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The structure of the confined swirling flow under different phase boundary conditions at the fixed end of the cylinder*

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The paper analyzes the complex topology of swirling flows generated in the cylinder by its rotating end face. Using the flow visualization for different parameters of swirl of the upper end of the cylinder, the general laws of the evolution of the region with a counter flow (bubble-like vortex decay) are shown regardless of the contact of the studied vortex flow with various liquids or gas at the free end. The research has found for the first time 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. For example, during the axial vortex breakdown, the modes of stationary vortex motion with the appearance of the recirculation zone contact with the interface surface of two media have been revealed, which is not typical for closed flows.

The results obtained are of interest for further development of vortex devices and reactors that provide complex vortex motion of ingredients for mass transfer intensification, both in terms of optimizing the operation of existing setups and for designing new devices.

Keywords: vortex apparatuses and reactors, vortex breakdown, heat and mass transfer in swirling flows.

Introduction

A cylinder with a rotating end face is an elementary model used in various vortex devices that intensify heat and mass transfer and other processes in various chemical and biological reactors, etc. In [1–3], various devices with different forms of contact of the swirling working fluid with the ambient medium on the non-rotating end face of the cylinder were considered. In the classic example of a swirling flow, this end face is a fixed solid cover made of the same material as the cylinder walls. In such a closed and completely filled cylinder, the regime flow parameters are the relative elongation h , equal to the ratio of the cylinder height to its radius (H/R), and the Reynolds number $Re = \Omega R^2/\nu$, where Ω is the angular velocity of the lid rotation, and ν is the kinematic viscosity of the liquid. In this flow, under the action of

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centrifugal forces, there is an outflow of liquid along the lid from the center to the periphery. Then the liquid, rotating, falls down along the walls of the cylinder and, unfolding at the bottom of the cylinder, concentrates into a central helical vortex with an upward flow along the axis. In [4] for moderate extensions of h (from 1.0 to 3.5), deviations from this obvious flow structure were visually recorded and systematized, with the registration of closed zones with counter flow in the central ascending vortex. Such stagnant recirculation zones are usually excluded from the general circulation motion that contributes to exchange processes, so the registration of modes with their appearance plays an important role in evaluating the operation of vortex reactors [5, 6].

In contrast to the given classical example, many vortex devices allow interaction of a rotating working fluid with free boundary of another liquid or air, for example, when the reactor is not fully filled with working fluid, etc. [2, 7]. This paper for the first time reports about the revealed similarity in the regularities of formation and evolution of recirculation zones at the center and on the free end of an intensely swirling stream generated in a non-uniformly filled cylinder by rotating the opposite end. In the course of comparison of the results of observations obtained in [2, 8, 10] and in this study, it is found that the scenario for the occurrence of a recirculation region is weakly dependent on the type of medium at the free boundary. Demonstration and analysis of this fact is the main goal of this work.

Experimental setup and methodology

To determine the diagram of the modes of occurrence of recirculating zones in a system of two immiscible liquids of different densities, the setup for non-contact optical methods for studying restricted swirling flows was used. It is shown in Fig. 1a, where $h_0 = h - h_w$ is the dimensionless height of the oil layer at rest (in the absence of disk rotation), normalized by R . The existence of recirculating zones on this setup for the classical case of a single liquid was previously established in [5, 11]. It was shown there that regardless of which end of the cylinder rotates, the stages of evolution of the vortex breakdown in a cylindrical container do not change and fully correspond to the diagram obtained in [4]. This means that gravity does not significantly affect the development of the flow structure. The experiments were performed in a vertical cylindrical container 1 with a radius $R = 144$ mm and a height of $50 \text{ mm} < h < 600$ mm, made of plexiglass of optical quality. For the studies, the container was filled with two immiscible liquids: water ($0 < z < h_w$) and sunflower oil ($h_w < z < h$), where z is the distance from the bottom of the container. At room temperature (22.6°C), the densities and kinematic viscosities of liquids are: $\rho_w = 1000 \text{ kg/m}^3$, $\rho_o = 920 \text{ kg/m}^3$, $\nu_w = 1.011 \text{ cSt}$, and

Fig. 1. Scheme of setup (a) and flow visualization example in the central cross section of the cylinder (b) at $h_0 = 1.5$, $h_w = 0.5$ and $Re = 800$.

See the text for explanations.

$\nu_0 = 54.86$ cSt; the indices “w” and “o” denote “water” and “oil”, respectively. The surface tension at the liquid interface boundary $\sigma = 0.0315$ N/m. The difference in the density of liquids provided a stable interface. A rotating disk with a radius $R_D = 143.5$ mm and a thickness of 10 mm was installed as the upper lid limiting the working height of the cylinder. The gap between the disk and the fixed cylinder walls was 0.5 mm and did not cause visible distortions in the vortex flow topology [11]. The motion of the liquids was generated by the upper disk, which rotated at an angular velocity Ω , while the other walls of the container were stationary. The disk rotation was set by the stepper motor 2, and its intensity was characterized by the Reynolds number $Re = \Omega R^2 / \nu_0$. To maintain a constant temperature with an accuracy of 0.1 °C and prevent optical distortion, a reservoir 3 with the size of $0.7 \times 0.7 \times 0.8$ m, filled with tap water was used. To study the characteristics, optical methods of non-contact diagnostics were applied, i.e., flow visualization in the central section of the cylinder using a laser “sheet”. The system included a Nd: YAG 4 pulsed laser with a wavelength of 532 nm, a laser sheet thickness of 1 mm, a pulse power of 120 MJ, and an operating frequency of 4 Hz. Images were recorded by the HiSense II 5 camera with a resolution of 1344×1024 pixels and a NIKON AF 28 mm f/2.8 d lens. Polyamide particles of neutral buoyancy with an average diameter of 10 microns were used as light scattering particles. For each flow mode, a series of 400 images was obtained with a time interval of 0.25 second and then averaged. Figure 1b shows an example of flow visualization for parameters $Re = 800$, $h_0 = 1.5 R$, and $h_w = 0.25 R$.

Experimental results and discussion

This study on the effect of non-rotating ends of different types on the flow state was carried out by comparing the results obtained by the above described method with the results of other observations. In [9], the flow in a cylindrical container with a rotating bottom and a free air boundary was studied analytically and numerically. In [8, 10], the flow was visualized for different values of aspect ratio (determined by the ratio of the cylinder radius to its height) using a laser sheet and a fluorescent dye. In all three cases, a stable axial recirculation zone of the return flow was formed (Fig. 2); it is characteristic of the flow structure in a monofluid. These modes are diagnosed fairly well, since the flow of the liquid remains stationary and the recirculation zone does not oscillate along the axis of the cylinder. In [8] and [10], the lower end of the cylinder rotated, while in this work, that was the upper end that rotated. Therefore, for a visual comparison and comparison of structures, the results of this work, presented in Figs. 2c, 3c, and 4c, are shown with a 180° rotation. In the case of a rotating bottom and a free surface, the conditions for the formation of an axial bubble collapse and its shape differ significantly from the results in a closed container [4]. In particular, it was found that as the Reynolds number increases, the return flow zone on the cylinder axis begins to increase in diameter, moves upstream along the cylinder axis, and then reaches the free surface (Fig. 3). With a further increase in the end face swirl, the area of contact of the return flow zone with the free boundary grows and the shape of the vortex changes: the lower “pole” of the bubble approaches the free boundary and the “bubble” is transformed into two axisymmetric “leaves”, thus changing its topology and ceasing to be axial (Fig. 4).

Fig. 2. Examples of occurrence of axial reverse flows in the interaction with free end faces from the media of different viscosity.

a: water/air, $h = 1.45$, $Re = 810$ [10];
b: glycerin/air, $h = 2.0$ and $Re = 1210$ [8];
c: oil/water, $h_0 = 1.5$, $Re = 800$ are the results of the present work.

Fig. 3. Examples of reverse flow zones at initial stage of interaction with the free end face for the media with different viscosity.

a: water/air, $h = 1.45$, $Re = 1010$ [10];
b: glycerin/air, $h = 1.5$, $Re = 975$ [8];
c: oil/water, $h_0 = 1.5$, $Re = 950$
are the results of this work.

Figure 5 shows the process of the “bubble” evolution, i.e., changing the position and shape of the return

113 flow area on the axis of the cylinder with increasing angular velocity of the disk rotation.
114 The bubble originates in the central part of the cylinder (Fig. 5a), then, as the Reynolds number
115 increases, it moves upstream (down to the interface of the two liquids), increasing in size
116 (Fig. 5b), and reaches the boundary (Fig. 5c). With a further increase in swirl, the preaxial
117 recirculation zone is deformed and its topology changes from the preaxial to the surface toroi-
118 dal one: it first becomes heart-shaped (Fig. 5d), and then completely splits into two leaves (Fig.
119 5e). For a more detailed comparison of the regions of existence of recirculating flows in
120 a cylindrical container under different types of boundary conditions at the fixed end of
121 the cylinder, diagrams of the modes of existence of the axial region of the return flow and
122 the adhesion of the “bubble” to the interface of the two media were constructed. To establish
123 these limits, a series of experiments were conducted with different regime parameters, and
124 the results were compared with the data from experimental and numerical simulations from
125 [4, 8, 9, 12].

126 The appearance of the area of return flow of the “bubble” was determined visually by
127 increasing the thickness of the trace of particles on the axis of the cylinder in a vertical section
128 with a step on the Reynolds number equal to 20. In a similar way (visually), the junction of
129 the return flow region to the interface and the subsequent change in the topology – the collapse
130 of the “bubble” into two leaves was recorded. Thus, the spread and uncertainty of the Reynolds
131 numbers was ± 20 .

132 Figure 6a reproduces a diagram of the occurrence of axial breakdown at the interaction
133 with different ends. Figure 6b reproduces the diagram of the recirculation zone contact with
134 the return flow of the interface between two media with a free surface. For a visual
135 representation of the results in the figure diagrams, the size of the symbols representing
136 experimental data (4 in Fig. 6a and 2 in Fig. 6b), has been chosen to deliberately cover the
137 uncertainty of the Reynolds number in the range of 30–40. It should be noted that for the case
138 of a solid bottom, the parameters at which the “bubble” contacts the stationary end of
139 the cylinder are not fixed, since the contact takes place in a developed non-stationary flow
140 mode, when the breakdown region is moving along the axis of the cylinder and its shape is
141 significantly distorted due to the influence of azimuthal wave modes [5].

Fig. 4. Examples of the interaction of reverse flow zone with free ends of media of different viscosities.

a: water/air, $h = 1.45$, $Re = 1850$ [10];
b: glycerin/air, $h = 1.5$, $Re = 2095$ [2];
c: oil/water, $h_0 = 1.5$, $Re = 2000$ –
results of this work.

Fig. 5. Flow structure in a cylindrical container with a rotating lid, filled with a two-component working fluid ($h_o = 1.0R$, $h_w = 0.5R$).
Re = 450 (a), 600 (b), 700 (c), 850 (d), and 1000 (e).

Fig. 6. Diagrams of the presence of a bubble-like area of the return flow on the axis of the cylinder (a) and the junction of the “bubble” to the interface of the two media (b).

- a: 1 — the area of existence of a bubble with a fixed solid end [4],
2 — the area of existence of an axial “bubble” on the axis of a cylinder with a rotating bottom and the free boundary obtained by numerical modeling in [9],
3 — experimental data [8], 4 — area of the bubble type return flow existence in the present study — in a closed cylinder with a top rotating lid and a “liquid” bottom;
b: 1 — data of the work [8], 2 — data of this work.

Conclusion

As a result of the conducted research, it has been found that the presence of an end face with a free surface, where the free surface is air or liquid of a different density, significantly affects the formation of a recirculation zone of the return flow, shifting the diagram of its formation to the region of smaller Reynolds numbers ($\Delta Re \approx 500$) and smaller relative elongation ($\Delta h \approx 0.5$). However, the use of contact 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 between the two media (Fig. 6a and 6b).

The results obtained are of interest for the development of vortex technologies both from the point of view of optimizing the operation of existing setups and designing new devices, since they regulate the modes of occurrence of recirculation flows.

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