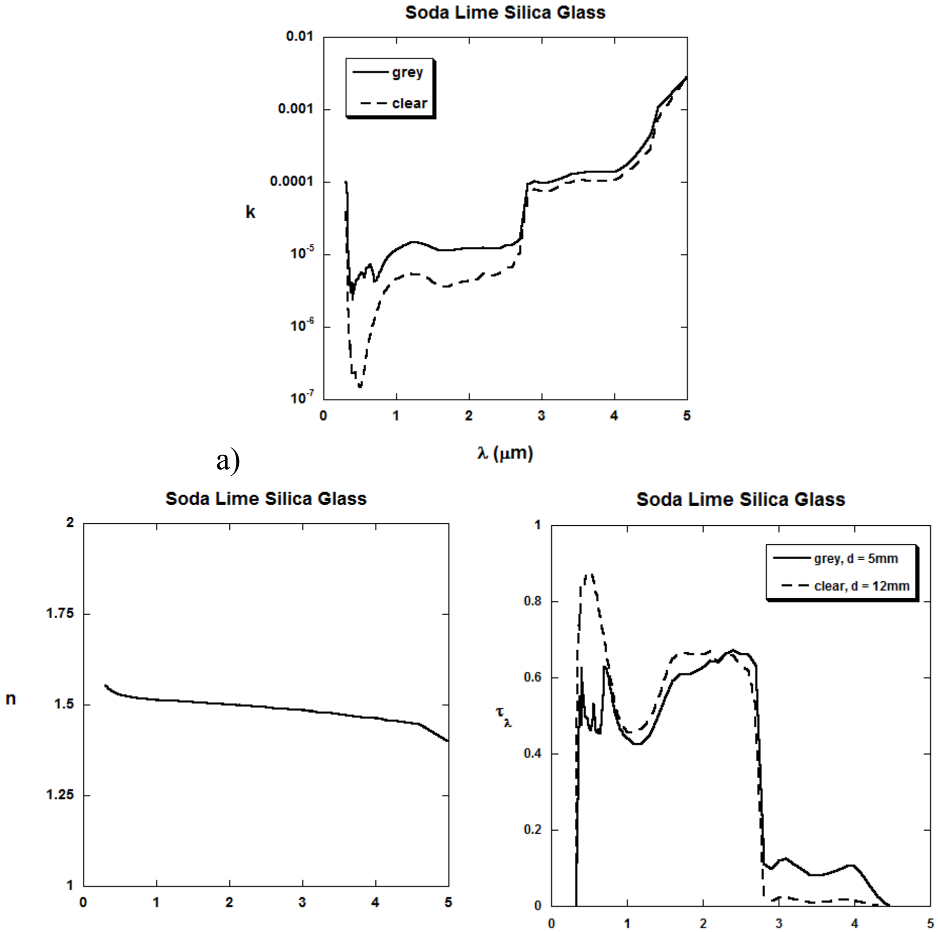
For radiation incident normally onto a glass with thickness, d, the spectral transmissivity, accounting for the multiple reflections occurring at the glass/air interface, is given by [3].

$$\tau_\lambda(d) = \frac{(1-\rho_\lambda)^2 e^{-\alpha_\lambda d}}{1-\rho_\lambda^2 e^{-2\alpha_\lambda d}} \tag{1a}$$

$$\rho_\lambda = \frac{(n-1)^2}{(n+1)^2} \tag{1b}$$

$$\alpha_\lambda = 4\pi \frac{k}{\lambda} \tag{1c}$$

where ρ_λ is the reflectivity of the glass/air interface and α_λ is the absorption coefficient of the glass. The real and imaginary parts of the glass index of refraction are represented by *n* and *k,* respectively, and they vary strongly with wavelength.



a)

b)

c)

Figures 1. a) The imaginary part and b) the real part of the complex index of refraction for a coated soda lime silica glass (grey) and an uncoated soda lime silica glass (clear), and c) the transmissivity of soda lime silica glass with different coatings and thicknesses.

The index of refraction for a typical window material (soda lime silica glass) is illustrated in Figs. 1a and 1b. In Fig. 1a, the imaginary part of the index of refraction for glass without coating (clear) and glass with coating (grey) are shown. The real part of the index of refraction is shown in Fig. 1b. Note that there is only one curve in Fig. 1b as adding coating to a glass has essentially no effect on the real part of the index of refraction. The transmissivities of the glasses are calculated using Eqns. (1) and they are shown in Fig. 1c. It can be seen that although the transmissivities for the two glasses are qualitatively similar, the "grey" glass has a slightly lower transmissivity in the visible region.

Consider a one-dimensional slab of isothermal and homogeneous gas mixture with a thickness, L, bounded by a glass with thickness, d. The emission from the mixture transmitted through the glass is given by:

$$q_g = \int_0^\infty e_{b,\lambda}(T_g)(1 - e^{-a_\lambda L})\tau_\lambda(d)d\lambda \tag{2}$$

where T_g is the temperature and L is the thickness of the mixture. The mixture is characterized physically by T_g, the soot volume fraction, f_v, and the partial pressure of two absorbing gas species written as $P_g = P_{\mathrm{CO_2}} + P_{\mathrm{H_2O}}$ and $F_{\mathrm{CO_2}} = P_{\mathrm{CO_2}}/P_g$ where $P_{\mathrm{CO_2}}$ and $P_{\mathrm{H_2O}}$ is partial pressure for CO_2 and H_2O, respectively. Formally, the definition of the glass total transmissivity due to the emission from the mixture, τ_{gl}, is:

$$q_g = \int_0^\infty e_{b,\lambda}(T_g)(1 - e^{-a_\lambda L})\tau_\lambda(d)d\lambda \tag{3a}$$

$$q_g = \sigma T_g^4 \varepsilon_g \tau_{gl} \tag{3b}$$

with ε_g being the emittance of the mixture which can be written as:

$$\varepsilon_g = \frac{1}{\sigma T_g^4}\int_0^\infty e_{b,\lambda}(T_g)(1 - e^{-a_\lambda L})d\lambda \tag{4}$$

For the emission from a black wall with temperature, T_w, the energy transmitted through the glass is given by:

$$q_w = \int_0^\infty e_{b,\lambda}(T_w)e^{-a_\lambda L}\tau_\lambda(d)d\lambda \tag{5}$$

and the total transmissivity due to the wall emission, $\tau_{gl,w}$, is defined as:

$$q_w = \sigma T_w^4(1 - \alpha_{w,g})\tau_{gl,w} \tag{6}$$

with

$$\alpha_{w,g} = \frac{1}{\sigma T_w^4}\int_0^\infty e_{b,\lambda}(T_w)(1 - e^{-a_\lambda L})d\lambda \tag{7}$$

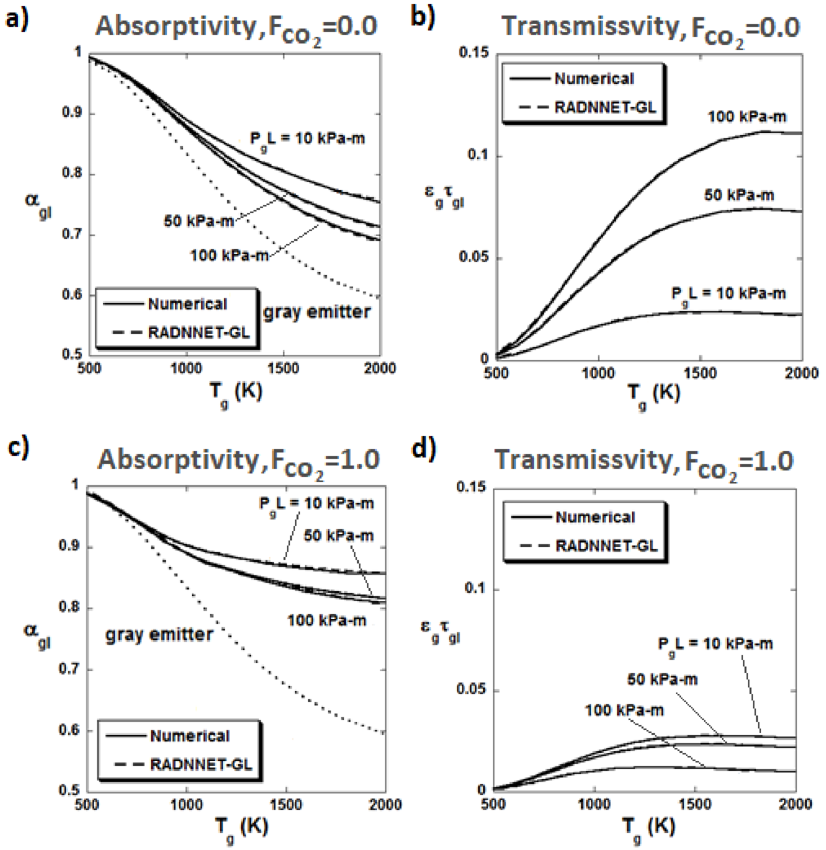
Note that the absorptance of the mixture, $\alpha_{w,g}$, is a function of both wall temperature and the mixture properties. The value of $\alpha_{w,g}$ is equal to the mixture's emittance, ε_g, when the wall temperature is identical to the mixture temperature. Eqns. (4) and (7) have been evaluated over the following range of values for the mixture' parameters (T_w, T_g, P_gL, F_{co_2}), using the RADCAL spectroscopic model [6]:

$$\begin{gathered} 0 \le P_gL \le 1000 \text{ kPa-m} \\ 0 \le F_{CO_2} \le 1.0 \\ 0 \le f_vL \le 10^{-6}\text{m} \\ 300 \text{ K} \le T_g \le 2000 \text{ K} \\ 300 \text{ K} \le T_w \le 1500 \text{ K} \end{gathered} \tag{8}$$

Numerical data for the two total transmissivities, τ_{gl} and $\tau_{gl,w}$, for the two glasses are generated by direct numerical integrations on Eqns. (2) and (5) using RADCAL and the transmissivity data presented in Fig. 1c. Note that the two total transmissivities are not identical even when the wall temperature is identical to the mixture temperature as they account for transmission of emitted energy from difference sources (wall and medium). Similar to [7, 8], in order to facilitate the calculations, a neural network, RADNNET-GL, is generated to correlate the glass transmissivities over the range of mixture properties as shown by Eqn.8.

3. Results and Discussion

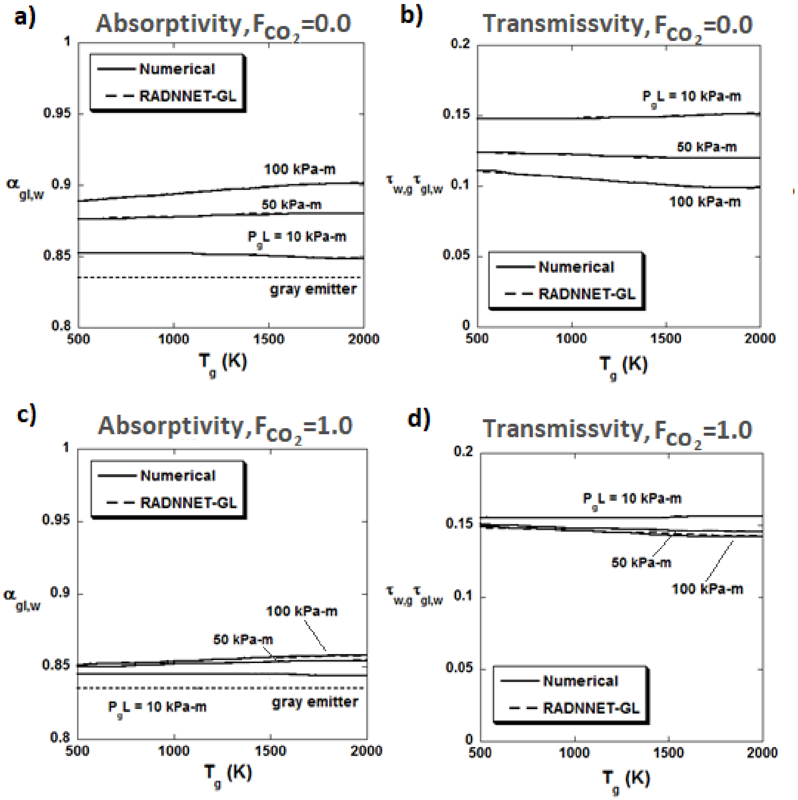
To illustrate the accuracy of the neural network, predictions generated by the neural network are shown along with the numerical results in all figures presented in this section. Qualitatively, results for the clear and grey glass are similar and to avoid redundancy, only data for the grey glass (with thickness of 5 mm) will be presented in this work. Numerical data for the clear glass (with thickness of 12 mm) was calculated, but not presented here.



Figures 2: The effect of the mixture properties (T_g, P_gL, F_{CO_2}) on the glass total absorptivity and the transmitted energy for emission from a $N_2/CO_2/H_2O$ mixture through a grey glass with thickness 5 mm.

The effect of the mixture temperature, T_g, the absorption gas pressure pathlength (p_gL) and the CO_2 fraction (F_{co_2}) on the total absorptivity of the grey glass ($\alpha_{gl} = 1 - \tau_{gl}$) is shown in Figs. 2a and 2c. The corresponding glass total absorptivity for a gray emitter is shown in the same figure for comparison. To illustrate the effects of mixture properties on the energy transmitted through the glass, results for $\varepsilon_g \tau_{gl}$ are presented in Figs. 2b and 2d. It is apparent that the mixture properties have profound effects on the glass total absorptivity and the transmitted radiation. Since there are two emission bands for H_2O (1.38 μm, 1.87 μm) and only one emission band for CO_2 (2 μm) in the short wavelength transparent spectral region of the glass, the incident radiation from a H_2O dominated mixture (F_{co_2}= 0) has a higher fraction of radiation emitted in that spectral region. The glass total absorptivity is thus lower and the transmitted energy is higher for a H_2O dominated mixture (F_{co_2}= 0, Figs. 2a and 2b) than a CO_2 dominated mixture (F_{co_2}= 1.0, Figs. 2c and 2d). The total absorptivity calculated with a gray emitter cannot capture the mixture effects and also deviates significantly from the numerical results, particularly in the region of high mixture temperature.

The effect of the mixture properties on the glass total absorptivity and the transmitted energy for radiation emitting from a black wall with a wall temperature from 1500 K, T_w, are shown in Figs. 3. Results show that the mixture properties also have significant effects. It is interesting to note that the effect of the absorbing gas pressure (P_gL) on the total absorptivity of the glass for radiation emitted from the wall is opposite to that for radiation emitted from the mixture. In general, the glass total absorptivity for radiation emitted from a wall increases with increasing absorbing gas pressure (P_gL). Physically, the increased absorption by the gas absorption bands in the transparent spectral region of the glass reduces the fraction of radiation in that spectral region incident on the glass. The glass total absorptivity thus increases. For emission from the wall, results in Figs. 3 also show that the glass total absorptivity has only a weak dependence on the mixture temperature. The glass total absorptivity calculated with a gray emitter again fails to capture the effect of the mixture.



Figures 3: The effect of the mixture properties (T_g, P_gL, F_{CO_2}) on the glass total absorptivity and the transmitted energy for emission from a gray wall with T_w = 1500K through a $N_2/CO_2/H_2O$ mixture and a grey glass with thickness 5 mm.

Conclusions and Future Work

The total absorptivity of glass in the presence of an emitting/absorbing gas/soot mixture is evaluated. Results show that mixture properties such as mixture temperature, concentration of the absorbing gas and soot have profound effects on the glass total absorptivity and the energy transmitted through the glass. The glass total absorptivity for radiation emitted from the mixture differs significantly from that for radiation emitted from the wall. In general, the glass total absorptivity calculated with a gray emitter is highly inaccurate and should not be used for actual engineering applications. A neural network, RADNNET-GL, is generated to correlate the numerical data of the total absorptivity for two common glasses. The neural network is shown to be an accurate and efficient tool for practical engineering applications. For future work, RADNNET-GL can be expanded similar to [8] to account for the multi-dimensional effects. For non-homogenous mixture environments, the concept of mean beam length suggested in [9] can be used to account for the effect.

4. References

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