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Research paper

Two-phase velocity measurement in a particle-laden jet

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Abstract

A horizontally discharging jet laden with solid sediment particles is investigated experimentally. The submerged jet discharges water with an initially horizontal direction into stagnant water of the same density but the presence of sediment particles produces jet effluent having a combined density greater than that of the ambient water. A modified particle-imaging velocimetry (PIV) technique is applied to estimate the velocity fields of the solid particle phase and the jet fluid liquid phase. Phase separation is achieved optically between the scattered light signals from the particles and the laser-induced fluorescence signal from the jet fluid dozed with a fluorescent dye. It is found that initial sediment concentrations below 0.1% volume fraction do not cause significant changes to the global properties of the jet flow. In jets of higher initial sediment concentrations, settling of sand particles are observed to drag the jet to spread with a downward-bending mean trajectory. Intensive particle–flow interaction is also observed in jets of high sediment concentrations.

Keywords: Jets; Sediment; PIV; LIF

1. Introduction

Two phase flows are found in many industrial and natural processes. The object of this paper is a particle-laden jet which can be observed in various areas of chemical engineering, environmental fluid mechanics and earth sciences. In environmental hydraulics, wastewater is discharged from outfalls in the form of a submerged jet into an ambient water body (Fischer et al., 1979). Residual solid particles are often present in the wastewater and the effluent is discharged as a particle-laden jet. In addition to the mixing and dilution of the liquid effluent phase, the fall out and settling of solid particles from the jet also give rise to many environmental problems, such as formation of sludge bank, consumption of dissolved oxygen in water body and even introduction of toxic materials to the food web of local ecosystem (Metcalf and Eddy Inc., 1991).

A multiphase flow is more complex than a single-phase flow not only because of the presence of more constituents but also due to possible interaction among the different phases. In jets and plumes, particle–turbulence interaction leading to modifications of turbulent flow behavior has been observed (Gore and Crowe, 1989). Hence, studies of particle-laden flows not only provide information of the sediment-carrying jet flow, open channel flow or slurry pipe flow but also give insights to the underlying mechanisms of particle–flow interaction which exist in a broad scope of multiphase flows. With limitations in theoretical treatments of phase interaction, researchers rely heavily on experimental investigations to study and derive empirical models for multiphase flow systems. The main challenge of any experimental study on multiphase flows is how to distinguish the flow signal of one phase while avoiding interference from those of the other phases. Once the signal of a particular phase is acquired, it can be measured and processed with various flow diagnostic techniques such as particle-image velocimetry (PIV) for the measurement of velocity vector field (Adrian, 2005) and laser-

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induced fluorescence (LIF) for scalar concentration measurement (Crimaldi, 2008).

The non-intrusive laser-based flow diagnostic techniques of PIV and LIF have been applied to two phase flow measurements. Previous works can be roughly categorized into two groups: (1) separation of phases by post-measurement imaging processing (e.g., Bryant et al., 2009), and (2) separation of phases by optical means during flow imaging (e.g., Jiang et al., 2005; Simiano et al., 2009). The first group of techniques recorded signals of the two phases on the same image while phase separation was achieved subsequently either by applying intensity difference or by image size differences (or by both). These post-measurement image processing algorithms usually require a lot of computations. For the second group, images of the two phases will be separated by the optical setup before images are taken by a camera. The optical methods require more hardware but less computation. The separated images can be further processed to give velocity fields or scalar fields.

Our study targets on turbulent particle-laden jets discharging in a stagnant environment. Most previous investigations of this topic studied vertical round jets (e.g., Carey et al., 1988; Neves and Fernando, 1995; Jiang et al., 2005), in which the discharging jet effluent and particle settling lie in the vertical direction and the mean flow is symmetrical. For a sediment-laden jet discharging in an initially horizontal direction, the effects of particle–flow interactions are more prominent because particle falling out occurs more readily and the mean flow is always asymmetrical in the vertical direction. When modeling sediment jets or plumes, researchers often assume that sediment particles are fully dilute so that they do not have a significant effect on the main flow phase and have little particle–particle interaction (Bleninger et al., 2002; Lane-Serff and Moran, 2005; Li, 2006; Cuthbertson and Davies, 2008). Here, we would like to focus our investigation on the limiting concentration level above which effects of sediment particles on the jet flow cannot be neglected. Especially, we aim to investigate the effect of particle concentrations on the mean global behavior of the jet flow over a large region of the jet flow.

We list the particle characteristics in some previous investigations on particle-laden flows in Table 1. It is noted that the particle concentration in almost all studies in sediment-laden jets, plumes and open channel flows was very low and not higher than 0.1% volume fraction (C_p) while much higher particle concentrations were used to study slurry pipe flows. Municipal wastewater discharges typically have very low particle concentrations (<1200 g/m^3) (Metcalf and Eddy Inc., 1991) but there may be situations such as slurry discharges or storm water discharges where particle concentrations and characteristics can vary widely.

Experimental studies of particle-laden jets have been based on point measurements (e.g., Barlow and Morrison, 1990; Calvo et al., 2009) and flow visualizations (e.g., Cardoso and Zarrebini, 2001; Li, 2006), but only a limited number of studies presented global velocity measurement (e.g., Jiang et al., 2005; Sadr and Klewicki, 2005). In our experiments, the non-intrusive global velocity measurement technique of PIV is used to measure velocities of the two phases of a horizontally issued particle-laden jet. We separate flow images of the jet fluid phase and the sand particle phase with optical means and modified PIV techniques are applied to these images to estimate the velocity fields for each phase. The outcomes of the experiments are expected to reveal the main global features of the two phases and give some indications of particle–flow interaction in the scales of jet eddies. In addition to pure momentum jet discharge, we shall continue in the future to apply our technique to the investigation of buoyant discharge, which is of more interest in environmental hydraulics.

2. Experiment techniques

2.1. Experimental setup

The experiments were conducted in a rectangular glass tank of length 1.8 m, width 1.2 m and height 0.6 m (Fig. 1). The

Table 1
Previous studies of particle-laden flow.

Literature	Particle properties			Application
	Diameter d_p (mm)	Density ρ_p (g/cm^3)	Vol. fraction C_p (%)	
Wilson and Pugh (1988)	0.1, 0.2, 0.5, 1.0	2.65	0–60	Slurry pipe flow
Matousek (2002)	0.12, 0.37, 1.85	2.65	12, 26	Slurry pipe flow
Lyn (1992)	0.15, 0.19, 0.24	2.65	<0.19	Open channel flow
Noguchi and Nezu (2009)	0.25, 0.37, 0.5, 1.0	1.2, 1.5	0.03–0.29	Open channel flow
Martin and Nokes (1988)	0.21–0.31, 0.31–0.42, 0.42–0.50	1.033	0.3	Thermal tank
Carey et al. (1988) [a]	0.007–0.120	3.21	<1.87	Vertical Sediment plume
Neves and Fernando (1995)	0.530, 0.799, 0.868	1.0445, 1.0251	0.0045–0.23	Vertical Sediment jet
Jiang et al. (2005)	0.075	1.51	0.19	Vertical Sediment jet
Lane-Serff and Moran (2005)	0.075–150, 0.150–0.300	2.65	<0.38	Angled Sediment jet
Bleninger et al. (2002)	0.45–0.50	1.022	0.02–0.47	Horizontal Sediment jet
Li (2006)	0.063–0.150, 0.150–0.212	2.65	0.15–0.17	Horizontal Sediment jet
Cuthbertson and Davies (2008)	0.500–0.600, 0.630–0.850	1.15, 1.50	∼0.1	Horizontal Sediment jet

[a] Ambient salt water density: 1.021 g/cm^3.