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Periodic structure of the dispersed phase in a forced jet and their effects on the particle dispersion

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ABSTRACT

This paper presents an experimental study on an acoustically forced particle-laden jet. The acoustic disturbances cause a train of strong periodical vortex due to the selected frequency and its high excitation level. The jet Reynolds number is not small ($Re = 11{,}900$) and the particle Stokes number is about one, responding partly to the forcing. The flow was tested using a Phase Doppler Anemometer (PDA). The paper includes measurements of both gas and dispersed phase over the whole forcing cycle. An external post-processing (developed by the authors) carefully corrects the bias inherent to the operation principles of the PDA in all supplied averages (including the phase-averaged values). This post-processing gives also some variables which were defined ad-hoc to characterize the periodic structure of the flow. Such information is never given in the previous literature. This work continues a previous study done by the authors.

Measurements detect three axial zones. The strong periodic gas vortices control the flow in the area close to the nozzle exit. They generate highly concentrated clusters of particles as well as tongue-shaped structures of radially ejected particles (or radial streaks). Downstream, the gas vortices vanish and inertia plays a central role in the development of the dispersed phase. The particle clustering ends here. Finally, all periodic motion disappears and flow degenerates into an unforced two-phase jet. Radially, the inertial zone of the particulate phase covers the outermost layers. The influence of the particle size is also discussed.

The radial dispersion of particles across certain section is quantified by means of a suitably defined parameter. This dispersion radius was measured at the end of the area disturbed by forcing for both the forced and unforced jet. Thus, the comparison assesses the total effect of forcing on the transversal dispersion. The dispersion of the whole size distribution and of each particle size is quantified. Results show that forcing enhances the dispersion and it is controlled mainly by the periodic streaks while turbulence has a secondary role. The streak shape is accurately computed from the measurements and its extension has been successfully related with the particle's history and it size by means of a suitably defined Stokes number.

Finally, this study supplies a set of high quality data useful to validate inherently unsteady numerical models. As stated by other authors, there is a lack of periodic well-characterized experiments for validation purposes which mimic the interaction between the particles and the large scales of turbulence.

Introduction

Since the second half of the 20th century, the dispersed multiphase flow is a relevant topic inside fluid mechanics. It is present in the study of natural phenomena (atmospheric dynamics, geology and erosion) as well as in a large number of applications (combustion, pneumatic transport, sprays). The first set of studies with a good enough characterization of the flow were carried out at that time (Goldschmidt and Eskinazi, 1966; Singamseti, 1966; Householder and Goldsmith, 1968; Hestroni and Soklov, 1971; Yuu et al., 1978). Most of them use conventional measurement techniques as hot wire anemometry and patternators to obtain the particle flux. Some key points were perceived for the first time during this period (as the particle–turbulence interaction). Laats (1966) and Laats and Frishman (1970) studied a two-phase turbulent jet and these works were remarkable since they covered a wide enough flow conditions, with particle-to-air mass loading up to 1.4 and Stokes numbers of order one. The results were

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discussed later in more detail by Melville and Bray (1979a,1979b) using physical arguments and similarity analysis, seeding light into this subject.

The development of new experimental techniques causes other set of studies (Modarres et al., 1984; Fleckhaus et al., 1987). They use intensively Laser-Doppler Anemometry (LDA), Phase-Doppler Anemometry (PDA), Particle Image Velocimetry (PIV) and other optical methods. The interesting work of Hardalupas et al. (1989) presents a particle-laden jet tested by means of a PDA. They define a Stokes number (*St*) based on the mean flow (besides the conventional based on the exit diameter D_0 and gas velocity U_0) and depict the “fan spreading” phenomenon which explains the large velocity fluctuation shown by heavy particles (with high Stokes number) as an effect of the initial injection conditions. Additional refinements in the PDA signal processing allow the experimentalists to measure the gas phase velocity. For example, Aísa et al. (2002) achieve this goal. In addition, they confirm the Hardalupas’ fan spreading as well as what the authors called “directional classification”, which is another consequence of particle inertia. The measurements of the gas velocity let Prevost et al. (1996) evaluate the momentum exchange between both phases in a particle-laden air jet.

The works cited till now obtain overall means of the dispersed phase. No details about the effect of turbulence on the dispersed phase are given despite of the fact that the large scales of turbulence play a central role in the particle dispersion. Although this subject was suggested previously (Laats, 1966; Laats and Frishman, 1970), Rudoff et al. (1989) and Hodges et al. (1994) report particle clusters which were correlated with the turbulent large scales. At present, the clustering, anisotropic distribution of particles and the modulation of turbulence is an important topic (see Gualtieri et al., 2013).

The effect of the large scales was studied using computational simulations and experimental work. A comprehensive review was done by Crowe et al. (1988). Chung and Troutt (1988) simulated a two-phase round jet using a discrete vortex model. Although the model is two-dimensional (the vortices are completely axisymmetric), it reproduces the general behavior of the shear layer surrounding the potential core (including the pairing of successive vortices). Simulations cover the dilute regime for which particles do not perturb the continuous phase. Their results show clearly the influence of the large scales on the particle movement. Particles are ejected from areas with high vorticity, cumulating in the zones of high strain. Simulations also show that particles with a Stokes number close to one could disperse more effectively than the fluid. Marting and Meiburg (1994) simulate a shear layer using the same computational techniques, obtaining similar conclusions.

To study the effect of the turbulent large scales in a simpler framework, some experimental work on acoustically forced particle-laden flows was done. Forcing induces quasi-periodical vortices which roughly mimic the effect of the large scales (Crow and Champagne, 1971). Longmire and Eaton (1992, 1994) studied a particle laden gas jet under unforced and forced development. They confirm the influence of the anisotropic turbulent large scales on the particles and the effect of the Stokes number on it. When forcing is enabled, the jet develops the explained train of periodic vortices. This periodic pattern of vortices generates particle clusters at the jet axis located between consecutive vortices (where the strain is high). The high vorticity vortex cores have virtually no particles but they are surrounded by backward bended particle streaks which emerge from the particle clusters. Vortex pairing was achieved when the jet exit is forced with two frequencies (a fundamental and a subharmonic) instead of a single one. Similar particle dispersion phenomena were observed by Swanson and Richards (1997) in their forced two-phase jet. In a more recent paper, Cerecedo et al. (2009) discuss the effects of the Saffman force and Magnus effect on the dispersion of particles with high inertia and large Stokes number inside a forced jet.

The work of Lázaro and Lasheras (1992a, b) deals with a two-phase shear layer. The authors find particle structures for the unforced flow inside the mixing area, similar to the streaks detected by Longmire and Eaton. These streaks were located in mean between two consecutive vortex cores developed by the Kelvin–Helmholtz instability. The authors postulate that streaks are the main cause of the transversal particles dispersion. They also found the particle spatial distribution shows self-similarity at the far field (in agreement with the results of Laats, 1966 and Laats and Frishman, 1970). This similarity implies that the particle dispersion depends on the particle size (and therefore on the Stokes number). When the shear layer is forced, spanwise vortices become temporal and spatially periodic following an arrangement similar to the one observed in the forced jets. Particles leave the high-vorticity vortex cores, concentrating in the high-strain braid regions between vortices while transversally ejected particles form the streaks around the vortices in agreement with that observed in the forced jets.

Kieger and Lasheras (1995) continues the work of Lázaro and Lasheras on forced shear layers. They investigate the effect of the vortex pairing on the particle dispersion as well as on the energy exchanges between both phases. Again, pairing was driven by a double-frequency forcing. After the paring, the spatial particle distribution becomes more homogeneous but the degree of homogenization depends on the particle size (through the Stokes number). The energy transfer is highly inhomogeneous and it decreases after de pairing because the characteristic time scale of the resulting vortex increases and the Stokes number of the particles becomes smaller.

Since the forced flows replicate roughly the unsteady, inhomogeneous and anisotropic particle dispersion caused by the turbulent large scales, they are suitable to validate numerical models. The Montecarlo Lagrangian simulation is considered now the most accurate model of the particle phase but some researchers are making significant efforts to improve the Eulerian–Eulerian models. This family of models shows an enhanced numerical efficiency but they have problems to reproduce some aspects of the dispersed phase behavior (Kah et al., 2010). Freret et al. (2009) characterizes a laminar low-Reynolds forced two-phase jet to validate its own Eulerian–Eulerian model. According to the authors, they built their own experiment since it is difficult to find a well-characterized unsteady flow. With the available data, the performance of their model was considered to be successful.

This work presents an experimental study about an acoustically forced turbulent particle-laden air jet. It continues a previous work done by the authors (Calvo et al., 2014) which studies the forced single-phase jet (without particles) and the continuous phase of the forced particle-laden flow under the same injection conditions of the present research. The dispersed phase consists of small glass spheres. Their size gives Stokes number of order one ($St \sim O(1)$) and the turbulent jet has a moderate Reynolds number.

Measurements were done using a two-component Phase-Doppler Anemometer (PDA) and they cover the whole forcing cycle. The instrument measures the velocity, diameter and the arrival phase-shift of each detected particle. In a previous work, Calvo et al. (2012) showed that the operating principles of the PDA induce bias in both the particle diameter and velocity distributions “seen” by the instrument. In the current work we develop an external post-processing to remove these intrinsic errors from any mean or moment of the reported physical magnitude. This task was undertaken because the PDA control software corrects the statistics of just a few magnitudes. The developed post-processing also calculates corrected phase-average values along the whole forcing cycle, obtaining a complete description of the periodic flow structure (phase-averaged particle velocity and rms velocity,