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Contribution of large structures to the anisotropic spread rate in a wall jet issuing from a round nozzle

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Introduction

It has long been known that coherent structures play an important role in the mixing and entrainment processes in turbulent flows. There are few flows, though, where their effect is as evident as in the three-dimensional wall jet exiting from a round nozzle (*cf* figure 1). After evolving for a short distance from its exit ($\approx 10 - 15D$, where D is the jet diameter), this flow undergoes a rather sudden transition to a flow that spreads significantly faster ($4 - 5$ times) in the direction parallel to the wall than in the direction normal to the wall. Somewhat surprisingly, this highly anisotropic spread rate is sustained into the far field and seems to be a feature of the fully developed wall jet (*v* figure 2). Launder and Rodi (1983) argued, using the equations of motion, that the large lateral growth rate is caused by the production of mean streamwise vorticity in the wall jet. They were not able, however, to identify the mechanism that produced the vorticity with the available measurements.

Recently, Matsuda *et al.* (1990) attempted to identify the mechanism that produced the streamwise vorticity using conditional averages of the lateral velocity component, w. Their measurements suggest that the base of the vortex ring structures produced by the round jet were retarded by the wall. As a result, the bottom part of the ring turns towards the wall causing the formation of streamwise vorticity near the wall. Matsuda *et al.* (1990) suggested that this was the mechanism that produced the large lateral spread rate in the wall jet.

The measurements reported by Matsuda *et al.* (1990) were confined to the very near field of the jet, $0 < x/D < 3$, which is before the region where the large lateral growth rate is normally observed in experiments. Thus, an obvious question to ask is whether this structure undergoes a further transition before it is capable of producing the large lateral growth spread observed in the experiments. Launder and Rodi (1983) also argued that the structure of the streamwise vorticity causing the large lateral growth rate in the far field is different from that in the near field. They speculated, though, that these structures in the far field may, in fact, be related to those in the near field even though the two differ. A similar idea has also been purposed by George (1989) and Ewing (1995) who argued that equilibrium state of turbulent flows may be influenced by the initial conditions of the flow due to the persistence of coherent structures produced in the near field.

The objective of this research is to identify how the large structures (and their role in causing the lateral spread rate) changes as the three dimensional wall jet evolves downstream. This is accomplished using flow visualization and hot wire measurements in the region $0 < x/d < 20$.

Scope of the Investigation

The research is being carried out using the three-dimensional wall jet facility at Queen's University. In this facility, the flow is conditioned in a settling chamber before it passes through a nozzle with a $25 : 1$ area contraction ratio and exits through an 2.8 in. diameter exit. The exit is mounted on a large backplane ($\approx$ 4 ft. x 8 ft.) the nozzle outlet (*v.* figure 1). The wall the jet develops on is 6 ft. in length and 8 ft. wide ($\approx$ 25 D x 35 D, where D is the diameter of the nozzle exit). The resulting flow can be sampled using hot-wire probes mounted on a three-dimensional traverse.

Initially, flow visualization was used to investigate the the dynamics of the large structures in this flow. In this investigation, the flow entering the settling chamber was seeded with CO_2 gas produced by boiling dry ice. Care was taken to ensure that the exit velocity was sufficiently large so that buoyancy did not play a role in the flow's evolution. The Reynolds number of the flow based on the outlet velocity and diameter was approximately $25,000$. The dynamics of the flow were examined by illuminating different planes in the flow using a laser sheet. The resulting images were captured using a video recorder with a framing speed of 60 frames/s and an aperture opening time of $1/125s$. A video capture board was then used to import these images into a PC.

The visualization of the wall jets spread in the near and intermediate field ($\approx x/D < 10$) are shown in figure 3. The first image in figure 3 shows the $x - z$ plane, parallel to the wall, $\approx 0.1D$ above the wall, while the second image shows the $x - y$ plane, normal to the wall, on the centerline of the jet. The disparity in the growth rate is evident in these figures. The cause of the large lateral growth rate can be seen more clearly be observing the images on the $x - y$ plane at $x/D = 6, 10$, and 14 shown in figures 4, 5, and 6. It is clear from the first image in these figures that the lateral growth rate is caused by flow being ejected laterally near the wall. It is interesting to note that the width of the ejections is increasing as the flow evolves downstream. Another interesting feature is that the flow is not continuously ejected laterally. Instead, the ejections appear to occur quasi-periodically even at $x/D = 14$. The second images in figures 4, 5, and 6 are typical examples of the flow when the fluid is not being ejected at the base of the flow. In all case, the flow is rounder than the realizations when the flow is being ejected. Of course, it is only possible to draw qualitative conclusions about the flow based on visualization techniques because it is not possible to see the entrained flow.

Thus, the next step in this investigations is to make hot wire measurements of the flow. Mean velocity and Reynolds stress measurements have been carried out in a related investigation of this flow for two cases where the base of the nozzle is elevated a distance of $x/D = 0.5$ and $x/D = 1/5$ above the wall. These measurements have not, as yet, been carried out for the case of interest in this investigation; *i.e.*, where the base of the nozzle is on the wall. This case will be explored in detail as part of this investigation.

Two different technics will then be used to examine the evolution in the structures in the intermediate field. Firstly, the two-point, two-time correlation, which is given by

$$R_{i,j}(\mathbf{x}, \mathbf{x}', t, t') = \overline{u_i(\mathbf{x}, t) u_j(\mathbf{x}', t)}, \tag{1}$$

will be measured to examine how the inclination angle of the structure relative to the wall evolves as the flow evolves downstream. Following the arguments of Lumley (1970), it should be possible to deduce information about the dominant structures in the flow using the two-point, two time correlation. For example, it should be possible to estimate the inclination angle of the dominant structure in the by examining the distribution in the time delay, $\tau = t - t'$, of the peak in the two-point, two-time correlation across the layer.

The shape of the structures will also be examined by measuring the conditionally averaged field (*cf* Matsuda *et al.* 1990 or Hayakawa and Hussain 1989). The quasi-periodic nature of the flow even at a distance of $x/D = 14$ suggest it should be possible to produce a fairly accurate image of the structure using this approach. It may be necessary, however, to use a local trigger in order to prevent a loss of information due to phase jitter between the signal detected near the nozzle outlet and the downstream location. The flow visualization suggests that the flow being ejected near the wall should provide a suitable triggering event if the vortex ring can not be detected at the top of the flow. (*i.e.*, along the entrainment boundary).

One of the advantages of using both these technics is that they are complementary so they should yield consistent measures of the structures. The former is independent of phase jitter but yields less detailed information about the structure than the latter. Thus, the information from the two-point, two-time correlation should provide a objective check of the detailed information deduced using the conditional average.

Summary

Flow visualization technics and hot-wire measurements will be used to examine the evolution of the vortical structures in the three dimensional wall jet that cause the large anisotropy in the lateral and normal spread rates. This information will be used to examine the mechanisms that sustain the motions causing the large lateral growth rate and to examine the transition from the near field structures to the far field structures. This measurements will also be used to determine if the structures in the far field are, in fact related to those occurring in the near field.

Acknowledgements

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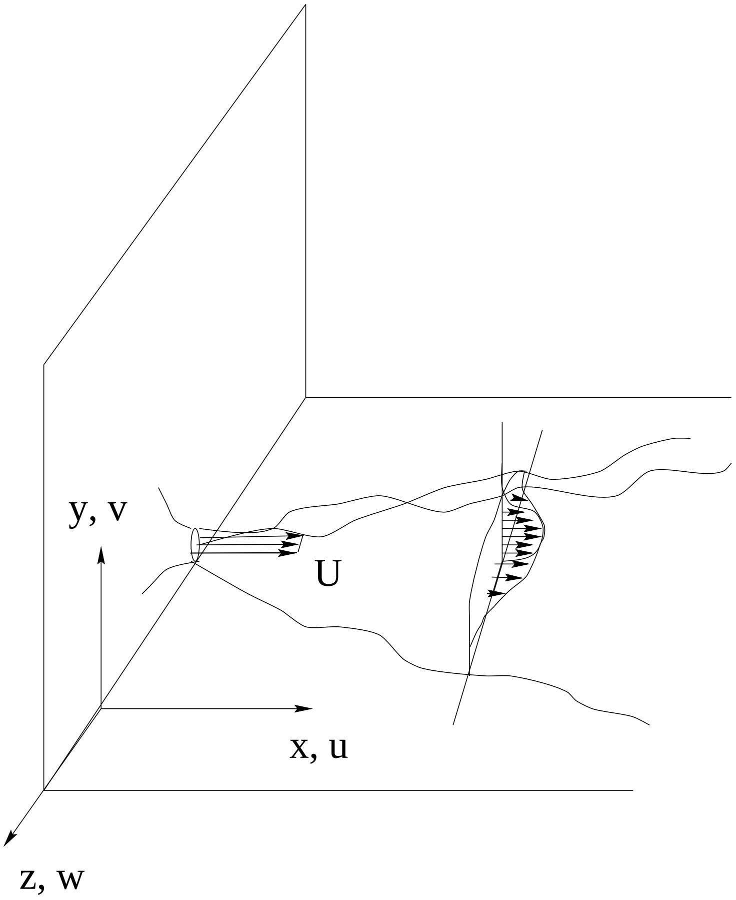

Figure 1: Schematic of the three-dimensional wall jet issuing from a round nozzle.

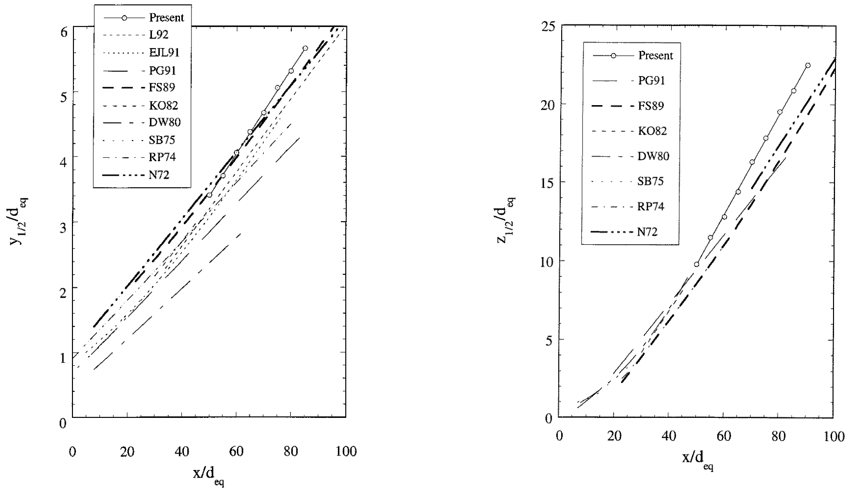

Figure 2: Typical growth rates of the three-dimensional wall jet in the far field (Abrahamsson, *et al.*, 1996). (a) distance between the point of peak velocity and the outer half-velocity point in the vertical direction (b) distance between the point of peak velocity and the half-velocity point in the lateral directions.

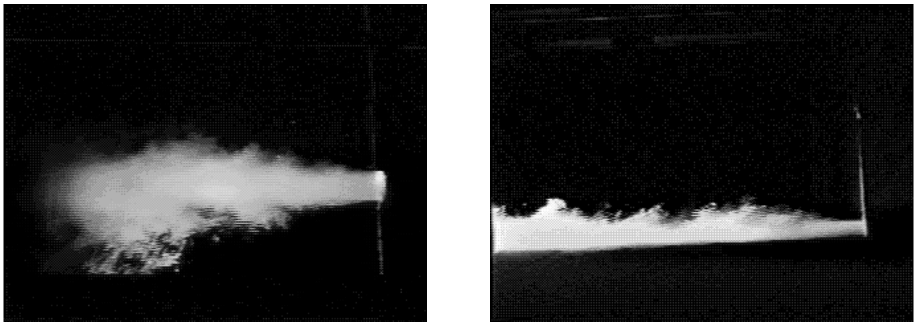

Figure 3: Visualization of the growth rates of the wall jet (a) $x-z$ plane parallel to the wall $\approx 0.1D$ above the wall (d) $x-y$ plane normal to the wall along the centerline of the jet.

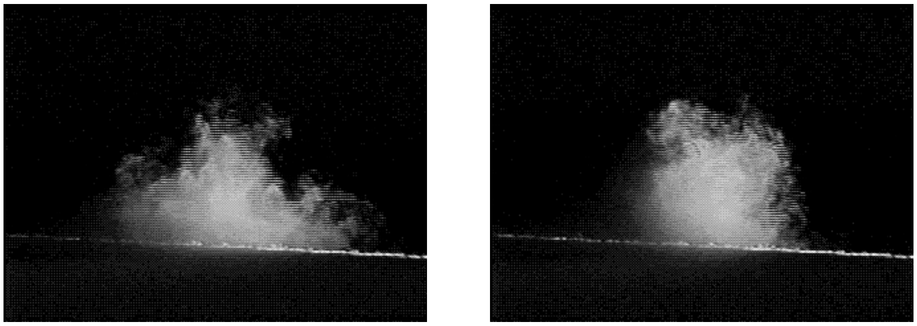

Figure 4: Visualization of flow structures on a $y-z$ plane at $x/D=6$ (a) during a phase where flow is being ejected near the wall (b) during a phase without significant flow ejection.

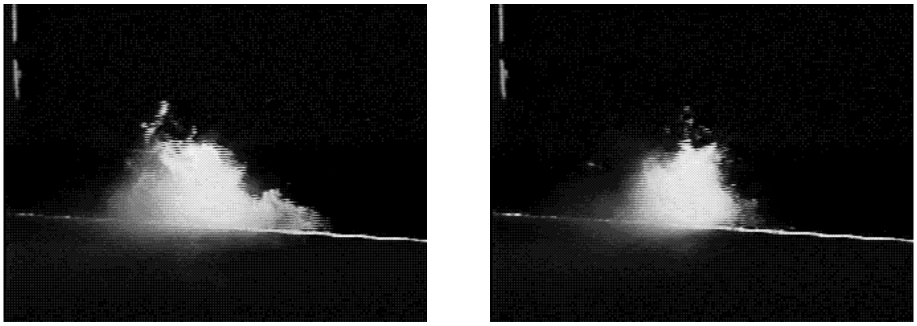

Figure 5: Visualization of flow structures on a $y-z$ plane at $x/D=10$ (a) during a phase where flow is being ejected near the wall (b) during a phase without significant flow ejection.

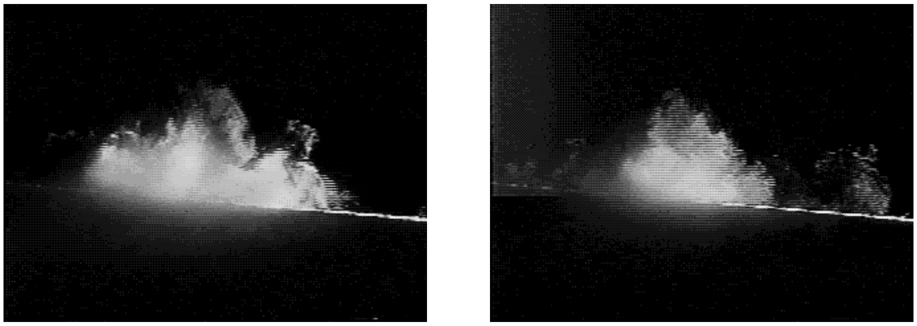

Figure 6: Visualization of flow structures on a $y - z$ plane at $x/D = 14$ (a) during a phase where flow is being ejected near the wall (b) during a phase without significant ejection.