Modeling of a Pulverized Coal Combustion with Non-Gray Gas Radiation Effects

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Introduction

In a pulverized coal combustor, in which various combustion product gases and poly-dispersed particulates are involved, the thermal radiation is considered to play as a significant role as other heat transfer modes. However, its satisfactory modeling is far from being complete since various complex physical phenomena are mingled one another together with intricate physical thermo-chemical properties.

Due to its rudimental difficulties in the phenomena concerned, in the modeling of radiation usually a gray gas assumption has been adopted for the participating media by assuming that the continuous soot radiation is predominant in the combustor [1-4]. However, the non-gray gases such as water vapor and carbon dioxide are intrinsically contained in the mixture so that its appropriate modeling is necessary. A great deal of efforts has been exercised to date to model accurately the non-gray behavior of the gases. Among others, the weighted sum of gray gases model (WSGGM), replacing the non-gray gas by an equivalent finite number of gray gases, is one of simplified but still reasonably practical application models. Since its development by Hottel and Sarofim [5] in the context of the zonal method, it has been applied to examine the effects of the radiation in spray combustion [6].

The main objectives in this study are to seek simultaneously the non-gray gas effects by water vapor and carbon dioxide as well as the gray effects by soot radiation in the pulverized coal combustion. Its results are validated by comparison with experimental results by Hassan et al.[7].

Formulations

The governing equations for two-phase reacting flow in this analysis are in the form of Eulerian approach for the gas phase and Lagrangian approach for the particulate phase while its gas-particle interaction is based on the so-called particle-source-in-cell method in the mass, momentum, species and energy equations [8]. In order to solve the radiative transfer equation, the discrete ordinates method (DOM) is employed with the weighted sum of gray gas model (WSGGM) for the non-gray effects by CO2 and H2O.

Gas phase

The time-averaged gas phase equations for steady, incompressible, turbulent flow in the axisymmetric coordinate can be written in the following form

\[
\frac{\partial (\rho U \Phi)}{\partial x} + \frac{1}{r} \frac{\partial (\rho V \Phi)}{\partial r} = \frac{\partial}{\partial x}\left( \Gamma_{\Phi} \frac{\partial \Phi}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r}\left( \Gamma_{\Phi} \frac{\partial \Phi}{\partial r} \right) + S_{\phi} + S_{\phi,p}
\]

where \( \Phi \), \( \Gamma_{\Phi} \), \( S_{\phi} \) are the representative dependent variable, the effective diffusion coefficient, and the source function for \( \Phi \) per unit volume. Replacement of \( \Phi \) with a value of 1 yields the continuity equation, while a substitution of \( U, V \) and \( W \) represents the momentum equation for each direction, respectively. Turbulence effects are here modeled using the widely used standard \( k-\varepsilon \) model in which the effective turbulent viscosity is denoted in the form of \( \mu_{eff} = C_{\mu} \rho k^2 / \varepsilon + \mu_t \).

The conservation equations for the species mass fraction and the enthalpy also have the form of Eq. (1), where \( \Phi \) is the mass fraction, \( Y_i \) \( (i = \text{volatiles, O}_2, \text{CO}_2, \text{and vapor H}_2\text{O}) \) or the enthalpy, \( h \), respectively. While \( S_{\phi} \) is the source or sink term for the gas phase, \( S_{\phi,p} \) is the one for the particle. For the numerical procedure a conventional TEACH code has been modified [9].

Particle Phase

The Lagrangian approach is used here to trace the particle behaviors and pulverized coal combustion. The
particle momentum equations in axisymmetric coordinates can be cast as follows; \[1, 10\]

\[
M_p \left( \frac{d\mathbf{U}_p}{dt} \right) = C_D \rho_g \left( \frac{A_p}{2} \right) \left[ \mathbf{U}_p - \mathbf{U}_g \right] \times \left[ \mathbf{U}_p - \mathbf{U}_g \right] + M_p g \tilde{S}
\]  

(2)

\[
\frac{d\tilde{S}_p}{dt} = \mathbf{U}_p
\]  

(3)

where \( \tilde{S}_p \) is the particle trajectory. Whereas \( M_p \) and \( A_p \) are the particle mass and the cross sectional area, \( \mathbf{U}_p \) and \( \mathbf{U}_g \) are the particle and gas velocities, respectively. \( C_D, \rho_g, \) and \( g \) are the particle drag coefficient, the gas density, and the gravitational acceleration, respectively.

The coal devolatilization is simulated by a single reaction model, while its char reaction is considered to be controlled by both physical diffusion of oxygen and chemical reaction at the particle surface \[11\]. The rate of change of the inner particle temperature, which is assumed uniform, is calculated from the following equation \[12\]

\[
m_p c_p \frac{dT_p}{dt} = Q_{t} - L_p \frac{dm_p}{dt}
\]  

(4)

where \( Q_{t} \) is the total heat feedback from outside environments which comprises \( Q_{pc} \), the conduction from gas, \( Q_{pb} \), heat liberated on the particle surface due to char reaction, and \( Q_{pr} \), the internal energy loss of particle due to radiation exchange as follows

\[
Q_{pc} = \pi t^2 \lambda \left( T_g - T_p \right)
\]  

(5)

\[
Q_{pb} = K \pi t^2 P_{\text{oa}} H_f
\]  

(6)

\[
Q_{pr} = \varepsilon p \pi^2 \left( 4 \pi \varepsilon - \sum_i I_i \omega_i \right)
\]  

(7)

where \( K \) is the factor related to the coefficients of physical diffusion as well as heterogeneous char reaction. While \( T_g \) and \( T_p \) are the gas and particle temperatures respectively, \( I_{\omega} = \sigma T_f^4 / \pi \) is blackbody intensity of the particle. The particle emissivity and unburned char mass fraction are denoted by \( \varepsilon_p = X_{\omega b} + 0.6(1 - X_{\omega b}) \) and \( X_{\omega b} \).

**Gas phase reaction**

Homogeneous reaction rate in the gaseous phase is here considered to be proportional to the turbulent time scale and to the smallest of the fuel, oxygen, or product concentrations;

\[
R_{hi} = \frac{P^a \varepsilon}{k} \min \left\{ \frac{am_{fu}}{s}, \frac{am_{ou}}{s}, \frac{am_{pr}}{1 + s} \right\}
\]  

(8)

where \( s \) is the stoichiometric mass ratio of oxygen to fuel while \( a=4, b=2 \) are empirical constants used in the eddy dissipation model \[13\].

**Radiation model: DOM with WSGGM**

Modest \[14\] has shown that the WSGGM can be used with any type of solution method for radiation, replacing the non-gray medium by an equivalent number of gray medium with corresponding absorption coefficients. When the non-gray gas mixture also contains nonscattering soot as well as scattering particulates, the equation of transfer can be written for a finite number of gray gas, soot and particulates as follows

\[
\frac{dl_k}{ds} = -\left( \kappa_{f,k} + \kappa_{r,k} + \kappa_{p,k} + \sigma_{sp,k} \right) I_k + \kappa_{f,k} w_{f,k} I_{f,k} + \kappa_{r,k} w_{r,k} I_{r,k} + \kappa_{p,k} w_{p,k} I_{p,k} + \frac{\sigma_{sp,k}}{4\pi} \int_{4\pi} l_{\omega} \Phi(\Omega) \Omega
\]  

(9)

where \( \kappa_{f,k}, \kappa_{r,k} \) and \( \kappa_{p,k} \) are the constant absorption coefficients of gas, soot and particulates respectively, while
$w_{g,k}$, $w_{s,k}$, and $w_{p,k}$ are corresponding weighting factors for gas, soot, and particulates. If the soot and particulates obey a gray gas assumption, it becomes $\kappa_{s,k} = \kappa_{g,k} = \kappa_{p,k} = \kappa$, $k = 1,2, \cdots N$. The total intensity can be obtained by summing up all the solutions obtained by integrating each RTE for the radiative intensity $I_k$ with weight for each gray gas [14].

As shown by Park [15], the weighting factor of the particle becomes the same as that of the gas as function of temperature so that $w_{p,k} = w_{s,k}(\kappa_g)$, when the same bands are shared by the gas and the particulates. Additionally, if thermal equilibrium holds between the soot and the gas, Eq. (9) reduces to the following simplified form

$$\frac{dI_k}{ds} = -(\kappa_{s,k} + \kappa_{p} + \sigma_{sp})I_k + (\kappa_{p,k} + \kappa_{s})w_{p,k}(\kappa_g)I_k + \frac{\sigma_{sp}}{4\pi} \int_{4\pi} I_k(\Omega)\Omega$$

(10)

**Combustor geometry**

In this study the cylindrical pulverized coal fired combustor is shaped as 0.6 m in internal diameter and 3 m long. A schematic of the swirl burner attached is shown in Fig. 1 and its operating conditions are tabulated in Table 1. Further input data for the coal injection and particle size distribution as well as operating conditions are taken from the experimental data by Hassan et al. [7].

![Fig.1 Schematic of the swirl burner (unit: mm)](image)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal flow rate, kg/hr</td>
<td>11.66</td>
</tr>
<tr>
<td>Primary air mass flow rate, kg/hr</td>
<td>21.7</td>
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<tr>
<td>Secondary air mass flow rate, kg/hr</td>
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<tr>
<td>Secondary air swirl number</td>
<td>1.0</td>
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<tr>
<td>Primary air preheat temperature, °C</td>
<td>80</td>
</tr>
<tr>
<td>Secondary air preheat temperature, °C</td>
<td>327</td>
</tr>
</tbody>
</table>

Table 1 Furnace operating conditions

In the following the results are obtained and compared for the non-gray case with WSGGM as well as for gray cases. The gas and soot absorption coefficients are set to $\kappa_g = 0.1$ and $\kappa_s = 0.4$ m$^{-1}$ for the gray1, respectively [4], $\kappa_s + \kappa_g = 0.32 + 0.28e^{-T/1135}$ for the gray2 [16], and $\kappa_g = 0.2Y_{volatiles} + 0.1(Y_{CO} + Y_{H2O})$ m$^{-1}$ for the gray3. The weighted gray gas factors were taken from Smith et al. [17]. The wall emissivity is set to $\varepsilon_w = 0.8$.

For the cases of the gray3 and WSGGM, the soot absorption coefficient is calculated by

$$\kappa_s = \frac{3.72f_sC_pT}{C_2}$$

(11)

where $f_s = 1.0 \times 10^{-6}$, $C_p = 36.08m/k\left[\left(\frac{n^2-k^2}{2}\right)^2 + 4n^2k^2\right], C_2 = 1.4388 cm \cdot K$, $n$ is the real part of the complex index of refraction, and $k$ is the absorptive index [14].

**Results and discussion**

A variation of radiative heat flux is numerically obtained along the axial wall in Fig. 2 and compared with the experimental ones. $X$ is the axial distance from the inlet and $D_f$ is the diameter of the furnace. The gray calculation with $\kappa_g = 0.1$ and $\kappa_s = 0.4$ m$^{-1}$ are actually arbitrary value of absorption coefficient based on the results of the others. Except for the case of gray3, all the numerical results quantitatively agree well with the experimental results. Especially at downstream regions, the result calculated by the WSGGM agrees better than others. In Fig. 3 the radial temperature distributions at three locations are compared with the experimental ones. When the radiation effect is not considered, the prediction over or under-estimates experimental one over all the domains. While a rather good agreement is observed at two downstream locations, at an upstream position of $X/D_f = 0.25$ some deviation is seen. The discrepancies therein between prediction and measurement are not surprising since it is the region where the recirculation zone exists [2, 4]. Although a supplementary verification is required, the calculated results show that the WSGGM is one of plausible tools in the prediction of non-gray gas radiation in a pulverized coal combustion.
References