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Effects on particle dispersion by turbulent transition in a jet

Kun Luo [a,*], Markus Klein [b], Jian-Ren Fan [a,*], Ke-Fa Cen [a]

[a] State Key Laboratory of Clean Energy Utilization and Institute for Thermal Power Engineering, Zhejiang University, Hangzhou 310027, PR China
[b] Technische Universität Darmstadt, FG Energie- und Kraftwerkstechnik, Petersenstraße 30, 64287 Darmstadt, Germany

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Abstract

The effects on particle dispersion by turbulence transition in a three-dimensional plane jet are investigated by means of direct numerical simulation. The governing equations of fluid motion are solved by a finite volume method and a fractional-step projection scheme. The particles are traced in the Lagrangian framework. It is found that the transition phenomenon of particle dispersion occurs during turbulence transition for particles at certain Stokes numbers. For particles at the intermediate Stokes numbers of 1 and 10, the dispersion changes from non-uniform to uniform patterns. These transition behaviors of particle dispersion reflect the self-selective mechanism between multi-scale structures in turbulent flows.

Keywords: Direct numerical simulation; Particle dispersion; Turbulence transition

1. Introduction

Understanding of particle dispersion in turbulence is important both in the study of turbulence physics and in many engineering applications, such as jet propulsion, coal combustion and aerosol reaction. So there has always been considerable interest in this issue for many years.

To predict the effects of large-scale structures on particle dispersion, Crowe et al. [1,2] first proposed the use of the Stokes number which is the ratio of the particle aerodynamic response time to the time scale associated with the large-scale organized vortex structures in the free shear flows. They found that the particle dispersion correlates closely with the Stokes number. Longmire and Eaton [3] experimentally investigated the nonevaporating droplet dispersion in a round jet. Their results, as well as those of Swanson and Richards [4] clearly showed that the particles at the Stokes numbers near unity concentrate largely in the high-strain-rate and low-vorticity regions. This non-uniform particle distribution is known as 'preferential concentration' [5]. Aggarwal et al. [6–8] used a finite-difference approach to simulate particle dispersion in a two-dimensional transitional axisymmetric jet and a plane shear layer. They believed that the particle dispersion is mainly governed by three basic mechanisms, namely, the vortex, centrifugal, and inertial mechanisms. In a previous study of the authors [9], the particle dispersion in a two-dimensional, weakly compressible plane jet has been investigated by direct numerical simulation. The local-focusing phenomenon and turbulence modulation were discussed. In addition, there are many other numerical or experimental results that support and reinforce the above physical model and findings, such as references [10–14].

However, all the above studies focus on the effects on particle dispersion by large-scale vortex structures. The effects on particle dispersion by turbulence transition from large-scale to small-scale structures are still unclear. It is well known that turbulence transition is a very important phenomenon in turbulent flows. This transition process may probably affect the dispersion patterns of particles, which will directly reflect the dispersion mechanism of particles. As the main motivation of the present study, the transitional effects on particle dispersion patterns in a three-dimensional turbulent jet will be investigated by direct numerical simulation. First the mathematical descrip-

* Corresponding author.
E-mail addresses: zjulk@zju.edu.cn (K. Luo), fanjr@zju.edu.cn (J.-R. Fan).

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tions will be introduced, and then the results will be reported. This is followed by conclusions and acknowledgement.

2. Mathematical descriptions

Fig. 1 shows the sketch of a three-dimensional particle-laden turbulent plane jet. The Reynolds number based on the nozzle width, the inflow velocity, and the kinematic viscosity is $\mathrm{Re} = U_0 * d/\nu = 4000$. The fluid is injected into the domain through the whole slot nozzle, but the particles are just injected through a square region located in the center of the slot with side length d.

The gas phase is regarded as an incompressible fluid. The inter-phase coupling effect between fluid and particles is neglected, which is different from the previous studies [9,15]. When the body force is not included, the non-dimensional governing equations for the fluid motion can be expressed as:

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{1}{\mathrm{Re}}\frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right), \tag{2}$$

where the characteristic velocity and length scales are U_0 and d, respectively.

To solve the above equations directly, the finite volume method and the fractional-step projection technique [16] are applied. Central differences are used for the spatial discretization and an explicit low-storage, third-order Runge–Kutta scheme [17] is used for time integration. A direct fast elliptic solver is used to solve the Poisson equation. To include the largest vortex structures in the simulations, the extension of the computational domain in the streamwise (x), lateral (y) and spanwise (z) direction has been set to $20d \times 20d \times 6.4d$. It is resolved with $400 \times 400 \times 128 = 20.48 \times 10^6$ staggered grid points. In x and z directions a uniform grid spacing with $\Delta x = \Delta z = \frac{1}{20}d$ is used. In y direction, the grid width has been set to $\Delta y = \frac{1}{30}d$ in the core shear region (i.e. $4.5d < y < 4.5d$) to capture all small-scale vortex structures. Outside this area the grid is stretched in lateral direction.

At the inlet boundary, the typical top-hat shape velocity profile with a fluctuation intensity of 2% is used. At the outflow boundary, Neumann boundary conditions for the velocity and the pressure are used. In the spanwise direction, periodic boundary conditions are applied. More details on the boundary conditions, initial conditions, numerical algorithms and code validation can be found in the studies of Klein et al. [18,19].

The particles are traced in the Lagrangian framework based on one-way coupling. Because the material density ratio of particles to fluid equals 2000, the possible force terms such as pressure gradient, virtual mass and Basset forces can be neglected [20,21]. Considering only the Stokes drag force, the non-dimensional governing equation for the particle motion can be written as:

$$\frac{d\mathbf{V}}{dt} = \frac{f}{\mathrm{St}}(\mathbf{U} - \mathbf{V}) \tag{3}$$

where $\mathbf{V}$ is the particle velocity vector, $\mathbf{U}$ is the fluid velocity vector at the position of the particle and f is the modified factor for Stokes drag force. The time scale is defined as d/U_0. The particle Stokes number is given by $\mathrm{St} = \frac{\rho_p d_p^2/(18\mu)}{d/U_0}$. The velocity and displacement of the particle can be obtained by integrating Eq. (3). Third-order Lagrangian interpolating polynomials are adopted to get the fluid velocity at the position of the particles.

To demonstrate the typical particle dispersion patterns, five kinds of particles at the Stokes number of 0.01, 0.1, 1, 10 and 100 are examined. For each case, 100 particles are injected every 5 time intervals. In previous studies [6–8], particles have usually been released after the initial transient effect has become negligible. But in the present study, the particle injection is started from time $t = 0$ to specifically examine the effects on particle dispersion by turbulence transition.

3. Numerical results and discussions

The distributions of particles at different Stokes numbers in the spanwise plane $z = 0$ at the non-dimensional times $t = 30$ and 106, as well as the contours of spanwise vorticity are shown in Figs. 2 and 3, respectively. In the figures, the black points represent particles and the colorized contours represent the spanwise vorticity. At time $t = 30$, the large-scale vortex structures are dominant. For $\mathrm{St} = 0.01$, the particles closely follow the vortex motion and disperse uniformly in the flow field. Most

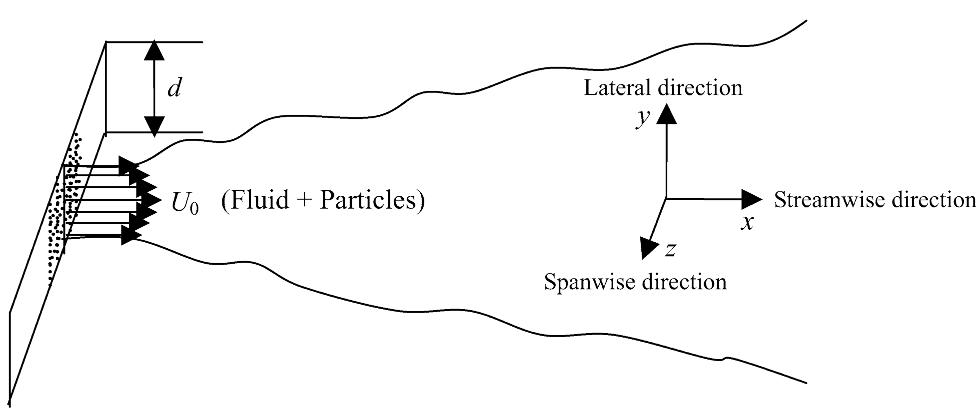

Fig. 1. Sketch of the three-dimensional particle-laden turbulent plane jet.