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AN EXPERIMENTAL STUDY OF RECTANGULAR SURFACE JETS

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ABSTRACT

The flow field for rectangular surface jets in a wide and deep water environment was studied using Particle Imaging Velocimetry (PIV) and a Laser Induced Fluorescence (LIF) visualization technique. Laminar and turbulent regimes were considered. Results showed that the jet spread linearly in both vertical and lateral directions. The vertical spreading rate of the rectangular jet was similar to the spreading rate of a plane surface jet. Flow visualization revealed two distinct jet regions with significantly different lateral spreading rates. Only a thin layer close to the surface was spreading at a rate much greater than the vertical spreading rate. Below this thin surface layer the jet was spreading at a rate comparable to the vertical spreading rate. The development and spreading of the thin surface layer appeared to be linked to dynamic interactions of stream wise vortices with the free surface.

Keywords: Rectangular Surface Jets, Flow Visualization, Particle Imaging Velocimetry, Spreading Rate

INTRODUCTION

Surface jets are seen in many engineering applications. They are important in controlling the environmental impact of wastewater discharges into rivers, lakes, and oceans. Mixing and transport of scalars, such as heat, oxygen, and chemical species are governed by the jet characteristics.

Surface jets differ from free and wall jets. In a surface jet, vertical turbulent fluctuations must vanish at the surface. In a free jet however, the mixing lengths are not restricted and remain large at the jet centerline, where the velocity is maximum. In addition, in a surface jet wall shear stresses are not present and turbulent intensities at the free surface boundary are smaller than those of a wall jet. Surface tension may also modify the lateral spreading of a jet at the surface (Anthony & Willmarth, 1992). Furthermore, it can be argued that rectangular jets are different from circular jets. Stream-wise rotating structures are generated at the corners of the rectangular jet-exit, which do not exist in a circular jet (Quinn, 1992).

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EXPERIMENT

The experimental apparatus consisted of a receiving tank, which is 1.30 m long, 0.80 m wide, and 0.40 m deep. Water flowed form a constant head-tank into a 0.40 × 0.25 × 0.25 m jet-tank and was released at the free surface of the receiving tank. The width of the rectangular jet was 56 mm at the exit and its depth, h, was 23 mm in one set of the tests and 28 mm in the other. The Reynolds number, Re, based on the hydraulic diameter, varied from 1350 to 22500. The jets were subcritical at the exit with a Froude number, Fr, less than 0.80. For these conditions there were no surface wave disturbances near the point of discharge.

The jet flow was visualized using a Laser Induced Fluorescence (LIF) visualization technique. A blue argon-ion laser was used to excite the fluorescence dye. Dye was added to the jet tank at a constant rate. A cylindrical lens was applied to produce a 10 mm thick laser sheet, which was oriented either horizontally, parallel to the surface, or vertically, parallel to the jet axis or normal to it. Images formed from fluorescence emission were recorded digitally at a rate of 60 frames per second. The jet flow field in its plane of symmetry was mapped using Particle Imaging Velocimetry (PIV).

RESULTS AND DISCUSSION

Fig. 1.a shows the downstream evolution of the jet vertical half-width, $Z_{0.5}$, for Reynolds number of 11000. The jet vertical half-width is defined as the vertical distance from the surface, at which the mean stream-wise velocity, U, is half of the local maximum mean stream-wise velocity, U_{max}. The line in Fig. 1.a represents a least square fit to the measured points. The virtual origin of this line is located at X/h = -16.6, and its slope is 0.05, which are comparable to the results of Rajaratnam and Humphries (1984). Martinuzzi *et al.* (1998) have also reported a similar jet half-width growth rate for a plane surface jet in a weak co-current. Normalized mean stream-wise velocity profiles are shown in Fig. 1.b.

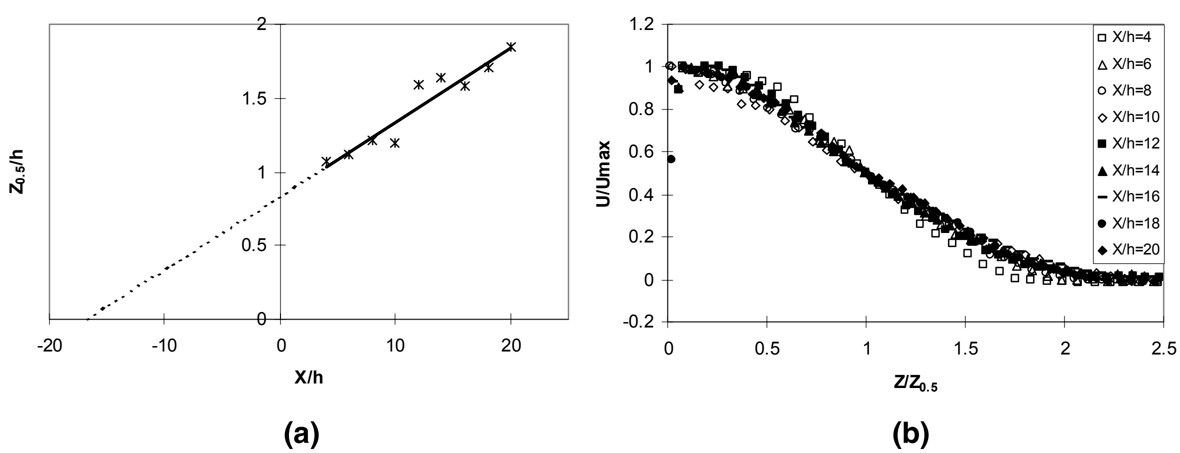

Fig. 1. a. Jet vertical half-width evolution; b. Mean stream-wise velocity profiles

Fig. 2 shows an instantaneous image in the plane of symmetry of the jet at Reynolds number of 10000. The black line in Fig. 2 corresponds to the spreading of the jet half-width, $Z_{0.5}$, obtained from PIV measurements (Fig. 1.a). The white line shows the development of $Z_{0.02}$, assuming Gaussian velocity profiles ($Z_{0.02}$ = 2 $Z_{0.5}$). The white line in Fig. 2 can be seen to define the boundary of the jet well.

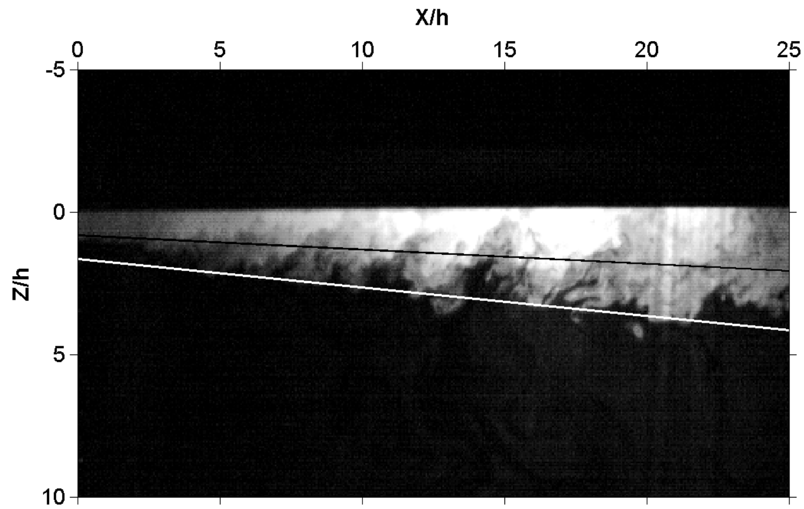

Fig. 2. Profile of the turbulent jet at its plane of symmetry

Figures 3.a and 3.b show instantaneous images of the jet at Reynolds number of 10000 obtained with horizontal laser sheets centered 14 mm and 5 mm below the surface respectively. The black and white lines shown in Fig 3.a are identical to the lines shown in Fig. 2. Again, the white line appears to define well the jet boundary below the surface. This would suggest that at some distance below the surface, vertical and lateral spreading rates are similar, which is the characteristic property of a free jet. Near the free surface, however, as shown in Fig. 3.b by the dash-dot line, the jet boundary spreads laterally with a slope of 0.45, which is four and a half time greater than the vertical spreading rate.

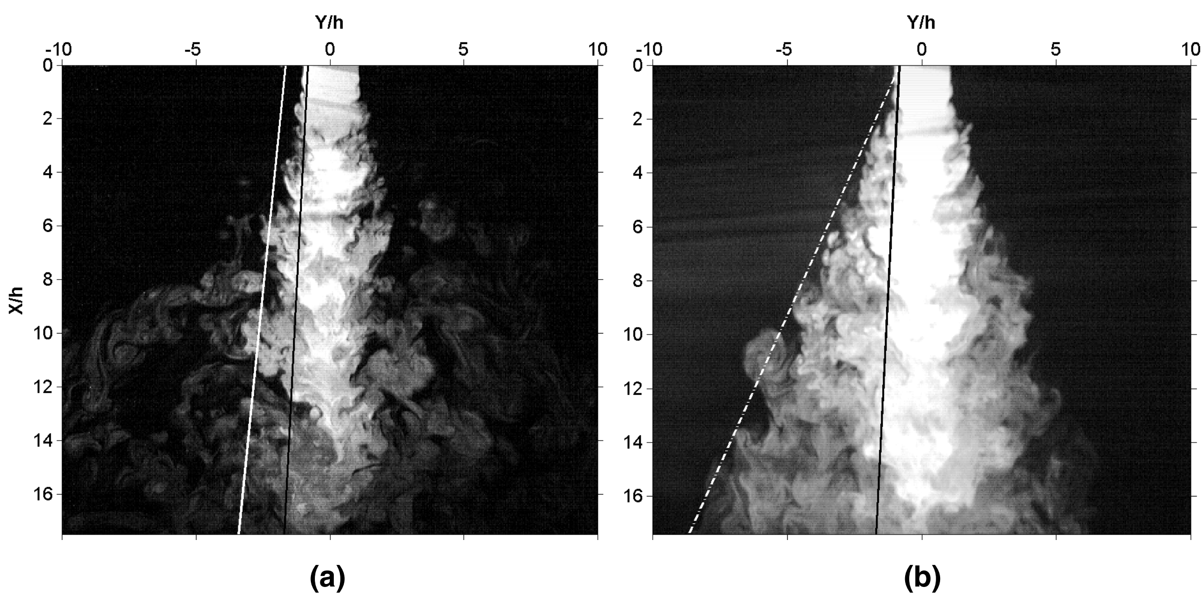

Fig. 3. Plan views of turbulent jet a. 14 mm below surface; b. 5 mm below surface

Figures 4.a and 4.b. show cross-section images of the jet at Reynolds numbers of 10000 and 1350, respectively, in a plane positioned at X/h = 20. The free surface in these images is at Z/h = 0. What is seen above this level is a reflection. Time sequences of the image shown in Fig. 4.a indicated that stream-wise vortices entrained fluid and pumped it outward away from the jet, forming a thin layer at the surface of water. This thin layer spread laterally faster than the jet fluid below. Clockwise rotating structures pumped the fluid to the right of the jet and counterclockwise rotating structures pumped it to the left. The pumping to the left or right occurred alternately and did not seem to be periodic. This behavior was not observed in the time sequences of the laminar jet image (Fig. 4.b), suggesting that the thin surface layer generated at a higher Reynolds number (Fig. 4.a) resulted from a transfer of energy from diminishing vertical velocity fluctuations to cross-stream velocity fluctuations. Anthony & Willmarth (1992) and Walker *et al.* (1995) have reported a similar phenomenon for round jets issuing beneath a free surface. The authors believe that stream-wise vortices generated at the corners of the rectangular jet exit can also contribute to this lateral spreading. This will be the subject of a future investigation.

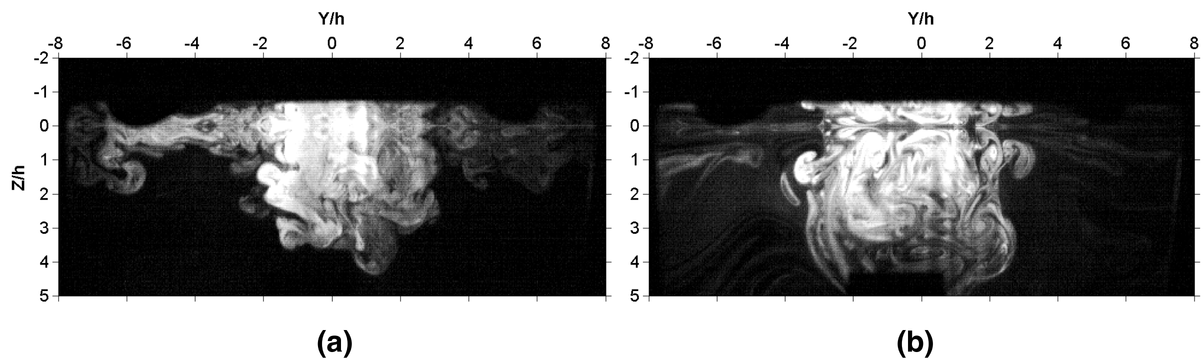

Fig. 4. Cross-stream views of a. turbulent jet (Re=10000); b. laminar jet (Re=1350)

No significant difference between the results for the jet at Reynolds number of 22500 and the jet at Reynolds number of 10000 was observed.

CONCLUSIONS

Rectangular surface jets were investigated using Particle Imaging Velocimetry (PIV) and a Laser Induced Fluorescence (LIF) visualization technique. Results have shown that the jet spreads linearly in the vertical and lateral directions. Below a thin surface layer, the lateral and vertical spreading rates of the turbulent jet were of similar magnitudes. However, at the surface a thin layer of flow diverged laterally away from the jet with a spreading rate approximately four and a half time greater than the vertical spreading rate. This layer appears to be the result of dynamic interactions of stream-wise rotating structures with the surface.

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