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Large eddy simulation of the gas-particle turbulent wake flow*

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Abstract: To find out the detailed characteristics of the coherent structures and associated particle dispersion in free shear flow, large eddy simulation method was adopted to investigate a two-dimensional particle-laden wake flow. The well-known Sub-grid Scale mode introduced by Smagorinsky was employed to simulate the gas flow field and Lagrangian approach was used to trace the particles. The results showed that the typical large-scale vortex structures exhibit a stable counter rotating arrangement of opposite sign, and alternately form from the near wall region, shed and move towards the downstream positions of the wake with the development of the flow. For particle dispersion, the Stokes number of particles is a key parameter. At the Stokes numbers of 1.4 and 3.8 the particles concentrate highly in the outer boundary regions. While the particles congregate densely in the vortex core regions at the Stokes number of 0.15, and the particles at Stokes number of 15 assemble in the vortex braid regions and the rib regions between the adjoining vortex structures.

Key words: Large eddy simulation, Plane wake, Coherent structures, Particle dispersion
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INTRODUCTION

Plane wake flow is one type of free shear flow and exists widely in nature and many engineering systems. To understand the kinetic character of the large-scale coherent vortex structures and particle dispersion in plane wake flow is helpful for improving many processes in energy engineering, chemical engineering and material engineering.

Large eddy simulation involves both direct simulation and Reynolds-averaged approaches. Methods have been developed in recent years to solve the problem of instantaneous gas flow field and to simulate high Reynolds number turbulence on the basis of actual computer level. Direct simulation techniques are applied to simulate larger scale anisotropic flows and time-average-type mode techniques are used to simulate the smaller scale isotropic flows.

The major objective of this work was to study the large-scale vortex structure dynamics and corresponding particle dispersion patterns in the gas-solid two-phase plane wake flow with large eddy simulation, and try to provide guidance for the associated industrial applications.

MATHEMATICAL MODEL

1. Flow configuration

The sketch of plane two-dimensional wake flow is shown in Fig. 1. The thickness of the splitter plate is $2S = 31.5$ mm and the velocity of free stream from each side of the plate for the wake is $U_0 = 3.3$ m/s. We assume that the gas flow is incompressible and the fluid properties are constant. The Reynolds number of the flow can be defined as $\mathrm{Re} = U_0 S/v = 6500$, where v is the kinematic viscosity of the fluid. In the centerline of the plate, the particles at density of $n_p = 4.7 \times 10^{11}/\mathrm{m}^3$ are injected at velocity of $U_1 = 0.4$ m/s from a 3.175 mm diameter hole into

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the wake flow. All geometrical lengths are scaled with S. The characteristic flow time is obtained as the characteristic length S, divided by the characteristic velocity U_0.

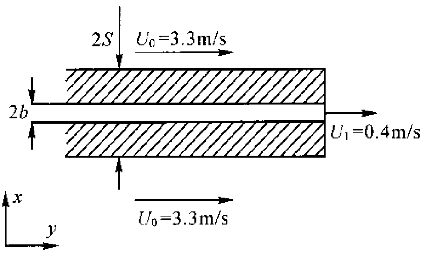

Fig.1 Sketch of plane wake flow

2. Flow-field simulation

In large eddy simulation, we adopt the well-known Sub-grid Scale mode introduced by Smagorinsky (1963) to simulate the gas flow field. The two-dimensional continuum equation and N-S equations can be described as follows (Jin *et al.*, 2002):

Continuum equation:

$$\frac{\partial}{\partial x}(\rho \bar{u}) + \frac{\partial}{\partial y}(\rho \bar{v}) = 0 \qquad (1)$$

Momentum equations:

$$\frac{\partial \bar{u}_i}{\partial t} = -\frac{\partial}{\partial x_j}\left[\overline{u_i u_j}\right] - \frac{\partial}{\partial x_i}\left[\frac{\bar{p}}{\rho}\right] + \frac{\partial}{\partial x_j}\left[(v + v_t)\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)\right] \qquad (2)$$

Where $v_t = (C_s \Delta)^2 |\bar{S}|$, $|\bar{S}| = (2\overline{S_{ij} S_{ij}})^{\frac{1}{2}}$, $S_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)$, $\Delta = (\Delta x \cdot \Delta y)^{\frac{1}{2}}$. $C_s = 0.15$ is used in this work.

3. Particle dispersion simulation

Since the density ratio $\rho_p/\rho_g > 1000$, the Basset force and the added force, can be neglected. The collisions between the particles can also be ignored because of low particle loading. In addition, the Saffman force and the Magnus force are neglected in this simulation too. So, only the drag force due to the relative velocity between the two phases is taken into account in study of the particle dispersion. Without considering the gravity force of the particles, the non-dimensional motion equation for the particle is expressed as (Fan *et al.*, 2001):

$$\frac{\mathrm{d}V}{\mathrm{d}t} = f/St(U - V) \qquad (3)$$

where V is the non-dimensional velocity of the particle; U is the non-dimensional velocity of the fluid at the particle position; t is the non-dimensional time; and St is the Stokes number defined as $St = \frac{\rho_p d_p^2/18\mu}{S/U_0}$; f is the modification factor for Stokes drag coefficient described by $f = 1 + 0.15 Re_p^{0.667}$. Re_p represents the relative Reynolds number for particles and is defined as $Re_p = |U - V| d_p / v$.

NUMERICAL METHOD AND BOUNDARY CONDITIONS

In our simulation, a two dimensional finite volume incompressible code based on $x \times y = 302 \times 401$ staggered cells covering the computational domain is used to solve the flow field. The span of the computational domain covers $x \times y = 40\ S \times 30\ S\ \mathrm{mm}^2$. The implicit second-order Crank-Nicolson difference scheme in time is used. Sommerfeld boundary conditions (Orlanski, 1976) at the outlet and free stream conditions in transverse direction are assumed. In particle dispersion simulation, we choose the particle diameter of 10μm, 30μm, 50μm, 100μm respectively to examine the dispersion patterns of different size particles in the plane wake. The corresponding particle Stokes numbers are 0.15, 1.4, 3.8 and 15, respectively. Our numerical simulation procedure was done according to the model mentioned above.

RESULTS AND DISCUSSIONS

1. Flow field

Fig.2 shows the vorticity contour at non-dimensional time of 20, 32, 44 and 56 in the whole computating domain. It shows clearly the flow character of plane wake, including the forming, developing, and shedding process of the large-scale vortex structures. A recirculating separation region exists near the downstream of the plate trailing edge. The front part of the recirculating area expands rapidly and the vorticity congregates gradually. In the big air bubble area that then comes into being, two eddy cores emerge and seems to be axially symmetric ($T = 20$). With the development of the air bubble area, new vorticity being continually injected into the two eddy cores causes the two eddy core areas to become larger and larger till they crack ($T = 32$).

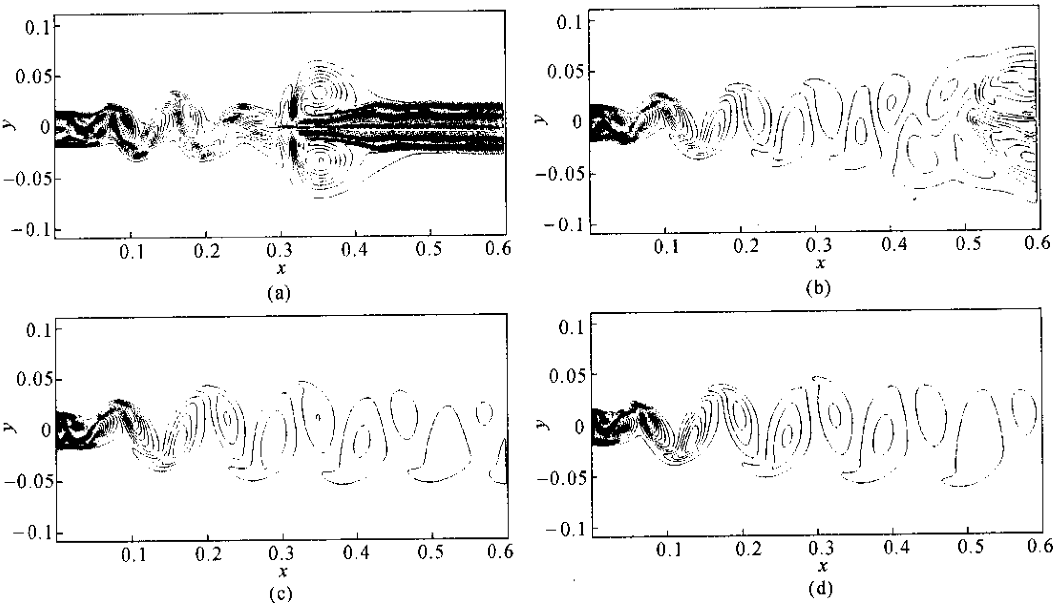

Fig.2 The vorticity contour at non-dimensional time of 20, 32, 44 and 56 in the whole flow field.
(a) $T = 20$; (b) $T = 32$; (c) $T = 44$; (d) $T = 56$

In the recirculating regime, there exists a no-vorticity triangular area at first. With the increasing of the circumfluence, the vorticity produced by each side of the plate fills the triangular area, so, the triangular area becomes smaller and smaller and the gas cling to the wall finally. With further development of the air bubble area and the regurgitant area near the wake, the typical large-scale vortex structures present between the wall and the air bubble area and assume stable counter-rotating opposite sign patterns, and alternately form from the near wall region, shed, and move towards the downstream positions of the wake with the development of the flow($T = 44$ and $T = 56$).

Fig. 3 is the vorticity contour in the near wake flow covering the initial region of the wake development($0 < \frac{x}{s} < 11$, $-3 < \frac{y}{s} < +3$) obtained by large eddy simulation. The figure is very similar to the typical instantaneous streakline patterns at the same region with the same conditions obtained from experiment (Yang *et al*., 2000) which verified the numerical simulation results.

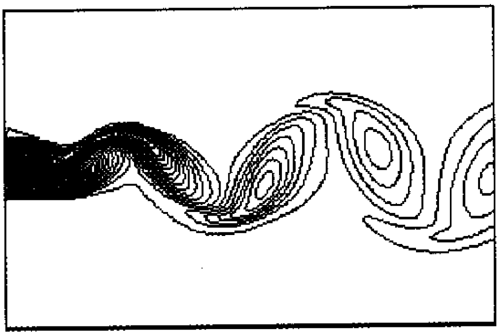

Fig.3 Contour of instantaneous vorticity obtained by large eddy simulation

2. Particle dispersion

Fig.4 of the spatial distribution of particles with Stokes number of 0.15 at $T = 78$ in the wake flow shows that the particles follow the fluid flow closely and that most particles congregate in the vortex core regions of the large-scale vortex structures. Some particles also distribute in the banded region connecting with the adjacent large-scale vortex structures. As a whole, the particles disperse in "vortex core-vortex braid-vortex core" pattern, similar to the large-scale coherent structures of the fluid. This dispersion pattern is associated with the smaller aerodynamic response time of particles. As the aerodynamic response time of particles is small enough, the particles can almost follow the gas with no relative slip. In this case, the coherent vortex structures of gas play a dominant role in the particle dispersion.

Fig.5 of the spatial distribution of particles with Stokes number of 1.4 at $T=78$ in the wake flow shows that most particles congregate densely in the outer boundary regions of the large-scale vortex structures and particles accumulate partly in the rib or saddle regions between the adjacent vortex structures. The particles, however, are extremely few in the central region of the vortex structures. The reason is that the particles with Stokes number of 1.4 are affected apparently by the centrifugal force of these large-scale vortex structures compared with the particles with Stokes number of 0.15. Impacted by the centrifugal force, the particles are thrown out from the vortex core regions and congregate in the outer boundary regions of the large-scale vortex structures. This result is in good agreement with previous numerical results(Tang *et al.*, 1992) and recent experimental results (Yang *et al.*, 2000).

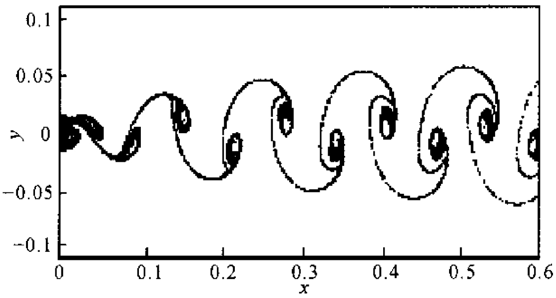

Fig.4 Spatial distribution of particles with $St=0.15$

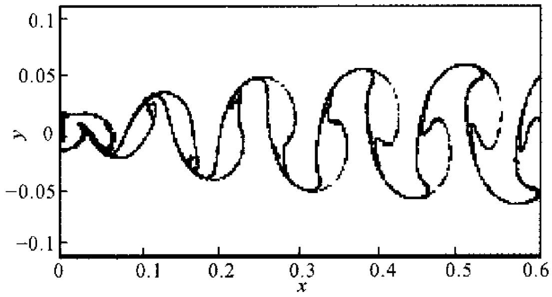

Fig.5 Spatial distribution of particles with $St=1.4$

Compared with dispersion patterns of particles with Stokes number of 1.4, particles with Stokes number of 3.8 are affected apparently by the centrifugal force of coherent vortex structures, but on the other hand, these particles begin to show their inertia effects. Fig.6 shows the spatial distribution of particles with Stokes number of 3.8 at $T=78$ in the wake flow. Because of the dominant action of large-scale vortex structures, the particles are still thrown out from vortex core regions and congregate in the outer boundary regions of vortex structures and rib region between the adjoining vortex structures. The particles disperse more apparently and distribute more evenly along the streamwise direction and the transverse direction due to their inertia effects.

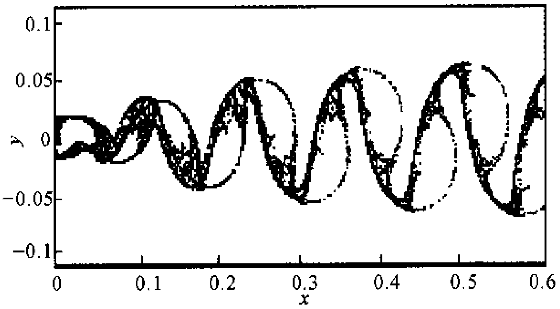

Fig.6 Spatial distribution of particles with $St=3.8$

Fig.7 shows the spatial distribution of particles with Stokes number of 15 at $T=78$ in the wake flow. These particles cover almost all the regions of large-scale vortex structures and have no similar distribution pattern of coherent eddy structures with the gas phase. But in the braid regions of vortex structures and rib regions between adjacent vortex structures, due to the effect of centrifugal force of vortex structures and inertia of particles, the particle concentrations are relative higher. In this case, the inertial effect of particles with larger Stokes number is more remarkable, and the effect on particle motion by large-scale vortex structures is mainly to change the particle motion direction and form the folding pattern of particle distribution.

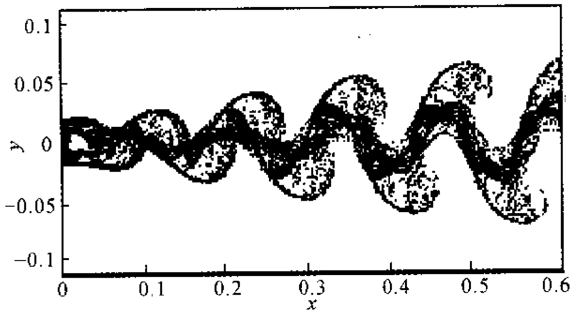

Fig.7 Spatial distribution of particles with *St* = 15

CONCLUSIONS

Large eddy simulation method is used to study the gas-solid two-phase plane wake flow. The Sub-grid Scale mode of Smagorinsky is used to simulate the gas flow field and Lagrangian approach is used to trace the particle motion. Firstly，the formation，the developing，the shedding and the moving towards downstream positions of the large-scale vortex structures in the plane wake are shown. Then，the results of particle dispersion show that the Stokes number of particles is a key parameter of the responding particle dispersion. The particles with Stokes number of 1.4 and 3.8 concentrate highly in the outer boundary regions； The particles with smaller Stokes number of 0.15 congregate densely in the vortex core regions of the large-scale vortex structures； While the particles with larger Stokes number of 15 assemble in the vortex braid regions and the rib regions between the adjoining vortex structures. The results using large eddy simulation agreed well with previous results（Yang *et al*.，2000； Tang *et al*.，1992）.

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