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INFLUENCE OF THE RADIATIVE PROPERTIES OF A PARTICIPATING MEDIUM ON THE TURBULENCE-RADIATION INTERACTION IN A NON-REACTING CHANNEL FLOW

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Abstract. *Turbulence-Radiation interaction (TRI) is a complex problem characterized by non-linear and transient effects. A fundamental study on TRI in a non-reactive internal flow of carbon dioxide is performed using computer fluid dynamics (CFD) applied in the open source FORTRAN-based code Fire Dynamics Simulator (FDS). It will be investigated the influence of radiative properties of the medium on the turbulence-radiation interaction, especially the effect of the treatment of the spectral dependence. Comparison between the time-averaged values of radiative properties and values of the same properties calculated from the time-averaged temperature and velocity fields are used to evaluate the TRI effect. Turbulence is modeled using large eddy simulation (LES) with the dynamic Smagorinsky model to resolve de sub-grid scale; for the solution of the radiative part of the problem the finite volume model is employed for the spatial integration and two models are used to account for the spectral integration, the gray gas model and the weighted-sum-of-gray-gases model. Results show that TRI does not have a significant impact on the overall heat transfer problem for non-reactive gas. However, TRI effects in fact showed to be more significant when considering the spectral dependence of the radiative properties, probably due to the increase in the non-linearity of the problem.*

Keywords: *Turbulence-radiation interaction, large eddy simulation, weighted-sum-of-gray-gases, gray gas model, Fire Dynamics Simulator*

1. INTRODUCTION

Turbulence-Radiation interaction (TRI) is characterized by the simultaneous influence of thermal radiation on the flow and species concentration field – i.e., radiation influence on the turbulence – 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 (Coelho, 2007). Since, individually, thermal radiation and turbulence are two of the most difficul 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.

Although some work on TRI can be found in the literature, investigating both reactive and non-reactive flows in many configurations, not much research has been done using the weighted-sum-of-gray-gases (WSGG) model for spectral integration. The WSGG model is method relatively simple and with low computation requirement, which can be employed to account for the spectral variations of the radiative properties when calculating the thermal radiative intensity field and radiative heat transfer. This model replaces the spectrum with a few gray gases and a transparent window to account for the spectral dependence of the radiative heat transfer problem (Hottel and Sarofim, 1967; Modest, 1991).

In this paper, TRI will be analyzing using the WSGG model for problem involving convective and radiative heat transfer in a non-reacting internal flow of a participating gas (carbon dioxide). The instantaneous flow and thermal fields will be obtained using large eddy simulation (LES), implemented in the open-source computer fluid dynamics (CFD) code FDS (Fire Dynamics Simulator), for cases with different turbulence intensities. TRI will be evaluated comparing the time average of the instantaneous values of radiative properties and the same radiative properties calculated from the time-averaged temperature and flow field. Results obtained modeling the participating medium as a gray gas will also be presented, so that the influence of the spectral dependence of the radiative properties on the TRI phenomenon can be estimated.

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 are neglected. The mass, momentum and energy equations are given, respectively, by

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

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

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

where ρ is the density of the fluid; u_i is the velocity component in the i-direction; x_i corresponds to the spatial coordinate; τ_{ij} is the viscous stress tensor, defined in Eq. (4); p is the pressure; h_s is the sensible enthalpy; $\dot{q}_i''$ represents the conductive, diffusive and radiative heat fluxes; δ_{ij} is the Kronecker delta; Ω is the spatial domain; and t represents the time domain.

$$\tau_{ij}=2\mu\left(S_{ij}-\frac{1}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right) \tag{4}$$

Where μ is the dynamic viscosity of the fluid and S_{ij} is given by

$$S_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \tag{5}$$

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 can be found in the FDS technical guide (McGrattan *et al.*, 2015), which is constantly updated.

2.1.2 Large eddy simulation (LES)

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 respectively the grid dimension in direction x, y and z. For the treatment of correlations between mass density and velocity that appears from this methodology, a mass-weighted or Favre filter is also defined. For example, the momentum equation, Eq. (2), can therefore be written as

$$\frac{\partial}{\partial t}\left(\bar{\rho}\tilde{u}_i\right)+\frac{\partial}{\partial u_j}\left(\bar{\rho}\tilde{u}_i\tilde{u}_j\right)=-\frac{\partial \bar{p}}{\partial x_i}-\frac{\partial \tau_{ij}^{dev}}{\partial x_j} \tag{6}$$

where $\bar{\rho}$ is the filtered density of the fluid, $\tilde{u}_i$ is the Favre filtered velocity component in direction i, $\bar{p}$ is the modified and filtered pressure term and τ_{ij}^{dev} is the total deviatoric stress (combination of the deviatoric part of the viscous and the sub-grid scale stresses). This last term incorporates variables that cannot be computed on the numeric grid, thus requiring a model to solve the so-called closure problem. τ_{ij}^{dev} is defined as

$$\tau_{ij}^{dev} = 2\left(\mu + \mu_t\right)\left[\frac{1}{3}\left(\nabla \cdot \tilde{\mathbf{u}}\right)^2 - \tilde{S}_{ij}\tilde{S}_{ij}\right] \tag{7}$$

where μ_t is the turbulent viscosity, and $\tilde{\mathbf{u}}$ and $\tilde{S}_{ij}$ are the Favre filtered forms of the velocity vector and of S_{ij}, respectively. Following tests with some turbulence models conducted by Velasco (2014) for a problem similar to the one studied in this paper, the dynamic Smagorinsky model (Germano *et al.*, 1991; Moin *et al.*, 1991) is adopted to define μ_t.

2.1.3 Radiation modeling

For the determination of the thermal radiation field in a participating medium it is 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 absorption and emission, but neglecting scattering, the RTE is given by

$$\frac{dI_\eta}{ds} = \kappa_\eta(s)I_\eta(s) + \kappa_\eta(s)I_{\eta b}(s) \tag{8}$$

where η is the wavenumber, κ_η is the spectral absorption coefficient and $I_{\eta b}$ is the blackbody spectral intensity at the temperature in position s, given by Planck's distribution law. The global solution of the radiative transfer problem requires the spatial and the spectral integrations of Eq. (7). In this study, the finite volume method (FVM) is used to perform the spatial integration. This method divides the total solid angle 4π 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 control angle and the continuous integral over the solid angle is approximated as a sum over all the discrete angles (Raithby and Chui, 1990). For the spectral integration, in this study two methodologies are used: the gray gas (GG) model and the weighted-sum-of-gray-gases (WSGG) model. These models are described in the next two subsections.

2.1.4 The gray gas model (GG)

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

$$\frac{dI}{ds} = \kappa(s)I(s) + \kappa(s)I_b(s) \tag{9}$$

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 κ is calculated from a correlation for CO_2 proposed by Cassol *et al.* (2015), given by

$$\kappa = p_i\left(c_0 + c_1T + c_2T^2 + c_3T^3 + c_4T^4 + c_5T^5\right) \tag{10}$$

where κ is given in cm^{-1}, p_i is the partial pressure of the species (in this case, for a flow of only CO_2, p_i = 1 atm) and c_i are constants coefficients of the correlation: c_0 = -6.4780 × 10^{-1} cm^{-1}atm^{-1}; c_1 = 4.2895 × 10^{-3} cm^{-1}atm^{-1}K^{-1}; c_2 = -6.6089 × 10^{-6} cm^{-1}atm^{-1}K^{-2}; c_3 = 4.4190 × 10^{-9} cm^{-1}atm^{-1}K^{-3}; c_4 = -1.3796 × 10^{-12} cm^{-1}atm^{-1}K^{-4}; and c_5 = 1.6484 × 10^{-16} cm^{-1}atm^{-1}K^{-5}. Using for T the temperature of the entering flow (1200 K), a value of 0.1689 cm^{-1} for the absorption coefficient is obtained.

2.1.5 The weighted-sum-of-gray-gases model (WSGG)

The gray gas model is not capable to provide reliable results when radiation in participating gases such as CO_2 or H_2O is important. An alternative and probably the most widely employed method, the WSGG is a model relatively simple and with low computational cost that has shown good agreement with line-by-line integration results for a number of different conditions – for example, in Dorigon *et al.* (2013) and Cassol *et al.* (2014). In this model, the spectrum of radiation is replaced by j gray gases with uniform absorption coefficients, κ_j, and transparent windows. Each gas can also be characterized by its pressure absorption coefficient, κ_{pj}, defined as $\kappa_{pj} = \kappa_j / p_i$. The RTE for each gas can be written as

$$\frac{dI_j}{ds} = \kappa_j I_j(s) + \kappa_j a_j(s) I_b(s) \tag{11}$$

where I_j is the radiative intensity for gas j and a_j is a weighting factor (called temperature coefficient) to represent the blackbody radiation emitted, at the temperature of the medium in position s, in the wavenumber interval represented by the gas j. 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 for different temperatures and pressure path-lengths). The correlations for CO_2 used in this study were produced and presented by Cassol *et al.* (2014), modeling the spectrum with four gray gases and a transparent window. The temperature coefficient is determined from the polynomial relation

$$a_j = b_{0,j} + b_{1,j}T + b_{2,j}T^2 + b_{3,j}T^3 + b_{4,j}T^4 \tag{12}$$

where $b_{i,j}$ are the constant coefficients for gas j. These coefficients along with the absorption coefficient for each gas are presented in Tab. 1. Finally, for the transparent window (which evidently has a null absorption coefficient), the temperature coefficient a_0 is obtained from the temperature coefficients of the gray gases. For a model with a total of N gray gases, we have

$$a_0(T) = 1 - \sum_{j=1}^{N} a_j(T) \tag{13}$$

Table 1. WSGG coefficients for CO_2 with four gray gases (Cassol *et al.*, 2014);

j	$\kappa_{p,j}$ (atm^{-1}m^{-1})	$b_{0,j}$	$b_{1,j}$ (K^{-1})	$b_{2,j}$ (K^{-2})	$b_{3,j}$ (K^{-3})	$b_{4,j}$ (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}

2.2 Numerical procedures

For the simulation of the problem, the open-source FORTRAN-based CFD code FDS is used. The solver, developed by the National Institute of Standards and Technology (NIST), uses second-order finite differences with uniform, structured and staggered meshes, and explicit temporal discretization. LES with a low Mach approximation and dynamic Smagorinsky turbulence model is used to determine the flow field; constant Schmidt and Prandtl numbers are assumed to calculate the turbulent diffusivity coefficients. Turbulence at the inlet boundary condition is generated using a synthetic eddy method (SEM), in which turbulent eddies 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). The effects of the SEM can be seen in Fig. 1, which presents the instantaneous and time-averaged velocity fields for all cases simulated in this study. Perturbations in the flow at the inlet boundary condition – that, as expected, are stronger for the higher value of turbulence intensity – are carried by the stream, but have no general effect in the time-averaged velocity profile

For the spatial discretization of the domain, a grid with 437,500 cells is utilized for the main case (for the preliminary simulations to determine the outlet interface temperature for radiation, coarser spatial e temporal meshes are adopted). A time-step of 10^{-3} is adopted and each case is simulated up to 25 s; however, the time-averages required for the TRI analysis are done considering only the final 15 s of calculation, assuming that the initial 10 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. An analysis of the quality of the spatial and angular discretizations is presented in the work of Velasco (2014), 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 carbon dioxide. Geometry and boundary conditions are similar to the configurations and parameters adopted by Velasco (2014). The computation domain is modeled as a square duct, as shown in Fig. 2, 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), and the temperature is equal to 1200 K. The lateral walls have a no-slip condition and are at a constant temperature of 400 K. For the outlet interface, an open condition to the outside 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 required an iterative calculation that is described in detail in Velasco (2014).

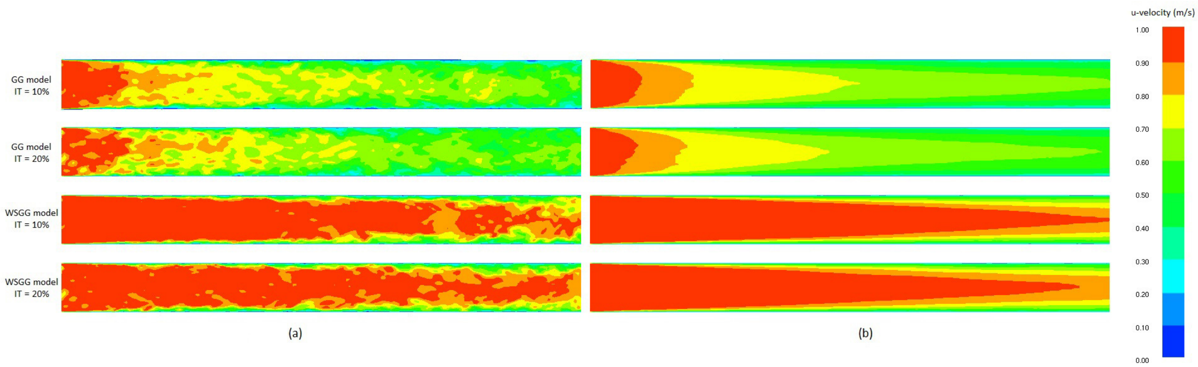

Figure 1. (a) Instantaneous and (b) time-averaged velocity field.

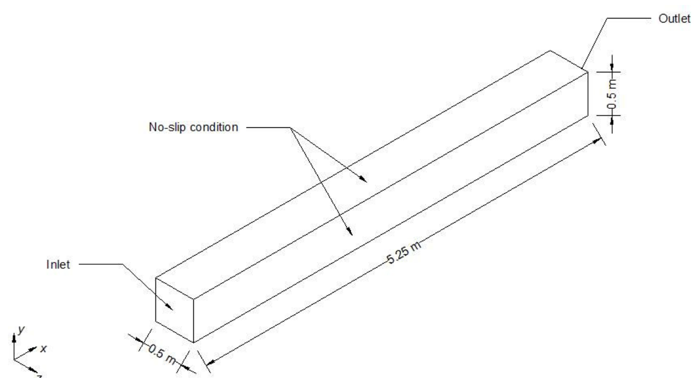

Figure 2. Computational domain and boundary conditions.

3. RESULTS

TRI is analyzed by the comparison of time-averaged radiative properties (namely, the radiative heat flux at the wall and the divergence of the radiative heat flux) obtained from the transient LES calculation, which will be called 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. Since turbulence intensity (*IT*) of the flow at the inlet boundary of the domain can be highly relevant to the fluid-dynamic phenomena (Cao and Meyers, 2013) for each model used for the RTE's spectral integration (the gray gas and the WSGG models) the same problem is simulated for an entering flow with $IT = 10\%$ and with $IT = 20\%$.

Figure 3(a) and (b) show the instantaneous (taken at t = 15 s) and time-averaged temperature fields for each case. While the temperature oscillations are clearly visible in all instantaneous profiles, the value of the turbulence intensity of the incoming flow does not affect significant the temperature field, except to add some temperature fluctuation at the earlier section of the domain. This result was also observed and discussed by Velasco (2014). The temperature field is much more affected by the spectral model used, with the WSGG model resulted in a much higher temperature over the whole domain than for the gray gas model. Since the gray gas model is not expected to yield good results for this type of flow and the WSGG model has been showed to be reliable for CO_2 radiative transfer problems (Dorigon *et al.*, 2013; Cassol *et al.*, 2014), the WSGG results are assumed to be closer to the physically correct result.

As it was explained, using the time-averaged temperature distribution (along with the time-averaged velocity field), the radiative properties are computed and compared with the result obtained time-averaging the instantaneous values of the same properties. Employing this methodology, Fig. 4(a) presents the percentage difference between the wall radiative heat fluxes along the duct length (x direction). The heat fluxes at each position in the x direction were 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). It is important to note that the percentage differences between radiative properties that will be discussed in the present section are a direct way to evaluate the magnitude of the TRI effect (the greater the difference, greater is the importance of the TRI on the problem).

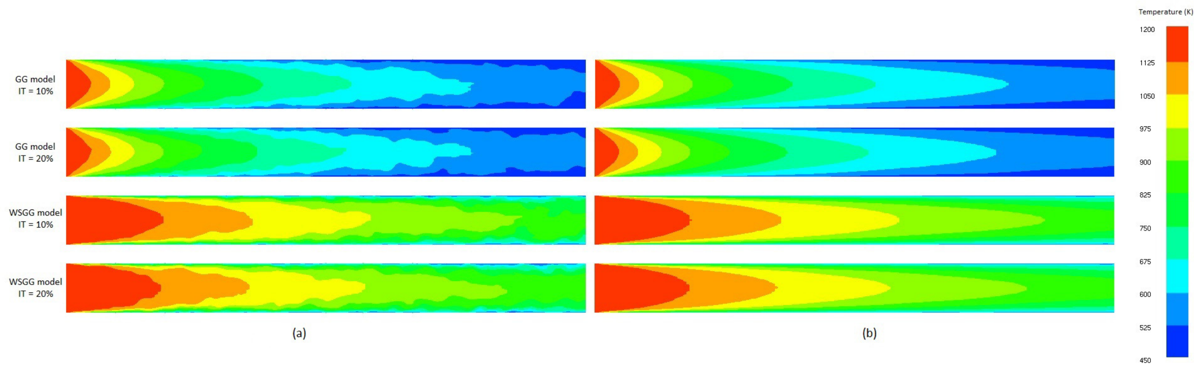

Figure 3. (a) Instantaneous and (b) time-averaged temperature fields.

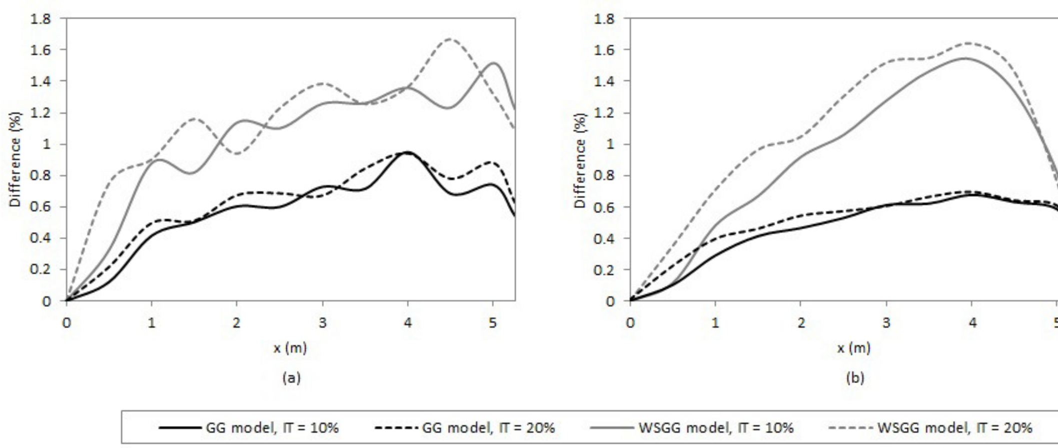

Figure 4. Percentage difference between "with TRI" and "without TRI" results for (a) the radiative heat flux at the wall and (b) the convective heat flux at the wall.

As a reference to assess the magnitude of the TRI effect on the overall problem, Fig. 4(b) presents the difference obtained using the same methodology for the convective wall heat flux. Since convection is a much more linear problem than radiation, it is expected that differences between convective heat fluxes with and without TRI will be significantly smaller. This, however, is not the case, and the differences for the convective heat fluxes are in the same order of magnitude as the differences for the radiative heat fluxes, which indicate that the TRI effects are not significant to the heat transfer problem. This was also found by other authors for participating gases in non-reacting flows (Mazumder and Modest, 1999; Gupta *et al.*, 2009). Nevertheless, it is important to note that, as Fig. 5 shows, for this problem the radiative heat flux is much more expressive that the convective heat flux for all positions in the domain.

Table 2 presents the results for the percentage difference for quantities integrated over all wall surfaces – the wall radiative heat transfer rate $\dot{q}_{w,r}$, the wall convective transfer heat rate $\dot{q}_{w,c}$, and the total wall heat transfer rate $\dot{q}_{w,t}$ – and the difference, averaged over all volumes, for the radiative heat flux divergence calculated at each cell inside the domain, $\nabla \cdot \dot{\mathbf{q}}_{\mathbf{r}}''$. Again, as it was observed in Fig. 3, the TRI influence on the wall heat transfer is of minor importance. However, when analyzing the divergence of the heat flux – an important term to represent the radiation effect on the energy equation – TRI becomes more relevant, especially for the WSGG calculations (i.e., when the spectral dependence of the radiative properties are accounted for). Still, even on the most critical case the effect of the TRI is not very significant, resulting in less than 10% of difference between "with TRI" and "without TRI" calculations.

A final observation concerns the methodology adopted for the evaluation of the TRI effect. Due to limitations of time and software, TRI was analyzed in the context of only LES simulation. Radiative properties calculated from the instantaneous transient flow field were compared with results obtained from the time-averaged temperature and velocity fields. However, the major influence of TRI arises in simulations employing the methodology of Reynolds-averaged

Navier Stokes (RANS), where the time-averaged temperature field affects and is simultaneously affected by the time-averaged radiative heat flux divergence field. Therefore, the turbulence-radiation interaction effect on the results (when compared to LES or direct numerical simulation results) is expected to be more significant than the behavior observed in this study.

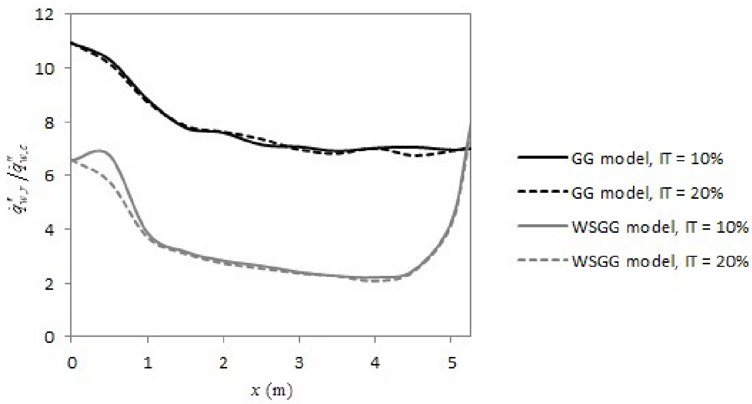

Figure 5. Comparison between radiative and convective heat fluxes at the wall.

Table 2. Percentage differences between "with TRI" and "without TRI" results for the radiative, convective and total wall heat transfer and for the radiative heat flux divergence.

Case	$\dot{q}_{w,r}$	$\dot{q}_{w,c}$	$\dot{q}_{w,t}$	$\nabla\cdot\dot{\mathbf{q}}''_{\mathbf{r}}$ (integrated)
GG model, IT = 10%	0.25348	0.37125	0.26533	1.3191
GG model, IT = 20%	0.32196	0.39343	0.32921	1.3819
WSGG model, IT = 10%	0.50483	0.82239	0.56986	9.3558
WSGG model, IT = 20%	0.63957	0.89828	0.69400	7.8855

4. CONCLUSIONS

This study presented an analysis of the turbulence-radiation interaction on a channel flow of carbon dioxide, using large eddy simulation to obtain the instantaneous flow field and the WSGG and the gray gas models to account for the spectral integration of the RTE. The TRI effect was analyzed comparing the time-averaged results for the radiative heat flux at the wall and the radiative heat flux divergence with the values for the same quantities obtained from the time-averaged temperature and velocity fields. The percentage difference between both quantities was not 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. When comparing results for the WSGG and the GG models, the first presented a higher influence of TRI, probably due to the capability of WSGG model to consider the radiative properties spectral dependence.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Cao, S. and Meyers, J., 2013. "Influence of turbulent boundary conditions on RANS simulations of pollutant dispersion in mechanically ventilated enclosures with transitional slot Reynolds number". *Applied Mechanics and Energy Conversion Section*, Vol. 59, p. 397-407.

Cassol, F., Brittes, R., Centeno, F.R., da Silva, C.V. and França, F.H.R., 2015. "Evaluation of the gray gas model to compute radiative transfer in non-isothermal, non-homogeneous participating medium containing CO_2, H_2O and soot". *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, Vol. 37, n. 1, p. 163-172.

Cassol, F., Brittes, R., França, F.H.R. and Ezekoye, O.A., 2014. "Aplication of the weighted-sum-of-gray-gases model for media composed of arbitrary concentrations of H_2O, CO_2 and soot". *International Journal of Heat and Mass Transfer*, Vol. 79, p. 796-806.

Coelho, P.J., 2007. "Numerical simulation of the interaction between turbulence an radiation in reactive flows". *Progress in Energy and Combustion Science*, Vol. 33, p. 311-383.

dos Santos, E.D., Isoldi, L.A, Petry, A.P. and França, F.H.R., 2014. "A numerical study of combined convective and radiative heat transfer in non-reactive turbulent channel flows with several optical thicknesses: a comparison between LES and RANS". *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, Vol. 36, p. 207-219.

Dorigon, L.J., Duciak, G., Brittes, R., Cassol, F., Galarça, M. and França, F.H.R., 2013. "WSGG correlations based on HITEMP2010 for computation of thermal radiation in non-isothermal, non-homogeneous H_2O/CO_2 mixtures". *International Journal of Heat and Mass Transfer*, Vol. 64, p. 863-873.

Gupta, A., Modest, M.F. and Haworth, D.C., 2009. "Large-eddy simulation of turbulence-radiation interactions in a turbulent planar channel flow". *Journal of Heat Transfer*, Vol 131, n. 6.

Germano, M., Piomelli, U., Moin P. and Cabot W.H., 1991. "A dynamic subgrid-scale eddy viscosity model". *Physics of Fluid A*, Vol. 3, n. 7, p. 1760-1765.

Hottel, H.C. and Sarofim, A.F., 1967. *Radiative transfer*. McGraw-Hill, United States of America.

Jarrin, N., 2008. *Synthetic inflow boundary conditions for the numerical simulation of turbulence*. Ph.D. thesis, University of Manchester, Manchester, United Kingdom.

Mazumder, S. and Modest, M.F., 1999. "Turbulence-radiation interaction in nonreactive flow of combustion gases". *Journal of Heat Transfer*, Vol. 121, n. 3.

McGrattan, K., Hostikka, S., McDermott, R., Floyd, J., Weinschenk, C. and Overholt, K., 2015. *Fire Dynamics Simulator Technical Reference Guide Volume 1: Mathematical Model.* NIST Spectial Publication 1018-1, 6th edition, Baltimore, Mariland, United States of America.

Modest, M.F. *Radiative heat transfer*. Academic Press, 2nd edition, United States of America.

Moin, P., Squires, K., Cabot W. and Lee S., 1991. "A dynamic subgrid-scale model for compressible turbulence and scalar transport". *Physics of Fluid A*, Vol. 3, n. 11, p. 2746-2757.

Raithby, G.D. and Chui, E.H., 1990. "A finite-volume method for predicting radiant heat transfer in enclosures with participating media". *Journal of Heat Transfer*, Vol 112, n. 2, op. 415-423.

Velasco, G.E. *Estudo da interação turbulência-radiação através do método de simulação de grandes escalas para meios participantes*. Master thesis, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil.

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