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COMPARATIVE STUDY OF GAS MIXTURE METHODS FOR THE SLW AND WSGG MODELS IN HOMOGENEOUS NON-ISOTHERMAL MEDIA

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Abstract. *This study presents a comparison between several different approaches to dealing with CO_2 and H_2O mixtures in 1D radiation problems. The WSGG and SLW spectral models were considered. The WSGG model for constant partial pressure ratio mixtures correlations and for individual species correlations was compared with SLW multiple integration, multiplication and with a generated ALBDF function for the gas mixture. Models accuracy was evaluated comparing solutions against the benchmark LBL integration. Homogeneous and isothermal, and homogeneous and non-isothermal media were considered. Results for the radiative heat flux and radiative heat source showed that the SLW with the ALBDF for mixture, the most accurate approach for uniform media, is still competitive in non-isothermal computations. The SLW multiplication approach gave the most reliable results combining computational efficiency and accuracy. Both WSGG approaches gave intermediate results while the SLW multiple integration approach proved itself to be the less recommendable choice to deal with participating gas mixtures in radiation computations.*

Keywords: *SLW model, ALBDF function, WSGG model, thermal radiation, spectral modeling*

1. INTRODUCTION

Modeling thermal radiation in participating media is a particularly challenging task due to the high irregular behavior of the radiative properties of gases with the wavenumber. Absorption spectra of common absorbing/emitting species such as water vapor (H_2O) and carbon dioxide (CO_2) present hundreds of thousands sometimes reaching up to millions of absorption lines. In addition to the complex spectral behavior there is the directional modeling of radiation. Another important aspect relates to modeling thermal radiation in multicomponent gas mixtures common in several applications such as reacting flows.

Solutions considering all participating gases absorption lines, such as the LBL integration, commonly used as benchmark to evaluate simpler models' accuracy, are very computationally demanding sometimes being prohibitive. As alternative the work of (Ziemniczak et al., 2019) proposes a methodology to reduce the number of spectral lines lowering drastically the computational costs of the LBL solution with acceptable accuracy loss. However, in CFD applications in multidimensional problems such as reacting flows (Rodrigues et al., 2019), the use of such model can still be an issue.

One of the most common choices in CFD applications is the well-known weighted-sum-of-gray-gases (WSGG) model due to its simplicity. Recent developments of the WSGG model presented new coefficients for multicomponent gas mixtures (Dorigon et al., 2013; Coelho and França, 2018) for constant partial pressure ratios. In alternative to the constant partial pressure ratio coefficients, the works of (Cassol et al., 2014; Consalvi et al., 2019) presents WSGG coefficients for individual species in order to account properly for inhomogeneous gas mixtures. In a recent work (Johansson et al., 2011; Bordbar et al., 2014) proposed new WSGG formulation and coefficients for variable partial pressure ratios.

The state-of-art spectral line weighted-sum-of-gray-gases (SLW) model has been receiving special attention with several developments in recent years. The SLW model is constructed based on the Absorption Line Blackbody Distribution Function (ALBDF) first presented by (Denison and Webb, 1993) and recently updated and tabulated by (Pearson et al., 2014). The classical SLW reference approach (Denison and Webb, 1995), the generalized SLW (Solovjov et al., 2016), the rank correlated SLW (Solovjov et al., 2017a) and the scaled SLW (Solovjov et al., 2017b) are the most recent developments, highlighting the rank correlated SLW that does not require the statement of a reference thermodynamic state. Several approaches to deal with multicomponent mixtures were presented by (Solovjov and Webb, 2000). Special attention given to the multiplication approach that consider the gas mixture as a single gray gas and preserves good accuracy with low computational cost. The multiple integration approach is the most computationally expensive, treating each gas individually and combining to form the mixture. The ALBDF generated for the gas mixture absorption cross-section is the most accurate treatment for uniform media, however for non-uniform mixtures a large number of previously computed ALBDF for several conditions, ideally all possible, is required, not being recommendable by the author.

In the present work the WSGG developments of (Dorigon et al., 2013) for constant partial pressure ratio mixture coefficients and for individual species coefficients of (Consalvi et al., 2019) were compared to the reference SLW approach of (Denison and Webb, 1995) with three methodologies for dealing with multicomponent gas mixtures (multiple integration, multiplication, and mixture computed ALBDF) in one dimensional problems. Three test cases considering homogeneous, isothermal and non-isothermal gas mixtures were investigated. Solution accuracy was evaluated against the benchmark LBL integration. Special attention is given to the mixture ALBDF SLW formulation. This work is an initial step in expanding the conception of previously tabulated ALBDF for gas mixtures to non-isothermal medium and to non-homogeneous media.

2. RADIATIVE TRANSFER EQUATION AND SPECTRAL MODELING

The radiative transfer equation (RTE) considers the effects of absorption, emission and scattering on radiation intensity for a given participating medium along a path *S*. For an absorbing, emitting and non-scattering medium, the RTE can be written as

$$\frac{dI_\eta(s)}{ds} = -\kappa_{\eta,mix}(s) I_\eta(s) + \kappa_{\eta,mix}(s) I_{\eta,b}(s) \tag{1}$$

where I_η and $I_{\eta,b}$ are the spectral intensity and the blackbody spectral intensity (given by the Planck's function), respectively, and κ_η is the spectral absorption coefficient for the gas mixture. The negative term on the RHS of Eq. (1) represents the radiation intensity attenuation due to medium absorption, while the positive term on the RHS represents the radiation intensity increment due to medium emission.

The solution of the RTE requires both directional and spectral modeling of the absorption coefficient. The directional solution was carried out with the Discrete Ordinates Method as outlined in (Ziemniczak et al., 2019). The spectral modeling of the absorption coefficient is the focus of the present study and is outlined in next subsections.

2.1 The line-by-line integration

The LBL integration solves the RTE, Eq. (1), for each of the participating species absorption spectral lines providing high accuracy in the solution, commonly used as benchmark for radiation problems, however at a remarkably high computational cost. For the present study the absorption spectra of CO_2 and H_2O were generated with the high resolution HITEMP2010 spectral database (Rothman et al., 2010) using the Lorentz profile (Coelho and França, 2018; Ziemniczak et al., 2019) at the condition of 1 atm and temperatures ranging from 400 K up to 2500 K. The wavenumber range was 0 cm^{-1} $\leq \eta \leq$ 25,000 cm^{-1}, with a spectral resolution of $\Delta\eta = 0.066$ cm^{-1} resulting in a total of 375,000 spectral absorption lines.

2.2 The weighted-sum-of-gray-gases model

The RTE for the weighted-sum-of-gray-gases (WSGG) model (Dorigon et al., 2013; Consalvi et al., 2019) can be written as

$$\frac{dI_j}{ds} = -\kappa_j I_j + \kappa_j a_j I_b(T);\ 0 \leq j \leq J \tag{2}$$

for which I_j is the *j*-th gray gases radiation intensity, κ_j and a_j are the gray gas absorption coefficient and their respective weighting factor, and $I_b = \sigma T^4/\pi$, is the blackbody intensity. The weighting factor are computed as a polynomial function of temperature as

$$a_j = \sum_{k=1}^{K} b_{j,k} T^{k-1} \tag{3}$$

where the $b_{j,k}$ are the polynomial coefficients and $a_0 = 1 - \sum_{j=1}^{J} a_j$ is the clear gas weight (assuring the energy conservation). For the purposes of the present study, two approaches for computing the participating gases mixture were considered: the first makes use of correlations obtained for mixtures at constant partial pressure rations (Dorigon et al., 2013) named from hereafter as WSGG mixture; the second considers correlations obtained for individual species (Consalvi et al., 2019) named from hereafter as WSGG individual.

WSGG mixture. For this approach, the gray gases weights are computed as in Eq. (3). The gray gases absorption coefficients are given as

$$\kappa_j = \kappa_{p,j} p\left(X_{CO_2} + X_{H_2O}\right) \tag{4}$$

in which $\kappa_{p,j}$ is the pressure-based absorption coefficient, p is the total pressure and X is the species mole fraction at the mixture. The $\kappa_{p,j}$ and $b_{j,k}$ were computed and tabulated by (Dorigon et al., 2013) for partial pressure ratios, p_{H_2O}/p_{CO_2}, equals to 1 and 2 for a total of four gray gases. Then the mixture, accounting for the clear gas (j = 0) has a total of J = 5 gray gases.

WSGG individual. For this approach, the gray gases weights and the absorption coefficients are computed for each species individually and then combined to form the mixture. The mixture weights and absorption coefficients are given as follows

$$a_j = a_{j_{CO_2}} \times a_{j_{H_2O}}\ ;\ 0 \le j_{CO_2} \le J_{CO_2}\ ,\ 0 \le j_{H_2O} \le J_{H_2O} \tag{5}$$

$$\kappa_j = pX_{CO_2} p\kappa_{p,j_{CO_2}} + pX_{H_2O}\kappa_{p,j_{H_2O}} \tag{6}$$

where the $\kappa_{p,j}$ and $b_{j,k}$ coefficients were obtained and tabulated by (Consalvi et al., 2019) for $J_{CO_2} = J_{H_2O} = 4$ gray gases. Then the mixture has a total of $J = \left(J_{CO_2}+1\right)\times\left(J_{H_2O}+1\right) = 25$ gray gases.

2.3 The spectral line weighted-sum-of-gray-gases model

The RTE for the spectral line weighted-sum-of-gray-gases (SLW) model takes the same form of the RTE derived for the WSGG model as expressed in Eq. (2). The main concept of the SLW model is that the classical LBL integration over the wavenumber can be replaced by the integration over a finite number of discrete absorption cross-sections. The gray gases weights and local values for the absorption cross-sections are computed with the Absorption Line Blackbody Distribution Function (ALBDF), first presented by (Denison and Webb, 1993).

The ALBDF function is defined as the fraction of the blackbody energy in the regions of the spectrum where the gas absorption cross-section at the local thermodynamic state, $C_\eta(\phi)$, is lower than a prescribed value C (Denison and Webb, 1993). Mathematically the ALBDF function is expressed as

$$F\left(C,\phi,T_b\right) = \int\limits_{\{\eta:\, C_\eta(\phi)<C\}} \frac{E_{b\eta}\left(T_b\right)}{E_b\left(T_b\right)} d\eta = \int_0^\infty H\left[C - C_\eta\left(\phi\right)\right] \frac{E_{b\eta}\left(T_b\right)}{E_b\left(T_b\right)} d\eta \tag{7}$$

in which $\phi = \left\{T_g, X, p\right\}$ is the thermodynamic state function of the gas temperature, T_g, mole fraction, X, and total pressure, p. T_b is the blackbody source temperature, $Eb\eta$ is the Planck's function, E_b is the Planck total emissive power, and H is the Heaviside step function. Then, the ALBDF is a monotonic crescent function of the continuous variable C_η ranging from 0 to 1.

The SLW model is a state-of-art model with several recent developments such as the Rank Correlated SLW (Solovjov et al., 2017a) and the Scaled SLW (Solovjov et al., 2017b). However, for the present study, the older development known as the reference approach SLW (RA-SLW) presented by (Denison and Webb, 1995) was chosen and is outlined as follows.

First the reference thermodynamic state ϕ_{ref} is chosen. Then the C-variable is partitioned into supplemental absorption cross-sections $\tilde{C}_j^{ref} = C_{\min}\left(C_{\max}/C_{\min}\right)^{j/n}$, $j = 0, 1, \ldots, n$, for all gray gases. Then the model is constructed through the steps below:

(1) The local supplemental absorption cross-section $\tilde{C}_j^{loc}$ are computed solving the implicit equation defined as

$$F\left(\tilde{C}_j^{loc}, \phi_{loc}, T_b = T_{ref}\right) = F\left(\tilde{C}_j^{ref}, \phi_{ref}, T_b = T_{ref}\right) \tag{8}$$

The local absorption cross-sections are computed as the geometric mean of the local supplemental absorption cross sections

$$C_j^{loc} = \sqrt{\tilde{C}_{j-1}^{loc}\tilde{C}_j^{loc}} \tag{9}$$

Then the local gray gases absorption coefficient is given as

$$\kappa_j^{loc} = N^{loc} X^{loc} C_j^{loc} \tag{10}$$

where N is the local gas molar density.

(2) The local gray gases weights are computed as

$$a_j^{loc} = F\left(\tilde{C}_j^{ref}, \phi_{ref}, T_b = T_{loc}\right) - F\left(\tilde{C}_{j-1}^{ref}, \phi_{ref}, T_b = T_{loc}\right) \tag{11}$$

Three methods were considered to compute the participating gases mixture as stated in (Solovjov and Webb, 2000): the multiple integration approach, the multiplication approach, and ALBDF functions generated for the exact condition of medium mole fractions, named from hereafter as ALBDF mixture.

Multiple integration. This approach consists in compute the gray gases weights and local absorption coefficients for each participating species individually and then combine to form the mixture coefficients. There are necessary two previously computed and tabulated ALBDF functions for each one of the participating species CO_2 and H_2O (obtention procedure and parameters details are outlined later). The gray gases weights are obtained for CO_2 and H_2O as described in Eq. (11), and the local absorption coefficients for CO_2 and H_2O are obtained as described in Eq. (8)-(10). The mixture parameters are computed for the weights and absorption coefficients as given by Eq. (5) and Eq. (6), respectively.

Multiplication. In this approach the mixture of participating species is treated as a single gas. The ALBDF for the single gas is defined as

$$\begin{aligned} &F_{X_{CO_2}C_{\eta,CO_2}+X_{H_2O}C_{\eta,H_2O}}\left(\tilde{C}_j^{ref}, T_g, T_b, X_{CO_2}, X_{H_2O}, p\right) = \\ &F_{C_{\eta,CO_2}}\left(\frac{\tilde{C}_j^{ref}}{X_{CO_2}}, T_g, T_b, X_{CO_2}, p\right) \times F_{C_{\eta,H_2O}}\left(\frac{\tilde{C}_j^{ref}}{X_{H_2O}}, T_g, T_b, X_{H_2O}, p\right) \end{aligned} \tag{12}$$

The gray gases weights and local absorption coefficients are computed as outlined in Eq. (11) and Eq. (8)-(10), respectively.

ALBDF mixture. In this approach the participating gases mixture is treated as a single gas as in the multiplication approach, however through a previously computed and tabulated ALBDF function for homogeneous medium with the mixture absorption cross-section $C_{\eta,mix}$ defined as

$$C_{\eta,mix} = X_{CO_2}C_{\eta,CO_2} + X_{H_2O}C_{\eta,H_2O} \tag{13}$$

The gray gases weights and absorption coefficients are computed as given in Eq. (11) and Eq. (8)-(10), respectively. This approach is the most accurate option to compute radiation in uniform (homogeneous and isothermal medium), however not practical to dealing with non-homogeneous mixtures being necessary many tabulated ALBDF, ideally for all possible conditions.

ALBDF function generation. The absorption cross-sections used to generate the ALBDF functions are the same used in the LBL integration. For CO_2 a single mole fraction condition was considered ($X_{CO_2} = 0$) while for H_2O two values were considered ($X_{H_2O} = 0.1$ and 0.2). For all cases 22 values of blackbody source temperature T_b and gas temperature T_g were considered, varying from 400 K to 2500 K in uniform intervals of 100 K. The supplemental absorption cross-sections were divided into 71 values logarithmically spaced between 10^{-25} cm^2/molecule and 10^{-17} cm^2/molecule.

3. TEST CASES

The problem under investigation consists of a one-dimensional slab medium filled with a homogeneous, isothermal and non-isothermal gas mixtures, bounded by black walls separated by a distance of S = 1 m. The medium is discretized into 201 evenly spaced points. Two mole fraction conditions are considered: $X_{CO_2} = X_{H_2O} = 0.1$; and $X_{CO_2} = 0.1$ and $X_{H_2O} = 0.2$, leading to partial pressure ratios of 2 and 1, respectively. Three temperature profiles are considered (Figure 1). For the isothermal medium, the walls temperatures are kept at 400 K.

$$T(s) = 1100 \text{ K} \tag{14}$$

$$T(s) = 400 \text{ K} + (1400 \text{ K})\sin^2\left(\frac{\pi s}{S}\right) \tag{15}$$

$$T(s) = 400 \text{ K} + (1400 \text{ K})\sin^2\left(\frac{2\pi s}{S}\right) \tag{16}$$

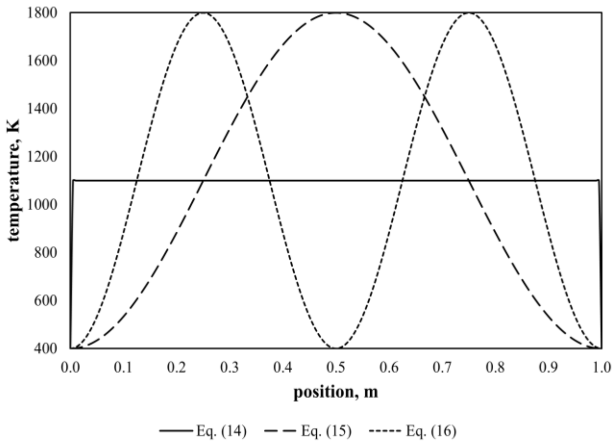

Figure 1. Test cases temperature profiles.

4. RESULTS AND DISCUSSIONS

The SLW results reported were obtained for a total of 71 gray gases (in the case of multiple integration approach this number relates to the number of gray gases of each species individually, thus the mixture has a total of 71^2 gray gases). This number of gray gases was chosen to match the total number of supplemental absorption cross-sections used to discretize the C-variable in the construction of the tabulated ALBDF functions. The thermodynamic reference state is required only for the non-isothermal cases and consists of the reference temperature only chosen to be represented as the medium maximum temperature. For the WSGG mixture and WSGG individual a total of 5 and 25 gray gases were considered, respectively.

The first case investigated was the isothermal homogeneous medium for both partial pressure ratios of 1 and 2, respectively. In these conditions the SLW ALBDF mixture approach presents the most accurate results in relation to the LBL integration, since the conditions match to ones those the ALBDF data were tabulated. Figure 2 show the solutions in comparison to the LBL benchmark. The error for the radiative heat flux and radiative heat source terms solutions are computed as

$$\delta = \frac{\left|\varsigma_{LBL} - \varsigma_{SLW/WSGG}\right|}{\max\left|\varsigma_{LBL}\right|} \times 100\% \tag{17}$$

where ς_{LBL} represents the LBL solution and the $\varsigma_{SLW/WSGG}$ represents the SLW or the WSGG solution of the radiative heat flux or radiative heat source terms.

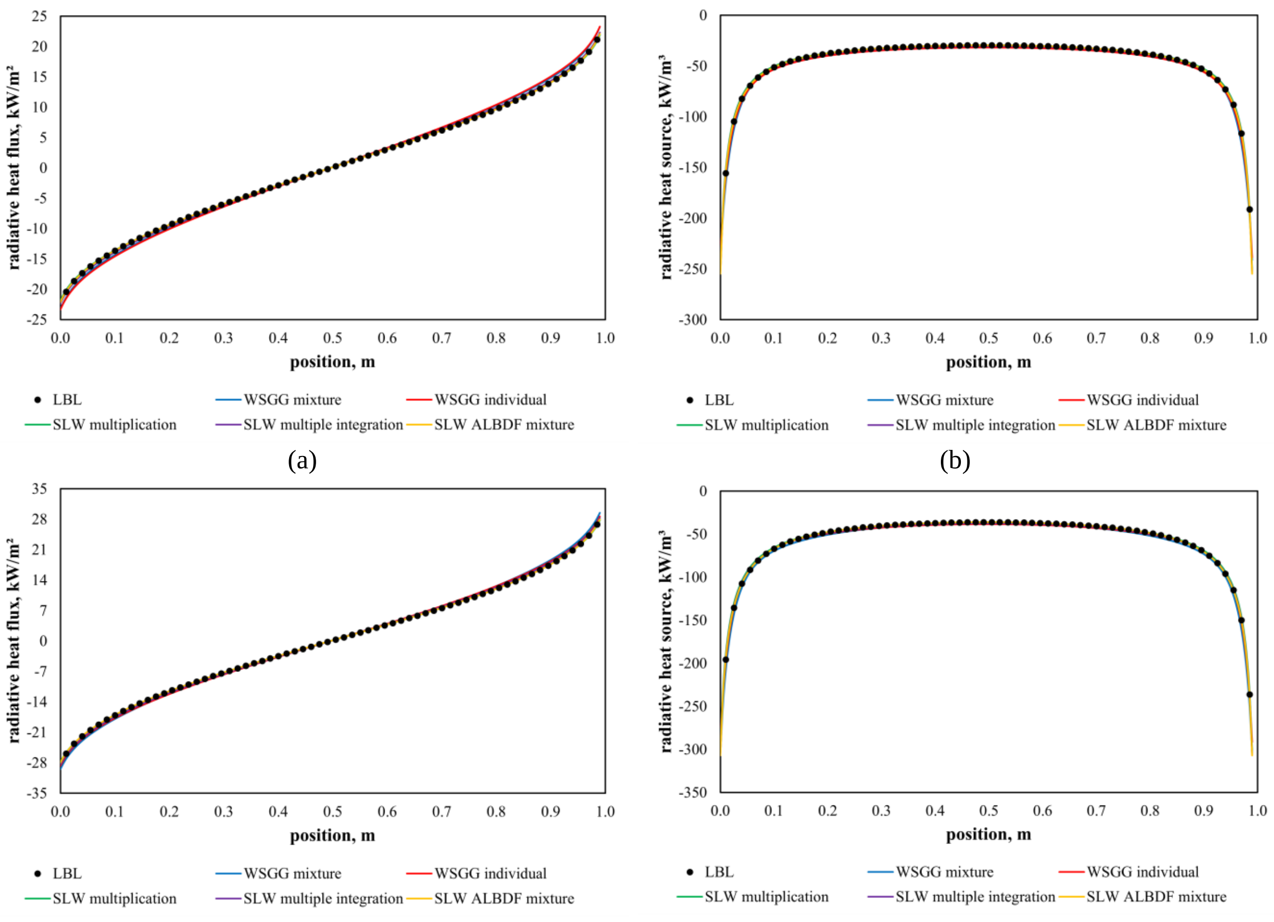

Figure 2. Partial pressure equals to 1: (a) radiative heat flux; (b) radiative heat source; partial pressure equals to 2: (c) radiative heat flux; (d) radiative heat source.

For this test case all spectral models presented good results in comparison to the LBL integration benchmark solution and no discrepancies can be seen from the Figure 2, except to the regions close to the walls where the curves tend to deviate (mainly for the radiative heat flux). Computed maximum and average (arithmetic) errors are presented in Table 1.

Table 1. Maximum and average errors computed for the homogeneous and isothermal medium.

Model	Partial pressure = 1				Partial pressure = 2			
	Radiative heat flux		Radiative heat source		Radiative heat flux		Radiative heat source	
	δ_{max}	δ_{avg}	δ_{max}	δ_{avg}	δ_{max}	δ_{avg}	δ_{max}	δ_{avg}
WSGG mixture	5.09	2.11	5.29	0.94	5.28	1.92	4.46	0.98
WSGG individual	5.36	2.65	6.34	1.00	2.53	1.67	5.13	0.61
SLW multiple integration	1.03	0.18	1.31	0.25	0.63	0.35	1.89	0.34
SLW multiplication	1.23	0.80	0.40	0.25	1.49	0.97	0.60	0.33
SLW ALBDF mixture	0.16	0.06	0.07	0.03	0.13	0.05	0.09	0.02

As it can be noticed, for both partial pressure ratios the results of the SLW model are consistently more accurate than the WSGG as expected since the ALBDF functions are generated directly from the absorption cross-section spectra of the participating species while the WSGG coefficients are obtained from the fitting of total emittance data computed with the LBL. The SLW ALBDF mixture proved itself to be the most accurate model for dealing with uniform media giving considerably lower values of both maximum and average errors in relation to the LBL benchmark. The SLW multiplication approach and SLW multiple integration presented very similar results with the advantage for the multiplication approach as it is much less computationally expensive.

Figure 3 shows the results for the second test case consisting of the homogeneous and non-isothermal medium with the temperature profile given by the Eq. (15). For non-isothermal media, the mixture correlations and/or ALBDF are expected to present considerably higher errors in relation to the uniform media. However, since the test case is homogeneous, the error rises only due to the temperature interpolation. This is relevant for the SLW model since it can be compared the deviations caused by temperature interpolation and mixture composition approach (for multiple integration and multiplication methods) and temperature interpolation only (for ALBDF mixture approach).

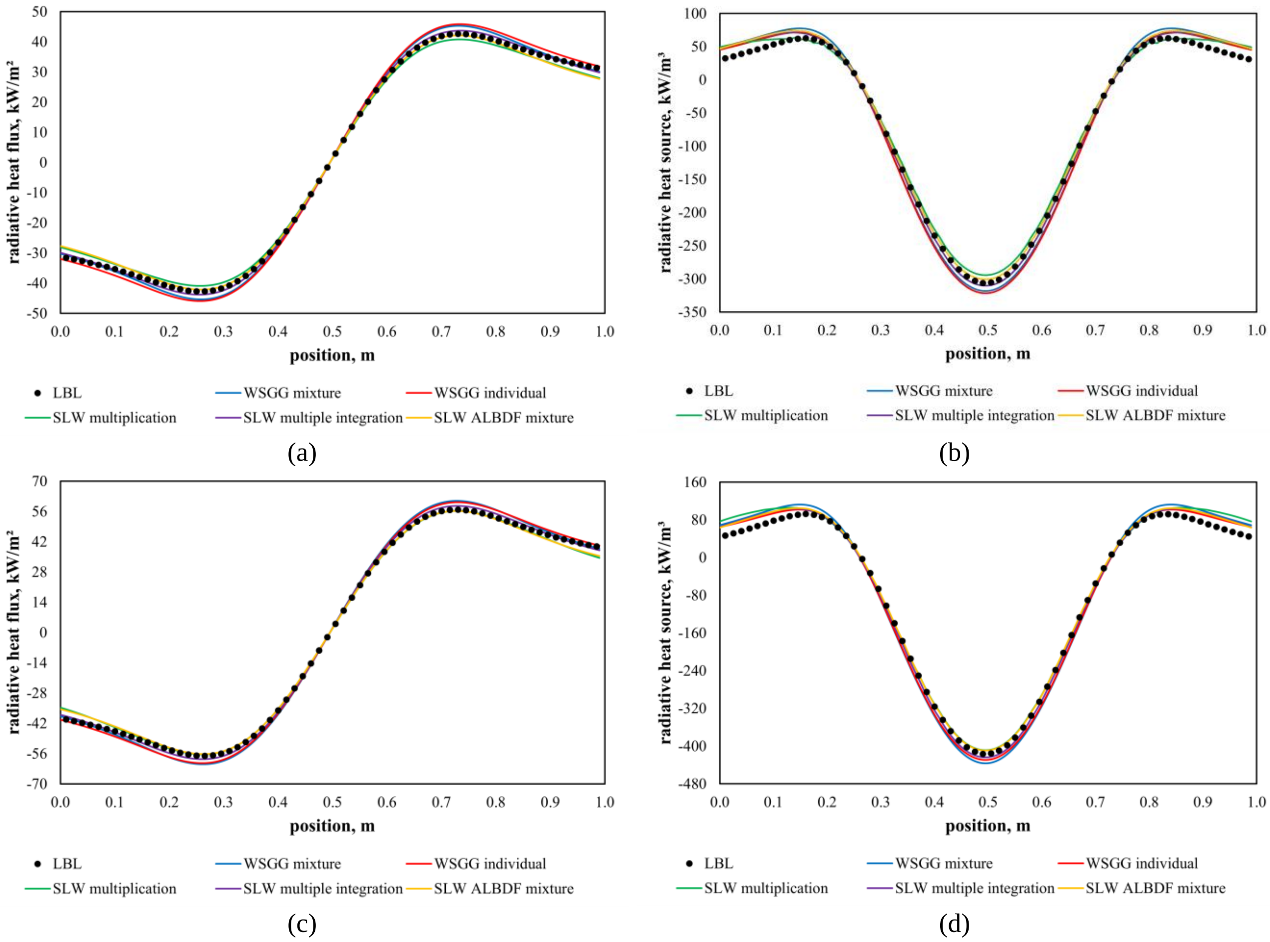

Figure 3. Partial pressure equals to 1: (a) radiative heat flux; (b) radiative heat source; partial pressure equals to 2: (c) radiative heat flux; (d) radiative heat source.

From Figure 3 deviations can be seen for all models both in the near wall regions and the maximum flux/source regions. Computed average and maximum errors are presented in Table 2.

Table 2. Maximum and average errors computed for the homogeneous and non-isothermal medium.

Model	Partial pressure = 1				Partial pressure = 2			
	Radiative heat flux		Radiative heat source		Radiative heat flux		Radiative heat source	
	δ_{max}	δ_{avg}	δ_{max}	δ_{avg}	δ_{max}	δ_{avg}	δ_{max}	δ_{avg}
WSGG mixture	6.16	3.35	6.01	4.16	6.91	3.87	6.14	4.29
WSGG individual	7.44	4.83	5.70	3.74	6.06	3.84	4.99	3.05
SLW multiple integration	7.52	3.67	6.21	2.55	8.95	2.24	8.26	2.75
SLW multiplication	3.21	1.56	5.50	2.33	2.97	1.77	5.41	2.44
SLW ALBDF mixture	8.33	2.53	5.61	2.34	7.50	2.29	5.14	2.09

Surprisingly the SLW ALBDF mixture approach presented good results with average errors as good as both multiple integration and multiplication approaches and seems to remain competitive. The SLW multiplication approach proved itself a more reliable approach for dealing with mixtures in this problem since presented both lower maximum and average errors. Other approaches, despite the low values of average errors, presented higher values of maximum errors. Again, all SLW models presented more accurate results than the WSGG model.

Test case three corresponds to the homogeneous and non-isothermal medium given by Eq. (16). It presents the most complex temperature profile and is the more challenging test case of the present study. Figure 4 show the results obtained for the spectral models in comparison to the LBL benchmark.

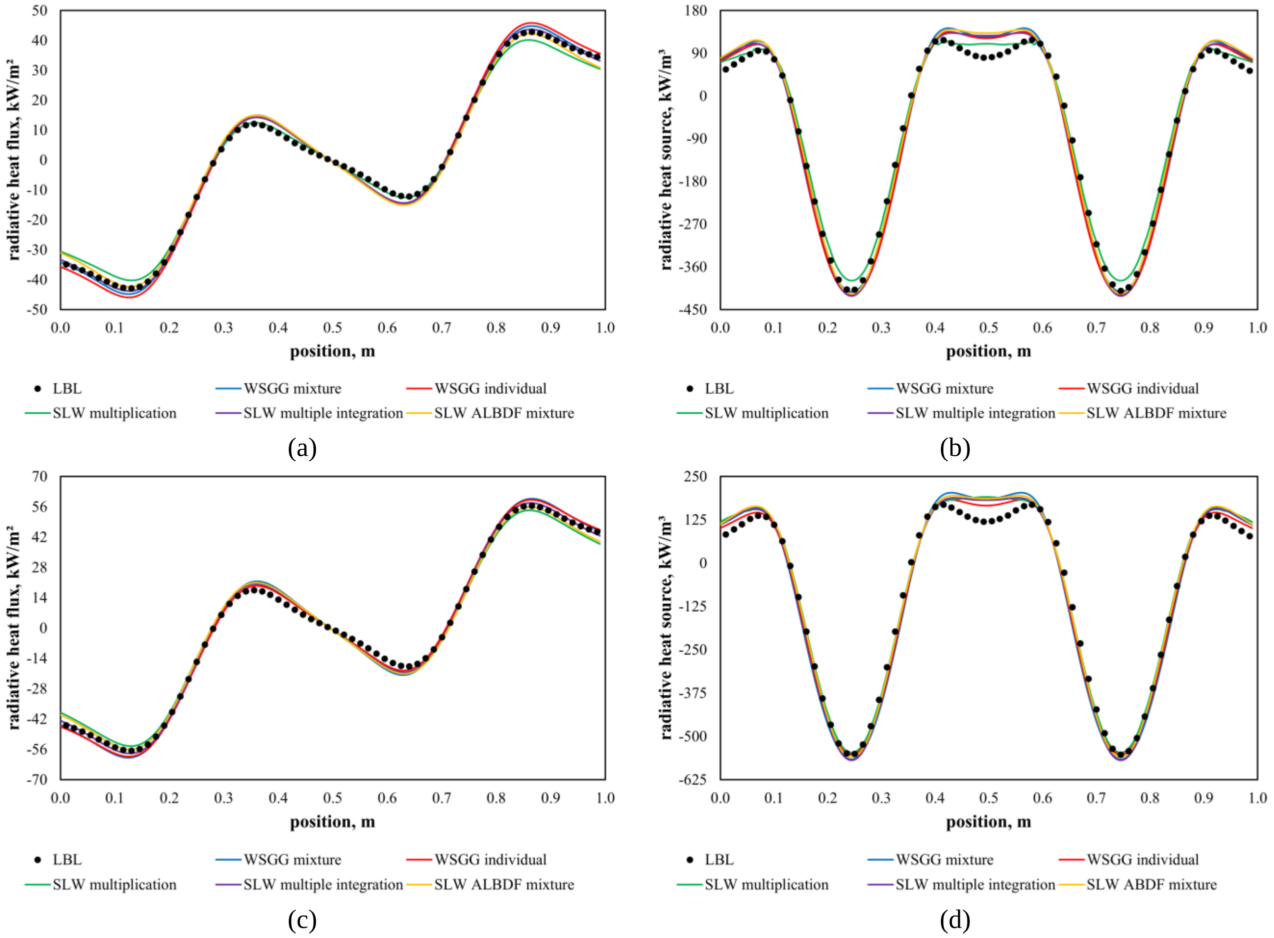

Figure 4. Partial pressure equals to 1: (a) radiative heat flux; (b) radiative heat source; partial pressure equals to 2: (c) radiative heat flux; (d) radiative heat source.

It can be seen from Figure 4 that all models presented considerable deviations in the near wall regions and at the region near the center of the domain. None of the models were able to reproduce properly the radiative heat source curve behavior in the region near the center of the domain however in the regions of maximum temperature results appear to have good accuracy. Table 3 presents the maximum and average errors in relation to the LBL benchmark solution.

Table 3. Maximum and average errors computed for the homogeneous and non-isothermal medium.

Model	Partial pressure = 1				Partial pressure = 2			
	Radiative heat flux		Radiative heat source		Radiative heat flux		Radiative heat source	
	δ_{max}	δ_{avg}	δ_{max}	δ_{avg}	δ_{max}	δ_{avg}	δ_{max}	δ_{avg}
WSGG mixture	7.61	3.17	10.47	5.28	8.21	3.98	11.74	5.59
WSGG individual	7.05	4.30	10.04	4.99	5.15	3.18	8.35	3.62
SLW multiple integration	8.89	3.47	7.06	2.91	9.12	4.24	12.93	3.54
SLW multiplication	6.23	2.43	11.21	4.08	6.27	2.49	11.29	4.10
SLW ALBDF mixture	7.71	3.81	12.65	4.35	7.15	3.48	11.99	3.97

For this case, the WSGG individual and SLW multiplication presented good results. Again, and surprisingly, the SLW ALBDF mixture approach presented competitive average errors, however with the high values of maximum error. The SLW multiple integration was able to give good results however is the more expensive approach. After all computations, the SLW multiplication appears to accomplish both reliable results and moderate computational expense being a viable choice to compute radiation. The SLW ALBDF mixture presented good results and seems to worth look forward and expands this approach do non-homogeneous media. Both WSGG approaches seem to give satisfactory results with the advantage of present low discrepancies between maximum and average errors. The SLW multiple integration is the more expensive approach presented and proved itself to be the less recommendable option to deal with participating gas mixtures.

5. CONCLUSIONS

The WSGG and the SLW models were applied in the solution of thermal radiation in homogeneous, isothermal and non-isothermal media. For the WSGG model two approaches for dealing with the participating gas mixture were investigated. One consisting of correlations obtained for constant partial pressure ratios and another consisting of correlations obtained for individual species. For the SLW model three different approaches were investigated. Two considering two tabulated ALBDF functions for the participating species and one consisting of ALBDF functions obtained for the mixture itself. Results were compared to LBL benchmark data and the error for the radiative heat flux and the radiative heat source were compared.

In general solutions presented similar errors, with the SLW being slightly more accurate than the WSGG approaches for gas mixture, however this depends on the problem being solved. The SLW multiplication approach presented good results for all test cases and lower discrepancies between maximum and average errors. Due to its computational efficiency can be considered as a good option to compute radiation in participating media. The SLW ALBDF mixture approach presented surprisingly good results for non-isothermal media being as competitive as both WSGG and SLW mixture approaches investigated. Due to its simplicity and low computational costs some studies in non-homogeneous media can be performed. The SLW multiplication approach presented high discrepancies between maximum and average errors and low consistency in the test case solutions and due to its high computational costs seems to be the less viable alternative for computing radiation in participating media.

6. ACKNOWLEDGEMENTS

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