Vortex breakdown in a two-fluid confined flow generated in a cylindrical container

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Abstract. Two-fluid swirling flows are rich in features of fundamental and practical interest. Among them, the most intriguing phenomenon that is important for applications is the formation of local circulation cells (vortex breakdown, VB). Our experimental study explores flows of two immiscible liquids in a sealed vertical cylindrical container driven by the rotating lid. The lid rotation generates the meridional circulation of an adjacent fluid, which serves as a rotating “liquid lid” for the lower fluid. The upper fluid goes from the cylinder axis to the periphery near the lid and back near the interface. This centrifugal circulation tends to propel the circulation in the main-fluid domain – in the lower fluid. As the angular speed of lid rotation increases, vortex breakdown occurs in the lower fluid. Using visualization of the flow and measurement of velocity by PIV method, we reveal common features of the VB development in the lower fluid at different thicknesses of the upper fluid. We show that the range of Reynolds numbers, where VB occurs, might be different depending on the volume of the upper liquid and its kinematic viscosity.

1. Introduction
Currently, various applications of swirling flows in vortex technologies are ahead of their detailed study. One of problems in using vortex devices is the loss of stability of axisymmetric swirling flows and the development of complex three-dimensional unsteady structures that significantly affect the transport processes [1]. An increase in the prediction accuracy for unsteady vortex flows is necessary in order to describe operating modes, improve vortex technologies, and to develop modern methods for their calculation. To increase the efficiency and reliability of vortex devices, a comprehensive scientific study of methods for controlling the characteristics of vortex flows and transfer processes is necessary. The most important practical direction is the development of vortex devices for improving heat and mass transfer processes in chemical, biological and energy technologies. For example in recent years, many industries (e.g., microbiological, pharmaceutical, and medical ones) require soft but efficient mixing of different ingredients and liquids. This requirement has led to the creation of gas-vortex bioreactors, whose advantage is in using a new mixing method, which provides soft circulation of biological medium necessary for aeration and photosynthesis.

To study the topology of vortex motion, a convenient model of a gas-vortex bioreactor is a sealed vertical cylindrical container filled with two immiscible liquids with a rotating lid [2]. Recent studies have shown that in such two-fluid flows there are topological phenomena of fundamental interest [3–5].

One important feature is vortex breakdown. This phenomenon causes a spontaneous change in the vortex-flow topology by the formation of recirculation zones (vortex breakdown bubbles-VBBs).
which contributes to additional mixing of ingredients and increases the yield of useful products in chemical gas and biological two-fluid vortex reactors. The experimental studies [6, 7] show how VB appears and disappears in either upper [6] or lower [7] fluids. The numerical and experimental work [8] reveals that the VB mechanism is common in one-fluid and two-fluid confined flows.

To perform soft mixing of working ingredients, one very attractive way is a “liquid lid” where the upper liquid serves as a vortex generator instead of solid disk. In order to study non-linear effects, which can intensify mass transfer in vortex bioreactors, we use a two-fluid flow configuration in a sealed vertical cylinder, driven by a rotating cover. These two immiscible liquids have different kinematic viscosities and densities. This experimental work verifies the influence of properties of the upper fluid on the evolution of the cell flow in the lower fluid in a confined cylindrical vortex reactor.

2. Experimental set up
To study a two-component fluid flow, we use the experimental setup, shown in figure 1, and apply contactless optical methods of measurements. We perform the experiments in a vertical cylindrical container of radius \( R = 45 \) mm and height \( H = 112.5 \) mm, made of optical glass. The stepper motor rotates the upper disk with an angular velocity \( \omega \) while the other walls are stationary. The lid rotation drives a fluid motion. The water jacket, which has a square cross-section, helps to correct optical distortion and to maintain constant temperature. The upper fluid diverges from the axis near the lid and converges to the axis near the interface. This centrifugal circulation drives a bulk counter-circulation of the lower fluid at a slow rotation. As the rotation intensifies, the centrifugal circulation also occurs in the lower fluid [4, 5].

![Figure 1. The scheme of fluid motion (left) and the experimental setup (right).](image)

Two liquids fill the container: the upper liquid is sunflower oil and the lower (near-bottom) liquid is water. The indices "o" and "w" denote "oil" and "water". At a room temperature of 22.6°C, the oil density and kinematic viscosity are \( \rho_o = 914.7 \) kg/m\(^3\), \( \nu_o = 49.1 \) mm\(^2\)/s. The water density is \( \rho_w = 1070 \) kg/m\(^3\) and kinematic viscosity is \( \nu_w = 1 \) mm\(^2\)/s. To measure the effect of the thickness of the upper fluid on the structure of the lower fluid flow, we perform the experiments for two cases: \( h_o = R \) and \( h_o = 0.5R \). The thickness of the lower fluid is \( h_w = 1.5R \) in both cases. The Reynolds number \( \text{Re} = \omega R^2/\nu_o \) characterizes the rotation strength.

We use Particle Image Velocimetry (PIV) to measure velocity fields in the vertical cross-section (figure 1). Polyamide beads of density 1030 kg/m\(^3\) and diameter around 10 μm serve as seeding light-scattering particles for both PIV measurements and visualization of flow pattern. The use of PIV allows obtaining an instantaneous velocity distribution in the investigated cross-section and observing an instantaneous flow pattern within the two-dimensional plane of a light sheet. As an optical source for forming the light sheet we use Nd: YAG pulsed laser POLIS v3.2 with the following characteristics: wavelength of 532 nm, light sheet thickness of 1 mm, the energy pulse power of 120
mJ, and the operation frequency of 2 Hz. A POLIS camera v1.0 with lenses Nikon AF 28 mm f/2.8D Nikkor serves to register images.

3. Development of vortex breakdown in the lower fluid

We perform PIV measurements in the range of $50 \leq \text{Re} \leq 500$ with a step of 50 in Re to explore vortex breakdown bubble evolution at $h_o = R$ and $h_o = 0.5R$. The main difficulty in the experimental investigation of VB development in lower fluids is that at steady-flow conditions, the maximal velocity of lower fluid is very small, compared with that of the upper fluid. Despite this feature, VB occurs namely in the lower fluid as shown below. To better understand why the VB occurs in the lower fluid, we introduce the Reynolds number $\text{Re}_l = V_w(h_o)R/\nu_w$, where $V_w$ is the maximal velocity of water. $\text{Re}_l$ characterizes the strength of the lower-fluid flow. $V_w$ is significantly smaller than $\omega R$ and strongly depends on $h_o$ because the motion decays downward (see the table in figure 2).

| $z/R$ | $V_{\text{max}}/(\omega R)$ |
|-------|-----------------------------|
| 2.5   | 1                           |
| 2.45  | 0.71                        |
| 2.4   | 0.48                        |
| 2.25  | 0.16                        |
| 2.0   | 0.11                        |
| 1.75  | 0.09                        |
| 1.5   | 0.05                        |

Figure 2. Distribution of axial velocity at the axis (plot) and the decay of swirl velocity in oil as $z$ decreases (table) at $\text{Re} = 250$ and $h_o = R$.

At $h_o = 0.5R$ and $h_o = R$, this decay may be 10 and 20 times, respectively. However, $V_w$ also can be significantly smaller than $\nu_o$ [7] and ratio of oil-to-water viscosities is 49 times in present experiments. Figure 2 shows the distribution of velocity at the axis (left) and the decay of swirl velocity as $z$ decreases (right) at $\text{Re} = 250$ and $h_o = R$; $z$ is the distance from the bottom.

Figure 3. Distribution of axial velocity at the axis in water for $h_o = 1R$ (left) and $h_o = 0.5R$ (right).

Figure 3 shows the transformation of the velocity distribution along the axis as $\text{Re}$ grows. It reveals that the maximum value of axial velocity $V_z$ increases and its location shifts toward the bottom. These changes are due to the growing centrifugal force. The small $z$-range of negative axial velocity emerges
near the axis at $z/R$ around 0.5 that indicates the VB location at $Re = 300$. A similar result is obtained also for the case $h_o = 0.5R$, but the Reynolds number at which VB emerges reduces from 300 to 100.

Figure 4 shows the visualization and PIV velocity field of meridional water motion for a few characteristic values of $Re$ at $h_o = 1R$ and $h_o = 0.5R$. For better resolution, the pictures are limited to the range of $0 \leq z \leq 1.5R$. In order to conveniently observe the patterns and to diminish the effect of random errors, the arrows depict velocity vectors normalized by their magnitude, i.e., only the velocity directions. Figure 4 reveals that the VBB emerges near the axis at $h_o = R$ for $Re = 300$ and at $h_o = 0.5R$ for $Re = 100$ near $z/R$ being around 0.5. In addition, figure 4 reveals that the VBB disappears at $Re = 400$ for $h_o = R$ and at $Re = 150$ for $h_o = 0.5R$.

![Figure 4](image_url)

**Figure 4.** Visualization (right) and PIV velocity field (left) of water meridional motion.

As Re increases, the meridional motion of the upper fluid (oil) transports the angular momentum from the lid downward near the sidewall and toward the axis along the interface. The convergence accelerates the rotation near the axis-interface intersection. The significantly increased centrifugal
force overcomes the convergence to the axis of the bulk water flow below the interface. Thus, the water convergence to the axis concentrates near the bottom, where a tornado-like ascending swirling jet develops. Near the axis-bottom intersection, this flow generates a local maximum of angular velocity and a local minimum of pressure. The low pressure sucks the downstream fluid and reverses it thus generating the local circulation cell. Due to the suction, the cell shifts towards the bottom, as Re increases that reduces water convergence to the axis and kills local circulation. The growing centrifugal force concentrates water circulation near the sidewall, and thus prevents the development of vortex breakdown for larger Re. These results confirm that the VB scenario in the lower fluid is common with those observed in the one-fluid flows [9] and in the upper fluid of two-fluid flows [8].

The range of Reynolds numbers can be different depending on the volume of the upper fluid and the kinematic viscosity ratio of the upper lower fluids. Such non-intrusive method of VB control can be a very attractive way of manipulating the flow pattern without complicating the design of the vortex reactor, for example, based on co-rotation and counter-rotation of a small disk embedded in the non-rotating end wall [10] or using polygonal geometry of a reactor [11].

**Conclusion**

This work shows that the vortex breakdown occurs in the lower fluid of two-fluid swirling flow driven by rotating lid in a sealed vertical container modelling a vortex bioreactor. Using the flow visualization and velocity measurements by PIV for different parameters of rotation of the upper end of the cylinder, this study reveals general features of the evolution of counter flow (bubble-like vortex breakdown, VB) which is common for two-fluid flows and single-fluid flows driven by the solid rotated end. Our research finds that the scenario for the appearance of the bubble-like vortex breakdown weakly depends on the properties of fluids. We reveal how the cellular pattern develops in the confined vortex flow of two-component immiscible liquids in the case, which we refer to as "liquid rotating lid". Its scenario appears similar to that occurring in a single-fluid flow and in the upper or lower fluids of a two-fluid flow. However, the range of the Reynolds numbers and angular velocity of disk can be different depending on the volume of the upper fluid and kinematic viscosity of the lower liquid. Therefore, this study can serve as the first step toward the “rotating liquid lid” technology for chemical and biological processes where fine, gentle, and nonintrusive mixing is favourable.

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