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Experimental investigation of the effect of jet inclination on bifurcation of laminar jets

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A B S T R A C T

Submerged buoyant jets show interesting phenomenon like bifurcation under specific flow conditions. A detailed quantitative experimental analysis of this hydrodynamic instability highlighting relative importance of associated parameters is addressed in this work. Regular water and brine solutions have been used as the experimental fluids and flow diagnosis has been performed using Particle Image Velocimetry and shadowgraphy. It is found that for certain ranges of Reynolds number and Grashof number, the incoming jet cannot flow as a single entity, but rather bifurcates into a main jet whose motion is governed by the initial momentum of the jet and a buoyancy dominated thin sheet. The effect of incoming flow rate, angle and velocity of injection, and the density difference between the fluids on bifurcation are explicitly studied. The regions of bifurcation have been mapped on the Re–$Gr^{1/2}$ plane for different orientations of both positive and negatively buoyant jet. The flow field reveals several interesting features like flow entrainment into the jet, jet bifurcation, bifurcation zone, transition zone and finally the turbulence of the jet.

1. Introduction

Effective transport and mixing capabilities of submerged jets have made them useful topics for investigation. Oceanographic applications in the form of bed load transportation (Francis and McCreath, 1979) using convective transport, and mixing of slurries (Hammad, 2002) have been two of the important uses of submerged jets. To minimize the impact of unavoidable emission of pollutants into the environment, their dispersion behavior needs to be predictable. It is important to study the buoyant flows of these pollutants since only then we can control the quality of our environment. A simple jet is a discharge of fluid into an identical fluid and is driven by its initial momentum. A plume on the other hand is purely driven by buoyancy. Buoyant jet is a jet with an initial momentum subjected to buoyancy which could be driven by density difference caused by temperature or concentration difference. Relative densities of the two fluids determine whether the flow is buoyant or non-buoyant. Simple jets with same density as that of the ambient fluid are dominated by initial momentum flux whose characteristics like velocity profiles and rate of entrainment are well established (Birch et al., 1978; Grandmaison et al., 1991; Hussein et al., 1994). In comparison, buoyant jets have received relatively less attention with the focus generally on vertically discharged jets (Lee, 1998; Pantokratoras, 1999; Pantzlaff and Lueptow, 1999; Tian and Roberts, 2003; Zhang and Baddour, 1998). The extensive importance of buoyant (positive or negative) jets in many engineering applications such as oceanography, meteorology, discharge of effluents and maintenance of salinity gradients in solar ponds provides the motivation for a detailed analysis of such jets. Though practical systems are often turbulent (Pantzlaff and Lueptow, 1999), laminar jets are often encountered in different situations and are more useful for fundamental studies. One such buoyant jet using fluids of different densities – water and brine solution is studied herein.

Injection of brine solution into solar pond (water) at appropriate velocities can remove the internal convective layer within its non-convective zone (Arakeri et al., 2000; Dewan et al., 1992). Thus, it can be used to increase the efficiency of solar energy conversion and electricity generation in salt gradient solar ponds. One of the most important works in this regard is that of Arakeri et al. (2000). Apart from highlighting the factors that govern the trajectory of such a horizontal buoyant jet, they have also mentioned the phenomenon of bifurcation in such systems. Bifurcation of buoyant jet is separation of the peripheral jet fluid from the primary core jet fluid under the effect of buoyancy. Shadowgraph visualization followed by an analysis assuming a top-hat density profile across the inner core of the jet has been done by Dewan

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et al. (1992). Realizing the importance of this interesting instability, such a system demands a further thorough quantitative investigation using non-intrusive diagnostic tools. Hence, in this study, we have gone beyond shadowgraph technique and investigated the velocity profile along the trajectory of the jet using Particle Image Velocimetry (PIV). Apart from the study of such horizontal buoyant jets, the effect of the inlet angle variation and negative buoyancy (i.e. injection of heavier liquid into lighter one) on such bifurcation is unexplored and is addressed in this study. The spreading of inclined jets impinging at the bottom have been experimentally studied (Papakonstantis and Christodoulou, 2010). Other experimental studies on negative buoyant jets mention trajectory of jets in calm, homogeneous environment (Zeitoun et al., 1970; Cipollina et al., 2005) but they have neither discussed bifurcation nor variation of velocity profiles. Such variation in inlet angle could be useful for mixing purposes (Shao and Law, 2010). Several theoretical studies addressed this jet instability using continuity and Navier–Stokes equation (Pawlowski et al., 2006) or boundary layer theory (Braun and Kluwick, 2003).

Till date, shadowgraph has been the principle diagnostic technique for flow visualization of buoyant jets (Satyanarayana and Jaluria, 1982; Kikkert et al., 2010; Arakeri et al., 2000; Dewan et al., 1992). Entrainment of the ambient fluid with buoyant jets is of great concern as it is a measure of spreading rate, loss of momentum along the flow direction and extent of mixing. The entrainment of plumes were experimentally found to be greater than the jets and was attributed to the presence of buoyancy (Sreenivas and Prasad, 2000). Laser Doppler Velocimeter (LDV) have been used to study the flow field and entrainment of air induced by a pool fire (Zhou and Gore, 1995). The entrainment mechanisms of round jets in crossflow is discussed (Yuan and Street, 1998). In the current study, the shadowgraph study has been extended to an analysis using PIV to provide a more detailed analysis on velocity.

In this work, characteristics of positively and negatively buoyant jets along with the bifurcation phenomenon have been investigated for three different angles of injection (0°, 30° and 60° anticlockwise w.r.t. the horizontal axis), the 0° configuration corresponds to the case studied by Arakeri et al. (2000) but for a different diameter nozzle. The effects of inertia and buoyancy are quantified in terms of Reynolds number $\left(Re = \frac{V_j d}{\nu}\right)$ and Grashof number $\left(\mathrm{Gr} = \frac{g \Delta\rho d^3}{\rho_j \nu^2}\right)$ respectively. The relative importance of buoyancy and inertia can be expressed in terms of a mixed convection parameter, Froude Number $\left(Fr = \frac{Re}{\sqrt{Gr}}\right)$, which is a ratio of inertia to buoyancy forces. The scaling of Re and Gr in the definition of Fr has motivated us to parameterize the jet dynamics on Re–$Gr^{1/2}$ plane, as also done by Arakeri et al. (2000), thereby comparing with their data and further extending to the case of inclined jets.

2. Measurement techniques

2.1. Experimental set-up

A schematic diagram of the experimental set-up, which is similar to that of Dewan et al. (1992) and Arakeri et al. (2000), is presented in Fig. 1. The jet injection facility used in the experiment consists of a centrifugal pump, flow control valve, rotameter, constant head tank (placed at a fixed height using a clamp and holding rod), pinch cock, air release valve, aspirator bottle connected to a U-type glass tube using a clamp. Liquid flows from constant head tank to the aspirator bottle through a flexible pipe. The flow is controlled with the help of pinch cock. The air is removed from the aspirator bottle, with an air release valve connected to the aspirator bottle. The exit tip of U-type glass tube was fully submerged into the rectangular tank of dimensions 0.21 m × 0.205 m × 0.45 m. Nozzles of diameter 3 mm and different angles (0°, 30° and 60° w.r.t. the horizontal axis) have been used to inject the fluid. Variation in quantity of brine created the density difference (measured using a hydrometer), which led to the formation of the jet.

2.2. Flow visualization and data interpretation

Flow visualization and analysis were done using both shadowgraphy and 2D PIV.

2.2.1. Shadowgraphy

A spherical source of light was placed at the back of the glass tank to illuminate the nozzle tip and the field of view. The shadow of the flow field was formed on the tracing paper attached to the front portion of the glass tank. Images were captured using a high resolution DSLR camera Nikon D3000 having a resolution of 10.2 mega-pixels.

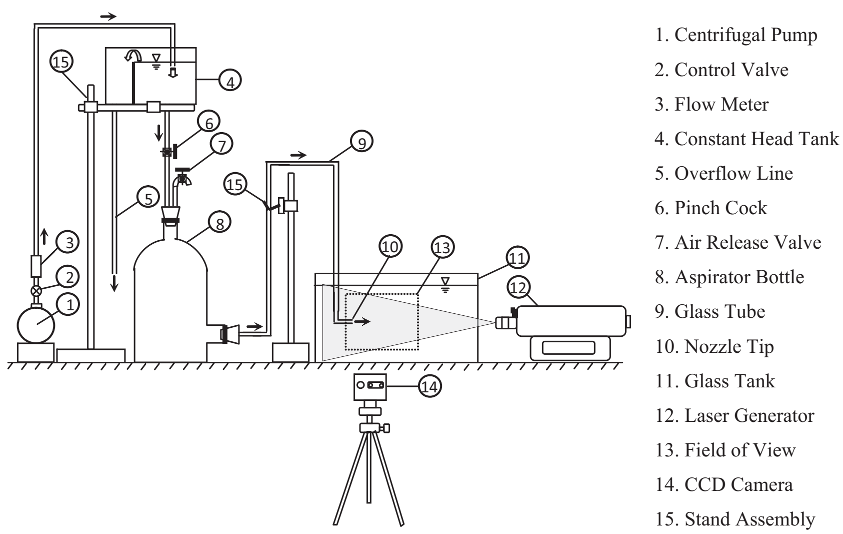

Fig. 1. Schematic diagram of the experimental setup and PIV system.