Common features of swirling motion of two immiscible fluids in closed vortex reactors

I V Naumov, V N Shtern, M A Tsoy and B R Sharifullin
Kutateladze Institute of Thermophysics SB RAS, 630090, Russia, Novosibirsk, Lavrentyeva str., 1
E-mail: naumov@itp.nsc.ru

Abstract. The paper analyses the typical topology of swirling flows of two immiscible fluids generated in the cylindrical container by its rotating end wall. 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 vortex flows with various liquids at the interface or the solid rotated end. In both fluids, the rotation generates centrifugal meridional circulations and a local circulation cell (vortex breakdown bubble, VBB). The research shows that the scenario for the VBB appearance depends weakly on the properties of the medium that restricts the circulation of the working fluid. Patterns and formation of cellular structure appear common for flows with “liquid bottom” and “liquid rotating lid”. The VBB scenario is similar to that occurring in a single-fluid flow and in the upper or lower fluids of a two-fluid flow, but the range of the Reynolds numbers can be different depending on the volume of the upper fluid and kinematic viscosity of the lower liquid. This study can serve as the first step in the “rotating liquid lid” and “liquid lid” technology for chemical and biological processes where fine, gentle, and nonintrusive mixing is favourable.

1. Introduction
The creation of promising vortex technologies is an extremely relevant direction for various chemical, biological, pharmaceutical reactors using vortex mixing processes. Efficient use of huge potential of closed vortex centrifugal mass and heat exchangers, simultaneously realizing the main properties of vortex and circulation motion of the confined flows, is primarily determined by flow patterns and by understanding of vortex motion at varying speeds of rotation. One of the problems with the use of vortex devices is the loss of steadiness and axially symmetry of swirling flows and the emergence of various complex three-dimensional non-stationary structures that significantly affects the transport processes in vortex devices [1].

Two-fluid flows recently attracted the attention of researchers due to applications in aerial vortex bioreactors [2, 3]. The air flow transports oxygen (O_2), required for tissue growth, to the interface. O_2 diffuses through the interface and is dissolved in water. The meridional circulation of water helps mix the dissolved O_2 and other ingredients. Thus the aerial vortex bioreactor provides nonintrusive and fine mixing required for efficient growth of tissue cultures. A proper model of an aerial vortex bioreactor is a sealed vertical cylindrical container (Fig. 1) whose lid rotates while other walls are stationary.
Recent studies revealed that such two-fluid flows have paradoxical features of fundamental and practical interest.

One important feature is a curious deformation of the interface. Its shape can significantly enlarge the interface area thus enhancing diffusion of O$_2$. To observe deformations of the interface in a laboratory, oil-water systems are suitable because the densities of oil and water are close [4]. Another important phenomenon is vortex breakdown. This phenomenon is characterized by spontaneous change of vortex-flow topology, e.g., the formation of recirculation zones (vortex breakdown bubbles, VBBs) which contributes to additional mixing of ingredients and increases yielding of useful products in chemical and biological two-fluid vortex reactors. The experimental study [5, 6] showed how VB appears and disappears in the upper fluid. The experimental study [7] detected VB in the lower fluid and tracked it evolution process as the rotation speeds up. The numerical and experimental work [8] revealed that the VB mechanism is similar in one-fluid and two-fluid confined flows.

The goal of current experimental work is to check the influence of properties of used liquids on the evolution of cellular flow and transition to non-stationary states of the vortex motion in closed cylindrical vortex reactors. Our study reveals common features of VBB formation in confined vortex flow of two-component immiscible [5, 7] for conditional modes named as "liquid bottom" and "liquid rotating lid". To study the nonlinear effects and the intensification of mass transfer in a vortex bioreactor, we use a flow in a sealed vertical cylinder, driven by its rotating lid, of two immiscible liquids of different kinematic viscosities and densities. The main difficulty in the experimental investigation of simultaneous VB development in both upper and lower fluids is that at steady-flow conditions, the velocity of the lower fluid is very small to be precisely measured when VB forms in the upper fluid.

2. Experimental set up
To study two-fluid flows, we use experimental setup (which serves as a bioreactor model), shown in Figure 1. This setup is suitable for using contactless optical methods in swirling motions. The lid of a sealed vertical cylindrical container, of radius $R$ and height $h$, rotates with angular velocity $\omega$, while the other walls are stationary. The axial extents at rest of the lower and upper fluids are $h_{w+}$ and $h_o$, respectively. The dimensions are: $R = 45$ mm, $h = 3.0R$, $h_{w+} = 0.1-1.5R$, and $h_o = 0.5-2.5R$. The lower fluid is water (hereafter referred to as water+) of density $\rho_{w+} = 1070$ kg/m$^3$ and kinematic viscosity $\nu_{w+} = 1$ mm$^2$/s. The upper fluid is sunflower oil of density $\rho_o = 920$ kg/m$^3$ and viscosity $\nu_o = 49$ mm$^2$/s. The flow is kept isothermal at 22.6 $^\circ$C. A water jacket with a square cross section helps correct optical distortion and maintains a constant temperature.

![Figure 1. Photo (a) and problem schematic (b) of the experimental set-up for measurements in the vertical cross-sections.](image-url)
The strength of rotation is characterized by the Reynolds number $Re = \frac{\omega R^2}{\nu_o}$. The visualization and the velocity fields in the vertical cross-section were measured using planar Particle Image Velocimetry (PIV). Polyamide beads, of density $1030 \text{ kg/m}^3$ and diameter around 10 μm, were employed as seeding light-scattering particles for both PIV measurements and visualization of flow pattern. The previous studies [4, 8] showed that the experimental (with tracers) and numerical (with no tracer) velocity profiles and flow patterns well agree in the upper fluid (oil). This agreement indicates that the presence of the tracer particles does not significantly disturb the flow. The amount of particles in the oil (plus the averaging procedure in tracking visualization) was sufficient for detecting of dual VB both up and down fluids. This makes it possible to obtain an instantaneous velocity distribution in the investigated vertical and horizontal cross sections and to observe an instantaneous flow patterns within the two-dimensional plane of a light sheet. As an optical source for forming the light sheet, we used Nd: YAG pulsed laser POLIS v3.2. Its characteristics are: wavelength is 532 nm; light sheet thickness is 1 mm; the energy pulse power is 120 mJ; and the operation frequency is 2 Hz. The measurements address the vertical cross-section located at the geometric center of the container and the horizontal cross-section for azimuthal velocity measurements using a mirror located at 45 degree below glass bottom of cylindrical container as it shown in Fig. 1(b). We registered images by POLIS camera v1.0 with lenses Nikon AF 28 mm f/2.8D Nikkor.

3. Results
This experimental study of a two-fluid swirling motion investigates the flow topological transformations for configuration of the confined vortex flow with two immiscible liquids with close but different densities. The rotating lid drives a flow in a sealed vertical cylindrical container. The upper fluid—sunflower oil—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 effect also take place in low fluid. These two factors tend to drive opposite meridional circulations of the lower fluid. What factor is stronger depends on Re. The slip develops if the centrifugal force overcomes and generates a cell of centrifugal circulation below the interface-axis intersection [10]. Such a scenario can occur even if the fluid densities are close.

3.1 Liquid bottom

![Diagram of the VB area](image1)

**Figure 2.** Diagram of the VB area: point line – with fixed solid end, circle and solid line – with liquid bottom; Photo VB: (a) $h_o = 1.5R$, $h_{w+} = 0.5R$ and (b) $h_o = 1.5R$, $h_{w+} = 0.1R$.

First, our study of the confined vortex flow in a vertical cross-section reveals that the scenario for the development of the cellular structure in the case of liquid bottom does not differ from that in the case of free surface where the bottom wall rotates [6]. This study on the effect of non-rotating ends of
different types on the flow state compares the recent results with the classical case of a single liquid [9]. Figure 2 presents the diagram of the VB area and photos of VB with different thickness of lower liquid. The appearance of the area of return flow of the "bubble" was determined visually by increasing the thickness of the trace of particles on the axis of the cylinder in a vertical section with a step on the Reynolds number equal to 20.

We analyze the topology of swirling flows generated in the cylinder by its rotating upper end. The research finds that the scenario for the appearance of the bubble-like breakdown region depends weakly on the properties of the medium that restricts the circulation of the working fluid, but differs significantly from the dynamics of vortex flows limited by the “solid” second wall – the fixed end of the cylinder. We also find that the presence of an end face with a free surface, significantly affects the formation of a recirculation zone of the return flow, shifting the diagram of its formation at the axis to smaller Reynolds numbers (ΔRe ≈ 500) and smaller relative aspect ratio (Δh ≈ 0.5R). However, the use of media with different densities and viscosities has no significant effect on both processes: the formation of an axial bubble and its contact with the interface (Fig. 2a and 2b).

### 3.2 Liquid rotating lid

The difficulty of using the term "liquid lid" may be that, unlike in the solid-body rotation, where the angular velocity is constant and the swirl velocity is maximal at the periphery of the disc, this is not the case for a liquid rotating fluid. This difference makes difficult to calculate the Reynolds number for the lower liquid because the maximal swirl velocity at the interface is not known in advance. The next important difference is that, unlike in the cases of a still disk, the interface of the two fluids not only rotates. At the interface, the radial velocity is not zero as the flow converges to the axis.

For investigation of the “liquid rotating lid” configuration the height $h_o$ was decreased and $h_w+$ was increased to $h_w+ ≥ 1.2R$ in order to compare with the VB diagram for solid bottom configuration (fig 2a). Figure 3(a) shows the flow pattern at $Re = 300$ where VB formed in the lower fluid (water+) with $h_o = 1.0R$, $h_w+ = 1.5R$. This photo shows the VBB located in the water domain. No VBB occurs in the upper fluid. The lower-fluid VB emerges at smaller Re compare with diagram in fig 2a than Re at which VBB emerges in the upper-fluid VB because $v_{w+}$ (1 mm$^2$/s) is drastically smaller than $v_o$ (49 mm$^2$/s).

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
The upper fluid, to be precisely measured when VB forms in the upper fluid. To better understand why the VB first occurs in lower fluids, we introduce the Reynolds number $Re_l = \frac{V_{w^+}R}{\nu_{w^+}}$, where $V_{w^+}$ is the maximal velocity of water. $Re_l$ characterizes the strength of the lower-fluid flow. $V_{w^+}$ is significantly smaller than $\omega R$ because the motion decays downward. However, $\nu_{w^+}$ also can be significantly smaller than $\nu_o$.

Figure 3b and Table 1 shows the decreasing of maximal azimuthal velocity ($V_{\theta_{\text{max}}}$) in the oil above the interface with increasing distance from rotated lid (located at $h = 2.5R$). The pattern of attenuation of the maximum velocity falls on almost one curve (figure 4).

Figure 4b illustrates the transformation of $r$-profiles of normalized azimuthal velocity $V_{\theta}$ as the distance from the rotating disk (located at $z = 2.5R$) increases at $Re = 100$. The location of $V_{\theta_{\text{max}}}$ shifts from $r = 1$ at $z = 2.5R$ to around $r = 0.5$ at $z = 1.54R$.

| Table 1. Normalized maximal tangential velocity ($V_{\theta_{\text{max}}}/(\omega R)$). |
|---|---|---|---|---|---|---|
| $Re$ | 2.46 | 2.43 | 2.39 | 1.94 | 1.72 | 1.61 |
| 50 | - | - | - | 0.044 | 0.034 | 0.031 |
| 100 | 0.81 | 0.66 | 0.45 | 0.09 | 0.047 | 0.035 | 0.034 |
| 150 | 0.75 | 0.64 | 0.52 | 0.095 | 0.053 | 0.041 | 0.04 |
| 200 | 0.69 | 0.58 | 0.46 | 0.098 | 0.063 | 0.052 | 0.048 |
| 300 | 0.67 | 0.58 | 0.48 | 0.11 | 0.065 | 0.06 | 0.051 |
| 420 | 0.64 | 0.58 | 0.49 | 0.11 | 0.07 | 0.06 | 0.051 |

The figure 4b illustrate the dependence on $Re$ of $r$-profiles of normalized azimuthal velocity $V_{\theta}$ at $z = 88$ mm. Away from the near-sidewall region, $V_{\theta}$ is proportional to $r$ and decreases as $Re$ increases. This indicates the formation of the boundary layer near the rotating lid.

![Figure 4](image-url)
fluid depends on two competing forces, induced by the upper-fluid motion: the centrifugal force and the viscous radial stresses at the interface.

Figure 5 shows that when the Reynolds number increases, the maximum value of $V_\theta$ in the upper fluid shifts to the cylinder axis. In contrast, the maximum value of $V_\theta$ in the lower fluid. Thus, in order to obtain the VB regime in the lower fluid, it is necessary to take into account these features and to select accordingly the viscosity ratio of the working liquids.

Figure 5b illustrates the transformation of r-profiles of normalized $V_\theta$ as the distance from the rotating disk (located at $z = 2.5R$) increases at $Re = 100$. The location of $V_{\theta\_max}$ shifts from $r = 1$ at $z = 2.5R$ to around $r = 0.5$ at $z = 1.54R$.

**Figure 5.** Radial profiles of $V_\theta$ above and below interface at $Re=100$ (a) and $Re= 300$ (b).

### 4. Conclusion

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 vortex flows with various liquids at the interface or 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 structure forms in the confined vortex flow of two-component immiscible liquid under conditional modes "liquid bottom" and "liquid rotating lid". This 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 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 in the “rotating liquid lid” technology for chemical and biological processes where fine, gentle, and nonintrusive mixing is favourable. The obtained results are important for the development of vortex devices and reactors where complex vortex motions of ingredients occur for mass transfer intensification. They can help both for optimizing the operation of existing devices and for designing new ones.

**Acknowledgments**

The development of PIV measurements and methodology of visualization was carried out under state contract (AAAA-A17-117030910025-7) with IT SB RAS. This work was partially supported by the Russian Foundation for Basic Research No.18-08-00508.
References

[1] Shtern V 2012 Counterflows: Paradoxical Fluid Mechanics Phenomena (New York: Cambridge University Press)

[2] Nielsen L K 1999 Bioreactors for hematopoietic cell culture Annu. Rev. Biomed. Eng. 1 129-152

[3] Dusting J, Sheridan J, Hourigan K 2006 A fluid dynamics approach to bioreactor design for cell and tissue culture Biotechnol. Bioeng. 94(6) 1196-208

[4] Carrión L, Herrada M A, Shtern V N 2017 Topology changes in a water-oil swirling flow Phys. Fluids 29 032109

[5] Naumov I V, Glavny V G, Sharifullin B R, Shtern V N 2019 Formation of a thin circulation layer in a two-fluid rotating flow Phys. Rev. Fluids 4 054702

[6] Naumov I V, Kashkarova M V, Mikkelsen R F, Okulov V L 2020 The structure of the confined swirling flow under different phase boundary conditions at the fixed end of the cylinder Thermophys. and Aeromech. 27(1) 89-94

[7] Naumov I V, Sharifullin B R, Shtern V N 2020 Vortex breakdown in the lower fluid of two-fluid swirling flow Phys. Fluids 32 014101

[8] Carrion L, Naumov I V, Sharifullin B R, Herrada M A, Shtern V N 2020 Mechanism of disappearance of vortex breakdown in a confined flow J. Eng. Thermophys. 29 49-66

[9] Naumov I V, Mikkelsen R F, Okulov V L 2017 Stagnation zone formation on the axis of a closed vortex flow Thermophys. Aeromechanics Thermophys. and Aeromech. 24(4) 561-567

[10] Naumov I V, Herrada M A, Sharifullin B R, Shtern V N 2018 Slip at the interface of a two-fluid swirling flow Phys. Fluids 30 074101