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Local-focusing phenomenon and turbulence modulation in particle-laden turbulent jets

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Abstract

A direct numerical simulation (DNS) technique based on two-way coupling is presented to study a particle-laden, weakly compressible turbulent plane jet. The physical characteristics of particle dispersion and turbulence modulation are investigated. It is found that a local-focusing phenomenon happens to the dispersion of the particles at the Stokes number of 1. As a whole, the particles at the Stokes number of 0.01 and 50 make the two-way coupled profiles of turbulence intensity wider and lower, but the particles at the Stokes number of 1 decrease turbulence intensities. This method is feasible and convenient to study the physical interactions between the continuum phase fluid and the dispersed solid particles at different Stokes numbers.

Keywords: Direct numerical simulation; Two-way coupling; Large-scale vortex structures; Particle dispersion; Turbulence modulation

1. Introduction

Gas–solid two-phase turbulent jets exist widely in engineering applications, such as pulverized coal combustion, jet propulsion and aerosol reactors. The ability to predict and control particle dispersion in jets is of great importance to optimize the design of engineering systems and obtain efficient applications. In addition, the physical interaction between the continuum phase and the dispersed phase is always one of the hot research topics.

Many studies have been carried out to investigate the particle dispersion in particle-laden jets [1–8]. It has been demonstrated that the effects of the large-scale structures on particle dispersion can be characterized in terms of the particle Stokes number, defined as the ratio of the particle aerodynamic response time to the time scale of the large-scale vortex structures. But most of these studies are based on the assumptions of incompressibility and one-way coupling. On the other hand, moderate mass loadings of particles

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can also modulate the gas-phase jet, which is known as turbulence modulation. In the past decades, many experiments have also been performed to study turbulence modulation by dispersed solid particles in gas–solid jets [9–15]. It has been found that the velocity decay in the centerline of two-phase turbulent jets is smaller than that of a single-phase turbulent jet. The spreading rate of two-way coupled jets also becomes smaller. However, the effects on large-scale coherent vortex structures of the gas phase jets by particles at different Stokes numbers were not measured and discussed. Especially, the particles used in previous experiments were quite large and the modulation on jet by particles at smaller Stokes numbers was not reported. But in numerical simulations, it is convenient to fully study the effects on the gas phase jet by all kinds of particles.

In this Letter, a direct numerical simulation (DNS) method based on two-way coupling is developed to study the particle dispersion and turbulence modulation in a gas–solid two-phase, weakly compressible plane jet. The main objective is to reveal the physical interaction between large-scale coherent vortex structures of the gas phase jet and the dispersed particles at different Stokes numbers.

The Letter is organized as follows. In Section 2 we describe the flow conditions. Section 3 introduces the governing equations and numerical schemes. The numerical results and discussions are given in Section 4. The last section is devoted to summary and conclusion.

2. Flow conditions

Fig. 1 shows the computational domain and flow configuration of the gas–solid two-phase turbulent plane jet. The flow is two-dimensional and weakly compressible. The velocity of high-speed stream is U_1 and the velocity of co-flow stream is U_2. $U_1/U_2 = 11$. The mean convective Mach number, $M_c = (U_1 - U_2)/(c_1 + c_2) = 0.15$. The ratio of the nozzle width d to the initial momentum thickness is set to be 20. The initial Reynolds number, *Re*, based on the nozzle width and the velocity difference between two streams, is 4500. Particles at different Stokes numbers are injected into the computational domain through the nozzle.

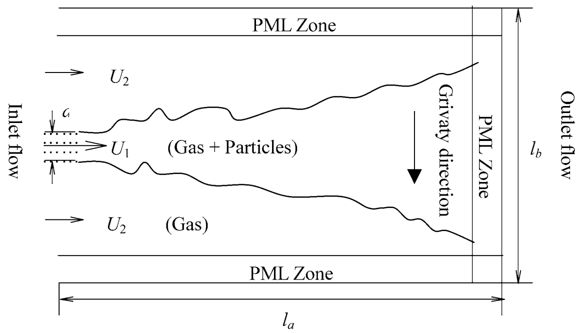

Fig. 1. Computational domain and flow configure of the particle-laden turbulent jet.

It is well known that for the simulation of turbulent flows in an open, non-periodic environment system, the proper artificial boundary conditions at the computational domain boundaries are very crucial to the simulation results. To obtain the accurate results, the boundary conditions and grid system are elaborately designed in the present simulation. The non-reflecting boundary conditions [16] and the sponger layers [17] are added to the outflow and the sidewall boundaries. At the jet inlet, outlet and sidewall boundaries, the viscous boundary conditions [18] are also used. In addition, the typical top-hat inflow profile for streamwise velocity is adopted. At the outflow boundary, the pressure correction is performed.

As shown in Fig. 1, the whole computational domain is divided into a physical domain and three perfectly matched layer (PML) buffer zones. It had been thought that the grid scale in any DNS should be smaller than the smallest turbulent scale, namely the Kolmogorov length scale. But the study of Moin et al. [19] suggested that if the grid scale is of the same order as the Kolmogorov length scale, the accuracy of DNS is enough. In the present simulation, the estimated Kolmogorov scale $\eta = 18$ μm. So in the physical domain we arrange the uniform grid with $\Delta x = \Delta y = 0.0667d = 41$ μm $= 2.28\eta$. But in the buffer zones, the stretching grid with 5% stretching ratio is employed. Total $257 \times 315 = 80955$ computational grid points are used with the whole domain dimensions $l_a = 17.656d$ and $l_b = 22.112d$.

Although DNS of three-dimensional sing-phase plane jets [20,21] has been carried out recently, the present study is based on a two-dimensional simulation. There are two reasons for this two-dimensional