13th Australasian Fluid Mechanics Conference
Monash University, Melbourne, Australia
13-18 December 1998

UNCONFINED VORTEX BREAKDOWN

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ABSTRACT

One of the most interesting features of swirling flows is the phenomenon called vortex breakdown. The vortex core undergoes an abrupt enlargement and the complete flow field must adjust accordingly. Whilst this often occurs in nature in an unconfined environment (tornadoes and dust devils), with the same in aeronautics (flow over delta wings), the flow is often studied in the laboratory in an enclosed cylinder. Wall effects can predominate, and so flow patterns and behaviour may be very different from the targeted fluid flow. This numerical study aims to simulate the swirling flow patterns in an essentially unconfined environment above a stationary base. The absence of recirculating fluid within this geometry produces many interesting flow patterns which are not seen in the fully bounded case.

INTRODUCTION

Many intensive experimental, computational and theoretical studies have been performed on the phenomenon of vortex breakdown since it was first observed in swirling flows by Peckham & Atkinson (1957). Review articles can be found in Hall (1972) and Delery (1994). The need for understanding is crucial since the flow pattern occurs in many industrial devices such as turbomachines and combustion chambers (Escudier, 1987), and in aeronautics. Most laboratory studies, however, have concentrated on fully enclosed geometries such as the torsionally driven cylindrical container (see Escudier, 1984) or the swirling flow within a pipe (Sarpkaya, 1971). The delineation of wall effects on the vortices produced and their behaviour in these systems is still not fully understood, and awaits further investigation.

Faler & Leibovich (1977) revealed using confined fluids that at least seven distinct breakdown structures could be witnessed within swirling flows. Three of them were spiral types, including an asymmetric one, three were bubbles, and yet another was a 'double helix' characterised by two triangular sheets that wrapped around each other. However, visualisation techniques (see Hourigan *et al*, 1995) may mask the number of truly separate structures that exist within these flows. As the wish is to remove wall boundary layer effects, it is natural to examine swirling flows that are essentially unconfined. However, with the production of turbulent vortex cores and flow fields for environmental flows (tornadoes, for example), the structures may bare little resemblance to those within the slow, laminar, confined experiments.

In order to directly compare breakdown structures, Khoo *et al* (1997) (referred to as '**Khoo97**' for the remainder of the paper) performed some experiments for 'unconfined' flow with similar conditions to those that had used for many years in the recirculating cases. Swirl was imparted by outer drum rotation, and a mouthpiece with a pump attached at the top centerline of the flow drew fluid from the working section. With the whole set-up being within a constantly filling tank, and perforations in the rotating drum walls, inflow is allowed from the sides. The base of the experiment however, remains stationary and visualisation was performed by dye injection from holes at fractional radii on this wall. More details of the experimental rig can be found in Khoo *et al* (1993). Their experiments revealed similar results to Faler & Leibovich (1977), however, a further breakdown type which they called 'conical' was also produced. It only exists over a limited range of the operating conditions and it is characterised by a high angular velocity, tightly wound spiral which spread radially outwards as its height increases. This had not been witnessed before, and they were unable to reproduce this feature in confined experiments.

In this initial study, the aim is the numerical simulation of some of these breakdown structures. Care must be taken however, as it is only recently that problems and false behaviour in the simulation of vortex breakdown within the torsionally driven cylinder have been revealed (Graham *et al*, 1998). Whilst the experimental results demonstrated that some of the breakdowns were three-dimensional and turbulent, these simulations will be performed using a steady, axisymmetric, laminar model. This allows not only a simplified understanding of the structures, but also a delineation of those that are caused by effects not covered by the assumptions.

The first section will concentrate on the formulation of the problem along with the specific geometrical detail. This is to be followed by the numerical scheme used in the production of the simulations. Results over the parameter range will then be presented, along with a discussion of their importance.

FORMULATION

Flow is considered in a similar geometry to that of the experiments performed by **Khoo97**. Figure 1 demonstrates a schematic of the flow for one axisymmetric slice. The outer wall (right-hand side) rotates at a prescribed angular velocity, and the flow enters from a limited section on this boundary. The inflow here is considered to be uniform and evenly distributed, as opposed to the experiments where the rotating drum was perforated at discrete points. The fluid exits through a narrow mouthpiece (radius of approximately 3% of the domain width) at the top, and the remainder of that boundary is a free surface. In the numerical simulations it is considered to be 'flat', given that the theoretical maximum surface elevation is less than 1% of the tank height, and have zero stress. The bottom wall is always stationary, and the left-hand wall is the $r = 0$ line of symmetry.

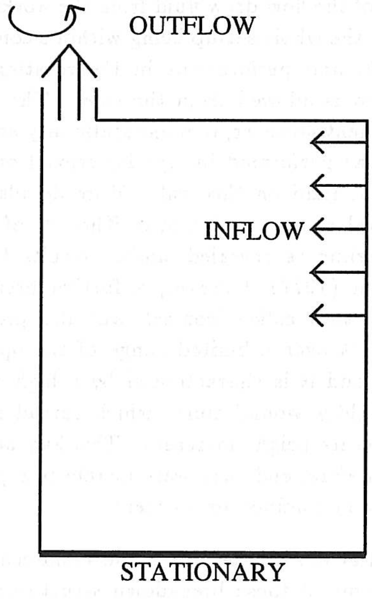

Figure 1. Schematic of the experimental set-up

For the mathematical formulation, the steady axisymmetric Navier-Stokes equations in cylindrical coordinates are considered;

$$\frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

$$u_r\frac{\partial u_r}{\partial r} + w\frac{\partial u_r}{\partial z} - \frac{u_\phi^2}{r} = -\frac{\partial P}{\partial r} + \ldots.$$
$$\ldots.\nu\left(\frac{\partial^2 u_r}{\partial r^2} + \frac{1}{r}\frac{\partial u_r}{\partial r} - \frac{u_r}{r^2} + \frac{\partial^2 u_r}{\partial z^2}\right) \tag{2}$$

$$u_r\frac{\partial u_\phi}{\partial r} + w\frac{\partial u_\phi}{\partial z} + \frac{u_r u_\phi}{r} = \ldots.$$
$$\ldots.\nu\left(\frac{\partial^2 u_\phi}{\partial r^2} + \frac{1}{r}\frac{\partial u_\phi}{\partial r} - \frac{u_\phi}{r^2} + \frac{\partial^2 u_\phi}{\partial z^2}\right) \tag{3}$$

$$u_r\frac{\partial w}{\partial r} + w\frac{\partial w}{\partial z} = -\frac{\partial P}{\partial z} + \ldots.$$
$$\ldots.\nu\left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r}\frac{\partial w}{\partial r} + \frac{\partial^2 w}{\partial z^2}\right) \tag{4}$$

Here the velocities in the (r, z) plane are given by (u_r, w), P is the reduced pressure, and u_ϕ is the out-of-plane azimuthal velocity. In the numerical simulations, the outer drum will have radius r_0 and have an inflow and azimuthal velocity of V_{inflow} and V_{drum} respectively. Using the same dimensional analysis as that of **Khoo97**, two free parameters are obtained, namely, the Reynolds number, Re, and Swirl ratio, S, as follows

$$Re = \frac{V_{drum} r_0}{\nu} \quad , \quad S = \frac{r_0 V_{drum}}{2V_{inflow} l}$$

where l is the length of the right-hand boundary that flow is allowed to enter from. Variations in these two parameters shall be examined for the remainder of the study.

NUMERICAL TECHNIQUE

The equations, (1)-(4), were discretised using the Galerkin finite-element method. Nine noded quadrilateral elements were used for the complete domain, and a penalty method (see Peyret & Taylor, 1983) was used in the formulation for pressure. In order to resolve the boundary layers that develop on the walls, the grid had Chebyshev compression towards all boundaries. Typically, a 120 × 120 mesh was used for all simulations, but grid refinement studies await further investigation (see Graham *et al*, 1998). The nonlinear set of equations were solved by Newton iteration, with the stopping criterion being that the norm of the velocity differences was less than 10^{-6}.

RESULTS AND DISCUSSION

Examining the experimental results, it is easy to observe that dramatic changes in flow patterns can occur over small changes in the $Re-S$ parameter space. Most of the flows appear to be unsteady in nature, with asymmetry and low turbulence intensity existing in some. Equally dominant states are also suggested by the presence of two or more different structures existing for periods of time at the same parameter values. Taking all of this in mind, the simulations here will concentrate on low Re flows to avoid turbulence being a determining feature in the obtained flow fields. Bubble structures will be the main focus, as the rest of the breakdowns appear to invalidate any axisymmetric assumption.

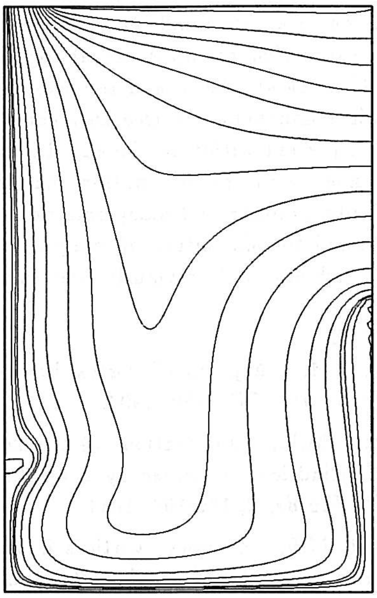

Figure 2. Streamlines for $Re = 175$ and $S = 2.5$

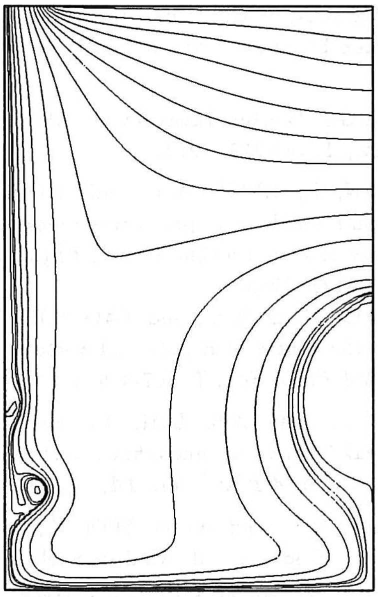

Figure 3. Streamlines for $Re = 450$ and $S = 2.5$

For low Re flows, **Khoo97** show that there exists a small band of the swirl ratio parameter space where a vortex is formed. If the swirl is decreased, the vortex can disappear, and if it is made too high, four states become equally dominant (two spirals, double helix and a flattened bubble). Choosing an arbitrarily small value initially, simulations shall be performed with Re varying. Figure 2 demonstrates the streamline pattern for $Re = 175$ and $S = 2.5$, a flow where it is clear to see that a weak vortex exists on the centerline. Streamline values have been chosen to visualise the vortices, but remain constant for the remainder of the paper. This pattern is similar to that observed within the fully confined case, but it exists here at much lower values of the free parameters. However, unlike the torsionally driven container case, if Re is increased further then this vortex dies away. The streamlines do go through some distortion after making the 90^o turn near the base, but no vortex is present. This continues until at $Re \sim 265$, a small vortex is formed off-the-axis. This continues to grow with changes in Re, and can be seen in Figure 3 with $Re = 450$. A second structure north of this vortex, near the centerline, can also be witnessed. Further increasing Re to 650, Figure 4 shows that the vortex intensity has increased slightly and its centre has moved south-west. Therefore, care must be taken in comparing the vortex positioning and bubble size between the experiments at high Re and those of the simulations.

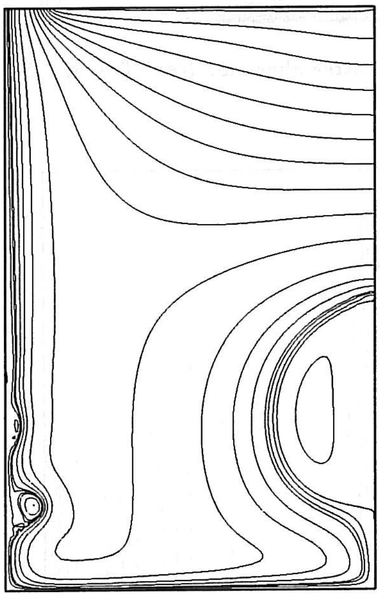

Figure 4. Streamlines for $Re = 650$ and $S = 2.5$

Increasing the swirl ($S = 7.5$), allows a similar behaviour over changes in Re to be witnessed. Figure 5 shows the streamline pattern for such a case with $Re = 650$. Results presented in **Khoo97** are for a slightly higher Reynolds number ($Re = 750$), but unfortunately the numerical scheme would not allow full convergence at this value. They showed that two flow patterns co-exist, namely a flattened bubble, which lies close to the centerline, and a spiral type, which spreads downstream. The former, however, was suggested to be unstable in nature. The numerical vortex generated lies very close in positioning to the major spiral arm in the distorted spiral breakdown observed in the experiments. The simulated flow does have the strong reversal and 'curling back' near the centerline mentioned in the experimental observations.

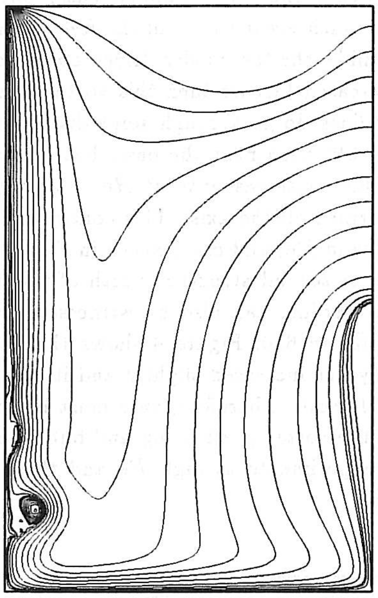

Figure 5. Streamlines for $Re = 650$ and $S = 7.5$

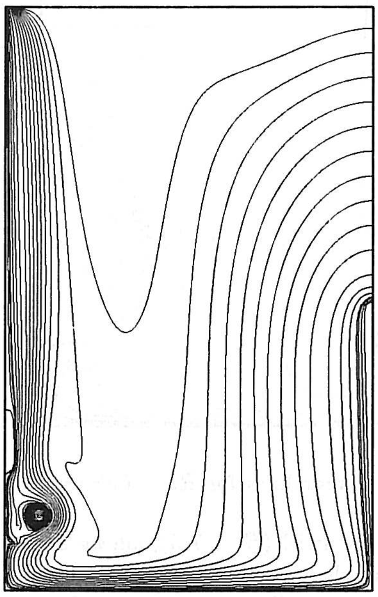

Figure 6. Streamlines for $Re = 650$ and $S = 12.5$

If the swirl ratio is further increased, $S = 12.5$, the pattern in Figure 6 can be seen. Once again, a stronger vortex away from the axis is formed, but this time a small elongated one also exists on the centerline. It is consistent with those obtained previously, but no spiral-like structures are observable. It thus appears that the simulation of such features will have to await further unsteady, fully three-dimensional calculations.

CONCLUSION

Numerical simulations have been performed for vortex breakdown in an essentially unconfined environment. The geometrical set-up is similar to the experiments of Khoo *et al* (1997), and removes the recirculating fluid component and free parameter dependence that is present within torsionally driven cylinder flows. Even with the assumption that the flow remains steady, laminar and axisymmetric, the system has allowed the simulation of many new vortex structures which have not previously been calculated.

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