MIXING CHARACTERISTICS OF 45º INCLINED DUCKBILL DENSE JETS IN CO-FLOWING CURRENTS

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ABSTRACT

An experimental investigation was conducted using the technique of Planar Laser Induced Fluorescence (PLIF) to examine the mixing characteristics of 45° inclined dense jets from a duckbill shape nozzle in co-flowing currents. The characteristics of duckbill jet, including concentration decay, centreline peak dilution and cross-sectional concentration distribution were investigated. The influence of two mounting orientations of the duckbill nozzle, namely vertical and horizontal, were also analyzed. The experimental results showed that two regimes, namely dense-jet- and co-flow-dominated, can be observed. Comparing to the available results in the literature for inclined circular dense jets, the centreline peak dilution for inclined duckbill dense jets is generally higher. With respect to the mounting orientation, the horizontal induces a relatively higher dilution but also a larger centreline peak height. Thus, the horizontal orientation would be preferable when the cover water depth is sufficient.

Keywords: Inclined dense jet, Planar Laser Induced Fluorescence (PLIF), duckbill valve, co-flows

1. INTRODUCTION

At present, the engineering practice of disposing dense effluents in coastal waters (e.g., from desalination plants or liquefied natural gas (LNG) regasification terminals) is based on discharging as inclined dense jets through submerged outfalls, in order to achieve rapid mixing with the surrounding ambient water within a limited region (i.e. the mixing zone) to meet the environmental requirements (Roberts et al., 2010). In almost all previous research related to inclined dense jets, circular nozzles were adopted as the baseline configuration. However, the implementation of non-return valves, particularly the rubber-made duckbill valves with their slender duckbill shape opening, is now prevalent for the outfall design with dense effluents to prevent the intrusion of ambient waters and suspended sediment into the outfall pipes, particularly during periods of low production for the desalination or LNG plants (Roberts, 2016). With the duckbill nozzle, the discharge velocity distribution at the nozzle exit and hence the momentum coefficient will differ from the circular nozzle. The different distributions will also affect the dilution behaviour, the effect of which has not been comprehensively investigated so far. Duckbill nozzle discharges induce the “axis-switching” phenomenon for the inclined dense jet due to the azimuthal distortion of vortex rings. In the presence of co-flows, the formation and development of the vortex rings will be modified, and the mixing characteristics of the inclined duckbill dense jet can be expected to differ from that in a stationary ambient particularly in strong currents. We note that a few previous studies had reported the mixing behavior of duckbill non-buoyant jets in currents. Lee and Tang (1999) used ADV and LIF techniques to investigate the mixing of non-buoyant duckbill jets in co-flows. Their measurements showed that within 12D, the turbulence intensity is much higher than that of circular jets. Similar conclusions were also drawn by Kuang and Lee (2001) who investigated duckbill non-buoyant jets in co-flows numerically. Other duckbill related previous studies, such as Lee et al. (1998), Lee et al. (2001) and Lee et al. (2004), mainly focused on the flow variation and elastic deformation of the valve. However, studies on the mixing characteristics of inclined duckbill dense jets in co-flowing currents have not been reported so far.

2. EXPERIMENTAL SETUP

Experiments were performed in a towing flume in the Environmental Hydraulics Laboratory at the Nanyang Environment and Water Research Institute, Nanyang Technological University, Singapore. The flume had a dimension of 6.4m (L)×1.0m (W) ×0.7m (H), as shown schematically in Figure 1. A dual-cavity pulsed laser (Dantec Dynamics, Class 4 Nd:Yag, DualPower 50-100 Laser, combined pulse repetition rate up to 100 Hz) was installed on a motorized towing system which can be moved along the flume below its transparent bottom. A high speed Charge-Coupled Device (CCD) digital camera fitted with 570nm low-pass filters (Dantec Dynamics, SpeedSense 1040) was also connected to the towing carriage. The camera can capture at a sampling rate of up to 193 frames per second with 8-bit grayscale and a maximum resolution of 2320×1726 pixels. The discharge nozzle was attached to a constant head tank placed on top of the towing carriage. The constant head tank was elevated at 1.2 m above the nozzle tip to provide the hydraulic driving head for the dense jet discharge. The flow rate was controlled by a solenoid valve and measured by a flowmeter (Yokogawa AXF015G). The towing system was precisely controlled and monitored by a centralized control panel to simulate the current with a constant speed (5 to 150 mm/s).

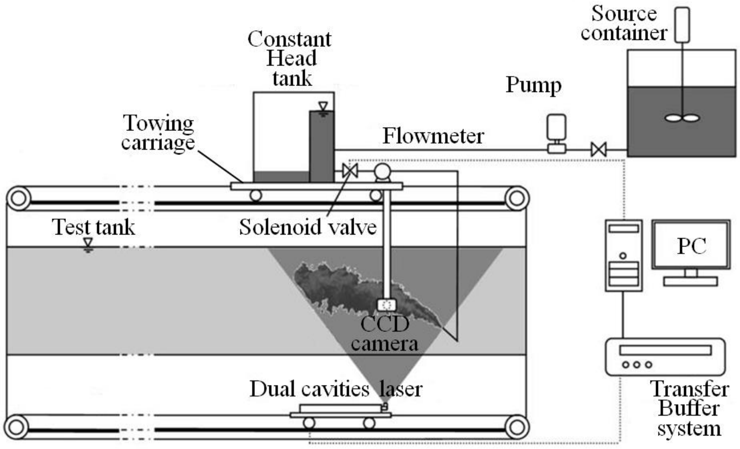

Figure 1 Experimental setup

The duckbill nozzle was fabricated by the laser sintering 3D printing technique, and the nozzle shape was precisely controlled by 3D printer according to Equation (1). Due to the complex geometry of the duckbill nozzle, arrays with curved segments were used to approximate the shape formation. In the present study, the duckbill shape was formed by a circular array consisting of two curved segments. The benchmark curved segment is expressed by:

$$y = m_1 \frac{m_2}{\sqrt{2\pi}} e^{-(\frac{x^2}{m_3})} - m_4, x \in [-a, a] \quad (1)$$

Here, a represented the semi-major axis duckbill shapes, which was equal to 12.5 mm; the coefficients were m1 = 35.4; m2 = 0.2; m3 = 30.0; m4 = 0.1. The open area of the duckbill nozzle used in the experiments was thus fixed at 78.5 mm^2.

Four different flow rates with the corresponding discharge *Fr* = 10, 15, 20 and 25 were generated, and each was tested up to nine different co-flow velocities (with the corresponding nominal Froude number *NFr* = 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 2.5 and 3.0) with the two mounting orientations. Two mounting orientations of the duckbill valve were also investigated in this study. We note that the common practice for the mounting orientation of duckbill valves is vertical at present (Roberts et al., 2010). However, the effect of the orientation on the dilution behavior has not been examined as far as we are aware, and this study hopes to provide more guidance for future designs.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Jet trajectory

Sample time-averaged jet trajectories from the experiments in co-flows are shown in Figure 2 for the case of *Fr* = 10. The jet trajectories in co-flows from the duckbill nozzle with the vertical mounting orientation are close to those from the circular nozzle in Jiang et al. (2019). On the other hand, the trajectories in co-flows with the horizontal orientation are much elevated when the current is weak. The increase in the rise height may be attributed to greater spreading in the minor axis plane (Ho and Gutmark, 1987) of the duckbill nozzle, which reduces the buoyancy difference and slows down the descending process. The difference between the two orientations diminishes under strong co-flows.

To provide specific details on the change in rise height, the non-dimensional centerline peak height (z_m/FrD) are plotted against *NFr* in Figure 3. Same as the previous studies with the circular nozzle, two regimes can be clearly observed from the figure. When the co-flowing current is weak (*NFr* < ~1.0 for vertical and ~ 0.8 for horizontal), the mixing behavior is jet-dominated, with z_m/FrD ~1.0 nearly independent of *NFr* for the vertical orientation, which is consistent with the previous results in stagnant ambient for inclined circular dense jets (Cipollina et al., 2005; Kikkert et al., 2007; Ferrari and Querzoli, 2010; Shao and Law, 2010; Papakonstantis et al., 2011; Lai and Lee, 2012). With larger *NFr* > 1.0, the co-flow becomes dominant, and *zm/FrD* decreases with *NFr* following the relationship of $z_m/FrD = 0.97NFr^{-0.36}$ and $1.00NFr^{-0.38}$ for the vertical and horizontal orientations, respectively. We note that the decrease of the rise height is slightly more than the -1/3 power law suggested by Chu (1975) for the circular nozzle. Finally, the transition between the dense-jet- and co-flow-dominated regimes occurs slightly earlier for the horizontal orientation as noted above. In addition, the centerline peak height for the horizontal orientation is also ~ 5% higher comparatively in weak co-flows.

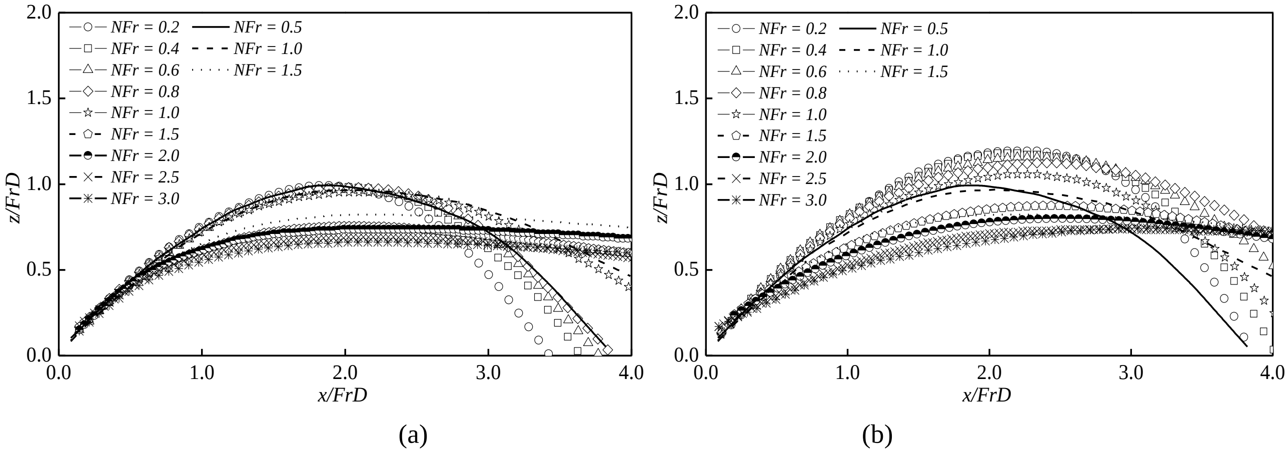

Figure 2 Trajectories for inclined dense jets from duckbill nozzle with (a) vertical and (b) horizontal mounting orientation, Fr = 10. (Solid and dashed lines represent the experimental results of inclined circular dense jet in co-flows from Jiang et al. (2018))

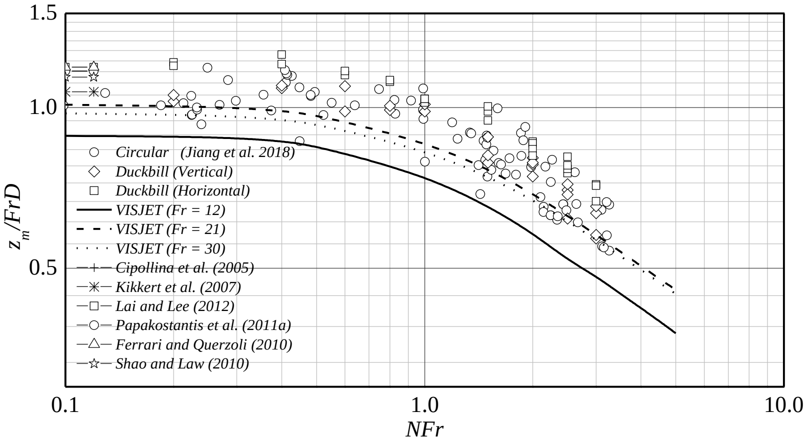

Figure 3 Relationship between zm/FrD and NFr

3.2 Concentration decay

Figure 4 (a) and (b) show the detailed comparison of the concentration decay for the inclined duckbill dense jet with vertical and horizontal orientations, respectively. From Figure 4 (a), the decay rate of the vertical orientation at *NFr* = 0.2 is smaller than the horizontal initially. However, it increases when approaching s/FrD = 1.0, and thereafter c_m/c_0 of the vertical orientation is nearly equivalent to horizontal at s/FrD = 1.2, with the value of 0.36. Further downstream, the decay rate of the vertical decreases which makes c_m/c_0 higher than the horizontal again. In particular, when s/FrD > 2.2, a second increase in the decay rate can be observed for the vertical orientation, which induces a lower c_m/c_0 value. The frequent change in the decay rate of the vertical orientation reveals symbolically that strong axis-switching occurs due to the distortion of the ring-like vortices during the rising and descending stages. Comparatively, the centerline concentration of horizontal mounting orientation in Figure 4 (b) shows lesser changes by the axis-switching process.

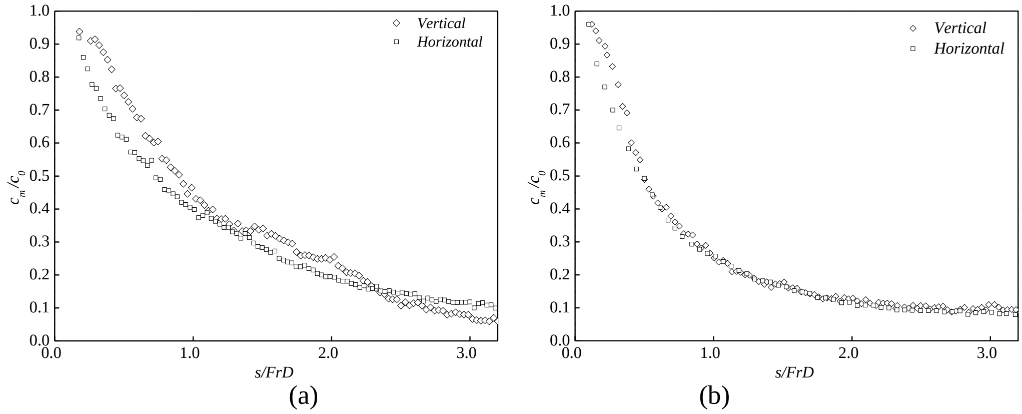

Figure 4 Concentration decay along the centerline with vertical and horizontal orientations at: (a) NFr = 0.2, and (b) NFr = 3.0 (Fr = 10)

4. CONCLUSIONS

The mixing characteristics of 45° inclined dense jets from the duckbill nozzle in co-flows were investigated with two mounting orientations experimentally using the PLIF technique. The results showed that the duckbill nozzle induces higher dilution than the circular nozzle under co-flows, thus the duckbill installation also contributes towards additional mixing of the dense effluent with surrounding waters in addition to preventing ambient intrusion. Two regimes, i.e. dense-jet-dominated and co-flow-dominated regimes, can be observed similar to the circular jet in co-flows, however their transition occurs at smaller *NFr* in general. Comparing the two orientations, the horizontal orientation has a higher rise height and larger dilution comparatively. Thus, based on the present results, the horizontal orientation would be preferable from the dilution point of view if the cover water depth is sufficient, while the vertical orientation can be adopted in shallow waters for full submergence considerations.

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