BRIEF COMMUNICATIONS

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Spiral streaklines in pre-vortex breakdown regions of axisymmetric swirling flows

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In steady swirling flows in closed cylinders, it has been common to observe the transition to spirals of otherwise straight dye streaklines. This occurs in the regions where bubble type breakdown occurs but at a slightly lower Reynolds number. These regions are of particular interest for those seeking to explain the origins of vortex breakdown. The hitherto unexplained occurrence of the spiral streaklines, postulated previously to be due to non-axisymmetry of the flow, is found to be due to small offsets of the dye injection from the central axis. The important implications of this finding are that (i) non-axisymmetry is not a necessary route to bubble-type vortex breakdown, and (ii) that flows displaying spiral streaklines may be still sufficiently axisymmetrical for comparison with numerical and theoretical treatments of the breakdown phenomenon. © *1995 American Institute of Physics.*

The torsionally driven cylinder cavity flow has been studied intensively over the last decade or so with both experimental and numerical approaches being used (e.g., Escudier;[1] Lopez;[2] Brown and Lopez[3]). Of particular interest in this type of flow is the occurrence of one or more bubble-type vortex breakdown regions as the Reynolds number is increased. From a theoretical point of view, investigation of the flow profile in these regions just prior to breakdown could give useful insight into the origin of vortex breakdown (Monkewitz[4]). However, it is important that sufficient control be maintained in experiments to provide a truly axisymmetric and steady field. Some recent observations using dye streaklines have cast doubt on whether this axisymmetry is being achieved.

Lopez and Perry,[5] in a study of the unsteady flow in a driven cylinder, have highlighted the often confused, and sometimes incorrect, interpretation of flow visualization using dye streaklines for unsteady flows. Unsteadiness in the cylinder flow can lead to the observation of 'fingers' appearing in the streaklines; these are not true flow structures but merely artefacts of the visualisation technique. For unsteady flows, the disparity between streaklines and streamlines has been long reported in the literature (e.g. Hama[6]), but frequently ignored. Apparent non-axisymmetry, as a result of this disparity, has emerged also from numerical studies of unsteady axisymmetric flows with vortex breakdown (Neitzel[7]). In the present paper, we shall show that in the driven cylinder, deceptive and illusory flow structures can appear even in the case of *steady* flow in the *absence* of vortex breakdown.

Spohn *et al.*[8] have recently undertaken a study of vortex breakdown in an open cylindrical container with a rotating bottom lid. Laser-induced fluorescent dye was released along the centerline near the non-rotating end to visualise the steady-state flow. For low Reynolds numbers, the dye streakline coincides with the centerline of the cylinder. Near a critical Reynolds number, spiral structures along the centerline of the cylinder were observed. Away from the spirals, the dye streakline was still coincident with the centerline of the cylinder. As the Reynolds number was further increased, the spirals underwent radial stretching, and eventually the spirals disappeared, being replaced by fully developed recirculation bubbles. Similar non-axisymmetric spirals have also been observed in swirling cylinder flows with a fixed cover by Escudier,[9] with the spirals being noted but not interpreted. Spohn *et al.*[8] remark that their observations, and those of Escudier, of non-axisymmetric spiral streaklines indicate that at least some parts of the flow are not perfectly axisymmetric. Furthermore, the authors state that these spiral streaklines suggest that more information about the flow surrounding the central dye filament is required.

It is the purpose of this Brief Communication to demonstrate that spiral regions in otherwise (apparent) straight axial streaklines along the center axis can appear in steady axisymmetric flows preceding vortex breakdown. These streakline patterns, hitherto unexplained or misinterpreted, need not be symptomatic of actual flow structures but arise out of

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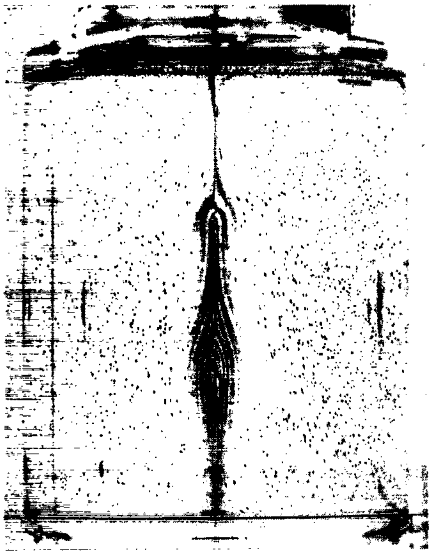


FIG. 1. Photograph (reverse image) of observed streakline for $Re = 1.9 \times 10^3$. Bottom lid is rotating, top lid is fixed. Dye is injected nominally at the center of the top lid.

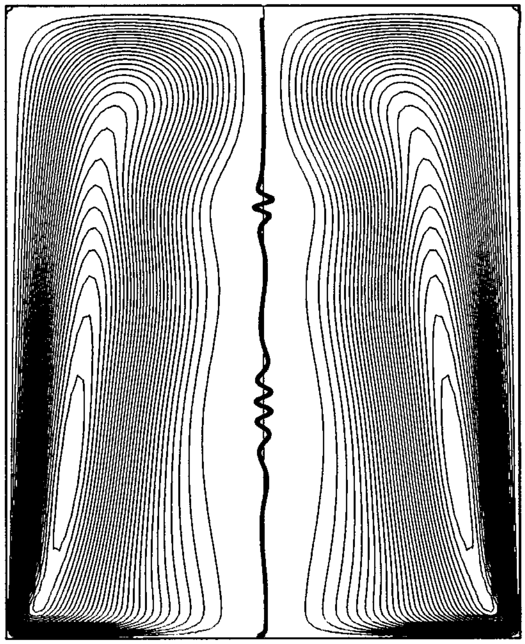


FIG. 2. Predicted streamlines for $Re = 1.9 \times 10^3$. Predicted particle streakline shown in bold. Particle injection at $5 \times 10^{-3} R$ below top lid and $8 \times 10^{-3} R$ off centerline.

(difficult to avoid) small experimental error in the injection of dye. The result is important in that it supports the conclusion of Escudier[9] that the bubble-type of vortex breakdown is essentially axisymmetric. It also restores confidence in the ability of experimental rigs to provide axisymmetric conditions for flows in the important stage just prior to breakdown.

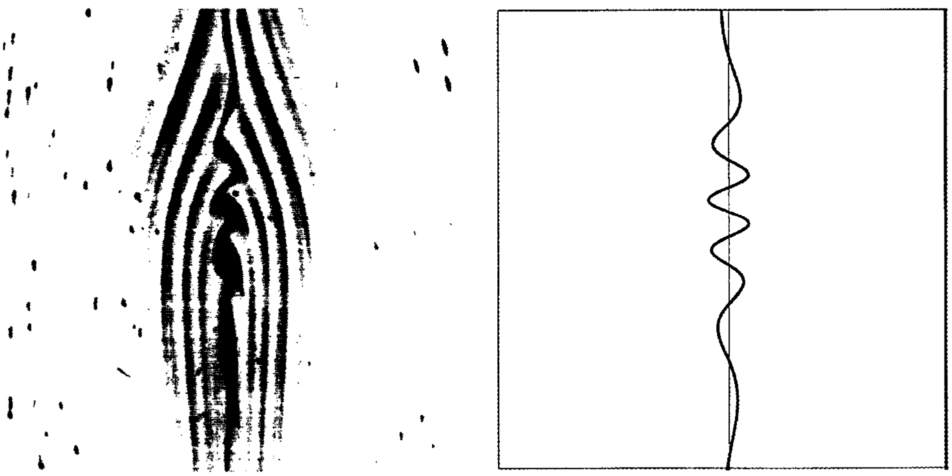
A brief outline of the design of the swirling rig used is presented here. The radius of the cylinder is 0.070 m. The rig includes a water bath which reduces optical distortion and also maintains a stable temperature in the working fluid. The rotating lid at the bottom is driven by an electric motor with a choice of reduction gearbox or direct belt drive to give a wide range of speeds up to over 1400 rpm.

Photographs were taken using a Nikon FM2 35 mm camera fitted with a 58 mm Nikkor Noct lens. Dye injection was used to visualise the structures. The dye was a small quantity of flourescein powder dissolved in some of the working fluid and was injected by means of a hypodermic syringe through a small diameter hose leading to a hole of diameter 0.5 mm in the center of the fixed lid. Illumination was by a Coherent Highlight argon-ion laser which was piped to the rig by a fibre optic cable and expanded into a light sheet by a cylindrical lens.

The fluid used for the present work was a solution of glycerol in water with 76% by weight of glycerol. The density of the fluid was 1197.6 kg m^{-3}. The viscosity was measured using a Contraves Rheomat 108 and was 0.044 ± 0.001 Pa s.

The Reynolds number for the swirling flow is defined as $Re = (\rho \Omega R^2)/\mu$, where ρ is the density, Ω the angular speed of the lid, R the radius of the cylinder and μ the fluid viscosity.

The solution of the Navier-Stokes equations for axisymmetric flow in cylindrical coordinates was obtained using the Galerkin finite-element method. The grid system employed



(a)

(b)

FIG. 3. (a) Enlargement of observed lower spiral in Fig. 1. (b) Enlargement of the predicted lower spiral in Fig. 2b.

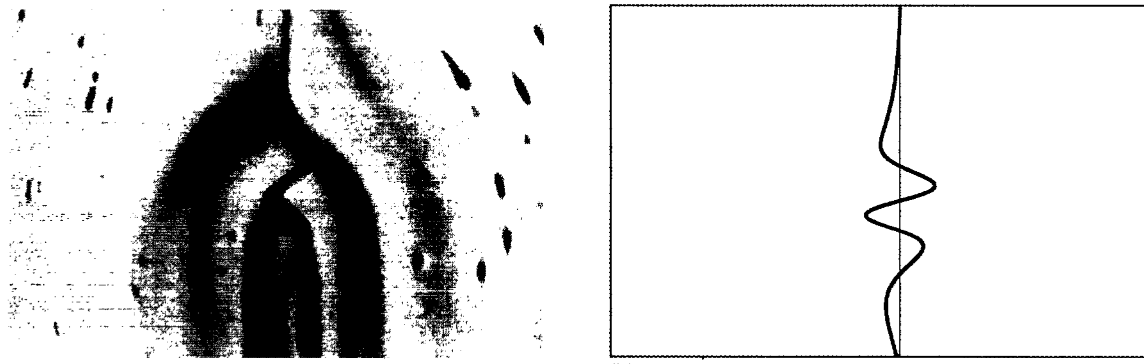

(a) (b)

FIG. 4. (a) Enlargement of observed upper spiral in Fig. 1. (b) Enlargement of predicted upper spiral in Fig. 2b.

consisted of uniform rectangular elements everywhere except for a compression near the rotating lid to resolve the Ekman layer. Results are presented for a grid with 201 nodes in the axial direction and 101 nodes in the radial direction. The penalty formulation with biquadratic Lagrangian interpolation for the velocity field and discontinuous bilinear Lagrangian interpolation for the pressure field was employed. The nonlinear set of equations was solved by Newton iteration.

Although a number of different Reynolds numbers were investigated, one typical result is presented here to illustrate the phenomenon of spirals.

The observed (steady) streaklines for Reynolds number ($\mathrm{Re}=1.90\pm0.08\times10^3$) are shown in Fig. 1. This Reynolds number is just below the critical number at which recirculation regions appear along the centerline. There are two spirals observed in the dye trace; one in the lower half of the cylinder, the other in the top half. As the Reynolds number was increased, the regions where the spirals were present transformed into recirculation bubbles, in line with the standard observation. The observed spirals were steady, being fixed in space without undergoing any corkscrew action with time.

In order to test whether the appearance of these spirals relies on some non-axisymmetry of the flow, as suggested by Spohn *et al.*,[8] axisymmetric numerical predictions at the same Reynolds number were made. Figure 2 shows the predicted streamlines for $\mathrm{Re}=1.90\times10^3$. Although some divergence of the streamlines occurs near the centerline of the cylinder, no recirculation regions were predicted.

The streaklines of particles, analogous to dye visualisation in the experiments, were predicted for particles introduced near the fixed lid. The streaklines shown in the figures are projections of three-dimensional streaklines. This is consistent with the finite width of the light sheet used in the experiments. If the particle was released precisely on the centerline, then of course it is constrained to move only on the centerline. However, particles released with a small radial offset produced the spiral patterns similar to those observed in the laboratory rig. Figure 2 also shows the predicted streakline for a particle released at 0.5% cylinder radius below the top lid and 0.8% cylinder radius off the centerline. Two spirals, as in the observed case, are predicted along the centerline. Figures 3 and 4 show close-up views of the predicted spirals and comparison with the analogous observed spirals. The exact number of turns in the predicted spirals was a function of the radial offset at which the particle was released. Particle release at half and twice the above radial offset still produced spirals, with one more or less turn.

We conclude that the apparent non-axisymmetry of the flow, observed by Spohn *et al.*[8] and in the present experiments, is deceptive. It arises from the fact that in flow visualisation, although dye is intended to be released precisely on the centerline of the cylinder, a small radial offset in its release is inevitable. This offset is however not noticeable in the streakline, which follows the centerline closely, until the dye trace reaches the near-breakdown region further down the centerline axis. In this region, there is a divergence of the streamlines, taking the dye trace further away from the centerline, where the swirl velocity becomes more significant and the spiralling more noticeable. Near the lower end of the near-breakdown region, the streamlines converge. The dye trace is again transported close to the centerline axis until another near-breakdown region is encountered. Note that only a plausibly small radial offset (less than 1% cylinder radius) for dye release is required to produce predicted spiral patterns similar to the observed spiral patterns.

ACKNOWLEDGMENT

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