Flow at the interface of two rotating fluids

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Abstract. Recent studies discovered a discontinuity of the radial velocity (slip) at the interface of two immiscible rotating fluids. This work investigates how this phenomenon depends on densities and viscosities of fluids. A sealed vertical cylindrical container models a bioreactor. The rotating lid drives the flow while other container walls are stationary. As the rotation intensifies, the slip develops at the interface. A conjecture is that the slip occurs due to a difference in fluid densities and the centrifugal force. To test this conjecture, this experimental work uses fluids of close densities and reveals that the slip does not disappear even if the density difference is small, compared with that in prior studies. For comparison, this study also explores the case where the densities significantly differ while the fluid viscosities are close. The slip occurs in this flow as well. A new conjecture is that competing effects of the upper-fluid rotation and convergence near the interface also can cause the slip. This study also shows that the slip is a robust phenomenon occurring in swirling flows of various fluids.

1. Introduction
Two-fluid vortex flows attract the attention of researchers due to applications in bioreactors. They also are of fundamental interest because of multiple topological transformations observed in these flows [1-3]. Progress in the field of tissue engineering has predetermined the need to grow cell massifs or cell tissues suitable for therapy in large volumes and became the reason for creating effective bioreactors from micro-sized to large tanks with the organization of a rotating circulation fluid flow in them [4-7]. Requirements for the device bioreactors include well-formed hydrodynamic flow, allowing for delivering nutrients and organizing gas exchange with the external environment. In individual processes, where adherent cells are cultivated (i.e., endothelial cells, epithelial cells, or chondrocytes), the surface properties of the swirling element and the avoidance of interaction with the impeller blades become important. In this regard, the process of creating bioreactors is hampered by some hydrodynamic constraints; therefore, the dynamics of fluid movement in bioreactors is one of the areas requiring close attention. Despite attempts to predict the flow in a real bioreactor, using both computational and experimental methods, there are only a few examples of successful hydrodynamic design [6, 8].

To study the nonlinear effects and intensification of mass transfer in a vortex bioreactor, we use a flow of two immiscible liquids of different kinematic viscosity and density in a sealed vertical cylinder, driven by its rotating lid.

There are very few experimental studies of swirling two-fluid flow in a cylinder with a rotating lid. The first experimental works explored the interface shapes in a flow of silicon [9] and soybean oil [10] and water. As the rotation intensifies, the interface takes shapes named, by the authors, hump, cusp, Mt. Fuji, and bell [9] and a vortex breakdown bubble emerges in the oil domain [10]. The numerical simulations [11] of this flow revealed that vortex breakdown also occurs in the water domain. The recent
studies [12, 13] investigated a swirling two-fluid flow in a sealed vertical cylindrical container filled with water and sunflower oil. These studies revealed a hysteresis associated with the contact angle between the water-oil interface and the cylinder walls. The next experimental findings [14, 15] revealed that a new circulation cell emerges near the interface and expands downward, while numerical simulation [11], performed under the continuity condition for all velocity and stress components, predict that the new cell emerges near the bottom and expands upward. One explanation of this contradiction is that there is a slip at the interface which occurs due to the centrifugal force and different fluid densities [14].

In the current experimental work, the densities of immiscible liquids are close. The goal is to check the effect of slip and to compare the scenario of flow development under the interface with that in the previously studied case of a large difference in densities and close kinematic viscosity [14, 15]. To this end, we study here the motion of liquids with (I) close kinematic viscosities and (II) close densities.

2. Experimental set up
To study two-fluid flows, we use experimental setup, shown in Figure 1. This setup is suitable for using contactless optical methods in swirling motions. Experiments are performed in a vertical cylindrical container of radius R = 45 mm and height h = h_o + h_g = 112.5 mm, made of optical glass. The upper disk rotates with angular velocity ω and forces the flow, while the other walls are fixed. The stepped motor sets the rotation of the disk. A water jacket with a square cross section helps correct optical distortion and maintains a constant temperature.

![Figure 1. The schematics of the experimental setup for measurements in the vertical (a) and horizontal (b) cross-sections.](image)

The container is filled with sunflower oil (o) as the upper liquid (h_o = 1R), and (I) with a glycerin-water solution (g) whose kinematic viscosity is close to that of oil or (II) with a solution of alcohol-glycerin (sg) whose density is close to that of oil, as the lower liquid (h_g = 1.5R). The indices "o", "g" and "sg" denote "oil", "glycerin-water solution" and "alcohol-glycerin solution". At a room temperature of 22.6°C, the fluid densities and kinematic viscosities are ρ_o = 914.7 kg/m^3, ρ_g = 1237 kg/m^3, ρ_sg = 922 kg/m^3, ν_o = 54.86 mm^2/s, ν_g = 42.82 mm^2/s, ν_sg = 7.366 mm^2/s. The Reynolds number Re = ωR^2/ν_o characterizes the rotation strength. We measure velocity fields using Particle Image Velocimetry (PIV). This makes it possible to obtain an instantaneous velocity distribution in the investigated vertical and horizontal cross sections and to observe an instantaneous flow pattern within the two-dimensional plane of a light sheet. We used Nd: YAG pulsed laser POLIS v3.2 as an optical source for forming the light sheet. 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, shown in Fig. 1(a), and the horizontal cross-section located at 2 mm below the interface, as Fig. 1(b) shows. We registered images by POLIS camera v1.0 with lenses Nikon AF 28 mm f/2.8D Nikkor.

3. Results
Our study of the flow in a vertical cross-section reveals that the scenario for the development of the cellular structure in the case of close densities does not significantly differ from that in the case of close viscosities. Figure 2 presents distribution of the axial velocity at axis in the lower fluid at different Re.

![Figure 2](image)

**Figure 2.** Velocity distribution at the axis for close kinematic viscosities (a) and close densities (b).

![Figure 3](image)

**Figure 3.** Tangential (Vt) and radial (Vr) velocity r-distributions at z = 65.5 mm
(● - close densities, ○ - close viscosities).

As Figure 2 shows, the developments of the cellular structure are similar ($V_z$ becomes positive first near the interface and then at the entire z-axis), but the velocity on the axis becomes positive at smaller
Re in the case of close densities. We also explored the distribution of velocity in the horizontal section (Fig. 3), particularly the profiles of the radial and tangential velocity components for the cases of close viscosities (I) and close densities (II) of fluids.

Figure 3 reveals that the profiles of the tangential velocity are almost the same for the cases (I) and (II). In contrast, the radial velocities differ by an order of magnitude in cases (I) and (II). A reason is that the meridian flow of the lower fluid depends on two competing forces, induced by the upper-fluid motion: the centrifugal force and the viscous radial stresses at the interface. The stresses are proportional to the dynamic viscosity of the lower fluid, which in case (I) is 8 times greater than in case (II). The fluid densities are not very different (their difference not exceeding 30%), the centrifugal force in both cases is of the same order. It is striking that the effect of slip (positive radial velocity at Re = 250) does not completely disappear in the case of close densities. A possible reason is that the competing forces can generate cells of both centrifugal and anti-centrifugal circulations of the lower fluid near the axis-interface intersection, as Re increases [15]. The slip develops as the cell with the centrifugal circulation emerges.

Conclusion
This experimental study of a two-fluid swirling motion investigates the flow topological transformations for liquids of close kinematic viscosities (I) and close densities (II). The rotating lid forces 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, slip of the radial velocity occurs at the interface near the rotation axis. The slip can occur due to the centrifugal force and difference in the fluid densities. This experimental work uses immiscible liquids whose densities are close in order to check whether the slip disappears if the density difference is small. We found that the slip does not disappear.

A conjecture is that the competing effects of the upper-fluid rotation and convergence near the interface also can cause the slip. 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. Such a scenario can occur even if the fluid densities are close.

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