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FLOW VISUALIZATION OF INTERACTIONS BETWEEN PARTICLE WAKES AND JET VORTICES

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ABSTRACT

The interactions between vortices of a round free shear jet and particle’s wakes are visualized by means of smoke-gas flow visualization technology. Particles in different diameters are fixed at different positions along the jet axial central line. The typical flow structural compositions of the gas jet at the different flow developing stages are presented. Particle wakes occur obviously for the larger particle when the particle Reynolds number is larger than 100, and they change the overall flow structural pattern. More ejections in the vortex rings are accused in the radial direction at the initial flow status. The large-scale structures are broken up because of the presence of the wakes behind large particles. The local turbulence anisotropy is then attenuated in the downstream. Small particles without wakes do not change the flow structure pattern. The results are valuable to develop accurate turbulence modulation models including wake effects.

Keywords: flow visualization, particle wakes, flow structures, round jet

INTRODUCTION

Particle modulation to turbulence is one of very important issues in two-phase turbulent flows, because it can in general change the local turbulence structures as well as turbulence intensity and further change the particle dispersion and hence increase the mixing between two phases. It is found that the particle modulation to turbulence is depended on the flow field location in a particle-lade jet(Gillandt, Fritsching and Bauckhage 2007, Wang et al. 2009). The far-field flow structures and flow intensity are determined by the evolution of near-field dynamics. More investigations show that particles can either depress or enhance the turbulence intensity(Sheen, et al. 1994, Cui et al. 2006,). It is also found that the wakes make contributions on the flow fluctuation level once they are generated behind particles(Sakabibara et al. 1996, Yarin and Hestroni 1994, Kenning and Crowe 1997, Prevost et al. 1996, Gillandt et al. 2007,). Therefore, understanding the interactions between jet flow structures and particles wakes is very important for revealing the mechanisms of particle modulation to turbulence.

The engineering prediction of two-phase turbulent flows requires the accurate turbulence models, which cannot be well established without the good understanding of particle modulation. Yuan and

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Michaelides(1992) proposed a semi-empirical model considering both the velocity defect in the wakes and the work associated with particles motions. Yarin and Hetsroni (1994) developed the model through a detailed description of particle wakes. However, both two models are not used to predict practical gas-particle flows. Yu and Zhou(2003) proposed a turbulence enhancement model taking the particle diameter as the mixing-length. Zeng et al. (2007) theoretically proposed the enhancement model by large eddy simulation of particle wake effects. However, none of the models are based on the observation and measurements of particle effects on the overall flow structures. For building an informative turbulence modulation model considering the particle wakes, it is necessary to understand the interaction between particles wakes and flow structures in a turbulent jet.

Historically, turbulent two-phase free jets have been studied by many researchers, but up to now it is still difficult to find a well-documented experimental study of interactions between jet wakes and particle wakes in the literatures aiming at the particle modulation to local flow structures. Therefore, in this study, the smoke-gas flow visualization technology is employed to study the particle wakes effects on jet flow structures. The flow visualization pictures at different cross sections in the downstream direction and in the sections along the central axial plane are both recorded in the experiments. The flow configuration of the jet with the fixed particles is analyzed through comparing the bench flow configurations in a particle-free jet.

EXPERIMENTAL SETUPS

The schematic diagram of experimental setup to generate free shear jet flow is shown in Fig.1. The environmental air is pumped into the fluid-tracer container, with a maximum volumetric flow rate of air 40 m^3/hr, and flows through the commutating section, the stabilization section, the contraction section and finally jet out. The experimental test section is surrounded by four glass baffles preventing from the interference and contamination.

The incense is burned inside the lab-made smoke-gas generator and then the smoke is taken by the air flow. The diameter of incense is usually less than 5μm, which is small enough as the fluid-tracer. The observation sections of the flow are illuminated by the laser-light sheet, which is generated by a pumped semi-conductor laser with the power of 2.5W. The light wave length is 532nm. The thickness of the laser sheet is less than 0.2mm in the experimental observation sections.

The experiment observations are documented by a Sony-digital video recorder, which has the function of high-speed recorder with a higher resolution of 800×600 pixel at 200fps.

Table 1 shows the flow and particle parameters adopted in the experiments. The jet nozzle is 20mm in diameter and the jet velocity measured at the central point of the exit plane is 1.3m/s and 3.1m/s. Therefore, the Reynolds number, $Re_{jc}=\rho U_{jc}D/\mu$, based on the nozzle diameter and the mean nozzle outlet velocity, in low speed case is 1,860 and in high speed case is 4,430, respectively.

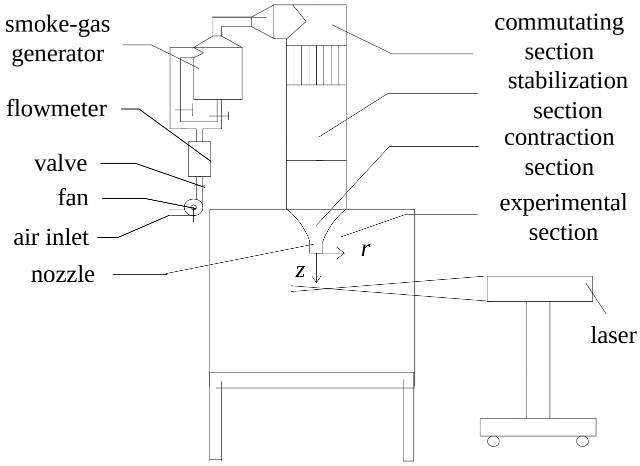


Fig. 1. Schematic diagram of the experimental system

In the present experiment, eight kinds of particles with smooth surface are selected. They are from 2mm to 16mm in diameter. The particle is fixed along the jet axial line. The axial spacing between the particle and the jet nozzle exit can be manually adjusted. The flow visualizations are performed first for the clear gas jet, and then the experiments are repeated at the same flow parameters when a single particle is fixed in the flow field.

The estimated priori particle Reynolds numbers, $Re_p=\rho U_{jc} d_p/\mu$, are also listed in Tab.1, using the mean jet exit axial velocity instead of the two-phase slip velocity. They are from 19 to 149 for the low-speed case and from 44 to 354 for the high-speed case.

Table 1. Flow and particle parameters in the experiments

	Flow parameters
Nozzle diameter	20mm
Central point exit velocity	3.1m/s, 1.3m/s
Fluid medium	Air
Particle diameter	2, 4, 6, 8, 10, 12, 14, 16 mm
Particle Reynolds number	19~149,44~354

RESULTS AND DISCUSSION

Flow patterns of the gas-phase free jet

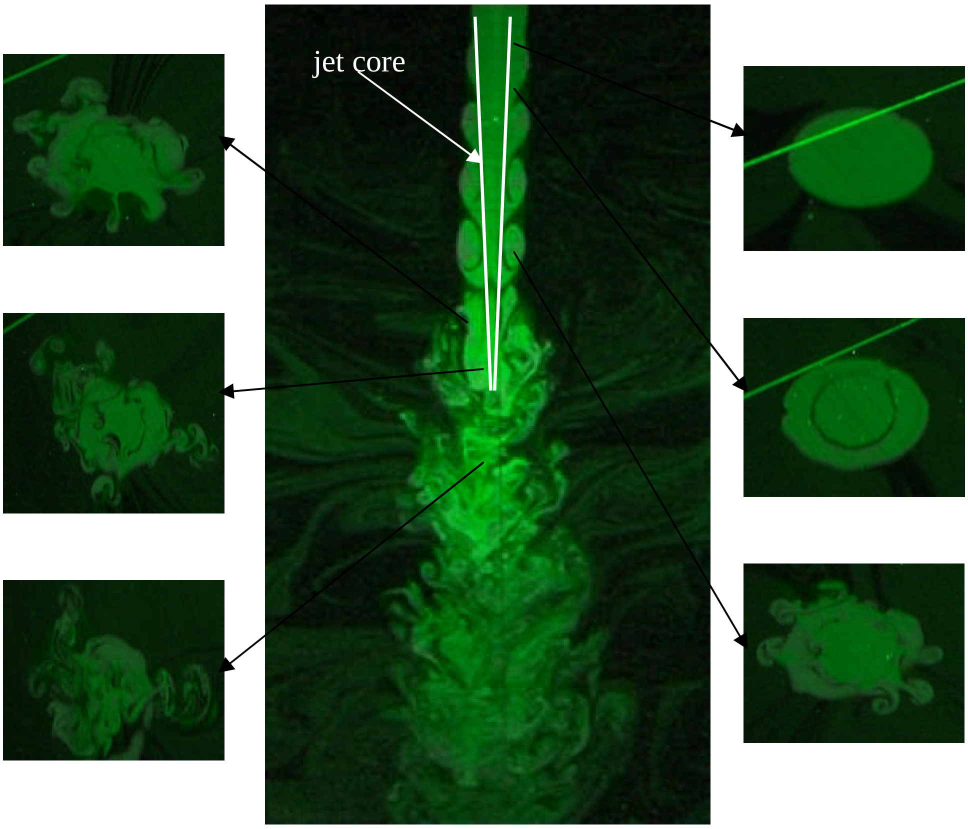


Fig. 2. Vortex structures at longitudinal and radial cross-sections of the round free-shear gas jet

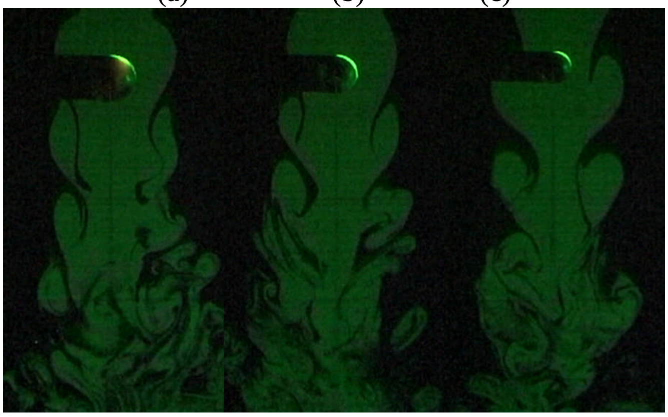
The transition process from the laminar to the turbulent flow is shown in Figure 2. The initial vortex rings roll up close to the nozzle exit. When the vortex rings develop downstream, the undulating ejections generate in the radial direction, which changes the regular pattern of vortex rings and finally results in the formation of streamwise structures. When the streamwise structures are broken up, the flow finishes the transition process from the laminar to the turbulence. The vortex pairs are also observed in the pictures.

The pictures in the radial-cross sections show the mixing between the jet fluid and the ambient fluid. The potential core is filled by the dyed fluid, appearing light and the undyed ambient fluid appears dark. The ambient fluid is entrained by the jet vortex ring into the jet, whereas the jet core fluid is ejected into the ambient fluid far which induces the jet diffusion in the radial direction.

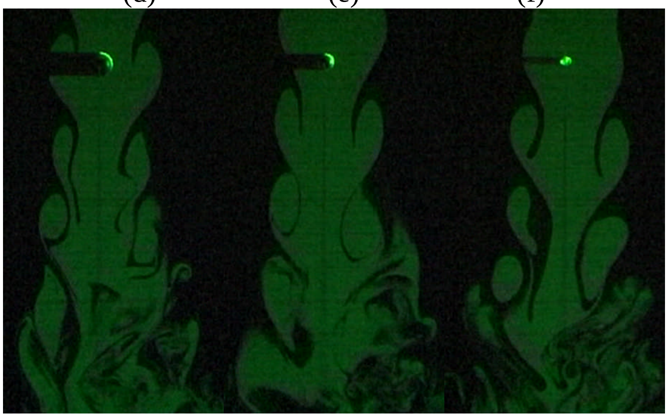
Interactions with a fixed-particle's wakes-the longitudinal observation

Figure 3 compares the vortex structures of the free shear gas jet at longitudinal section with those when a particle is fixed in the flow field, the center of which is at the position of z/D=2. The velocity at the jet nozzle exit is 1.3m/s. Particles are placed in the potential core region of the jet, where the characteristic flow structures are the rolling up vortex rings. There are two main influences of particle in the free shear jet flow field. Firstly, the particle changes the flow passage, which induces the flow instability earlier. Secondly, for the particles in diameter larger than 10mm, the wakes are formed behind them, but no wakes are behind the smaller particles. The placed large particles in the flow field accelerate the flow development. The particle wakes interact with the jet vortex rings, which makes the vortex rings broken up, i.e., the large scale structures are destroyed earlier compared with the flow without placed larger particles. The flow patterns are even not changed by the placed small particles. The flow over the small particles still yields to Stokes flow, and no oscillating and shedding wakes behind particles.

(a) (b) (c)



(d) (e) (f)



(g) (h) (i)

Fig. 3. Comparisons of vortex structures with and without a fixed-particle at longitudinal sections, particle fixed at z/D=2, low speed case. (a) free jet (b) 16mm particle (c) 14mm particle (d) 12mm particle (e) 10mm particle (f) 8mm particle (g) 6mm particle (h) 4mm particle (i) 2mm particle

Figure 4 compares the vortex structures of the free shear gas jet at longitudinal section with those when a particle is fixed in the flow field, the center of which is at the position of z/D=4. The particles are placed close to the end of the jet core, where the flow structures are more complex than those at the flow initial status. The interactions of particle wakes with jet vortex are very obviously observed. The large scale structures are broken up due to the particle wakes shedding and oscillating. The jet is accelerated hence because of the presence of the fixed large particles and the flow is further developed to the turbulence. However, for the small particles, there are no obvious wakes behind them. Therefore, the jet flow pattern is the very similar with that of particle-free jet.

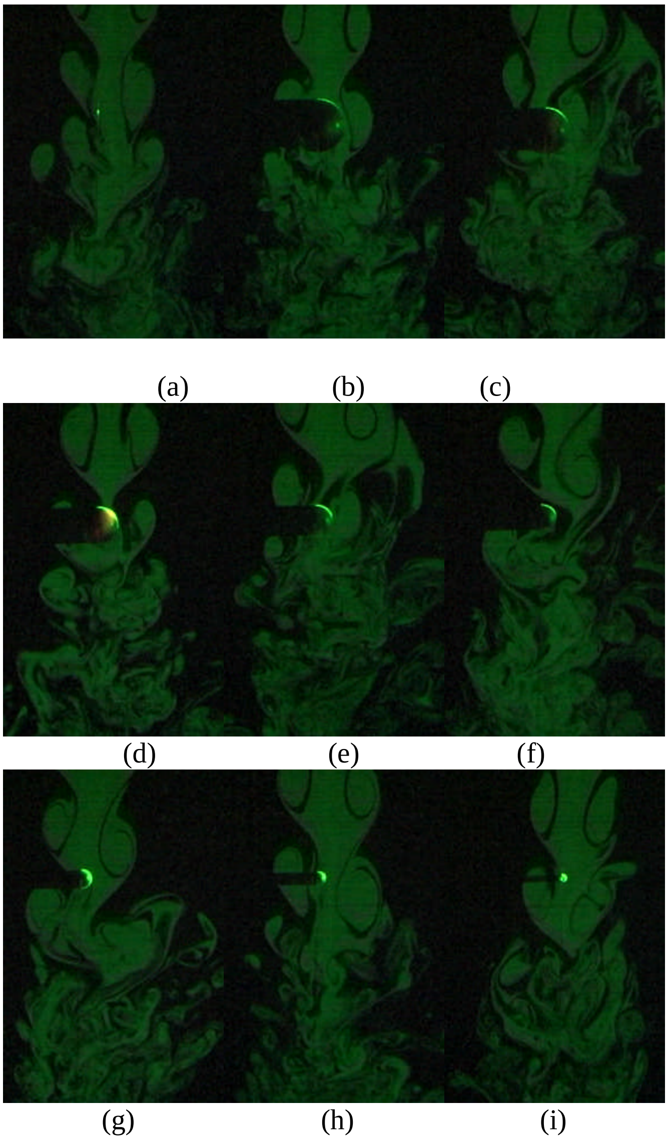
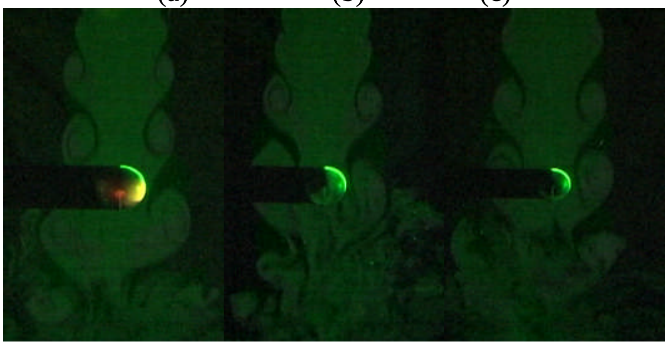


Fig. 4. Comparisons of vortex structures with and without a fixed-particle at longitudinal sections, particle fixed at z/D=4, low speed case. (a) free jet (b) 16mm particle (c) 14mm particle (d) 12mm particle (e) 10mm particle (f) 8mm particle (g) 6mm particle (h) 4mm particle (i) 2mm particle

The comparisons of flow structural compositions are presented in Figure 5 for the high speed jet at longitudinal sections. The particle is fixed in the jet central axial line, at the position of z/D=2. As the jet speed is increased, the flow transition process from the laminar to the turbulence is shortened. The particle Reynolds number also increases with the jet speed. Therefore, the wakes are observed for particles in diameter from 16 mm to 8mm, accordingly the Reynolds number from 354 to 177, larger than 150. The interaction between jet vortexes and particle wakes increases the flow structure's developments, for instance vortex pairs and vortex breaking up.

Figure 6 shows the interactions of wakes and turbulent eddies in the downstream position of the jet at z/D=6.5, where the flow is almost fully developed. The eddy characteristics length scale is generally less than or equal to the particle's size in these regions. Due to decaying of the axial velocity of the jet fluid, the particle Reynolds number is not larger than 150 here, and hence not obvious wakes are observed behind median particles, for example in diameter 8-12mm. It is shown that the homogeneous turbulent flow fields with very small turbulent structures are observed behind the larger particles in diameter of 14mm and 16mm. Smaller particles do not even change the turbulent eddy structures.

(a) (b) (c)



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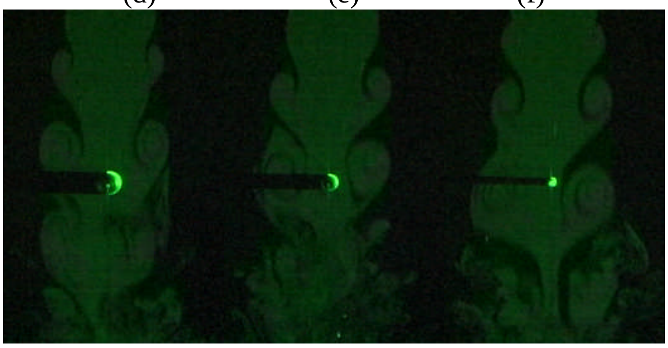
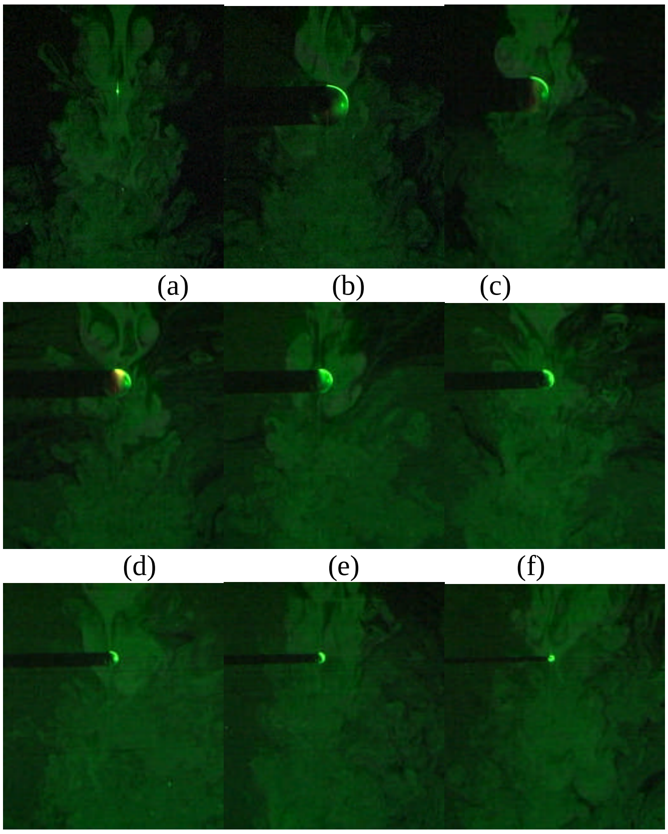


(g) (h) (i)

Fig. 5. Comparisons of vortex structures with and without a fixed-particle at longitudinal sections, particle fixed at z/D=2, high speed case. (a) free jet (b) 16mm particle (c) 14mm particle (d) 12mm particle (e) 10mm particle (f) 8mm particle (g) 6mm particle (h) 4mm particle (i) 2mm particle



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Fig. 6. Comparisons of vortex structures with and without a fixed-particle at longitudinal sections, particle fixed at z/D=6.5, high speed case. (a) free jet (b) 16mm particle (c) 14mm particle (d) 12mm particle (e) 10mm particle (f) 8mm particle (g) 6mm particle (h) 4mm particle (i) 2mm particle

Interactions with a fixed-particle's wakes-the radial observation

Figure 7 compares the vortex structures of the free-shear gas jet at the radial section with those when a particle is fixed in the flow field, the center of which is at the position of z/D=2 for the low speed case. It is very clear the large particles change the flow patterns: on one side the particle diffuses the jet core fluid due to the variation of the flow passage; on the other side the particle accelerates the flow instability. The entrainment is stronger and the ejections in the radial direction accused by the particle wakes enhance the mixing with the ambient fluid. Therefore, it can be concluded that the flow structures are more abundant for the jet with a fixed larger particle. However, for the small particles, the particle Reynolds number is small, and there are no obvious wakes behind them. Therefore, the jet flow pattern with a fixed particle is very similar with that of particle-free jet.

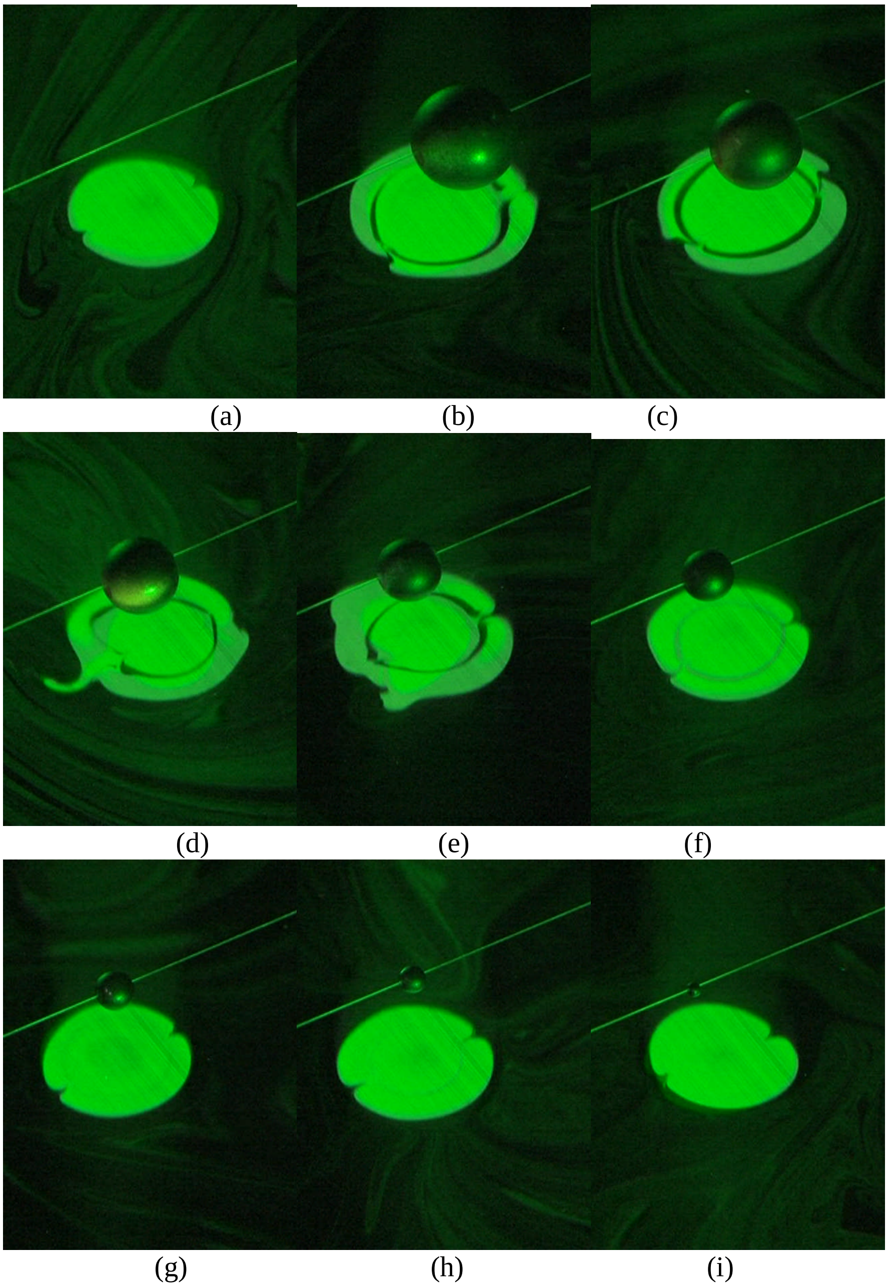


Fig. 7. Comparisons of vortex structures with and without a fixed-particle at radial sections, particle fixed at *z*/*D*=2, low speed case. (a) free jet (b) 16mm particle (c) 14mm particle (d) 12mm particle (e) 10mm particle (f) 8mm particle (g) 6mm particle (h) 4mm particle (i) 2mm particle

SUMMARIES

The flow vortex structures of a free-shear round jet and the effects of particles with and without wakes on them are studied by means of smoke-gas flow visualization technology in this study.

The overall flow developing process is presented to show the transition from the laminar to the turbulence, including the typical structural compositions of rolling-up vortex at the initial status, vortex pairs, streamwise structures and the broken-up eddies in the turbulent status. The very important paw-like structures in the mushroom heads occurring in the early stage of the jet are observed in the experiments, which are the structures by the ejection of jet core fluid in the radial direction.

Eight kinds of particle in diameter from 2mm to 16mm are fixed in the jet central line, respectively. Particle wakes occur obviously when the particle Reynolds number is larger than 100 either for low speed jet or high speed case. The wakes behind larger particles change the overall flow structure pattern of the jet. They not only accelerate the flow instability but also accuse more radial ejections and enhance the mixing of fluid. The destroy function of particle wakes on large scale flow structures leads the local flow into a developed status immediately in the far field. The local turbulence anisotropy is accordingly attenuated. Smaller particles without wakes do not change the flow structure pattern. The present results are valuable to develop accurate turbulence modulation models considering particle wake effects.

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