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Radiative modelling by the zonal method and WSGG model in inhomogeneous axisymmetric cylindrical enclosure

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Abstract
Nongray radiation calculations are carried out for a case problem available in the literature. The problem is a non-isothermal and inhomogeneous CO_2-H_2O-N_2 gas mixture confined within an axisymmetric cylindrical furnace. The numerical procedure is based on the zonal method associated with the weighted sum of gray gases (WSGG) model. The effect of the wall emissivity on the heat flux losses is discussed. It is shown that this property affects strongly the furnace efficiency and that the most important heat fluxes are those leaving through the circumferential boundary. The numerical procedure adopted in this work is found to be effective and may be relied on to simulate coupled turbulent combustion-radiation in fired furnaces.

1. Introduction

Radiation thermal process occurs in many industrial applications, mainly in fired furnaces and boilers. In such systems, resolving the radiative transfer equation (RTE) is necessary to predict the spatial temperature and heat flux distributions as well as the radiative wall heat losses. It is interesting to note that with a comprehensive mathematical model and fairly realistic gas radiative properties model, satisfactory and relatively fast numerical predictions may be obtained. An exhaustive numerical investigation [1] was achieved in a 3-D cylindrical complex geometry. The author coupled a computational fluid dynamics (CFD) code with the radiation-turbulence-chemistry and combustion interactions. Recently, the zone method and the WSGG model both apply more and more to two and three-dimensional complex geometries [2-5]. It these references, the predicted temperature and flux fields are satisfactory as compared with data obtained from experiments conducted on different fired plants.

In the present work, the zonal method formulated in terms of interchange areas associated with a spatial absorption coefficient distribution due to Murty et al's model [6], were applied to deal with thermal radiation transfer within a cylindrical axisymmetric enclosure. The medium is an inhomogeneous CO_2-H_2O-N_2 gas mixture with 10%, 20% and 70% respectively. This case problem was already investigated particularly by Moghari et al [2]. The effectiveness of the numerical procedure adopted is assessed. The internal boundary emissivity effect on the wall flux is discussed as it plays an important role in the heat exchange process which in turn affects the furnace efficiency.

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2. Mathematical formulation

In the standard zone method, the enclosure is divided into gas and surface zones which are small enough to justify the assumption that the radiative properties are uniform in each individual zone. First, the direct exchange areas (DEAs) are numerically estimated for each gray gas then used to evaluate the total exchange areas (TEAs) by solving matrix relations [3, 7, 8]. The former needs only to be assessed once for each single gray gas before solving the governing energy balance equations overall the surface and volume zones. The net radiative heat flux on a surface zone A_i may be expressed as [8]

$$q_i = \sum_{j=1}^{\Gamma_s} \overrightarrow{S_j S_i}\, E^{\circ}_{s,j} + \sum_{k=1}^{\Gamma_g} \overrightarrow{G_k S_i}\, E^{\circ}_{g,k} - A_i \varepsilon_i E^{\circ}_{s,i} \tag{2}$$

where $E_{s,j}$ and $E_{g,k}$ are the blackbody emissive powers of surface zone j and gas volume k, respectively. $\overrightarrow{S_i S_j}$ and $\overrightarrow{G_i S_j}$ represent the directed flux areas (DFAs) for surface-to-surface and gas-to-surface radiative exchange, respectively. The WSGG model has been initially developed by Hottel and Sarofim within the framework of the zonal method [9]. It consists in substituting a set of several virtual gas components for the real gas. Each gray gas is assigned a constant absorption coefficient, and thus the total gas or gas-soot mixture emissivity is

$$\varepsilon_g(T) = \sum_n a_{g,n}(T)[1 - e^{K_{g\,n} L}] \tag{3}$$

DEAs are calculated for an axisymmetric cylindrical geometry confining an inhomogeneous CO_2-H_2O-N_2 gas mixture. A bilinear interpolation scheme is thus used to evaluate the absorption coefficient of the inhomogeneous medium at any point. Integration procedure is based on the trapezoidal scheme together with the Richardson acceleration algorithm. A three-dimensional integral is calculated for each zone pair by integrating over the path joining their midpoints and the full 2π azimuthal interval. Axisymmetry and reciprocity of DEAs make it possible to reduce considerably the computation requirements.

3. Analysis of the results

To check the validity of the proposed numerical procedure it is considered an axisymmetric cylindrical enclosure (radius: 1 m, height=4 m) filled with a CO_2-H_2O-N_2 gas mixture at atmospheric pressure. The temperature distribution is due to Coelho [10] taken later by Moghari et al [2]. The absorption coefficient field is calculated as in [6].

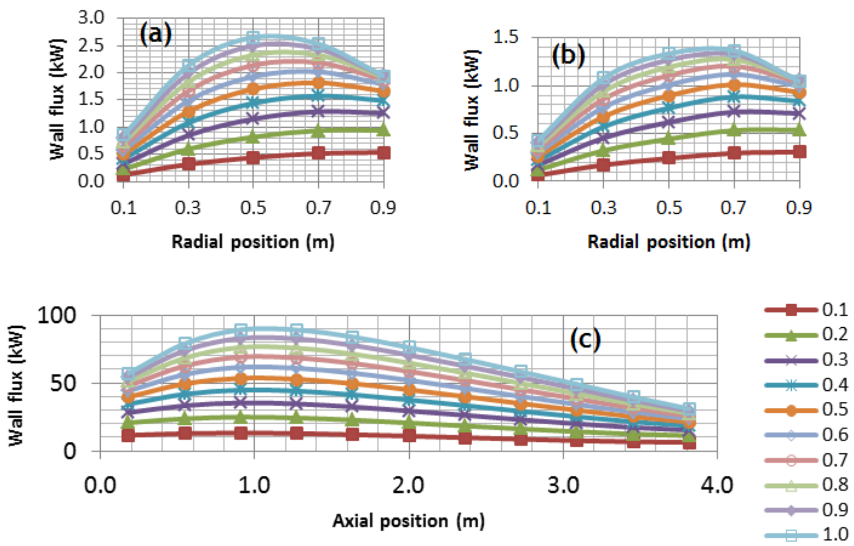

Fig. 2 Wall emissivity effect on the wall heat flux through the (a) lower base (b) upper base and (c) lateral surface.

Figure 2 depicts the net radiative wall flux on both bases and the circumferential surface of the cylindrical system. It is shown that the wall flux losses increase with the internal boundary emissivity on all the surface zones. This flux is found to be zero for totally reflecting internal surface. The flux increases with the radial position starting from zero due to axisymmetry of the studied problem, tends to be uniform close to the centre then decreases. It is worth noting that the flux on a given surface zone, lying on the lower base, is almost the double of its value on the corresponding surface zone of the upper base located at the same radial coordinate. This is foreseeable as the enclosure is a bottom fired system (Fig. 2 a-b). The flux through the circumferential boundary zones takes excessive values as compared to those calculated on the different surface zones of the two bases as shown in Fig. 2-c. It is usually best to consider small wall emissivities in order to minimize energy losses. Actually, the radiative wall property is subject to changes due to the wall deposits such as ash. This alters the furnace efficiency and thus the enclosure requires a regular cleaning.

4. Conclusion

The zonal method associated with the WSGG model is applied to numerically predict wall heat fluxes in an axisymmetric cylindrical enclosure. The participating medium is an inhomogeneous and non-isotherme CO_2-H_2O-N_2 gas mixture. The absorption coefficient along a path length joining the centers of a zone pair, is obtained by bilinear interpolation. The current results show that the radiative thermal losses are higher in the lateral surface than those occurring in both upper and lower bases. Maximum heat exchange occurred at the centre region of the surrounding boundaries as the system is a bottom fired furnace. The effect of the internal wall emissivity on the fired furnace efficiency is discussed. The numerical mathematical radiation model seems to be reliable and thus may be extended to investigate combustion-radiation interactions in other industrial applications.

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