ANALYSIS OF THE INFLUENCE OF THE SPECTRAL DEPENDENCE OF RADIATIVE PROPERTIES OF A PARTICIPATING MEDIUM IN THE TURBULENCE-RADIATIVE INTERACTION IN A NON-REACTING CHANNEL FLOW

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Abstract. *The phenomenon of turbulence-radiation interaction (TRI) has been demonstrated experimentally, theoretically and numerically to be important in a great number of engineering applications. This paper presents a numerical study on the subject, focusing on a non-reacting channel flow of participating gases (carbon dioxide and water vapor) and employing computer fluid dynamics. An open source Fortran-based finite volume method code, Fire Dynamics Simulator (FDS), is used for the analysis. The main objective of the present work is to perform a fundamental study on the influence of including or not the spectral dependence of the radiative properties of the participating medium on the magnitude of TRI effects. Large Eddy Simulation (LES) is adopted to model turbulence, and to resolve the sub-grid scale terms the dynamic Smagorinsky model is used. To model the consideration or not of the spectral variation of radiative properties, the weighted-sum-of-gray-gases (WSGG) and the gray gas (GG) models are implemented, respectively. Comparing the differences between results for the wall heat fluxes and the volumetric radiative heat source obtained from solutions considering and neglecting the TRI effects, the phenomenon is shown not to be significant in the problem studied, which agrees with previous studies on non-reacting flows. Nevertheless, an evident influence on the turbulence-radiation interaction magnitude is observed when the spectral variation of radiation properties is included in the solution of radiative heat transfer; however, this influence can be positive, contributing to increase the TRI effects when compared to the results for a gray medium, or negative, decreasing the effects of the phenomenon, depending on the problem that is analyzed.*

Keywords*: Turbulence-radiation interaction, Large Eddy Simulation, spectral dependence, weighted-sum-of-gray-gases model, Fire Dynamics Simulator*

1. INTRODUCTION

Turbulence-radiation interaction (TRI) is a phenomenon characterized by the simultaneous influence of thermal radiation on the flow and species concentration fields – due to the dependence of the density field on the temperature field, which in turn depends on the radiative heat transfer – and the influence of turbulent fluctuations of the flow field on the temperature and species concentration, combined with the dependence of the radiative properties of the medium on temperature and species concentration, which ultimately influences the radiation field. Therefore, radiation influences and is influenced by turbulence. Since, individually, thermal radiation and turbulence are two of the most difficult fundamental and practical engineering problems due to their inherent nonlinearities and vast ranges of length and time scales, TRI is naturally an even greater challenge (Coelho, 2007).

The importance of the turbulence-radiation interaction has been demonstrated experimentally, theoretically and numerically for a number of diferent types of turbulent problems (Modest, 2005; Coelho, 2007). However, not much research has been using the weighted-sum-of-gray-gases (WSGG) model for the spectral integration of the radiative transfer equation (RTE). The WSGG model is a relatively simple model, with low computational cost, that can account for the spectral variations of the radiative properties of the participating gas when solving the radiative problem (Modest, 2003).

In this paper, the magnitude of the TRI effects when the WSGG model is implemented is compared to the magnitude of the phenomenon for calculations using a gray gas assumption – i.e., neglecting the spectral variation of the radiative properties. The main objective is to assess how does the consideration or not of the spectral dependence of the radiative heat transfer problem impacts the turbulence-radiation interaction. Instantaneous flow and thermal field are obtained through large eddy simulation (LES) of a problem consisting of a turbulent non-reacting channel flow of a participating homogeneous gas, that can be composed of carbon dioxide or water vapor. TRI is evaluated comparing the time average of the instantaneous values of quantities associated with the heat transfer problem (namely, radiative heat flux to the wall and the divergence of the radiative heat flux over the entire computational domain) and the same quantities calculated from the time-averaged temperature and flow field.

2. METHODOLOGY

2.1 Mathematical Model

2.1.1 Mass, Momentum and Energy Transport Equations

The fundamental transport equations are solved for a compressible flow of a single non-reacting species in a flow field for which gravitational effects and other body forces are neglected. The mass, momentum and energy balance equations are given, respectively, by

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i\right)=0 \qquad (i = 1, 2 \text{ and } 3) \text{ in } t\times\Omega \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho u_i\right)+\frac{\partial}{\partial u_j}\left(\rho u_i u_j\right)= -\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left\{\mu\left[\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right]\right\} \qquad (i, j, k = 1, 2 \text{ and } 3) \text{ in } t\times\Omega \tag{2}$$

$$\frac{\partial}{\partial t}\left(\rho h_s\right)+\frac{\partial}{\partial x_i}\left(\rho h_s u_i\right)=\frac{\partial p}{\partial t}+u_i\frac{\partial p}{\partial x_i}-\frac{\partial q_i''}{\partial x_i} \qquad (i = 1, 2 \text{ and } 3) \text{ in } t\times\Omega \tag{3}$$

where ρ and μ are the density and the dynamic viscosity of the fluid, respectively; u_i is the velocity component in the i-direction; x_i corresponds to the spatial coordinate; δ_{ij} is the Kronecker delta operator; p is the pressure; h_s is the sensible enthalpy, q_i'' represents the conductive, diffusive and radiative heat fluxes; and Ω and t represent the spatial and time domains, respectively.

In the FDS algorithm, a low Mach number approximation, proposed by Rehm and Baum (1978), is introduced to simplify the previous equations and they are further manipulated from their original form to facilitate the implementation of the numerical solver. More details on the mathematical formulation and methodology of solution can be found in the FDS technical guide (McGrattan et al., 2015), which is constantly updated.

2.1.2 Large Eddy Simulation

The LES fundamental equations are derived by the application of a low-pass filter of width Δ to the transport equations; the filter width is defined in terms of the cell volume, $\Delta = (\delta x\ \delta y\ \delta z)^{1/3}$, where δx, δy and δz are the grid dimension in directions x, y and z. For the treatment of mass density and velocity correlations that derives from this methodology, a mass-weighted or Favre filter is also defined. For example, the momentum equation, Eq. (2), can therefore be written as

$$\frac{\partial}{\partial t}\left(\bar{\rho}\tilde{u}_i\right)+\frac{\partial}{\partial u_j}\left(\bar{\rho}\tilde{u}_i\tilde{u}_j\right)= -\frac{\partial \bar{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left\{\left(\mu+\mu_t\right)\left[\left(\frac{\partial \tilde{u}_i}{\partial x_j}+\frac{\partial \tilde{u}_j}{\partial x_i}\right)-\frac{2}{3}\delta_{ij}\frac{\partial \tilde{u}_k}{\partial x_k}\right]\right\} \qquad (i, j, k = 1, 2 \text{ and } 3) \text{ in } t\times\Omega \tag{4}$$

where the bar and the tilde indicate a filtered and Favre filtered variable, respectively, and μ_t is the turbulent viscosity. Following tests with some turbulence models conducted by Velasco (2014) for a problem similar to the one studied in this paper, the dynamic Smagorinsy model (Germano et al., 1991; Moin et al., 1991) is adopted to compute μ_t.

2.1.3 Radiation Modeling

For the determination of the thermal radiation field in a participating medium it is usually necessary to solve the radiative heat transfer equation (RTE), that establishes the variation of the spectral radiation intensity I_η along a certain path s in the medium. Considering that energy can be absorbed and emitted, but neglecting scattering, the RTE is given by

$$\frac{dI_\eta}{ds} = \kappa_\eta I_\eta + \kappa_\eta I_{\eta b} \tag{5}$$

where η is the radiation wavenumber; κ_η is the spectral absorption coefficient of the medium; and $I_{\eta b}$ is the blackbody spectral intensity, given by Planck's distribution law.

The global solution of the radiative transfer problem requires the spatial and spectral integrations of Eq. (5). In the present study, the finite volume method (FVM) is used to perform the first integration. This method divides the total solid angle 4π on each point in a finite number of control angles inside which the intensity is assumed to be constant relative to direction; the RTE is then solved for each of these control angles and the continuous integral over the entire unit sphere is approximated as a summation over the results for all the discrete angles (Raithby and Chui, 1990).

For the spectral integration, two methodologies are used, as a means of neglecting or accounting the dependence of radiative properties on the wavenumber: the gray gas model (GG) and the weighted-sum-of-gray-gases model. These models are described in the next two subsections.

2.1.4 The Gray Gas Model

A simple methodology to solve the RTE spectral integration problem is to assume that the participating medium is a gray gas. Therefore, its spectral coefficient is independent of the radiation wavenumber and the spectral dependence of the RTE can be dropped, leading to

$$\frac{dI}{ds} = \kappa I + \kappa I_b \tag{6}$$

where I is the total radiative intensity; κ is the absorption coefficient; and I_b is the total blackbody intensity. In this study, the value of κ for each of the participating gases considered (carbon dioxide and water vapor) is calculated from a correlation proposed by Cassol et al. (2015), given by

$$\kappa_\chi = p_\chi \sum_{i=0}^{5} c_{\chi,\mathrm{i}} T^i \tag{7}$$

where χ is an index representing the species under consideration; p_χ is the partial pressure of said species (in this study, p_χ = 1 atm for all cases); T is the local temperature; and $c_{\chi,i}$ are the constant coefficients of the correlation. The values of $c_{\chi,i}$ for CO_2 and H_2O are given in Tab. 1.

Table 1. Polynomial coefficients for the absorption coefficient calculation in the gray gas model (Cassol et al., 2015).

χ	$c_{\chi,0}$ (m^{-1}atm^{-1})	$c_{\chi,1}$ (m^{-1}atm^{-1}K^{-1})	$c_{\chi,2}$ (m^{-1}atm^{-1}K^{-1})	$c_{\chi,3}$ (m^{-1}atm^{-1}K^{-1})	$c_{\chi,4}$ (m^{-1}atm^{-1}K^{-1})	$c_{\chi,5}$ (m^{-1}atm^{-1}K^{-1})
CO_2	-6.4780×10^{1}	4.2895×10^{-1}	-6.6089×10^{-4}	4.4190×10^{-7}	-1.3796×10^{-10}	1.6484×10^{-14}
H_2O	7.502×10^{1}	-1.9716×10^{-1}	-2.1998×10^{-4}	-1.2492×10^{-7}	3.5385×10^{-11}	-3.9663×10^{-11}

Two approaches for the GG model are used in this paper. In the first one, the value of the absorption coefficient varies locally inside the computational domain, as a function of the local temperature, according to Eq. (7); and, in the second one, κ has a constant value over the entirety of the domain, calculated using for T in Eq. (7) the flow temperature at the inlet, which results in κ = 16.855 m^{-1} for CO_2 and κ = 3.524 m^{-1} for H_2O. This approaches are called $GG_{\kappa(T)}$ and GG_κ, respectively.

2.1.4 The Weighted-Sum-of-Gray-Gases Model

An alternative to the gray gas model, which is not capable to provide reliable results for radiative heat problems involving participating gases such as CO_2 and H_2O, is the weighted-sum-of-gray-gases model, a methodology relatively simple and with low computational cost that has shown good agreement with line-by-line integration results for a number of different situations (Dorigon et al., 2013; Cassol et al., 2014). In the WSGG model, the spectrum of radiation is replaced by g gray gases with uniform absorption coefficients κ_g and transparent windows. The RTE for each gray gas can then be written as

$$\frac{dI_g}{ds} = \kappa_g I_g + \kappa_g a_g I_b \tag{8}$$

where I_j is the radiative intensity for gas g and a_j is a weighting factor (also called temperature coefficient) to represent the blackbody radiation fraction emitted at the local temperature of the medium in position s in the wavenumber interval represented by the gas g.

The absorption and temperature coefficients of each gray gas are obtained from correlations, which in turn are determined from fitting global radiation data (typically, of total emittance). The correlations for CO_2 and H_2O used in this study are the ones produced and presented by Cassol et al. (2014), and assume a modeling of the spectrum using four gray gases plus the transparent windows. The temperature coefficient is described by the polynomial relation

$$a_g = \sum_{g=0}^{4} b_{0,g} T^g \tag{9}$$

where $b_{i,g}$ are the constant coefficients for gas g. The values of these coefficients for carbon dioxide and for water vapor, along with the value of their pressure absorption coefficients $\kappa_{p,g}$ (defined as the absorption coefficient divided by the partial pressure of the species), are given in Tabs. 2 and 3, respectively.

Table 2. WSGG coefficients for CO_2 with four gray gases (Cassol *et al.*, 2014).

g	$\kappa_{p,g}$ (atm^{-1}m^{-1})	$b_{0,g}$	$b_{1,g}$ (K^{-1})	$b_{2,g}$ (K^{-2})	$b_{3,g}$ (K^{-3})	$b_{4,g}$ (K^{-4})
1	0.138	0.09990	64.41×10^{-5}	-86.94×10^{-8}	41.27×10^{-11}	-67.74×10^{-15}
2	1.895	0.00942	10.36×10^{-5}	-2.277×10^{-8}	-2.134×10^{-11}	6.497×10^{-15}
3	13.301	0.14511	-30.76×10^{-5}	37.65×10^{-8}	-18.41×10^{-11}	30.16×10^{-15}
4	340.811	−0.02915	25.23×10^{-5}	26.10×10^{-8}	9.965×10^{-11}	-13.26×10^{-15}

Table 3. WSGG coefficients for H_2O with four gray gases (Cassol *et al.*, 2014).

g	$\kappa_{p,g}$ (atm^{-1}m^{-1})	$b_{0,g}$	$b_{1,g}$ (K^{-1})	$b_{2,g}$ (K^{-2})	$b_{3,g}$ (K^{-3})	$b_{4,g}$ (K^{-4})
1	0.171	0.06617	55.48×10^{-5}	-48.41×10^{-8}	22.27×10^{-11}	-40.17×10^{-15}
2	1.551	0.11045	0.576×10^{-5}	24.00×10^{-8}	-17.01×10^{-11}	30.96×10^{-15}
3	5.562	−0.04915	70.63×10^{-5}	-70.12×10^{-8}	-26.07×10^{-11}	-34.94×10^{-15}
4	49.159	−0.23675	-18.91×10^{-5}	-0.907×10^{-8}	4.082×10^{-11}	-8.778×10^{-15}

Finally, for the transparent window, the temperature coefficient a_0 is obtained from the temperature coefficients of the gray gases. For a model with a total of four gray gases, we have

$$a_0 = 1 - \sum_{g=1}^{4} a_g \tag{10}$$

2.2 Numerical Procedures

For the simulation of the problem, the open-source Fortran-based computer fluid dynamics code FDS is used. The solver, developed by the National Institute of Standards and Technology of the United States of America, uses second-order finite differences with uniform, structured and staggered meshes, and explicit second-order temporal discretization. LES with a low Mach approximation and dynamic Smagorinsky turbulence model is employed to determine the flow field; turbulence at the inlet boundary condition is generated using a synthetic eddy method (SEM), in which turbulent eddies of random sizes are injected into the flow at random positions on the boundary and advect with the mean flow over a short distance near the boundary (Jarrin, 2008).

For the spatial discretization of the domain, a grid with 156 816 cells and a time-step of 10^{-3} s are utilized for the main case (for the preliminary simulations to determine the outlet interface temperature for radiation, coarser spatial e temporal meshes are adopted). Each case is simulated up to 20 s; however, the time-averages required for the TRI analysis are done considering only the final 15 s of calculation, assuming that the initial 5 s is the time necessary for the flow and thermal fields to stabilize. The radiative transport equation is solved with the finite volume method using the same grid as for the hydrodynamic solver. The spectral integration is resolved with either the gray gas model or the WSGG model with four gray gases, and the spatial integration is accounted for with the FVM with 100 control angles for the discretization. Analyses of the quality of the spatial, temporal and angular discretizations are presented in Fraga (2016), for a case with similar configuration and parameters.

2.3 Geometry and Boundary Conditions

TRI is investigated in the context of a high temperature non-reacting channel flow of a homogeneous participating gas, the composition of which can be entirely of carbon dioxide (without any diluted non-participating species – i.e., partial pressure equals to unity) or water vapor, also in its totality. Geometry and boundary conditions are similar to the configurations and parameters adopted by Velasco (2014) and Fraga (2016). The computational domain is modeled as a square duct, as shown in Fig. 1, with cross-sectional area of 0.25 m² and 5.25 m of length; the scale of the geometry is comparable to conventional heat exchangers such as steam generators or exhaust manifolds of internal combustion engines. At the inlet interface, fluid is injected with a prescribed constant and uniform velocity and temperature. The flow velocity is defined as to result in a Reynolds number (calculated in terms of the hydraulic diameter) of 5100, similar to others studies on TRI (Dos Santos, 2014; Velasco, 2014; Fraga, 2016), and the incoming flow temperature is equal to 1200 K; turbulent eddies generated at the inlet boundary maintain the turbulence intensity in 10% throughout the simulation. The lateral walls of the domain have a no-slip condition and are at a constant temperature of 400 K. For the outlet interface, an open condition to an atmospheric pressure outside environment is assumed and the temperature for radiation is taken as the bulk mean temperature calculated in the last cells of the domain in the longitudinal direction. For each case analyzed, the determination of this temperature requires an iterative calculation that is described in detail in Fraga (2016).

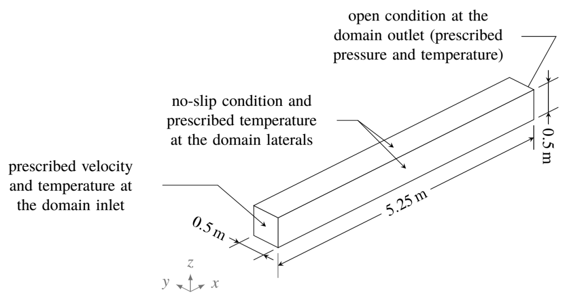

Figure 1. Computational domain and boundary conditions.

3. RESULTS

The turbulence-radiation interaction is analyzed by the comparison of mean (in time) quantities related to the radiative heat transfer problem obtained from the transient LES calculation, which are called here the results “with TRI”, and the radiative properties computed from the time-averaged temperature and velocity field, named the “without TRI” results. Due to the highly non-linear behavior of the radiative heat transfer, it should be possible to observe and consequently evaluate the difference between the two solutions.

Figures 2(a) and 2(b) show the percentage relative difference between the mean radiative wall heat fluxes along the duct length (the x-direction) computed by the “with TRI” and “without TRI” solutions for a medium composed of carbon dioxide or water vapor, respectively, while Figs. 2(c) and 2(d) present the same differences but for the mean convective heat flux at the wall. In these figures, the heat fluxes at each position in the x-direction are obtained as the average of the wall heat fluxes for the four walls at the same distance x from the duct entrance (the heat flux at each wall was taken as the value of the heat flux at its middle point).

Another quantity reported to assess the TRI effects is the mean radiative heat source term, calculated as the negative value of the radiative heat flux divergence. For each case studied here, the difference between “with TRI” and “without TRI” results for this quantity along the central longitudinal plane of the domain is shown in Fig. 3, while Tab. 3 presents the local maximum (over the whole three-dimensional field) and domain-average values of the difference. To avoid issues arising from close to zero local values of the radiative heat source term, that would significantly increase the difference due to the very small values in the denominator, the results presented in Fig. 3 and Tab. 3 are absolute differences between “with TRI” and “without TRI” solutions normalized by the maximum value of the mean radiative heat source term in the entire domain.

As it can be seen in Figs. 2(a) and 2(b), the differences between “with TRI” and “without TRI” mean radiative heat fluxes at the wall are less than 2% for any of the spectral models implemented; for the mean radiative heat source, Tab. 3 reports maximum differences of about 1% and domain-average differences of 0.1%, again for every model tested. Additionally, Fig. 2 shows that “with TRI” and “without TRI” mean convective heat fluxes present errors of the same magnitude as the ones for the radiative heat flux. Since convection is a much more linear process than radiation, and seeing that TRI is promoted by nonlinearities in the coupling between turbulence and radiation (Coelho, 2007), we expected to find much greater differences for the mean radiative heat flux than for the mean convective heat flux if turbulence-radiation interaction effects were important. All these observations indicate that TRI does not have a significant contribution to the transfer problem studied in this paper. The same conclusion was found by other authors for participating gases in non-reacting flows (Mazumder and Modest, 1999; Gupta et al., 2009; Velasco, 2014; Fraga, 2016).

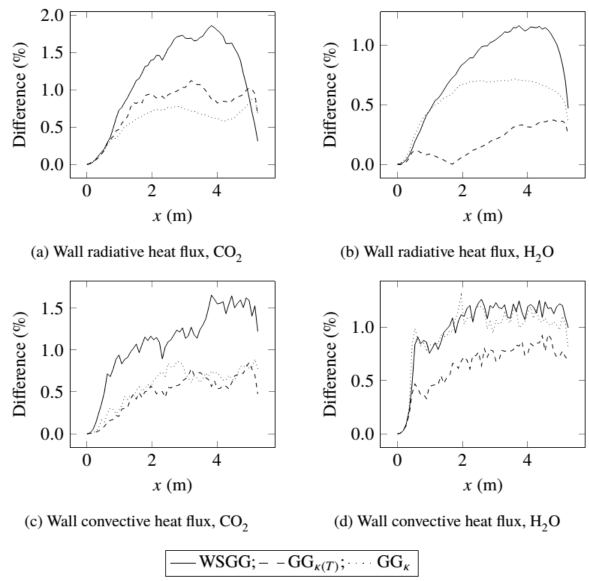

Figure 2. Relative difference between solutions considering and neglecting TRI effects for the wall heat fluxes. From left to right: results for CO_2 and H_2O; from top to bottom: wall radiative heat flux and wall convective heat flux.

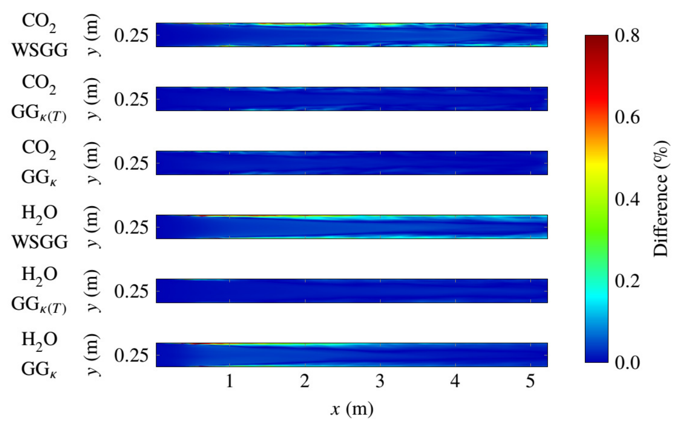

Figure 3. Normalized difference between the mean radiative heat source computed by "with TRI" and "without TRI" solutions along the middle longitudinal plane of the domain.

Table 3. Local maximum and domain-averaged values of the percentage normalized difference between the mean volumetric radiative heat source computed by "with TRI" and "without TRI" solutions.

Spectral model	CO_2		H_2O	
	Average	Maximum	Average	Maximum
WSGG	0,086	1,180	0,105	1,118
$GG_{\kappa(T)}$	0,020	0,510	0,017	0,619
GG_{κ}	0,018	0,462	0,073	1,278

As for comparisons between results for the three spectral models used, from Figs. 2(a) and 2(b) it is clear that the TRI effects are more relevant when applying the WSGG model, especially in regions far away from the inlet or the outlet of the gas flow. The small difference between results for the models near the domain entrance or exit can be explained by the fact that a constant value of temperature is imposed at these surfaces; therefore, the regions are subjected to less fluctuations and, consequently, to an overall minor contribution of turbulence-radiation interactions. In Tab. 3, although the local maximum difference for the mean radiative heat source term does not present a definitive trend for one spectral model to the other, domain-averaged values of the difference agree with Fig. 2, portraying a greater contribution of TRI for the WSGG model, which can also be observed for the two-dimensional fields in Fig. 3.

An explanation for the greater TRI influence for the solution using the WSGG model than for the solution implementing the gray gas assumption can be found in part in the study of Hall and Vranos (1994), in which it is reported that different spectral bands of a participating gas (i.e., almost infinitesimal parts of the radiation wavelength spectrum) respond differently to temperature fluctuations, depending on how the blackbody radiation intensity varies with temperature inside the band. Thus, the mean radiation intensity – and, consequently, time-averages of others related quantities, such as the radiative heat flux and the volumetric radiative heat source – can be strongly affected by turbulent fluctuations in certain regions of the spectrum, while in other regions not be affected at all. When the spectral dependence of the problem is neglected, as in gray gas models, this effect is not captured.

Therefore, since the spectral variation of the radiative properties is accounted for in the WSGG model, it is expected that the turbulence-radiation effects have a different magnitude than that of the GG models. The fact that the WSGG model leads to larger differences between "with TRI" and "without TRI" solutions indicates that the summation over the entire spectrum of TRI contributions for each spectral band results in an amplification of the phenomenon in the problem studied here. However, it is not possible to generalize this behavior for all problems and assume the consideration of spectral dependence will always result in an increase in the turbulence-radiation interaction (compared to a gray gas model); in fact, for example, Modest (2005) found the opposite behavior in an analysis of the Sandia D flame, in which TRI proved to be more relevant using a gray gas model.

It is interesting to observe that, among the gray gas models, the $GG_{\kappa(T)}$ model (that assumes a polynomial dependence of the absorption coefficient on the local temperature) leads to greater differences – both for the mean radiative heat flux and for the mean radiative heat source – than the GG_{κ} model (that uses a constant value of κ) when the medium was composed of H_2O, while for the participating gas composed of CO_2 the behavior was inverted. This is due to the form of the correlation between the absorption coefficient and the blackbody radiation intensity, as illustrated in Fig. 4. For water vapor, the correlation is negative over the entire range of gas temperatures, resulting in a negative contribution to the time-averaged RTE when solved neglecting TRI effects (compared to the RTE in the GG_{κ} model, in which the correlation is zero); ultimately, this yields relatively smaller differences between "with TRI" and "without TRI" mean wall radiative heat fluxes. On the other hand, the correlation between κ and I_b for carbon dioxide is positive for the temperature range predominant in the computational domain (400 K to 650 K); therefore, there is a positive contribution to the RTE and an increase in the relative difference between "with TRI" and "without TRI" results, compared to the GG_{κ} model.

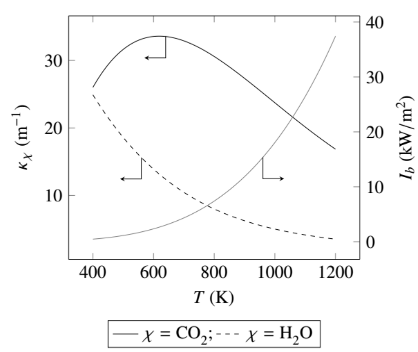

Figure 4. Absorption coefficient for CO_2 and H_2O, computed using Eq. (7) and correlations given by Cassol et al. (2015), and blackbody radiation intensity in the range of temperatures of the gas in the problem studied.

4. CONCLUSIONS

This study presented an analysis of the turbulence-radiation interaction on a channel flow of a non-reacting participating gas, using large eddy simulation to obtain the instantaneous flow field and analyzing the magnitude of TRI effects by the comparison of time-average results for quantities related to the radiative heat transfer problem with values of the same quantities obtained from time-averaged temperature and velocity fields. The weighted-sum-of-gray-gases model and two variations of the gray gas model were employed as a means to evaluate how the inclusion or not of the spectral variation of the radiative properties impacts the TRI.

The percentage difference between "with TRI" and "without TRI" results, both for the mean wall radiative heat flux and for the mean volumetric radiative heat source term, was shown not to be significant, signaling that the TRI does not have much impact on the overall heat transfer problem considered, which agrees with other studies on non-reactive flows. Nevertheless, when comparing results for the WSGG and GG models, the first presented a higher influence of TRI, probably due to its capacity to account for the way different bands of the radiative spectrum respond to temperature fluctuations. However, this influence can be positive, contributing to increase TRI effects when compared to the results for a gray medium, or negative, decreasing the effects of the phenomenon, depending on the problem studied.

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