EXPERIMENTAL STUDY OF THE FLOW FIELD OF A TURBULENT BUOYANT JET IN A CONFINED DENSER FLUID

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ABSTRACT

This study investigates the mean axial velocity at the centreline of a buoyant jet, which is discharged vertically upwards from a source into a denser bounded fluid contained in an open channel without flow. The presence of a buoyant jet is studied experimentally using a Particle Image Velocimetry (PIV). This optical method of fluid visualisation is used to obtain instantaneous measurements of the mean velocity. The experiments were conducted in a channel of 6.5 m length, 7.5 cm width and 25 cm height. The 0.6-cm round source in diameter that supplies the buoyant jet with fresh water was fixed at 5 cm over the flow depth. The velocity fields of the buoyant jet were determined analysing 50 pairs of photographs per experiment. These fields were used to quantify the behaviour of the buoyant jet in the surrounding fluid (salt water) with several densities and flow depths. The time interval between a pair of images was about 1.5 ms, whilst the measurements were conducted at a 120 x 100 mm region in a 4-m distance from the channel's entrance. Results show that the depth and density of salt water can affect the flow dynamics. Flow velocity is reduced with increased depth of salt water, due to wall effects, whilst increase in the salt density increases the buoyant forces and hence the velocity rate.

Keywords: Buoyant jet, Wall effect, PIV measurements, Laboratory experiments, Mean axial velocity, Density difference.

1. Introduction

Turbulent buoyant jets and plumes have been studied theoretically and experimentally, the latter by using both fresh and salt water (Chen and Rodi, 1980; Ferrari and Querzoli, 2010). Papanicolaou and List (1988) experimentally investigated the mean and turbulent properties of round vertical turbulent buoyant jets, combined with appropriate dimensional analysis. More recently, Yannopoulos and Noutsopoulos (2006a) investigated combinations of two, three and five identical round vertical turbulent buoyant jets. The analysis led to unified analytical expressions concerning the normalized axial velocity and concentration distributions along the jet axis: (a) for a pair of buoyant jets, and (b) for a jet of an infinite row of buoyant jets. Yannopoulos and Noutsopoulos (2006b) further developed a model to predict the mean axial velocities and the mean concentration of the combined fields of a series of N jets or plumes, where N (2, ∞).

Recent efforts have introduced the Particle Image Velocimetry (PIV) technology to investigate flow dynamics. Among others, Pechlivanidis *et al*. (2012) investigated experimentally the turbulent characteristics of open-channel flow using a PIV. More recently, Pechlivanidis *et al*.

(2015) performed experiments to explore the effect of impermeable bed on the turbulent flow. Measurements of velocity were taken for horizontal channel slope at different heights using the PIV. Keramaris and Pechlivanidis (2015) assessed the effects of turbulent flow on the velocity distribution in an open channel in a half-separated (impermeable and permeable) bed using a 2-D PIV.

In this study, the mean axial velocity at the centreline of a buoyant jet, which is discharged vertically upwards from a source in a confined fluid (salt water), in an open channel without flow is calculated experimentally using a PIV. The following questions will be addressed: 1) Does the salt water depth, channel walls and free surface affect the flow dynamics? and 2) what is the salt water density effect on the velocity rate?

2. Experimental procedure - measurements

In total, fifteen experiments were carried out in the laboratory of Hydraulics in the Department of Civil Infrastructure Engineering of the Alexander Technological Educational Institute of Thessaloniki, Greece. The experiments were conducted in a horizontal channel of 6.5 m long, 7.5 cm wide and 25 cm deep (Fig. 1). The velocity of the buoyant jet was measured at 7130 points of the jet centerline for a horizontal channel bed. These fields were used to quantify the behaviour of the buoyant jet (with fresh water of density ρ_0 = 1.000 gr/cm^3, which is discharged vertically upwards from a tank with fresh water in a salt water. Herein we use different salt water densities (ρ_a=1.010, 1.015, 1.020, 1.025 and 1.030 gr/cm^3) and three different flow depths (y=70, 100 and 150 mm). The source, which supplies the buoyant jet with fresh water, was fixed at 5cm over the channel bottom.

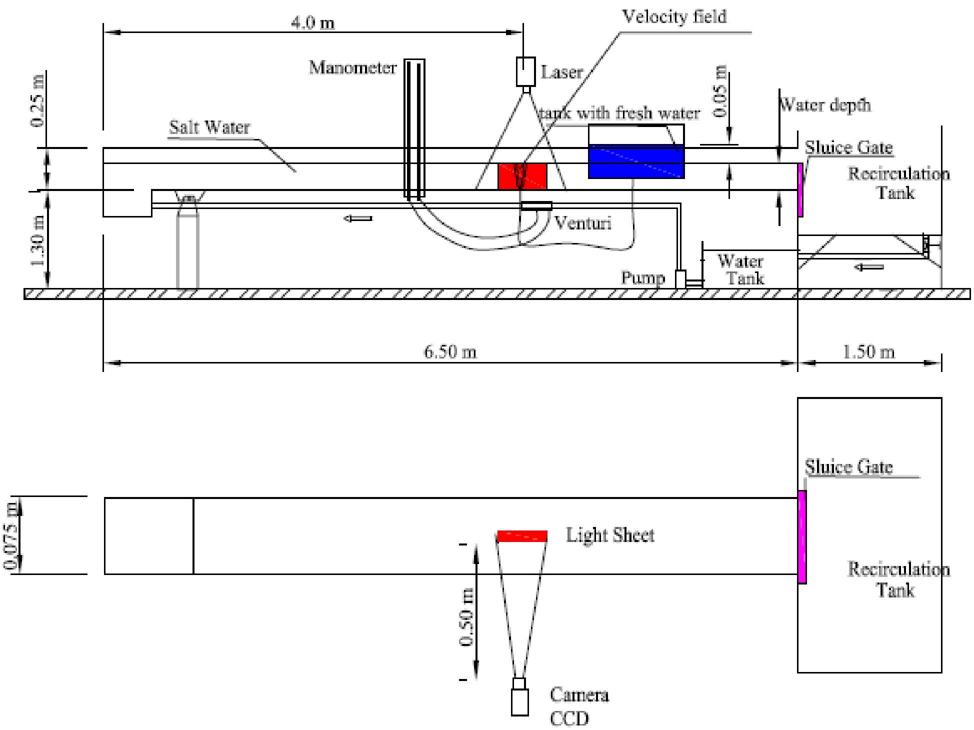

Figure 1: Experimental set-up (open channel).

Measurements of the velocity were taken for the horizontal channel using a 2-D Particle Image Velocimetry (PIV). The PIV system used for the measurement of the velocity distribution in the flow domain consists of a twin pulsed Nd: Yag lasers (532 nm wavelength, 300 mjoule/pulse at 10 Hz), a cross correlation 8 bit 1K x 1K CCD camera (Kodak MEGAPLUS ES 1.0), a synchronizer, a computer, an image acquisition system and a PIV analysis software (Insight 3G). The laser beams were combined and formed a 1-mm wide sheet by using semi-cylindrical optics. The camera image size creates a 1600 x 1192 pixel array and the dimension of the velocity field was kept to 120 x 110 mm for all the experiments. This means that the resolution of the captured images was typically 13.33 pixel/mm, whilst the pixel length was 0.075 mm/pixel. The laser was installed above the open channel at a distance of 50 cm from the water free surface, while the camera viewed from an orthogonal direction (Fig. 1). Twin images were recorded with a temporal interval of 1.5 ms. In total, 50 pairs of images were captured per experiment. The plane photographs were divided into interrogation spots measuring 16 x 32 pixels (1.2 x 2.4 mm). The fluid is generally seeded with tracer particles that, for the purposes of PIV, are generally assumed to follow the flow dynamics (Wereley and Meinhart, 2010). These particles have a size of about 10 μm in clean water. The motion of the seeding particles is used to calculate the velocity vectors of the flow. The distance between two neighbour velocity vectors is 1.5 mm. From the velocity field we can find the profile of the flow at each vertical direction or the mean space profile in the area. PIVs use the particle concentration method to identify individual particles in an image and follow their flow (Raffel *et al.*, 2007). The experimental uncertainty of the measured velocity with this technique is approximately ± 2%. Figure 2 shows the motion of the buoyant jet and the intense turbulent mixture. The temporal interval of these two photographs is 0.25 s.

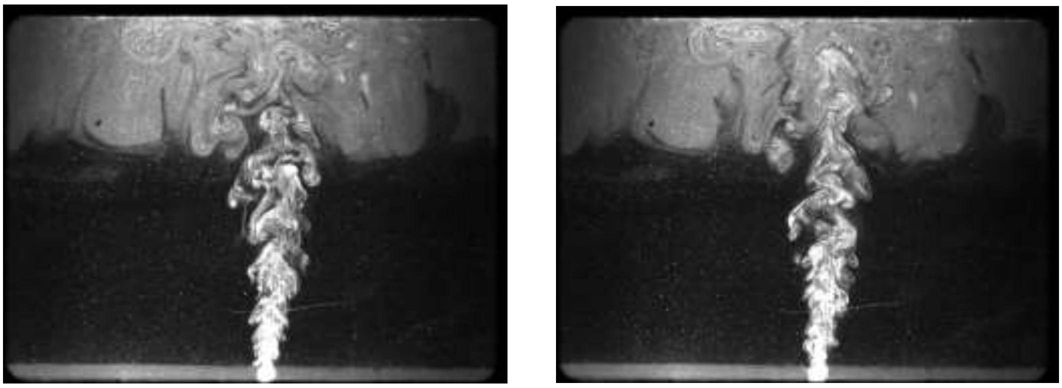

Figure 2: Photographs of a buoyant jet (differed by 0.25 s).

3. Results

Herein, the mean rate of the motion of 200 different time positions was taken. The impact of salt water depth on the flow dynamics and the impact of water density on flow dynamics can be assessed by comparing results from Fig. 3 and 4. We estimated the mean velocity of each position in the plethora instantaneous fields, and this resulted into a final field which is depicted in diagram (a) in all the figures below (Fig. 3-4). In these figures, the velocity profiles follow a Gaussian distribution, and the velocity vectors are spaced at a distance of about 1.5 mm. Thus, each profile is abstained from the adjacent 1.5 mm and each vector from the adjacent 1.5 mm. At the 6-mm nozzle in diameter, the fluid (fresh water) with density ρ_0=1.000gr/cm^3 has the same form in its velocity profile (diagram (d) in all figures). The increase of the velocity vector is apparent due to the buoyant forces. This increase is evident from the diagrams (b) in all the figures below. These diagrams define the change of the mean velocity in the vertical direction within a range equal to the maximum range of the velocity profiles; velocity increases and eventually decreases. The diagrams (c) give the velocity profiles at 5 different horizontal positions from the bed to almost near the free surface. From these values the average velocity rate is determined (bold black solid line). Any motion is due to the non-verticality of the jet. Comparison of the figures below shows that the increase of the salt water depth results into a reduction of the velocity (Fig. 3 and 4). Finally, the increase of the density of the salt in the fluid water results into an increase of the velocity rate. This is expected, since the increase of the density of the salt water increases the buoyant forces.

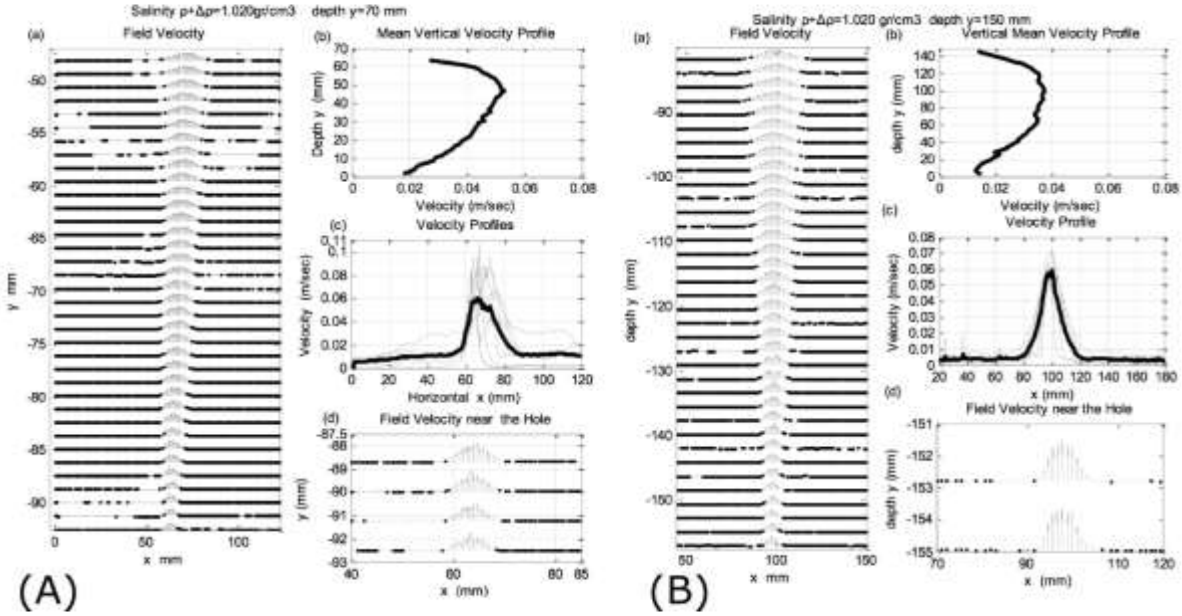

Figure 3: Buoyant jet with ρ_0=1.000 gr/cm^3, salt water with ρ_a=ρ+Δρ=1.020 gr/cm^3 and water depth: (A) y=70 mm, and (B) y=150 mm.

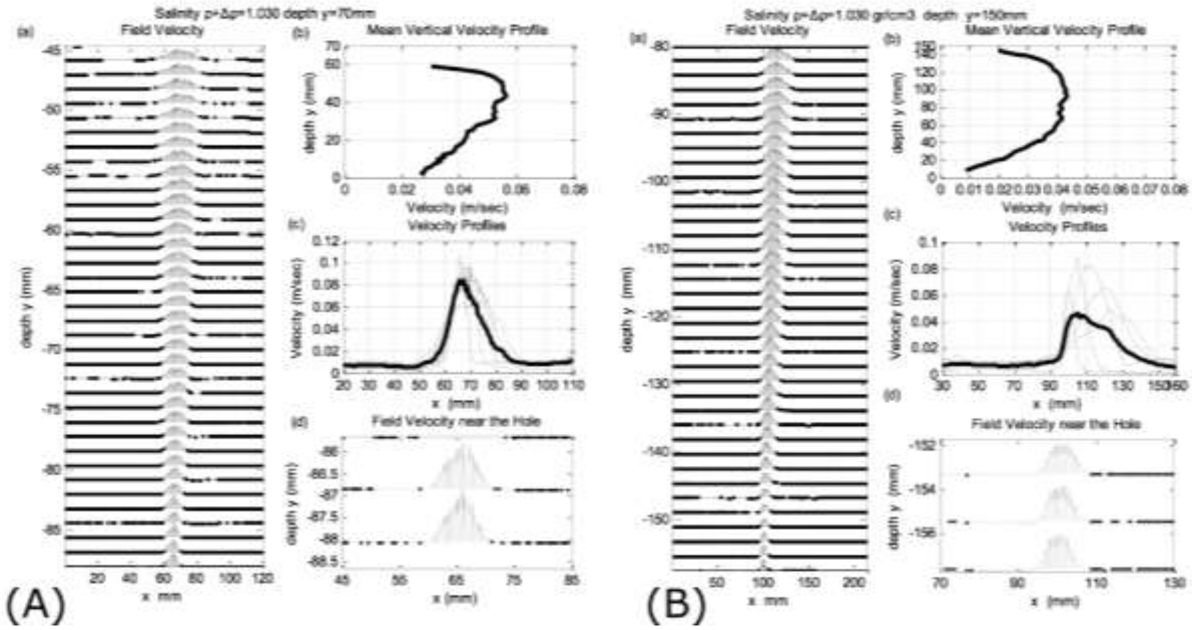

Figure 4: Buoyant jet with ρ_0=1.000 gr/cm^3, salt water with ρ_a=ρ+Δρ=1.030 gr/cm^3 and water depth: (A) y=70 mm, and (B) y=150 mm.

The velocity reduction with the increase of the salt water depth may be attributed to wall effects. The nozzle of the buoyant jet generates large eddies of about the same size, which rise up as spheres in a bounded environment. According to Arsenijević *et al*. (2010), a retardation of the sphere velocity is observed when the sphere-to-width ratio λ is greater than 0.05. For the present study, λ = 0.6/7.5 = 0.08 >0.05 and therefore wall effects may be present. Another reason of the velocity retardation is the proximity to the water surface, because, as the buoyant jet approaches the water surface, its vertical velocity tends to zero and horizontal velocities are developed due to continuity conservation. This phenomenon is evident in the photographs of Fig. 2.

4. Conclusions

The flow dynamics at the centreline of a buoyant jet discharged vertically upwards from a nozzle protruding in salt water of an open channel without flow has investigated. Flow dynamics are influenced by the properties of the jet and the confined ambient fluid, i.e. depth and densities. In particular, we may conclude that:

- The velocity profiles follow a Gaussian distribution, while the axial velocity increases and eventually decreases in the vertical direction.
- Increase of the salt water depth results to a reduction of the flow velocity, due to channel wall effects and the proximity to the free surface.
- The increase of the salt water density results into an increase of the velocity rate, due to the increase of the buoyant forces.

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