Control of vortex breakdown in confined two-fluid flows

I V Naumov, B R Sharifullin and V N Shtern
Kutateladze Institute of Thermophysics SB RAS, 630090, Novosibirsk, Russia
Novosibirsk State University, 630090, Novosibirsk, Russia
E-mail: naumov@itp.nsc.ru

Abstract. This paper describes the first experimental evidence of how vortex breakdown develops and disappears in both upper and lower fluids in a sealed vertical cylindrical container, where two immiscible fluids circulate driven by the rotating lid while other walls are stationary. The rotating lid generates both swirling and meridional circulations of the upper and lower fluids. The most intriguing and practically important flow phenomenon is the formation of local circulation cells (vortex breakdown). Our experimental study reveals that vortex breakdown can occur in (a) upper, (b) lower, and (c) both fluids. The kind of flow pattern depends on properties of liquids. The vortex breakdown flows can intensify heat and mass transfer.

1. Introduction
Starting with report [1], more than thousand papers studied the vortex breakdown (VB) phenomenon. This lasting attention is due to (a) important technological applications and (b) apparently enigmatic mechanism of VB. The VB affects the lift and drag forces of delta-wing aircraft, stabilizes flame in combustion chambers, helps mixing ingredients in chemical and biological reactors, and weakens tornadoes [2]. We explore possible applications of VB for heat pipes.

Following Vogel [3] and Escudier [4], many researchers used a sealed cylindrical container for fundamental studies of VB. The simple geometry of container and absence of ambient disturbances ease both experimental and numerical studies that helps understand the VB physics.

Two-fluid flows recently attracted the attention of researchers due to applications in aerial vortex bioreactors [5-8]. Air transports oxygen, required for tissue growth, to the interface [5]. The oxygen diffuses through the interface and dissolves in water. The meridional circulation of water helps mix the dissolved oxygen and other ingredients. Thus, the aerial vortex bioreactor provides nonintrusive fine mixing required for efficient growth of tissue cultures [6]. A proper model of an aerial vortex bioreactor is a sealed vertical cylindrical container whose lid rotates while other walls are stationary [7]. Recent studies have revealed that such two-fluid flows have paradoxical features of fundamental and practical interest. One important feature is spectacular deformations of the interface. Its shape can significantly enlarge the interface area thus enhancing mass transfer. To observe deformations of the interface in a laboratory, oil-water systems are suitable because the densities of oil and water are close. Fujimoto and Takeda first performed such a study [9]. Their experiments revealed impressive bends of the interface in a flow of silicon oil and water. As the rotation intensifies, the interface takes shapes named by Fujimoto and Takeda as “hump”, “cusp”, “Mt. Fuji”, and “bell”.

Another important phenomenon is vortex breakdown in the upper fluid first observed by Tsai et al. in a flow of soybean oil and water [10]. The experimental studies [11, 12] showed how VB appears and disappears in the upper fluid. These works revealed that the VB mechanism is similar in one-fluid
and two-fluid confined flows. However, the studies [9-12] provided no information on what is a pattern of flow in the lower-fluid domain. The main difficulty is that at steady-flow conditions, the velocity of the lower fluid is so small compared with that in the upper fluid that cannot be easily detected. Our study overcame this difficulty by (a) selecting proper volumes and properties of the lower and upper fluids, (b) using enhanced laser illumination, and (c) averaging 500 images of instantaneous velocity fields. This advance in the experimental technique helped us to discover new striking fluid-mechanics phenomena: VB in the lower fluid and double vortex breakdown, simultaneously developing in both fluids, as the rotation intensifies. The resulting multicellular flow can significantly intensify heat and mass transfer in heat exchangers.

2. Problem Formulation

Figure 1 (a) shows a schematic of device geometry and flow pattern at Re = 200 where VB is presented neither in the upper nor in the lower liquid (fig 1b). 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; \( g \) is the gravitational acceleration.

![Figure 1.](image)

**Figure 1.** (a) Schematics of the experimental setup for measurements in the vertical cross-section; (b) photo (left) and velocity field (right) of oil-water meridional motion at Re = 200.

The dimensions of the flow domain are: \( R = 45 \text{ mm} \), \( h = 2.5R \), \( h_w = 1.5R \), and \( h_o = R \). The upper fluid is sunflower oil of density \( \rho_o = 920 \text{ kg/m}^3 \) and viscosity \( \nu_o = 49 \text{ mm}^2/\text{s} \). The lower fluid is a glycerol-water solution with different concentration of glycerol of 78% or 33% (hereafter referred to as glycerin or water+, respectively). The strength of rotation is characterized by the Reynolds number \( Re = \omega R^2/\nu_o \). We measure the velocity fields, using the Particle Image Velocimetry (PIV), and employ polyamide beads with the density of 1030 kg/m\(^3\) and diameter of around 10 \( \mu \text{m} \), as seeding light-scattering particles for both PIV measurements and visualization of flow pattern (figure 1(b)). Paper [13] describes the experimental technique in more detail.

The previous study [12] 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 the dual VB in both upper and lower fluids. This allows obtaining instantaneous velocity distributions and observing instantaneous flow patterns in 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 of 532 nm; light sheet thickness of 1 mm; the energy pulse power of 120 mJ; and the operation frequency of 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 degrees below the 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. Discussion of experimental results

Figure 2(a) is a photo of VB bubble observed in the centre of oil domain at Re = 700 [11]. The lower fluid in case I is the glycerol-water (78% - 22 %) solution of density $\rho_g = 1208 \text{ kg/m}^3$ and kinematic viscosity $\nu_g = 43 \text{ mm}^2/\text{s}$. No VB occurs in the lower fluid.

Figure 2(b) shows the flow pattern at Re = 300 in the case II where the lower fluid is water with $\rho_w = 1000 \text{ kg/m}^3$ and viscosity $\nu_w = 1 \text{ mm}^2/\text{s}$. This photo shows the VB bubble located in the water domain. No VB bubble occurs in the upper fluid. The lower-fluid VB emerges at smaller Re than that in the upper-fluid VB because $\nu_w (1 \text{ mm}^2/\text{s})$ is drastically smaller than $\nu_o (49 \text{ mm}^2/\text{s})$.

The main difficulty in the experimental investigation of simultaneous VB development in both upper and lower fluids is that at steady-flow conditions, the maximal velocity of lower fluid is very small, compared with that of the upper fluid, to be precisely measured when VB forms in the upper fluid. To better understand why the VBBs simultaneously emerge in both fluids, we introduce the Reynolds number $Re_l = V_{w+}R/\nu_w$, where $V_{w+}$ is the maximal velocity of water+. Re characterizes the strength of the lower-fluid flow. $V_{w+}$ is significantly smaller than $\omega R$ because the motion decays downward. However, $\nu_{w+}$ can be also significantly smaller than $\nu_o$. By choosing a proper water-glycerol solution, we found such $\nu_{w+}$ value which makes Re and Re$^l$ almost equal. This finding results in the simultaneous vortex breakdown in both fluids. Figures 2(c) show the flow pattern at Re = 700 in the case III where the lower fluid is the glycerol-water (33%-67%) solution (water+) with $\rho_{w+} = 1070 \text{ kg/m}^3$ and $\nu_{w+} = 3 \text{ mm}^2/\text{s}$. In this case, VB bubbles exist in both upper and lower fluids.

Figure 3 shows the transformation of the velocity distribution along the axis as Re grows, which provides some details of VB development in the cases I-III (see Fig.2) in (I) upper, (II) lower, and (III) both fluids. Figure 3 reveals that the maximum value of axial velocity $V_z$ in lower fluid increases and its location shifts toward the bottom, as Re grows. These changes are due to the growing centrifugal force. It presses a fast-rotating fluid to periphery and thus postpones its convergence to the axis until the fluid reaches the dead-end vicinity. This results in a jet-like boundary layer where the fluid goes down near the sidewall, converges to the axis near the bottom, and rises along the axis. The similar development of VB in the lower fluid occurs in case II where velocity profile in upper fluid has no local minimum at the z axis. In case III, the system parameters and kinematic viscosity of lower fluid
are selected so that the VB also develops in the upper fluid. This observation has revealed that the VB mechanism is similar in both one-fluid and two-fluid confined flows for upper and lower fluids.

**Figure 3.** Development of VB in the upper and lower fluids in cases I, II and III.
Conclusions
Our experimental study reveals that vortex breakdown can occur in (a) upper, (b) lower, and (c) both fluids depending on control parameters and on the upper-to-lower fluid viscosity ratio. The revealed double-VB pattern looks especially unusual and impressive. Multiple circulation cells of this flow should provide efficient heat and mass transfer. It is shown that two-fluid swirling flow can be effectively controlled by selecting appropriate volumes and properties of the lower and upper fluids. The considered vortex breakdown flows can be used in biological and chemical reactors where flows with slow velocities and low Reynolds numbers may be practical.

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