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THE VELOCITY FIELD OF A RECTANGULAR WALL JET

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ABSTRACT

The three dimensional near field of a rectangular (10:1) jet issuing parallel to a plane wall has been investigated experimentally. Complete maps of the mean and fluctuating velocity, including Reynolds stresses have been obtained using hot wire anemometry. These data reveal that in the near field, the flow is dominated by a complex interaction of vortices, the existence and stability of which are explained by boundary layer interaction in the settling chamber and perturbed Taylor vortex array arguments, respectively. The data show that outside the near field, complete symmetry of the flow is recovered.

INTRODUCTION

Unique features of the flows from rectangular sharp-edged orifices are the development of a *vena contracta* in the lateral YZ-plane and the formation of streamwise saddle-shaped velocity profiles. These velocity distributions are most pronounced beyond the initial development region of the flow (i.e. in the characteristic decay region). Why the velocity irregularities develop has not yet been conclusively identified, although it has been suggested by the present authors Pollard and Schwab (1988), Schwab (1986) and Schwab and Pollard (1985) that they are due to boundary layer interaction inside the settling chamber.

Detailed accounts of work on three-dimensional wall jets from various exit geometries can be found in Launder and Rodi (1981, 1983). While free shear flows originating from rectangular, sharp-edged nozzles (particularly those of aspect ratio 10) have been studied to some extent, the corresponding wall jet has received only limited attention (Viets and Sforza, 1966 and Sforza and Herbst, 1967).

This paper presents the experimental investigation of a three-dimensional wall jet issuing from a rectangular sharp-edged orifice of aspect ratio 10. Complete maps of the mean velocity vector, the turbulence intensities and two of the Reynolds shear stresses are provided covering the near and far fields of the flow. Hot-wire measurements at 20 streamwise locations extending up to 200 slot heights downstream were carried out to overcome the limitations of previous investigations.

The present contribution aims at both documenting this type of wall bounded flow as well as gaining insight into the driving mechanism for the *vena contracta*, the saddle-backed velocity profiles and how they are affected by the presence of a wall.

THE EXPERIMENTS

Air was passed through flow straightening devices (baffle, honeycomb and screens) in order to attain a uniform velocity profile at the jet exit plane. After discharge through a rectangular, sharp-edged orifice the jet developed into the stagnant surroundings along a flat plate. The slot height, h, measured 7mm. The experimental apparatus was enclosed by a double layer of mesh wire screens (excluding the downstream end) to prevent room draughts from influencing the flow. The exit Re_h=23,000. See Pollard and Schwab (1988) and Schwab (1985) for further details.

The origins of the coordinate axes (x/h=0 and y/h=0) were defined at the geometric centre of the orifice. The z/h=0 position was chosen at the wall surface. The streamwise mean velocity at the location y/h=0 and z/h=1.3 (displacement of geometric nozzle centre from the wall) served as a datum for non-dimensionalisation of all measured instantaneous velocities at any one streamwise x/h location.

MEASUREMENT RESULTS

The evolution of the mean axial flow field at selected downstream locations is illustrated in Figure 1. The U velocity distribution is uniform close to the jet discharge plane at x/h=1 and resembles a top-hat profile. An increase in velocity with respect to its centre value is noted in the corner regions of the flow and appears as a ridge towards the jet boundaries. As in the free jet case (Pollard and Schwab, 1988) these velocity peaks develop within the potential core of the jet and are apparent in all profile maps in the initial development region in planes away from the horizontal centre.

Turbulent diffusion decreases the magnitude of the saddle-backed velocity profiles beyond x/h=10. It is observed that the flow distribution approaches symmetry again. The lateral and transverse velocity profiles reach the self-preserved state. This is evident in Figure 2 where individual velocity profiles are scaled with respect to the lateral and transverse half-widths of the flow. The cross-sectional outline of the jet thus transforms with increasing downstream distance from an essentially rectangular shape at x/h=1 to an oval upper contour at x/h=30.

The growth behaviour of the wall jet based on the respective half-width distributions is illustrated in Figure 3. In the normal direction the flow is seen to spread almost linearly shortly after it leaves the orifice. The average spreading angle within the range up to x/h=200 is estimated to be 6.5 degrees, marginally higher than the average rate of 5.5 degrees quoted by Launder and Rodi (1981) for jets from various orifice geometries. In the lateral direction the jet width is seen to decrease initially as the flow leaves the orifice: a *vena contracta* is formed. As compared to the free jet, it is evident that the presence of the wall initially retards spanwise growth. The lateral extent of the jet remains approximately constant in the range up to x/h=40, beyond which the spread progressively increases. The growth rate in the far field is approximately 18.5 degrees. This is distinctly different from jets emanating from other orifice geometries that yield about 29 degrees (Launder and Rodi, 1981). See Schwab and Pollard (1989) for more details.

A compilation of the measured V and W velocity profiles is presented in the form of vector plots in Figure 4. This cross-stream velocity pattern at the jet exit is characterized by inwardly directed vectors (towards the jet axis, in planes away from the centre). This is consistent with the contraction of the flow inside the settling chamber, upstream of the orifice. As soon as the flow leaves the orifice the vectors indicate a clockwise motion (x/h=2). This is similar to the free jet case studied in the authors' laboratory (Pollard and Schwab, 1988) where a distinct rotational pattern was observed encompassing the entire core of the jet. For comparison, Figure 5 depicts the secondary flow of the free jet including the orifice outline and the cross-sectional contour as scaled from flow visualisation (Schwab et al., 1986). For the wall jet, it is evident that the general character of the secondary flow is altered by the presence of the wall. Vortices are observed in the upper right and lower left corners, but no secondary flow of this kind can be discerned in the upper left and lower right corners. Both flows are observed to straighten out as the rotational motion and the vortices disappear completely and symmetry with respect to the vertical centre-plane is approached at x/h=20.

The distributions of the longitudinal turbulence intensity in the initial development region of the flow are presented in Figure 6 (profiles are only shown for the lower portion of the jet). The corresponding v' and w' profiles are similar in distribution and magnitude. For a complete account of all measurements the reader is referred to Schwab, 1986.

The turbulence intensities within the first 5 slot heights display small magnitudes across the jet core with sharp increases towards the edges of the flow. After the shear layers consumed the essentially laminar potential core (x/h=5), turbulent mixing is no longer restricted to the eges of the flow and normal stress levels in the jet centres reach 15 %. Similarly to the development of the mean streamwise velocities, wall effects convected by the complex cross flow lead to skewed and asymmetric distributions of the turbulence quantities. Turbulence activity is greatly enhanced near the centre corresponding to the location where the mean streamwise velocity is retarded by the wall. Within the first 30 slot heights the imposition of the wall leads to a slight decrease of the fluctuations in the normal direction as compared to u' or v'. Minima in turbulence intensity profiles are observed and are located in close proximity to the off-centre peaks in the axial mean velocity profiles. This has been measured previously in three-dimensional free jets, see Pollard and Schwab (1988) and Tsuchiya et al. (1986). The asymmetries induced in the near flow field are seen to slowly disappear in the further development of the jet, but it is not until approximately x/h=100 that the turbulence structure of the wall jet approaches symmetry again. This confirms previous perceptions that the turbulent structure has a long 'memory' as compared to the mean quantities.

The measured levels of momentum transport by turbulence in the lateral and transverse direction ($\overline{u'v'}$ and $\overline{u'w'}$ respectively) are, in general, less than 1 % of the reference velocity squared. Space precludes either further comment or inclusion of figures.

DISCUSSION OF RESULTS

The flow maps obtained within the framework of this study indicate a number of trends for the gross flow features observed. After a finite development length within the settling chamber the flow is being forced to contract severely at different rates along two planes. This gives rise to boundary layer interaction with associated different strain rates prompting the flow to form vortices. The sense of the vortices is clockwise positive in the upper right quadrant. Although only two vortices could be clearly identified by the present measurements there is reason to believe that vortices would form within all four quadrants of the flow. This implies that for a square jet emanating from a square settling chamber no vortices are expected. Experiments and computations confirm this statement (Pollard and Schwab, 1988). The vortices which "interact in such a way as to produce a preferred direction of swirl", Pollard and Schwab(1988), can be explained by way of Taylor's (1923) vortex array. Valentine and Mohamed (1989) have shown that given a two dimensional array of vortices, say four, each rotating such that one located in the upper right corner rotates clock-wise, a small perturbation (of order 0.01%) introduced into the centre of the two vortices with positive values of Ψ, cause the vortices to merge as shown in Figure 9. There is a striking similarity between this Figure and Figures 5 and 6. This clearly indicates that even the most optimistic experimentalist would be hard pressed to ensure symmetrical conditions to the level needed to ensure completely stable near field results. As noted by Pollard and Schwab (1988), alternate directions to the preferred direction of swirl have only been partially successful to date.

CONCLUSION

The flow field of a three-dimensional wall jet emanating from a rectangular sharpe-edged orifice has been investigated. The conclusions drawn and the effects imposed by the wall on the free shear flow are summarized as:

The initial growth in the lateral direction is impeded by the wall thereby enhancing the spread normal to the plate; behond the characteristic decay region this trend is reversed yielding a ratio of lateral to transverse spreading rates of 3:1.

An anisotropic Reynolds stress field far downstream appears to contribute to the larger spanwise growth of the jet providing a source for streamwise vorticity.

Secondary vortices develop in the near field of the jet as a result of boundary layer interaction inside the settling chamber. An as yet unidentified instability creates an asymmetric flow pattern in the near field; complete symmetry is again recovered at approximately x/h=30.

Due to the complex cross-flow pattern the division of the flow into an inner and outer layer is not clear-cut; the influence of the wall is propagated into the outer layer by the secondary flow, giving rise to skewed and asymmetric mean velocity profiles in the near field.

Beyond the characteristic decay region (x/h=30) no trace of irregularities can be discerned; the profiles in the lateral and transverse directions approach the self-similar state.

ACKNOWLEDGEMENTS

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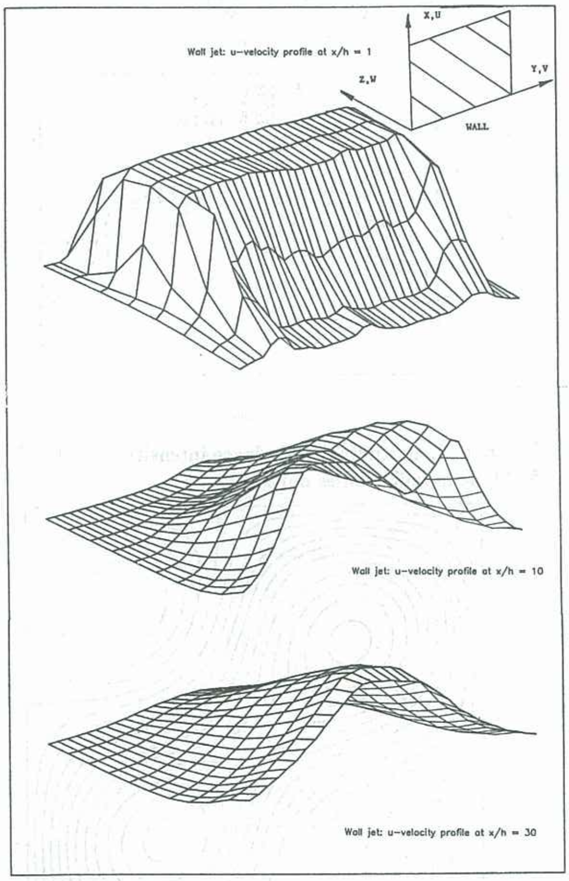

Figure 1: 3-D wire mesh plots of axial mean velocity at various x/h downstream of exit plane.

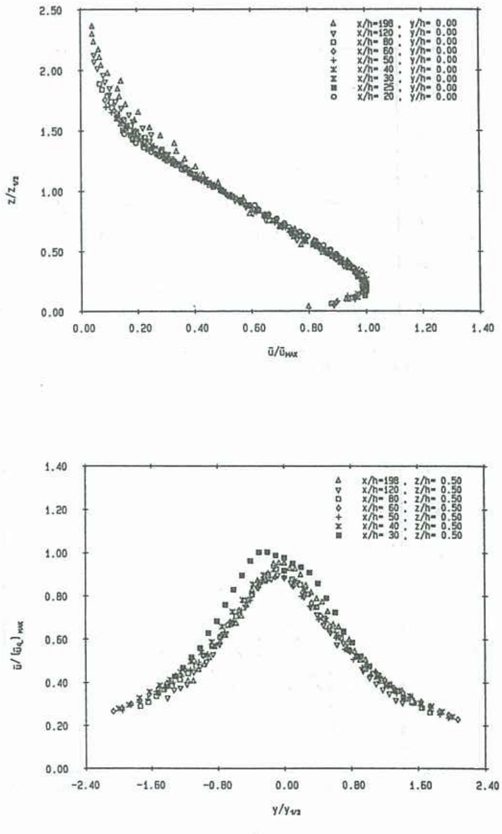

Figure 2: Self-similar axial mean velocity profiles in the transverse (Z) and lateral (Y) directions.

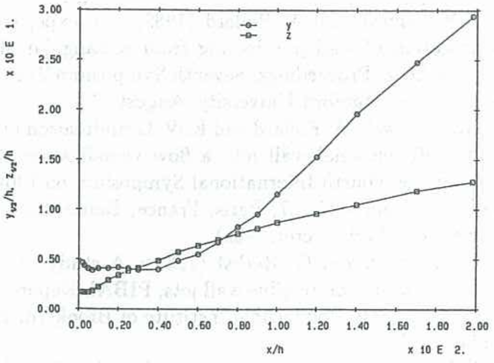

Figure 3: Lateral and transverse growth behaviour.

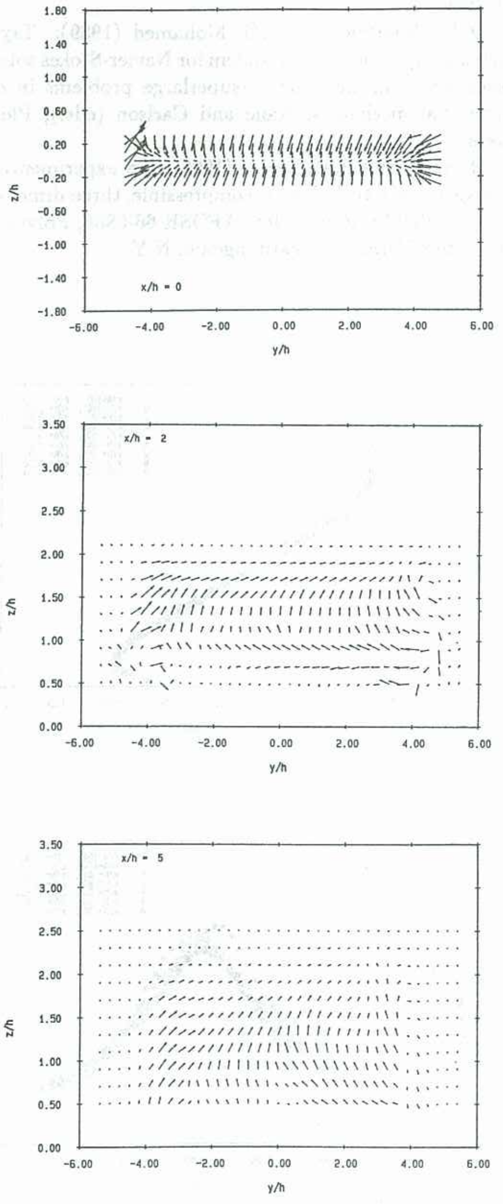

Figure 4: Cross-stream velocity vectors at x/h = 0, 2, 5 respectively.

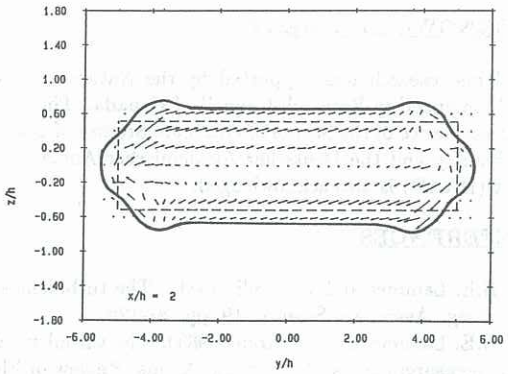

Figure 5: Cross-stream velocity vectors from free-jet including outline of orifice and flow visualisation outline/interface all at x/h=2.

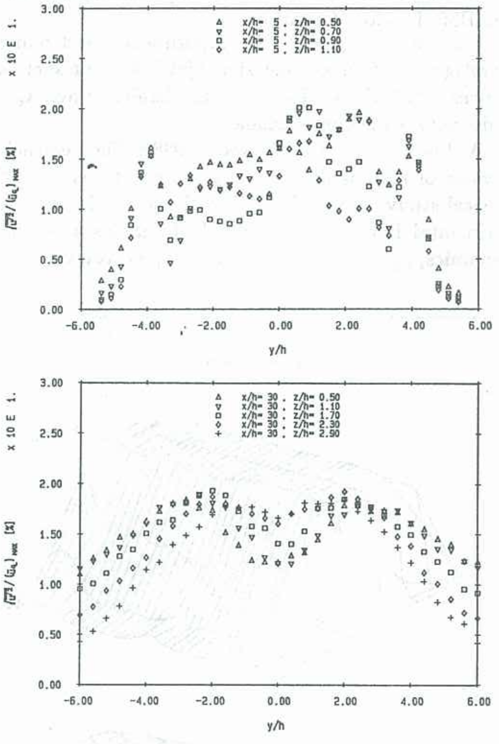

Figure 6: Longitudinal turbulence intensity (%) at x/h = 5, 30, near-wall profiles only.

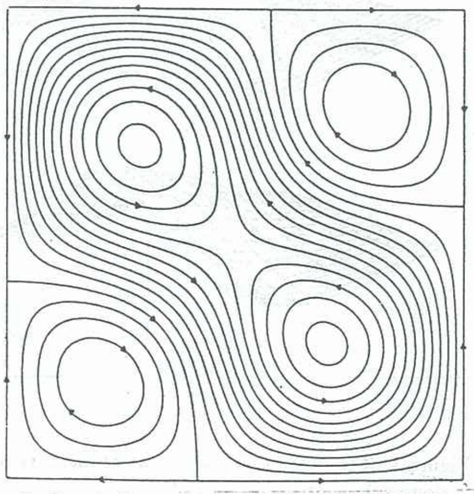

Figure 7: Onset of merging vortices after application of small perturbation {From: Valentine and Mohamed, 1989}