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EVALUATION OF THE SRI AND THE WSGG MODELS IN HIGH PRESSURE SUPERCRITICAL CO₂ MEDIA

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Abstract. Engineering applications involving the use of supercritical CO₂ (s-CO₂), such as thermal power cycles and thermal energy storage systems, have been gaining an increasing interest in the recent years. In the thermodynamic conditions common in such applications, the s-CO₂ can participate significantly in the overall radiative heat transfer, even in conditions that consider moderately low temperatures. Despite this, most studies involving these engineering applications of s-CO₂ neglect the radiative heat transfer phenomenon, mainly due the computational cost required for its calculations. To aggravate this, there are currently few alternatives in the literature of less CPU intensive approximate radiation models that are applicable to these conditions. With this in mind, the present work evaluates two distinct approaches to account for radiative transfer in s-CO₂ applications: the spectrally reduced integration (SRI) method and the weighted-sum-of-gray-gases (WSGG) model. The WSGG is a global gas model that replaces the highly irregular behavior of the absorption coefficient of CO₂ by a few gray gases. Despite its simplicity, this model is able to result in satisfactory levels of accuracy, especially when considering its low computational cost. It is also expected that the high pressure and moderately low temperatures studied will improve the accuracy of the WSGG – as the behavior of the CO₂ absorption spectrum in such conditions becomes closer to what is observed in gray gases. The SRI, on the other hand, is a highly accurate methodology that is suitable to generate benchmark solutions of the radiative transfer in participating gas media. Furthermore, independent studies show that the ratio between accuracy and CPU time is even better when dealing with high pressure gas media composed of only CO₂. Thus, the present study aims to provide new WSGG correlations as an alternative for faster approximate calculations in s-CO₂ media while also evaluating the applicability of the SRI for benchmark solutions in such conditions. In summary, it is expected that both methodologies will present satisfactory performance, each in its own merit, depending on whether the user favors high accuracy or faster solution time.

Keywords: supercritical CO₂, radiative heat transfer, high pressure, spectrally reduced integration, weighted-sum-of-gray-gases

1. INTRODUCTION

The use of supercritical CO₂ (s-CO₂) in engineering applications – e.g. thermal power cycles and thermal energy storage systems – has been gaining an increasing interest in the recent years, mainly due to its operational and environmental advantages over other working fluid alternatives (Khivsara *et al.*, 2016; da Rosa *et al.*, 2022; Battisti *et al.*, 2022; Delsoto *et al.*, 2023). In the thermodynamic conditions common in such applications, the s-CO₂ medium can participate significantly in the overall radiative heat transfer, especially if high temperatures are involved. For instance, the study from Khivsara *et al.* (2016) concluded that, for a s-CO₂ heat transfer equipment in a Brayton cycle, neglecting thermal radiation can lead to large errors in the wall temperature predictions. Independent studies also show that, even when considering low temperatures, the Planck mean absorption coefficient of this working fluid can be significantly higher than what is observed in other applications where thermal radiation play a dominant roll in the overall heat transfer balance of the problem. In spite of that, most studies involving these s-CO₂ engineering equipment do not account for this heat transfer phenomenon, mainly due the high computational cost required for the solution of the radiative transfer equation (RTE) in such conditions.

In a participating medium composed of s-CO₂, the highly irregular wavenumber dependence of the absorption coefficient makes the spectral integration of the RTE too CPU intensive. Thus, accounting for this spectral behavior in detail – which is referred to as the line-by-line (LBL) methodology (Modest, 2013; Howell *et al.*, 2016) – is often limited to

the generation of benchmark solutions that are used to validate other approximate, more efficient gas models. The most widely employed gas modeling alternatives can be divided into two groups: the band models (Rivière and Soufiani, 2012; Cai and Modest, 2014) and the global models (Coelho and França, 2018; Pearson *et al.*, 2014; Modest and Riazzi, 2005). Among these possibilities, the weighted-sum-of-gray-gases (WSGG) is a simple and efficient gas model that can result in satisfactory accuracy for a variety of applications (Kangwanpongpan *et al.*, 2012; Dorigon *et al.*, 2013; Bordbar *et al.*, 2014; Coelho and França, 2018). However, to the authors' best knowledge, there are no WSGG correlations for s-CO₂ conditions available in the literature. One of the few studies that consider thermal radiation in its calculations, the one from Khivsara *et al.* (2016), employ only a simple gray band model gas. Therefore, there is demand for other up to date alternatives that are advantageous either in terms of efficiency or accuracy.

Regarding highly accurate methodologies, the CPU time required for a LBL integration of the RTE can be prohibitive even when only a benchmark solution is desired. This was the case in the studies from Rodrigues *et al.* (2019); Consalvi *et al.* (2020), which had to generate approximate benchmark solutions using the direct spectral integration (DSI) (Ziemiczak *et al.*, 2019) and the narrow band correlated *k*-distribution (NBCK) (Cai and Modest, 2014) methodologies. With this in mind, Coelho *et al.* (2021) proposed the spectrally reduced integration (SRI), which is an improved version of the DSI that only apply coarser wavenumber discretizations on the bands that are less important to the overall radiative heat transfer of the problem. In the following study from Coelho *et al.* (2023), it was concluded that the SRI is a great alternative to solve high pressure CO₂ participating media, being competitive with the NBCK and significantly more efficient than the LBL.

Following this discussion, the present work evaluates two distinct approaches to account for radiative transfer in s-CO₂ thermal energy storage systems: the SRI method, for benchmark and highly accurate solutions, and the WSGG model, for approximate, more efficient solutions. Due to the high pressure and moderately low temperatures involved in s-CO₂ thermal energy storage systems, is expected that the accuracy of the WSGG should be even more satisfactory than what is usually reported in the literature (Bordbar *et al.*, 2014; Coelho and França, 2017, 2018; Bordbar *et al.*, 2021). Similarly, since the total pressure considered in the present work are higher than those studied by Coelho *et al.* (2023), it is also expected that the SRI should be even more competitive than what is reported in that study. Thus, the present study aims to provide new WSGG correlations, as an alternative for faster approximate calculations in s-CO₂ media, while also evaluating the applicability of the SRI for benchmark solutions in such conditions.

2. METHODOLOGY

For the CO₂ participating gas medium considered in the present study, the scattering effect is negligible and the RTE is then given by (Modest, 2013; Howell *et al.*, 2016)

$$\frac{dI_\eta}{ds} = -\kappa_\eta I_\eta + \kappa_\eta I_{b\eta} \quad (1)$$

where κ_η is the absorption coefficient of the participating medium, I_η is the spectral radiation intensity, $I_{b\eta}$ is the spectral blackbody radiation intensity, and s is the path length along a line of sight. Since the medium is composed of only CO₂, the absorption coefficient κ_η is calculated as

$$\kappa_\eta(p, T, Y_c) = N(p, T) Y_c C_{\eta,c}(p, T, Y_c) \quad (2)$$

in which N is the gas molar density and $\kappa_{\eta,c}$, Y_c and $C_{\eta,c}$ are, respectively, the absorption coefficient, the mole fraction and the absorption cross-section for the CO₂ species. It is apparent from Eq. (2) that the wavenumber dependence of κ_η is inherited exclusively from $C_{\eta,c}$. These CO₂ absorption cross-sections – when considering the Lorentz profile for the broadening of the spectral lines – are then calculated by

$$C_\eta = \sum_{k=1}^K C_{\eta,k} = \sum_{k=1}^K \frac{S_k}{\pi} \frac{\gamma_k}{\gamma_k^2 + (\eta - \eta_k)^2} \quad (3)$$

where K is the total number of significant spectral lines for the wavenumber interval located at the η , $C_{\eta,k}$ is the contribution of the spectral line k to the absorption cross-section, S_k is the integrated line intensity, γ_k is the line half-width for the chosen line profile, and η_k is the wavenumber position of the center of the spectral line that is being considered. The line half-width γ_k is calculated using the high-resolution spectroscopic database HITEMP2010 (Rothman *et al.*, 2010) and is given by

$$\gamma_k = \left(\frac{T_{ref}}{T} \right)^{n_i} (p_c \gamma_{self,k} + (p - p_i) \gamma_{air,k}) \quad (4)$$

where $T_{ref} = 296$ K is the reference temperature of the HITEMP2010 database, n_i is the temperature dependence coefficient, p_c is the partial pressure of CO₂, $\gamma_{self,k}$ is the half-width due to the line self-broadening, and $\gamma_{air,k}$ is the

half-width due to the broadening caused by air. Finally, the integrated line intensity S_k is then obtained through (Rothman *et al.*, 2010)

$$S_k(T) = S_k(T_{ref}) \frac{Q(T_{ref})}{Q(T)} \frac{\exp(-C_2 E_k/T)}{\exp(-C_2 E_k/T_{ref})} \frac{[1 - \exp(-C_2 \eta_k/T)]}{[1 - \exp(-C_2 \eta_k/T_{ref})]} \quad (5)$$

in which Q is the total internal partition sum, E_k is the energy of the lower state, and η_k is the wavenumber location of line k . The line parameters η_k , n_i , $\gamma_{self,k}$, $\gamma_{air,k}$, $S_k(T_{ref})$, Q , and E_k are taken from the high resolution spectroscopic database HITEMP2010 (Rothman *et al.*, 2010).

In this work, the absorption cross-sections $C_{\eta,c}$ are calculated considering a mole fraction of $Y_c = 1$, temperatures ranging from 308 K to 356 K, and the total pressure values of 75 atm, 90 atm, 105 atm, 125 atm and 150 atm. The CO₂ absorption spectrum is considered ranging from 0 to 25 000 cm⁻¹. For each of the total pressure conditions evaluated, a wavenumber grid analysis was performed, similar to the one presented in the study by Coelho *et al.* (2021). It was found that spectral intervals of $\Delta\eta = 5$ cm⁻¹, 6 cm⁻¹, 6.67 cm⁻¹, 8.83 cm⁻¹ and 10 cm⁻¹ were enough for, respectively, the total pressures of 75 atm, 90 atm, 105 atm, 125 atm and 150 atm. Following the recommendations from Pearson *et al.* (2014), a line wing cutoff equal to $600\gamma_k$ was considered, in order to address the overestimation of the line broadening caused by the Lorentz profile in high total pressure conditions.

The reference LBL is then calculated using this absorption cross-section database to solve the RTE from Eq. (1). When the discrete ordinates method (DOM) is employed to solve Eq. (1) in a one-dimensional domain, the spectral radiative heat flux and source term are given by

$$q_{r,\eta}(x) = \sum_{l=1}^{n_d} [2\pi\mu_l\omega_l(I_{\eta,l}^+(x) - I_{\eta,l}^-(x))] \quad (6)$$

$$S_{r,\eta}(x) = \sum_{l=1}^{n_d} [2\pi\kappa_\eta\omega_l(I_{\eta,l}^+(x) - I_{\eta,l}^-(x))] - 4\pi\kappa_\eta I_{b\eta} \quad (7)$$

where w_l is the quadrature weight for the l th direction, n_d is the total number of directions l , μ_l is the direction cosine associated with the l th direction, and $I_{\eta,l}^+$ and $I_{\eta,l}^-$ are, respectively, the spectral radiation intensity for outward ($\mu_l > 0$) and inward ($\mu_l < 0$) fluxes. The LBL total emissivities are also calculated from the absorption cross-sections $C_{\eta,c}$, such that (Modest, 2013; Howell *et al.*, 2016)

$$\epsilon = \frac{\int_0^\infty I_{b\eta}[1 - \exp(-\kappa_\eta S)] d\eta}{\sigma T^4/\pi} \quad (8)$$

in which S is the dimension of the path length along the line of sight considered.

The SRI method solves the RTE in the same manner as the LBL, but employing non-uniform wavenumber discretization schemes that consider coarser spectral meshes on the regions that are less important to the overall radiative transfer of a problem (Coelho *et al.*, 2021). Therefore, when also using the DOM to solve the RTE in a one-dimensional domain, it also considers Eqs. (6) and (7). To define which are the most relevant regions of the spectrum, Coelho *et al.* (2021) proposed the spectral contributions of the bands to the radiative heat flux and source term, which are calculated as

$$\zeta_{q_r}(\eta) = \frac{1}{L} \int_0^L |q_{r,\eta}(x)| dx \quad (9)$$

$$\zeta_{S_r}(\eta) = \frac{1}{L} \int_0^L |S_{r,\eta}(x)| dx \quad (10)$$

where L is the distance between the two parallel black walls and ζ_{q_r} and ζ_{S_r} are, respectively, the spectral contributions of each wavenumber η to the radiative heat flux and source term. These quantities represent how each wavenumber interval from the absorption spectrum of the participating gas mixture impacts the overall radiative transfer through the medium (Coelho *et al.*, 2021). Following the methodology described in Coelho *et al.* (2021), the SRI discretization schemes are then calculated from Eqs. (9) and (10).

3. RESULTS

The first results of the present study, illustrated in Figure 1, consist of emissivity charts for participating media composed of only CO₂ (i.e. $Y_c = 1$) for temperatures ranging from 308 K to 356 K, path length dimensions of 0.001 m, 0.01 m and 0.1 m, and total pressure values of 75 atm, 90 atm, 105 atm and 125 atm. The path lengths higher than 0.1 m are not displayed in the figure since their emissivity distributions are too close to the 0.1 m one. Furthermore, for $S > 0.4$ m, the curves become too close to the maximum emissivity value of 1 for the whole temperature range considered here. This is

a consequence of the high optical thickness of the participating media – which is caused by a combination of high total pressure, high CO₂ mole fraction, and low temperatures. If compared to the CO₂ emissivity charts presented in the work by Pearson *et al.* (2014) for 50 atm, it can be noticed that the curves from Figure 1 display a similar behavior, despite the higher total pressure considered here. It is also apparent that the emissivity values increase with total pressure, which is also observed by several other studies (Pearson *et al.*, 2014; Coelho and França, 2017, 2018) and is the expected outcome since the total emissivity increases with the optical thickness of the medium (Modest, 2013). Due to the low temperature range considered, the decrease of the emissivity values as the temperature increases is low when compared to the charts presented in previous studies. In fact, this effect also seems to attenuate as the total pressure increases – which is once more a consequence of the increase in the optical thickness.

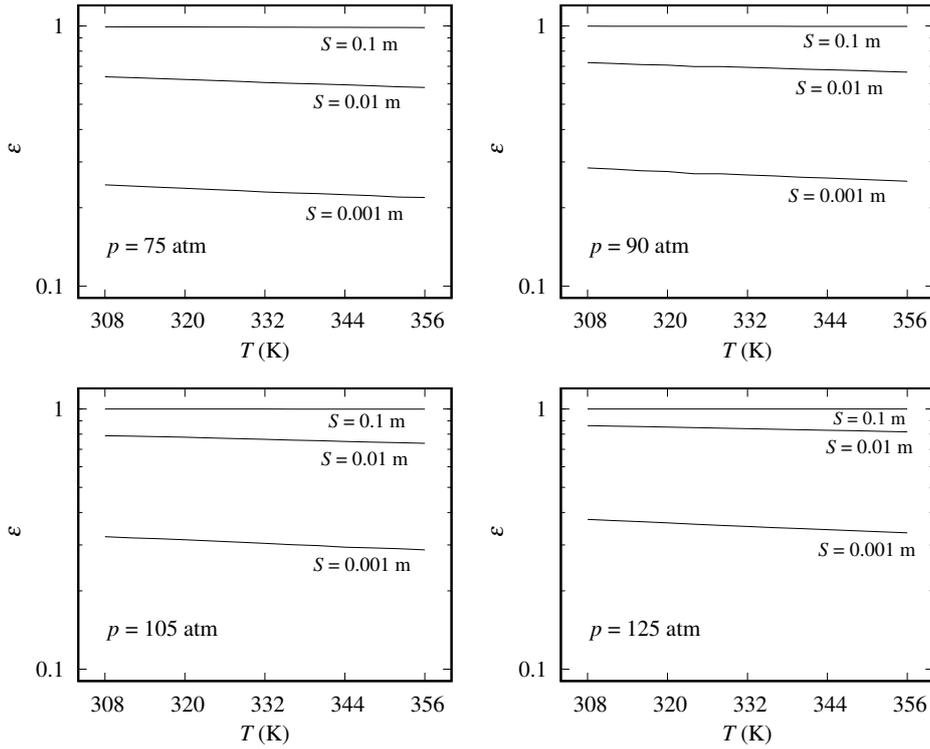


Figure 1. Total emissivity charts for CO₂ media with $Y_c = 1$ for temperatures from 308 K to 356 K, path length of 0.001 m, 0.01 m and 0.1 m, and total pressures of 75 atm, 90 atm, 105 atm and 125 atm.

The total emissivity charts from Figure 1 can be directly used in less sophisticated, more practical engineering gas models Modest (2013) that involve s-CO₂ applications in the temperature and total pressure conditions considered here. However, in the framework of the present study, the goal is to employ them to generate new WSGG correlations focused on s-CO₂ thermal energy storage systems. The fitting procedure of these WSGG coefficients is still under development, but they are planned to be reported on a future publication regarding this topic. It is expected that the WSGG will be an interesting alternative for efficient approximate solutions of the RTE, as concluded by other previous studies that developed WSGG models for high pressure participating media Coelho and França (2017, 2018); Consalvi *et al.* (2020); Bordbar *et al.* (2021).

The following results are relative to the other methodology evaluated in the present study, the SRI. For this analysis, a test case consisting of an one-dimensional slab problem is proposed. The 1D domain is filled with only CO₂ (i.e. $Y_c = 1$) and considers a temperature distribution given by

$$T = 308 \text{ K} + 48 \text{ K} \sin^2(\pi x/L) \quad (11)$$

where $L = 1$ m is the length of the slab. The participating medium is bounded by two black walls at $T = 308$ K. For such configuration, this test case is solved for three values of total pressure: 75 atm, 105 atm and 150 atm. These conditions were chosen to represent a s-CO₂ thermal energy storage system that is transferring heat to the outside, through the black walls, at three different operation total pressures. Based on the results presented by Coelho *et al.* (2023), the discretization scheme S8, initially proposed by Coelho *et al.* (2021), is employed in all the SRI results presented in this study. As usually considered in other works involving the SRI (Coelho *et al.*, 2020, 2021, 2023), the performance of the method is compared to the LBL reference solution in terms of both accuracy and computational cost – evaluated, respectively, through average and maximum deviations and the number of RTE solutions in the wavenumber, n_{RTE_n} , which is directly

proportional to the CPU time of the solution.

The number of spectral RTE solutions and the average and maximum deviations of the SRI S8 methodology for the total pressures of 75 atm, 105 atm and 150 atm is presented in Table 1. These deviations are calculated as a comparison between the LBL and the SRI methods in terms of the predictions of the radiative source term and heat flux throughout the domain. According to this data, the SRI is able to result in highly accurate solutions of the analyzed test case for all the total pressure values considered. These solutions also displayed great CPU efficiency, especially for the highest total pressure of 150 atm, as the n_{RTE_η} is almost inversely proportional to increase in pressure. Therefore, as initially expected due to the conclusions from Coelho *et al.* (2023), the SRI is a great alternative to obtain efficient benchmark solutions of CO₂ media at high total pressure conditions – such as the ones observed in s-CO₂ applications. In fact, the CPU cost reported in Table 1 is approximately twenty eight times faster than the reference LBL considered in the present study, which ranges from 0 cm⁻¹ to 25 000 cm⁻¹. In this regard, the higher wavenumber range considered in the present study makes the use of the SRI even more advantageous than what was observed in the study from Coelho *et al.* (2023). When comparing with the NBCK solutions from Coelho *et al.* (2023), the SRI S8 solutions from Table 1 are even more competitive than the SRI methods presented in that study.

Table 1. Number of spectral RTE solutions and average and maximum deviations of the SRI method in terms of radiative source term and heat flux calculations.

p_t (atm)	Method	n_{RTE_η}	$\delta_{S_r,avg}$ (%)	$\delta_{q_{r,x},avg}$ (%)	$\delta_{S_r,max}$ (%)	$\delta_{q_{r,x},max}$ (%)
75	SRI S8	178	0.13	0.25	0.22	0.46
105	SRI S8	129	0.11	0.21	0.19	0.39
150	SRI S8	93	0.08	0.18	0.15	0.32

4. CONCLUSIONS

The present study proposes two methodologies to model thermal radiation in high pressure supercritical CO₂ participating media: one for faster approximate calculations of the RTE and the other to obtain benchmark solutions that are significantly more efficient than the LBL method. The first methodology, the WSGG, consider correlations that are developed based on total emissivity data of s-CO₂. At the current state of the work, the emissivity charts were generated and presented here. Results showed that – mainly due to the high optical thickness of the media considered – the emissivity curves barely change for path lengths over 0.4 m. In agreement with observations from previous studies (Pearson *et al.*, 2014; Coelho and França, 2017, 2018; Bordbar *et al.*, 2021), it was also noticed that the magnitude of the total emissivity increase with the total pressure. The data presented can be used to develop approximate and more practical engineering gas models, such as the WSGG.

The second methodology, the SRI, employs non-uniform wavenumber discretization schemes to obtain highly accurate solutions several times faster than the LBL reference calculations (Coelho *et al.*, 2021). In the present study, a one-dimensional test case representative of applications involving s-CO₂ thermal energy storage systems was solved using the S8 scheme, first proposed in the work from Coelho *et al.* (2021). As initially expected due to the conclusions from Coelho *et al.* (2023), the SRI S8 presented a competitive ratio between accuracy and computational cost of the solutions for all the values of total pressure considered. In fact, since the LBL reference solution of the present study employed a higher wavenumber range, the SRI methodology was even more advantage in the s-CO₂ scenario analyzed, resulting in benchmark levels of accuracy approximately twenty eight times faster than the LBL method. Finally, it is also concluded that the SRI is even more competitive with the NBCK presented in Coelho *et al.* (2021) when dealing with conditions typical of s-CO₂.

The next step of this research is to develop WSGG coefficients for s-CO₂ thermal energy storage applications – based on the emissivity data presented in the present study – and compare its accuracy with the LBL and SRI benchmark solutions. This procedure is already under development and its results should be reported on a future publication on this topic. Other than that, proposing different test cases and increasing the number of total pressure values considered are also two proposals of continuity for this work.

5. REFERENCES

- Battisti, F., de Araujo Passos, L. and da Silva, A., 2022. “Economic and environmental assessment of a CO₂ solar-powered plant with packed-bed thermal energy storage”. *Applied Energy*, Vol. 314, p. 118913.
- Bordbar, H., Coelho, F.R., Fraga, G.C., França, F.H. and Hostikka, S., 2021. “Pressure-dependent weighted-sum-of-gray-gases models for heterogeneous CO₂-H₂O mixtures at sub- and super-atmospheric pressure”. *International Journal of Heat and Mass Transfer*, Vol. 173, p. 121207.

- Bordbar, M.H., Wećel, G. and Hyppänen, T., 2014. “A line by line based weighted sum of gray gases model for inhomogeneous CO₂–H₂O mixture in oxy-fired combustion”. *Combustion and Flame*, Vol. 161, No. 9, pp. 2435–2445.
- Cai, J. and Modest, M.F., 2014. “Improved full-spectrum k-distribution implementation for inhomogeneous media using a narrow-band database”. *Journal of Quantitative Spectroscopy and Radiative Transfer*, Vol. 141, pp. 65–72.
- Coelho, F.R. and França, F.H., 2018. “WSGG correlations based on HITEMP2010 for gas mixtures of H₂O and CO₂ in high total pressure conditions”. *International Journal of Heat and Mass Transfer*, Vol. 127, pp. 105–114.
- Coelho, F.R., Ziemniczak, A., Roy, S.P. and França, F.H., 2021. “A new line-by-line methodology based on the spectral contributions of the bands”. *International Journal of Heat and Mass Transfer*, Vol. 164, p. 120423.
- Coelho, F.R., Fraga, G.C., Roy, S.P. and França, F.H.R., 2023. “Comparison between the sri and nbck methods in high total pressure H₂O and CO₂ mixtures”. In *Proceedings of the 10th International Symposium on Radiative Transfer*. Tessalônica, Grécia.
- Coelho, F.R., França, F. and Roy, S., 2020. “Evaluation of the accuracy of the SRI method in non-homogeneous conditions”. In *Proceedings of the 18th Brazilian Congress of Thermal Sciences and Engineering*. ABCM.
- Coelho, F.R. and França, F.H.R., 2017. “WSGG correlations for H₂O and CO₂ in high pressure conditions”. In *Proceedings of the 24th ABCM International Congress of Mechanical Engineering*. ABCM.
- Consalvi, J., Andre, F., Coelho, F., Franca, F., Nmira, F., Galtier, M., Solovjov, V. and Webb, B., 2020. “Assessment of engineering gas radiative property models in high pressure turbulent jet diffusion flames”. *Journal of Quantitative Spectroscopy and Radiative Transfer*, Vol. 253, p. 107169.
- da Rosa, O.C., da Silva, A.K. and Gosselin, L., 2022. “Geometric and operational analysis of a heat recuperator operating with s-CO₂ near the pseudocritical region”. *Applied Thermal Engineering*, Vol. 215, p. 118933.
- Delsoto, G., Battisti, F. and da Silva, A., 2023. “Dynamic modeling and control of a solar-powered brayton cycle using supercritical CO₂ and optimization of its thermal energy storage”. *Renewable Energy*, Vol. 206, pp. 336–356.
- Dorigon, L.J., Duciak, G., Brittes, R., Cassol, F., Galarça, M. and França, F.H., 2013. “WSGG correlations based on HITEMP2010 for computation of thermal radiation in non-isothermal, non-homogeneous H₂O/CO₂ mixtures”. *International Journal of Heat and Mass Transfer*, Vol. 64, pp. 863–873.
- Howell, J.R., Mengüç, M.P. and Siegel, R., 2016. *Thermal Radiation Heat Transfer*. CRC press, 6th edition.
- Kangwanpongpan, T., França, F.H., da Silva, R.C., Schneider, P.S. and Krautz, H.J., 2012. “New correlations for the weighted-sum-of-gray-gases model in oxy-fuel conditions based on HITEMP 2010 database”. *International Journal of Heat and Mass Transfer*, Vol. 55, No. 25, pp. 7419–7433.
- Khivsara, S.D., Srinivasan, V. and Dutta, P., 2016. “Radiative heating of supercritical carbon dioxide flowing through tubes”. *Applied Thermal Engineering*, Vol. 109, pp. 871–877.
- Modest, M.F., 2013. *Radiative Heat Transfer*. Academic Press.
- Modest, M.F. and Riazzi, R.J., 2005. “Assembly of full-spectrum k-distributions from a narrow-band database effects of mixing gases, gases and nongray absorbing particles, and mixtures with nongray scatterers in nongray enclosures”. *Journal of Quantitative Spectroscopy and Radiative Transfer*, Vol. 90, No. 2, pp. 169–189.
- Pearson, J.T., Webb, B.W., Solovjov, V.P. and Ma, J., 2014. “Effect of total pressure on the absorption line blackbody distribution function and radiative transfer in H₂O, CO₂, and CO”. *Journal of Quantitative Spectroscopy and Radiative Transfer*, Vol. 143, pp. 100–110.
- Rivière, P. and Soufiani, A., 2012. “Updated band model parameters for H₂O, CO₂, CH₄ and CO radiation at high temperature”. *International Journal of Heat and Mass Transfer*, Vol. 55, No. 13-14, pp. 3349–3358.
- Rodrigues, L.G.P., Machado, I.M., Ziemniczak, A., Pereira, F.M., Pagot, P.R. and França, F.H.R., 2019. “Comparisons between numerical simulations and experimental measurements of radiative heat flux for a series of CH₄/N₂ diluted laminar non-premixed flames”. *Combustion Science and Technology*, pp. 1–22.
- Rothman, L., Gordon, I., Barber, R., Dothe, H., Gamache, R., Goldman, A., Perevalov, V., Tashkun, S. and Tennyson, J., 2010. “HITEMP, the high-temperature molecular spectroscopic database”. *Journal of Quantitative Spectroscopy and Radiative Transfer*, Vol. 111, No. 15, pp. 2139–2150.
- Ziemniczak, A., Coelho, F.R., Pereira, F.M., Pagot, P.R. and França, F.H.R., 2019. “Evaluation of the discretization in the spectral resolution for the solution of the line-by-line method in problems with participating gases”. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, Vol. 41, No. 9.

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