INFLUENCE OF THE GRID REFINEMENT ON THE THERMAL RADIATION FIELD

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Abstract. *The present work aims at investigating the influence of the domain discretization on the prediction of the divergence of the radiative flux in a participant medium. This parameter is important for the coupling between convection and thermal radiation heat transfer, including flows with turbulence-radiation interactions (TRI). In order to achieve this purpose, the radiative transfer equation is solved employing the Zonal Method for a three-dimensional cubical enclosure of dimensions H=W=L=1 m filled with participant medium. The domain is discretized in cubical zones of dimension B. The participanting medium is treated as a gray gas and scattering is neglected. The temperature field as a function of coordinates x and z is imposed along the enclosure domain. From this temperature field, the average divergence of the radiative flux in the entire domain, as well as in hot and cold regions, is reached. It is presented that more refined grids are required for the highest temperature regions, even when average parameters are under evaluation. Moreover, the influence of the grid refinement over the local divergence of the radiative flux is obtained. These results show that the grid refinement becomes more important for higher temperature gradients in x and z directions. For all performed simulations the local radiative field is more influenced by the grid refinement than the average one. Three different absorption coefficients is also employed for the simulation of the radiative transfer in the participant medium (*κ *= 0.03* m^{-1}*, 0.3* m^{-1} *and 3.0* m^{-1}*). From these simulations it is observed that the optical thickeness changes the influence of the radiant grid over the average and local divergence of the radiative flux.*

Keywords*: Radiative grid, divergence of radiative flux, temperature influence, participant medium, optical thickness*

1. INTRODUCTION

The radiative heat transfer dominates the physical phenomena when high temperatures are present, i.e., it is important for the study of many engineering applications, for example: combustion, flames and rockets propulsion systems. According to Jones and Paul (2005) this mechanism has also become important for the development of thermal devices. For instance, the inaccurate prediction of temperature surfaces of a combustor can led to an excessive amount of air entering in the combustion chamber, reducing the efficiency of the equipment as well as the time between failures, and increasing the pollutant emission.

Some difficulties for the solution of combined problems (convection and radiation) are associated with their nonlinearity and high computing cost. According to Białecki and Węcel (2004) a common practice is therefore to neglect the coupling between modes and solve pure convection or radiation problems. Other problem that arises is that, for simulations of convection heat transfer, it is necessary to generate fine numerical meshes to capture the small scale phenomena. One the other hand, the employment of convective grids for the simulation of radiative problem can lead to an excessive computational effort, making the problem unsolved. According to Białecki and Węcel (2004), due to the long distance interactions characteristic to heat radiation, coarse internal meshes can be used in heat radiation problems without seriously influencing the accuracy of the solution. In this way, the solution of conjugate convection and radiation heat transfer has been considered with different radiative grids (coarser) than the ones employed for the convective problem for the simulation of laminar (Ibrahim and Lemonnier, 2009) and for the treatment of turbulence-radiation interactions (TRI) with the stochastic method (Kounalakis *et al.*, 1988; Coelho, 2004; Coelho, 2007) Reynolds Averaged Navier-Stokes (RANS) (Mazumder and Modest, 1999; Wang *et al.*, 2008) or Large-Eddy Simulations (Jones and Paul, 2005; Dos Santos *et al.*, 2008; Gupta *et al.*, 2009).

However, to the authors knowledge, it has not been presented in the literature studies on the influence of the grid refinement as well as of the temperature interpolation from a finer grid (convective) to a coarser grid (radiative) over the predictions of the radiative field. In this way, the present work aims at studying the influence of the domain discretization over the prediction of the divergence of the radiative flux in a participant medium. In order to achieve this purpose, the radiative transfer equation is solved employing the Zonal Method for a three-dimensional cubical enclosure of dimensions H=W=L=1 m filled with participating medium. A temperature field is imposed as a function of coordinates x and z for the finest radiative grid and is interpolated for the coarser ones mimicking the effect of the temperature obtained from a convective problem. The average divergence of the radiative flux for the entire enclosure and for lower and higher temperature portions of the cavity, named zone 1 and 2, are obtained. The local divergence of the radiative flux for several placements is also obtained, allowing the evaluation of the grid refinement over the average and local radiative field. For all performed simulations, three different absorption coefficients are employed for the simulation of the radiative transfer in the participating medium (κ = 0.03 m^{-1}, 0.3 m^{-1} and 3.0 m^{-1}) in order to investigate if the optical thickness modifies the influence of the grid refinement over the predictions of average and local radiative field.

2. MATHEMATICAL MODELING

For the determination of the thermal radiation field it is necessary to solve the radiative transfer equation (Siegel and Howell, 2002). This equation for a non-scattering medium is given by:

$$\frac{dI_\eta}{dx} = -\kappa_\eta I_\eta + \kappa_\eta I_{b\eta} \tag{1}$$

where I_η is the spectral intensity (W/m²·μm·sr) at wavenumber η (m^{-1}), $I_{b\eta}$ is the blackbody intensity (W/m²·μm·sr), and κ_η is the spectral absorption coefficient (m^{-1}). The above equation can be a priori solved for every single value of κ_η, but it would lead to a computational effort that would be prohibitive for most cases, with exception perhaps of one-dimensional geometries.

Nevertheless, when the gas is considered gray, Eq. (1) becomes independent of the wavenumber η and the radiative transfer equation could be rewritten by the following expression:

$$\frac{dI}{dx} = -\kappa I + \kappa I_b \tag{2}$$

It is worth mentioning that for a real gas the behavior of the absorption coefficient as a function of wavelength is significantly different from the one estimated by the gray gas model. More advanced models such as: Weighted-Sum-of-Gray-Gases (WSGG) (Hottel and Sarofim, 1967; Smith *et al.*, 1982; Modest, 1991), Spectral Line based Weighted-Sum-of-Gray-Gases (SLW) (Denison and Webb, 1993) and Cumulative Wavenumber (CW) (Solovjov and Webb, 2002) has been employed in the literature for the approach of this problem. This simplification is used with the sole objective of understanding some characteristics of thermal radiation field without considering the difficulties concerned with the spectral effects. One example is the study of the influence of the grid refinement over the estimative of the divergence of the radiative flux, which is the scope of the present work.

With the purpose to couple the thermal radiation field and convection heat transfer, it is necessary to take into account the divergence of the radiative flux ($\nabla \mathbf{q}_R$) which is inserted into the energy equation. Since the energy transfer by thermal radiation happens in an instantaneous time scale, it can be naturally inserted as a source term in the energy equation. This term is determined from the radiation intensity field and, for a gray gas, can be written as:

$$\nabla \mathbf{q_R} = \kappa\left(4\pi I_b - \int_{4\pi} I d\Omega\right) \tag{3}$$

3. THE ZONAL METHOD

The Zonal Method (ZM) involves the subdivision of the medium domain into gas volumes (zones of gas) where the temperature is assumed isothermal. The surrounding domain is also divided in surface zones. In this method an energy balance is performed for each zone and all radiative quantities (emissive power, radiosity and irradiation) are assumed uniform. From this energy balance, it is generated a system of equations to determine the unknowns of the problem: radiative flux or temperature (Hottel and Sarofim, 1967; Siegel and Howell, 2002).

It is well documented in the literature that the ZM method has some limitations, such as the insertion of the scattering and the compatibilization of the radiative grid with those required in convective problems. In spite of this, this method has proved to be powerful for the solution of three-dimensional problems and has been employed in the thermal design of engineering equipments (Siegel and Howell, 2002).

For the Zonal Method the net volumetric radiative heat rate for a volume zone V_γ is given by:

$$q_{R\gamma} = \frac{1}{V_\gamma}\left[4V_\gamma \kappa \sigma T_\gamma^4 - \sum_{\gamma^*=1}^{\Gamma} \overline{g_{\gamma^*} g_\gamma} \sigma T_{\gamma^*}^4 - \sum_{j=1}^{J} \overline{s_j g_\gamma} q_{0,j}\right] \tag{4}$$

where κ is the absorption coefficient (m^{-1}), γ is the index concerned with the volume zone V_γ, γ^* is the index related with the surrounding zones, σ is the Stefan-Boltzmann constant (5.67 × 10^{-8} W/m²K^4) and $q_{0,j}$ is the radiosity of surface j (W/m²). On the right-hand side of Eq. (4) the first term is the radiative energy emitted by the volume zone V_γ, while the second and the third terms account for the absorption of radiation from the other volume zones $V_{\gamma*}$ and surface zones A_j, respectively. The gas-to-gas and the surface-to-gas directed-exchange areas, $\overline{g_\gamma g_{\gamma*}}$, $\overline{s_k g_\gamma}$ (m²) are given, respectively, by:

$$\overline{g_{\gamma*} g_\gamma} = \int_{V_{\gamma*}} \int_{V_\gamma} \frac{\kappa^2}{\pi S_{\gamma^*-\gamma}^2} \exp\left[-\int_{S_{\gamma^*}}^{S_\gamma} \kappa_\lambda \left(S^*\right) dS^* \right] dV_\gamma dV_{\gamma*} \tag{5}$$

$$\overline{s_j g_\gamma} = \int_{V_\gamma} \int_{A_j} \frac{\kappa \cos\theta_j}{\pi S_{\gamma-j}^2} \exp\left[-\int_{S_\gamma}^{S_j} \kappa_\lambda \left(S^*\right) dS^* \right] dA_j dV_\gamma \tag{6}$$

where $S_{\gamma*-\gamma}$ is the path length between two volume zones of gas $V_{\gamma*}$ and V_γ, $S_{\gamma\text{-}j}$ is the path length between a volume zone of gas V_γ and a surface zone A_j and θ_j is the angle between the orthonormal vector to the area A_j and the radiative intensity that reaches this surface (rad).

The radiosity, $q_{0,j}$, corresponds to the sum of the emission and the reflection from surface A_j and is given by:

$$q_{0,j} = \varepsilon_j \sigma T_j^4 + \left(1 - \varepsilon_j\right) q_{i,j} \tag{7}$$

in which $q_{i,j}$ is the irradiation on surface zone A_j (W/m²) and T_j is its temperature (K), which from the zonal method is written by:

$$q_{i,j} = \frac{1}{A_j}\left(\sum_{\gamma=1}^{\Gamma} \overline{g_\gamma s_j} \sigma T_\gamma^4 + \sum_{k=1}^{K} \overline{s_k s_j} q_{0,j} \right) \tag{8}$$

where $\overline{g_\gamma s_j}$ and $\overline{s_k s_j}$ are the gas-to-surface and the surface-to-surface direct-exchange areas (m²). The gas-to-surface direct-exchange area is similar to the surface-to-gas direct-exchange area, given by Eq. (6), and for the sake of simplicity it will not be rewritten. The surface-to-surface direct-exchange area ($\overline{s_k s_j}$) is given by:

$$\overline{s_k s_j} = \int_{A_j} \int_{A_k} \exp\left[-\int_{S_j}^{S_k} \kappa_\lambda \left(S^*\right) dS^* \right] \frac{\cos\theta_j \cos\theta_k}{\pi S_{j-k}^2} dA_j dA_k \tag{9}$$

The radiative heat flux on surface zone A_j is given by:

$$q_{R,j} = \left(q_{i,j} - q_{0,j}\right) \tag{10}$$

In the present work the direct-exchange areas for application in rectangular domains are determined from the work of Tucker (1986), which obtained algebraic correlations from numerical integration of Eq. (5), (6) and (9). Exponential functions are obtained for the nearest cubical zones and surfaces, while for higher distances between surface-surface and gas-surface the zones are treated as differential ones. The expressions for the direct-exchange areas can be seen in Tucker (1986).

One effective way to test the accuracy of the computation of the direct-exchange areas is that they satisfy the energy conservation principle. From the application of this principle to each gas and surface zone the following relations are obtained:

$$\left(4\kappa V\right)_\gamma = \sum_{j=1}^{N} \overline{g_\gamma s_j} + \sum_{\gamma*=1}^{\Gamma} \overline{g_\gamma g_{\gamma*}} \tag{11}$$

$$A_i = \sum_{j=1}^{N} \overline{s_i s_j} + \sum_{\gamma=1}^{\Gamma} \overline{s_i g_\gamma} \tag{12}$$

4. DESCRIPTION OF THE PROBLEM

The problem taken into account in the present work is a cubical enclosure of dimensions $H = L = W = 1$ m filled with participant medium. Figure 1(a) and 1(b) shows the cavity domain and the thermal boundary conditions in its lower and upper surfaces. The surfaces of the enclosure are treated as perfectly black, i.e., their total hemispherical emissivities are $\varepsilon_w = 1$. It can also be observed that the radiative enclosure is divided in two zones, namely zone 1 and zone 2. This subdivision is performed with the purpose to evaluate the mean divergence of the radiative flux for the entire domain as well as for colder and hotter portions of the enclosure. As previously stated the medium is treated as a gray gas and the radiative transfer equation is solved with the zonal method. Three different absorption coefficients are employed for the simulation of the radiative transfer in the participant medium ($\kappa = 0.03$ m^{-1}, 0.3 m^{-1} and 3.0 m^{-1}) to verify if more refined radiative grids are required when the optical thickness increases. For the discretization of the enclosure domain, it is employed cubical zones of dimension B.

In the present work the temperature field is imposed as a function of coordinates x and z along the entire enclosure, i.e., it is not determined from the energy equation. This simplifies the analysis since there the radiation can be decoupled from other heat transfer mechanisms (conduction or convection). The temperature field (K) as a function of spatial coordinates (m) is given by Eq. (13) and Fig. 2 depicts the temperature field as a function of z for the following placements: $x = 0.0$ m, 0.2 m, 0.8 m and 1.0 m.

$$T(x, y) = 10248z^5x - 25648z^4x + 24570z^3x - 11172z^2x + 2689.4zx + 300 \tag{13}$$

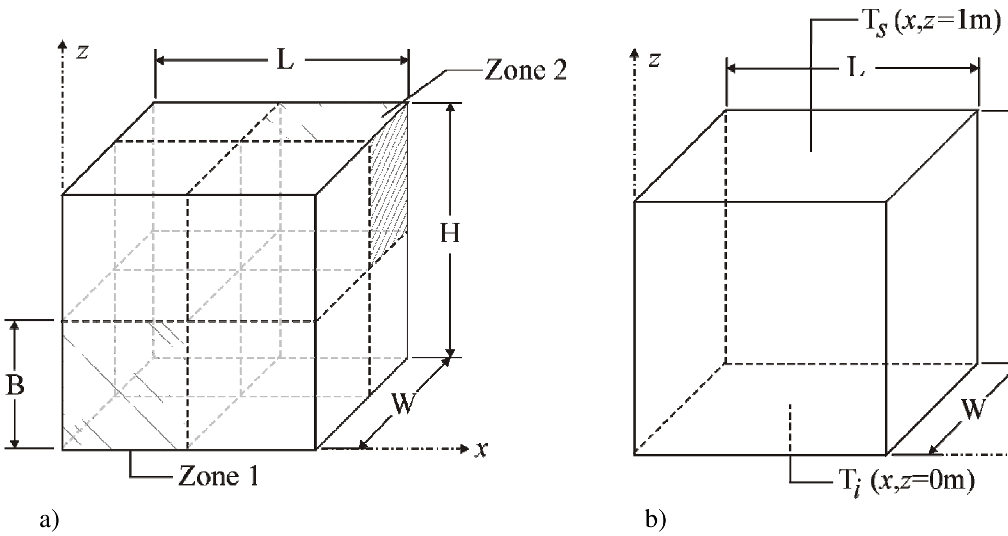


Figure 1. Cubical enclosure: (a) domain and zones specifications, (b) boundary conditions at the lower and the upper surfaces.

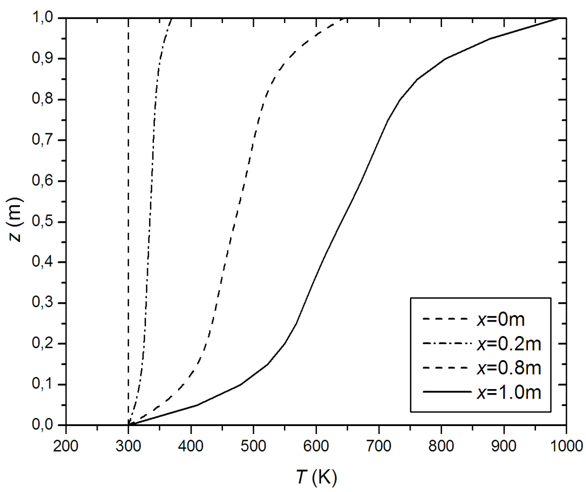


Figure 2. Imposed temperature field as a function of the z coordinate for several values of $x = 0.0$ m, 0.2 m, 0.8 m and 1.0 m.

5. RESULTS AND DISCUSSION

Firstly, it is evaluated the average divergence of the radiative flux in the entire enclosure as well as for zones 1 and 2, which represents the regions of lower and higher temperature in the enclosure, respectively. Figure 3 presents the average divergence of the radiative flux as a function of the zone dimension (B) for a medium with $\kappa = 0.3$ m^{-1} and for the previously mentioned gas regions. The results show that zone 2 is the most influenced by the decrease of B, i.e., with the grid refinement. For this cavity portion, the difference between the average divergence of the radiative flux for $B = 0.05$ m and $B = 0.0625$ m is approximately 1.5%, while for the entire cavity and zone 1 the difference was approximately, 0.6% and 0.06%, respectively. In addition, the average divergence of the radiative flux for zone 1 does not vary significantly for zones that are more refined than $B = 0.25$ m. Nevertheless, the variation of the mean divergence of the radiative flux in zone 2 still varies for this grid, indicating that higher temperature zones require more refined radiative grids than colder zones.

It is also of interest to investigate the local divergence of the radiative flux for several placements inside the enclosure domain. In order to perform this analysis, several numerical monitoring lines are inserted along the enclosure in order to evaluate the divergence of the radiative flux as a function of coordinate x for several placements of coordinate z. For the simulation with $\kappa = 0.3$ m^{-1} four numerical monitoring lines are inserted in the following placements: $z = 0.0625$ m, $z = 0.01876$ m, $z = 0.5626$ m and $z = 0.9375$ m. The first placement represents the nearest zones of gas to the lower surface, the second and third monitoring lines represent intermediate positions and the last placement is concerned with the nearest zones of gas to the upper surface. The profiles of local divergence of the radiative flux are obtained for two successive radiative grids: $B = 0.0625$ m and $B = 0.125$ m. For all performed simulations the results are collected at $y = 0.0625$ m.

Figures 4a and 4b shows the local divergence of the radiative flux for two successive grids ($B = 0.0625$ m and $B = 0.125$ m) and $\kappa = 0.3$ m^{-1} at positions $z = 0.0625$ m and $z = 0.1876$ m, respectively. For $z = 0.0625$ m (Fig. 4a) the mean difference between the profile obtained with $B = 0.0625$ m and $B = 0.125$ m is approximately 1.0% and the highest difference happens at $x = 0.9375$ m, this value is lower than 5%. For $z = 0.1876$ m (Fig. 4b) the mean difference between $B = 0.0625$ m and $B = 0.125$ m is of approximately 1.8% with a maximum difference of almost 60% at $x = 0.9375$ m. The steep increase of the difference of the local divergence of the radiative flux at $x = 0.9375$ m for $z = 0.1876$ m in comparison with $z = 0.0625$ m is concerned with the decrease of the magnitude of the local divergence of the radiative flux. It is also observed that in both placements the difference of the local divergence of the radiative flux from the coarser ($B = 0.125$ m) to the finer ($B = 0.0625$ m) grids increases as the coordinate x increases, reflecting the increase of the temperature gradient in this direction.

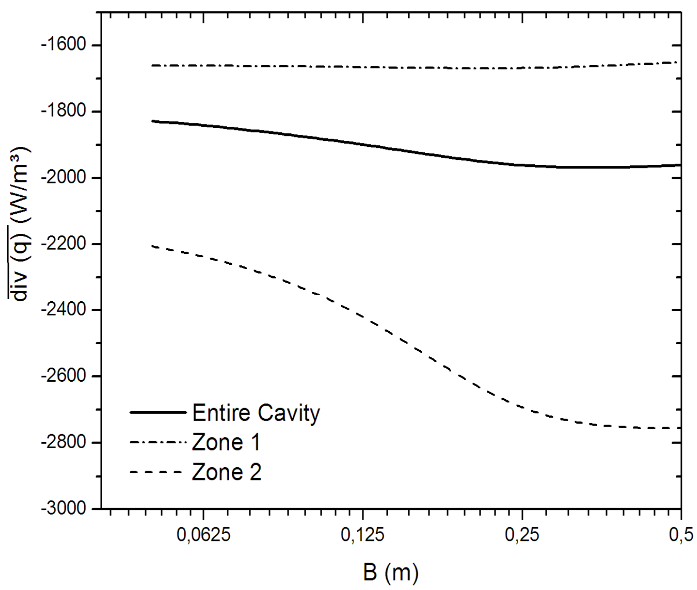


Figure 3. Average divergence of the radiative flux in the entire cavity and in zones 1 and 2 for $\kappa = 0.3$ m^{-1}.

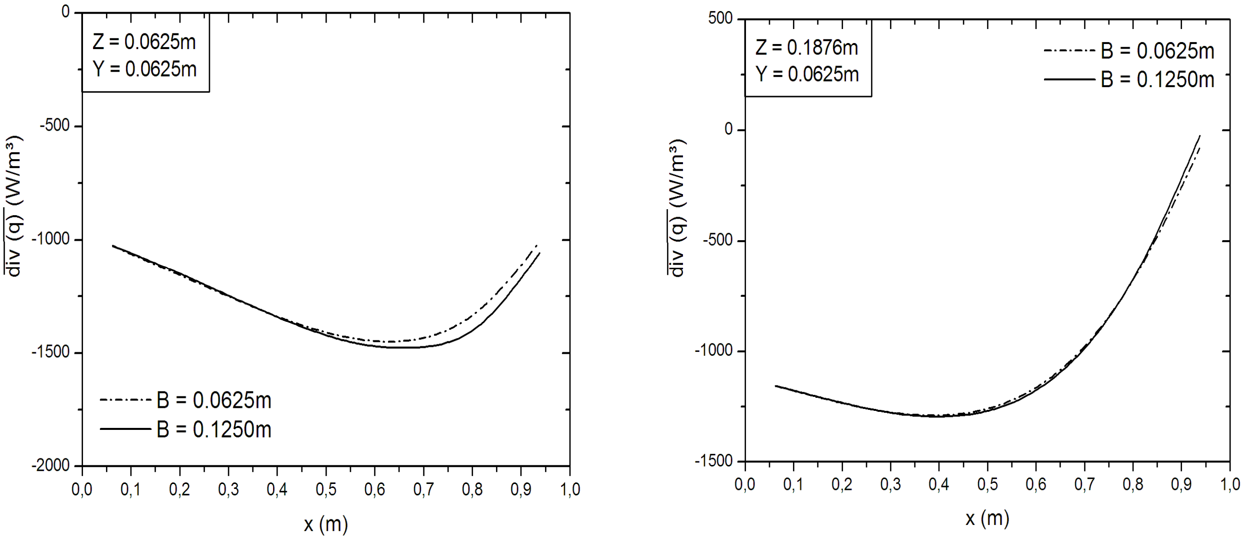
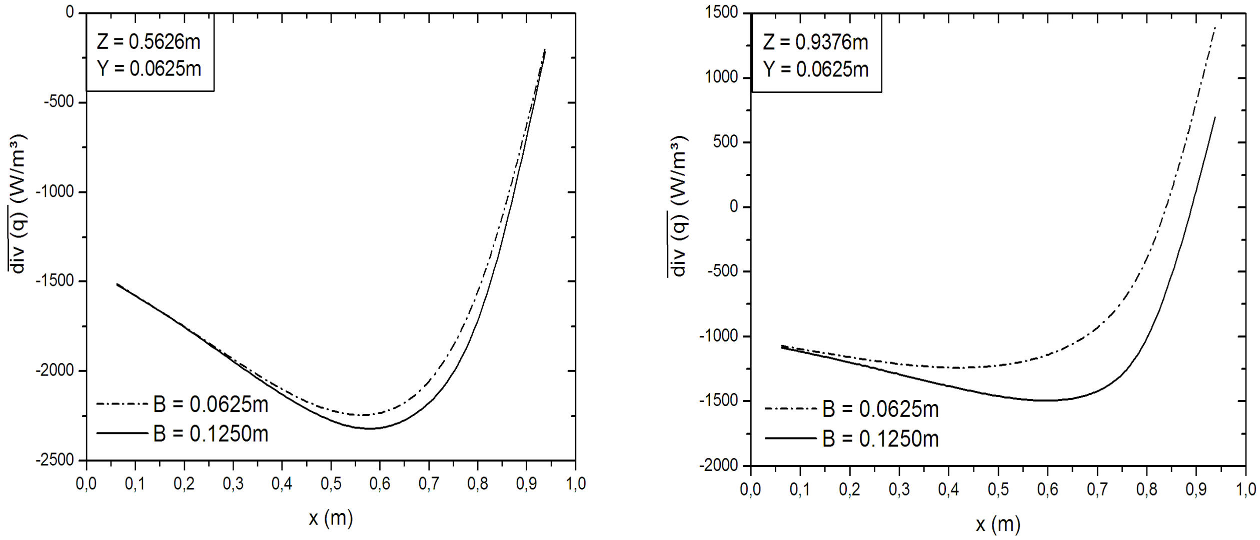


Figure 4. Local divergence of the radiative flux for two different grid refinements (B = 0.0625 m and 0.1250 m) and κ = 0.3 m^{-1} in the following placements of enclosure: (a) z = 0.0625 m, and (b) z = 0.1876 m.

Figures 5a and 5b shows the local divergence of the radiative flux for two different grid refinements (B = 0.0625 m and B = 0.125 m) and κ = 0.3 m^{-1} at positions z = 0.5626 m and z = 0.9376 m, respectively. For z = 0.5626 m the mean difference between the profile of the divergence of the radiative flux obtained with B = 0.0625 m and B = 0.125 m is approximately 1.1%. The highest difference is observed at x = 0.9375 m and is approximately 10.0%. The maximum difference occurs at this point (x = 0.9375 m) also due to the decrease of the magnitude of the divergence of the radiative flux, even that profiles presented in Fig. 5a seems to indicate the highest difference at x ~ 0.6 m. Furthermore, the average and local differences between the profiles for B = 0.125 m and B = 0.0625 m at z = 0.5626 m (Fig. 5a) seem more intense than the difference for the profiles at z = 0.1876 m (Fig. 4b). However, the magnitude of the divergence of the radiative flux is higher at z = 0.5626 m than the magnitude at z = 0.1876 m, reflecting in the average and local difference of the divergence of the radiative flux. This fact can be explained by the gradient of temperature in x and z directions, which is higher for the zone at x = 0.9375 m and z = 0.1876 m than for the zone at x = 0.9375 m and z = 0.5676 m, i.e., the increase of the energy emitted by a gas zone for this region of the cavity is counterbalanced by the decrease of the temperature gradient in the intermediate zone of the cavity. This comparison allows observing that the radiative grid refinement will be also a function of the temperature gradient near the analyzed zone. For z = 0.9376 m the mean difference between the profile of the divergence of the radiative flux obtained with B = 0.0625 m and B = 0.125 m is approximately 40% and the maximum difference is higher than 100%. These results stress that the higher influence of the grid refinement on the prediction of the radiative field for regions with higher temperature and intensive temperature gradients. Moreover, the two obtained profiles, for the grids with B = 0.125 m and B = 0.0625 m, are not in close agreement.

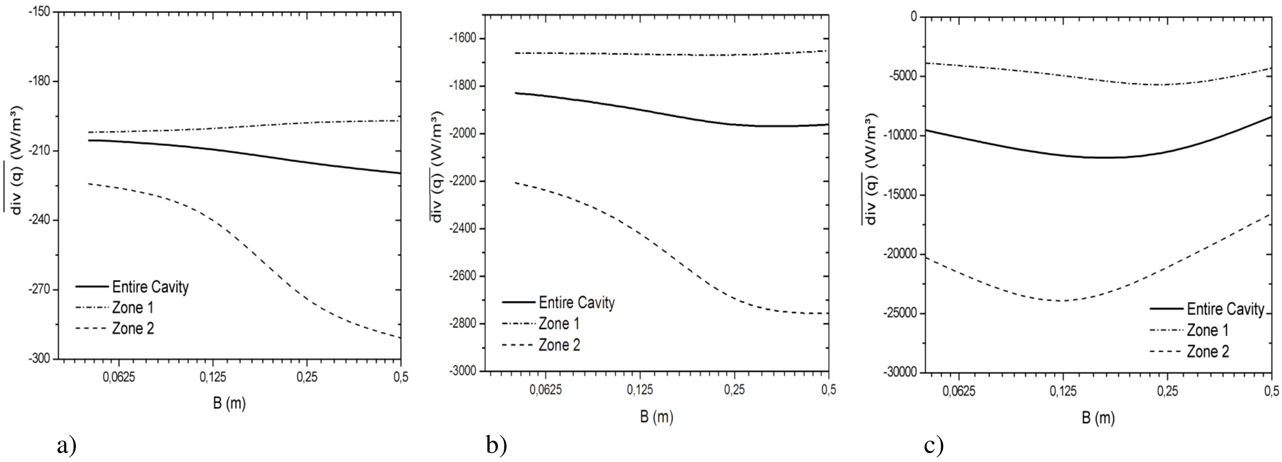
In order to understand the influence of the grid refinement over the prediction of average and local divergence of the radiative flux for different optical thickness, the previous simulations were also performed with absorption coefficients of κ = 0.03 m^{-1} and 3.0 m^{-1}. Figures 6a, 6b and 6c shows the average divergence of the radiative flux as a function of the zone dimension (B) for a medium with κ = 0.03 m^{-1}, κ = 0.3 m^{-1} and κ = 3.0 m^{-1}. In the present evaluation, Fig. 3 is reintroduced here as Fig. 6b. For κ = 0.03 m^{-1} (Fig. 6a) the behavior of the average divergence of the radiative flux was similar to the one observed for κ = 0.3 m^{-1}. However, for this case the difference of the average divergence of the radiative flux for B = 0.05 m and B = 0.0625 m for the entire enclosure was reduced in almost 10 times. For zones 1 and 2 the variation of the average divergence of the radiative flux for κ = 0.03 m^{-1} is also lower than for κ = 0.3 m^{-1}: 0.4% and 0.02%, respectively. For κ = 3.0 m^{-1} (Fig. 6c), the difference of the average divergence of the radiative flux increases for all analyzed zones. Moreover, the behavior of the average divergence of the radiative flux is not asymptotic at B = 0.05 m for any analyzed zones, indicating that more refined zones are required. The relative differences of the average divergence of the radiative flux for B = 0.05 m and B = 0.0625 m for the entire cavity, zone 1 and zone 2 are 6.3%, 6.7% and 4.8%, respectively.



a) b)

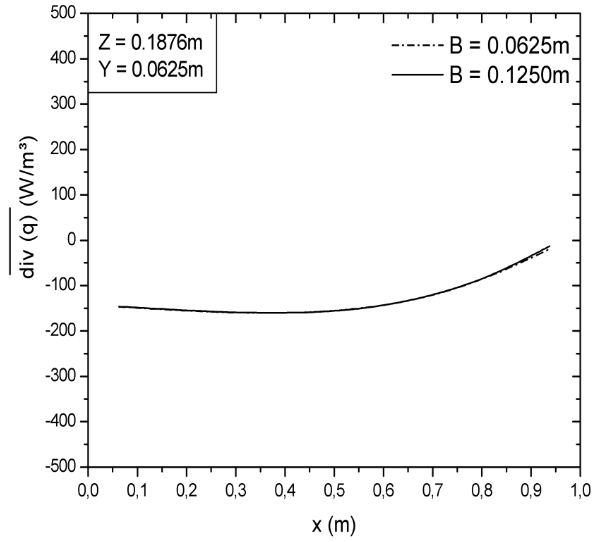
Figure 5. Local divergence of the radiative flux for two different grid refinements (B = 0.0625 m and 0.1250 m) and κ = 0.3 m^{-1} in the following placements of enclosure: (a) z = 0.5626 m, and (b) z = 0.9376 m.

The local evaluation of the influence of grid refinement in the radiative field for several optical thickness was performed by the insertion of numerical monitoring lines at the placements z = 0.1876 m and z = 0.9376 m, which proved to be the most sensitive regions for κ = 0.3 m^{-1}. Figures 7a and 7b shows the local divergence of the radiative flux for two different grid refinements (B = 0.0625 m and B = 0.125 m) and κ = 0.03 m^{-1} at positions z = 0.1876 m and z = 0.9376 m, respectively. For z = 0.1876 m (Fig. 7a) the profile of local divergence of the radiative flux is almost independent of grid. The average divergence for the two successive grids analyzed is approximately 0.5% with a maximum difference of 2.2%. For z = 0.9376 m (Fig. 7b), the difference between the local divergence of the radiative fluxes obtained with two successive grids is also reduced for κ = 0.03 m^{-1} in comparison to the medium with κ =0.3 m^{-1}. The average local difference for this case is approximately 30% and the maximum difference is of 80%. This maximum difference results from the reduction of the magnitude of the divergence of the radiative flux.

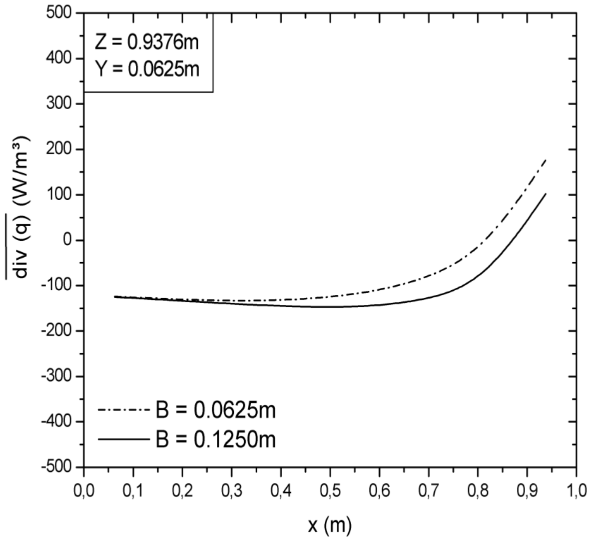


a) b) c)

Figure 6. Effect of the absorption coefficient on the mean divergence of the radiative flux: (a) κ = 0.03 m^{-1}, (b) κ = 0.3 m^{-1} and (c) κ = 3.0 m^{-1}.



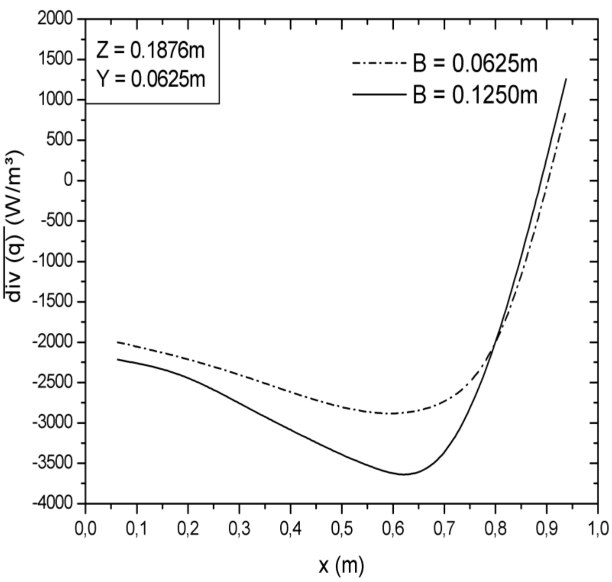
a)



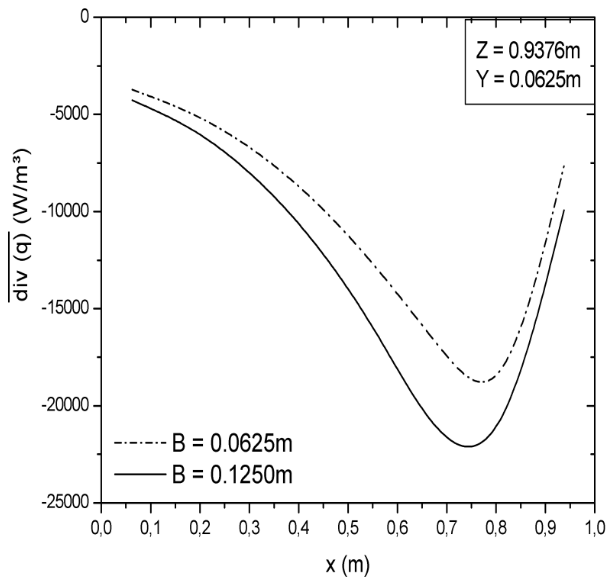
b)

Figure 7. Local divergence of the radiative flux for two different grid refinements (B = 0.0625 m and 0.1250 m) and κ = 0.03 m^{-1} in the following placements of enclosure: (a) z = 0.1876 m, (b) z = 0.9376 m.

Figures 8a and 8b shows the local divergence of the radiative flux for two different grid refinements (B = 0.0625 m and B = 0.125 m) and κ = 3.0 m^{-1} at positions z = 0.1876 m and z = 0.9376 m, respectively. For z = 0.1876 m (Fig. 8a) the profiles obtained with B = 0.0625 m and B = 0.125 m presents some important differences, even qualitatively. For instance, the minimum divergence of the radiative flux predicted with the grid of zone dimension B = 0.1250 m is -3780 W/m³, while for the grid B = 0.0625 m it is -2914 W/m³, with a difference of about 30%. The mean difference between the profiles at z = 0.1876 m is 15% and the maximum difference is 35%. For z = 0.9375 m the mean difference between the profiles at z = 0.9375 m is 20% and the maximum is 40%. For κ = 3.0 m^{-1} it can be observed that the grid refinement influenced not only hotter regions of the enclosure but also the colder regions. This behavior increases the difference of the average divergence of the radiative flux for all zones investigated. Moreover, the increase of the optical thickness increased the influence of the grid refinement over the local radiative field at regions of lower temperature.



a)



b)

Figure 8. Local divergence of the radiative flux for two different grid refinements (B = 0.0625 m and 0.1250 m) and κ = 3.0 m^{-1} in the following placements of enclosure: (a) z = 0.1876 m, (b) z = 0.9376 m.

6. CONCLUSIONS

In the present work, it was investigated the influence of the domain discretization on the prediction of the average and local divergence of the radiative flux. The radiant field is solved with the zonal method for a three-dimensional cubical enclosure of dimensions $H = W = L = 1$ m filled with participant medium and the domain is discretized in cubical zones of dimension B. The participant medium was treated as a gray gas and scattering was neglected. Three different absorption coefficients were employed for the simulation of the radiative transfer in the participant medium ($\kappa = 0.03$ m^{-1}, 0.3 m^{-1} and 3.0 m^{-1}) to gain understanding if more refined radiative grids are necessary when the optical thickness is changed.

The results for the average divergence of the radiative flux for the entire cavity and zones 1 and 2 shown that the highest temperature zone (zone 2) was the most influenced by the decrease of B, specially when the absorption coefficients were $\kappa = 0.03$ m^{-1} and 0.3 m^{-1}. For $\kappa = 3.0$ m^{-1} the differences between the average divergence of the radiative flux increases for all evaluated portions of the domain, but the high temperature region was still the most influenced by the grid refinement. Moreover, the local evaluation of the radiative field allowed the observation that not only higher temperature regions were more influenced by the grid refinement than the lower temperature regions, but it also depends on where the highest temperature gradients were placed. This fact was evidenced when a comparison were performed between the difference obtained for two successive grids at $z = 0.1876$ m and $z = 0.5626$ m, where the average and local difference were observed in the region of lower temperature. Furthermore, the local radiative field was subjected to a higher influence of the refinement grid than the average field for all performed simulations.

To summarize, the results led to the following general recommendations concerned with the effect of the grid refinement on the prediction of the radiative field (for decoupled or coupled convection/radiative heat transfer): 1) coarser grids are required for optical thin mediums, i.e., the difference between convective and radiative grids has lower influence on the accuracy of the radiative field solution as the optical thickness of the participating medium is decreased; 2) grids more refined are required not only for regions subjected to higher temperature gradients but also for higher temperature regions and 3) for optically thick mediums, the influence of the magnitude of the temperature field is almost insensitive on the grid refinement, for these cases the grid refinement are mainly required in regions where the highest temperature gradients are placed.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Białecki, R. A., Węcel, G., 2004, “Solution of Conjugate Radiation Convection Problems by a BEM FVM Technique, JQSRT, Vol. 84, pp. 539-550.

Coelho, P. J., 2004, “Detailed Numerical Simulation of Radiative Transfer in a Non Luminous Turbulent Jet Diffusion Flame, Combust. Flame, Vol. 136, pp. 481-492.

Coelho, P. J., 2007, “Numerical Simulation of the Interaction between Turbulence and Radiation in Reactive Flows”, Proc. Energy Combust. Sci., Vol. 33, pp. 311-383.

Denison, M. K., Webb, B. W., 1993, “An absorption-line Blackbody Distribution Function for Efficient Calculation of Total Gas Radiative Transfer”, JQSRT, Vol. 50, pp. 499-510.

Dos Santos, R. G., Lecanu, S., Ducruix, S., Gicquel, O., Iacona, E., Veynante, D., 2008, “Coupled Large Eddy Simulations of Turbulent Combustion and Radiative Heat Transfer”, Combust. Flame, Vol. 152, pp. 387 – 400.

Gupta, A., Modest, M.F., Haworth, D.C., 2009, “Large-Eddy Simulation of Turbulence-Radiation Interactions in a Turbulent Planar Channel Flow”, J. Heat Transf., vol. 131, 061704-1– 061704-8.

Hottel, H.C., Sarofim, A. F., 1967, “Radiative Transfer”, McGraw-Hill Book Company.

Ibrahim, A., Lemmonier, D., “Numerical Study of Coupled Double-Diffusive Natural Convection and Radiation in a Square Cavity Filled with a N2–CO2 Mixture”, Int. Commun. Heat Mass Transf., Vol. 36, pp. 197-202.

Jones, W.P., Paul, M.C., 2005, “Combination of DOM with LES in a Gas Turbine Combustor”, Int. J. Eng. Science, Vol. 43, pp. 379-397.

Kounalakis, M. E., Gore, J. P., Faeth, G. M., 1988, “Turbulence/radiation interactions in nonpremixed hydrogen/air flames”, 22nd symposium (international) on combustion, Pittsburgh, pp. 1281 – 1290.

Mazumder, S., Modest, M. F., 1999, “Turbulence-radiation interactions in nonreactive flow of combustion gases”, J. Heat Transf., Vol. 121, pp. 726 – 729.

Modest, M. F., 1991, “The Weighted-sum-of-gray-gases Model for Arbitrary Solution Methods in Radiative Transfer”, J. Heat Transf., Vol. 113, pp. 650-656.

Siegel, R., Howell, J. R., 2002, “Thermal Radiation Heat Transfer”, Taylor & Francis, New York, USA.

Smith, T. F., Shen, Z. F., Friedman, J. N., 1982, "Evaluation of Coefficients for the Weighted Sum of Gray Gases Model", J. Heat Transf., Vol. 104, pp. 602-608.

Solovjov, V. P., Webb, B. W., 2002, "A Local Spectrum Correlated Model for Radiative Transfer in Non-uniform Gas Media", JQSRT, Vol. 73, pp. 361-373.

Tucker, R. J., 1986, "Direct Exchange Areas for Calculating Radiation Transfer in Rectangular Furnaces", J. Heat Transfer, Vol. 108, pp. 707 – 710.

Wang, A., Modest, M. F., Haworth, D. C., Wang, L., 2008, "Monte Carlo simulation of radiative heat transfer and turbulence interactions in methane/air jet flames", JQRST, Vol. 109, pp. 269 – 279.

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