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Numerical analysis of gas-particle two-phase wake flow by vortex method

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Abstract

The two-dimensional wake gas flows behind a flat plate, loaded with solid particles of the Stokes number 0.15 and 1.4, are simulated through the vortex method proposed by the authors in a prior study. The simulated particle distribution is confirmed to agree with the experimentally visualized result. The simulation clarifies that the loaded particles make the gas mean velocity gradient in the wake cross-section gentler and that the gas turbulent intensity reduces by the particle except near the wake centerline.

Keywords: Numerical analysis; Vortex method; Particulate wake; Particle dispersion

1. Introduction

Gas-free shear layers containing small solid particles are frequently observed in various industrial equipment, such as chemical reactors and internal-combustion engines. A number of investigations have been done on such gas-particle two-phase free shear layers to elucidate the flow phenomena, such as the particle behavior and the change in the gas flow due to the particle [1]. Brown and Roshko [2] had clarified that the development and momentum transport of single-phase mixing layer are dominated by the large-scale organized eddies. Thus, the relation between the organized eddies in free shear layers and the particle movement has received considerable attention. Crowe et al. [3] made a hypothesis that the particle motion could be classified by the responsiveness of the particle to the large-scale eddies, and they proposed the Stokes number, which is the ratio of the particle response time to the characteristic time of the fluid flow, as a parameter estimating the particle motion. The number density and velocity of the particle in various free shear flows, such as plane mixing layers [4,5], jet [6] and wakes [7,8], were measured to confirm the validity of the classification. But the particle mass loading ratio in the measurements was so low that the effect on the flows has been unclarified.

Recently, vortex methods have been usefully applied to analyze single-phase free shear flows [9]. This is because the methods can directly calculate the development of vortex structure, such as the formation and deformation of vortices. The methods promise to be applicable to simulate gas-particle two-phase free shear flow. The particle motion in axisymmetrical jet [10], two-dimensional mixing layers [5,11] and plane wake [12] has been simulated. But the simulations were performed by a one-way method ignoring the interaction between the two phases. Thus, the authors [13] have proposed a two-way vortex method for gas-particle two-phase free turbulent flow. The method was applied to calculate a plane mixing layer [14] and a slit nozzle jet [15]. The calculations demonstrated that the simulated gas turbulent features, such as the velocity decay in the streamwise direction and the momentum diffusion in the cross-stream direction, are favorably compared with the corresponding measurements. This suggests the proposed method can supplement the experimental works. In the succeeding study

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[16], the method was employed to calculate the particulate jet induced by free falling particles in a quiescent air, and the effects of the particle diameter and mass loading ratio on the entrained air flow rate were successfully simulated.

Wake flow is an example of free shear layers and a number of knowledge on single-phase wakes have been accumulated. But the wake laden with solid particles has been rarely investigated, except for the above-mentioned experiments [7,8] and one-way numerical simulation [12] for the low mass loading ratio. Therefore, there are many unclarified issues, such as the particle motion and the effect of particle on the wake gas flow, for the high mass loading ratio.

In this study, a gas-particle two-phase wake is simulated by the two-way vortex method proposed by the authors. The two-dimensional wake, used for the experimental visualization of particle motion by Yang et al. [8], is chosen as the simulation model, in which small glass particles are loaded into the wake air flow behind a flat plate. It is confirmed that the obtained particle distribution agrees with the visualized results. The simulation also makes clear the effects of particle mass loading ratio on the particle motion and wake air flow that have not been investigated.

2. Basic equations and numerical method

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 and density.
(4) The collision between the particles is negligible.

2.2. Governing equations for gas and particle

The conservation equations for the gas-phase are expressed as follows under the assumption (1).

$$\nabla \cdot \boldsymbol{u}_{\mathrm{g}} = 0 \tag{1}$$

$$\frac{\partial \boldsymbol{u}_{\mathrm{g}}}{\partial t} + \left(\boldsymbol{u}_{\mathrm{g}} \cdot \nabla\right)\boldsymbol{u}_{\mathrm{g}} = -\frac{1}{\rho_{\mathrm{g}}}\nabla p + \nu \nabla^2 \boldsymbol{u}_{\mathrm{g}} - \frac{1}{\rho_{\mathrm{g}}}\boldsymbol{F}_{\mathrm{D}} \tag{2}$$

where $\boldsymbol{F}_{\mathrm{D}}$ is the force exerted by the particle acting on the gas-phase per unit volume.

Using the 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 [11]. The lift force is neglected with reference to the study simulating the particle motion in a mixing layer [11]. Consequently, the equation of motion for a particle (mass m) is written as:

$$m\frac{\mathrm{d}\boldsymbol{u}_{\mathrm{p}}}{\mathrm{d}t} = \boldsymbol{f}_{\mathrm{D}} + m\boldsymbol{g} \tag{3}$$

where the drag force $\boldsymbol{f}_{\mathrm{D}}$ is given by the following from the assumption (3).

$$\boldsymbol{f}_{\mathrm{D}} = \left(\pi d^2 \rho_{\mathrm{g}}/8\right) C_{\mathrm{D}} |\boldsymbol{u}_{\mathrm{g}} - \boldsymbol{u}_{\mathrm{p}}| \left(\boldsymbol{u}_{\mathrm{g}} - \boldsymbol{u}_{\mathrm{p}}\right) \tag{4}$$

Here, d is the particle diameter and the drag coefficient C_{D} is estimated as [17]:

$$C_{\mathrm{D}} = \left(24/Re_{\mathrm{p}}\right)\left(1 + 0.15 Re_{\mathrm{p}}^{0.687}\right) \tag{5}$$

where $Re_{\mathrm{p}}=d|\boldsymbol{u}_{\mathrm{g}}-\boldsymbol{u}_{\mathrm{p}}|/\nu$.

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 and calculating condition

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 is derived. Calculating a two-dimensional flow field, the equation is written as:

$$\frac{\mathrm{D}\omega}{\mathrm{D}t} = \nu \nabla^2 \omega - \frac{1}{\rho_{\mathrm{g}}} \nabla \times \boldsymbol{F}_{\mathrm{D}} \tag{6}$$

The gas velocity $\boldsymbol{u}_{\mathrm{g}}$ at $\boldsymbol{x}$ is given by the Biot-Savart equation, which is obtained by integrating the equation defining the vorticity:

$$\boldsymbol{u}_{\mathrm{g}}(\boldsymbol{x}) = -\frac{1}{2\pi}\int \frac{(\boldsymbol{x}-\boldsymbol{x}') \times \omega(\boldsymbol{x}')}{|\boldsymbol{x}-\boldsymbol{x}'|^2} d\boldsymbol{x}' + \boldsymbol{u}_{\mathrm{g}0} \tag{7}$$

where $\boldsymbol{u}_{\mathrm{g}0}$ is the velocity for potential flow.

The vorticity field is discretized by vortex elements. A vortex element having a viscous core proposed for single-phase flow [18] is used. When the vortex element α at $\boldsymbol{x}^{\alpha}$ is supposed to have a circulation Γ_{α} and a core radius σ_{α}, the vorticity at $\boldsymbol{x}$, $\omega^{\alpha}(\boldsymbol{x})$, induced by the vortex element is expressed as:

$$\omega^{\alpha}(\boldsymbol{x}) = \frac{\Gamma_{\alpha}}{\sigma_{\alpha}^2} f\left(\frac{|\boldsymbol{x}-\boldsymbol{x}^{\alpha}|}{\sigma_{\alpha}}\right) \tag{8}$$

where the core function $f(\varepsilon)$ is defined as follows.

$$f(\varepsilon) = \begin{cases} 1/(2\pi\varepsilon) & \varepsilon \le 1 \\ 0 & \varepsilon > 1 \end{cases} \tag{9}$$