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# ESTIMATION OF THE TOTAL ABSORPTIVITY OF NON-GRAY SURFACES BOUNDING PARTICIPATING MEDIA

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***Abstract.*** *The study of the heat transfer by radiation is complex, but essential for the correct design of systems that operate at high temperatures, such as ovens and furnaces. These systems impose another degree of difficulty for the problem, that is the presence of combustion products, such as carbon dioxide and water vapor, which are opaque to the thermal radiation. Different solution methods were developed over the years in order to solve these problems, such as the gray gas (GG), weighted-sum-of-gray-gases (WSGG) and spectral line-based WSGG (SLW) models. These models provide good accuracy, at a fraction of the computational cost of the line-by-line-integration, which is the benchmark method. The main disadvantage of these models is the fact that it not possible to evaluate a participating medium bound by non-gray walls. However, recent studies proved that assuming a reference temperature for the evaluation of the absorptivity of a non-gray wall bounding combustion products provided a good agreement to the LBL solution. So, the present study provides a deeper investigation of the influence of the required reference temperature for different conditions. A non-gray surface is subjected by thermal radiation travelling through a mixture of water vapor and carbon dioxide, emitted by a black surface in a unidimensional path. Different non-symmetrical temperature profiles are evaluated as well as different concentration of the species and spectral properties for the non-gray surface. Multiple reference temperatures were evaluated and the resulting total absorptivity of the surface is then compared to the LBL solution. From the results obtained, it is possible to estimate a reference temperature that provides accurate results for the total absorptivity of the non-gray surface.*

***Keywords:*** *thermal radiation, non-gray walls, heat transfer, total absorptivity*

## 1. INTRODUCTION

Even with the improvements of computational power over the years, the evaluation of thermal radiation within participating media in large scale is still very demanding. Common engineering problems, such as the design of ovens, furnaces or combustion chambers can be greatly improved if the thermal radiation is accounted for in the initial steps of their design. Due to their operation at elevated temperatures and also, in many cases, the presence of combustion products, the thermal radiation takes a major role in their operation, therefore it must be accounted for.

Nevertheless, due to the directional and spectral dependence of thermal radiation, the solution of the radiative intensity field, can be excessively time consuming, if done by the line-by-line (LBL) integration. Where, to obtain the most accurate result, hundreds of thousands of spectral lines must be evaluated, at every point of the domain and every direction. The feasibility of this method is small for larger models with complex geometries that must be evaluated in three dimensions.

To overcome this, a number of models have been developed over the years, providing good accuracy at moderate computational times. However, some of this models have a strict applicability, where not many can handle the behavior of participating media bound by non-gray walls, hampering the correct estimation of the intensity field and causing deviations from the exact solution. Despite this, some models were developed aiming to improve the solution of the intensity field on domains bounded by non-gray walls, providing good accuracy and small computational times.

Da Fonseca et al. 2018, assessed the utilization of the WSGG methodology for use on heat transfer over a domain bounded by non-gray walls and permeated by a mixture of $CO_2$ and $H_2O$. The methodology consisted in the assumption that the absorption coefficient of the medium is assumed to be randomly spread over the entire spectrum, with an equal probability. The heat flux deviation from the LBL solution was reduced in one of the studied scenarios from 9% with the assumption of a gray wall, to 4.6% when the wall was assumed non-gray. One of the main findings of the study was that the assumption of the absorptivity being equal to the emissivity at the wall temperature was not adequate for most scenarios, and that could provide larger deviations in some cases.

In 2019, Da Silva and colleagues modified the SLW methodology, where it was assumed a reference state, for the computation of properties, such as the absorption cross-section and total absorptivity of the walls. The group evaluated the radiative heat flux and radiative source terms over an 1D slab permeated by a mixture of $CO_2$ and $H_2O$, at 1 atm, subjected to non-uniform temperature distributions. The researchers encountered similar results that of Da Fonseca et al. 2018, where the methodology provided a better representation of the radiative transfer, when compared to the black and gray wall modelling.

Da Fonseca et al. in 2019, provided a an in depth study for the employment of reference temperatures for the estimation of the heat transfer over participating media, accounting for non-gray bounding walls. The main problem was solved assuming the reference temperature being a spatial average of the media temperature, following the work of Da Silva et al. 2019, for the calculation of the total hemispherical absorptivity. The results encountered proved a good agreement between the LBL integration and their method, providing a reduction in computational time proportional to the number of the wall spectral bands, when compared to similar methods that evaluate the spectral bands separately. The group also evaluated the influence on the heat flux and source term deviations for a range of reference temperatures, which proved to impact greatly the final result, ranging from 2%, up to 20%.

With the good accuracy of the results obtained in the aforementioned study and the relative efficiency in computational time of the WSGG method, this study proposes to evaluate in depth the influence of the reference temperature to the total absorptivity estimation of a non-gray surface bounding participating media. This study focused on performing the LBL integration of an unidimensional domain to evaluate the absorptivity of the non-gray surface. These values were compared to different reference temperatures, obtained by the temperature profiles in which the domain was subjected to. The optimal reference temperatures could then be stablished, in order to apply to future WSGG studies employing the reference temperature approach for solving problems with non-gray walls.

## 2. METHODOLOGY

### 2.1 Spectral properties of surfaces

Surfaces can be represented as an idealized model, called blackbody, which is a perfect emitter and absorber. Surfaces considered black, absorb all of the incoming radiation incident to them, regardless of the wavelength, therefore are they can be called gray. Also, independent the temperature or wavelength being evaluated, no other surface can emit more energy than the blackbody. Finally, the blackbody is diffuse, therefore the emitted energy is independent of the outgoing angle (Bergman and Lavine, 2017).

However, real surfaces, do not possess the same properties as the ones mentioned for the blackbody, instead they are compared to it. The emission of a real surface is compared to the one of a blackbody using the property called emissivity, which in its spectral directional form is given by:

$$\varepsilon_{\lambda,\theta}(\lambda,\theta,\phi,T)=\frac{I_{\lambda,e}(\lambda,\theta,\phi,T)}{I_{\lambda,b}(\lambda,T)} \tag{1}$$

where $\varepsilon$ is the emissivity, $\lambda$ is the wavelength, $T$ is the temperature, $I$ is the radiative intensity, $\theta$ is the polar direction, $\varphi$ is the azimuthal direction, and the subscripts $e$ and $b$ correspond to the emitted portion and the blackbody energy, respectively. While in respect of the absorbed portion of a real surface, the property called absorptivity is employed, given by:

$$\alpha_{\lambda,\theta}(\lambda,\theta,\ \phi)=\frac{I_{\lambda,i,abs}(\lambda,\theta,\phi)}{I_{\lambda,i}(\lambda,\theta,\ \phi)} \tag{2}$$

where $\alpha$ is the absorptivity and the subscripts $i$ and $abs$ correspond to the incident and absorbed radiation portions, respectively. Eq. (2) is in its spectral directional form. It should be noted that the absorptivity is not a surface property, due to its relation to the incoming radiation (Modest, 2013). Therefore, with the modification of the incoming radiation, a common occurrence in problems with changes in composition of participating media, the total absorptivity value can suffer changes.

### 2.2 Radiative heat transfer in participating media

The thermal radiation incident to a molecule or particle of the media can modify the amount and also the direction of radiation of the particular path the rays were travelling along. This is caused by the distinct energy levels of the atoms in the molecules, where at specific levels, the atom can receive the impact of a incident photon and absorb its energy, therefore attenuating the intensity along the radiation path. Or, at a specific level, release a photon, which would consist in the augmentation of the incident ray (Modest, 2013).

The total amount of radiation absorbed through the medium at a specific optical path is proportional to the magnitude of the energy and the length travelled by the radiation beam (Modest, 2013). By this definition, it is possible to write the variation of radiation intensity due to absorption by:

$$dI_{\lambda,abs}=-\kappa_\lambda I_\lambda ds \tag{3}$$

where $\kappa$ is the absorption coefficient of the participating media and $s$ is the radiation path.

The radiation can also be emitted by the participating media, therefore the radiation travelling along the path can be augmented by emission. This is expressed by:

$$dI_{\lambda,em}=\kappa_\lambda I_{b,\lambda} ds \tag{4}$$

where the subscript *em* represents the emission portion of the intensity.

When neglecting the effects of scattering, which is one of the assumptions of this study, one can combine Eq. (3) and Eq. (4), which results in the radiative transfer equation, (RTE).

$$\frac{dI_\lambda}{ds}=\kappa_\lambda (I_{b,\lambda}-I_\lambda) \tag{5}$$

Eq. (5) represents the variation of intensity along an optical path $s$, where this variation is represented as augmentation due to emission or attenuation due to absorption. These effects are represented by the first and second terms inside the parentheses of the right-hand side of the equation.

## 2.3 Line-by-line (LBL) integration

To evaluate the radiative transfer along a path, if the spectral data is available, one could solve the radiative transfer equation, Eq. (5) for all locations of the spectrum. Then the integral of the results is calculated to obtain the total intensity ($I$) along the path $s$. This is known as the line-by-line integration method, or LBL. With this methodology, thermal radiation problems can be solved with a high degree of accuracy. However, due to the fact that thousands of spectral lines are evaluated to compute the spectral integration over a single direction, this method is deemed computationally expensive and not desirable for larger models due to high computational times. Also, this method requires the knowledge of the spectral properties of the participating medium over the entire spectrum. This is usually done by using spectral databases, which are used to provide the absorption coefficients of each of the participating species. The most commonly used databases are the HITRAN (Gordon *et al.*, 2017) and HITEMP (Rothman *et al.*, 2010). To illustrate, Figure 1 presents a segment of the absorption coefficients for $CO_2$ at 1000 K and 1.0 atm, between 3400 and 3850 $cm^{-1}$. It can be seen the strong spectral dependence of the absorption coefficient, which could affect the resultant absorptivity values of non-gray walls bounding participating media.

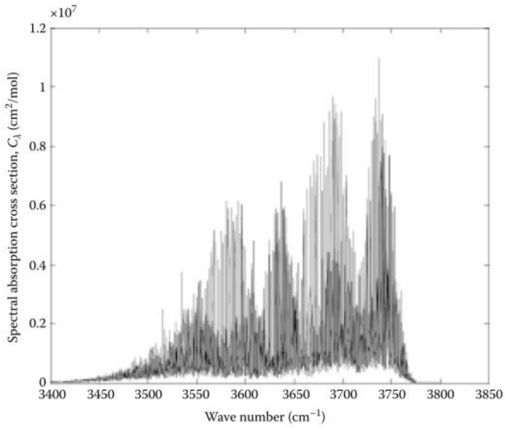


Figure 1. Spectral absorption cross-section for $CO_2$ at 1000K and 1atm for a portion of the spectrum [Howell *et al.* 2012].

## 2.4 Total surface absorptivity and benchmark reference temperature

One of the objectives of this work is to calculate the total absorptivity of a non-gray surface bounding a non-gray media, by utilizing the blackbody distribution and a certain reference temperature (Howell *et al.*, 2012).

$$\alpha_\theta=\varepsilon_1 F_{0\to\lambda_1 T}+\varepsilon_2 F_{\lambda_1 T\to\lambda_2 T}+... \tag{6}$$

where $F$ corresponds to the blackbody emission fraction and its subscripts represent the spectral bands at constant spectral emissivity of the non-gray surface.

Equation (6) is used in this study alongside a number of reference temperatures to estimate the total absorptivity of the surface. These reference temperatures are, the average temperature of the medium, $T_{avg}$, the wall temperature, $T_{wall}$ and the arithmetic average between both of them, $T_{w,avg}$. The benchmark reference temperature, $T_{reb}$ is a concept also evaluated in this work. This quantity represents the required temperature in which the total directional absorptivity calculated by means of a blackbody distribution would be equal to the one by the LBL solution. Using this benchmark reference temperature, it is possible to compare its value to the respective references previously mentioned, then evaluating how they fare against the LBL solution for either the temperature and total absorptivity.

## 3. PROBLEM DESCRIPTION

The study comprises the evaluation of the heat transfer through radiation of hemispherical domain of radius $r$=1m, permeated by participating medium at the pressure of 1atm for 12 test cases. Due to the conditions of symmetry proposed, where there is no variation of properties in the polar and azimuthal coordinates, only on the radial one, this domain is considered unidimensional, as seen in Figure 2(a). In this study, two mixtures of $CO_2$ and $H_2O$ were evaluated. These mixtures represent a molar ratio of $H_2O$ of 1.0 and 2.0, where the $CO_2$ molar fraction was kept constant, at 0.2.

At the hemisphere center, $r$=0, is located a non-gray surface, called the control surface in this study. Two different spectral profiles were evaluated for this control surface, shown as ε-Profile 1 and 2 on Figure 2(b). These profiles give the spectral emissivity of the surface at given points of the spectrum. The hemisphere border, coordinate $r=R$ shown in Figure 2(a), is modelled as a blackbody, where its temperature follows the participating media temperature distribution.

$$T(r)=(400\ K)*\left[1+\left(\frac{10}{0,9}\right)\frac{r}{R}-\frac{5}{0,9^2}\left(\frac{r}{R}\right)^2\right] \tag{7}$$

$$T(r)=(400\ K)*\left[1+\left(\frac{10}{0,9}\right)\left(\frac{R-r}{R}\right)-\frac{5}{0,9^2}\left(\frac{R-r}{R}\right)^2\right] \tag{8}$$

$$T(r)=(400\ K)*\left[1+\left(\frac{10}{0,5}\right)\frac{r}{R}-\frac{5}{0,5^2}\left(\frac{r}{R}\right)^2\right] \tag{9}$$

A total of three temperature profiles were evaluated, called Profile 1, Profile 2 and Profile 3. These temperature profiles follow a temperature distribution given by Eq. (7), Eq. (8) and Eq. (9), respectively. The difference between these temperature profiles is the position at which the maximum temperature is located on the radial coordinate. Profile 1 represents a temperature distribution where $T_{max}$ occurs at $r$*=0.9 and Profile 2, at $r$*=0.1, therefore these temperature profiles are mirrored versions of each other. Profile 3 presents a symmetrical temperature distribution, where the maximum temperature occurs at $r$*=0.5. The variable $r$* is the non-dimensional radial length of the hemisphere. All temperature profiles achieve a maximum temperature, $T_{max}$, of 2400K, while $T_{wall}$ is 2032.65K, 2375.31K and 400K for Profiles 1, 2 and 3, respectively.

For the spectral integration of the RTE, the LBL method was employed, where the HITEMP 2010 database was used as the means to obtain the absorption coefficient of the species. The HITEMP files were generated within the spectral range from 0 to 25000 cm$^{-1}$ at a resolution of approximately 0.067 cm$^{-1}$. With this configuration, a total of 375.000 spectral lines were evaluated for each case. The spatial integration of the RTE was performed using the finite-volume-method (FVM). The domain was divided into equally spaced elements in the radial coordinate of the hemisphere, and the polar and azimuthal coordinates were neglected due to the symmetry condition of the domain. A mesh sensitivity analysis was performed and showed that 100 elements is sufficient neglect any significant errors due to the spatial discretization.

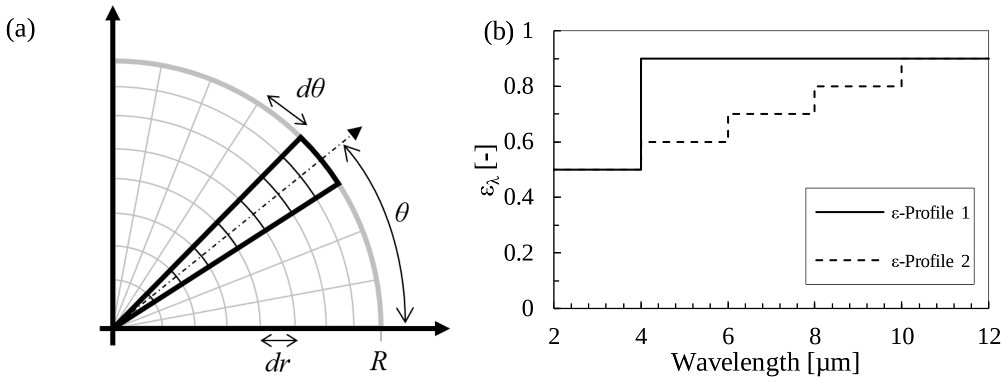


Figure 2. (a) Domain representation. (b) Spectral properties of the control surface.

## 4. RESULTS AND DISCUSSION

### 4.1 Total absorptivity for temperature Profile 1

The first results evaluates are the ones focused on the temperature Profile 1, represented by Eq. (7). The results are organized as function of the molar fraction of $H_2O$ of the mixture, for each of the spectral emissivity profiles, or ε-Profiles, of the control surface.

Figure 3(a) present the obtained results of the total absorptivity of the control surface of the ε-Profile 1. It is possible to observe that that there exists only a small variation of the absorptivity values for the two molar ratios studies. The absorptivity values obtained by the LBL integration ranged from 0.527 to 0.529. These values are shown in markers. When comparing these values to the reference temperature methodology, traced as lines in the figure, the reference temperature that provided the better agreement to the LBL results was the hemisphere wall temperature, $T_{wall}$. With this reference, the total absorptivity error achieved values of 1.9% and 2.2% for the cases with a molar ratio of $H_2O$ of 1.0 and 2.0, respectively.

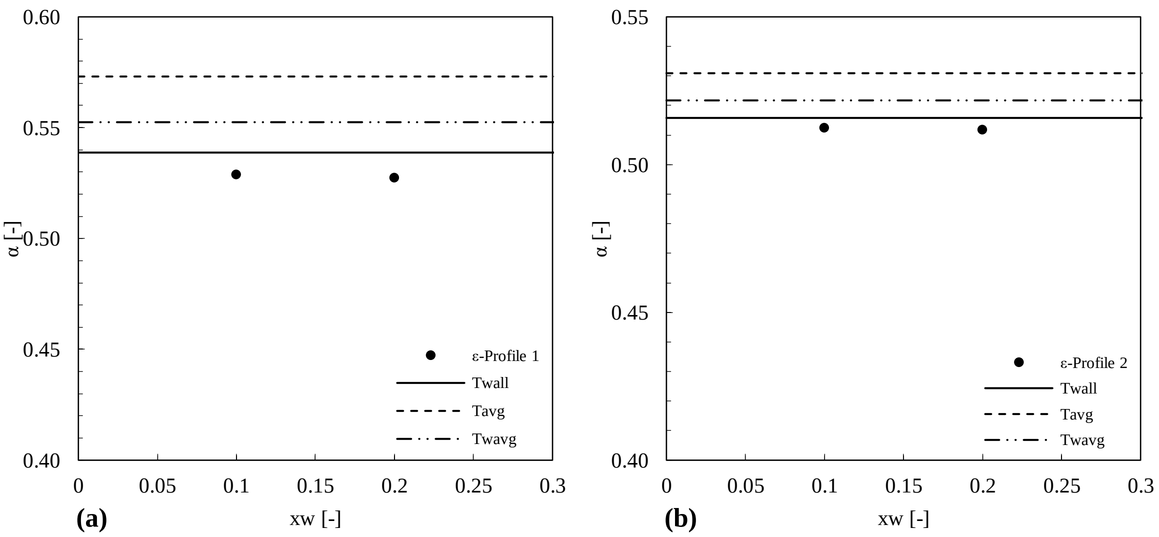


Figure 3. (a) Total absorptivity for the spectral emissivity profile (ε-Profile) 1 and (b) for ε-Profile 2.

Figure 3(b) shows the results of total absorptivity versus molar concentration fo $H_2O$ for the ε-Profile 2. With this emissivity profile, the total absorptivity results calculated by the LBL integration of the RTE achieved values between 0.511 and 0.512. Comparing these values to the ones obtained by assuming a blackbody distribution and the reference temperatures, the reference temperature that provided the closest match to the benchmark values was again $T_{wall}$. The deviation to the LBL solution using this reference temperature achieved small values, ranging between 0.6% and 0.8%, proving to be an excellent estimation of the total absorptivity of a non-gray surface bounding non-gray medium. It should be also noted that with the ε-Profile 2, the range of total absorptivities obtained was much smaller than the ones obtained from ε-Profile 1. Therefore the deviations from the LBL solution was significantly lower for all reference temperatures, in this specific case.

### 4.2 Total absorptivity for temperature Profile 2

This subsection presents the total absorptivity results for the second temperature profile in this study, Profile 2, represented by Eq. (8) for the two molar concentrations of $CO_2$ and $H_2O$. Again the results are presented as a function of the molar concentration of $H_2O$ of the mixture.

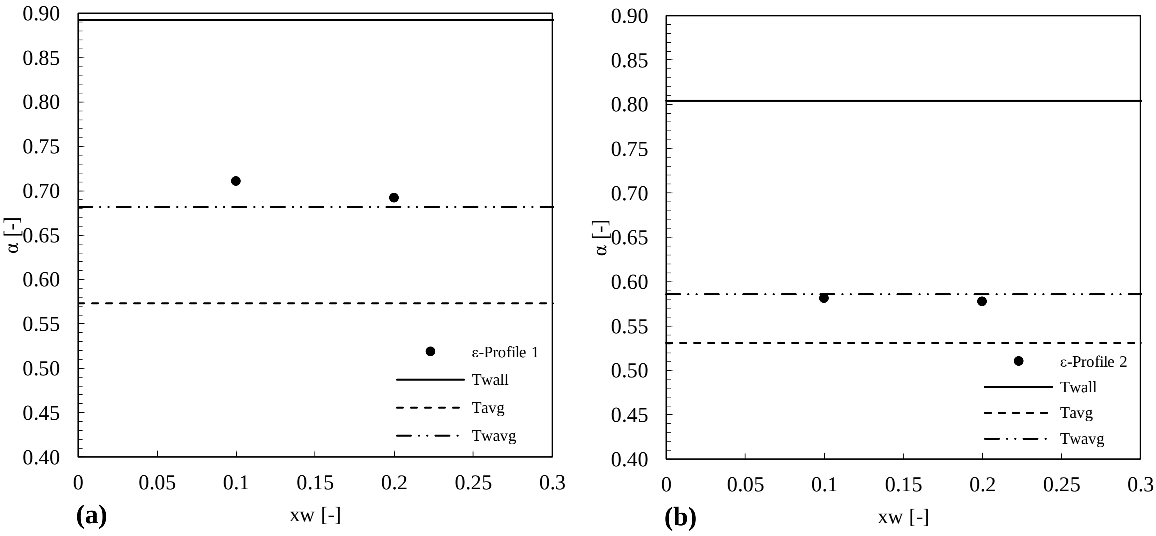


Figure 4. (a) Total absorptivity for the spectral emissivity profile (ε-Profile) 1 and (b) for ε-Profile 2.

Figure 4(a) presents the total absorptivity of the control surface modeled with the spectral properties given by ε-Profile 1.The markers represent the benchmark absorptivity values calculated by the LBL integration, where it achieved values of 0.710 and 0.692 for an $H_2O$ molar ratio of 1.0 and 2.0, respectively. From these values, the reference temperature that provided the smallest deviation to the benchmark results was the mean between the average temperature of the mixture and the temperature of the hemisphere wall, $T_{w,avg}$.

Compared to the previous temperature profile, Profile 2 provided a larger variation of the absorptivity value with respect of the optical thickness of the medium, that is the molar concentration of the species. Even with this large variation, $T_{w,avg}$ still provided the best agreement with the LBL results.

In Figure 4(b) the ε-Profile 2 is evaluated. With this surface emissivity profile, there was little modification to the total absorptivity value for the two mixtures studied, going from 0.582 for the mixture of $CO_2$ and $H_2O$ molar fraction of 0.1 and 0.1 respectively, to 0.578 when the molar fraction of $H_2O$ was increased to 0.2. When compared to the values obtained by the reference temperature, shown as lines in the figure, it is noted that again $T_{w,avg}$ provides the best agreement to the benchmark values, reaching a deviation of only 0.7% for a molar ratio of 1.0 and 1.3% for a molar ratio of 2.0 of the mixture.

### 4.3 Total absorptivity for temperature Profile 3

The final temperature profile evaluated in this work, Profile 3, which provides a symmetrical temperature distribution along the domain is evaluated in this section. This profile provides a maximum temperature of 2400K at equal distance from the control surface and the hemisphere wall, there which are at 400K. The temperature distribution is represented by Eq. (9).

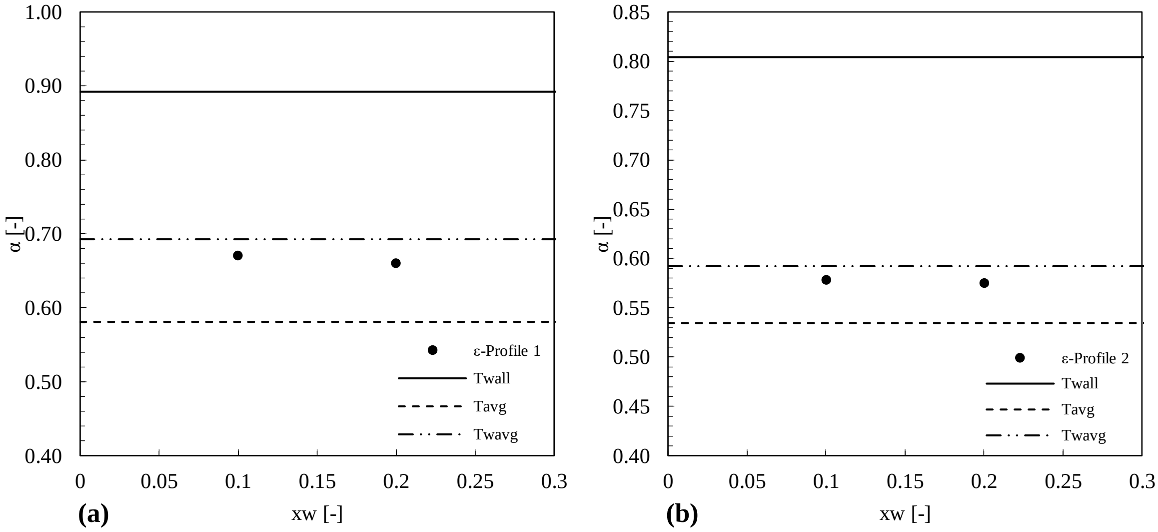


Figure 5 (a) Total absorptivity for the spectral emissivity profile (ε-Profile) 1 and (b) for ε-Profile 2.

Figure 5(a) provides the comparison between the total absorptivity of the control surface modelled by the ε-Profile 1 when subjected by incident radiation whose path was composed by a mixture of $CO_2$ and $H_2O$ with a temperature distribution given by Eq. (9). From the results obtained, it is possible to verify that the LBL absorptivity lies between the ones calculated by $T_{avg}$ and $T_{w,avg}$. There was a small variation in the absorptivity with the increase of $H_2O$ molar fraction, going from 0.671 to 0.661 for $X_w$=0.1 and 0.2, respectively. This results showed that the absorptivity has a tendency be smaller for thicker media, in the test cases performed. For the range of molar fractions simulated, combined to this temperature distribution, the usage of either $T_{avg}$ and $T_{w,avg}$ would provide an adequate estimation of the behavior of the total absorptivity, while the latter being the most satisfactory.

Figure 5(b) presents the same aforementioned analysis, but for the spectral emissivity profile ε-Profile 2. Similar results were obtained, where the usage of $T_{w,avg}$ would provide the most accurate representation of the total absorptivity of the surface of all the reference temperatures studied. The absorptivities ranged from 0.578 to 0.575 for a molar ratio of 1.0 and 2.0, respectively. Again, it was verified a small variation of the absorptivity for these distinct molar concentration, therefore proving the small sensibility of the total absorptivity to the optical thicknesses evaluated.

### 4.4 Benchmark reference temperature

The benchmark reference temperature, $T_{reb}$, is calculated by the procedure described in 2.4. This variable is evaluated against the reference temperatures obtained by the three temperature profiles studied. The objective of the evaluation of $T_{reb}$, is to determine the applicability of this reference temperature methodology, for the different surface emissivity profiles. This is done due to the fact that the reference temperature is independent of the ε-Profiles, hence the comparison is made easier.

In Figure 6, the values for $T_{reb}$ are shown as markers, for the two different ε-Profiles evaluated. On the abscissa one can observe the influence of the increase of molar fraction of water vapor. The reference temperatures, being unaltered by the mixture, are represented as lines in the graph.

Figure 6(a) presents the results obtained for the temperature Profile 1, where the maximum temperature occurs close to the hemisphere wall, at the non-dimensional radial position $r^*$=0.9. From the results of $T_{reb}$, one can observe that for the four test cases, the benchmark temperature achieved values higher than the maximum temperature of the domain, 2400K. This could be linked to the method that is being executed for the calculation of the total absorptivity of the surface, where it is being assumed a blackbody energy distribution over the spectrum for the representation of a non-gray-surface bounding non-gray medium. The non-gray medium possess a spectral profile, where it can emit or absorb energy at widely different levels over the spectrum. This in turn can weigh the total absorptivity value toward a specific value of the profile. In this case, since the total absorptivity resulted in a small value through the LBL integration, this correspond to higher temperatures when dealing with a blackbody energy distribution. Despite the somewhat significant deviation between $T_{wall}$ and $T_{reb}$, this reference temperature still provided an excellent estimation of the total absorptivity value for the control surface, as evaluated on previous sections.

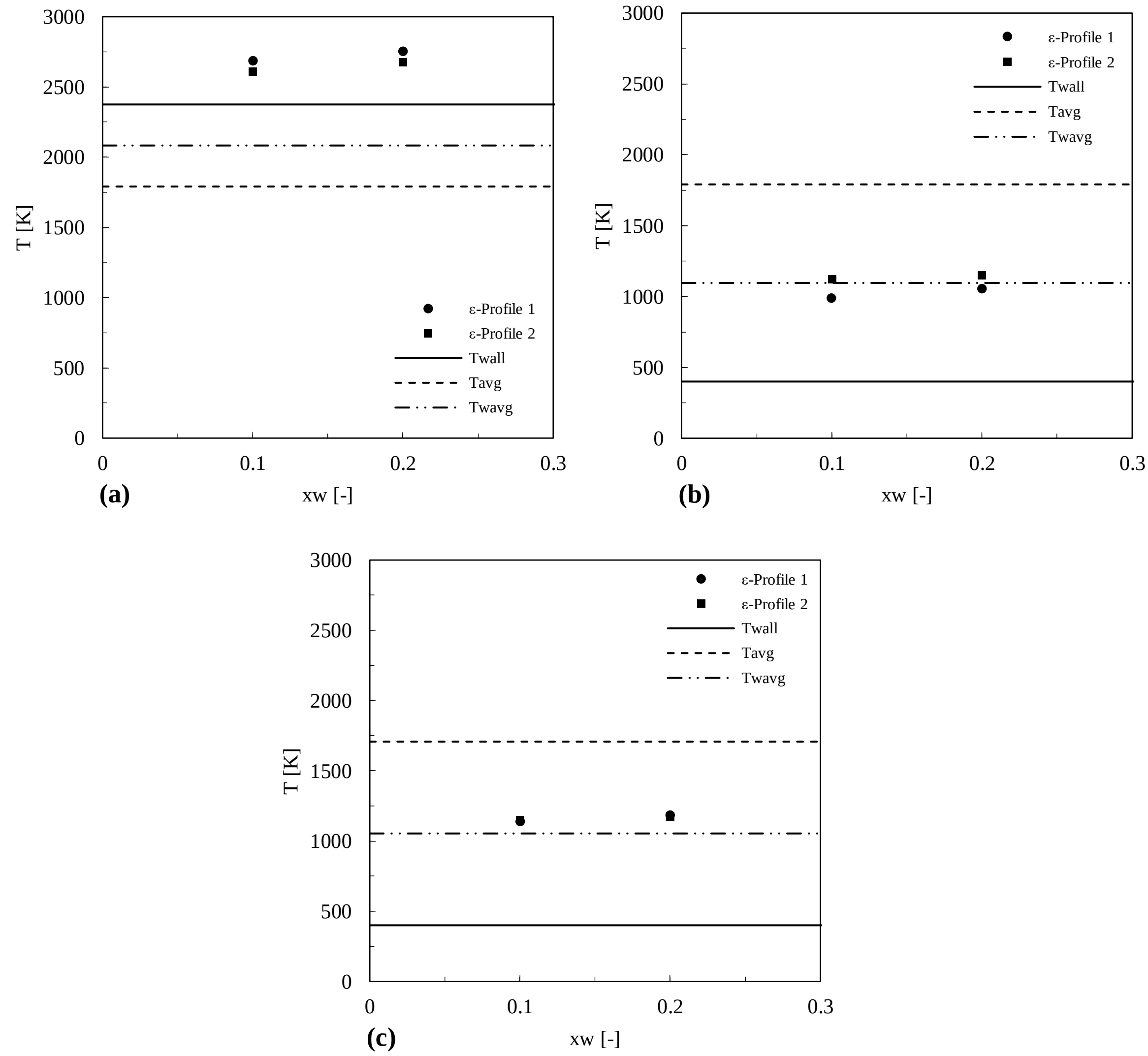


Figure 6. (a) Benchmark reference temperature for the temperature Profile 1 (a), Profile 2 (b) and Profile 3 (c).

Figure 6(b) presents a similar evaluation of $T_{reb}$ against the references. It is observed a small difference in the value for the benchmark reference temperature with respect of variation in molar concentration of the species, with a small tendency of increase for a medium with higher concentration of participating media. Also, between the two surface emissivity profiles, the value of $T_{w,avg}$ closely matched the LBL calculated ones. This corroborates with the results obtained in the previous section and shows the applicability of this reference temperature for the estimation of the total absorptivity of the control surface.

While Figure 6(c) shows the results obtained of $T_{reb}$ for the symmetrical temperature profile, Profile 3. The value of these temperatures suffered little variation when comparing both surface emissivity profiles, noting that the markers on the image are overlapping. Also, the same trend of an increase of the $T_{reb}$ with the increase of species concentration, this can be attributed to the method used and on the ε-Profiles themselves. Where for a blackbody distribution, higher temperatures weigh more on smaller wavelengths, and the evaluated surface emissivity profiles have smaller absorptivities at the lower end of the spectrum.

Table 1 presents the summary of the results obtained in this study, comprising $T_{reb}$, the total LBL absorptivities and the deviations encountered for each of the references. Overall, the reference temperature methodology promised good agreement with the results, with the selected references that better correlate with LBL data were $T_{wall}$ for the temperature Profile 1 and $T_{w,avg}$ for the Profile 2 and 3.

Table 1. Summary of results obtained.

| Temp. Profile | ε-Profile | $X_c$ [-] | $X_w$ [-] | $T_{reb}$ [K] | $\alpha_{LBL}$ [-] | $\delta T_{avg}$ [-] | $\delta T_{wall}$ [-] | $\delta T_{w,avg}$ [-] |
|---|---|---|---|---|---|---|---|---|
| Profile 1 | ε-1 | 0.2 | 0.1 | 2683.1 | 0.529 | 8.3% | 1.9% | 4.4% |
| | | 0.2 | 0.2 | 2751.5 | 0.527 | 8.7% | 2.2% | 4.8% |
| | ε-2 | 0.2 | 0.1 | 2611.9 | 0.512 | 3.6% | 0.6% | 1.8% |
| | | 0.2 | 0.2 | 2679.8 | 0.512 | 3.8% | 0.8% | 2.0% |
| Profile 2 | ε-1 | 0.2 | 0.1 | 990.3 | 0.710 | 19.3% | 25.6% | 4.1% |
| | | 0.2 | 0.2 | 1055.8 | 0.692 | 17.2% | 28.9% | 1.5% |
| | ε-2 | 0.2 | 0.1 | 1125.2 | 0.582 | 8.7% | 38.2% | 0.7% |
| | | 0.2 | 0.2 | 1152.4 | 0.578 | 8.2% | 39.1% | 1.3% |
| Profile 3 | ε-1 | 0.2 | 0.1 | 1137.4 | 0.671 | 13.5% | 32.9% | 3.2% |
| | | 0.2 | 0.2 | 1182.6 | 0.661 | 12.1% | 35.0% | 4.8% |
| | ε-2 | 0.2 | 0.1 | 1149.5 | 0.578 | 7.6% | 39.0% | 2.4% |
| | | 0.2 | 0.2 | 1176.0 | 0.575 | 7.1% | 39.8% | 3.0% |

## 5. CONCLUSIONS

A study regarding the evaluation of the thermal radiation heat transfer over a participating media bound by a non-gray wall, called control surface, and a black one was presented. A total of 12 test cases were studied, for two different participating media compositions, two surface emissivity profiles for the control surface and three non-uniform temperature profiles over the domain.

The LBL integration method was used to compute the RTE over the domain, and the total absorptivity of the non-gray surface was compared to the ones obtained by estimation of a blackbody distribution for the surface and different reference temperatures given by the temperature profiles. The benchmark reference temperature, that is, the reference temperature that would achieve the total absorptivity obtained by the LBL integration method was also evaluated.

The results showed good agreement of total absorptivity using the reference temperatures to the LBL solutions, where deviations achieved values as low as 0.2% for the preferred references. One of the temperature profiles, Profile 1, is described by a parabolic temperature distribution with its maximum value of 2400K close to the black surface, at a non-dimensional distance of $r^*$=0.9. For this profile, the preferred reference temperature was the temperature of the black wall, $T_{wall}$. This showed a strong influence of the black surface over the results.

For the temperature distribution represented by the temperature Profile 2, which is a mirrored version of the aforementioned profile, with the maximum temperature occurring at $r^*$=0.1. The total absorptivity value calculated via $T_{w,avg}$ provided the closest match to the LBL solution. Using this reference temperature, the error ranged from 0.7% to 4.1% for the total absorptivity values.

When the domain was subjected to the symmetrical temperature distribution, with its maximum temperature occurring at $r^*$=0.5, the usage of the reference methodology was once again satisfactory for the estimation of the total absorptivity of a non-gray surface. The employment of $T_{w,avg}$ provided the smallest errors of the total absorptivity from the other references, ranging from 3.2 to 4.8% for the ε-Profile 1. The results also showed little variation of the range of molar concentration of the species studied, therefore being applicable for molar concentrations in between the ones presented.

The benchmark reference temperatures provided an interesting insight on the evaluation of the results, showing higher values than the maximum temperature of the domain. These results can be explained by the cire development of the methodology, where a blackbody distribution is used for the determination of total properties of non-gray walls bounding non-gray media. The results obtained in this study can provide a better understanding of the applicability of the reference temperature approach, and guide the selection of the optimal reference temperature for the application on global models, such as WSGG and SLW methodologies.

## 6. ACKNOWLEDGEMENTS

This optional section must be placed before the list of references.

## 7. REFERENCES

Bergman, T; Lavine, A. Fundamentals of Heat and Mass Transfer. 8th. ed. New York: Wiley, 2017. v. 148

Da Fonseca, R. J. C.; Fraga, G. C.; Da Silva, R. B.; França, F. H. R. Application of the WSGG model to solve the radiative transfer in gaseous systems with nongray boundaries. Journal of Heat Transfer, v. 140, n. 5, 2018.

Da Silva, R. M.; Da Fonseca, R. J. C.; França, F. H. R. Radiative transfer prediction in participating medium bounded with nongray walls using the SLW model. Journal of the Brazilian Society of Mechanical Sciences and Engineering, v. 41, n. 12, p. 1-8, 2019.

Da Fonseca, R. J. C. ; Fraga, G. C.; França, F. H. R. A new approach for computing the total absorptivity of non-gray surfaces in radiative heat exchanges with a participating medium. In: , 2019. 25th International Congress of Mechanical Engineering., 2019.

Gordon, I. E., Rothman, L. S., Hill, C., Kochanov, R. V., Tan, Y., Bernath, P. F., ... & Zak, E. J. (2017). The HITRAN2016 molecular spectroscopic database. Journal of Quantitative Spectroscopy and Radiative Transfer, 203, 3-69.

HOWELL, J.; MENGÜÇ, P.; SIEGEL, R. Thermal radiation heat transfer. New York: CRC Press, 2012.

Modest, M. F., 2013. Radiative Heat Transfer. Academic Press.

Rothman, L. S., Gordon, I. E., Barber, R. J., Dothe, H., Gamache, R. R., Goldman, A., … Tennyson, J. (2010). HITEMP, the high-temperature molecular spectroscopic database. Journal of Quantitative Spectroscopy and Radiative Transfer, 111(15), 2139–2150.

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