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Three-dimensional vortex simulation for particulate jet generated by free falling particles

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Abstract

The particulate jet generated by solid particles falling from a circular orifice into an unbounded quiescent air is simulated. The three-dimensional vortex method, proposed for the analysis of particle-laden free turbulent flow in a prior study, is employed for the simulation. It is found that the falling particles induce complicated three-dimensional unsteady air flow involving large-scale eddies. The air takes its maximum velocity at the jet centerline, and the velocity profile satisfies the self-similarity around the centerline. The effect of particle diameter on the velocity distribution for the two phases is investigated. The entrained air flow rate is favorably compared with the value predicted by the analytical models.

Keywords: Multiphase flow; Numerical analysis; Fluid mechanics; Vortex method; Particulate jet; Air entrainment

1. Introduction

In industrial equipments handling solid particles, the free fall of the particles is frequently utilized to transport the particles to a lower level. A falling particle drags the surrounding air. Therefore, when a number of particles fall, they influence the surrounding air and a downward air flow loaded with particles results. This particulate jet creates various problems such as dispersion of dust (Hemeon, 1962). Thus, a few studies have been performed on the entrained air flow rate. To predict the entrained air flow rate, Hemeon (1962) has investigated the air flow induced by a single falling particle and proposed an analytical model called the single particle model, which can consider the particle diameter, density and mass flow rate. Plinke et al. (1991) have performed experiments on various particles, such as sand and cement, and showed that the entrained air flow rate increases with the falling distance. Cooper and Arnold (1995) have proposed analytical models called the massive particle model and the miscible plume model for the entrained air flow rate due to coarse and fine particles, respectively. They have also discussed the accuracy of the models through the measurement of the air flow rate due to alumina particles.

Since the grasp of a particulate jet is indispensable to the accurate prediction for the entrained air flow rate, a few studies have explored the flow characteristics of particulate jets. Ogata et al. (2000, 2001) have measured the velocity of glass particles (mean diameter of 454 μm) falling from a circular orifice, and found it to be higher than the falling velocity of a single particle. They have estimated the air velocity from the measured particle velocity and found that the air takes its maximum velocity at the jet centerline. Ogata et al. (2000) have also conducted a steady flow analysis by employing a k–ε turbulent model and obtained the velocity distribution which agrees nearly with the measurement.

Recently, vortex methods have been usefully applied to analyze single-phase free turbulent flows (Winckelmans and Leonard, 1993). This is because the methods can directly calculate the development of vortical structure, such as the

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formation and deformation of vortices, without employing any turbulent model. The methods promise to be applicable to simulate gas–particle two-phase free turbulent flow. Because the particle motion is chiefly governed by the large-scale eddies. To analyze the particle motion in plane mixing layer, vortex methods have been employed to simulate the gas flow (Wen et al., 1992; Chein and Chung, 1987). But the methods were only a one-way method ignoring the influence of particle on the gas flow. The current authors (Uchiyama and Naruse, 2001) have proposed a two-dimensional vortex method for a gas flow loaded with small solid particles. The vortex method was applied to calculate a mixing layer (Uchiyama and Naruse, 2002), a jet (Uchiyama and Naruse, 2003) and a wake flow behind a plate (Uchiyama and Yagami, 2005) to simulate the effect of particle on the flow development and the relation between the large-scale eddy and the particle motion. The simulations demonstrated that the method can supplement experimental works. In the succeeding study (Uchiyama, 2004) the vortex method was employed to simulate the particulate jet induced by particles falling from a slit orifice into an unbounded quiescent air. The simulation revealed that the air flow having complicated large-scale vortical structure is induced, and it was shown that the entrained air flow rate agrees with the results predicted by the analytical models. Uchiyama and Fukase (2005a) proposed a three-dimensional vortex method for the gas–particle two-phase free turbulent flow. The method simultaneously calculates the behavior of the vortex elements, discretizing the gas flow field, and the particle motion by the Lagrangian approach. For the two-way coupling between the two phases, the two-dimensional method (Uchiyama and Naruse, 2001) is extended, in which the effect of particle on the gas flow is considered through the change of vorticity in the grid cells resolving the computational region. Uchiyama and Fukase (2005a) also applied the vortex method to simulate the air jet, loaded with glass particles with diameter of 100 μm, issuing from a round nozzle into the co-flowing air stream. They confirmed that the air turbulent modulations due to the particle, such as the relaxation of velocity decay and the decrement in the spread of jet at the fully developed region, agree with the existing knowledge on the two-phase jet. Uchiyama and Fukase (2005b) explored the effect of particle diameter on the particle-laden air jet by the vortex method, and clarified that the air turbulent modulations due to the particle become markedly as the particle diameter decreases.

In this study, the above-mentioned three-dimensional vortex method is applied to simulate the particulate jet induced by solid particles falling from a circular orifice into an unbounded quiescent air. In order to relate this study to those of Ogata et al. (2000, 2001) where spherical glass particles of 454 μm in diameter and 2590 kg/m^3 in density were used, glass particles with diameter $d = 300, 400, 500$ μm are employed in this study. The simulation highlights that unsteady air flows with three-dimensional large-scale eddies are induced by the falling particles. The effect of particle diameter on the velocity distributions of the particle and air is investigated, and the entrained air flow rate is confirmed to agree well with those predicted by the existing analytical models.

2. Basic equations and numerical method

2.1. Assumptions

The following assumptions are employed for the simulation.

(1) The air is incompressible.
(2) The particle density is much larger than the air.
(3) The particle has a spherical shape with uniform diameter and density.
(4) The collision between the particles is negligible.

2.2. Governing equations

The conservation equations for the mass and momentum of the air are expressed as follows under assumption (1):

$$\nabla \cdot \boldsymbol{u}_g = 0, \tag{1}$$

$$\frac{\partial \boldsymbol{u}_g}{\partial t} + (\boldsymbol{u}_g \cdot \nabla)\boldsymbol{u}_g = -\frac{1}{\rho_g}\nabla p + \nu \nabla^2 \boldsymbol{u}_g - \frac{1}{\rho_g}\boldsymbol{F}_D, \tag{2}$$

where $\boldsymbol{F}_D$ is the force exerted by the particle acting on the air per unit volume.

Using assumption (2), the dominant forces on the particle are the drag and gravitational forces, while the virtual mass force, the Basset force and the pressure gradient force are negligible (Chein and Chung, 1987). The lift force is neglected with reference to the study simulating the particle motion in a mixing layer (Chein and Chung, 1987). Consequently, the equation of motion for a particle (mass m) is written as

$$m\frac{\mathrm{d}\boldsymbol{u}_p}{\mathrm{d}t} = \boldsymbol{f}_D + m\boldsymbol{g}, \tag{3}$$

where the drag force $\boldsymbol{f}_D$ is given by the following from assumption (3):

$$\boldsymbol{f}_D = (\pi d^2 \rho_g / 8) C_D |\boldsymbol{u}_g - \boldsymbol{u}_p| (\boldsymbol{u}_g - \boldsymbol{u}_p). \tag{4}$$

Here, d is the particle diameter, and the drag coefficient C_D is estimated as (Schiller and Naumann, 1933)

$$C_D = (24/Re_p)(1 + 0.15 Re_p^{0.687}), \tag{5}$$

where $Re_p = d|\boldsymbol{u}_g - \boldsymbol{u}_p|/\nu$.

For the simultaneous calculation of Eqs. (1)–(3), a vortex method is used to solve Eqs. (1) and (2), and the Lagrangian approach is applied to Eq. (3).

2.3. Discretization of air vorticity field by vortex element

When taking the curl of Eq. (2) and substituting Eq. (1) into the resultant equation, the vorticity equation for the air is derived

$$\frac{\mathrm{D}\boldsymbol{\omega}}{\mathrm{D}t} = (\boldsymbol{\omega} \cdot \nabla)\boldsymbol{u}_g + \nu \nabla^2 \boldsymbol{\omega} - \frac{1}{\rho_g}\nabla \times \boldsymbol{F}_D. \tag{6}$$