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Vortex simulation of gas-particle two-phase compound round jet

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Abstract

This study is concerned with the three-dimensional numerical simulation of an air jet, loaded with spherical glass particles, issuing with velocity U_0 from a nozzle of diameter $D=12$ mm into the air co-flowing with velocity U_a. The flow direction is vertically downward. The Reynolds number U_0D/v is 2×10^4, and the velocity ratio U_a/U_0 is 0.27. The particle diameter is 100 µm, and the Stokes number is 200. The particle mass loading ratio ranges from 0 to 0.4. The particle-laden air jet is simulated by the three-dimensional vortex method proposed in a prior study. The simulation demonstrates that the air turbulence modulations due to the particles, such as the relaxation of the velocity decay, the decrement of the momentum diffusion in the radial direction at the fully developed region, and the reduction of the turbulent intensity and Reynolds shear stress, are successfully captured by the method. The effect of the particle mass loading ratio on the air turbulence modulations is investigated.

Keywords: Numerical analysis; Gas-particle two-phase jet; Vortex method; Turbulence modulation

1. Introduction

Particle-laden gas jets are observed in various industrial equipment, such as pulverizedcoal combustors, solid rocket engines and sand-blasting machines. For the gas-particle two-phase jets issuing from a round nozzle, Shuen et al. [1], Modarress et al. [2] and Fleckhaus et al. [3] measured the mean velocity, the turbulent intensity and the Reynolds shear stress. By these experimental investigations, the gas turbulence modulations due to the loaded particles, such as the relaxation of the velocity decay, the decrement of the momentum diffusion in the radial direction at the fully developed region, and the reduction of the turbulent intensity and Reynolds shear stress, were clarified. A few numerical simulations have also been conducted. Elghobashi et al. [4], Shuen et al. [5], and Mostafa and Mongia [6] independently proposed $k-\varepsilon$ turbulent models, and they reported that the mean velocity and kinetic energy of turbulence for the round jets are successfully analyzed by the models. They simulated the steady and axisymmetrical jets by using a number of model constants. Therefore, the simulations do not promise to have high reliability and applicability. To analyze the flow more accurately, Yuu et al. performed the direct numerical simulation on a round jet [7] and the large eddy simulation on a slit nozzle jet [8]. They got valuable results, such as the instantaneous velocity distributions for the two phases in the jet cross-sections. Their simulations demonstrated that the effect of particle on the development and momentum diffusion of the gas-phase can be computed.

Recently, vortex methods have been usefully applied to analyze various flow fields. Especially, free turbulent flows, in which the organized large-scale eddies play a dominant role, were successfully simulated, as reviewed by Leonard [9], Cottet and Koumoutsakos [10] and Kamemoto [11]. This is because the methods can directly calculate the development of vortical flow by tracing the motion of the vortex elements having vorticity through the Lagrange approach. To extend the applicability of vortex methods, one of the authors [12] proposed a two-dimensional vortex method for gas-particle two-phase free turbulent flow in a prior paper. In the succeeding papers, the method was applied to a plane mixing layer [13], a slit nozzle jet [14] and a wake flow behind a plate [15] 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 the experimental work. Uchiyama [16] employed the proposed vortex method to analyze the particulate jet induced by particles falling in an unbounded

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quiescent air. The air flow having complicated vortical structure was calculated, and the entrained air flow rate was confirmed to agree with the measurement. Uchiyama and Naruse [17] also presented a numerical method for gas-particle two-phase free turbulent flow, which is based on the vortex in cell method originally proposed for single-phase flow analyses. As the method computes the convection of vortex element without employing the Biot-Savart equation, it allows the computation with less CPU time than the vortex method.

Though a number of simulations for single-phase jet have been performed by using vortex methods, most of them are two-dimensional [18–20]. There are few three-dimensional simulations, except for the analyses by Kiya et al. [21] and Izawa and Kiya [22]. But the analyses were performed only for the developing region of an impulsively started jet, and the statistical properties, such as the mean velocity and the turbulent intensity, were not calculated. To discuss the applicability of a three-dimensional vortex method for single-phase jet, Uchiyama [23] simulated a single-phase compound round jet, which issues from a circular nozzle into the co-flowing stream. The simulation revealed that the mean velocity and the turbulent intensity are reasonably computed by the vortex method.

The authors [24] proposed a three-dimensional vortex method for gas-particle two-phase compound round jet in their prior paper. For the two-way coupling, the two-dimensional method presented by Uchiyama and Naruse [12] is extended. The method takes account of the effect of particle on the gas flow through the change of vorticity in the grids resolving the flow field. The three-dimensional vortex method was employed for the simulation of a two-phase compound jet to investigate the effect of the particle diameter [25]. It was also applied to calculate the particulate jet induced by particles falling in an unbounded quiescent air [26].

The objective of this study is to apply the three-dimensional two-way vortex method to simulate a two-phase compound jet, loaded with glass particles with diameter of 100 μm, issuing from a round nozzle into the co-flowing air stream. The gas turbulence modulations due to the particle are simulated, and the effect of the particle mass loading ratio is investigated.

2. Basic equations

2.1. Assumptions

The following assumptions are employed for the simulation.

(1) The gas-phase is incompressible.
(2) The density of the particle is much larger than that of the gas.
(3) The particle has a spherical shape with uniform diameter.
(4) The collision between the particles is negligible.

2.2. Governing equations for gas and particle

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

$$\nabla \cdot u_g = 0 \tag{1}$$

$$\frac{\partial u_g}{\partial t} + (u_g \cdot \nabla) u_g = -\frac{1}{\rho_g} \nabla p + \nu \nabla^2 u_g - \frac{1}{\rho_g} F_D \tag{2}$$

where u_g is the gas velocity, t the time, ρ_g the gas density, p the pressure, ν the kinematic viscosity of the gas, and F_D the force exerted by the particle acting on the gas-phase 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 [27]. The lift force is neglected with reference to the studies simulating the particle motion in a jet [18], a plane wake [28] and mixing layers [27,29].

Consequently, the equation of motion for a particle (mass m) is written as:

$$m \frac{du_p}{dt} = f_D + mg \tag{3}$$

where u_p is the particle velocity, g the gravitational constant. The drag force f_D is given by the following from assumption (3).

$$f_D = (\pi d^2 \rho_g / 8) C_D |u_g - u_p| (u_g - u_p) \tag{4}$$

Here, d is the particle diameter, and the drag coefficient C_D is estimated as [30]:

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

where the particle Reynolds number Re_p is defined as $Re_p = d|u_g - u_p|/\nu$.

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).

3. Numerical method

3.1. Discretization of gas 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 gas-phase is derived:

$$\frac{D\omega}{Dt} = (\omega \cdot \nabla) u_g + \nu \nabla^2 \omega - \frac{1}{\rho_g} \nabla \times F_D \tag{6}$$

where the vorticity ω is defined as $\omega = \nabla \times u_g$.

The gas velocity u_g at x is given by the Biot-Savart equation, which is obtained by integrating the equation defining the vorticity:

$$u_g(x) = -\frac{1}{4\pi} \int \frac{(x - x') \times \omega(x')}{|x - x'|^3} d^3x' + u_{g0} \tag{7}$$

where u_{g0} denotes the velocity of potential flow.

The vorticity field is discretized by vortex elements. This study employs a blob model [31], which is frequently used to solve single-phase flow.

The vortex element has a cylindrical shape as illustrated in Fig. 1, while the vorticity distribution is spherical with a finite core radius.