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Flow Visualization and Laser Measurement on Particle Modulation to Gas-Phase Turbulence

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Abstract : Particle modulation to turbulence is investigated experimentally by means of PDPA, PIV and flow visualization for a gas-particle two-phase jet flow. Large particles can enhance the small-scale vortex, so that gas-phase turbulence intensity is increased, while small particles may delay the rolling up of the gas vortex, so that gas-phase turbulence intensity is attenuated. The critical particle size range for such different effects is between 150 μm and 200 μm, corresponding to the Stokes number is between 88 and 157 under the present flow conditions. The PIV results show small particles can retain the gas-phase vortex structure, while large particles can break large vortex structure. The particle Stokes number is not the only judgment standard whether particles enhance or attenuate gas-phase turbulence. The CTI (Change of Turbulence Intensity) number can mark off particle modulation on turbulence in two-phase flow, but more studies are needed.

Keywords : Two-phase jet, PDPA, PIV, Flow visualization, Turbulence modulation.

1. Introduction

Two-phase turbulent jet flows have wide applications in the fields of pulverized coal burners, spray combustions, engine injections, and so on. Particle modulation to gas-phase turbulence has been paid more attention these years, since it is one of the most important problems for revealing the inter-phase interaction mechanism in gas-particle two-phase flows. For single phase jet flows, their typical characteristics have been obtained by means of flow visualization and laser measuring technology (e.g., Tesar et al., 2005; Kontis, 2005; Hwang et al., 2005). However, only several studies of solid particle modulation to gas-phase turbulence are carried through. Few of them are by means of experiment. For instance, Sheen et al. (1994) measured the far field flows in a two-phase jet at Reynolds number 20,000, and they showed that the axial turbulent intensity of gas phase was increased due to the existence of large particles, while the radial and azimuthal turbulent intensities were both decreased. Another important conclusion gained by them was that turbulent intensities of all components were always lower, for the existence of small particles, than those of a single-phase jet flow. Hetsroni and Sokolov (1971), Tsuji et al. (1988), Levy and Lockwood (1981), Parthasarathy and Faeth (1987), as well as Sakakibara (1996) also studied the modulation by different particles in two-phase jet flows. It was shown that large particles could enhance gas-phase turbulence intensity, while small particles can attenuate turbulence intensity. However, none of them gave the critical size of particle for judging when particles enhance or attenuate turbulence intensity.

In this paper, particle modulation to gas-phase turbulence is studied in the near field of a dilute gas-particle jet by using flow visualization and measuring technology of PDPA and PIV. The critical particle size and physical mechanism for particle enhancing or attenuating gas-phase turbulence are obtained.

2. Experiment Setup

The experiment system is shown in Fig. 1. The air is driven by pump and its flux is controlled by a valve. Flow rate is measured by a flow meter. After the flow meter, the airflow is divided into two parts: primary part and bypass part. The primary part flows through a smoke generator which generates very small gas-phase tracing particles, in flow visualization while the bypass part flows through a particle feeder where large glass particles are added into flows. Airflows with both small and large particles from two pipes converge into a conditioning segment and jet to the 1,200 mm × 500 mm × 500 mm enclosed experiment observational segment after a contraction section designed according to the Vetorxiskey curve over a length of 200 mm. The jet nozzle is long enough that a developed flow can be achieved at its exit. The frontal side of the experimental segment is made of glass, by which the jet performance can be observed and recorded.

Observations and measurements are carried out in the experimental segment. The qualitative flow fields and quantitative velocity characteristics are then obtained by the methods of flow visualization, PDPA and PIV measurement technology. Solid state green laser with 532 nm wavelength and 150 mW power is adopted in flow visualization. Dantec 3D Phase Doppler Particle Analyser (PDPA) is used for quantitative measurements. Double-pulsed laser with time interval 200 µs and energy 100 mJ is used in PIV.

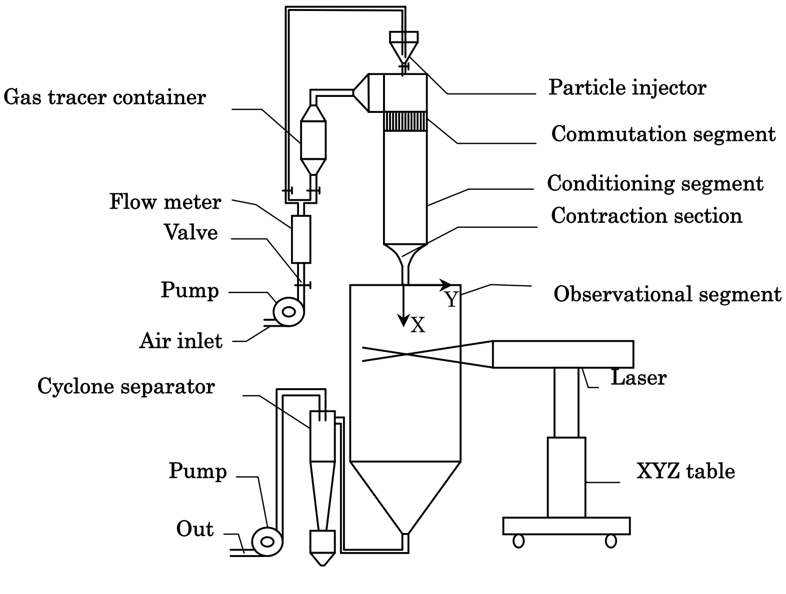

Fig. 1. Schematics of experiment system.

3. Results and Discussions

3.1 The Effects of Particle on Coherent Structures

The burning incense is used to visualize the gas phase. Figure 2 shows the gas-phase large scale coherent structures at different Reynolds numbers (based on the diameter of nozzle and mean outlet velocity). Here the jet nozzle diameter D is 20 mm. The flow visualization results showed that gas-phase coherent structures roll up earlier with increase of Reynolds numbers. Figure 3 shows the large-scale vortex structure of jet flows with and without laden particles at the Re = 9400. The bulk particulate mass loading ratio at the inlet is 0.6. Comparing with the single-phase flow, the positions of gas-phase vortexes-rolling in two-phase flows are delayed by the laden small particles, whereas they are advanced by the laden large particles.

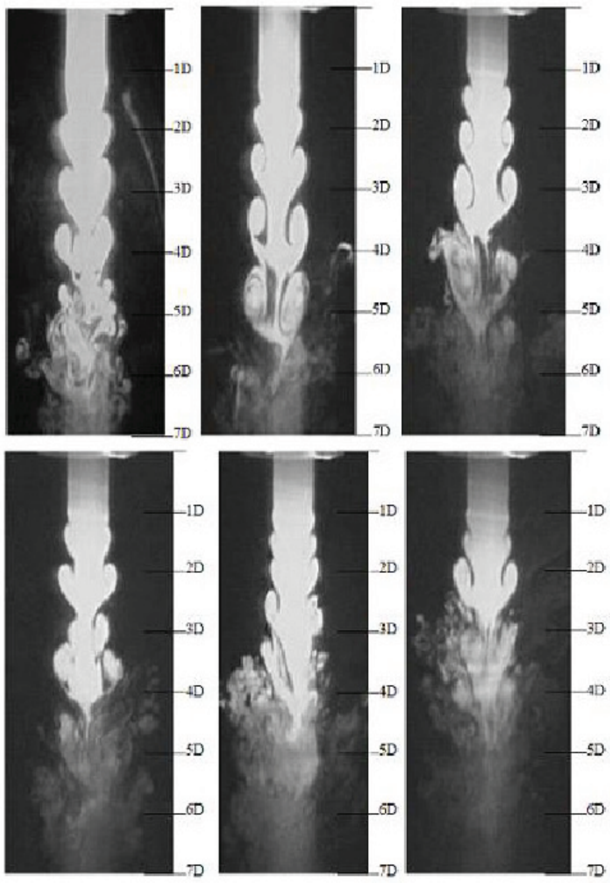

Fig. 2. Vortex structure of jet flows at different Re (Top: from left to right Reynolds numbers are 2500, 5000 and 7500 respectively; Bottom: from left to right Reynolds numbers are 10000, 12500 and 13750 respectively).

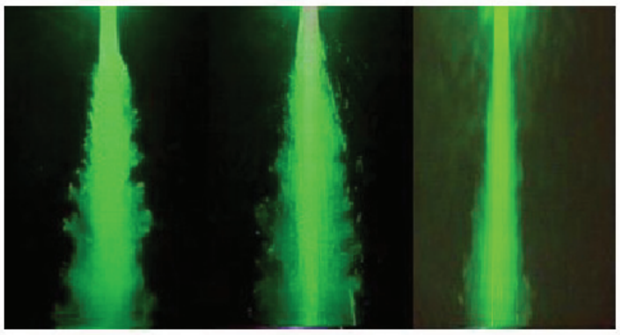

Fig. 3. Jet flow patterns with and without laden particles (from left to right: single phase, laden with 350 μm particles and laden with 50 μm particles).

Figure 4 shows the flow structures in different radial sections for the same Re number 9400. It is shown that the coherent structure can be enhanced by 350μm particles for their rapidly expanding in radial direction, whereas they are restrained by 50μm particles. It is explained that the energy is transferred from gas phase to solid particle phase when vortexes roll up, which leads to delay of gas-phase vortexes rolling up. Small particles follow vortex motions and absorb energy, resulting in reduction of fluid diffusion. Whereas, large particles absorb energy from gas-phase eddies but they do not follow vortex motions due to their large inertia. They penetrate through vortexes and take gas-phase to diffuse around rapidly. In the single phase flow, vortexes like mushroom roll up in section of x/D = 4 and they are strongly unsymmetrical azimuthally. However, the asymmetry disappears while large particles are added into flows, and flows seem isotropy azimuthally. It means that the flow instability in tangential and radial directions is restrained by present of particles.

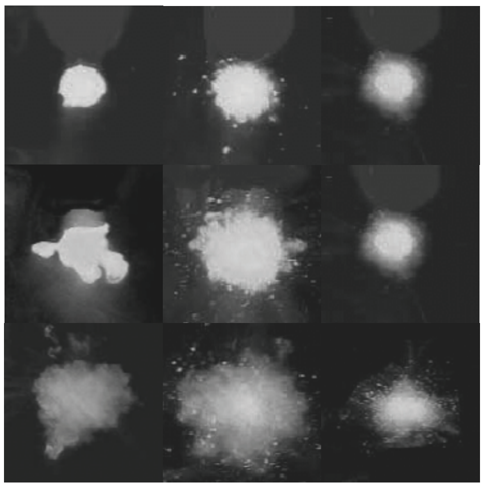

Fig. 4. Jet flow patterns with and without laden particles in radial sections at different axial positions (from top to bottom: x/D = 2.5, 4 and 7, from left to right: single phase, laden with 350 μm particles and laden with 50 μm particles).

Flow visualization for two-phase jet flows laden with different size particles is shown in Fig. 5. Here, the nozzle diameter D is 40 mm and the Re number is 13,600. Six kinds of glass particles are selected with different diameter of d_p = 50, 100, 150, 200, 250 and 300 μm, and their St numbers are 10, 39, 88, 157, 245 and 352 respectively. In qualitative, from left to right in Fig. 5, the gas-phase coherent structures become weaker with the particle diameter or the particle Stokes number. Large particles break up the large-scale vortex ring, and induce vortex shedding due to their large inertia and large velocity slip between two phases.

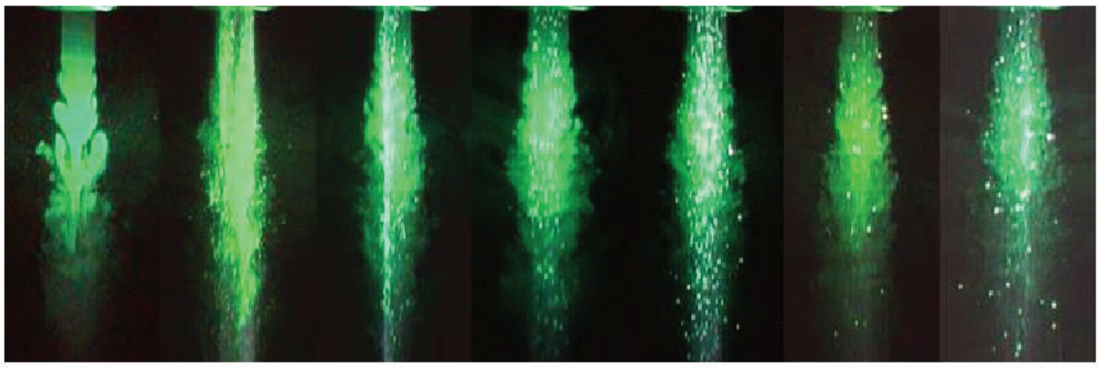

Fig. 5. Jet flow structures for different particles at Re = 13600 (From left to right: without laden particles, laden with 50 μm, 100 μm, 150 μm, 200 μm, 250 μm and 300 μm particles respectively).

3.2 The Effects of Particle on Turbulence Intensity

The gas-phase turbulence intensities with and without laden particles are measured by PDPA, in which the tracer particles of gas phase are fine particles of calcium carbonate with diameter less than 3 μm. In order to show the turbulence modulation by particle, dimensionless number CTI (Change of Turbulence Intensity) is defined as:

$$\mathrm{CTI} = \frac{\sigma_{\mathrm{TP}} - \sigma_{\mathrm{F}}}{\sigma_{\mathrm{F}}} \tag{1}$$

It means the change of turbulence intensity. The σ_{TP} and σ_{F} are gas-phase turbulence intensity laden with and without particles respectively.

CTI > 0 means particles enhance gas turbulence intensity, while CTI < 0 means particles attenuate gas turbulence intensity. The particulate mass loading ratio at the inlet is 0.6 in the experiment. Turbulence intensities of gas phase in the cross section of x/D = 5 and those along the jet axis from x/D = 1 to x/D = 20 are measured by means of PDPA. 158 measurement samples are obtained and classified into groups based on particle diameters. The mean CTI number is calculated for each particle size, which is shown in Fig. 6. The results show that small particles less than 150 μm (St = 88) can attenuate gas turbulence intensity, while large particles more than 200 μm (St = 157) can enhance gas turbulence intensity. The main aim in this section is to find the critical size of laden particles for gas-phase turbulence modulation from attenuating to enhancing by particles. So, the CTI numbers don't obtain when laden particles' sizes are less than 50 μm and larger then 300 μm. The changes of CTI sign with particle size are meaningful, while the changes of CTI value with particle size are just a statistical data scattering.

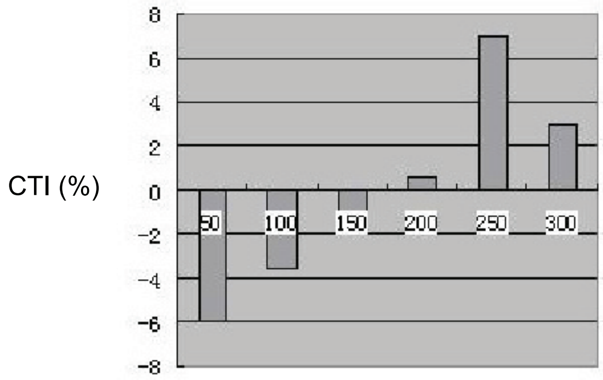

Fig. 6. CTI number with different laden particles.

3.3 The Effects of Particle on Gas Vorticity Fields

The burning incense is used to visualize the gas phase in PIV measurement. The tracing particles images of gas phase flows in near field from x/D = 0.1 to x/D = 1.8 are recorded by PIV system. The velocity fields are obtained by MQD (minimum quadratic difference) method. The vorticity fields are then calculated based on the obtained velocity fields and shown in Fig. 7. Here, the nozzle diameter is 40 mm and Re number is 5300. Three kinds of particle with diameters of 50 μm, 200 μm and 300 μm are selected to study modulation of gas-phase vorticity by particles. The particulate mass loading ratio is 1. It can be shown that particles of 200 μm and 300 μm have similar modulation to gas-phase vorticity. They both promote the fluid diffusion, so a large amount of vortex structures in very small scale reproduce close to the nozzle. However, the small-particle case is sharply different from large ones. Small particles cannot accelerate eddies to break up, but they can keep the vortex structures stability from the large eddy structures injecting into the field, which are thin and long strips. Thus, 50 μm particles have the function on keeping volutes of large-scale structure. It agrees with the observing results of flow visualization.

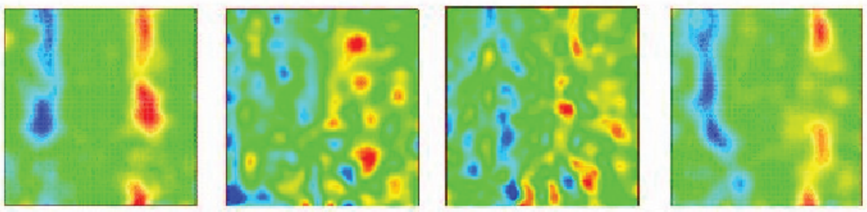

Fig. 7. Gas-phase vorticity distribution modulated by different particles (from left to right: single phase, gas phase with 300 μm, 200 μm and 50 μm particles respectively).

4. Conclusion

(1) The effects of particles on the gas-phase turbulence in the near fields of jet flow are investigated by using flow visualization, PDPA and PIV methods.

(2) Large particles can enhance the small-scale vortex, so that gas-phase turbulence intensity is enhanced, while small particles may delay the rolling up of the gas-phase vortex, so that gas-phase turbulence intensity is attenuated. The critical particle size for such effects is between 150 μm and 200 μm, corresponding to the Stokes number is between 88 and 157.

(3) The vortex fields of gas phase are obtained by PIV for cases laden with and without particles. It also shows small particles can retain the gas-phase vortex structure, while large particles can break up large vortex structure.

Acknowledgements

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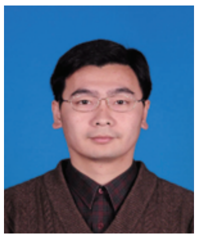
Author Profile



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