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Experimental study of sand jet front in water

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ABSTRACT

An experimental study was conducted to examine the behaviour of a sand jet front in water and its associated fluid motions with different sand particle sizes and initial sand jet diameters. The shape of sand jet front was found to be directly related to the particle Reynolds number of sand particles. The frontal velocity along the centreline of the jet axis was measured and compared to that of single-phase buoyant jets and particle thermals. The jet front settling velocity of small particles was found to be as large as 5 times that of the individual particle settling velocity. The presence of particles and the additional momentum generated by particles were found to reduce the growth rate of the jet front width, compared with those of the single-phase buoyant jets and particle thermals. Evolution of vortices and their structure were extracted from velocity fields by employing Galilean velocity decomposition and a local vortex identification technique. It was shown that, radial convection velocity can change the shape of the vortices. Large radial convection velocity transformed the vortex from semi-circular shape to elongated ellipsoid vortex. Effect of particles on turbulence of the carrier phase was studied. It was found that smaller particles increase turbulence attenuation of the carrier phase. Effect of particles on the modulation of turbulence can be described by the Stokes number along the jet axis. A classification was made for solid–liquid and solid–gas turbulent jets and new formulations were proposed to show the correlation between Stokes number and the turbulence attenuation of particle-laden turbulent jets.

1. Introduction

Particle-laden jets are commonly observed when particles are released instantaneously into water bodies such as in marine bed capping, dredged material disposal, as well as aqueous industrial waste disposal (Buhler and Papantoniou, 1991; Bush et al., 2003). The behaviour of these jets is determined by the size, concentration and density of the suspended particles. A number of experimental and numerical studies have been conducted to investigate the hydrodynamic behaviour of steady-state particle-laden jets (Virdung and Rasmuson, 2007; Wang et al., 2009a; Hall et al., 2010; Gan and Nichels, 2010; Azimi et al., 2011) but less attention has been devoted to the study of the fronts of particle-laden jets with relatively high particle concentrations.

Mean axial and radial velocities, turbulent fluctuations and Reynolds stresses of the solid–liquid jets with low solid concentration (e.g., solid concentration of less than 0.2%) were measured by many investigators such as Muste et al. (1998), Arai et al. (2003), Jiang et al., 2005 and Virdung and Rasmuson (2007). In the case of low solid concentration, the effect of particle–particle interaction was assumed to be negligible. But in slurry jets with high solid concentration, particle–particle interaction can play an important role in the hydrodynamics of the jet (Hall et al., 2010). Therefore, effect of particle–particle interaction on the averaged axial and radial velocities and turbulent fluctuations of the slurry jets with high particle concentration needs to be explored. Earlier studies by Muste et al. (1998) tried to include the effect of particles on the turbulence of particle-laden jets. Influence of particles on the turbulence of the carrier phase is known as turbulence modulation. The physics of turbulence modulation has been discussed by many researchers (Gore and Crowe, 1989, 1991; Wang et al., 2009a). A comprehensive comparison of turbulence modulation effects of two-phase flow in pipes, bubbly flows and particle-laden jets was made to investigate the influence of particles in variations of turbulence intensity (Crowe, 2000).

The unsteady behaviour and the development of the two-phase liquid–air jets were studied by Hill and Ouellette (1999), Rottenkolber et al. (2002) and Marugán-Cruz et al. (2009). Experimental investigation of the transient jets indicated that the time scale of the jet evolution could be formulated as a function of momentum and buoyancy fluxes (Pantzlaff and Lueptow, 1999). In the release of a fixed amount of particles in stagnant water, the evolution of the particle cloud and its velocity were correlated with the buoyancy force exerted by the particles whereas the frontal evolution of a continuous release of particles can be correlated with the buoyancy flux of the jets (Noh and Fernando, 1993; Noh, 2000; Bush et al., 2003). The condition under which the particle cloud

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settles as a thermal or as a swarm of individual particles was investigated by Bush et al. (2003). The dependence of the normalized cloud velocity on the normalized buoyancy force of a particle cloud was correlated and it was found that when the normalized buoyancy is less than 0.1, particles descended as a swarm of individual particles and for the normalized buoyancy above 0.1, settlement of particles resembles a thermal. Most experimental studies have been focused on the release of a fixed amount of particles to form a cloud thermal or swarm of particles (Noh and Fernando, 1993; Noh, 2000; Bush et al., 2003). So far no attention has been made to study the particle cloud due to continuous release of particles. It will be useful to study the effect of initial momentum flux on the behaviour of particle clouds.

The unsteady behaviour of particle-laden jets/plumes and the evolution of particle cloud can be classified into different regimes by introducing some critical parameters such as particle Reynolds number, and particle Froude number. Nicolas (2002) classified the settling of particle cloud in water and glycerine into four different regimes: stable jet, unstable jet with blobs formation, spiral jet with dispersion and atomized jet. He found that a capillary-like instability with formation of blobs and dispersion of the jet particles occurs when the particle Reynolds number is over unity. Experimental studies have been performed to investigate the location of sedimentation after release of particles into a quiescent and cross flow ambient conditions (Ruggaber, 2000; Gensheimer, 2010). The physical mechanisms and the characteristic of the cloud of particles as it descended in the water column were investigated by Ruggaber (2000). In his experiments effects of practical release parameters such as release location (i.e., release height) and moisture content were investigated. He found that the thermal phase of particle clouds can be subdivided into turbulent thermals in the absence of spherical vortex and circulating thermals in the presence of vortices.

An interesting flow feature that has long been associated with starting jets is the formation of vortex structure. The formation of the vortex is largely due to the roll up of the jet shear layer as it is introduced into the ambient. The generation, formation, and evolution of vortex rings have been the subject of numerous experimental, analytical and numerical studies (Gharib et al., 1998; Krueger and Gharib, 2003; Arakeri et al., 2004; Pottebaum and Gharib, 2004; Bond and Johari, 2005; Bond and Johari, 2010) but to the authors' knowledge, no experimental work has been devoted to study the vortex structure of a particle-laden starting jet. The formation of buoyant thermal and vortex rings was generated by the motion of a piston pushing a column of fluid of length of L through a nozzle of diameter d. Tube aspect ratio L/d was found to be a key parameter in the prediction of vortex circulation and vortex translation velocity. Bond and Johari (2005) investigated the effect of tube aspect ratio ranging from 2 to 8. They found that the higher aspect ratio leads to higher circulation. Shusser and Gharib (2000) proposed a direct correlation between the propagation velocity of a vortex ring and the vortex circulation.

Vortex structures and eddies can be extracted from two dimensional velocity vector field to provide more information about the effect of particles on the mixing mechanism and frontal entrainment of the starting sand jets. Reynolds decomposition is considered as the traditional method of vortex extraction; however, several other methods including Large Eddy Simulation (LES) and Galilean decomposition have been employed (Adrian et al., 2000; Wu and Christensen, 2006; Natrajan et al., 2007). Besides the well-known Reynolds decomposition, identification of vortices in a velocity field can be accomplished by filtering the velocity fields such as Gaussian filter, LES method, or by translating the instantaneous velocity field with convection velocity (Galilean method). Adrian et al. (2000) investigated different turbulent extracting techniques to interpret the velocity field and vortex structures in the turbulent pipe and channel flows.

It should be mentioned that the Reynolds decomposition does not always provide the best visualizing pattern of the turbulent mechanics of a flow and it removes large scale motions that are associated with the mean flow. Furthermore, in transient phenomenon time averaging is not permitted, since Reynolds decomposition is not able to resolve the vortex structure. On the other hand, Galilean transformation was found as a simplest method of decomposition (Wu and Christensen, 2006; Natrajan et al., 2007). In this method, the computed convection velocity corresponds to a different translational velocity of vortices embedded within the flow. When the convection velocity matches with a vortex's translational velocity, it becomes recognizable in the velocity vector pattern.

Local vortices can be identified by analysing the velocity gradient tensor and the three invariants of velocity gradient tensor. The symmetric and antisymmetric parts of the velocity gradient tensor are called strain rate tensor and vorticity tensor, respectively. Local vortex identification techniques could be an excellent tool to assess the contributions of the small and large scale vortex structures to the overall dynamics of the flow (Jeong and Hussain, 1995; Zhou et al., 1999). The reviews of Chakraborty et al. (2005) and Kolář (2007) describe much of the current understanding of vortex extraction techniques as well as some limitations in employing these techniques.

This paper is aimed at investigating the onset of particle-laden turbulent jets in still water with special emphasis on the effects of nozzle diameter and particle size on the hydrodynamics of the particle-laden jets. Effect of nozzle diameter and particle size on the shape and velocity of the front can help to understand the changes on vortex formation and the mixing capacity of the front jets. Since many factors are involved in this study such as time, particle concentration, nozzle diameter, particle size and the excess momentum generated by particles, a close comparison between the results of this study with the results of the classical experimental studies having less complexity (i.e., the single-phase jet front, single-phase vortex, particle-laden turbulent jets and particle thermals) can address the effect of each controlling parameter on the characteristics of jet fronts and their differences with the results found in the literature. Detailed simulation of the unsteady behaviour of the sediment-laden jets with high initial concentration is a challenge for CFD modellers. Consequently, the results provided in this paper can also be used for validation of numerical models. Turbulent modulation is also one of the important parameters for the prediction of the mixing capability of such jets. Effect of particle size on turbulent modulation is investigated and correlations are introduced by a comprehensive comparison of other experimental studies in the literature. The paper is organized as follows: the experimental methods and the velocity measurement techniques are described in Section 2. In Section 3, dimensional analysis is used to investigate the effect of controlling parameters on the hydrodynamics of the jets. Experimental results including the study of the evolution of the frontal particle-laden jets, frontal velocity measurements and half-width growth rate are presented in Section 4. Effect of nozzle diameter and particle size on the axial and radial velocities, vortex structure and turbulence modulation are discussed in Section 5. Finally, a summary and conclusions of this study are presented in Section 6.

2. Laboratory experiment

Experiments were conducted in a 133 cm square tank filled with tap water, and the water depth was fixed at 92 cm for all experiments, using an overflow drain. A schematic view of the