Three-Dimensionality of Trajectories of Experimental Tracers in a Steady Axisymmetric Swirling Flow: Effect of Density Mismatch*

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Abstract. The motion of tracer particles used for visualization in a steady axisymmetric swirling flow in a closed rotating disk–cylinder system is studied numerically. It is assumed that there exists a density mismatch between the particles and the fluid. It is shown that such a slight density mismatch leads to a deviation of the particle motion from steady axisymmetric streamlines, which in its turn yields non-axisymmetric patterns of the visualized flow. This gives a possible explanation for an existing disagreement between several experimental and numerical studies.

1. Introduction

The swirling flow in a closed rotating disk–cylinder system attracted the attention of many experimental and numerical studies during the two last decades (see [1–20] and references therein). The main objective of these studies was the vortex breakdown observed experimentally in this system and reproduced in various numerical studies. It was shown that the vortex breakdown appears and disappears as a continuous change of the flow topology and is not caused by an instability of the flow [9]. Recently, the main attention was drawn towards instabilities of the primary axisymmetric steady flow [9, 10] and further development of supercritical oscillatory flows that can be axisymmetric or three-dimensional [8, 11–20].

There exists a certain controversy related to the axisymmetry to non-axisymmetry (i.e., three-dimensional) transition of this flow, which occurs at relatively large Reynolds numbers. Following the conclusions of the experimental study [1] it is widely believed that at aspect ratios \(A = \text{height}/\text{radius}\) of the cylinder varying between approximately 1.5 and 3.5 the vortex breakdown is axisymmetric. This was supported by a number of axisymmetric calculations, e.g., [8] and [9], which reproduced the appearance and disappearance of the vortex breakdown for the same parameters as those observed in experiments [1]. Calculations with a sufficient accuracy were able to reproduce the experimentally observed size and position

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of the separation vortex bubble. Furthermore, a study of the topological bifurcations of the axisymmetric streamlines [14] also reproduced the experimental boundaries of the vortex breakdown. On the other hand, the authors of experimental study [11] argued that the patterns produced by tracers of visualization particles immersed in the flow are not axisymmetric and recalled that in all previous experiments done for this and similar configurations [1–7, 16, 21–23] the non-symmetry of such patterns is clearly seen. Figure 1 shows some such asymmetric experimental tracer patterns, reproduced from [1–4, 11, 22]. All the experimental photos are arranged so that the rotating disk is on the top of the cylinder. The asymmetry can be observed (i) inside of the vortex breakdown bubble (Figure 1(a),(b),(d)–(h)), (ii) as “streaks” coming out of the bubble in the downstream axial direction (Figure 1(a),(b),(d)–(g)), (iii) by spiraling streaklines observed in the axial cross-section of the cylinder (Figure 1(c)), and (iv) by non-symmetric tracer patterns in the axial cross-section taken very close to the rotating disk (not shown in Figure 1, see [11]). In [11] the non-symmetry of the tracer patterns was attributed to non-axisymmetry of the stationary flow which has the developed vortex breakdown structure. It was also argued that the separation vortex bubble is not closed, as follows from the axisymmetric models, but open, which creates the non-symmetric tracer “streaks” coming out of the bubble [11]. These findings were supported by three-dimensional numerical simulations [12, 13], where similar non-axisymmetric streaklines structures were calculated. In summary, the discussion in [11] and [12] questioned the validity of previous axisymmetric studies.

On the contrary, recent analysis of the stability of steady axisymmetric states with respect to three-dimensional perturbations [10] showed that the axisymmetric flows with vortex breakdown remain stable up to the transition to an oscillatory state. Moreover, the stability results of [10] indicate that for aspect ratios between 1.63 and 2.76 even the oscillatory instability is axisymmetric, thus confirming the early conclusions of [1]. The results of three-dimensional stability analysis [10] were recently validated by a series of fully three-dimensional time-dependent calculations [15, 17–19], as shown in Figure 2. Thus, the results of [18] confirmed that in the vicinity of \( A = 1.6 \) there is a switch between the three-dimensional mode \( k = 2 \) and

![Figure 1. Experimental patterns of the streaklines. (a) [11], \( \gamma = 1.75, Re = 1850 \), visualization by fluorescent dye; (b),(c) [11], \( \gamma = 1.75, Re = 1850 \), visualization by electrolytic precipitation, meridional and axial cross-sections, respectively; (d) [1], \( \gamma = 1.5, Re = 1747 \), visualization by laser-induced fluorescence; (e) [22], \( \gamma = 3, Re = 1655 \), visualization by polystyrene particles; (f) [2], \( \gamma = 2.24, Re = 2039 \), visualization by K. Roesner (private communication); (g) [3], \( \gamma = 2, Re = 2200 \), visualization by fluorescent sodium dye; (h) [4], \( \gamma = 2.5, Re = 2000 \), visualization by small plastic spheres. Figure parts (a), (b), (c) and (e) are reproduced here with the kind permission of Cambridge University Press (resp. Figs. 4(a), 7(f) and 8(c) from [11] and Fig. 7(a) from [22]); part (f) was kindly supplied by Prof. K.G. Roesner; part (g) is reproduced here with the kind permission of ASME International.](image)