Tracer visualization of vortex breakdown patterns in confined and unconfined flows

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Abstract. Current work deals with the study of swirling laminar flows in confined and unconfined flows in order to identify common patterns considering the phenomenon of vortex breakdown. Two types of vortex breakdown patterns are created: spiral and bubble. To catch the main flow features the modern tracer visualization technique adapted to experimental conditions is used. Measurements of velocity distributions are conducted via two-component LDA system. This work also confirms some ideas proposed by (Jones et al. 2015) about generalization of vortex breakdown conditions in different geometries.

1. Introduction

The attention to vortex breakdown is explained by many technical applications in which this phenomenon is involved. Onset of the vortex breakdown has a strong impact on the performance of the engineering application especially considering the issues of heat transfer in respect to the flow patterns [1,2]. Vortex breakdown is usually associated with an abrupt change of vortex core structure accompanied by drastic changes in axial velocity on the axis occurring a swirling flow. There are different types of vortex breakdown but two main types can be distinguished: spiral and bubble breakdowns. The vortex breakdown bubble (VBB) can be described as stagnation point on the axis, followed by a substantially axisymmetric region of recirculation that looks like vortex core expansion. The spiral form is the deviation of the vortex core from the axis without any change in the core size. Detailed information on the causes of vortex breakdown and its various patterns can be found in review papers [3,4]. A large number of experimental works have been devoted to the study of vortex breakdown for both closed geometries [5–7] and pipes flow [8,9].

Vortex breakdown is widely described in literature but some questions related to the generalization of systems of various geometry by a single theoretical approach, are still open. Escudier summarized the data on confined axisymmetrical geometries in the diagram form methodically changing the aspect ratio h/R and Reynolds number [10]. Naumov et al. added another dimension to this diagram - the transition from the cylinder to the polygonal geometry of the containers [11, 12] and thereby found that in diagram Re-Ar (aspect ratio H/R) reducing the number of cross-section angles from eight to four shifts the axial coordinate of bubble breakdown to higher Reynolds numbers and a smaller aspect ratio. Sorensen et al. showed that at high aspect ratio (height to radius ratio in closed cylindrical system) there are stable different modes of helical multiplets [13] which can intensify nonintrusive mixing. The experimental studies in configuration with two immiscible vortex flows for bioreactor application [14] showed in detail how VBB appears and disappears in the upper fluid. VBB was detected in the lower fluid and its evolution process was traced with an increase in the rotation speed. Carrion conducting numerical and
experimental investigation et al. [15] revealed that the VBB scenarios in one-fluid confined flows is similar to the VBB scenarios in the upper fluid of two-fluid flows and in the lower-fluid. Jones using CFD techniques, made the first attempt to find correlation between the flow in the pipe and the flow in confined geometry by using the modified vortex numbers Re’ and S’ [16]. It has been shown that the spiral type of breakdown is replaced by an axisymmetric breakdown in an open pipe as the Reynolds number is reduced, spiral breakdown modes stabilize at lower Reynolds number, leading to an axisymmetric breakdown state as a stable evolved flow solution. For the pipe, breakdown appears at a significantly lower S’. Jones suggest that in a closed cylindrical container where a vortex flow is generated by a rotating lid and it is impossible to separately control the Reynolds number and the swirl intensity, the spiral vortex breakdown cannot exist. However, this is a controversial issue and the use of quite high Ar allow for some spiral pattern observation as it shown below.

2. Experimental setup
The experiments were carried out in the hydrodynamic facilities at Kutateladze Institute of Thermophysics SB RAS. First test rig is a closed hydrodynamic circuit with a working section in the form of a transparent conical pipe with a taper angle of 8°30’ for studying swirling flows in a wide range of Reynolds numbers from 500 to 500000 and swirl numbers S from 0 to 2. The swirl in the inlet cone section was created by rotating blade swirler that described in detail in work [17]. The stepper motor was used to control the rotation of the belt drive allowing for smooth adjustment of the rotation frequency. In conical pipe system it is possible to independently control Re and S to investigate a specific region in Re/S space. But main difficulty is to obtain stable VBB in a conical pipe with a sufficiently large opening angle, because It was shown and confirmed in [18,19] that the divergent channel has destabilization effect that leads to the domination of spiral vortex mode.

For comparison of vortex breakdown patterns in confined and unconfined flows another experimental setup was used. The flow was driven by the bottom rotating lid in a vertical cylindrical container that had the same design as in work [20] with higher inlet diameter of 144 mm. As a working medium, a 30% mixture of glycerol with water was used. Two different Ar were studied. Ar=2 was chosen for classical single vortex breakdown visualization and Ar = 6 for attempt to find the onset of spiral breakdown form. Photo of the test sections with the cone and cylindrical container are presented in figure 1. The yellow dashed rectangle indicates the area of interest for visualization. Polyamide particles of 20 microns were used as tracers and a 2W solid state laser supplied with cylindrical lens provided laser sheet visualization.

Figure 1. Photo of test sections with tracer visualization by a laser-sheet in the mid plane.
CMOS camera PCO 1200 hs. with 1024*1024 resolution at 5Hz frame rate was used for registering tracers. In order to get long tracks in real time with high contrast the standard method for image acquisition was improved by subtracting a pre-measured average intensity value. This procedure can be written as:

\[ A_k = \frac{\sum_{i=1}^{N+k} A_i}{N} - \bar{A} \]  

(1)

where \( A_i \) is the intensity of each image, \( \bar{A} \) is the pre-measured average value of intensity for a certain period of time, which was selected for each flow mode separately, \( m \) is the total number of frames, \( N \) is the floating averaging window also selected separately for each experiment to obtain a sufficient track length and optimal contrast. The real time visualization allows tuning the parameters to achieve required regime. Quantitative measurements were provided via two-component LDA (laser Doppler anemometry) system LAD-06i developed at the Institute of Thermophysics SB RAS. A two-frequency differential optical configuration was applied with a frequency shift of 80 MHz based on a Bragg cell to eliminate the directional ambiguity focal distance of 0.5m and measurement volume of 0.05×0.05×1mm (in air). LDA system was mounted on an automated traversing system for high precision adjustments to the measurement position. The chosen measurement step along the radial coordinate was 2 mm.

3. Results and discussion

To better understand the relationship between the torsionally driven cylinder flow and the flows observed in other open geometries, the experimental data at different geometries are required. We have already tried to compare different vortex breakdown patterns at close main parameters \( Re' \) and \( S' \) introduced in [16] as follows:

\[ Re' = \frac{u_{max} R_c}{v}, \quad S' = \frac{\omega_{max}}{u_{max}} \]  

(2)

where \( u_{max} \) is the the maximum axial velocity, \( \omega_{max} \) is the the maximum tangential velocity, and \( R_c \) is the vortex core radius defined as position of maximum tangential velocity.

The results of visualization obtained in the axial plane (figure 2) clearly show a helical vortex pattern which remains unchanged over time but looks slightly different for different geometries.

![Figure 2. Visualization of the of spiral vortex breakdown for closed cylinder with Ar = 6 (left) and cone channel S' = 0.74, Re' = 210 (right).](image)
For closed cylinder with rotating lid spiral vortex breakdown was observed only at large aspect ratio close to unsteady regime at high Reynolds number. One can see unperturbed vortex core on the axis and some deviation in the lower part. At high image exposition, traces of tracers also take spiral shape. For conical swirling flow tracers clearly indicate the vortex core shift caused by its spiral form. To obtain bubble vortex breakdown in conical tube the rotating speed of swirler was changed very slowly because the flow pattern was very sensitive to all disturbance. In figure 3 one can see the axisymmetrical recirculation bubble for both geometries.

![Image](image.jpg)

**Figure 3.** Visualization of bubble vortex breakdown $S' = 1.05$, $Re' = 53$ for confined flow in cylinder at $Ar = 2$ and $S' = 1.12$, $Re' = 49$ for conical tube.

It can be seen that the trail behind the bubble in conical geometry is less swirled than in the cylindrical cavity in which diagonal traces of tracers are visible. Also, the bubble in the cone has a more elongated shape along the axis, which practically does not change in its proportions with an increase in the Reynolds number. In turn, the bubble in the confined geometry with the growth of $Re$ becomes shorter and is elongated along the radius. These differences are clearly visible if you pay attention to the angle of the tracks around the recirculation bubble. The calculated values of $S'$ and $Re'$ have good correlation with the diagram [16], it was observed that in order to switch to spiral vortex breakdown from bubble, it is necessary to decrease the swirl parameter and the Reynolds number. Quantitative data used in $S'$ and $Re'$ calculation were obtained via LDA measurements. The example of LDA velocity field for cone section is presented in figure 4.
Figure 4. Distribution of the axial velocity component in the mid plane obtained via LDA technique for bubble vortex regime at $S^' = 1.12$, $Re^' = 49$.

White area in the upper figure indicates the recirculation bubble that is symmetrical relative to vertical axis. It can be noted that the maximum axial velocity after flowing around the bubble shifts from the periphery to the centre.

Conclusions
The tracer visualisation technique has been improved and adapted for slow processes in confined and unconfined flows at low $Re$ numbers. Bubble vortex breakdown was observed at closed vortex $Re'$ and $S'$ introduced by Jones [16] for both confined flow in cylinder with rotating lid and for unconfined flow in conical tube with rotating swirler. At high aspect ratio $Ar = 6$ the stable spiral vortex breakdown was found previously not observed in confined flows.

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