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TURBULENCE MEASUREMENTS IN A RECTANGULAR SURFACE JET

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ABSTRACT

The flow field for a rectangular surface jet in its plane of symmetry was studied using a two component Laser Doppler Velocimetry (LDV) system. Turbulent regimes with two different Reynolds numbers were considered. Measurements of mean and r.m.s. velocity components and Reynolds shear stress were carried out at several downstream locations. The results showed that after an initial development, the jet reached a self-similar state in both cases. The growth rate of the jet in the self-similar region was about half the growth rate of a plane surface jet. At the surface, the energy from diminishing vertical velocity fluctuations was transferred to the other components of the fluctuations. This led to the development of a thin surface layer, whose lateral spreading rate was much higher compared to the bulk of the jet fluid below.

Keywords: Surface Jets, Turbulence Structure, LDV Measurements

INTRODUCTION

Surface jets are relevant to many engineering applications, ranging from remote sensing of the wake of a ship to anticipating the environmental effects of the discharge of pollutants into rivers, lakes, and oceans. It is important to understand the structure of the jet because it determines its interaction with the surrounding fluid. Mixing and transport of scalars, such as temperature, oxygen, and chemical species are governed by the jet turbulence characteristics.

Surface jets differ from free jets and wall jets in many critical aspects that control transport and diffusion. In a free jet, the mixing lengths are not restricted and remain large at the jet centreline. In a surface jet however, vertical turbulent fluctuations diminish at the surface and mixing lengths decrease accordingly. Wall shear stresses are not present in a surface jet and as a result, turbulent intensities at the jet boundary are smaller compared to 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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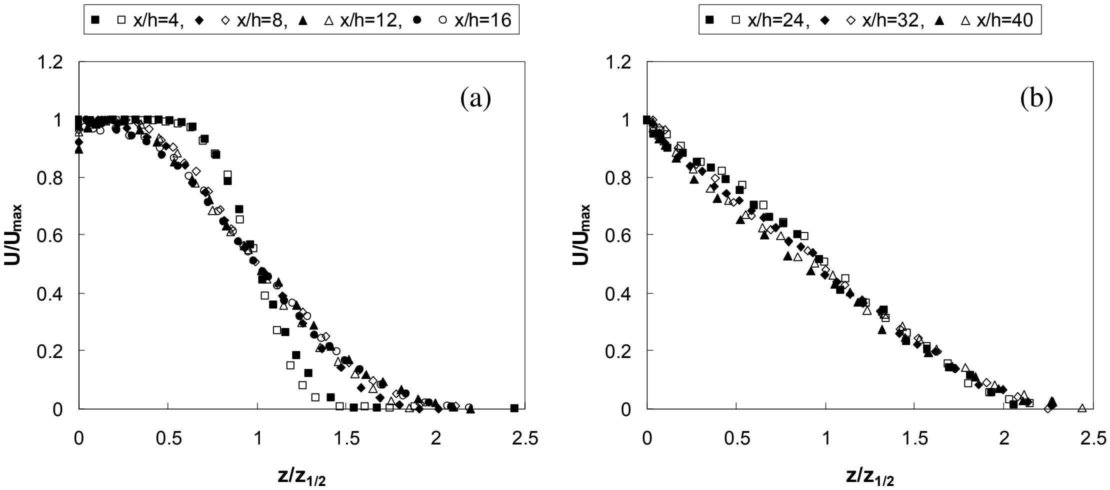

Fig. 1. Mean stream-wise velocity profiles

EXPERIMENT

The experimental apparatus consisted of a receiving tank, which was 1.30 m long, 0.80 m wide, and 0.40 m deep. Water flowed from 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 25 mm at the exit and its depth, h, was 13 mm. A pump circulated the flow to keep the fluid properties and the seeding uniform through out the apparatus. Two jets with different Reynolds numbers were investigated: one with a Reynolds number of 4500 and the other with a Reynolds number of 9000. Reynolds numbers were calculated based on the jet hydraulic diameter. In both cases, the flow at the jet-exit was sub-critical. Froude numbers were calculated based on the depth of the jet.

The measurements were done using a TSI two-component Laser Doppler Velocimetry system. Vertical velocity profiles in the jet plane of symmetry were measured at seven downstream locations: x/h = 4, 8, 12, 16, 24, 32, and 40. Swean Jr. et al. (1989) discussed that a plane surface jet is not influenced by confinement up to a downstream distance equal to the total depth of the surrounding fluid. With this criterion, this jet would have remained unaffected by the bottom wall of the receiving tank up to the last downstream location, at which the measurements were done.

RESULTS

Fig. 1 shows mean stream-wise velocity profiles for both low Reynolds number and high Reynolds number cases. Velocity is normalized by the maximum local velocity, U_{max}, and depth is normalized by the local jet half-width, $z_{1/2}$, the depth at which the velocity is equal to the half the maximum local velocity. Similar to a plane surface jet (Martinuzzi et al., 1998), three distinct regions can be identified: (i) a potential core at x/h=4, where the jet is characterized by an almost uniform profile; (ii) a development region between x/h=4 and x/h=16, where the profiles can be approximated by a hyperbolic distribution, similar to free jets; and (iii) a fully-developed region beyond x/h=16, where the profiles are almost linear, resembling shear layers (Schlichting, 1979).

It can be shown from conservation of momentum that there exists a similarity solution for a three dimensional surface jet, if the jet maximum local velocity is inversely proportional to the downstream distance. Development of the maximum stream-wise velocity with downstream distance for both cases is shown in Fig. 2.a. Velocities are normalized by the velocity at the jet-exit, U_0, for each case. The velocities gradually approach and then beyond x/h=16 follow the line:

$$\frac{U_{max}}{U_0} = 13\left(\frac{x}{h}\right)^{-1} \tag{1}$$

This indicates that the jet is self-similar in the fully-developed region, as it is seen in Fig. 1.b.

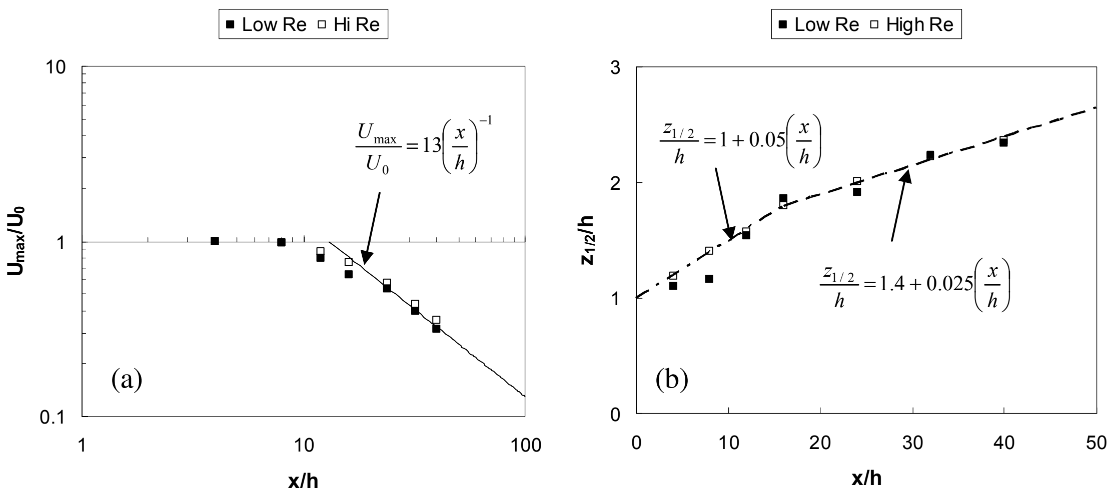

Fig. 2. Downstream development of:
a) maximum stream-wise velocity; b) jet half-width

Fig 2.b shows the development of the jet half-width with downstream distance for both cases. In the development region, the jet grows initially with a rate of 0.05, which is similar to the growth rate of a plane surface jet reported by Martinuzzi et al. (1998). This is also consistent with the results from flow visualization (Gholamreza-Kashi et al., 2003). In the fully-developed region however, the growth rate reduces to 0.025. This is believed to be the result of formation of a thin layer of fluid at the surface. This surface layer was observed to spread laterally at a much higher rate than the bulk of the jet fluid below (Gholamreza-Kashi et al., 2003), at the cost of the growth of the jet in the vertical direction.

r.m.s. stream-wise and vertical velocity profiles in the fully-developed region for both cases are shown in Fig 3.a and 3.b, respectively. These profiles also show self-similarity. At the surface, while vertical velocity fluctuations diminish (Fig. 3.b), stream-wise velocity fluctuations increase (Fig. 3.a). This confirms that at the surface, the energy is transferred from diminishing vertical velocity fluctuations to the other components of fluctuations (Walker et al., 1995). Normalized maximum r.m.s. stream-wise velocity is about 0.25, compared to 0.20 for a plane surface jet (Martinuzzi et al., 1998).

CONCLUSIONS

Two-component LDV measurements were carried out in the plane of symmetry of a rectangular surface jet. Turbulent regimes with two different Reynolds numbers were investigated. Mean and r.m.s. velocity components and Reynolds shear stress were measured at several downstream locations. The jet reached a self-similar state after an initial development. The growth rate of the jet in the self-similar region was about half the growth rate of a plane surface jet. Vertical component of the turbulence fluctuations were diminished at the surface and their energy was transferred to the other components. This is believed to be the cause behind the formation of a thin surface layer, which is observed to have a much higher lateral spreading rate than that of the bulk of the jet fluid below.

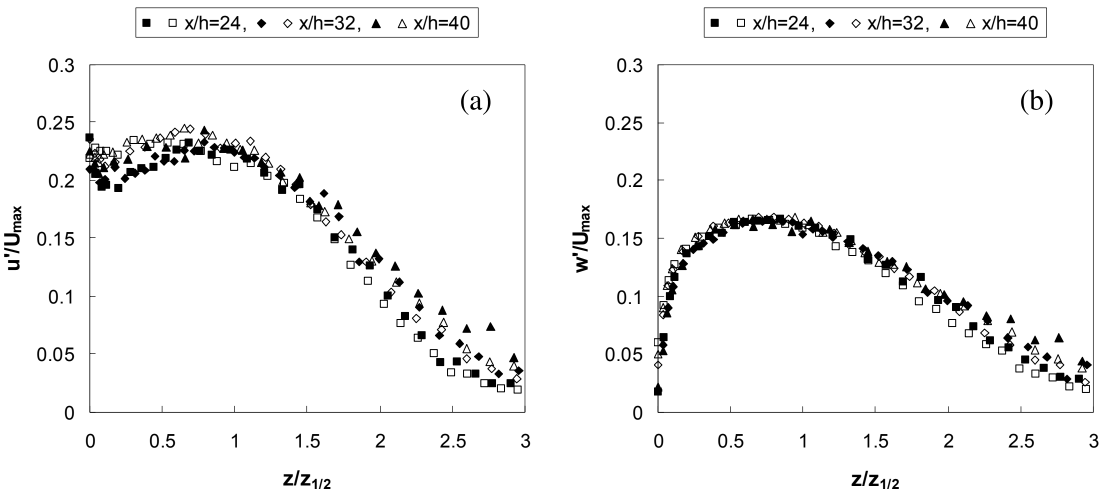

Fig. 3. Profiles of: a) r.m.s. stream-wise velocity; b) r.m.s. vertical velocity

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