Dynamics of two liquids in a non-uniformly rotating horizontal cylinder

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Abstract. Controlling the shape of the interfacial boundary is an important technological task. The effect of rotation velocity modulation on the interface between light viscous and denser low viscosity fluid in a rotating horizontal cylinder is studied experimentally. Liquids are characterized by a high contrast of viscosities, these are glycerin and a low-viscosity (denser) fluorinert FC-40. Glycerin is stained with rhodamine, which makes it possible to study the shape of the interface by photo registration with high accuracy when illuminating liquids with a green laser, which causes rhodamine fluorescence. Experiments are carried out in the centrifuged state of liquids when the gravity field has no effect while varying the rotation speed, as well as the amplitude and frequency of librations. It is found that librations qualitatively change the shape of the interface near the ends of the cavity without affecting the cylindrical interface in the middle cavity part. It is shown that this is due to different "viscous" interactions of liquids with the ends of the oscillating cavity, as a result of which the interface near the ends performs radial oscillations with a frequency of librations, and the latter leads to an averaged radial displacement of the wetting boundary of the ends, which increases with the modulation amplitude. At certain amplitudes, the contact line reaches the outer boundary of the cavity. It is shown that the dynamic equilibrium of the interface between liquids of different densities is determined by the averaged interaction of liquids of different viscosity with the oscillating ends.

1 Introduction

Interfacial boundaries (liquid interfaces) are an integral and very common object of a wide variety of processes in modern technologies and nature. In particular, the behavior of interfaces determines the intensity of heat and mass transfer on them, which makes the problem of managing interfaces, especially relevant. An important factor characteristic of interfaces is oscillations and waves [1], which affect fluid flows and all the processes near the interface. The issues of vibration impact on interfaces for their control attract the attention of scientists – the monograph [2] is devoted to the averaged effects associated with interface oscillations. An important factor from the applied and scientific points of view that determines the averaged dynamics of multiphase systems is rotation [3, 4]. In rotating

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systems, the behavior of multiphase systems changes qualitatively as a result of the action of inertial forces. It also applies to the issues of "vibrational hydromechanics".

As found in [5], the non-uniform rotation of a cavity with liquids of different densities leads to the fact that the axisymmetric (in a centrifugal force field) interface changes its shape, and a quasi-stationary azimuthally periodic relief is formed on the interface. This averaged effect was found in a rotating cavity in the form of an axisymmetric thin disk in the case of the high contrast of liquid viscosities; it is determined by the difference in the viscous interaction of liquids with the walls of the slotted gap. The question of the role of the distance between the ends of an axisymmetric cavity filled with two different densities liquids with a high contrast of viscosities during non-uniform rotation remains topical.

This work aims to experimentally study the dynamics of two fluids with a high contrast of viscosities in a non-uniformly rotating cylinder, the length of which is much greater than the thickness of the Stokes boundary layers. The study revealed qualitatively new phenomena, the rotational oscillations of the cavity lead to the appearance of new quasi-stationary forms of the liquid interface near the ends, which differ from the cylindrical shape in the case of uniform rotation.

2 Experimental setup and technique

The experimental cuvette is a long cylindrical cavity *1* (Fig. 1), machined in a Plexiglas block in the form of a long parallelepiped of the square cross-section. The polished sides of the Plexiglas block reduce optical distortion when observing fluid dynamics from the side. The length of the working cavity is L = 7.4 cm, and the radius of the working cavity is R = 3.0 cm. The cuvette is driven around a horizontal axis by a stepper motor *2* model FL86S TH118-6004A using an SMD-42-type controller.

The cell motion law is described by the equation:

$$\Omega=\Omega_{\mathrm{rot}}(1+\varepsilon(\cos \Omega_{\mathrm{lib}}t)) \tag{1}$$

Where Ω is the angular velocity of the cavity rotation, Ω_{rot} is the constant component of the velocity, Ω_{lib} is the cyclic libration frequency, ε is the amplitude of the velocity modulation.

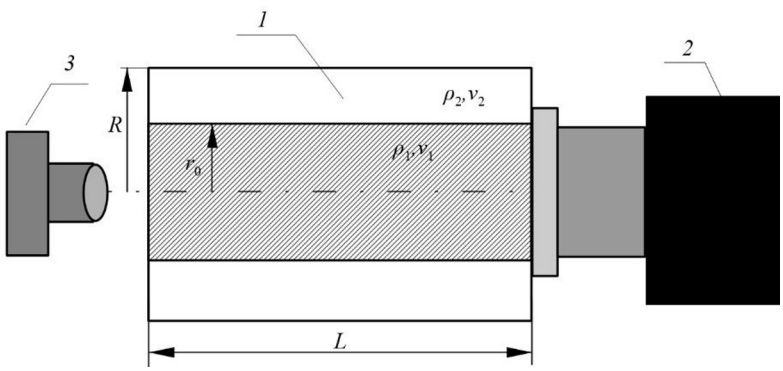


Fig.1. Scheme of the experimental setup (side view): *1* – cuvette; *2* – stepper motor, *3* – speed camera.

Experiments are carried out in the range of rotation frequency $f_{\mathrm{rot}}=\Omega_{\mathrm{rot}}/2\pi$=5–7 rps and libration frequency $f_{\mathrm{lib}}=\Omega_{\mathrm{lib}}/2\pi$=1–3 Hz. Velocity modulation amplitude varies in the range ε=0–0.7. During the experiment, the shape of the radial boundary of a viscous liquid, which is visualized with rhodamine, is recorded using a high-speed video camera *3* CamRecord

Optronis CL600x2 with a frame rate of n = 420 frames per second. Video recording is performed from the side of the front transparent end and the cavity sidewall. In the first case, the camera is installed coaxially with the cuvette rotation axis. Processing the results of photo and video recordings is performed on a computer.

As liquids, glycerin is used, the kinematic viscosity of which is ν_1=1210 cSt, and the density is ρ_1=1.26 g/cm^3, and fluorinert FC-40 with a kinematic viscosity ν_2=2.5 cSt and density ρ_2=1.85 g/cm^3. Glycerin is dyed with rhodamine, which makes it possible to determine the interface of liquids with high accuracy by photo recording using a red-light filter and the illumination of liquids with a green laser. Rhodamine dye does not change the physicochemical properties of glycerin since its concentration does not exceed ~ 10^{-4}%.

When shooting from the end of the cuvette, the camera focuses on the liquid interface near the end of the cavity. The laser is positioned so that the laser knife passes along the end perpendicular to the axis of the cuvette rotation, illuminating the area near the end.
Experiments are carried out under conditions when a system of liquids of different densities is in a centrifuged state. In this case, the centrifugal force exceeds the force of gravity, as a result of which the light liquid is located near the axis of the cavity in the form of a straight axisymmetric cylinder with a radius of r_0 (Fig. 1). Observations show that librations lead to a displacement of the contact line along the radius (Fig. 2), while the viscous fluid performs axisymmetric radial vibrations near the ends of the cavity. In some phases, a viscous liquid near the end flows down to the inner cylinder, leaving a thin film at the end of the cavity with a radius of r_{cl}. In the opposite phase, the liquid flows, protruding beyond the end wetting area in the form of a tongue with a radius r_t. Note that during the oscillations of a viscous fluid, the axisymmetric contact line practically does not shift. This behavior of the interface determines the experimental technique.

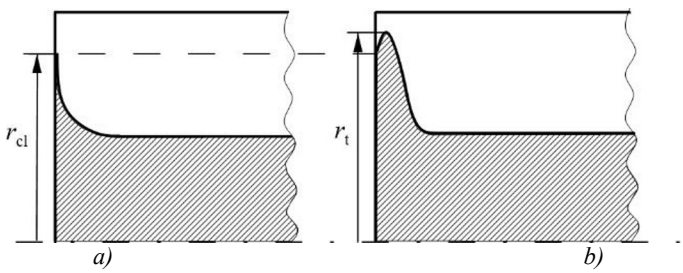


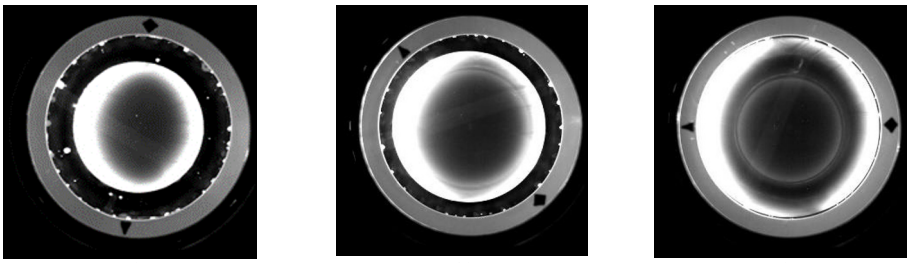
Fig. 2. Schematic representation of the interface in the axial section in opposite phases: maximum compression (*a*), maximum expansion of the tongue of a viscous liquid (*b*).

Shooting from the cavity sidewall is carried out in such a way that the sides of the parallelepiped are perpendicular to the optical axis of the camera. To do this, the frame rate and the rotation speed of the cavity f_{rot} are adjusted so that the cuvette is in the desired position at the time of frame registration. When librations are turned on, the cuvette rotation speed is not synchronized with the frame rate, therefore, from a large number of frames, those frames are selected and processed in which the cuvette walls are perpendicular to the optical axis of the camera. In this case, the liquids in the cuvette are illuminated by scattered laser light.

3 Results

In the absence of librations, the internal liquid column has a radius of r_0. When the cavity rotation rate is modulated, a light (more viscous) fluid performs radial oscillations near the ends of the cavity with the modulation frequency. In this case, the wetting boundary of the ends with a viscous liquid (the radius of the contact line) is displaced in the radial direction while maintaining axial symmetry (Fig. 3*a*, *b*). With an increase in the amplitude of librations

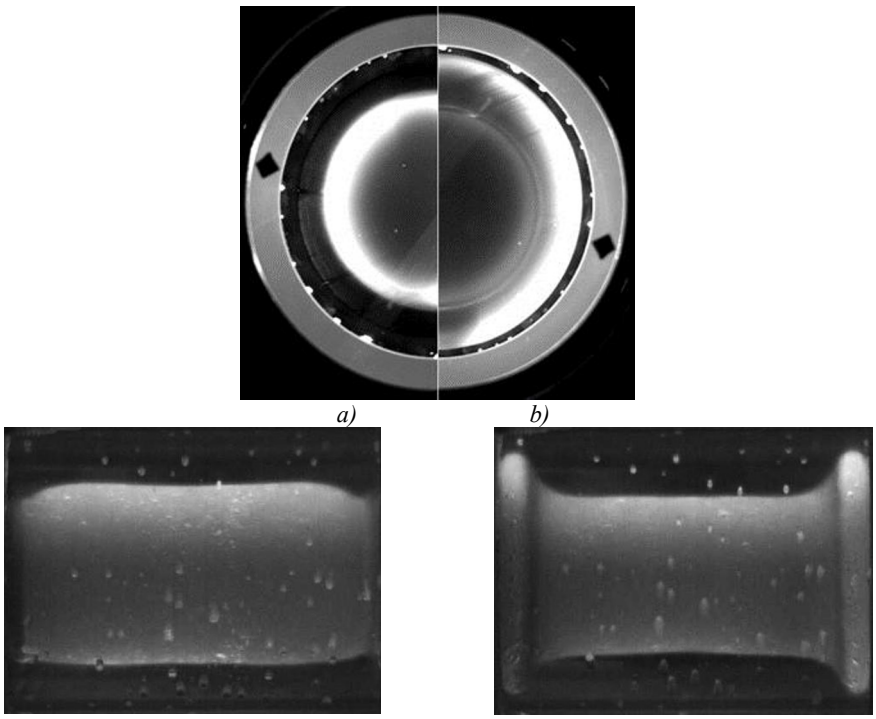
at a fixed rotation rate and frequency of librations, the radius of the contact line (wetting area of the end of the cavity) increases. At some values of the amplitude of velocity modulation are reached, the viscous light liquid completely covers the end of the cuvette and, for a part of the libration period, passes to the side surface of the cavity (Fig. 3*c*).



a) *b)* *c)*

Fig. 3. Areas of end wetting with a light viscous liquid at f_{rot}=6 rps, f_{lib}= 1 Hz, ε: 0 (*a*), 0.30 (*b*), 0.45 (*c*).

The interface of liquids near the ends makes one oscillation per period of librations. In the phase of maximum compression (in the phase of deceleration of the cavity), the viscous light liquid displaces towards the axis, remaining on the end of the cavity in the form of a thin film. In the phase of the accelerated motion of the cavity, the liquid flows onto this film and protrudes beyond the wetting boundary of the end wall with the liquid in the form of an axisymmetric "tongue". In this case, the tip of the tongue is exposed outside the wetting area without touching the end of the cavity (Fig. 4).



a) *b)* *c)* *d)*

Fig. 4. The shape of the interface in the phases of maximum compression: end view (*a*), side view (*c*), and maximum expansion: end view (*b*), side view (*d*).

Fig. 5 shows the dependencies of the relative apparent radius of the liquid interface and the angular coordinate of the cavity (in a uniformly rotating frame of reference) on time. The angular coordinate changes according to the law: $\alpha=\alpha_0*\sin(\Omega_{lib}*t)$. The horizontal sections on the graph correspond to the radius of the contact line r_{cl}. These indicate that during the accelerated motion of the cavity, the viscous liquid on the ends remains in the form of a film, while the film size (the boundary of the wetting region) does not change significantly. In the phase of the minimum rotation velocity of the cavity, the liquid protrudes beyond the film boundary in the form of a tongue, the size of which changes per the non-horizontal sections of the graph. The graph shows the displacements of the "tongue" tip r_t from the axis of rotation. In the deceleration phase, the liquid flows down to the axis of the cavity, remaining on the end in the form of a film, while the radius of the film remains practically unchanged. Fig. 5 indicates that the viscous liquid near the ends oscillates with the frequency of librations. At the same time, in the central part of the cylinder, the interfacial boundary retains its cylindrical shape.

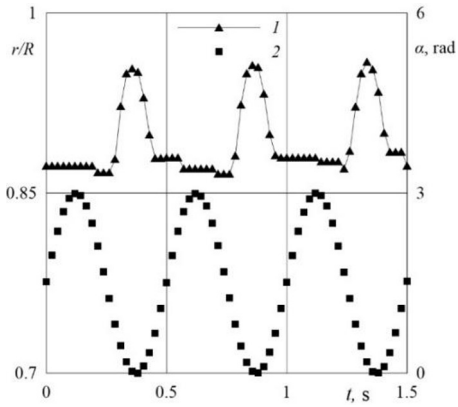


Fig. 5. Time-dependencies of the relative apparent radius *r* of the interface near the end (*1*), and the angular coordinate of the cavity in a rotating frame of reference (*2*).

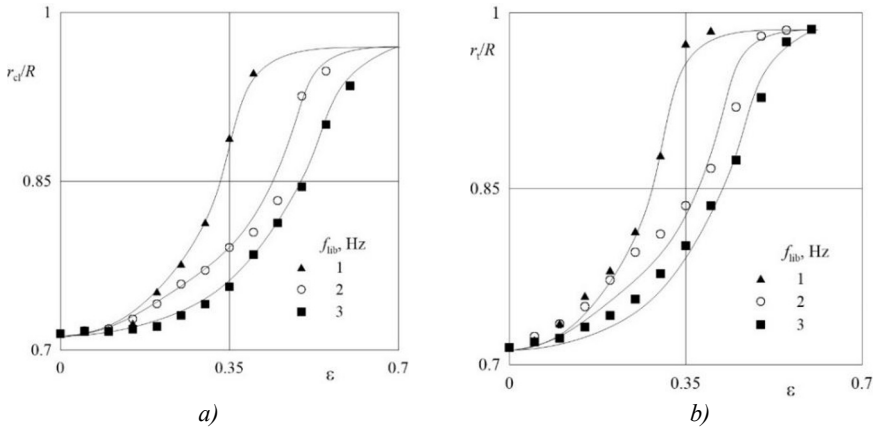


Fig.6. Libration amplitude dependencies of the contact line r_{cl} relative radius (*a*) and the tongue r_t relative radius (*b*) for f_{rot}=7 rps and f_{lib}=1–3 Hz.

It can be seen in Fig. 6 that at a definite rotation frequency f_{rot} and a given libration amplitude, the radius of the contact line r_{cl} and the tip of the "tongue" r_t decreases with an increase in the libration frequency f_{lib} (Fig. 6 *a* and *b*). The horizontal sections of the curves

in Fig. 6 (at large values of the modulation amplitude) correspond to the conditions when the tongue reaches the side wall of the cavity, while the viscous liquid completely covers the end. With an increase in the frequency of librations, the complete wetting of the cavity end by a viscous light liquid occurs at large values of the libration amplitude. Comparing graphs, *a*) and *b*) in Fig. 6, one can conclude that the distance of the contact line from the axis r_{cl} is always less than the one of the tongue r_t. The film does not completely cover the end even when the protruding tongue of liquid passes to the side surface of the cavity.

At a given libration frequency f_{lib}, the values of the radius of the contact line r_{cl} and the tongue r_t at different rotation speeds f_{rot}, depending on the libration amplitude, are consistent with each other (Fig. 7). It follows from this that the dynamics of the interface under the conditions of the study does not depend on the rotation rate and is determined by the amplitude and frequency of rotation rate modulation.

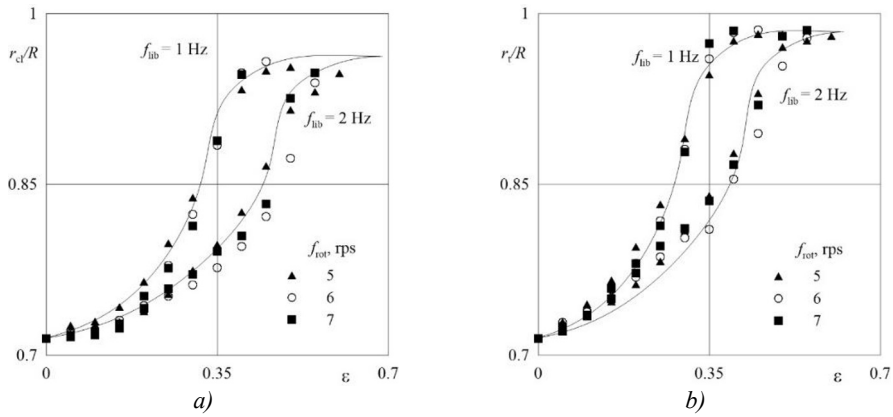


Fig. 7. The relative radius of the contact line (*a*) and the radius of the tongue (*b*) in dependence on the libration amplitude ε at f_{rot}=5–7 rps and f_{lib}=1–2 Hz.

4 Discussion

Figure 8*a* shows the dependence of the relative tongue radius r_t on the libration amplitude for different relative filling of the cavity with liquids at a definite rotation frequency f_{rot}=6 rps and different libration frequencies f_{lib}. Dark and light signs on the graph correspond to different r_0. Regardless of r_0, as the libration frequency increases, the amplitude value of the displacement of the tongue of a viscous fluid at a given rotation speed decreases. At a lower r_0, a light viscous liquid reaches the outer boundary of the cavity at larger values of the libration amplitude. Otherwise, the interface dynamics at different values of r_0 remain the same.

It follows from Figs. 6–7 and 8*a*, that a decrease in the libration frequency leads to an increase in the effect of radial displacement of the quasi-equilibrium contact line at a given velocity modulation amplitude. Analysis of the results shows that the experimental points obtained at different f_{lib} are in satisfactory agreement with each other (Fig. 8*b*) depending on the parameter ξ, which is calculated by a formula $\xi = \varepsilon\sqrt{f_{rot}/f_{lib}}$. One can expect that the parameter ξ in some way characterizes the ratio of the average vibrational force acting on the interface near the end of the librating cavity to the centrifugal force of inertia. The nature of the discovered phenomenon needs further study.

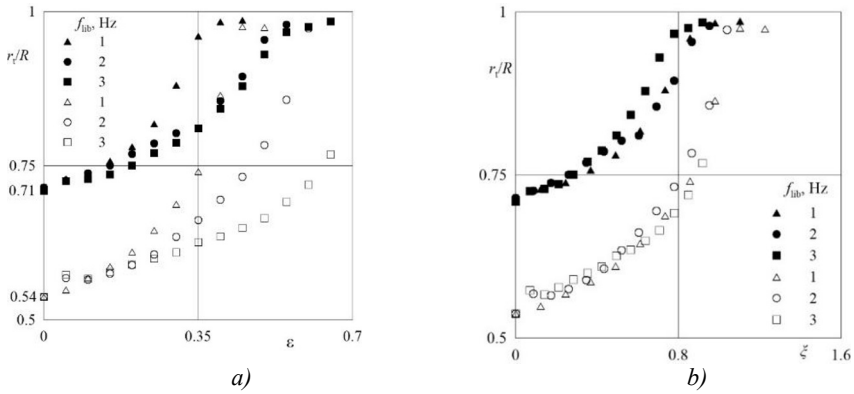


Fig. 8. Dependence of the relative tongue radius r_t: *a*) on the libration amplitude ε and *b*) on the parameter ξ; for different relative filling at f_{rot} =6 rps and f_{lib} =1−3 Hz.

5 Conclusion

A new vibrational effect – a radial displacement of the contact line of two liquids of different densities close to the cylindrical cavity ends under condition of non-uniforms rotation – has been experimentally discovered. This phenomenon occurs when a light liquid located near the axis of rotation under the action of centrifugal force has a high viscosity. It is shown that the effect is associated with different "viscous" interactions of the investigated pair of liquids with the oscillating end boundary of the cavity. In the investigated region of the experimental parameters, the average dynamics of the interface does not depend on the rotation frequency f_{rot} and are determined by the libration amplitude ε and the libration frequency f_{lib}. With an increase in the velocity modulation amplitude at a given libration frequency, the area of wetting by a light liquid of the end increases. This phenomenon is explained by radial oscillations of the interface near the end, which occur with the frequency of librations; the amplitude of the boundary oscillations increases with the amplitude of the rotation rate modulation. It should be noted that with an increase in the libration amplitude, a light liquid could completely cover the end of the cavity and, despite the centrifugal force field, reach the side boundary of the rotating cavity. The discovered phenomenon is of great scientific interest, and further research is planned.

6 Acknowledgments

This work was supported by the Ministry of Education of the Russian Federation (project No. KPZU-2023-0002).

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