Multi-cellular pattern of a two-fluid swirling flow in a closed cylinder

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Abstract. This experimental study explores an intriguing phenomenon occurring in two-fluid swirling flows. In a sealed vertical cylindrical container, the flow is driven by the rotating lid while other walls are stationary. The lid rotation generates the meridional circulation of an adjacent fluid. The fluid goes from the cylinder axis to the periphery near the lid and back near the interface. This centrifugal circulation tends to propel the counter-circulation of the lower fluid. In contrast, the rotation tends to propel the co-circulation of the lower fluid. Thus, the two competing factors — (1) swirl and (2) meridional velocities at the interface — tend to push the lower fluid in opposite directions. As the rotation intensifies, factor (1) dominates over factor (2) and the new flow cell emerges near the interface in the lower fluid. The emergence of the new flow cell was predicted by numerical simulations. The current work provides the first experimental evidence of the new-cell development in the lower fluid.

1. Introduction

Swirling two-fluid flows attract the attention of researchers due to applications in aerial vortex bioreactors and are of fundamental interest due to their striking features and nontrivial topology [1-7]. Fujimoto & Takeda [4] experimentally studied interface shapes in a flow of water and silicone oil driven by the rotating lid in a vertical sealed cylindrical container. As the rotation intensifies, the interface becomes strongly and unusually deformed. The experiment of Tsai et al. [5] revealed vortex breakdown in the oil flow and the numerical simulations by Carrion et al. [3] predicted that vortex breakdown also occurs in the water flow.

The combined experimental and numerical study [7] of a sunflower-oil-water system first performed measurements of velocity in the oil domain. These experimental results agree with the numerical prediction. Unfortunately, no velocity measurement was achieved in the water domain, because the velocity magnitude in water was too small to be detected. As shown below (figure 2), the first change in the flow topology occurs at the Reynolds number Re around 100 and the characteristic velocity in glycerin being 19 µm/s (table 1). In water, the velocity would be even 43 times (the glycerin-to-water viscosity ratio) less. The signal-to-noise ratio is too small for velocities less than 1 micron per second. This makes problematic velocity measurements and flow visualization.

The current study overcomes this limitation by replacing water with a water-glycerin solution (hereafter referred to as “glycerin” for brevity) whose viscosity is close to that of the oil while the density difference for oil and glycerin is more than that for oil and water. This modification and the
averaging of 200 PIV images (in order to increase the signal-to-noise ratio) allow for measuring velocity and to experimentally identify flow patterns in the lower liquid as well. These first-obtained results for the lower-fluid flow disclosed a controversy between the numerical predictions and the experimental observations and measurements.

2. Experimental set up
We study a two-fluid flow in a sealed vertical cylindrical container of radius R and height h. The flow is driven by the lid, rotating with angular velocity \( \omega \), while the other walls are stationary. Figure 1 shows a schematic of the problem. The axial extents at rest of the heavy and light fluids are \( h_g \) and \( h_o \) respectively; \( g \) is the gravitational acceleration. The dimensions are: \( R = 45 \) mm, \( h = 2.5 R \), \( h_g = 1.5 R \), and \( h_o = R \). The heavy fluid is a glycerine-water solution of density \( \rho_g = 1208 \text{ kg/m}^3 \) and kinematic viscosity \( \nu_g = 42.82 \times 10^{-6} \text{ m}^2/\text{s} \). The light fluid is sunflower oil of density \( \rho_o = 920 \text{ kg/m}^3 \) and viscosity \( \nu_o = 54.86 \times 10^{-6} \text{ m}^2/\text{s} \). Estimated surface tension at the interface is \( \sigma = 0.0315 \text{ N/m} \). The flow is kept isothermal at the room temperature 22.6\(^\circ\)C.

The rotation strength is characterized by the Reynolds number \( \text{Re} = \omega R^2/\nu_o \). The velocity fields were measured by Particle Image Velocimetry (PIV). The use of PIV makes it possible to obtain an instantaneous velocity distribution in the investigated cross section and to observe an instantaneous flow pattern within the two-dimensional plane of a light knife. The pulsed laser creates the thin light knife and illuminates small particles suspended in the investigated stream. The particle positions at the time of two consecutive laser flashes are recorded on two frames of a digital camera. The flow velocity is determined by the calculation of the motion that the particles make during the time between laser flashes. Polyamide beads, of density 1030 kg/m\(^3\) and diameter around 20 \( \mu \text{m} \), were employed as seeding light-scattering particles for both the flow visualization and PIV measurements.

3. Development cellular structure in two-fluid flow
Figure 2 shows photos of meridional circulation and measured profiles of velocity along the axis at a few characteristic values of the Reynolds number. The interface is observed as the light horizontal lane. The images of meridional circulation were obtained by averaging 100 frames and inverting the average image. At \( \text{Re} = 50 \), the maximal axial velocity magnitude is 4.83 mm/s in oil and 0.0124 mm/s in glycerine. At \( \text{Re} = 300 \), the maximal axial velocity magnitude is 27.61 mm/s in oil and 1.48 mm/s in glycerine. To conveniently observe the velocity profiles of oil and glycerine in one figure, \( V_z^{1/3} \) is plotted.
Figure 2. Visualization of meridional circulation and measured velocity along the axis at Re = 50 (a), 100 (b), 200 (c) and 300 (d).

Unfortunately, details of the meridional circulation of glycerine are not quite clear (especially for small Re) in figure 2 because the smaller Re is, the smaller the signal-to-noise ratio is. In the oil domain, the light reflection from the rotating lid and from the interface limits the observation of the upper-fluid flow. Despite these limitations, figure 2 reveals the key result of this study: the new flow cell emerges in the glycerine domain near the interface-axis intersection and expands downward. This feature is also confirmed by the PIV measurements of the velocity distributions along the axis discussed next.

The results, shown in figure 2, confirm that as Re increases, the velocity at the axis becomes positive in some range below the interface. The positive range of is small in the glycerine at Re = 100, but eventually occupies the entire axis as figure 2(d) shows at Re 300. This is a direct effect of enhanced swirl, which tends to generate the centrifugal circulation in the glycerine domain as well. The development of a new circulation cell in the lower liquid occurs similarly as in mono-fluid swirling flows [8]. However, the presence of an upper liquid, which serves as a deformable liquid “cover”, significantly affects the cellular structure.

Table 1 lists dimensional characteristic velocities. V_z denotes the velocity at the axis; subscripts g and o mean glycerine and oil, respectively; max and min correspond to the maximal and minimal values. Since the glycerine velocities are very small compared with the oil velocities at low Re, figure 2 plots V_z^{1/3} in order to conveniently observe the velocity profiles of oil and glycerine in one figure.

Figure 2(a) depicts the distribution typical of slow motion: the velocity at the axis is positive (directed upward) in the oil domain and negative (directed downward) in the glycerin domain. This corresponds to the centrifugal meridional circulation of oil which generates the counter-circulation of
glycerin as figure 1 schematically depicts. At Re = 100, a small cell of the centrifugal circulation of glycerin is located below the interface-axis intersection. At Re = 200, this cell occupies around the upper half of the glycerin domain. At Re = 300, the centrifugal circulation occupies nearly the entire glycerin domain. This transformation is the effect of enhancing swirl, which tends to generate the centrifugal circulation in the glycerin domain as well. Figure 3 depicts the axial velocity distribution along the axis in glycerin.

Imagine that the interface is a thin layer filled with oil-glycerin emulsion. Since the glycerin density is larger than the oil density, the centrifugal force pushes glycerin particles to the periphery stronger than it pushes oil particles. This can cause a difference in the radial velocity of oil and glycerin particles. As swirl intensifies, the difference increases and despite the oil radial velocity remains negative, i.e. oil converges to the axis, the glycerin radial velocity can become positive at the interface. The resulting radial divergence of glycerin can cause the development of glycerin centrifugal circulation near the interface.

As the Reynolds number further increases (more 300), the interface is strongly deformed (upward near the axis and downward near the sidewall) as figure 4 illustrates. Figure 4 shows the appearance and disappearance of recirculation region in oil flow. The oil flow is one-cellular in figure 4(a). The new cell is observed above the interface in figure 4(b). This cell expands in figure 4(c). Then the axial extent of oil cell decreases. The cell totally disappears in figure 4(d). The laser gives a glare when passing through the interface. Therefore, there is a scatter of points on the photos near the interface. In this case velocity differences in oil and glycerin are not too big according table 1.

### Table 1. Characteristic velocities in mm/s.

| Re  | \(\omega R\) | \(V_{zo\, min}\) | \(V_{zo\, max}\) | \(V_{zg\, max}\) | \(V_{zg\, min}\) |
|-----|-------------|-----------------|-----------------|-----------------|-----------------|
| 50  | 61          | 0               | 4.83            | 0               | -0.012          |
| 100 | 122         | 0               | 11.5            | 0.001           | -0.019          |
| 200 | 244         | 0               | 21              | 0.218           | -0.055          |
| 300 | 367         | 0               | 30.2            | 1.28            | 0               |
| 600 | 734         | 6.1             | 17.7            | 12.2            | -5.7            |
| 700 | 856         | -0.8            | 19.5            | 15.5            | -10.1           |
| 800 | 978         | -3.9            | 18.6            | 22.4            | -19.4           |
| 1000| 1223        | 0.4             | 19.2            | 30.9            | -32.6           |

![Figure 3](image_url)  
**Figure 3.** Measured velocity along the axis in the glycerine at different Re.
Figure 4. Visualization of emergence and disappearance of near-axis oil cell as Re increases and measured velocity along the axis at Re = 600 (a), 700 (b), 800 (c) and 1000 (d).

The development of the vortex breakdown (VB) in the upper liquid occurs similarly to that in mono-fluid flocs [9, 10]. However, the presence of a lower liquid, which serves as a liquid “bottom”, significantly affects the formation of recirculation zone in the upper fluid. The VB emergence occurs at lower Re and the VB bubble has a shorter axial extent.

The results, presented in figure 3, show that at large Re, the thin layer of circulation is located below the interface-axis intersection. As Re further increases, its axial extent first increases, as figures 4(a) and 4(b) illustrate, and then decreases, as figures 4(c) and 4(d) illustrate.

4. Conclusion
This study reveals an intriguing development of the multi-cellular structure in a two-fluid flow. The motion is driven by the rotating lid 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, one more circulation cell first emerges in the lower fluid and then the VB bubble appears and disappears in the upper fluid.

Since the lower-fluid flow is weak compared with the upper-fluid flow, it has been neither visualized nor measured in prior experimental studies. This difficulty is overcome here by using a water-glycerin solution for the lower fluid. Its viscosity is chosen to be close to the upper-fluid viscosity. This viscosity is larger by two orders of magnitude than the viscosity of water, which served
as the lower fluid in prior studies. The enlarged viscosity made possible both the flow visualization and PIV velocity measurements in the lower fluid as well.

The experimental results revealed that the new circulation cell emerges in the lower fluid near the interface-axis intersection. As the Reynolds number further increases, a new circulation cell in the lower liquid develops similarly to that mono-fluid swirling flows. Then the interface strongly bends (upward near the axis and downward near the sidewall) and the thin layer of reversal circulation emerges in glycerin again below the interface-axis intersection.

The VB occurs in the upper liquid at 600<Re<1000 similarly to that in mono-fluid swirling flows. However, the presence of a lower liquid, which forms a liquid “bottom”, significantly affects the formation of the recirculation zone. The VB occurs at lower Re and the axial extent of VB bubble is smaller.

Acknowledgments
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