Interaction of Coherent Structures with the Free Surface in Rectangular Surface Jets

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1. Introduction

Surface jets are seen in many engineering problems, ranging from remote sensing of ship wakes to anticipating the impacts of discharging liquid waste into the environment. Rectangular surface jets are of particular interest in environmental engineering, where liquid waste is discharged using channels with rectangular cross-section.

There has been considerable experimental research on submerged circular jet interacting with the free surface [1, 2, and 3]. Similarity of the turbulence structure of the submerged jet to that of a ship wake has made it a suitable subject in remote sensing studies [1]. In most of these studies, the measurements have been done as far as a short distance downstream of the point where the jet reached the free surface. As shown in [4], at this location the jet would have still been in a developing stage. In contrast, in the present study the rectangular surface jet is immediately released at the free surface. This allows the study of concurrent development of the jet below and at the surface, while the jet reaches a fully-developed stage in a shorter downstream distance [5].

In this paper, the coherent structures in a rectangular surface jet are studied. The relationship between the origin of the surface current and the interaction of these structures with the free surface is investigated.

2. Experiment

The experimental apparatus consisted of a jet chamber, a test section, and an end section incorporated to minimize the confinement effects. Water flowed from a constant head tank to the jet chamber, where it was converged and released at the free surface of the test section. The Reynolds number based on the jet hydraulic diameter was about 4500, and the Froude number based on the height of the jet at the exit was about 0.9.

LIF flow visualization was carried out to qualitatively observe the macroscopic behaviour of the jet. An Argon-Ion laser was used to excite the fluorescence dye. Images formed were recorded at a rate of 60 Hz using a CCD camera. PIV measurements were done to identify and investigate the coherent structures in the flow. To obtain the mean flow field 1200 frames, which were sampled at a rate of 1 Hz, were averaged. The instantaneous flow field was sampled at a rate of 15 Hz. Details of the experimental procedures are described in [4].

3. Results

Figure 1 shows the visualization of the flow in a cross-stream plane at a downstream distance of $x/h = 16$, where h is the height of the jet at the exit. At the free surface, a thin layer of flow is observed, which has spread far beyond the bulk of the jet below. This layer is called the 'surface current' and was shown by [1]. A theory is developed by [3] and [7], where the turbulence anisotropy near the free surface is thought to be the origin of the surface current.

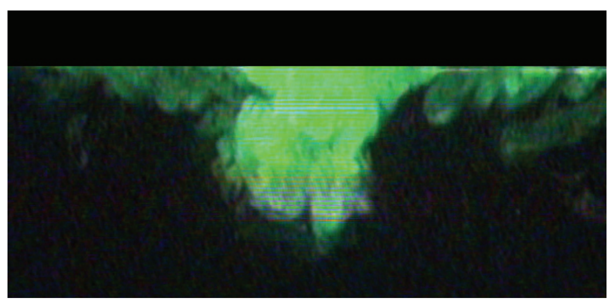

Fig. 1. Flow visualization in a cross-stream plane at $x/h = 16$

Time sequences about the image shown in Fig. 1 show that stream-wise vortices formed at the shear layer entrain the fluid from sides and below, and move toward the free surface. As a result of interaction of these structures with the free surface, the fluid is ejected laterally away from the jet. This ejection occurs alternately to the left and right in a cyclical but non-periodic fashion, forming the surface current. Therefore, the surface current cannot be simply originated from the turbulence anisotropy near the free surface.

Two-dimensional mean velocity vectors and vorticity contours (vertical and lateral components) in cross-stream planes at *x/h* = 16 and 32 are shown in Fig. 2. At *x/h* = 16, where the jet is developing [5], two stream-wise counter-rotating vortices are detected. These vortices are the result of averaging many structures seen in the instantaneous flow field, which are distributed in both side of the jet centre. Near the edges, the flow moving toward the free surface is forced to diverge and move laterally, forming a 'splat' even [8]. To balance the flow approaching the free surface, at the centre the flow leaves the free surface, forming an 'anti-splat' event [8].

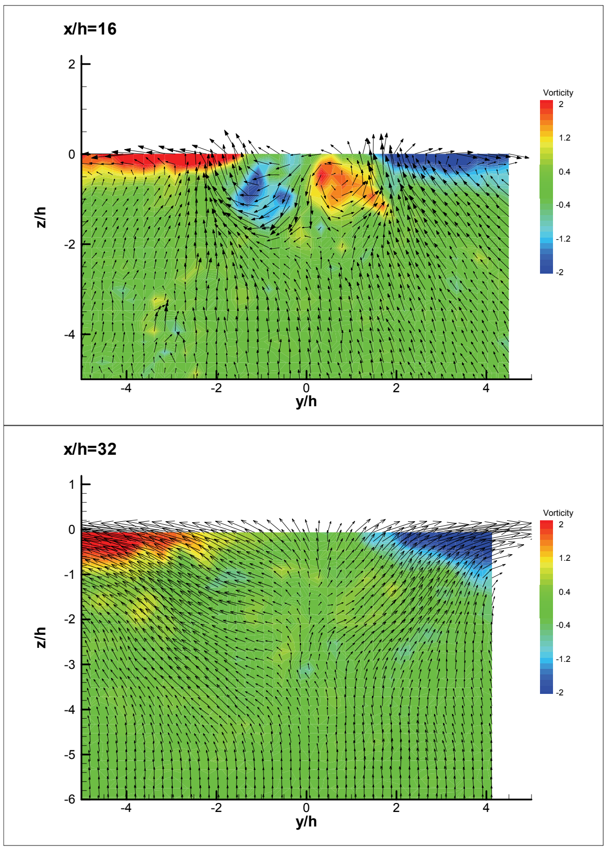

Fig. 2. Mean velocity and vorticity fields (V, W) at *x/h* = 16 and 32

Further downstream, at *x/h* = 32, where the jet is developed [5], there is no trace of those counter-rotating vortices in the mean flow. This is because the vortices that persist downstream are randomly distributed in time. Sometimes they join together, and sometimes, as observed in the instantaneous flow field in a horizontal plane at the surface (stream-wise and lateral components) and shown by [8], they reorient normal to the surface and attach to the free surface. As a result, in the mean flow field the fluid is vertically entrained into the jet and is laterally ejected at the free surface.

In an investigation of buoyant surface jets [9], after the turbulence was suppressed by buoyancy, at the edges of the jet ring vortices or fronts were observed that continued to get their energy from stretching along their axis as they spread at the surface. The stream-wise structures observed here are most likely parts of these ring vortices that are generated at the shear layer.

4. Conclusions

A rectangular surface jet is investigated using LIF visualization and PIV measurements. The results show that ring vortices or fronts are formed at the shear layer, and while entraining the ambient fluid, move toward the free surface. After reaching the free surface these vortices stretch along their axis, ejecting the entrained fluid laterally away from the jet. This mechanism creates a thin layer of flow at the free surface, which spreads far beyond the bulk of the jet below, called the 'surface current'.

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