International Journal of Multiphase Flow 35 (2009) 468–483

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Experimental study on a non-dilute two-phase coflowing jet: Dynamics of particles in the near flow field

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ARTICLE INFO

Article history:
Received 13 December 2007
Received in revised form 9 July 2008
Accepted 12 July 2008
Available online 27 July 2008

Keywords:
Particulate flows
Saffman lift force
Particle concentration

ABSTRACT

The dynamics of particles in multi-phase jets has been widely studied due to its importance for a broad range of practical applications. The present work describes an experimental investigation on an initially non-dilute two-phase jet, aimed at improving the understanding in this field. A two-color PDPA has been employed to measure simultaneously the velocity and size of particles. The measurements are post-processed to check the reliability of the results and to derive information on particle volume flux as an indication of their concentration. Acoustic forcing is applied in order to control coherent structures, which are responsible for mixing and transport phenomena, and also to get phase-locked measurements. Phase-averaged statistics enabled to *freeze* the jet structure, not visible in the time-averaged data. The results along the jet centerline confirm that drag forces and the spread angle of the jet initially control particle dispersion, very near the nozzle exit ($x/D < 4$). However, as the vortical structures evolve forming tongue-shaped structures, the total particle volume flux is augmented when these structures connect with the main stream ($x/D > 5$). This is due to an increase of the number of smaller size particles, even when a decrease of the number of larger size particle is observed. Further analysis at five cross-stream sections across two consecutive vortices confirm that small particles are convected around the coherent structure and then incorporated to the main stream, increasing the particle concentration at the jet core. On the other hand, the number of larger particles (as well as their contribution to axial volume flux) starts to decay in regions of high azymuthal vorticity. This behaviour is partly ascribed to the transversal lift force, associated to the large spatial gradients observed in these regions. Saffman and Magnus forces have been estimated to be comparable or even greater than radial drag forces. The results suggest that the Saffman force might accelerate particles in radial direction, inducing a high radial volumetric flow rate from high to low axial velocity regions.

1. Introduction

The knowledge on particle concentration in multi-phase jets is an important topic, due to its relevance for many industrial applications. For instance, particle dispersion and concentration greatly influence the performance and efficiency of combustion systems. In spite of significant advances in computational methods, many experimental investigations have been conducted on these flows in order to improve their understanding and explain some peculiar behaviors.

Maxey and Riley (1983) developed the general expression for the fluid forces acting on a small rigid sphere. After the latter work, many researchers scrutinized how particles behave in cases with small ratios of gas and particle densities, frequently in dilute regimes (i.e., low loading mass ratio). Maxey and Riley expressed the particle acceleration in terms of the aerodynamic drag force, the pressure gradient, the virtual mass induced drag, the weight and the Basset history force. An order of magnitude analysis (Chung and Troutt (1988), Sbrizzai et al. (2004)) has revealed that the forces caused by the virtual mass and the pressure gradient are of the order of the density ratio (ρ_g/ρ_p), and the Basset force is of the order of $(\rho_g/\rho_p)^{1/2}$, while the drag (the *dominant force*) is of the order of characteristic time ratio (t_g/t_p). In the present investigation, $\rho_g/\rho_p < 5{*}10^{-4}$, and, thus, the drag and gravity forces are considered as the relevant terms in the particle motion equation, which takes the form

$$\frac{d\mathbf{u}_p}{dt} = -\frac{3}{4}\frac{C_D}{d_p}\frac{\rho_g}{\rho_p}|\mathbf{u}_g - \mathbf{u}_p|(\mathbf{u}_g - \mathbf{u}_p) + g \tag{1}$$

$\mathbf{u}(u, v, w)$ is the velocity, C_D the particle aerodynamic drag coefficient, ρ is the density, d_p is the particle diameter, and $\mathbf{g}$ is the gravity acceleration. Subscripts g and p denote gas and particle variables, respectively. Should l_c and U_c be suitable characteristic length and velocity scales, Eq. (1) can be rewritten in dimensionless form as

$$\frac{d\mathbf{u}_p^*}{dt^*} = \frac{1}{S_t}(\mathbf{u}_g^* - \mathbf{u}_p^*) + \frac{1}{F_r} = F_D + F_g \tag{2}$$

S_t is the Stokes number, F_r the Froude number, and F_D and F_g stand for dimensionless drag and gravity forces, respectively. The star is used for dimensionless variables.

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doi:10.1016/j.ijmultiphaseflow.2008.07.003

Based on Maxey and Riley investigation, Chung and Troutt (1988) proposed that particle dynamics in the near flow field of a jet is controlled by large-scale structures. Martin and Meiburg (1994) emphasized that idea. This motivated the use of acoustic forcing in a number of works to control and enhance coherent structures in order to gain further insight into particle dispersion phenomena. Among others, Longmire and Eaton (1992), Lázaro and Lasheras (1992a,b), and Swanson and Richards (1997), demonstrated that particle concentration depends not only on particle size but also on the flow field induced by large-scale structures. For example, Longmire and Eaton (1992), using Particle Image Velocimetry, PIV, and Aísa et al. (2002), using Phase Doppler Particle Analyser, PDPA, showed that particles with Stokes numbers, St, up to ~6, disperse more effectively in the flow field. This is consistent with the value of St obtained by Martin and Meiburg (1994) in a computational simulation. Moreover, Longmire and Eaton (1992) found that the limit of St for particle dispersion increases up to 12 when external forcing is applied. Differences between both results tend to confirm that large-scale structures play an important role on the distribution of particles within the flow field. However, the question pertaining to how the motion of particles in the near field is affected by these structures still remains.

On the other hand, Lázaro and Lasheras (1992b) and Longmire and Eaton (1992), among others, demonstrated that particles altered the basic flow structure even for a dilute regime, and that streamwise gas-particle slip velocity increased at the jet exit as the particle mass loading ratio (defined as the ratio of particle to air mass flow rates) became larger (Park and Chen (1989)). Swanson and Richards (1997) also showed that the slip velocity was higher when the gas-phase axial mean velocity increased at the jet nozzle. It should be noticed that, as the slip velocity significantly departs from zero, the hypothesis that the Reynolds number, based on the relative gas/particle velocity, is much smaller than unity, essential to used Stokes' drag, is no longer fulfilled.

Although some investigators ascribed particle dispersion only to aerodynamic drag (Longmire and Eaton (1992), Martin and Meiburg (1994), and Anderson and Longmire (1995)), others like Bagchi and Balachandar (2002a,b), Cherukat et al. (1999), Kurose and Komori (1999), and You et al. (2003) observed that for locally sheared flows the vortex structure might cause particle dispersion through Saffman forces and Magnus effects. The latter were suggested to significantly contribute to the radial particle dispersion.

In a previous work, Cerecedo et al. (2004) analyzed the changes of flow structure caused by forcing; their results indicated very large spatial gradients of the axial velocities induced by the generated large-scale structures. This suggested that both Saffman and Magnus effects should be taken into account in the general particle motion equation, specially for flows with spatial velocity gradients, **G** (See Fig. 1).

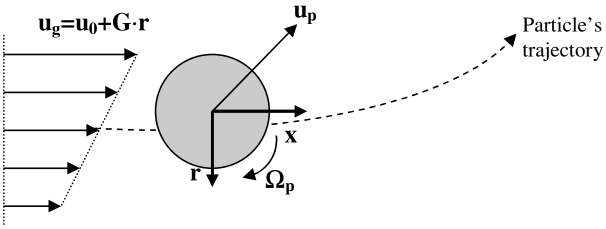

Fig. 1. Particle traveling in a shear flow. High spatial gradients or particle rotation alter particle trajectory by Saffman and Magnus effects, respectively.

If the particle is convected along by a vortical structure and the flow is directed downward, the axial and radial equations of particle motion for u_p and v_p, respectively, are given by

$$\begin{aligned} m_p \frac{du_p}{dt} &= -\frac{3}{4}\frac{C_D}{d_p}\frac{\rho_g}{\rho_p} m_p |u_g - u_p|(u_g - u_p) + m_p g \\ m_p \frac{dv_p}{dt} &= -\frac{3}{4}\frac{C_D}{d_p}\frac{\rho_g}{\rho_p} m_p |v_g - v_p|(v_g - v_p) + m_p \omega^2 r - F_{ls} - F_{lr} \end{aligned} \tag{3}$$

where m_p is the particle mass, $\boldsymbol{\omega}$ is the vorticity, and F_{ls} and F_{lr} are the lift forces due to shear and to particle rotation, respectively.

The present work is aimed at describing gas/particle interactions in the near flow field (where large-scale structures are visible) of an initially non-dilute two-phase jet. Acoustic forcing is applied to enhance large-scale structures, and to get phase-averaged (phase-locked) measurements. The initial loading mass ratio is 0.3, corresponding approximately to 40% of that of a stoichiometric mixture of a liquid hydrocarbon fuel. For the flow velocity, particle characteristics and loading mass ratio used in this work, a large axial slip velocity between phases is obtained at the nozzle exit, where conditions for Stokes' drag are therefore not fulfilled. In order to *freeze* coherent structures phase-averaged statistics, defined as the ensemble average of many realizations occurring at a specific time phase in the forcing cycle, are obtained with a two-color Phase Doppler Particle Analyzer (PDPA). Taking advantage of the phase-locked measurements, particle concentrations along the jet centerline and at five different downstream cross sections corresponding to the spatial evolution of a vortical structure are analysed in terms of the axial particle volume flux (ψ_x) and radial volumetric flow rate (g_r). Some comparisons are made with the results obtained by Aísa et al. (2002), who measured time-averaged variables for the same unforced jet. Conclusions are drawn on how coherent structures can influence particle dispersion.

2. Experimental facilities

2.1. Jet rig

The experimental setup has been described in previous works (Aísa et al. (2002), Cerecedo et al. (2004)), and only a brief reminder is provided here. The facility (Fig. 2) consists of an air supply system, a nozzle with a contraction coefficient of 5.13, a methacrylate chamber, and particle feeders (cyclone-like for tracers and vibrating device for solid-particles). A compressor provides the main air flow, the flow rate being measured with an orifice plate. The air flows vertically downward through a pipe 77D long and discharges through a nozzle ($D = 12$ mm) mounted inside the methacrylate chamber. The latter has a square cross section of 480×480 mm^2 and is 1.15 m long. The mean discharge air velocity at the nozzle exit (U_0) is fixed at 15 m/s for all the studied jets, with a resulting Reynolds number of 1.2×10^4 based on the nozzle diameter. A low velocity (0.2 m/s) secondary air stream (coflow) is induced inside the chamber by a fan.

A loudspeaker, installed on the opposite side to the nozzle in order to acoustically force the jet, is fed with a sine wave signal, generated by a filtered train of pulses from a Transistor–Transistor-Logic Circuit (TTL). To acquire phase-averaged measurements, burst detection is inhibited at all times except during a 15° window, initialized on the 0° phase of the forcing signal. The same TTL circuit is employed to inhibit the data acquisition, avoiding time delays.

Cerecedo et al. (2004) pointed out that there exists a simple statistical relationship between *time-averages*, $\overline{\eta(t)}$, and *phase-averages*, $\langle\eta(\phi)\rangle$,[1] through the equation

$$\overline{\eta(t)} = \frac{1}{2\pi}\int_0^{2\pi} \langle\eta(\phi)\rangle \, d\phi \tag{4}$$

Cerecedo et al. (2004) identified 400 Hz as the principal frequency for the generated flow. Thus, the jet is acoustically forced at this fre-

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[1] In the present work, phase-averaged (also called phase-locked) properties are denoted by brakes "⟨⟩". For time-averages the overbar will be omitted.