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Influence of the upper liquid layer on vortex breakdown in the bioreactor model

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The motion caused by rotation of the upper disk in a stationary vertical cylindrical container filled with two immiscible fluids is studied experimentally. The vortex breakdown the emergence of reversed motion on the cylinder axis in the lower liquid is investigated as a function of the thickness of the upper liquid layer. It is found that despite the fact that the motion of the upper fluid converges spirally to the cylinder axis near the interface, the vortex breakdown in the lower fluid occurs similarly to what is observed in the case of a single fluid, with the upper disk swirling. This curious result may be practically important for the operation of vortex bioreactors.

Keywords: Confined swirling flow, vortex dynamics, bubbly vortex breakdown, immiscible fluids.

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A working fluid in vortex units often interacts with another fluid or gas (e.g., in the case of incomplete filling of a reactor with a working medium [1–3]). The examination of specifics of quasi-stationary rotational motion of immiscible media in such units is important both in the context of optimization of performance of existing setups and for the design of new devices. A system of two immiscible fluids in a cylindrical container with a rotating upper or lower end face (disk) is convenient for experimental modeling of chemical and biological reactors, since it has a simple geometry and a small number of governing parameters [4].

The swirling flow regime of a single fluid is governed by two parameters: aspect ratio H/R (H is the fluid height and R is the cylindrical container radius) and Reynolds number $\mathrm{Re} = \omega R^2/\nu$ (ω is the angular disk velocity and ν is the kinematic viscosity of the fluid). Since the disk is rotating, the centrifugal force pushes adjacent fluid away from the axis to the periphery and induces meridional circulation: the fluid moves down at the side wall, reaches the stationary bottom, converges spirally to the axis there, moves up, and returns to the peripheral region of the disk. The converging motion triggers an increase in angular velocity on approach to the axis. The pressure on the vortex axis is lower than in the periphery, and a more intense rotation induces the emergence of regions of reduced pressure near the intersection between the cylinder axis and the bottom, thus reducing and reverting partially the velocity on the axis and forming vortex breakdown regions, which are easy to observe visually [4]. In 1984, Escudier [5] has examined thoroughly the process of vortex breakdown in a closed swirling flow in a cylindrical container with a rotating disk and plotted a diagram of existence of such a process. The results of subsequent experimental and numerical studies verified the invariance of these parameters within an interval of control parameters spanning over more than two orders of magnitude for $0.1 \leqslant H/R \leqslant 3.5$ and the lack of influence of the gravity force in the case when a swirling disk bounded a cylinder from above or from below [4]. It should be added that the vortex breakdown effect is commonplace in the process of formation of a vortex structure when the flow swirling intensity increases. For example, it is observed in aircraft and turbine wing- and blade-tip vortices, swirl burners and furnaces, and biological and chemical reactors [6–8].

Vortex devices with swirling motion of the working fluid set by rotation of the other fluid are specific in that each of the two media undergoes separate meridional circulation (Fig. 1, a), thus making it hard to calculate the Reynolds number for the working medium. While the rotation of a solid body is characterized by a constant angular velocity and the maximum of its linear velocity is located in the periphery, the same is not true for a rotating fluid medium. An important distinction is that the radial velocity at the interface between two fluids is nonzero, since the swirling lighter fluid converges spirally to the cylinder axis [9] and actually serves not as a solid, but as a fluid (soft) disk for the working fluid (Fig. 1, a).

The experimental study performed in [10] provided the first evidence of vortex breakdown in the lower fluid (with the upper fluid layer being fixed). Measurements of the velocity distribution demonstrated that the vortex breakdown in the lower fluid proceeds in the same way as in a single fluid [9,11] and the formation of a bubble-type vortex breakdown region, which is easy to observe visually, provides an opportunity to determine the patterns of swirling motion of the working medium that is not in direct contact with the swirler.

In the present study, we examine experimentally the emergence, evolution, and vanishing of vortex breakdown in a closed cylinder with a rotating upper end face in the

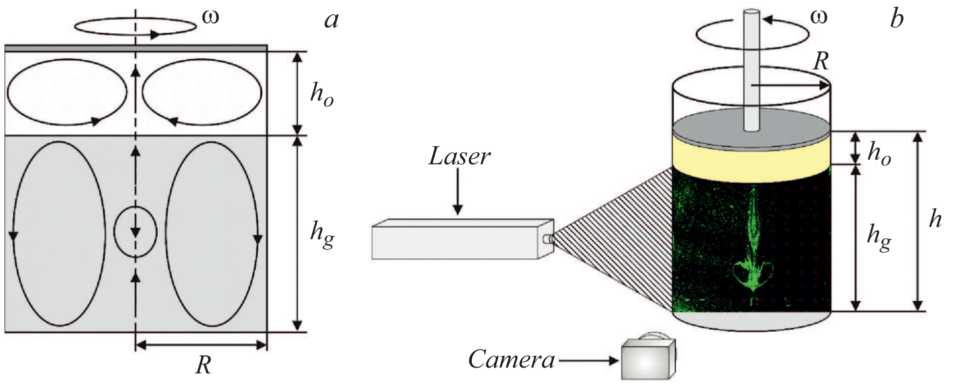

Figure 1. Diagram of meridional circulation of two immiscible fluids [9] (*a*) and diagram of the experimental setup (*b*).

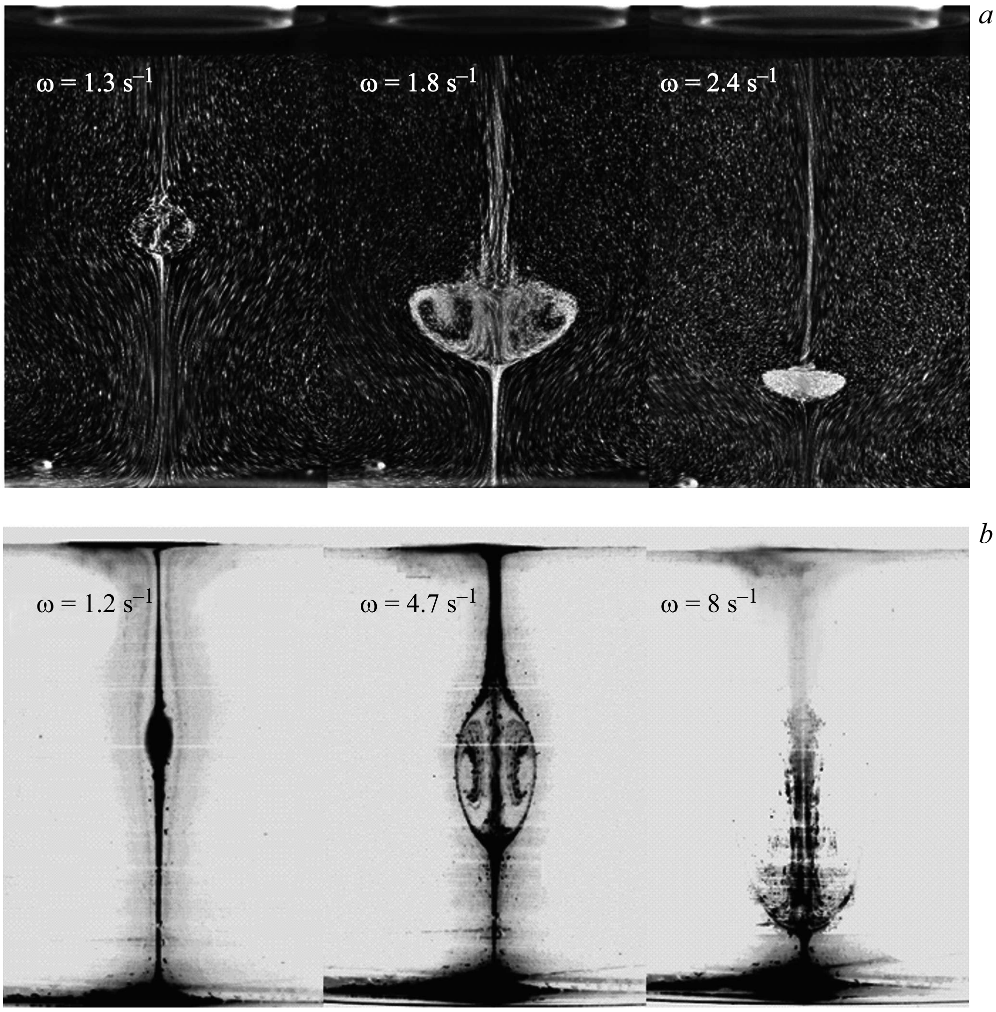

Figure 2. Photographic images of flow illustrating the emergence and breakdown of a vortex in a single fluid (positive images at $h_g = 1.5R$, $h_o = 0$) (*a*) and in the lower fluid (negative images at $h_g = 1.5R$, $h_o = 0.25R$) (*b*).

presence of a lighter fluid layer of a varying thickness. The study was performed using a cylindrical container (radius $R = 47$ mm) that was made from optically transparent glass and had a rotating upper end face; the height of the lower (working) fluid layer was h_g, and the height of the upper fluid layer was h_o (Fig. 1, *b*). The height of the system of two fluids was $h = h_g + h_o$. A hydroglyceric solution (with 33% of glycerol by volume) served as the working fluid, and sunflower oil was the lighter fluid. The density and the kinematic viscosity of these fluids at

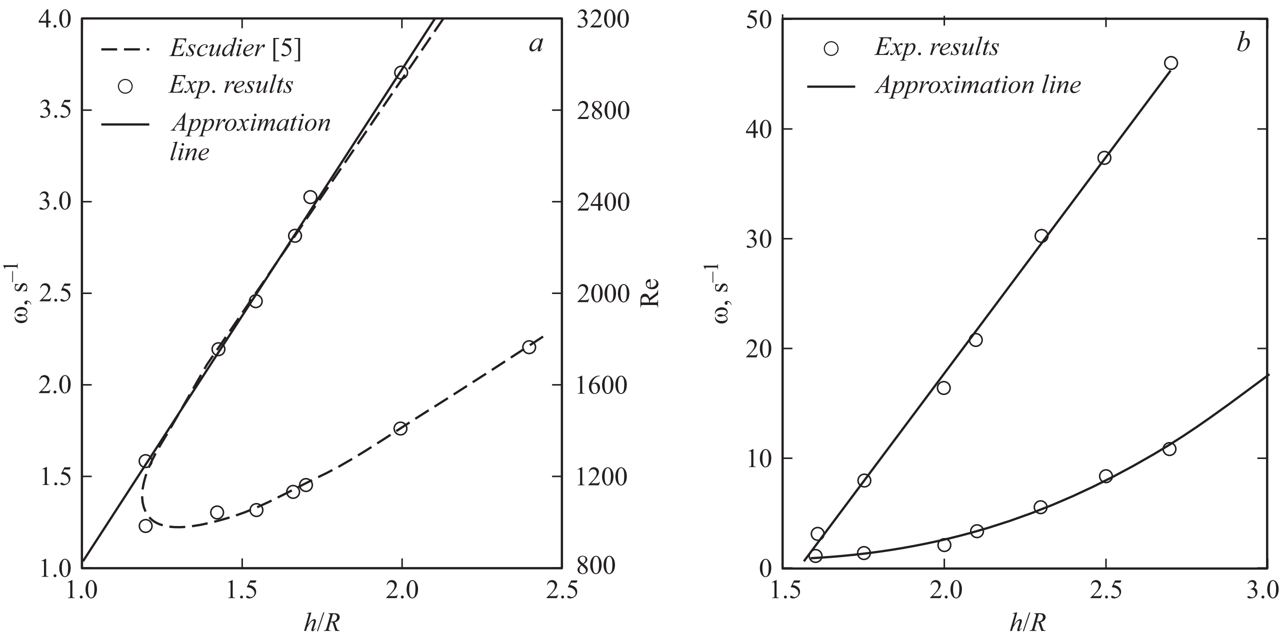

Figure 3. Diagram of bubbly breakdown of vortex motion. *a* — The case of a single fluid; *b* — the case of two fluids at a fixed value of $h_g = 1.5R$ and variable h_o.

room temperature (22.6°C) were 1080 kg/m^3, 2.7 mm^2/s and 916 kg/m^3, 41.9 mm^2/s, respectively.

Polyamide particles with a density of 1030 kg/m^3 and a diameter around 10 μm acted as light-scattering particles. The laser light sheet method was used to visualize the swirling flow structure in a vertical meridional section. A Ximea MC023MG-SY CMOS camera (resolution: 2.3 MP (1936 × 1216 pixels), frame rate: 165 fps, sensor: Sony IMX174 LLJ-C) with a Nikon AF Nikkor 28mm f/2.8D lens was used for imaging. Figure 2 presents photographic images depicting the evolution of bubbly breakdown with an increase in angular velocity of the disk rotation in the case of a single fluid with $h_o = 0$ and the case of two fluids with $h_o = 0.25R$.

Figure 3, *a* presents the map of existence of bubbly breakdown for a single fluid (hydroglyceric solution) at $h_o = 0$. The fluid height varied from $1.2R$ to $2.5R$. The lower (upper) part of the curve in Fig. 3, *a* corresponds to the emergence (vanishing) of vortex breakdown with an increase in swirling intensity at each fixed value of h/R.

In order to compare the results with the data obtained by Escudier [5], which are represented by the dashed curve in Fig. 3, *a*, two scales (angular disk velocity ω in rad/s and the Reynolds number scale) are provided in the figure. The emergence of a region of reverse „bubble“ flow was monitored visually by tracking the increase in width of the particle trail on the cylinder axis in a vertical section on changing the angular disk velocity pitch by 0.2 rad/s. The subsequent variation of the „bubble“ breakdown topology was monitored in the same way (visually). The scatter and uncertainty in a series of ten experiments of the same type were ± 0.1 rad/s. The size of symbols illustrating the obtained experimental data in Figs. 3, *a* and *b*) was chosen so that they would definitely mask the observed scatter. Relations $y = 0.5x^2 - 1x + 1.7$ (lower branch) and $y = 2.7x - 1.6$ (upper branch) were used for polynomial approximation of the experimental results.

Figure 3, *b* shows the diagram of existence of bubbly breakdown in the lower fluid in the case of two fluids. The height of the lower fluid layer was fixed in experiments ($h_g = 1.5R$), while height h_o of the upper fluid (sunflower oil) varied from $0.1R$ to $1.25R$, providing total height $h = (1.6–2.75)R$. As in the case of a single fluid, a „bubble“ nucleates in the working medium on the axis in the central part of the cylinder (lower curve) and then expands as the swirling intensity increases, shifting downward to the stationary bottom along with the flow. As the swirling intensity grows further, the bubble undergoes breakdown: its shape first becomes heart-like, and then it breaks down, altering its own topology (upper branch). Circles in Fig. 3, *b* denote the measurement data, while solid curves represent the polynomial approximations: $y = 7.4x^2 - 22.4x + 17.8$ for the lower branch and $y = 39.5x - 61.2$ for the upper branch. It follows from the comparison of diagrams and approximating curves in Fig. 3 that the curves for systems of one and two fluids are similar in shape, but differ in positioning. Although the minimum ω value at which vortex breakdown commences is 1.2 rad/s in Fig. 3, *a* and about 1.1 rad/s in Fig. 3, *b*, the large difference in approximation coefficients is attributable to a significant difference in viscosity of the used fluids.

The obtained results demonstrate that the curves bounding the vortex breakdown region behave in a similar fashion in the cases of one fluid and two immiscible fluids. It was found that although meridional circulation proceeds in the lighter fluid layer between the upper rotating disk and the working medium [9,11], this layer does not affect the overall patterns of formation of the vortex breakdown region upon variation of the aspect ratio. The angular momentum attenuation, which causes the breakdown diagram to shift into the region of more intense swirling as the aspect ratio increases, is proportional to the growth of the upper fluid layer and, as in the case of a single fluid, is attributable to viscous friction against the cylinder walls.

It is fair to assume that the vortex breakdown scenario is governed by an increase in the overall cylinder height and is unaffected by whether we raise the thickness of the upper or the lower (as in the case with a single medium) working fluid layer. This intriguing result may be of practical importance for the operation of two-fluid vortex reactors.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A.V. Savelyeva, A.A. Nemudraya, V.F. Podgornyi, N.V. Laburkina, Yu.A. Ramazanov, A.P. Repkov, E.V. Kuligina, V.A. Richter, Biotechnol. Appl. Biochem., **64** (5), 712 (2017). DOI: 10.1002/bab.1527

[2] S. Fang, P.W. Todd, T.R. Hanley, Chem. Eng. Sci., **170**, 597 (2017). DOI: 10.1016/j.ces.2017.03.019

[3] T.O. Chaplina, in *Physical and mathematical modeling of earth and environment processes*, ed. by V. Karev, D. Klimov, K. Pokazeev (Springer, Cham, 2019), p. 159. DOI: 10.1007/978-3-030-11533-3_17

[4] V. Shtern, *Cellular flows. Topological metamorphoses in fluid mechanics* (Cambridge University Press, Cambridge, 2018). DOI: 10.1017/9781108290579

[5] M.P. Escudier, Exp. Fluids, **2** (4), 189 (1984). DOI: 10.1007/BF00571864

[6] P. Moise, J. Mathew, J. Fluid Mech., **873**, 322 (2019). DOI: 10.1017/jfm.2019.401

[7] S. Sharma, P.B. Sachan, N. Kumar, R. Ranjan, S. Kumar, K. Poddar, Phys. Fluids, **33** (9), 093606 (2021). DOI: 10.1063/5.0061025

[8] S.V. Alekseenko, S.S. Abdurakipov, M.Y. Hrebtov, M.P. Tokarev, V.M. Dulin, D.M. Markovich, Int. J. Heat Fluid Flow, **70**, 363 (2018). DOI: 10.1016/j.ijheatfluidflow.2017.12.009

[9] I.V. Naumov, V.N. Shtern, Priroda, No. 4, 12 (2021) (in Russian). DOI: 10.7868/S0032874X21040025

[10] I.V. Naumov, B.R. Sharifullin, M.A. Tsoy, V.N. Shtern, Phys. Fluids, **32** (6), 061706 (2020). DOI: 10.1063/5.0012156

[11] I.V. Naumov, B.R. Sharifullin, V.N. Shtern, Phys. Fluids, **32** (1), 014101 (2020). DOI: 10.1063/1.5132584