Experimental Study of Substance Transfer in Vortex and Wave Flows in Multicomponent Media

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Abstract. The fine structure of the phase boundary surfaces between the oil body and water and also between the liquid (water or immiscible hydrocarbons) and air in a compound vortex is studied experimentally, including the beginning of the emulsions formation. The experiments showed that a uniform layer of hydrocarbons on the water free surface is pulled together into the oil body located on the flow axis. Some portions of the oil remain on the free surface in the form of spiral arms, either continuous or decomposed into separate drops. At high angular speeds of rotation the oil droplets can be found all over the liquid – air contact surface. The contact surface geometry depends on the parameters of the vortex flow, determined by angular velocity of inductor rotation and quantitative composition of medium. The dynamics of the solid-state transfer marker - plastic or ice in the compound vortex of two fluid water-oil analyzed. It is shown that the motion of the marker, inscribed on the surface of the composite vortex complex and includes a tangential displacement, radial displacement and spinning about its own axis. Character movement depends on the experimental conditions, the type of liquid and form a marker. Radial velocity of motion increases to handle liquids with oil slick and at the same time, the angular velocity of its rotation around the vertical axis of the flow is markedly reduced.

Keywords: Vortex · Wave · Flow · Marker · Visualization

1 Introduction

Submerged jets and shear flows are often found in nature and various technical applications, such as mixing, burning, generation of sound disturbances, etc. Vortex structures are quite common, we are faced with such currents as when using different technical devices, and in natural systems - in the atmosphere and the ocean. Scales of such currents fluctuate in the widest range and can reach huge sizes. On Earth, the largest vortices are the synoptic - atmospheric cyclones of medium latitudes, the characteristic transverse dimensions of which are 1500–2000 km; vortices in the open ocean, reaching a size of 100–200 km across. Also, vortices are formed at the ends of the wings of aircraft and when the flow is separated from the sharp edges of aircraft and ships (Fig. 1).

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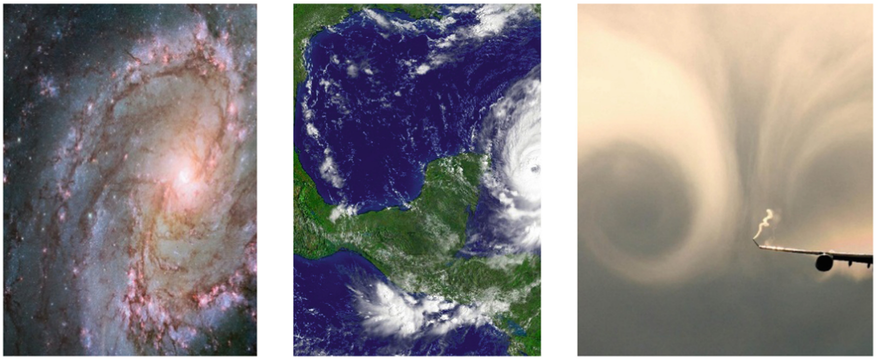


a *b* *c*

Fig. 1. Vortex structures of different scales: (*a*) spiral galaxy M83 [1]; (*b*) cyclone over the Atlantic Ocean [2]; (*c*) vortices from the wings of aircraft [3].

The study of the processes of matter transport in vortex currents is one of the traditional problems of fluid mechanics, the practical value of its results for the problems of ecology and the development of industrial technologies is steadily growing. In recent years, one of the main products of surface contamination of water bodies, both small and the entire World Ocean, are fragments of plastics in the form of raw materials, products and packaging.

Garbage in various forms enters the aquatic environment, where it is transported, degraded and accumulated at certain levels of the ecosystem.

In connection with the growth of the volume and nomenclature of pollutants entering the environment, it is of interest to study the transfer of markers in various types of vortex flows developing both in pure liquid and in a multilayer formed by mixing and immiscible components. Of special interest is the study of the transfer of markers in a layer of a liquid covered with an oil or oil film formed by the flow of substances from natural and anthropogenic sources [4]. The ecological effect of the film depends on its thickness and coating density, the presence of “clean windows” has a positive effect on gas exchange in polluted waters.

Observations of marine systems have made it possible to distinguish a number of general features of the propagation of impurities. Solid-state remnants are destroyed by the action of waves, wind and solar radiation, scattered, submerged to the bottom or thrown ashore, partially transported to ocean circulation centers, where they can assemble into compact “garbage islands” [5].

To clarify the dynamics of the processes of solid impurities transport in the ocean and to register the main characteristics of currents, vortices and waves of various nature, freely drifting drifters on the surface and buoys of neutral buoyancy in the marine environment are actively used in the ocean (only the “Argo” project is currently monitoring the movement more than 3800 buoys [6]. Interpretation of the buoyed data is based on the assumption of complete entrainment of the suspended body by currents. However, the adequacy of the assumed assumption needs to be refined taking into account the regularities of the real behavior of bodies in the vortex flows of a homogeneous, multilayered or continuously stratified fluid. Experimental studies of the dynamics of free bodies of neutral buoyancy were carried out in [7], in this paper the focus is on the transfer of markers in a two-layer fluid.

The increased concentration of oil coming from natural and industrial sources under natural conditions was observed in the form of separate, narrow bands, paradoxically oriented in intense wave fields [8]. The length of such bands, causing serious pollution of the coast, can reach many tens of kilometers [4, 9].

Observations in marine conditions provide important factual material. However, due to the complexity and variety of concurrent natural processes, the data obtained can not be unambiguously interpreted.

In many cases, the amount of data is insufficient to identify the underlying mechanisms based on different flow models and to determine their parameters. In addition to observations of the transfer of markers under natural conditions (in the atmosphere and in the hydrosphere), laboratory modeling of the transport process, including wave and eddy currents, began to develop in recent years.

The transport of matter in wave channels of simple geometry with a wave-product set at one of the ends was studied in [10]. Studies of the movement of markers are often carried out in circular cylindrical containers, a rotational disk in the top cover [11] or the bottom of the working volume creates a vortex flow [12].

As shown earlier experiments, a liquid marker, in particular oil, can be located on the surface of such a vortex in the form of spiral bands and forms a compact oil body in the vicinity of the rotation axis [11].

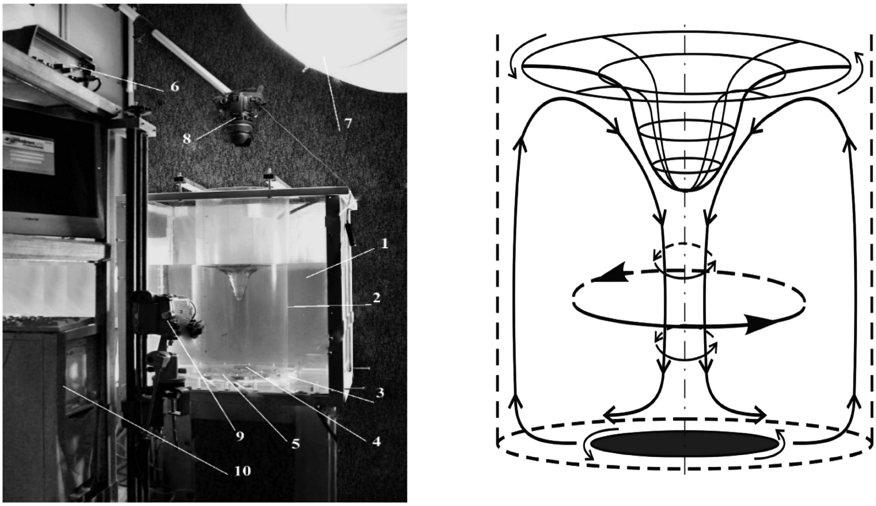
In this case, the shape of the free surface and the interface of the components in multilayer fluids depends on many factors: the type of liquid, container dimensions, angular velocity of rotation and the position of the inductor [13, 14]. In a two-layer liquid with an activator rotating at moderate angular velocities in the layer of oil lying above, a number of characteristic forms of an oil body are identified: a hill, a pointed peak, a smoothed peak (Fujiyama), a bell [10]. The axisymmetric cavern at high angular velocities of the disk installed in the thickness of the liquid acquires an angular shape reflecting the change in the symmetry of the velocity field in the thickness of the liquid [15, 16].

An equally complex picture is recorded during the transfer of a solid-state marker, which in flows with a shift not only rotates around the center of the vortex, but also revolves around its own axis [5]. Such forced movements of the body perturb vortex currents and additionally affect the transport of liquid markers.

In this paper, the fine structure of the oil-water-liquid interface and liquid (water or immiscible hydrocarbons) - air in a composite vortex, including the regime of the formation of emulsions, has been experimentally studied. As a research object, massively used liquids (sunflower and aviation oils, petroleum, diesel fuel, as well as their mixtures in different proportions) were chosen. Also in the article dynamics of the transfer of a solid marker - plastic or ice in a composite vortex in a two-layer liquid water-oil/petroleum was investigated.

2 Experimental Setup and Flow Parameters

Our experiments were performed on the Rotational Vortex Flow setup (Fig. 2*a*). The open cylindrical container *1* with diameter 29:4 cm is filled with water. The water level is set 40 cm. To decrease optical distortions of the recorded flow pattern, the cylindrical container is put into the rectangular tank *2* with plane walls, the size of the tank is 63.6 × 44.6 × 70.0 cm. The activator of vortex motion, the flat disk *3* (2 mm thickness), is located in the center of the tank bottom. To flatten the bottom of the cylindrical container on the level of the upper edge of the disk the false bottom *4* is mounted. The disk is activated by an electric motor with the frequency from 200 to 1200 rpm, with a signal converter block.



a *b*

Fig. 2. The experimental setup (*a*) and the scheme of a compound-vortex (*b*) induced by the rotating disk in the cylindrical container.

The photo- and video-recordings of the flow pattern are performed simultaneously from the top 5 and side 6 views. The control of the experiment and the data recording is committed to PC 7. The water volume is illuminated by a white-light source with a dispersive sheet 8. The container is equipped with a hydraulic system. In all experiments, the illumination and location of the cameras are chosen to provide visibility of all details of the liquid free surface.

The complex flow in the container, the schematic pattern of which is shown in Fig. 1b, contains both the vortex and wave components. The uniformly rotating disk swirls the liquid about the vertical axis due to no-slip condition and rejects it towards the vertical container sidewall. The accelerated liquid uprises along the container sidewall and is then displaced towards the centre along the free surface, and descends near the rotation axis, forming a flow, which compensates the constant transport along the disk surface (Fig. 2*b*).

Free surface made it possible to apply a wide range of markers and to control the conditions for their introduction. As ice and solid-state markers, plastic, with a diameter of 1 cm or 2 cm and a height of 0.5 cm were used, immiscible liquids - aviation fuel and oil in a volume of 30 ml. In experiments with the addition of oil and aviation oil, an immiscible impurity was added to the surface of the resting liquid, then the inductor was set in motion and markers were placed in the steady vortex flow. Each new experiment began after the attenuation of all visible movements in the basin.

The composite vortex flow is characterized by a set of dimensional and dimensionless parameters, the values of which are given in Tables 1, 2, where ρ_w, ρ_o, ρ_a – density of water, oil and air, respectively, $R = 7.5\,\text{cm}$, Ω – rotational speed of the inductor drive, g – acceleration of gravity, ν_w - kinematic viscosity of water, coefficients of surface tension on contact surfaces - water-air σ_w^a, oil-air σ_o^a, water-oil σ_w^o, $L_\Omega = g/\Omega^2$ - the characteristic length scale (under the conditions of these experiments $0.02 < L_\Omega < 10$), $\delta_\Omega^\nu = \sqrt{\nu_w/\Omega}$ – scale of the Ekman layer on the surface of a rotating disk (under the conditions of these experiments is sufficiently small and is within $0.02\ \text{cm} < \delta_\Omega^\nu < 0.1\ \text{cm}$).

Table 1. Basic flow parameters.

Parameter	Minimum value	Maximum value	Characteristic value
Reynolds number $\text{Re}_\Omega^w = (R_d^2\Omega)/\nu_w$	$5.6 \cdot 10^3$	$1.4 \cdot 10^5$	$7.3 \cdot 10^5$
Froude number $\text{Fr} = (R_d^2\Omega^2)/gH$	10^{-3}	0.9	0.4415
Bond numbers $\text{Bo}_w^a = gH(\rho_w - \rho_a)/\sigma_w^a$	–	–	0.055
$\text{Bo}_o^a = gH(\rho_o - \rho_a)/\sigma_o^a$	–	–	0.109
$\text{Bo}_w^o = gH(\rho_w - \rho_o)/\sigma_w^o$	–	–	0.257
Atwood numbers $\text{At}_w^a = (\rho_w - \rho_a)/(\rho_w + \rho_a)$	–	–	0.998
$\text{At}_o^a = (\rho_o - \rho_a)/(\rho_o + \rho_a)$	–	–	0.997
$\text{At}_w^o = (\rho_w - \rho_o)/(\rho_w + \rho_o)$	–	–	0.099

The values of Reynolds numbers are typical for vortex and nonstationary-vortex flows. At given values of Froude numbers, the wave deformations of the free surface play an appreciable, and at the smallest values Fr - decisive role. Moderate Bond numbers indicate the possibility of small-scale effects in flow patterns.

Table 2. Characteristic scales of the problem.

Parameter	Value
$\xi_H = R_d/H$	0.38
$\xi_0 = R_d/R_c$	1.0
$\xi_b = 2R_k/h_k$	0.8
$L_\Omega = g/\Omega^2$	$3{,}9 \times 10^3$
$\delta_\Omega = \sqrt{\nu/\Omega}$	3×10^{-4}

3 Experimental Study of the Transport of Immiscible Liquid Admixture in a Vortex Flow

Comparison of the size of the oil body, depending on the amount and physical properties of the immiscible impurity added to the stream, shows that increasing the viscosity of the marking additive leads to a decrease in the vertical size of the oil body. Also, the vertical dimension of the area occupied by the immiscible liquid in the flow is affected by the surface tension coefficient. With its growth, the depth of retraction of the impurity increases (Fig. 3).

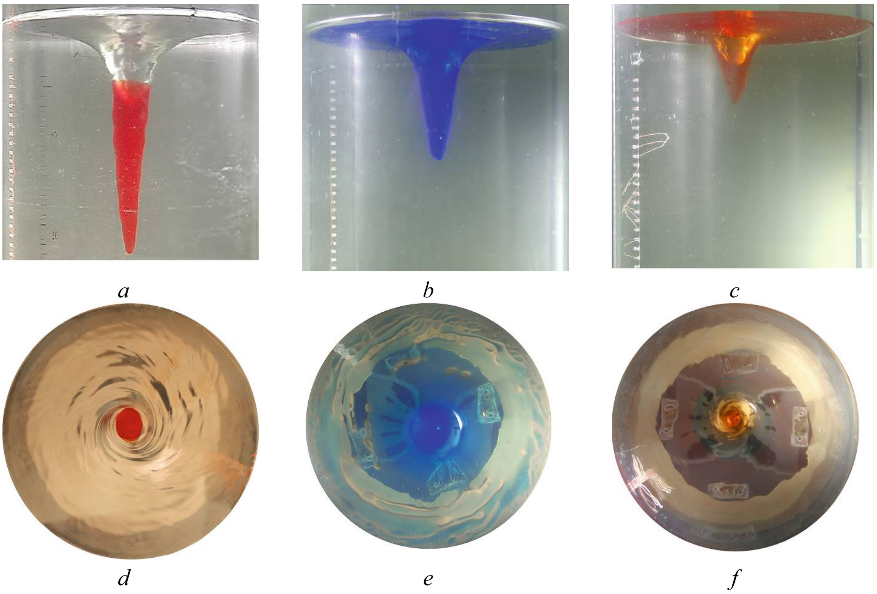


Fig. 3. Flow patterns in a composite vortex with addition immiscible liquid admixture ($V_k = 150\,\text{ml}\, H_w = 40\,\text{cm}$, $R_d = 7.5\,\text{cm}$): (*a* and d) sunflower oil, $\Omega_d = 770\,\text{rev/min}$; (*b* and *e*) – mixture of equal parts of sunflower oil and diesel fuel, $\Omega_d = 750\,\text{rev/min}$; (*c* and *f*) – diesel fuel, $\Omega_d = 820$ rev/min.

Dependences of the vertical dimensions of the surface cavity and oil body depend on the rotational speed of the activator are interpolated by linear functions $h_t = A\,\Omega + \mathrm{B}$, the coefficients included in them are given in Table 3.

Table 3. Coefficients of linear interpolations of the dimensions of the oil body.

	A	B
Sunflower oil	2.33 ± 0.13	−11.66 ± 1.30
Sunflower oil and diesel fuel	2.09 ± 0.27	−8.44 ± 0.67
Petroleum	1.88 ± 0.16	−8.01 ± 0.55
Diesel fuel	1.66 ± 0.21	−7.74 ± 1.48

There is a clear tendency to reduce the vertical dimensions of the oil body with a decrease in the density and surface tension coefficient of the impurity added to the flow, which is confirmed by the approximations obtained.

Saving forms the central part of the oil body when changing the angular speed of disc rotation allows to characterize the relative change in the ratio of one of its dimensions $\xi_m = 2R_m/h_m$ as a function of Reynolds number (Re) [9].

An increase in the rotation speed of the disk leads to an increase in the vertical component of the flow velocity at the center of the container and, correspondingly, to the shear stress at the boundary between the water and oil body. In the range of parameters Re from 500 to 12000, the dependence is represented by two linear functions $\xi_m = a\,\mathrm{Re} + b$: for small Reynolds numbers (less than 2,500), the angular coefficient is large $a = (-10.3 \pm 2.4) \times 10^{-4}, b = 2.2 \pm 0.4$ and rapid change in the ratio of the height of the oil body to its diameter near the free surface is observed, at large Reynolds numbers the line becomes flatter $a = (4.0 \pm 2.0) \times 10^{-5}$, $b = 0.7 \pm 0.1$, the change in the ratio of the diameter and height of the oil body is insignificant (Fig. 4).

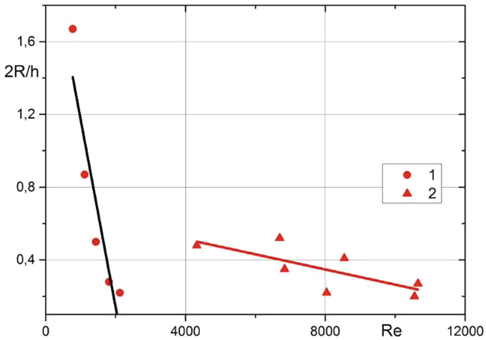


Fig. 4. Dependence of the oil body acuity coefficient ξ_b on the flow parameters: *1* – Sunflower oil; *2* – Petroleum.

The stability of the interface between the water and the oil body and the shape of the contact area of the liquids at the bottom of the cavity depend on the type of marker. At identical angular velocities of rotation of the disk, the water-oil boundary remains unchanged (Fig. 5*a*), and drops start to separate from the oil body in the water-aviation oil system (Fig. 5*b*). The rotating oil body is preserved when the rotational speed of the disk is increased (Fig. 5*c*), while in the water-aviation oil system an invert emulsion-cells with water, contoured by an angular oil shell-begins to form on the flow axis.

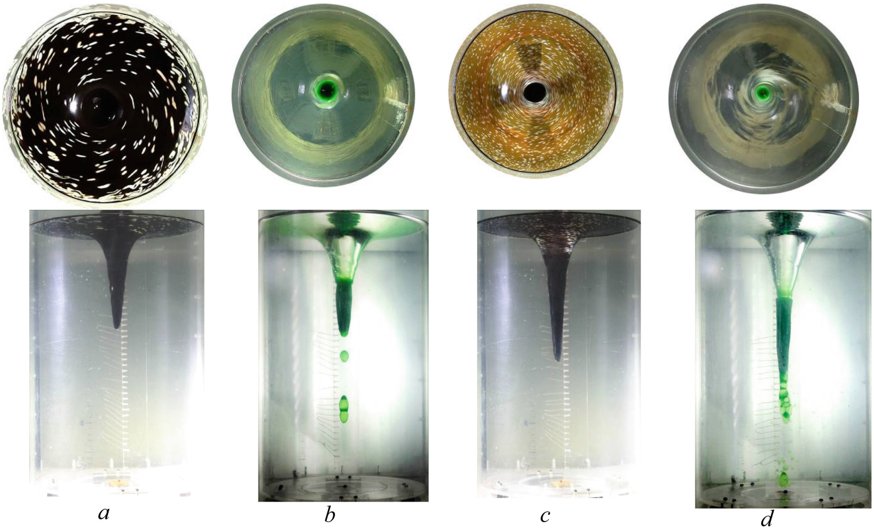
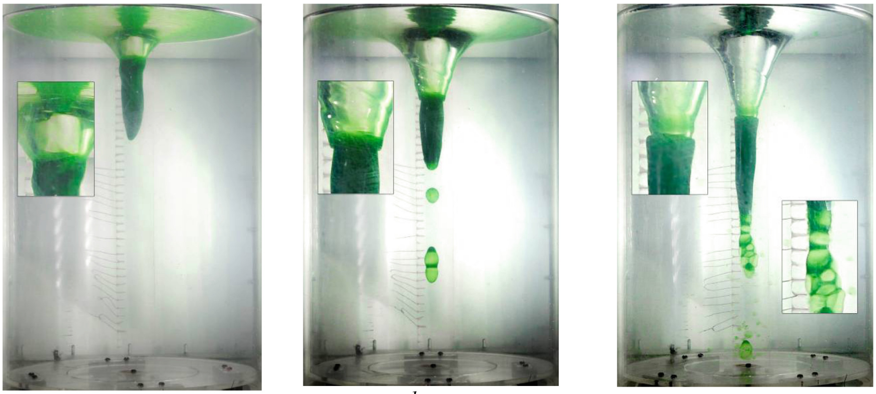


Fig. 5. Different types of immiscible marker in a vortex flow under different experimental conditions ($V_k = 150\,\text{ml}$, $H_w = 40\,\text{cm}$): (*a*) petroleum, $\Omega_d = 770$ rev/min; (*b*) aviation oil, $\Omega_d = 820$ rev/min; (*c*) petroleum, $\Omega_d = 1020$ rev/min; (*d*) aviation oil, $\Omega_d = 1050$ rev/min.

The general picture of the flow in the region of the contact of the oil body with the air cavern at various angular velocities of disk rotation is shown in Fig. 6. When the oil layer covers the entire free surface, the walls of the cavity are smooth, the transition of the oil from the inner to the outer surface of the cavity occurs smoothly, without singularities (Fig. 6*a*). With an increase in the disk rotation frequency, spiral waves are observed on the surface of the cavern, and in the region of the marker transition from the outside of the cavern to other types of markers. Separating from the lower edge of the oil body, spherical drops combine into groups and partially merge, forming pear-shaped bodies. With a further increase in the speed of rotation, the step in the region of the oil transition line from the outer to the inner side of the surface of the liquid becomes more pronounced, and instead of the drops of the direct emulsion, invert cells are formed at the lower edge of the body (an enlarged picture of the flow pattern is shown in the sidebar on the right in Fig. 5*c*). The dimensions of the emulsion cells range from 0.8 to 3.5 cm.



a *b* *c*

Fig. 6. Change in the shape of the oil body (aviation oil) when the rotational speed of the activator ($V_k = 150\,\text{ml}, H_w = 40\,\text{cm}, R_d = 7.5\,\text{cm}$): (*a–c*) $\Omega_d = 670, 820, 1050$ rev/min.

4 Motion of Solid Markers in the Compound Vortex

Our experiments (consisting of three separate experiments with the same boundary conditions for each marker) were carried out for ice and solid-state markers, plastic, with a diameter of 1 cm or 2 cm and a height of 0.5 cm were used. One of the objectives of this work was to determine whether the shape of the active scalar will affect its displacement in the fluid flow. The cylindrical container was filled with liquid to a predetermined level (40 cm). Then, the activator was turned on. After the decay of transients, the markers were placed on the surface of the liquid at a distance equal to half the radius of the container. At the same time, the video recording was begun. The captured video was divided into still images during processing. Each still image shows the position of the center marker, its orientation in space and trajectory.

The shapes of the marker trajectory depend on its initial position. There is a separatrix, which separates the region of different marker motion [5]. From one region, a marker will move to the vortex center, and from the other one, a marker will move to the side walls of the container.

The marker in the container rotates around the center of the vortex and around its own axis, forces and moments act on it (Fig. 7). Friction on the water surface twists the marker around its own axis (due to the difference in speed). Also under the surface there is a current directed toward the center of the free surface, which also creates friction.

The motion of the marker is described in several coordinate systems (Fig. 8). As a base coordinate system - Cartesian *X0Y* is chosen whose center is on the axis of flow and the axes are orthogonal to the walls of the basin, and cylindrical (r, ψ).

The radial position of the marker is given by the radius vector r. With the center of the marker is a mobile Cartesian coordinate system $X_a 0_0 Y_a$, which allows to determine the rotation angle of the marker around the proper axis φ. The rotation is investigated using the applied risk located along the axis $0_0 X_a$. The marker radially moved to the

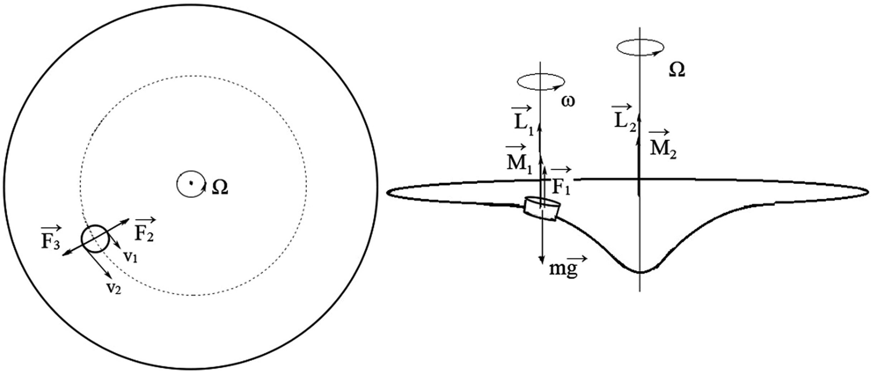


Fig. 7. Marker motion: (*a*) - top view: (*b*) - side view. F_1 – the force of Archimedes, F_2 – the centripetal force, F_3 – the centrifugal force, M_1 – the moment of force relative to the center of the marker, L_1 – the angular momentum relative to the center of the marker, M_2 – the moment of force relative to the vortex center, L_2 – the angular momentum relative to the vortex center, mg – the gravity, v_1 и v_2 – the velocities at the edge of the marker.

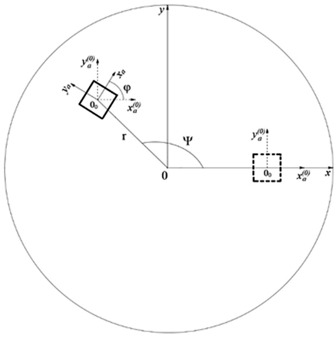


Fig. 8. Coordinate system.

center of the vortex flow and rotated around its own axis in all the experiments carried out. Differences in the character of motion of the marker in the composite vortex in pure water and on the surface of a two-layer water-oil liquid (oil volume V_k = 50 ml, thickness of unperturbed layer Δ = 1.5 mm) are illustrated by samples from the videograms shown in Fig. 9.

In pure water, the cylindrical marker moves along with the fluid flow around the central vertical axis, moves slowly toward the center and simultaneously rotates around its own axis. The tangential component of the velocity of the center of the marker in pure water at $\Omega = 9.2\,\mathrm{s}^{-1}$ at a distance of r = 8.1 cm from the center is $v_\varphi = 2.26\,\mathrm{cm/s}$ and changes slowly as it moves to the center of the flow. During the time of observation between the ones shown in Fig. 9, a, b frames (40 s) the marker makes 11 revolutions and shifts to the center by 4.3 cm and 48 turns around its own axis.

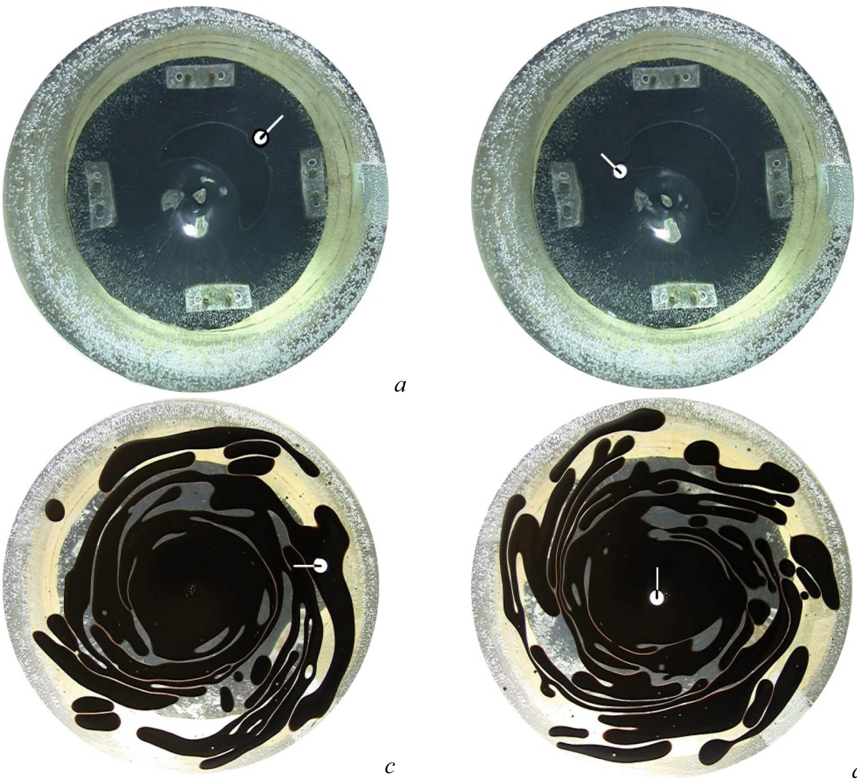


Fig. 9. Transferring a circular marker in a composite vortex $(H_w = 40\,\mathrm{cm}, R_d = 7.5\,\mathrm{cm}$, $\Omega_d = 9.2\,\mathrm{s}^1$: $(a,\ b)$ – pure water $(t = 10, 50\,\mathrm{s}), \mathrm{Re}_\Omega^w = 51562.5$, $\mathrm{Fr} = 0.119$; (c, d) – two-layer liquid (water and petroleum $V_k = 50\,\mathrm{ml})$ $(t = 10, 50\,\mathrm{s})$ (for clarity, the risks are continued by white lines in the figures).

Under the same conditions $(H_w = 40\,\mathrm{cm}, R_d = 7.5\,\mathrm{cm}, \Omega_d = 9.2\,\mathrm{s}^1)$ two-layer liquid (water and petroleum the cylindrical marker within t = 40 s has time to make 8 revolutions around the center $(\psi = 16\pi)$, 17 turns around its own axis $(\varphi = 34\pi)$ and falls into the center of rotation at the bottom of the surface cavity, passing the distance $\Delta r = 8.1\,\mathrm{cm}$ (in a homogeneous fluid at the same angular velocity of rotation of the disc, the marker is displaced to a shorter distance $\Delta r = 4.3\,\mathrm{cm}$).

In order to obtain the motion characteristics of the markers, the processing of video films was carried out, during which the temporal variability of the following parameters was determined: the distance between the marker and flow centers $r(t)$, the angular displacement of the marker's center in the laboratory coordinate system $\psi(t)$, the rotation angle of the marker around its own center $\varphi(t)$, which allows determining the functional connection between the angles φ and ψ.

Each experiment was repeated at least three times, the graphs show average values for the whole set of experiments. Temporal variability of the radial position of the markers in a homogeneous (curve 1) and two-layer (curve 2) liquid is shown in Fig. 10.

In a homogeneous liquid, the circular marker oscillates near a certain position and slowly moves to the edge of the basin, while in the liquid with the oil film it moves quickly enough to the center.

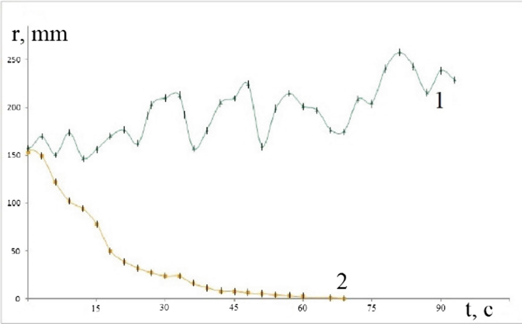


Fig. 10. Radial position of the circular marker in the composite vortex ($H_w = 40\,\text{cm}$, $R_d = 7.5\,\text{cm}$, $\Omega_d = 10.8\,\text{s}^{-1}$, $\text{Re}_\Omega^w = 60927.5$, $\text{Fr} = 0.165$): *1* – pure water, *2* – two-layer liquid (water and petroleum $V_k = 50\,\text{ml}$).

The nature of the rotation of the marker depends on its shape and angular velocity of rotation of the activator disk Ω_d. The round marker after a short interval of involvement (t = 5 s) in the center of the flow rotates with an almost constant angular velocity, the value of which increases monotonically with increasing disk rotation speed: $\dot{\varphi}_1^c = d\varphi_1^c/dt = 66.6$; $\varphi_2 = d\varphi_2^c/dt = 99.3$; $\dot{\varphi}_3 = d\varphi_3^c/dt = 134.8$.

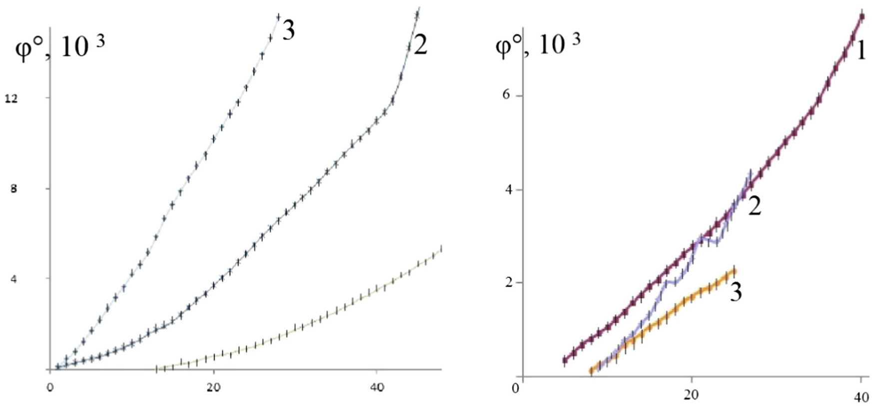
The measured values of the rotation angle φ along the entire marker track are approximated by functions $\varphi_c = 0.07\,t^{2.9}$ (for $\Omega_d = 3.3\,\text{c}^{-1}$), $\varphi_c = 55.82\,t^{1.4}$ (for $\Omega_d = 9.2\,\text{c}^{-1}$), $\varphi_c = 185.42\,t^{1.34}$ (for Ω_d =16.7 c^{-1} (Fig. 11).

The square marker also rotates with an almost constant angular velocity at a small angular velocity of rotation of the disk $\dot{\varphi}_1^s = d\varphi_1^s/dt = 30.1(\Omega_d = 3.3\,\text{s}^{-1})$ and with a large velocity $\dot{\varphi}_3 = d\varphi_3^s/dt = 128.2(\Omega_d = 16.7\,\text{s}^{-1})$. At intermediate values of the angular velocity of the activator disc $\Omega_d = 9.2\,\text{s}^{-1}$, the square marker is not verified unequally (curve 2, Fig. 11*b*), which reflects the complex nature of the interaction of the dragged square marker with the main current.

Perhaps the irregular nature of the rotation is due to the interaction of the marker with inertial and spiral waves that arise arbitrarily on the surface of a rotating fluid [14], the most pronounced for a given flow regime.

The trajectories of a square marker are approximated by functions $\varphi_s = 40.8\,t^{1.4}$ (for $\Omega_d = 3.3\,\text{s}^{-1}$), $\Omega_s = 0.77\,t^{2.68}$ (for $\Omega_d = 9.2\,\text{s}^{-1}$), $\varphi_s = 1.4\,t^{2.4}$ (for $\Omega_d = 16.7\,\text{s}^{-1}$).

The features of the motion of various markers in a liquid with an oil film are illustrated by photographs of flow patterns shown in Fig. 12. The experiments showed that the very distribution of oil over the surface of the composite vortex is not homogeneous, oil can spread into a film and collect in an oil body in the vicinity of the



a *b*

Fig. 11. Dependence of the angle of rotation around its own axis on time ($H_w = 40\,\text{cm}, R_d = 7.5\,\text{cm}$): *1* – $\Omega_d = 3.3\,\text{s}^{-1}$ ($\text{Re}^w_\Omega = 18750$ Fr = 0.016), – $\Omega_d = 9.2\,\text{s}^{-1}$ ($\text{Re}^n_Q = 51750$, $\text{Fr} = 0.119$), 3 – $\Omega_d = 16.7\,\text{s}^{-1}$ ($\text{Re}^w_\Omega = 93750$, $\text{Fr} = 0.392$): (*a*) – round marker, (*b*) - square marker.

rotation axis [17]. Petroleum covered the surface of the vortex almost completely in experiments with moderate angular rotational speeds of the activator disk.

With an increase in the angular velocity of rotation of the disk, the thickness and nature of the distribution of the oil film along the surface of the water decreases. The inserted marker leaves a trace that is practically free of oil (Fig. 12). At the same time, the own rotation of the marker relative to its own center remains.

The geometry of the marker trace depends on all the parameters of the problem (the angular velocity of the inductor rotation, the depth of water, the amount of oil - the thickness of the initial layer), and also the shape of the marker.

A round marker rotates around the center, revolves around its own axis, and forms characteristic structures including compact regions without an oil film, the shape of which depends on the duration of the motion. The square, like the round marker, also rotates and leaving a trace of variable thickness behind it (Fig. 12*c*).

Qualitative features of the trace are preserved even in the case of the motion of the ice marker to the stage of the onset of melting (Fig. 12*d*). In this case, the contours of the track are more even than for the solid-state marker, in addition, in this case the marker is also rotated around its own axis.

5 Conclusion

The experiments showed that a uniform layer of hydrocarbons on the water free surface is pulled together into the oil body located on the flow axis. Some portions of the oil remain on the free surface in the form of spiral arms, either continuous or decomposed into separate drops. At high angular speeds of rotation the oil droplets can be found all

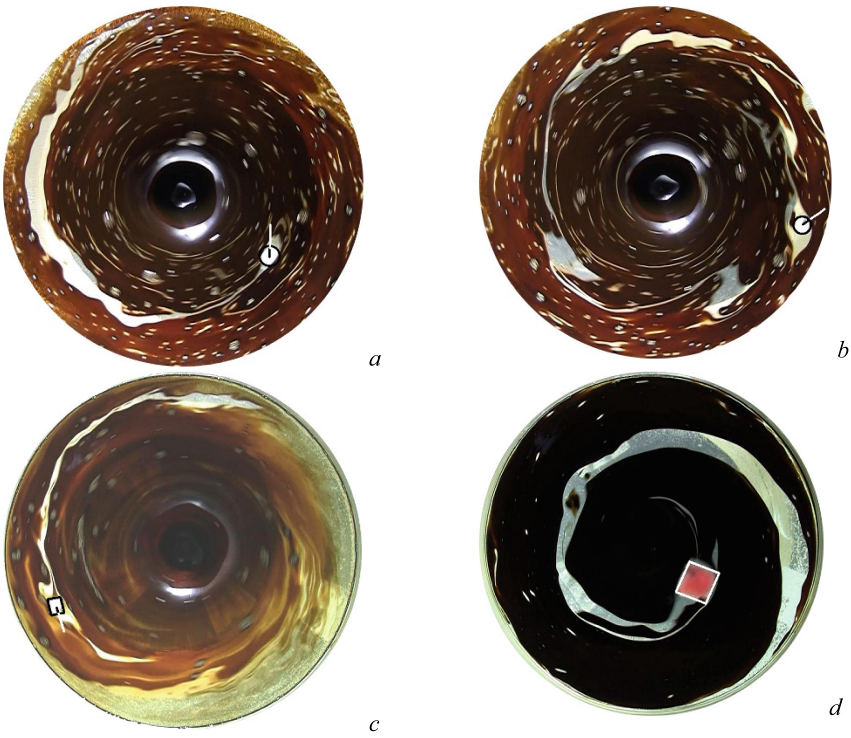


Fig. 12. Rupture of oil film by a free drift marker ($H_w = 40\,\text{cm}, R_d = 7.5\,\text{cm}, V_k = 50\,\text{ml}$): (*a*, *b*) – round marker ($\Omega_d = 13.7\,\text{s}^{-1}$, $t = 6, 10\,\text{s}$), $\text{Re}_\Omega^w = 77062.5$, $\text{Fr} = 0.261$; (*c*) – square marker ($\Omega_d = 3.3\,\text{s}^{-1}$, $t = 3\,\text{s}$, $\Omega = 18750, \text{Fr} = 0.016$); (*d*) – ice ($\Omega_d = 10.8\,\text{s}^{-1}$, $t = 4$ s, $\text{Re}_\Omega^w = 60927.5, Fr = 0.165$).

over the liquid – air contact surface. The contact surface geometry depends on the parameters of the vortex flow, determined by angular velocity of inductor rotation and quantitative composition of medium.

The conditions for the loss of continuity of the interface depend on the type of impurity. At average angular velocities of rotation, a direct emulsion is formed, both types are observed with increasing speed, and at high rates - an invert emulsion.

The experiments showed that the movement of the marker introduced on the surface of the composite vortex is complex and includes tangential displacement (rotation relative to the center of the flow), radial displacement and rotation relative to its own axis. The nature of the movement depends on the conditions of the experiments (the depth of the liquid and the rotational speed of the activator disk), the type of liquid (homogeneous or two-layered with oil film), and the shape of the marker.

The inserted marker, both solid and melting ice, slides relative to the upper layer of the liquid and leaves a trace of a complex shape behind it.

The angular velocities of rotation and rotation around the flow center are related by a functional dependence determined by the flow parameters and the properties of the marker (volume, mass, size and shape). In this case, circular markers develop over time a higher speed of rotation around the center of the vortex, as well as their own.

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