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Original Research Paper

Experimental and numerical investigation of effects of particle shape and size distribution on particles' dispersion in a coaxial jet flow

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ABSTRACT

In this study, an experimental and a numerical investigations are performed to investigate the effect of particle's shape and size distribution on its dispersion behavior. Firstly, particle dispersion of pulverized coal and spherical polymer particles is observed by Particle Image Velocimetry (PIV) technique in the experiment. Secondly, a simulation is performed to analyze the particle dispersion in detail. Spherical and spheroidal motion models are applied to particle's movement to investigate the shape effect. Furthermore, monodisperse and polydisperse for particles are applied to investigate the size distribution effect on the dispersion. Experimental results show that in the jet turbulence flow, pulverized coal particles, which have complex shapes and various sizes, have quite different dispersion behavior compared to spherical particles. In terms of the results of the simulation, this difference is mainly caused by the size distribution effect. Although particle's shape affects the dispersity, it is weakened by the size distribution effect.

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1. Introduction

Gas-particle two-phase flows are widely utilized in coal industries. For instance, in coal-fired power plants, which are one of the largest industries in terms of power production and CO_2 emission, there is an urgent need to realize clean coal technology to reduce the CO_2 emission. It is important to achieve a deeper understanding of the two-phase reacting fields on pulverized coal combustion boilers or coal gasifiers, which consume a great amount of coal. In these furnaces, coal particles are injected into the reacting field and heated. They release devolatilized gases and after then combust in the form of char-reaction. Synchronously, the devolatilized gases are heated and burning, keep to maintain the flame [1]. Therefore, the particle dispersion is an important aspect of the maintaining of the coal combustion flame. Because unequally distributed particles can result in unequally distributed burnable gases, and subsequently lead to the extinguishing of the flame.

In a furnace, it is hard to observe it directly due to the extremely high temperature and pressure. Computational Fluid Dynamics (CFD) is frequently used to study such flow field. Watanabe and colleagues [2–7] have performed numerical simulations of pulverized coal combustion and gasification on a wide range of reactor scales and investigated the detailed behavior of coal flames. The group of Kempf [8–10] works on the modeling of the coal combustion and the application of Large Eddy Simulation. Muto et al. [11] studied the effects of the particle swelling and shrinkage during the devolatilization and char combustion on the flame characteristics. Many findings in the coal combustion field assume that coal particles are spherical, simplifying the numerical problems and reducing the computational cost, but particles prepared by a pulverizer have non-spherical shapes. In order to consider the particle's shape effect, some non-spherical particle motion models are proposed. Most of these models pay attention to the spheroidal particle and modify the drag coefficient [12–15] because generally the particle's drag force dominate the motion of the particle. These researches are mainly focused on a single spheroidal particle's motion modeling. How the particle dispersity are affected while using non-spherical model is limited in the literature. On the influence on the particle concentration and velocity in a turbulent flow, many experimental efforts have been done, such as Tsuji et al. [16], Fleckhaus et al. [17], Frishman et al. [18], and Lau and Nathan [19,20]. They measured and obtained the profiles of the particle concentration and velocity via Laser Doppler Anemometry (LDA) or Particle Image Velocimetry (PIV).

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In this paper, we firstly do an experiment to observe the particle dispersion in a coaxial jet flow by PIV approach. And pulverized coal and spherical polymer particles are used to compare with each other. Then we do a simulation to reproduce the experiment. We describe a spheroidal particle's motion by a sine curve's PDF with a practical view, and the model effect is discussed by comparing to the result of the traditional spherical motion model. The influence on the particle dispersion behavior is discussed in two aspects, the effect of particle's shape and the effect of particle's size.

2. Experimental details

Fig. 1 showed the schematic diagram of the experiment. In the experiment, the particles were transported by the air flow and injected vertically into space via a coaxial jet. A laser sheet was deployed and the particle's behavior was caught by PIV. The laser sheet was applied at a different height of 0, 20, 30, 60, 90, 120, 150, 180, and 210 mm from the burner exit. At each height, 1000 graphics were taken. The particles instantaneous dispersion appearance were obtained. The time-averaged dispersion and velocity profiles were given by a post-processing. Two cases were performed, one used pulverized coal and the other used spherical polymer particles. The details of the samples were listed in Table 1. The COAL case used pulverized coal, which had a composition of complex shapes. The diameter mainly distributed in a range from few tens to hundreds micrometer. For the POLYMER case, the particle was made of polymer, which density was about 1200 kg/m^3, close to real coal density. The shape was spherical and the diameter was highly concentrated. During the experiment, both the particle mass flux rate and the gas flow rate were measured and kept to be constant. In this study, the averaged flow velocity was adjusted to 7.59 m/s and the particle mass flux rate was kept 1.29194×10^{-4} kg/s.

3. Numerical methods

3.1. Governing equations

In this study, Large Eddy Simulation (LES) is applied for the gas phase. The governing equations are expressed as

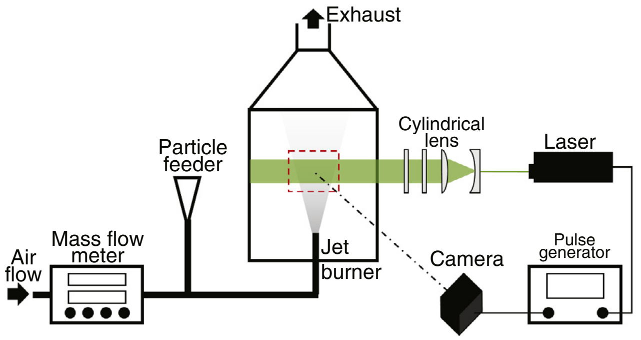

Fig. 1. The schematic design of the experiment configuration.

Table 1
The cases performed in the experiment.

	Cases	Particle shape	Diameter [μm]
Exp.	COAL	Complex	Polydisperse
	POLYMER	Spherical	28

$$\frac{\partial \overline{\rho}_f}{\partial t} + \frac{\partial \overline{\rho}_f \tilde{u}_j}{\partial x_j} = S_m, \tag{1}$$

$$\frac{\partial \overline{\rho}_f \tilde{u}_i}{\partial t} + \frac{\partial \overline{\rho}_f \tilde{u}_j \tilde{u}_i}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial \overline{\sigma}_{ij}}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} + \overline{\rho}_f g + S_{u_i}, \tag{2}$$

here ρ_f, u_i, p, and σ_{ij} are the gas phase density, velocity, pressure, and viscous stress tensor, respectively. τ_{ij} is the subgrid-scale (SGS) effect in LES. $^-$ and $^\sim$ denote the spatial and Favre filtering. S_m and S_{u_i} are the interactions between the gas and solid particle phases. Since the mass transfer does not happen in this study, S_m is zero.

In the case of the individual particles moving in the fluid, their motion is tracked by the Lagrangian manner with the Particle-Source-In-Cell(PSI-Cell) [21] method. The governing equations are given by

$$\frac{dx_{i,p}}{dt} = u_{i,p}, \tag{3}$$

$$\frac{du_{i,p}}{dt} = \frac{f_d}{\tau_p}(\tilde{u}_i - u_{i,p}) + g, \tag{4}$$

here $x_{i,p}$ and $u_{i,p}$ are the particle position and velocity respectively. f_d is the correction of the drag force of the particle. τ_p is the response time of a particle, calculated as

$$\tau_p = \frac{d_p^2 \rho_p}{18\mu}, \tag{5}$$

d_p and ρ_p are the diameter and density of the particle, and μ is the viscosity of the fluid.

The S_{u_i} in Eq. (2) is written as

$$S_{u_i} = -\frac{1}{\Delta V}\Sigma \frac{m_p f_d}{\tau_p}(\tilde{u}_i - u_{i,p}). \tag{6}$$

where ΔV is the control volume of the gas phase.

Particle's Stokes number (St_k) is the value of the τ_p over the Kolmogorov time scale of the fluid. It is well known that around $St_k = 1$ the particles reach the most clustering.

3.2. Motion model of the spherical and spheroidal particle

Previously, by employing the Arbitrary Lagrangian-Eulerian (ALE) method, we numerically investigated a single spheroidal particle's motion [22]. As the first stage of the modeling of a spheroidal particle motion, we modified the drag coefficient to describe a spheroidal particle's motion in terms of a sine curve's PDF [23]. This modification can predict the particle's rotation effect on its movement behavior.

The modification is described as

$$\log_{10} C_D = \log_{10} C_{Dmin} + (\log_{10} C_{Dmax} - \log_{10} C_{Dmin}) * \frac{\sin(2\pi\theta) + 1}{2}, \tag{7}$$

where θ is a random number between 0 and 1. C_{Dmax} and C_{Dmin} are the C_D values obtained from the spheroidal particle's maximum and minimum C_D curves respectively. These curves are approximated in a form of the formulas suggested by Clift et al. [24] and proposed by Haider and Levenspiel [25].

$$C_D = \begin{cases} \frac{24}{Re}\left(1 + A * Re^{B - C*\log_{10} Re}\right), & Re \le 10 \\ \frac{24}{Re}\left(1 + X * Re^{Y}\right), & 10 < Re \leqslant 100 \end{cases} \tag{8}$$

$$Re = \frac{\rho_f(\tilde{u}_i - u_{i,p})d_p}{\mu} \tag{9}$$

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