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The Effect of Combustion Type on the Radiation Heat Transfer in Back Pass Channel of a CFB Boiler

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1. Introduction

The obvious needs of reducing CO2 emission and implementing the world energy resources in a sustainable way caused an increasing attention to designing more efficient combustion systems. In this regard, the accurate and computationally efficient numerical tools and models for simulating the complex heat and mass transfer phenomena in combustion systems play a significant role. Due to high temperature of combustion products in industrial furnaces, a major part of heat transfer from combustion products to walls is carried out by means of radiative heat transfer. The energy produced by combustion is transferred to participating media and surrounding walls through the emission of gases and absorption and scattering of particles. The radiation heat transfer, the reflection in the walls and scattering of particles are directional phenomena which lead to demand of solution of integro-differntial conservation equation for radiative heat transfer known as radiative transfer equation. In addition, the radiative properties of combustion gases are wave length dependent and the exact solution of RTE in fully participating media is only possible if the radiation transfer equation would be solved for all the wave numbers in electromagnetic wave spectrum. This kind of solution which can be done through line by line calculation, integrating all the spectral line of the gases in the spectrum, is computationally expensive and is not possible except for very simple cases or for producing benchmarks. As a common practice, in engineering calculation and also most of CFD calculations, the spectral changes of gas radiative properties are ignored and the entire spectrum is treated by a constant average value, i.e. gray gas modeling. Between these two extreme cases of line by line calculation and gray gas model, there are several approximate methods in which the spectral features of gas radiation is taken into account, e.g. exponential wide band model (EWBM) [1], and non gray banded approach [2].

The weighted sum of gray gases (WSGG) model, as an approximate method for non gray radiative heat transfer modeling of combustion gases, has been founded by Hotel and Sarofim in the framework of their radiative zone method [3]. A set of coefficients for WSGG model proposed by Smith et al [4] has been used widely in radiation

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heat transfer calculations both for gray and non gray modeling. However, it should be noticed that these coefficients have been derived based on emissivity chart of CO2-H2O mixtures in the air-fired combustion scenario. Implementing them in the oxy-fired conditions may lead to uncertain level of inaccuracy.

In this research, the radiative heat transfer in the backpass channel of a CFB boiler have been calculated by using the modified version of zone method and WSGG model for both air and oxygen fired conditions. The standard WSGG model is used for air-fired condition while a new WSGG model [5] which is specifically proposed for oxy-fired condition has been used for modeling the oxy-fired case.

2. Theory

In zone method, the radiation transfer equation is solved in a much coarser cell structure than those usually used in CFD calculation to solve turbulent fluid flow. By this way, the computational domain and surrounding walls are decomposed to some coarse volume and coarse surface zones in which the gradient of temperature and radiative properties are ignored. Then the direct exchange area (DEA) between each pair of zones is calculated which represent the amount of radiation emitting from certain point of the domain and is directly (without being reflected by surfaces) extinct in the volume zones or directly reaches the surface zones. If the walls of the domain have some reflection, then another coefficient named total exchange area (TEA) is needed to be calculated which include total radiation heat transfer between each pair of zones either directly or by being reflected by surface zones in the system. Using the pre-calculated DEAs and TEAs, the radiation heat balance for each surface and volume zone is formed and by solving the resulted system of algebraic equations, the amount of radiative source term in the volume zones and radiative heat flux in the walls are obtained.

The radiative zone method can easily implement WSGG model for non gray radiative heat transfer modeling of CO2-H2O mixtures. In WSGG model, the spectral behavior of gases are modeled by summation of several gray gases each one accumulates a certain range of spectral absorption coefficient and the weighting factors are the black body emissive power corresponded to each of gray absorption coefficient. The emissivity of gas mixture is calculated as

$$\varepsilon_t = \sum_{i=0}^{N_g} a_i \left[1 - e^{-k_i L}\right] \quad (1)$$

Where a_i represents the weighting factor, L is the path length and N_g is the number of gray gases used in the model. Usually using 3 or 4 gray gas is enough for providing a good level of accuracy. Using the coefficient of WSGG model, the radiative source term in the volume zones and radiative heat flux in the surface zones are calculated as

$$RST_i = \sum_{l=0}^{N_g}\left[\sum_{j=1}^{M}\left[\left(s_j s_i\right)_l \left(a_l(T_i)\sigma T_i^4 - a_l(T_j)\sigma T_j^4\right)\right] + \sum_{j=1}^{N}\left[\left(g_j s_i\right)_l \left(a_l(T_i)\sigma T_i^4 - a_l(T_j)\sigma T_j^4\right)\right]\right] \quad (2)$$

$$q_i = \sum_{l=0}^{N_g}\left[\sum_{j=1}^{M}\left[\left(s_j g_i\right)_l \left(a_l(T_i)\sigma T_i^4 - a_l(T_j)\sigma T_j^4\right)\right] + \sum_{j=1}^{N}\left[\left(g_j g_i\right)_l \left(a_l(T_i)\sigma T_i^4 - a_l(T_j)\sigma T_j^4\right)\right]\right] \quad (3)$$

Where ss, sg, gg represent the DEA between surface to surface, surface to gas and gas to gas zones, respectively. $M, N, T,$ and σ are number of surface zones, number of volume zones, temperature of the zones and Stefan-Boltzmann constant, respectively. While the last two equations are limited to not scattering media and black walls, the non gray modeling can be extended to support the isotropic scattering in media and diffuse reflection in the walls. The difference is in using the total exchange area (TEA) instead of DEA in last two equations.

One of the main problems of zone method is accurate calculation of DEA. Usually the formulations of DEA include up to 6 order integrals which cause computationally expensive and complex calculations. The other problem is that for the neighbor zones, there are singularities in the integrations. To avoid these problems, in this research, the simple and accurate correlations for DEA, obtained by authors have been used [6].

As mentioned, WSGG model can be used in gray gas modeling as well. In this case, the calculated total emissivity by eq. 1 is implemented in Beer's law to obtain the gray absorption coefficient of the mixture. Then the DEA and TEA are calculated between each pair of the zones and the radiative balance is written for each volume and surface zones. The radiation balance equations form a system of algebraic equations. Solving this system of equations, the radiative heat flux in the surface zones and the radiative source term in the volume zones are obtained.

3. Numerical Model for Backpass Channel

The geometry of back pass channel studied in this research is shown in Fig.1. Commercial CFD software of Fluent has been used to solve all the balance equations except radiation one. The radiation heat transfer is solved by the zone method as already described. Gray and non gray modelings have been done for both cases of oxygen and air-fired combustion scenario. The walls are assumed black and to show the results, three lines are shown in Fig. 1(b).

Fig. 2 (a, b) shows the effect of spectral radiative features of the gases on the results of radiation heat transfer modeling. Fig. 2(a) shows the radiative heat flux in line 1 shown in Fig. 1(b) for both case of gray and non gray using the air-fired combustion conditions. Fig. 2(b) shows the same comparison for line 2 shown in Fig.1 (b) using the oxy-fired combustion conditions. As it is shown ignoring spectral behavior of gases in radiation heat transfer calculations (gray gas modeling), which is a common practice in engineering calculations of combustion systems, may cause up to 40% over estimation of radiative heat flux in some regions.

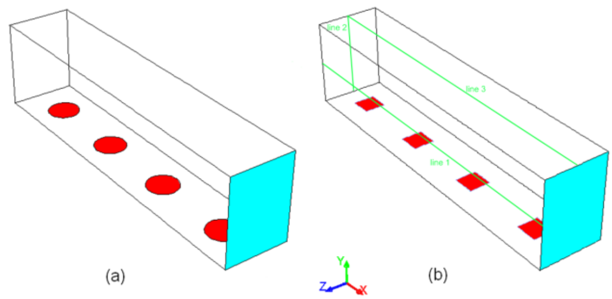

Fig. 1. The geometry of the large scale backpass channel. The red colored parts illustrated the inlet sections while the cyan colored parts shows the outlet section. (a) The original geometry. (b) The modified version used in zonal calculations.

To show the effect of combustion type on the radiative heat transfer, the radiative heat flux in line 3 shown in fig.1(b) obtained by non gray zone method for the case of air and oxygen fired combustion have been compared in Fig. 2(c). As Fig. 2(c) shows the radiative heat flux calculated by non gray zone method for the case of oxygen fired combustion, can be up to 40% larger than those calculated for the case of air-fired combustion.

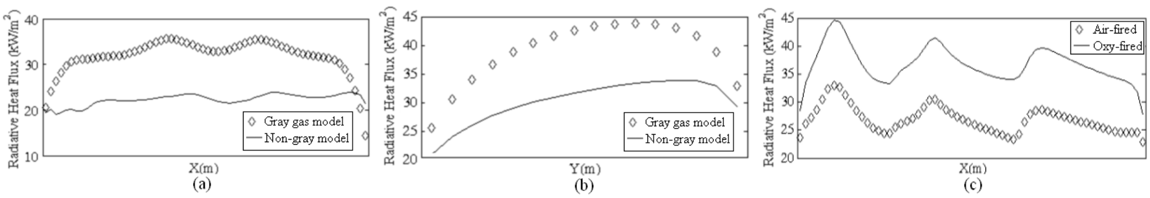

Fig. 2 : (a) The radiative heat flux in line 1 shown in Fig. 1(b) for air-fired case. (b) The radiative heat flux in line 2 shown in Fig. 1(b) for oxy-fired case. (c) The radiative heat flux in line 3 shown in Fig. 1(b) for both cases of air and oxy-fired combustion calculated by non gray zone method.

4. Conclusions and Remarks

The radiative heat transfer in a large backpass channel of a CFB boiler has been analyzed by using gray and non gray zone method and the effect of spectral radiative properties of the gases and combustion type (air/oxy fired) on the radiative heat flux on the walls has been addressed.

5. References

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