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Effects of offset height on the turbulent characteristics of a surface attaching jet

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ABSTRACT

The effects of offset height ratio on the turbulent characteristics and evolution of coherent structures in a surface attaching jet issuing from a square orifice nozzle are investigated. The experiments were conducted at four offset height ratios, $h/d = 1$ to 4 and at Reynolds number of 5500 using a particle image velocimetry system. Mean velocities, second to fourth order turbulent moments, as well as the production terms in the transport equations of the Reynolds stresses were used to characterize the flow field. The results showed that reducing the offset height ratio significantly decreases the decay rate in the far field and attenuates the Reynolds stresses and their production terms, especially in the upper shear layer of the jet. However, the surface mean velocity and Reynolds stresses substantially increased beyond the attachment point as offset height ratio decreases. Galilean decomposition, swirling strength and linear stochastic estimation of the velocity fields revealed that the free surface suppresses the growth of the spanwise vortex cores that are generated from the shear layer instability and aligned with the edge of the upper shear layer. Two-point correlations of swirling strength and of velocity fluctuations and proper orthogonal decomposition (POD) were used to examine the influence of offset height ratio on the turbulent structures in the surface attaching jet.

1. Introduction

A turbulent jet interacting with a free surface is encountered in diverse engineering and hydraulic applications such as wastewater discharge into shallow water bodies, purification of water through aerators, and pump jets of ships. The presence of the free surface gives rise to the jet's deflection and attachment, damping of the surface-normal velocity component and enhanced anisotropy at the free surface which complicates the flow physics compared to free jets. Understanding the mixing and turbulent transport phenomena of surface attaching jets is an important step in developing efficient fluid engineering models.

The mixing and turbulent characteristics of free jets have been extensively investigated (e.g., Aleyasin et al., 2017a, 2017b; Fellouah and Pollard, 2009; Ghasemi et al., 2015; Hussein et al., 1994; Manivannan and Sridhar, 2013; Mi et al., 2001; Quinn and Militzer, 1988). Currently, there is intense interest in the measurement of the turbulent characteristics of free jets emanating from non-circular nozzles (e.g., Aleyasin et al., 2017a, 2017b; Ghasemi et al., 2015; Mi et al., 2001; Quinn and Militzer, 1988). These research efforts indicate that non-circular nozzles are a better configuration for enhancing turbulent mixing and momentum transfer when compared to a circular nozzle. It is always speculated that the tendency to enhance mixing can be directly attributed to the dynamics of large-scale organized (or coherent) structures in the free jet which function to entrain ambient fluid into the jet. The coherent structures, often reported as strongly interacting vortex rings and hairpin-like vortices, have been observed in the near field region (Liepmann and Gharib, 1992), transition region (Weisgraber and Liepmann, 1998) and far-field region (Shinneeb et al., 2008) of the jet. In the case of non-circular nozzles, the rapid deformation of the vortex rings leads to enhanced entrainment as well as faster jet spreading in comparison to their circular counterparts (Gutmark et al., 1989).

Despite the large body of literature on the mixing and turbulent characteristics of free jets, far less is documented with regards to surface attaching jets. As shown in Fig. 1, a surface attaching jet is formed when a nozzle of width, d, and exit velocity, U_j, is placed at an offset height distance (h) measured from a free surface to the center of the nozzle so that upon discharge the jet interacts with the free surface. The distance from the center of the nozzle to the solid wall (H) is sufficiently large so that the development of the jet is not influenced by the wall. The streamwise location where the jet attaches to the free surface is

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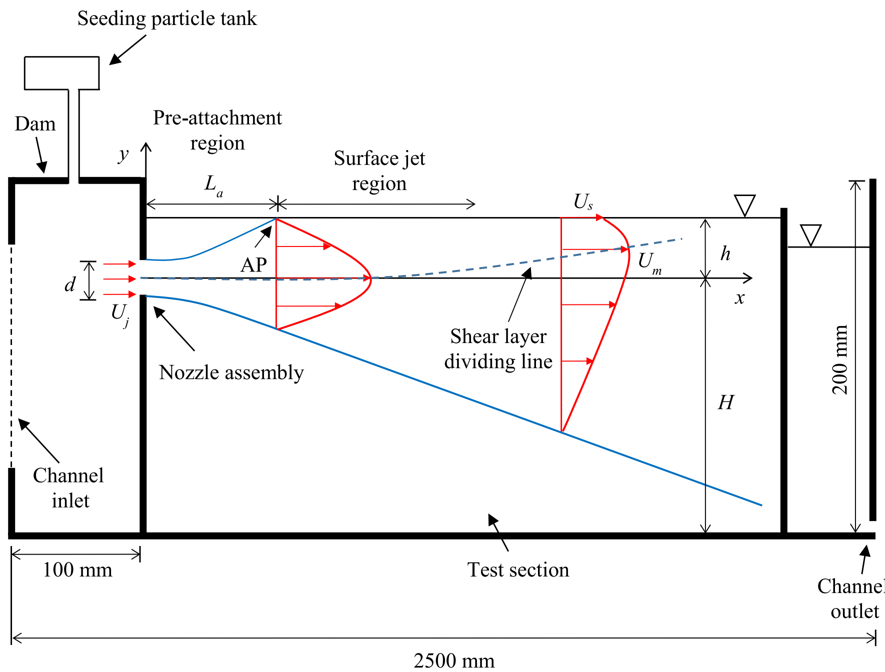

Fig. 1. Schematic diagram of surface attaching jet in the test section.

known as attachment point (AP) and this location increases with increasing offset height ratio (h/d) but decreases with Froude number based on the exit velocity and offset height (Essel and Tachie, 2017). The flow field of a surface jet can be divided into the pre-attachment region which starts from the nozzle exit and ends at the attachment point and the surface jet region which is located downstream from the attachment point. The surface jet region is characterized by non-zero streamwise and spanwise velocities at the free surface. For instance, Anthony and Willmarth (1992) and Walker et al. (1995) reported that the surface-normal velocity fluctuations diminished, while streamwise and spanwise velocity fluctuations were enhanced at the free surface due the turbulent kinetic energy redistribution from the surface-normal stress to the surface-parallel stresses.

The surface attaching jet is a two-shear layer flow separated by a shear layer dividing line which passes through the loci of local maximum streamwise mean velocity, U_m. The shear layer dividing line deflects from the nozzle centerline and moves towards the free surface as the jet develops downstream. The upper and lower portions of the dividing line within the jet flow region are subsequently referred to as the upper and lower shear layers, respectively. Tian et al. (2012) performed particle image velocimetry (PIV) measurements of a surface attaching jet at an offset height ratio of $h/d = 5$. From the analysis of velocity profiles at several horizontal planes, it was found that the lower shear layer is less affected by the free surface compared to the upper shear layer.

Studies related to the effects of initial conditions such as offset height ratio (Madnia and Bernal, 1994; Sankar et al., 2008; Tay et al., 2017) and Reynolds number (Walker et al., 1995) on the characteristics of surface attaching jets have also been reported in the past. However, most of the studies were conducted using single-point measurement techniques such as hot-film anemometry and laser Doppler velocimetry which are more challenging for measuring the surface statistics and examining the large-scale organized structures in the flow. With recent advancements in measurement techniques such as the whole-field PIV, there is the need for refined measurements to characterize the effects of initial conditions on the free surface dynamics, the turbulent transport phenomenon and the coherent structures in the surface attaching jets.

In the present study, a PIV technique is used to perform measurements of single- and multi-point turbulent statistics of a surface attaching jet issuing from a square nozzle at h/d = 1, 2, 3 and 4 and Reynolds number based on U_j and d of $Re = 5500$. The similarity scaling of the mean velocity and turbulence statistics, joint probability density function (JPDF) and two-point correlations of the velocity fluctuations have been reported in a previous paper (Tay et al., 2017). It was found that the influence of the free surface is to substantially reduce the jet spreading rate and streamwise growth of the large-scale structures in the upper shear layer compared to the lower shear layer. The objective of the present paper is to provide more detailed aspects of the turbulence structure of the surface jet with emphasis on the third and fourth order moments, production of turbulent kinetic energy, swirling strength and proper orthogonal decomposition (POD).

2. Experimental setup

The experiments were conducted in an open water channel with length of 2500 mm, width of 200 mm and height of 200 mm as shown in Fig. 1. A brief description of the channel was provided in the previous studies from the same research group by Tay et al. (2017). The channel walls were fabricated from transparent acrylic plates to facilitate optical access. A nozzle assembly was positioned 100 mm from the inlet of the channel and the jet was issued from a square orifice nozzle of width, d = 10 mm and plate thickness of 3 mm. As indicated in Fig. 1, the Cartesian coordinate system adopted has the origin located at the center of the nozzle at the exit plane; x and y represent the streamwise and surface-normal directions, respectively. U, V, u, and v represent the streamwise mean velocity, surface-normal mean velocity, streamwise fluctuating velocity and surface-normal fluctuating velocity, respectively. Four offset height ratios were investigated by adjusting the water depth such that the distances from the nozzle's centerline to the free surface were h/d = 1, 2, 3 and 4. For each experiment, the Reynolds number based on exit velocity, U_j and d were kept constant at $Re = 5500$. The choice of Reynolds number is based on previous investigation that showed the mean flow and turbulent characteristics of the surface jet issuing from the same square nozzle at $h/d = 2$ are independent of Reynolds number for $Re \geq 3700$ (Rahman and Tachie, 2016). The corresponding Froude numbers based on U_j and h were Fr = 1.76, 1.24, 1.01, and 0.88, for h/d = 1, 2, 3 and 4, respectively.