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Technical Note

Large eddy simulation of particle response to turbulence along its trajectory in a backward-facing step turbulent flow

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Abstract

In order to understand particle response to turbulence along its path, properties of the particle phase and gas phase are compared and analyzed for a turbulent flow over a backward-facing step. The turbulent gas phase is simulated numerically using large eddy simulation and the particle phase is modeled by means of Lagrangian methods. The particle Stokes number ranges from 0.01 to 111.18 and the Reynolds number is 18,400, based on the step height and the inlet mean velocity. Particle velocities, fluid velocities and vorticity along particle trajectory as well as particle dispersion are obtained so as to provide information on particle response to turbulence. Results show that particle behavior depends heavily on the local fluid turbulence along its path, especially for small particles. Particles follow a path along which the gas-phase vorticity is small. However, large particles maintain the inertia along their trajectories without responding to the fluid fluctuations.

Keywords: Particle dispersion; Large eddy simulation; Particle-laden flow; Lagrangian particle tracking

1. Introduction

Dilute particle-laden turbulent flows are of great importance in nature and in many industrial applications such as pneumatic transport of solids, coal combustion, and deposition from paint sprays, classifiers and cyclones. The motion of a solid particle is often dominated by its mass and the turbulence encountered by the particle along its trajectory.

Particle dispersions are affected by the ratio of particle relaxation response time to the characteristic flow time related to the coherent structures. This ratio is generally known as the Stokes number. Crowe et al. [1,2] described a conceptual model for particles dispersed by vortices based on the two-phase planar mixing layer flow and two-phase jet flow. The effect of vortices on the particles depends on parameters such as particle size and density, as well as other fluid properties. They also attempted to provide the parameters to describe the extent of particle dispersion affected by large eddy structures. However, these particles do not disperse uniformly as turbulence influences their trajectory as shown by Eaton and Fessler [3] and Coppen et al. [4].

In general, numerical models based on time-averaged behavior do not take into account particle dispersions dominated by large-scale coherent structures and the single particle response to turbulence along its trajectory.

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Large eddy simulation (LES), calculates directly the large energy containing eddies, while modeling the small scale eddies thus requiring less computational time and memory as compared with direct numerical simulation (DNS) and still maintaining reasonable accuracy. As the large-scale structures are calculated explicitly in LES, it permits a more accurate representation of the particle turbulence interactions.

As motion of the particle is largely dominated by the response of the particle to the fluid fluctuating velocity, fluid turbulence along the trajectory has to be studied. In this paper, particle motion over a three-dimensional backward-facing step is numerically simulated by means of LES for the gas flow and a Lagrangian trajectory method for the particle phase.

2. Numerical simulation

The backward-facing step height and channel height are chosen to be $H = 0.0267$ m and $h = 0.04$ m, respectively, representing an expansion ratio was 5:3. Reynolds number, based on the step height and inlet mean velocity, is 18,400.

For the LES simulation of the continuous phase, the resolved scales interact with the unresolved scales via the sub-grid-scale (SGS) stress term, which is approximated by the eddy viscosity hypothesis. The eddy viscosity is defined as

$$v_T = C\overline{\Delta}^2|\overline{S}|, \qquad (1)$$

where the resolved-scale strain rate tensor is given by

$$\overline{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right). \qquad (2)$$

$|\overline{S}| = \sqrt{2\overline{S}_{ij}\overline{S}_{ij}}$ is the magnitude of $\overline{S}_{ij}$ and the model coefficient C in the SGS model is taken as 0.13 in this paper.

The inlet boundary condition at the step is assumed to have a uniform velocity distribution of $U(y)$ with a white noise ξ. An improved non-reflective Sommerfeld open boundary condition is used at the outlet so that the coherent structures are transported downstream without any distortion. No-slip condition is applied at the solid wall using a local dynamic wall model. In addition, periodic boundary conditions are used in the span-wise direction.

The unsteady Navier–Stokes equations are solved numerically using the fractional step method as described by Kim and Moin [5] and Wu et al. [6]. The continuity equation is satisfied through a Poisson equation for the pressure correction term, and is solved using Fourier series expansions in the stream-wise and span-wise directions with tri-diagonal matrix inversion. The equations are discretized spatially on a fully staggered Cartesian grid. The derivatives are approximated using second-order central difference for the viscous term and the convective term is discretized by a hybrid skew-symmetric scheme [7] to reduce the aliasing errors and numerical instability. In addition, the momentum equations are integrated explicitly using a third-order Runge–Kutta algorithm.

Motion of the particles is predicted using a Lagrangian approach, based on the following assumptions:

(a) all particles are non-evaporating rigid spheres with material density, $\rho_p = 2500$ kg/m^3;
(b) particle density is assumed to be large compared with density of the fluid;

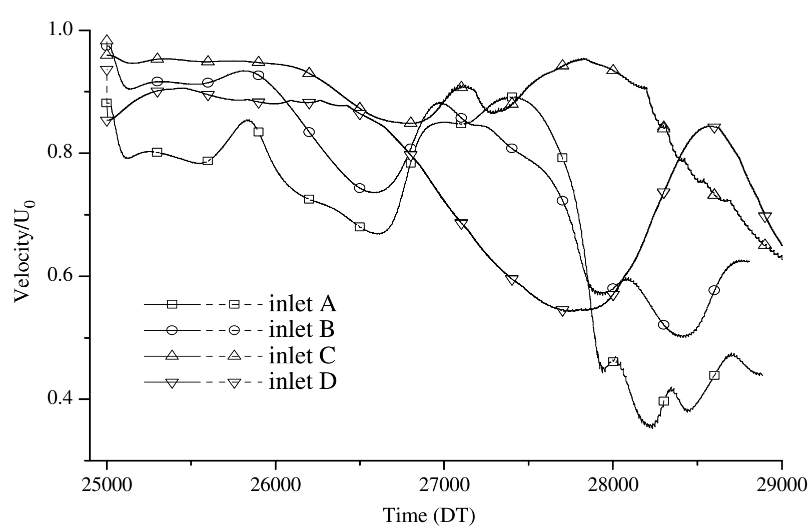

Fig. 1. Instantaneous velocities along the trajectories of the 2 μm particles (— particle, - - - fluid).

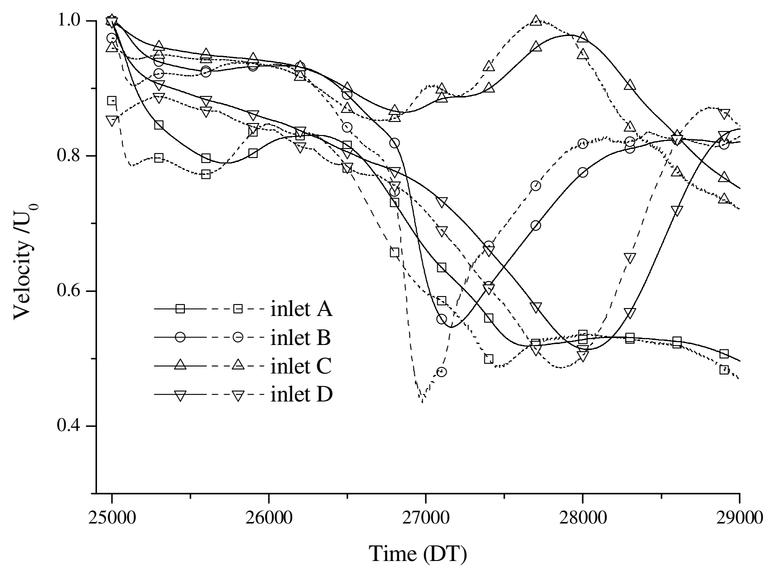

Fig. 2. Instantaneous velocities along the trajectories of the 20 μm particles (— particle, --- fluid).

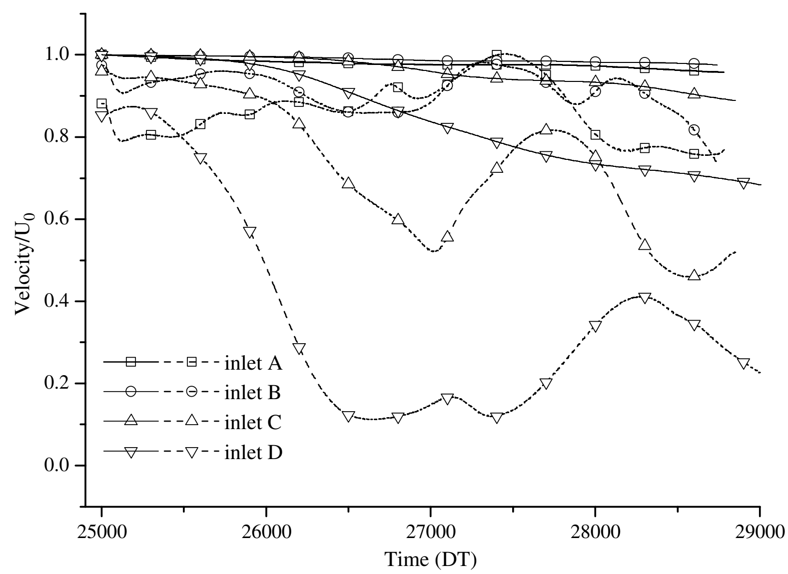

Fig. 3. Instantaneous velocities along the trajectories of the 200 μm particles (— particle, --- fluid).

(c) particle–particle interactions are negligible;
(d) effect of the flow structure by the particles is neglected due to the small mass loading ratio of less than 5%.

Particles of three different diameters, 2, 20 and 200 μm, corresponding to Stokes numbers of 0.011, 1.112 and 111.184, respectively, are released into the backward-facing step with the same inlet velocity of the gas phase.

3. Results and discussions

3.1. Spatial distribution of instantaneous velocities

Particles are released into the backward-facing step at four different inlet locations, at $y/H = 1.31$, 1.63, 1.94 and 2.25 and denoted as A, B, C and D, respectively. Figs. 1–3 show velocities of the two phases along the particle trajectory for the three different particle sizes.

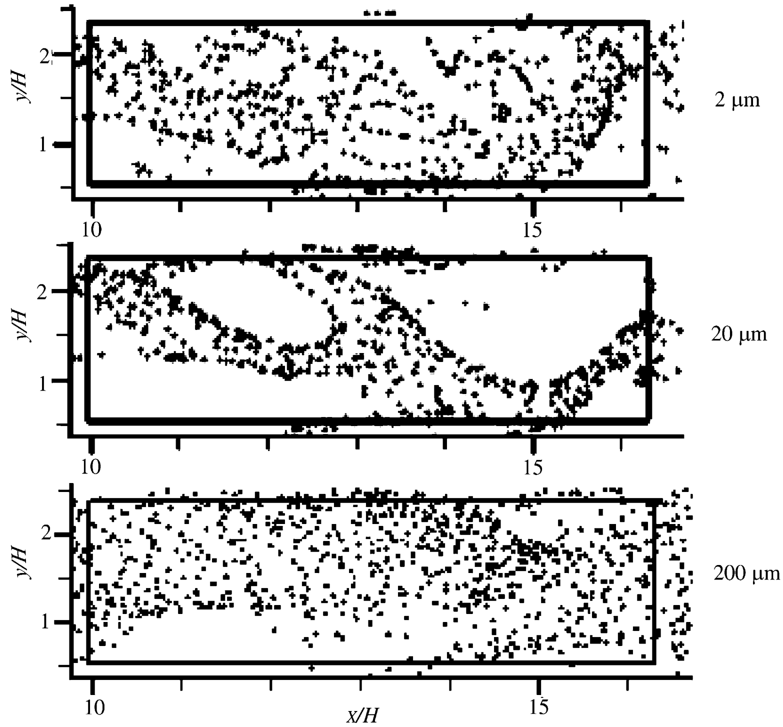

Fig. 4. Preferential concentration of particles.

Fig. 1 shows that spatial distribution of particle velocity for the smaller particle of 2 μm diameter follows the fluid velocity very closely irrespective of where the particles are released. Fig. 2 shows that the particles of 20 μm diameter do not follow the fluid closely and there is a time lag for the particle to reach the level of the fluid velocity.

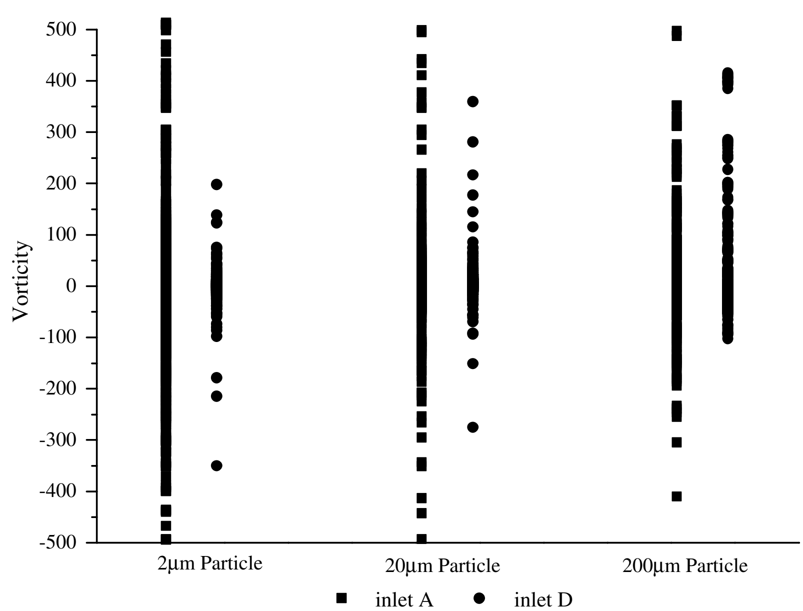

Fig. 5. Stream-wise vorticity along the trajectories of particles of different sizes.

Table 1
Particle velocity variance along its path

Particle diameter (μm)	Inlet location A	Inlet location B	Inlet location C	Inlet location D
2	0.17217	0.13898	0.10188	0.12923
20	0.15686	0.11435	0.05982	0.11833
200	0.01863	0.00678	0.00373	0.12035

As shown in Fig. 3, particles of 200 μm diameter do not respond to the fluid fluctuations. Due to the larger size, these particles maintain their inertia causing a larger velocity slip between the particle and the fluid.

It can be seen from Figs. 1–3 that smaller particles are more affected by turbulence, thus having a higher fluctuating velocity component, while larger particles have a lower fluctuating velocity component. Within the vortical structure, there is a larger instantaneous slip velocity between larger particles and the gas phase. Furthermore, smaller particles tend to concentrate in regions of lower vorticity, a phenomenon confirmed by the experimental studies of McAndrew [8].

3.2. Vorticity and particle velocity along the particle trajectory

As shown in Fig. 4, particles tend to concentrate preferentially in certain regions. Particularly, the small to medium sized particles tend to concentrate more distinctly. In order to investigate the distribution of particles in the flow field, span-wise vorticity of the gas phase seen by particles along their trajectories are investigated. As the near wall region is of particular significance, the particles released into the flow from locations A and D are investigated. Fig. 5 shows the distribution of non-dimensional vorticity along the particle trajectories. For particles released from locations A and D, they move in the shear layer region containing vortices of different sizes. Particles of 2 μm cross the large and medium sized vortices, while 20 μm particles move along the edgy of the large and medium sized vortices with weak vorticity. The range of vorticity encountered by particles of 2 μm is larger than that for particles of 20 μm. On the other hand, larger particles of 200 μm are hardly affected by the vortical structure as they penetrate through the small, medium and also large vortices. The range of vorticity encountered by the large particle are wider than that of the small and medium sized particles. Preferential concentration of small and medium sized particles are more evident than for the large particles. It can be seen from Fig. 5 that particles tend to concentrate preferentially in regions of weak vorticity, especially for medium sized particles.

Table 1 shows particle's velocity variance along its path. Here particle's velocity variance is defined as

$$\gamma_{\rm p} = \sqrt{\langle u_{\rm p}'^2 \rangle_l} / \langle \bar{u}_{\rm p} \rangle_l, \tag{3}$$

where $\langle\ \rangle_l$ means averaging along particle path.

Variance of particle velocity decreases as particle's size increases, since particle is losing their ability to respond to fluid fluctuation, wherever particle is released into the turbulent flow.

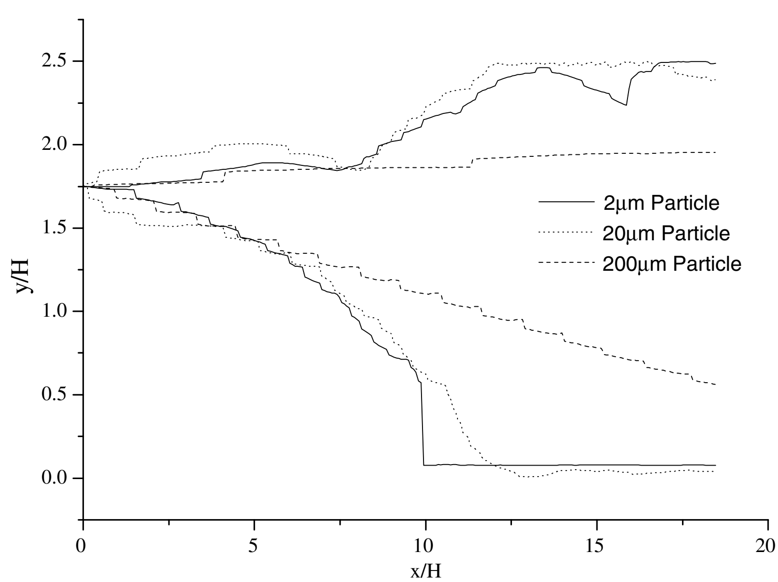

Fig. 6. Particle dispersion envelopes.

3.3. Particle dispersion

The trajectories of different particles show that large particles run through the main flow region, hardly affected by the vortical structures. With decreasing particle diameter, the particle phase interacts more with the vortices and finally, penetrates the shear layer.

Fig. 6 provides the dispersion envelope for different particles, released into the flow at $y/H = 1.75$. The dispersion envelope represents a boundary for particle dispersion. It can be seen that the particles disperse more widely with decreased particle diameters. In addition, it can be seen that the flow shear also increases particle dispersion. Motion of the 2 μm particles is completely dominated by the gas-phase vortices and their trajectories reach the lower wall when x/H is greater than 10.

4. Conclusions

The characteristics of single particle response to the fluid turbulence along its trajectory are numerically studied by means of large eddy simulation for the gas phase and by a Lagrangian tracking method for the particle phase. Two-phase instantaneous velocities, vorticity and velocity variations along the particle trajectories as well as particle dispersion envelopes are obtained to examine the particle response to turbulence along its trajectory. For small particles, corresponding to small Stokes number, the velocity of particle is similar to that of the fluid carrying the particles. For medium sized particles, corresponding to Stokes number of near unity, there is a time lag between the velocities of the two phases, although the particles still follow the gas phase. On the other hand, for large particles, corresponding to large Stokes number, there is significant velocity slip between velocities of the two phases.

In addition, there is a tendency of preferential particle concentration in regions of weak vorticity, particularly for particles of Stokes number near unity. The smaller sized particles also tend to disperse more widely.

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