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Full Length Article

Predictions of soot formation and its effect on the flame temperature of a pulverized coal-air turbulent jet

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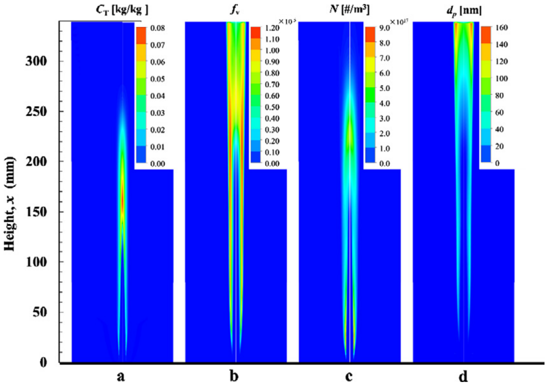
GRAPHICAL ABSTRACT



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ABSTRACT

The distributions of soot volume fraction, soot number density, and soot particle size in a coal-air turbulent jet flame was numerically investigated using a soot formation model developed in our previous study. In addition, the effect of radiation from different radiative media on the flame temperature was assessed and discussed. Validated by the reported experimental measurements, the distribution of soot volume fraction in the turbulent air-coal jet flame was well predicted. It was also found that soot particles were formed and accumulated in the high temperature zone with remarkable oxygen deficient. In the same time, the temperature of the coal-air jet flame was reduced remarkably by soot radiation but barely by soot formation. For the simulated flame, at a downstream location of 200 mm from the jet exit, the heat loss caused by the thermal radiation of coal particles, soot particles and gas species resulted in a temperature decrease of 262 K, 238 K and 102 K respectively. Different radiative media induced remarkably different distributions of absorption coefficient, and the emitting heat loss from the media was determined by the local absorption coefficient and temperature.

1. Introduction

Soot formation has been studied for several decades, but mostly for the gaseous hydrocarbon flames [1–3]. In fact, during the combustion of pulverized coal particles, soot could be also massively produced [4,5]. On one hand, if they are emitted to the air, soot particles become pollutants that are severely harmful to human health and environment. On the other hand, soot particles behave as solid radiation emitters in the furnace, enhancing radiative heat transfer between the flame and membrane walls [6], and influencing flame temperature and NO_x formation. Thus, studying the soot

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formation and its radiation effect on the coal-air flames is of significance for the combustor design and emission control.

Some laboratory experimental studies have been conducted on soot formation in the coal-air jet flames. It was found soot formation mainly occurs in the area with high concentration of released volatile in the early combustion phase of the coal-air jet [7,8]. Under pyrolysis conditions (i.e., O_2-free conditions), as reported by Ma et al. [9], volatiles released from the particles in a dilute coal stream form a "soot cloud" at high temperature regions. The size of the formed primary soot particles varies from 25 nm to 60 nm. Operational parameters such as the O_2 molar fraction (x_{O2}), temperature, as well as the convection intensity significantly affect the soot yields around a coal cylinder [4]. Recently, Hayashi et al. [7] applied Laser Induced Incandescence (LII) technique to detect the soot volume fraction (f_v) in a coal-air jet flame. They found that the laser energy must be carefully controlled to exclude the interference of coal particles, and soot particles exist in the space between the high coal concentration zone and the flame front, and f_v varies non-monotonically along the flame [7]. However, few studies were conducted on the detailed soot distribution in the coal-air jet flame and the radiative effect of the soot particles on the flame temperature.

Given that the coupling between the soot formation and flame radiation is too complicated and expensive to measure, Computational Fluid Dynamics (CFD) simulation was conducted in this study alternatively as it was much cost-effective and capable to reveal some insights that the measurement could not do. In our previous study, a transient mathematical model was developed to describe soot formation during the combustion of single coal particles [10]. In that model, the major sub-processes such as nucleation, oxidation, and agglomeration of soot particles were considered, inheriting the merits of the static semi-empirical model given by Fletcher and his coworkers [5,8]. The model described the essential characteristics of soot evolution in coal combustion with rather low computational cost, and well predicted flame temperature T_f and f_v under different x_{O2}'s against recent experimental results measured in a drop tube furnace by Khatami et al. [11].

In this study, the single-coal-particle model was integrated into a commercial CFD code to investigate soot formation in a pulverized coal jet flame, as well as the soot effect on the flame characteristics including temperature and heat radiation. To validate the modeling, numerical results of flame temperature, major species and soot distribution were compared with the experimental data obtained by the researchers in the Central Research Institute of Electric Power Industry (CRIEPI), Japan [7,12,13]. The flame temperatures with different radiation settings were also calculated and the results were compared with the experimental data to identify the contribution of soot radiation on radiative heat transfer in a coal jet flame.

2. Numerical methodology

2.1. Problem description of the simulation

Fig. 1 illustrated the configuration of the pulverized coal jet flame used in the present simulation. It had the same settings as those in experimental studies by Hayashi et al. [7] and Hwang et al. [12]. The mixture of pulverized coal particles and air was ejected from a tube of 6 mm inner diameter. Methane (CH_4) co-flow was supplied through an annular slit burner (0.5 mm in width) around the central tube, as used to ignite and stabilize the jet flame in the experiments.

In the simulation, two-dimensional meshing was used due to the axial symmetry. The domain ranged over $-60\text{ mm} < x < 340\text{ mm}$ and $0 < r < 100\text{ mm}$. The meshes near the burner exit as well as the flame zone were refined to improve the spatial resolution of the coal flame. The number of meshes was ~70,400, and the mesh independence verification was conducted to make sure that the spatial resolution was enough and would not affect the results. The burner exit was defined as $x = 0$, and the inlets of the air, CH_4 and ambient air were set to $x = -60$ mm.

Velocity-inlet boundaries were used for the inlets of main air flow and CH_4, while atmospheric pressure outlet boundaries were used for the top outlet. A small amount of co-flow air (0.5 m/s) was used between the acrylic duct surrounding the flame and the CH_4 flame [14]. All initial flows were of ambient temperature. In the experiments, the flow rates of the air flow and CH_4 flow were set at $1.80 \times 10^{-4}\ \text{Nm}^3/\text{s}$ and $2.33 \times 10^{-5}\ \text{Nm}^3/\text{s}$ respectively. The air flow rate through the burner, included that used for the pulverized coal feeding, was set the same as that used by Hashimoto et al. [15] in the simulation, namely $2.07 \times 10^{-4}\ \text{Nm}^3/\text{s}$. A Newlands bituminous coal with 26.9% volatile (in dry ash basis) was tested [7], and the coal feeding rate was kept at 1.49×10^{-4} kg/s. The particle size distribution was assumed to meet the Rosin-Rammler approximation.

2.2. Mathematical approaches

2.2.1. Governing equations for soot formation

The governing equations of tar mass fraction (Y_T), soot mass fraction (Y_S), and soot number density (N_S) are as follows,

Tar mass fraction:

$$\vec{\nabla}\cdot(\rho_g \vec{u}\, Y_T) = \vec{\nabla}\cdot\left(\frac{\mu}{Sc_{YT}}\vec{\nabla} Y_T\right) + S_{Y_T} \tag{1}$$

Soot mass fraction:

$$\vec{\nabla}\cdot(\rho_g \vec{u}\, Y_S) = \vec{\nabla}\cdot\left(\frac{\mu}{Sc_{YS}}\vec{\nabla} Y_S\right) + S_{Y_S} \tag{2}$$

Soot number density:

$$\vec{\nabla}\cdot(\rho_g \vec{u}\, N_S) = \vec{\nabla}\cdot\left(\frac{\mu}{Sc_{NS}}\vec{\nabla} N_S\right) + S_{N_S} \tag{3}$$

where ρ_g is the gas density, $\vec{u}$ is the velocity vector, and μ is the turbulent viscosity of the gas. Sc_{YS}, Sc_{YT}, Sc_{NS} are the turbulent Schmidt numbers of Y_S, Y_T and N_S respectively. Both S_{CYS} and S_{CNS} are set as 700 [10] and Sc_{YT} is chosen as 5.6. Here, Sc_{YT} is larger than that of other gas species (~0.7 [16]) as the molecule weight of tar is rather large. S_{YT}, S_{YS} and S_{NS} are the source terms of Y_T,Y_S and N_S respectively, and they were obtained from the soot models of Brown and Fletcher [8].

The soot equations were coupled with the equations of continuity, momentum and energy conservation and solved by Ansys Fluent [17]. The radiative transfer, species mass fraction, and temperature were solved using the default algorithm. The equations of Y_T, Y_S and N_S were solved by implementing the three variables as user defined scalars (UDS).

2.2.2. Radiation calculation

Discrete Ordinates Method (DOM) was selected to calculate the thermal radiation with gray body assumption for gas and particle properties. As soot particles and coal particles were also involved in the radiation calculation, the traditional radiative transfer equation (RTE) was rewritten in the form of Eq. (4),

$$\begin{aligned}\nabla\cdot\left(I\left(\vec{r},\vec{s}\right)\vec{s}\right) + (\alpha + \alpha_{\text{coal}} + \sigma_{sca})I\left(\vec{r},\vec{s}\right) \\ = \alpha n_r^2\frac{\sigma T^4}{\pi} + E_{\text{coal}} + \frac{\sigma_{sca}}{4\pi}\int_0^{4\pi} I\left(\vec{r},\vec{s}'\right)\Phi\left(\vec{s},\vec{s}'\right)d\Omega'\end{aligned} \tag{4}$$