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Heavy Particles in the Near Field of a Turbulent Jet

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Abstract

Understanding turbulent two-phase flow, in which a solid phase is dispersed into a fluid, is of great importance in many industrial applications such as cyclone separators, mixing and combustion devices and chemical reactors and for knowledge of two-phase flow phenomena. An important class of turbulent two-phase flows is represented by jets, and consequently many works focused on the turbulence modification induced by solid particles in various jets configurations. The aim of this work is to advance the actual knowledge on the physical phenomena involved in turbulent two-phase jets and to provide new experimental data. A solid particle laden fully developed water turbulent pipe jet is investigated by means of Particle Image Velocimetry at a Reynolds number equal to about 15000, based on the jet bulk velocity, providing samples of instantaneous velocity fields. A statistical analysis of these samples showed that the laden jet reduces the centerline velocity much faster than the unladen case. At the same time, fluctuations are strongly altered for the two-phase flow, being dampened in shear layers.

1 Introduction

Many studies, such as Kussin and Sommerfeld (2002) and Gore and Crowe (1989), investigated the effects of particles dispersion in a fluid and the modification on the latter due to the presence of a solid phase. Balachandar and Eaton (2010) used the parameter d_p/L, where d_p is the solid particle diameter and L is the characteristic eddy length scale (usually the integral length), to characterize the effects on velocity fluctuations due to the presence of particles. For $d_p/L > 0.1$, turbulence intensity is enhanced by solid phase, whereas for $d_p/L < 0.1$ it is decreased. This has been also established by Elghobashi (1994), cf. Fig. 1, in which the key parameters are the Stokes number, $\mathrm{St} = \tau_p/\tau_f$, where $\tau_p = \rho_p d_p^2/(18\rho_f \nu_f)$ and $\tau_f = L/u'$ are the response times being subscripts "p" and "f" respectively referred to particle and fluid, ρ the density, ν the kinematic viscosity and u' the velocity standard deviation, and the volumetric solid phase concentration $\Phi_p = V_p/V$, with V_p the solid phase volume and V the total volume. If $\mathrm{St} < 1$, the solid phase enhances turbulent velocity fluctuations and hence turbulent dissipation, whereas for $\mathrm{St} > 1$ it damps fluctuations and dissipation. The main problems with those general views are that flow scales change with the local flow conditions and in addition specific features of a given configuration are not considered, e.g. boundary conditions.

Particle-laden jets are an important class of flow and many works focused on turbulence modification induced by solid particles in various jets configurations, reporting uncertainties and disagreements with previous described views (Sadr and Klewicki (2005)). Lau and Nathan (2016) showed that the Stokes number plays an important role, especially in jets, not only in turbulence modification but also in particles dispersion, which is often important in combustion applications. Since the full characterization of particle-laden turbulent jets requires the simultaneous measurement of the velocity field of both phases, together with the local, instantaneous particle size and number density, several experimental techniques on simultaneous velocity measurements (Kosiwczuk et al. (2005), Driscoll et al. (2003), Khalitov and Longmire (2002)) and on particles identification (Lau and Nathan (2017), Capone et al. (2014)) have appeared in recent years. Nevertheless, this physical phenomenon still remains extremely tough.

The present paper investigates the effect of aluminum spherical particles, with a diameter of 30 µm, on a fully developed turbulent water pipe jet in the near-field region, i.e. $x/D < 20$ where D is the pipe outlet diameter equal to 2 cm. Aluminum has a relative density $\rho_p/\rho_f = 2.7$ then, if we consider an integral length of the order of millimeters, the Stokes number is around 0.01. The volume concentration has been chosen around 10^{-5}. Higher concentrations were unacceptable because of the extremely intense light scattering

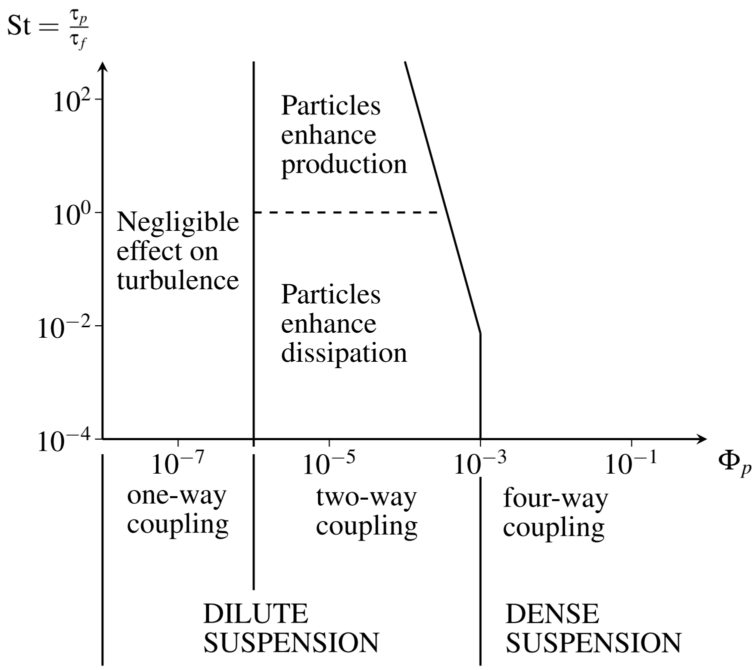
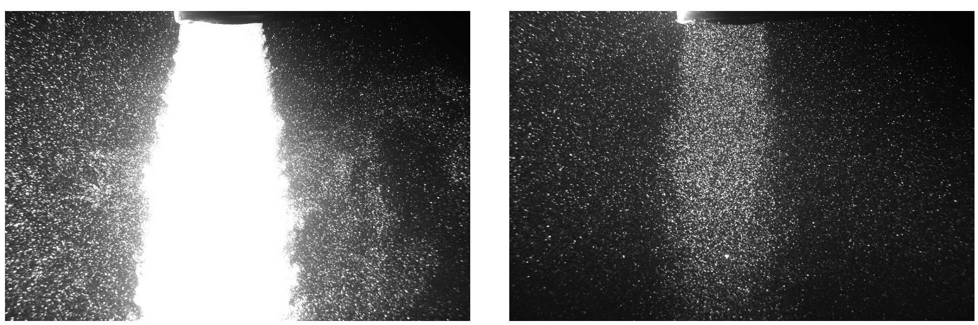


Figure 1: Elghobashi (1994) diagram.



(a) $\Phi_p \gg 10^{-5}$ (b) $\Phi_p \approx 10^{-5}$

Figure 2: Sample Mie scattering images of aluminum particles laden jet.

due to the presence of a lot of particles, hence yielding useless white images as in Figure 2(a). Therefore, according to Figure 1, the present particles should enhance turbulence dissipation. No phase discrimination has been performed but two-phase Mie scattering images, as in Fig. 2(b), are processed by cross-correlation PIV software in order to analyze the average behavior of the flow, being present in each correlation window both solid and liquid phases.

2 Experimental setup

The experimental apparatus is schematically described in Figure 3. The pipe was placed vertically downward within a water tank to avoid gravity bias. Another suspended tank fed the pipe issuing a constant flow rate such that the exit bulk velocity, U_b, is equal to $1\,\mathrm{m\,s^{-1}}$, yielding a Reynolds number

$$\mathrm{Re} = \frac{U_b D}{\nu_f} \approx 15000. \tag{1}$$

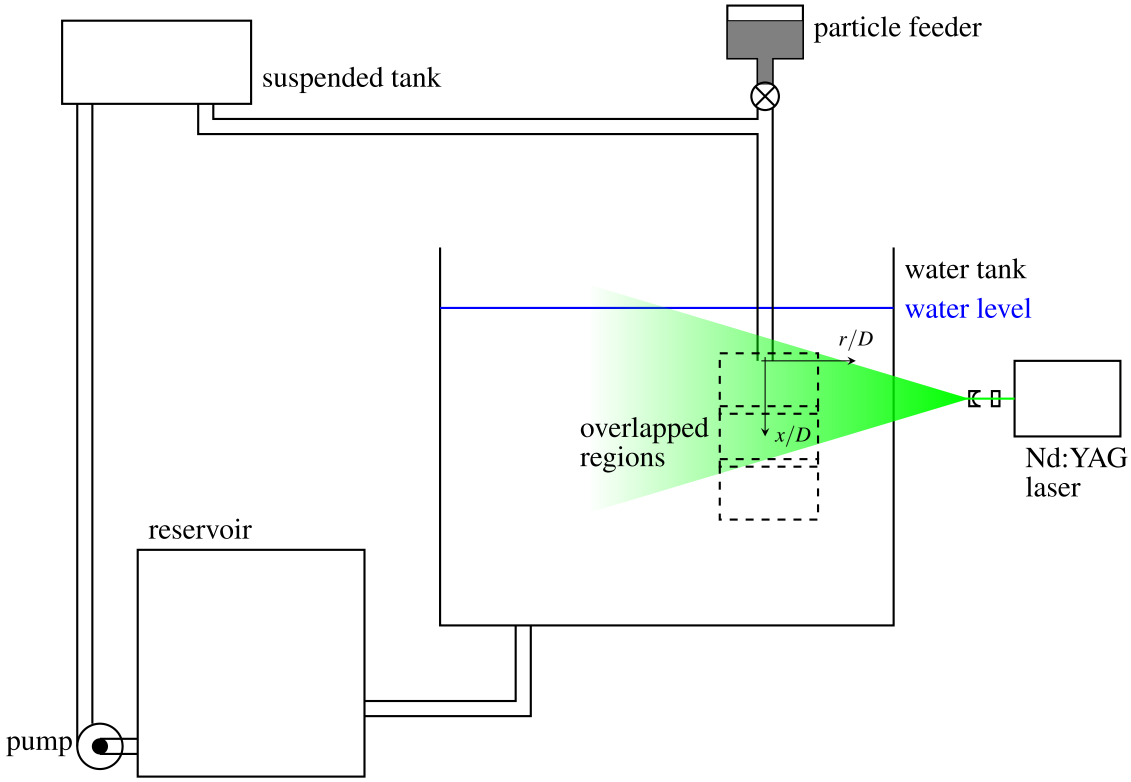


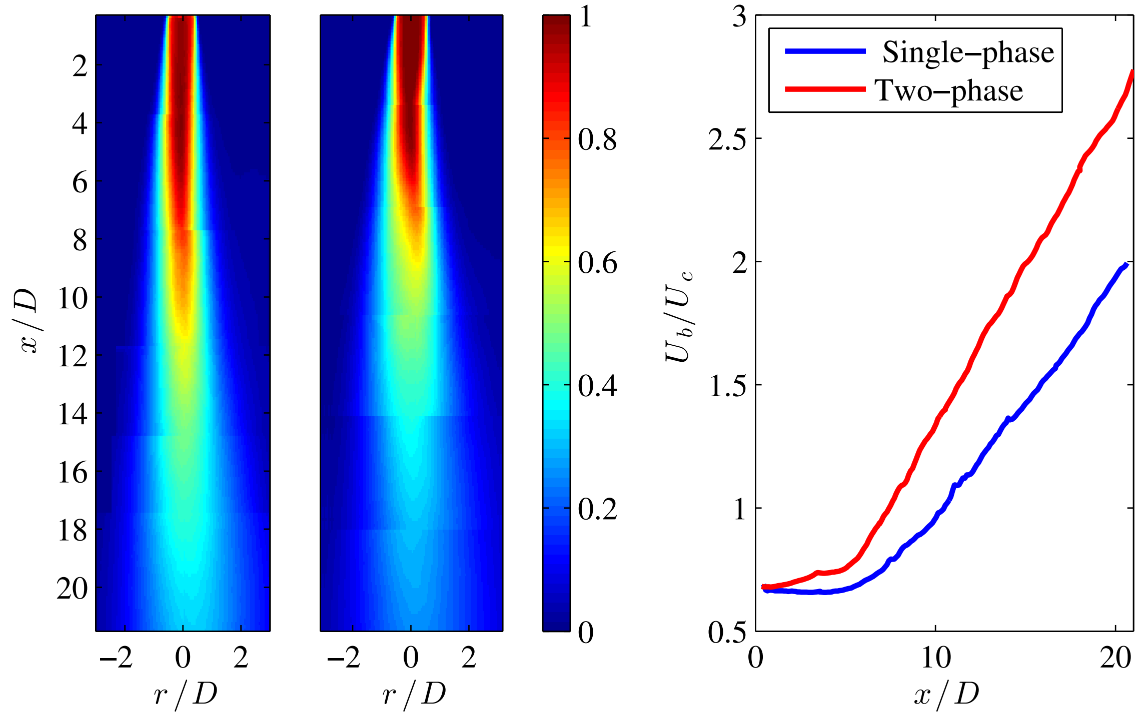
Figure 3: Schematics of the experimental setup.

Aluminum particles were mixed in water within a pressurized bin and injected with a flow rate of around $20\,\text{mL}\,\text{min}^{-1}$, which is negligible with respect to the flow rate of the main pipe. The aluminum concentration within the feeding bin was calibrated in order to obtain the desired global volume fraction, i.e. $\Phi_p \approx 10^{-5}$. Moreover, the relative velocity of the solid particles with respect to the carrying fluid due to gravity can be approximated by

$$\tilde{u}_s = \frac{2g(\rho_p - \rho_f)d_p^2}{36\mu_f}, \tag{2}$$

(μ_f is the dynamic viscosity of the fluid and g the gravitational acceleration) that with the present densities, $\rho_p \sim \rho_f$, is negligible. Therefore, according to Hetsroni (1989), the equation used for the relaxation time τ_p is valid. The distance from where particles had been injected and the exit of the jet was 1 m, whereas the total length of the pipe, L_p, was greater than 2.5 m leading to a length-to-diameter ratio of $L_p/D \geq 125$.

Two Nd:YAG (532 nm) CFR laser beams (around 3 mm diameter) were combined in a single optical axis and provided two consecutive pulses with a repetition frequency of 5 Hz. A cylindrical lens transformed the beam into a light sheet that illuminated the jet center-plane. A cross-correlation camera was placed orthogonally to this plane and acquired 1000 pairs of images synchronously with the laser pulses. The camera mounted a Nikon f=50 mm objective and a 48 mm extension tube in order to zoom-in the field of view, which was $70\,\text{mm} \times 105\,\text{mm}$ that corresponds to $3.5D \times 5.25D$. Hence, six overlapped regions were acquired in order to investigate the near-field region. The resolution of the camera was 668×2004 pixels. Water was seeded with hollow glass spherical tracers with a mean diameter equal to 10 μm and relative density equal to 1.05. Once each pair of images had been processed by cross-correlation PIV software, in order to derive the instantaneous velocity field, statistical quantities were derived by averaging the whole sample.



(a) single-phase (b) two-phase (c)

Figure 4: Mean streamwise velocity, U/U_b, for single-phase flow (a), two-phase flow (b) and evolution of the mean centerline velocity, U_c, for both single and two-phase flows (c).

3 Results

The streamwise mean velocity field, obtained by averaging a sample of 1000 instantaneous velocity fields for each of the six overlapped regions, is reported for both unladen and laden configurations, respectively in Fig. 4(a) and Fig. 4(b). Though a slight slope is visible in the evolution of centerline velocity, U_c, within the potential core for the laden jet (Fig. 4(c)), velocity starts to decay between four and six diameters from the jet exit as prescribed by Fellouah et al. (2009) but with two different slopes. It is clearly observed that the laden jet reduces the velocity along the axis much faster than in the unladen case. Despite for single-phase flows, this phenomenon was observed by Amielh et al. (1996) for jets of different densities but exactly in the opposite way.

Velocity fluctuations are instead coherent with the prescribed regime, that is of particles enhancing dissipation. Fluctuations for the two-phase flow are globally weaker than the unladen jet, as shown in Figure 5, where profiles of the streamwise velocity standard deviation are reported for increasing x/D. Along the centerline, reported in Figure 6, we observe a concentrated peak before $7D$ for the two-phase flow and a high fluctuating region between $7D$ and $11D$ for the single-phase flow.

4 Conclusion

A Particle Image Velocimetry investigation of an aluminum particle laden turbulent water jet is conducted. Mean field and fluctuations of the streamwise velocity is analyzed and compared to the results obtained for a single phase jet in the same condition of the laden one in order to give an insight of the effect of solid particles on turbulence. The addition of aluminum particle with a mean diameter of 30 µm to the flow yielded a faster reduction of the streamwise velocity along the centerline but did not modify the potential core. Fluctuations, instead, showed different behavior also near the nozzle. They are globally weaker in the laden jet than in the unladen one. Moreover, the highest fluctuations of velocity along the centerline are displaced closer to the nozzle in comparison to unladen jets.

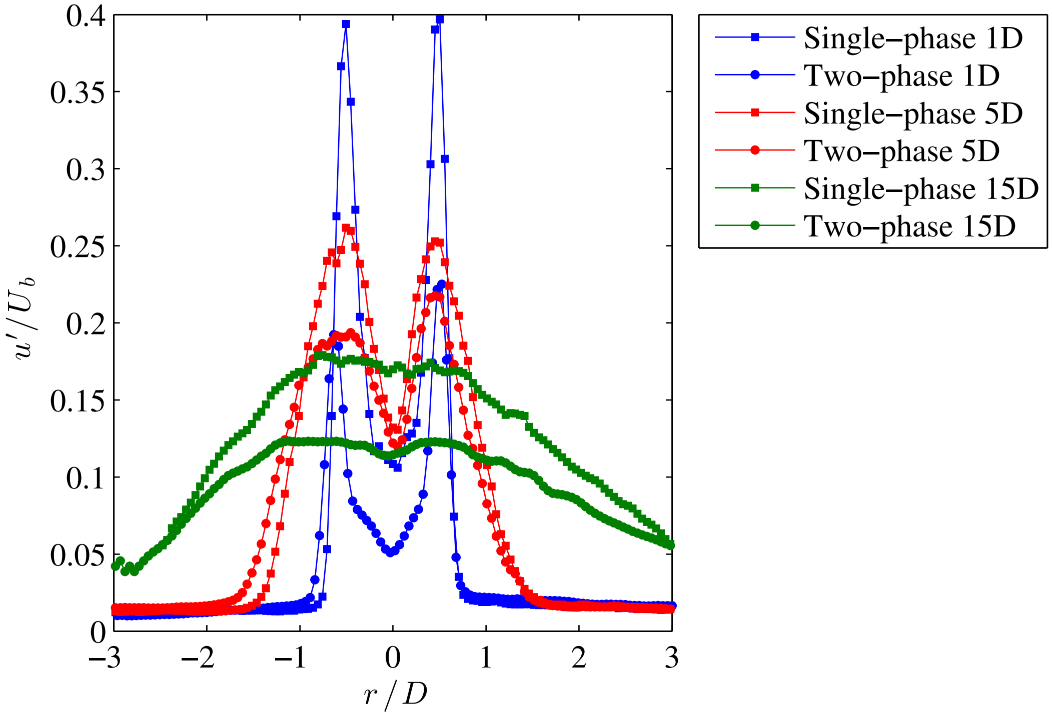


Figure 5: Streamwise velocity rms at several distances from the jet exit.

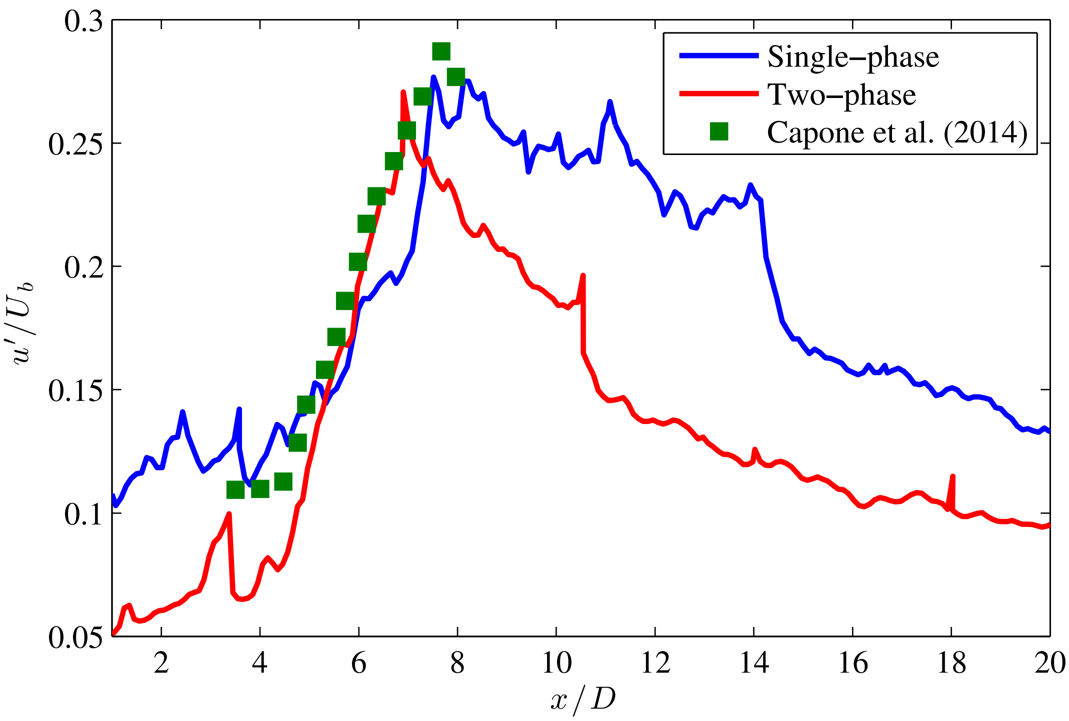


Figure 6: Evolution of the streamwise velocity rms along the centerline.

Despite the density of the dispersed phase is not so different from the one of the carrying fluid, the effects on the global flowfield are not negligible. Therefore, an investigation varying the solid phase density above and below the one of the water should be carried out. In addition, the phase discrimination is needed for a better comprehension of the physical phenomenon. It would provide either density distribution of the solid phase or simultaneous velocity field of each single phase. It is useful for this purpose to increase the image resolution but, reasonably, it would increase the number of acquisition regions to cover an appropriate portion of space.

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