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AXIAL FLOW REGIMES IN A CONFINED VORTEX

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ABSTRACT

Annular regions of reversed axial flow have been observed in highly swirled confined vortices. The aim of the present paper is to examine transition to this regime with increase in swirl. Vortex breakdown was associated with an initial transition from laminar to turbulent flow. A second transition of the unidirectional, turbulent, post-breakdown flow to annular reversed axial flow occurred at a higher swirl level.

INTRODUCTION

Extensive regions of reversed axial flow are not uncommon in confined vortex flows. Nuttal (1953) identified three modes of axial flow: positive axial flow everywhere (regime I), reversed axial flow at the centre of the vortex (regime II) and an annulus of reversed axial flow (regime III). Transition from one regime to the next was achieved by an increase in swirl intensity, although Binnie (1957) later found that endwalls were necessary to achieve regime III. Several explanations for this behaviour have been proposed in the literature, however, it is difficult to form general conclusions because of the variety of apparatus, boundary conditions and flow parameters used.

Transition from regime I to regime II can occur as a result of vortex breakdown. Harvey (1962) investigated vortex breakdown in a guide vane driven apparatus with a flared tube and uniform, screened outlet. At low swirl, a uni-directional vortex (regime I) was obtained, but as the swirl intensity increased, a breakdown appeared downstream. The breakdown moved upstream with further increase in the swirl intensity, eventually disappearing to leave a vortex with a core region of reversed axial velocity which filled the entire tube (regime II). He did not, however, report any observation of regime III.

Similar behaviour was reported by Escudier & Keller (1985) who measured the flow field in a model swirl stabilised combustion chamber. They observed regime II flow and, in addition, found that the introduction of a contraction at the outlet had a severe effect on the upstream flow in this case. They therefore deduced that the post–breakdown, regime II flow was subcritical (i.e. capable of sustaining infinitesimal waves which propagate against the flow). In this case, the post-breakdown flow reverted to a uni-directional flow with a central axial jet and an axial velocity minima in the annular region surrounding the jet, as if the flow were approaching regime III.

Mattner *et al.* (1996) examined a jet driven vortex flow which exhibited regime III axial flow at high swirl. Their apparatus included an endplate with an orifice which acted as a throttle to govern the flow rate. As they reduced the swirl intensity, the peak velocities decreased, the core size increased and the flow became asymmetric. At a particular swirl intensity, a sudden change to solid body rotation and regime I axial flow occurred. Flow visualisation indicated that the transition between these states was marked by a long, large amplitude, asymmetric standing wave on the core. Unlike the previous investigations, regime II and vortex breakdown were not observed.

However, the apparatus used by Mattner *et al.* (1996) suffered from a high degree of asymmetry and large turbulence intensities even at low swirl. The purpose of the present investigation, therefore, is to re-examine the transition to regime III flow in an improved version of the apparatus used by Mattner *et al.* (1996). Particular attention has been paid to establishing a low turbulence flow with a high degree of symmetry.

EXPERIMENTAL METHOD

The apparatus used by Mattner *et al.* (1996) was modified by sealing the tangential jets and installing sixteen adjustable guide vanes in the settling chamber and is shown in figure 1. Swirl was controlled by the blade angle β defined as the angle between the blade chord and a radial line from the axis of symmetry. A centrepiece was fixed above the vanes to guide the fluid smoothly into the working section. The chief advantage of this scheme is that it allows the turbulence to be substantially reduced by the introduction of screens and honeycomb prior to the guide vanes. An overflow weir fixed the height of the free surface and an orifice of diameter 14.25 mm at the outlet to the working section fixed the flow rate. The working

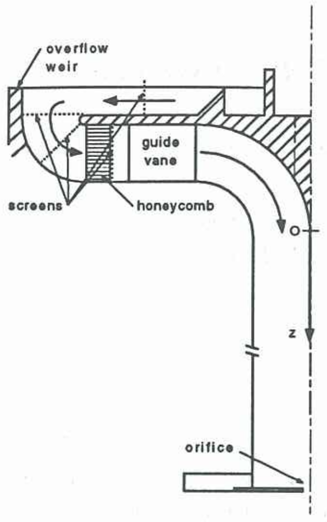


Figure 1: Radial cross-section of the apparatus.

section consisted of a straight perspex tube of inner radius $R = 85.5$ mm and length $L = 902$ mm. Axial position was referenced to an origin located at the beginning of the straight section and was measured positive in the direction of the mean axial flow.

Flow visualisation was conducted by injecting dye through a hole at the apex of the centrepiece. Volume flow rate was determined by measuring the time interval to collect a mass of fluid in a bucket. This procedure gave results repeatable to better than 1%. A Thermo Systems (TSI) 9100-7 two component laser Doppler velocimetry (LDV) system was used to measure the azimuthal and axial velocities. Frequency shifting was used to resolve flow reversals and reduce fringe bias. TSI IFA550 counter type processors were used to process the Doppler signal. Raw data was permanently stored and statistics calculated using inter-arrival time weighting (sample & hold) or controlled sampling techniques.

RESULTS AND DISCUSSION

Flow Parameters: The volume flow rate $Q = 5.30 \times 10^{-4}$ m^3s^{-1} was found to be independent of swirl. When measurements were extended into the wall boundary layer, integration of the axial velocity profile at zero swirl gave a flow rate within 2% of this value. The pipe Reynolds number was defined as $Re = 2W_bR/\nu$ where $W_b = Q/\pi R^2$ (ie. the bulk axial velocity) and ν the kinematic viscosity. Variation of this parameter was caused by temperature (and, therefore, property) variation of the working fluid and is reflected in table 1.

Assuming that the flow at the trailing edge of a guide vane is parallel to its chord and a uniform radial velocity, Escudier (1988) suggests that the maximum

β (deg)	Ω	Re
20	0.526	4819 ± 94
27	0.755	4608 ± 239
30	0.868	4867 ± 192
40	1.35	4581 ± 82
50	2.17	4561 ± 93
70	18.0	4489 ± 148

Table 1: Flow parameters.

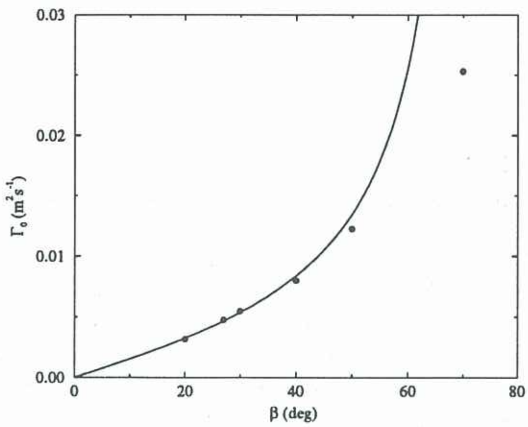


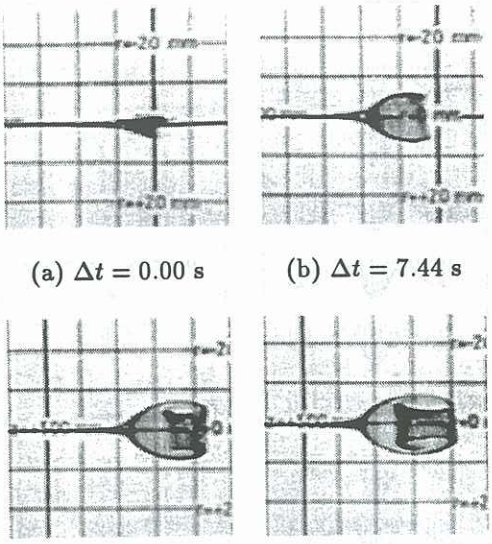
Figure 2: Equation 1 plotted versus blade angle β together with Γ_0 estimated from circulation profiles measured in the pipe.

circulation Γ_0 imparted to the flow is given by

$$\Gamma_0 = \frac{Q}{H} \frac{\sin\beta}{\cos\beta - d/R'} \quad (1)$$

where H is the vane span, d the distance from the vane shaft to its trailing edge and R' the distance from the vane shaft to the axis of symmetry. For the present apparatus $H = 85.5$ mm, $d = 73.0$ mm and $R' = 252$ mm. Equation (1) is shown in figure 2 plotted versus the blade angle, together with the maximum circulation estimated from circulation distributions measured in the pipe. For $\beta > 40^o$, equation (1) and the data diverge. Equation (1) indicates a singularity in Γ_0 as $\cos\beta \rightarrow d/R'$ and it is therefore likely that the assumptions upon which (1) is based fail for large β. Furthermore, it becomes increasingly difficult to estimate Γ_0 from the experimental data for large β as there is no plateau in the circulation profiles. Despite these limitations, equation (1) is often used to calculate a swirl parameter, presently defined as $\Omega = \Gamma_0 R/Q$ and calculated in table 1.

Flow Visualisation: For $\beta \leq 20^o$ the flow appears laminar and steady. A sudden increase in β by 1–2^o leads to one or more axisymmetric disturbances which evolve in both space and time, similar to those shown in figure 3. For $\beta \leq 25^o$ they eventually decay or are swept out of the working section. For



(a) $\Delta t = 0.00$ s (b) $\Delta t = 7.44$ s

(c) $\Delta t = 12.6$ s (d) $\Delta t = 16.7$ s

Figure 3: Transient behaviour. Note that z is positive left to right.

$25^o \leq \beta \leq 30^o$ these disturbances develop into an asymmetric, periodic, spiral pattern (figure 4) which settles to an equilibrium position within the working section. The transient and asymptotic phenomena are characterised by stagnation zones near the leading edge consistent with vortex breakdown. Note that the values of β quoted are typical but that it was impossible to reproduce them on separate occasions. The reasons for this variation have not yet been determined. As β is increased further, the equilibrium position of the spiral disturbance moves further upstream until it disappears from view in the contraction. In the pipe, the dye indicates a turbulent vortex core which increases in radius with increase in β. At very high $\beta \sim 70^o$, dye can be found throughout the cross–section of the pipe, however an unsteady inner core of increased dye concentration was observed close to the axis.

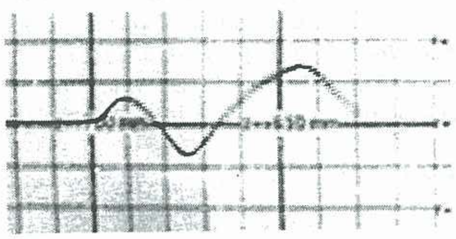


Figure 4: Ultimate behaviour. Note that z is positive left to right.

Mean Velocities: Mean axial and azimuthal velocity profiles and turbulence statistics were recorded at nine equi-spaced stations along the pipe, from $z/R = 2.95$ to $z/R = 7.62$. Figures 5 through 10 show the mean axial velocity profiles for various β. Note that the tube walls are represented by the lines bounding the profiles on either side and that the aspect ratio of the diagrams is correct. Orientation of the diagrams is also correct, with z positive down the page in the direction of the mean axial flow. The vector length scale, however, has been reduced by a factor $\lambda = 0.8$ and 0.4 for figures 9 and 10 respectively.

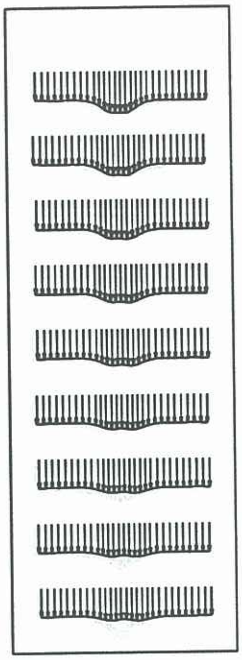


Figure 5: $\beta = 20°$.

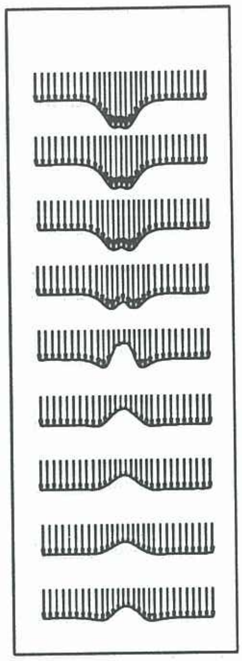


Figure 6: $\beta = 27°$.

Figure 5 shows positive axial flow throughout the pipe for steady, laminar flow at $\beta = 20^o$. The axial velocity peak near the centre of the vortex is typical of vane driven vortices, however, closer inspection shows that local maxima occur either side of centre. This is consistent with the shedding of a wake from the centrepiece. At $\beta = 27^o$, a spiral disturbance is present in the pipe, however, as mentioned previously, its position could not be exactly reproduced on separate occasions. Figure 6 was therefore constructed from two sets of data when the disturbance occurred between $z/R = 4.70$ and 5.87. This diagram should therefore be considered to give profiles ***typical*** of those when the spiral disturbance is present. Due to this and the poor axial resolution of the measurements, it is impossible to comment on the structure of the disturbance or its severity. Clearly evident, however, is the transition from a "jet–like" axial velocity profile to a "wake–like" profile, which is typical of pre– and post– breakdown behaviour respectively. The data does not indicate that axial flow reversal or stagnation (which are typical properties of vortex breakdown) occurred in a mean sense.

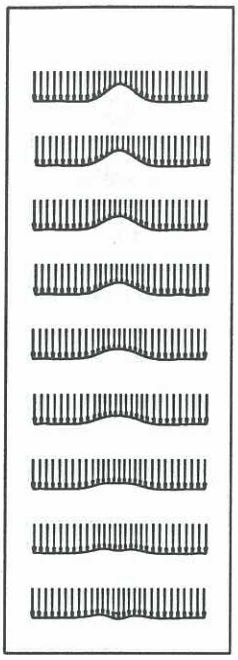


Figure 7: $\beta = 30°$.

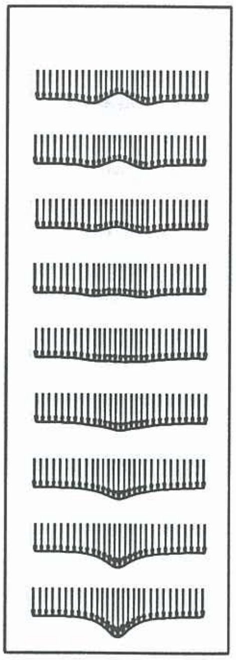


Figure 8: $\beta = 40°$.

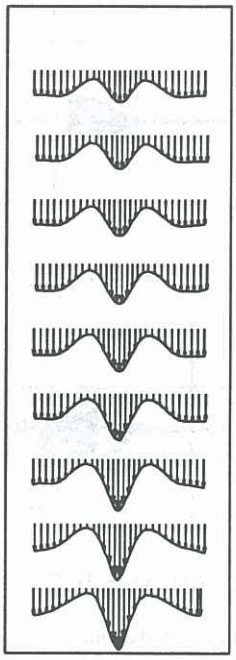


Figure 9: $\beta = 50°$.

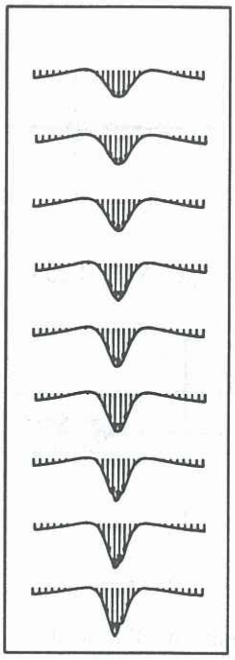


Figure 10: $\beta = 70°$.

Figures 7 and 8 show that for $\beta = 30^o$–40^o, the flow recovers from the wake-like post-breakdown profile back towards a jet-like profile with axial distance. The mean axial flow remains uni-directional which contrasts with the observations of Harvey (1962) but is consistent with the effect of a contraction on a subcritical vortex observed by Escudier and Keller (1985). As mentioned earlier, Harvey's apparatus had no end-wall other than a screen (i.e. no sudden contraction).

Figure 9 shows that the flow at $\beta = 50^o$ is approaching regime III as there are two axial velocity minima away from the centre of the vortex. There is no evidence of this behaviour at $\beta = 40^o$ and further measurements are required between $\beta = 40^o$ and 50^o to determine if this second transition is sudden or gradual. A large peak in the axial velocity has developed at the centre of the vortex. Again, these trends are similar to those exhibited in the profiles measured by Escudier and Keller (1985). In that case, they were the result of the introduction of a contraction into a subcritical, post-breakdown flow. Their contraction was much less severe than the present. Although it is difficult to determine from figure 10 due its scale, an annulus of reversed axial flow has developed at $\beta = 70^o$.

The similarity to the behaviour observed by Escudier and Keller (1985) suggests that regime III is the upstream effect of a severe contraction in a subcritical, post-breakdown flow. However, Mattner *et al.* (1996) found that changes in downstream boundary conditions (including a uniform outlet) affected the detail of the upstream flow, but not the flow regime.

CONCLUSION

The similarity of these axial velocity profiles to those measured at high swirl by Mattner *et al.* (1996) in the jet driven vortex suggests that regime III is not dependent on upstream boundary conditions or caused by possible separation over the guidevanes at high β. A disturbance, similar to vortex breakdown, leads to a turbulent uni-directional vortex which then makes a second transition to regime III. The details of this process were not observed by Mattner *et al.* (1996) due to the unsteadiness and asymmetry of their flow.

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