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An application of Spectral line-based weighted sum of grey gases (SLW) model with geometric optics approximation for radiative heat transfer in 3-D participating media

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HIGHLIGHTS

► MOL–SLW and geometric optics are found to provide more accurate solutions.
► Parametric studies are carried out for the effect of size parameter and presence of particles.
► MOL–SLW predictions are sensitive to both the size parameter and particle load.

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ABSTRACT

A three-dimensional radiation code based on method of lines (MOL) solution of discrete ordinates method (DOM) coupled with spectral line-based weighted sum of grey gases (SLW) model and geometric optics approximation for particles is developed and its predictive ability is tested by applying it to the freeboard of a 0.3 MW_t Atmospheric Bubbling Fluidized Bed Combustor (ABFBC) containing a non-grey, absorbing, emitting and isotropically scattering particle laden flue gas and comparing its predictions with measurements and former predictions obtained by the grey gas model with Mie theory for particles. The MOL of DOM with SLW and geometric optics assumption are found to provide more accurate solutions for incident radiative heat flux than grey gas model with Mie theory particularly for high particle loading. Parametric studies are also carried out to investigate the effect of size parameter and presence of particles on fluxes. MOL–SLW predictions are found to be sensitive to both the size parameter and particle load.

1. Introduction

As the efficiency of fluidized bed combustion technology depends upon the heat recovered in freeboard, where the dominant mode of heat transfer is radiation, predictive accuracy and computational efficiency of the solution method as well as the predictive accuracy of radiative property estimation method for the particle laden combustion gases is of significant importance in modelling the performance of such systems. Previous work regarding the search for the most accurate and computationally efficient solution method in the freeboard of fluidized bed combustors revealed that MOL solution of DOM meets all the requirements [1–3]. This solution method was utilized to investigate the effect of radiative property estimation method for particle laden combustion gases by assuming grey radiation behaviour for both particles and gas and employing Leckner's correlations for gas and Mie theory [4] for particles [5]. Predicted incident radiative fluxes on the walls were benchmarked against measurements and found to be in reasonable agreement.

The present study has been carried out in an attempt to extend this study further and analyze the effect of non-grey gas analysis together with size parameter evaluated from actual particle size distribution of fly ash in the freeboard on incident radiative heat fluxes. For this purpose, a three-dimensional radiation code based on MOL of DOM with SLW and geometric optics approximation was developed and its predictive ability was tested by applying it to the freeboard of a 0.3 MW_t ABFBC containing a non-grey, absorbing, emitting and isotropically scattering particle laden flue gas and comparing its predictions with measurements [5]. The analysis is

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finalized by a parametric study for determination of the effect of size parameter and particles on radiative transfer in the freeboard under recycle conditions.

2. Description of solution and the radiative property estimation methods

2.1. Solution method: MOL solution of DOM

MOL solution of DOM provides efficient and flexible computation using various higher-order approximations for temporal and spatial discretization. This approach involves the time derivate addition of intensity into the discrete ordinates equations given by Schiesser [6]. Application of MOL solution of DOM for each discrete ordinate m and each grey gas j yields

$$k_t\frac{\partial I_j^m}{\partial t} = -\zeta_m\frac{\partial I_j^m}{\partial s} + (\kappa_\mathrm{p} + \kappa_{\mathrm{g},j})\ a_j I_\mathrm{b} - (\kappa_\mathrm{p} + \kappa_{\mathrm{g},j} + \sigma_\mathrm{p})\ I_j^m + \frac{\sigma_\mathrm{p}}{4\pi}\sum_{m'=1}^{M}\Phi(\Omega_{m'},\Omega_m)w_{m'}I_j^{m'} \tag{1}$$

where t is the pseudo-time variable and k_t is a time constant with dimension $[(\mathrm{m/s})^{-1}]$ which is introduced to maintain dimensional consistence in the equation and is taken as unity. Real-time solutions can be obtained by dividing pseudo-time solutions by the speed of light. $\Phi(\Omega_{m'},\Omega_m)$ is the phase function for scattering and M is the total number of ordinates used in the approximation and $w_{m'}$ is the angular quadrature weight associated with the incoming direction $\Omega_{m'}$. In Eq. (1); I represents radiation intensity at the discrete ordinate direction Ω_m, κ_p and σ_p indicate the absorption and scattering coefficient of fly ash particles, respectively, while κ_g means absorption coefficient of each grey gas, and a is used for the blackbody weights determined from the absorption-line distribution functions in the Spectral line-based weighted sum of grey gases (SLW) model [7].

If the boundary of the medium is a diffuse grey wall at a specified temperature, Eq. (1) is subjected to following the boundary condition

$$I_j^m(\mathbf{r}_\mathrm{w}) = \varepsilon_\mathrm{w}a_jI_\mathrm{b}(\mathbf{r}_\mathrm{w}) + \frac{(1-\varepsilon_\mathrm{w})}{\pi}\sum_{m'=1} I_j^{m'}(\mathbf{r}_\mathrm{w})\zeta_{m'}w_{m'} \tag{2}$$

Intensity distribution is determined by solving Eq. (1) with the boundary conditions given in Eq. (2).

Following to MOL approach, the system of PDEs, Eq. (1) is transformed into an ODE initial-value problem by using finite difference approximations. Starting from an initial condition for radiation intensities in all directions, the resulting ODE system is integrated until steady state by using a powerful ODE solver. The ODE solver takes the burden of time discretization and chooses the time steps in a way that maintains the accuracy and stability of the evolving solution. Any initial condition can be chosen to start the integration, as its effect on the steady-state solution decays to insignificance. In order to stop the integration at the steady state, a convergence criterion is introduced. If the intensities at all nodes and ordinates for all grey gases satisfy the condition given below, the solution at the time is considered to be the steady-state solution and the integration is terminated [8]. The condition for steady state is

$$\frac{|I_t - I_{t-1}|}{I_{t-1}} < \in \tag{3}$$

where $\in$ is the error tolerance and the subscript t and $t-1$ denote the solutions at current time and at previous time, respectively. Therefore, the steady-state intensities at all grid points for all grey gases can be evaluated by solving Eqs. (1) and (2).

2.2. Gas radiative property model: spectral line-based weighted sum of grey gases

In the SLW model, the non-grey gas is replaced by a number of grey gases which are logarithmically spaced between 3×10^{-5} and 60 $\mathrm{m^2/mol}$ for water vapour and 3×10^{-5} and 120 $\mathrm{m^2/mol}$ for carbon dioxide as recommended by Denison and Webb [9].

The grey gas weights a_j are calculated through absorption-line blackbody distribution functions, Fs derived from high-resolution HITRAN database [10]. Denison and Webb provided simple mathematical correlations for absorption-line blackbody distributions functions for H_2O and CO_2, respectively [11,12]. In order to calculate total heat transfer rates in a mixture of two gases, H_2O and CO_2, the RTE [Eq. (1)] for isotropic scattering is modified by including an additional grey gas index, k, to account for the second species

$$k_t\frac{\partial I_{j,k}^m}{\partial t} = -\zeta_m\frac{\partial I_{j,k}^m}{\partial s} + \left[\kappa_\mathrm{p} + (\kappa_\mathrm{g})_{j,k}\right] a_{j,k}I_\mathrm{b} - \left[\kappa_\mathrm{p} + (\kappa_\mathrm{g})_{j,k} + \sigma_\mathrm{p}\right] I_{j,k}^m + \frac{\sigma_\mathrm{p}}{4\pi}\sum_{m'=1}^{M} w_{m'}I_{j,k}^{m'} \tag{4}$$

The indices j and k denote the jth and kth grey gas for H_2O and CO_2, respectively. It has been shown by Denison and Webb [13] that the joint grey gas weights are well approximated by the product of the two individual weights:

$$a_{j,k} = a_j\cdot a_k \tag{5}$$

The absorption coefficients $\kappa_{j,k}$ are given as the sum of contributions of the two species [14]:

$$\kappa_{j,k} = N_\mathrm{w}\cdot C_{\mathrm{abs,w},j} + N_\mathrm{c}\cdot C_{\mathrm{abs,c},k} \tag{6}$$

where N_w and N_c are the molar densities, $C_{\mathrm{abs,w},j}$ and $C_{\mathrm{abs,c},k}$ are absorption cross-sections of H_2O and CO_2, respectively.

3. Description of test rig

The main body of the test rig is the modular combustor formed by five modules of internal cross-section of 0.45 m × 0.45 m and 1 m height. Inner walls of the modules are lined with alumina based refractory bricks and insulated. The first and fifth modules from the bottom refer to bed and cooler, respectively, and the ones in between are the freeboard modules. There exist two cooling surfaces in the modular combustor, one in the bed and the other in the cooler providing 0.35 $\mathrm{m^2}$ and 4.3 $\mathrm{m^2}$ of cooling surfaces, respectively. There are 14 ports for thermocouples and 10 ports for gas sampling probes along the combustor. Two ports for feeding coal/limestone mixture are provided in the bed module, one 0.22 m, the other 0.85 m above the distributor plate.

Analytical system of the test rig consists of a bank of analyzers for O_2, CO, CO_2, SO_2 and NO/NO_x. In order to measure concentrations of O_2, CO, CO_2, SO_2, NO_x at the combustor exit at steady state, combustion gas is sampled from the exit of the combustor and passed through gas conditioning system where the sample is filtered, dried and cooled. After the measurement of species concentrations, sample gas is vented to the atmosphere. The test rig is equipped with a data acquisition and control system namely Bailey INFI 90. The output signals from analyzers and process values such as temperatures, air and water flow rates, pressures and speed of screw conveyors are logged by means of a data acquisition and