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Experimental Modeling of the Shifting of Floating Objects in "Garbage Islands"

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Abstract—We studied the movements of polypropylene markers in a composite vortex as a model for the transport of garbage in the ocean in the laboratory setting. We showed that when in motion a marker rotates around the center, as well as around its own axis. We determined the dependence of the angular velocities of marker rotation on the distance to the center of a vortex, whose values depend on the size of the markers at fixed permanent conditions. We found the separatrix that divides the areas of the initial positions, from which the marker is displaced upon further movement to the center of the vortex or to the container walls.

Keywords: garbage islands, compound vortex, movement trajectories of solid-state markers

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INTRODUCTION

Beginning in the 1980s the attention of the public and the scientific communities was attracted by an increase in the amount of drifting plastic waste in the waters of the World Ocean. Measurement of the concentration of plastic in the surface waters of The North Pacific Ocean [1] revealed an increased concentration in the areas that are controlled by certain ocean currents. In 1997, Charles Moore found a huge accumulation of plastic in the Pacific Ocean in the North Pacific current systems, which was named the "Great Pacific Garbage Patch." The area of the "Big Pacific spot" according to various estimates ranges from 700000 to 15 million square kilometers and the total mass of the waste exceeds 100 million tons [2] and at the same time is constantly increasing. The floating waste is mostly small pieces of plastic, which concentrate in the upper (30 m) water layer (Figure 1) [3].

Subsequently, these concentrations have been found in other oceans, in places where the current system forms stable circulation zones. Today, we know about the five most massive clusters of waste: two in the Pacific, two in the Atlantic and one in the Indian Ocean [4, 5]. To monitor these trash islands and to study pollution-related problems the 5 Gyres Institute was established in 2009 [6].

The problem of the study of "garbage islands" is complicated by the fact that the transport routes of vessels pass by these areas, while satellite observations are not possible because of the transparency of the plastic, the small sizes of plastic particles, and due to the fact that most of the particles are below the water surface. At the same time, the unpredictable behavior of garbage patches presents a great danger for coastal areas.

The theoretical description of waste transfer is greatly complicated by the large number of factors that influence this process. In this situation, laboratory simulation, which allows one to control the external parameters, may help in assessing the impact of various factors on the dynamics of both the island's garbage and the dynamics of the elements of which it consists.

The objective of this work is an experimental study of the dynamics of floating particles on the surface of a composite vortex and the modeling of a vortex system with a sink in the center and the influx of fluid at the periphery.

1. Laboratory Facility

Experiments were carried out on the Vortical current with torsion (VCT) of a unique installation of unique stands and installations (USI) "hydrophysical

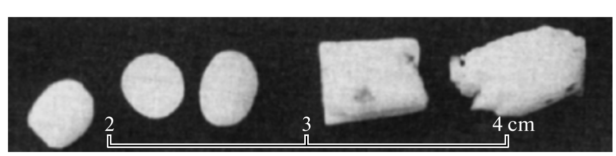

Fig. 1. Typical particles of plastic in a sample from the surface layer of the contaminated area.

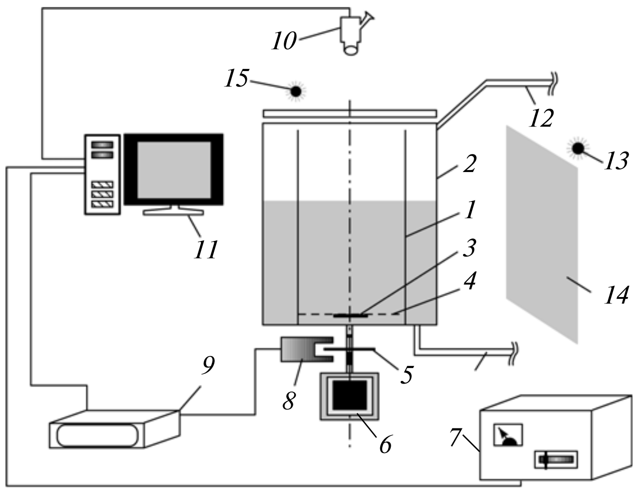

Fig. 2. The scheme of the laboratory apparatus.

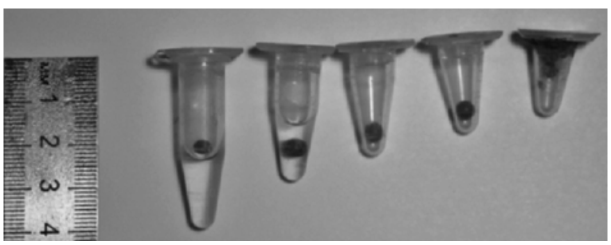

Fig. 3. The markers that were used in the experiment.

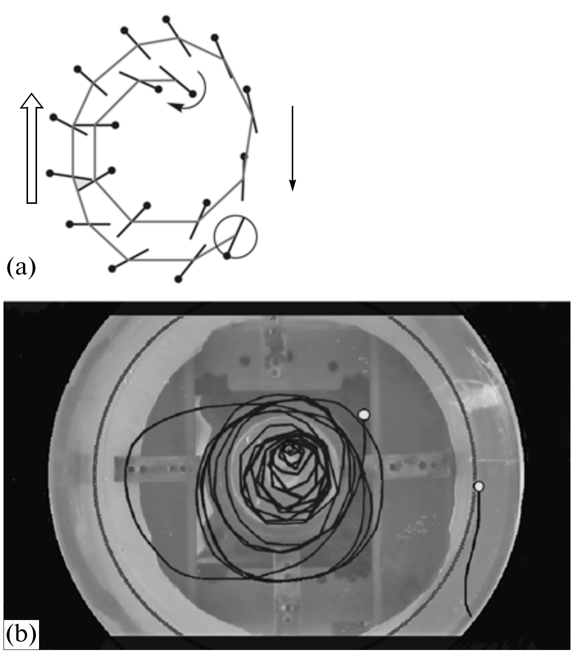

Fig. 4. (a) The schematic of the marker movement on the seventh and eighth revolutions. (b) The trajectories of a single marker.

complex for modeling hydrodynamic processes in the environment and their impacts on the submarine technical facilities, as well as the distributions of impurities in the ocean and atmosphere (the HPhC of the Russian Academy of Sciences Institute for Problems in Mechanics)."

The scheme of the laboratory setup is shown in Figure 2. The basis of the installation is a working cell, viz., a cylinder with a height of 70 cm and an inner diameter of 4.29 cm. To reduce optical distortion when taking pictures of currents, the cylinder was placed inside an open parallelepiped $64 \times 45 \times 70$ cm in size in a metal frame, *2*. A shaft passes through the geometric center of the container through a packing seal. It is directly connected with an electric motor, *6*, whose rotational speed can range from 200 to 2500 rev/min.

The choice of rotation frequency, which in these experiments was kept constant at $\Omega = 650$ r/min and 900 r/min, was carried out by the control unit, *7*. On the activator the shaft, *3*, was installed with a smooth disc diameter of 5 cm and a 2 mm thickness.

The upper edge of the disk was located at a distance of 2 cm from the bottom of the pool.

A false bottom, *4*, was located at the level of the upper edge.

To determine the angular velocity of the disk activator a support drive with slots, *5*, was located on the shaft of the electric motor.

The angular velocity of disk rotation was determined by means of a frequency counter, *9*, that recorded the data from the optical sensor, *8*.

Video observation of the flow pattern was carried out using a digital camera, *10*, which is a Panasonic NV-MX500 that is located vertically above the center of the basin. An electronic viewfinder that is used in the camera can direct the axis of the camera lens right of the central axis of the basin. Management of the experiment and data logging was conducted using a PC, *11*.

For filling and draining the pool we used a hydraulic system, *12*. Lighting the flow region was carried out with a source of white light, *13*, with a diffusing screen, *14*, or an ultraviolet light bulb, *15*.

Before starting the experiment, the installation was filled with degassed tap water. The depth of the liquid layer in these experiments was 30 cm. Lighting conditions (the angle and height of the projector) were selected so that under further processing of the image all the details of the free surface were visible and distinguishable.

On the surface of the liquid a set of floating markers of varying heights was placed, as shown in Figure 3. We used polypropylene tubes with a diameter of 9 mm, which were weighted (for vertical orientation in the water) with lead balls as markers. On the cover of markers special tags were placed that allow observa-

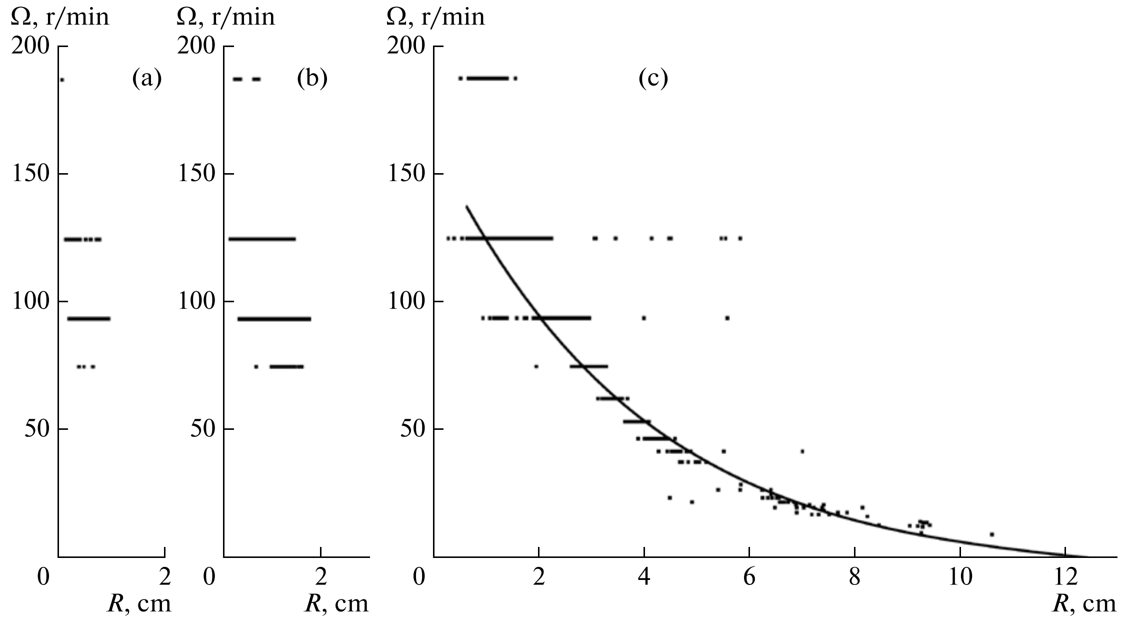

Fig. 5. The distribution of the angular velocity Ω of the marker height of 2.5 cm, depending on the distance between the center of the marker and the center of the vortex R. Velocity of the rotation activator: a) 500 r/min, b) 650 r/min, c) 900 r/min.

tion from above in order to distinguish the markers from each other and keep track of their orientation in the basin.

Each new experiment was started after the decay of all visible movements in the basin. Before starting the recording, camera alignment was carried out using a special system of marks. Video recording of marker movements began after the movement on the surface took an established character and continued for about 5 minutes. Processing of the finished material in Adobe Photoshop allowed us to trace the trajectory of markers and their angular positions, the angular position of the label on the top and measure the distance from the center of the marker to the center of the cavity, which indicates the center of rotation of the surface layer of liquid R, the angular velocity of marker rotation around the center of the cavity Ω, and the natural frequency of marker rotation around its axis ω.

When processing freeze frames with movement through the basin surface the markers were superimposed on each other in order to record the movement of the marker center and the rotation angle of the marker.

RESULTS

Figure 4 shows an example of the trajectories of a single marker with a height of 2.5 cm. The bright grease dot denotes the initial position of the marker, which is shifted to the center (Figure 4b). The circular line indicates the separatrix, which separates the primary position that determines the direction of predominant marker movement to the center of the vortex, or to the walls of the container.

The trajectories of the markers showed that the center of the vortex exit at the surface of the liquid tends to be shifted from the symmetry center of the container.

The details of the marker movement are shown in Figure 4a for the seventh and eighth turns. Here, a large arrow denotes the direction of disk rotation and the liquid in the container about a vertical axis as a whole. The thin arrow indicates the direction of the marker movement, whose initial position is indicated by a gray circle with a diameter that is equal to the diameter of the marker on the scale of the trajectory. The rotation direction of the marker around its own axis shows the curve arrow near the last point of the eighth turn. All angular velocities in this experiment are anticyclonic (clockwise rotation). On a reducible segment angular velocities are not constant and at the seventh circuit $\Omega = 8.6$ r/min, $\omega = 7.5$ r/min, $\omega/\Omega = 0.9$ and $\Omega = 20$ev/m, $\omega = 10.8$ r/min, $\omega/\Omega = 0.5$ at the eighth circuit.

From the beginning of the movement, the set of markers that were placed approximately at a distance of half the radius of the cell began to move towards the center of the vortex that was created in the container. Upon reaching the center, the markers began to interact with each other, resulting in periodic "crashes" of markers at some distance from the center. Thus, in addition to the rotation of markers around a common center we observed rotation of the markers around their own axis.

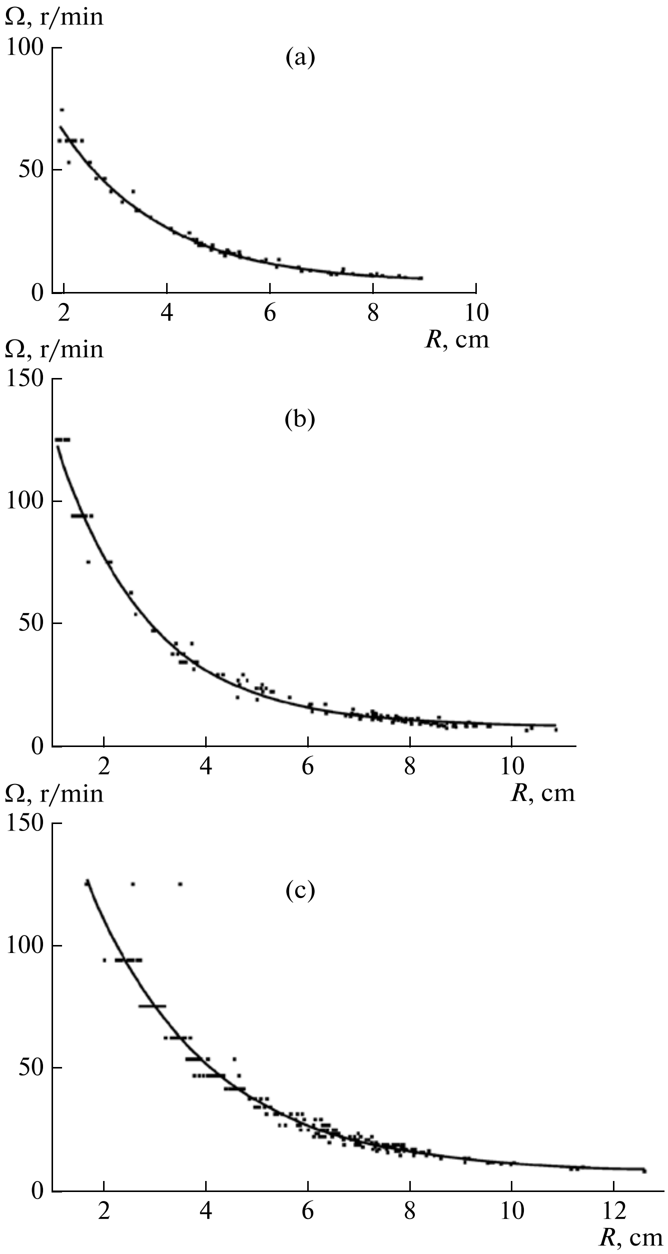

Fig. 6. The distribution of the angular velocity Ω of the marker height of 3 cm, depending on the distance between the center of the marker and the center of the vortex *R*. The velocity of the rotation activator: a) 500 r/min, b) 650 r/min, c) 900 r/min.

One of the most important characteristics of the marker motion is the angular velocity of the marker relative to the point of maximum depth of the liquid (vortex center) Ω.

The distribution of angular velocity Ω depending on the distance between the center of the marker and the center of the vortex *R* are presented in Figures 5–7. Measurements were carried out for three markers of different lengths (2.5 cm, Figure 5; 3 cm, Figure 6; and 4 cm, Figure 7) at three different rotation frequencies of the disk activator: 500 r/min, a); 650 r/min, b); and 900 r/min, c). This experiment showed that the trajectories of markers of different sizes differed from each other at different frequencies.

Thus, throughout the experiment the marker height of 2.5 cm at frequencies of rotation of the disk activator of 500 r/min and 650 r/m was located near the center of rotation of the fluid and moved away from it by no more than 2 cm. However, with increasing disk rotation speed to 900 r/min we observed, "crashes" of the marker that reached distances of up to 11 cm from the center, which is about 2/3 of the container radius.

During the experiment the distribution of distances from the center of the marker height of 3 cm were of a much more uniform character, but more frequently the marker was located at a distance equal to about half the container radius.

For the marker height of 4 cm the reverse situation was observed: at frequencies of 500 r/min and 650 r/min the marker made periodic "crashes"; with an increasing rotation frequency of the activator up to 900 r/min the marker moved to the center of the vortex and remained in it.

We can approximate the distributions of the angular velocity of markers $\Omega(R)$ in all cases, except the case of permanent marker location in the center of the vortex, by an exponential dependence of $\Omega(R) = \Omega_1\exp(-R/R_1) + \Omega_0$.

The velocity shift in the vortex formed shear stresses that twisted the marker around its own axis. Figure 8 shows the eigen-value distribution of marker rotation speeds with 3 and 4 cm at a frequency of disk activator rotation of 650 r/min.

These distributions are also approximated by the dependence: $\omega(R) = \omega_1\exp(-R/R_1) + \omega_0$, with the coefficients $\omega_0 = -0.8 \pm 3.0$, $\omega_1 = 191.3 \pm 18.3$, $R_1 = 1.91 \pm 0.26$ and $\omega_0 = 4.6 \pm 3.6$, $\omega_1 = 192.7 \pm 8.6$, $R_1 = 1.86 \pm 0.15$, which coincide within the error limits, respectively. For both dependences, we traced waveform deviations of their own rotation speeds from the exponential dependence, which was apparently caused by spiral waves that are present on the liquid surface [7].

CONCLUSIONS

1. Looping experiments on the trajectories of solid-state markers in a composite vortex at fixed values of fluid depth and the rotational speed of a disk activator made it possible to determine the kinematic parameters of movements.

2. The trajectory of marker motion depends on its initial position. An area exists in which the marker will move not to the center of the vortex but in the direc-

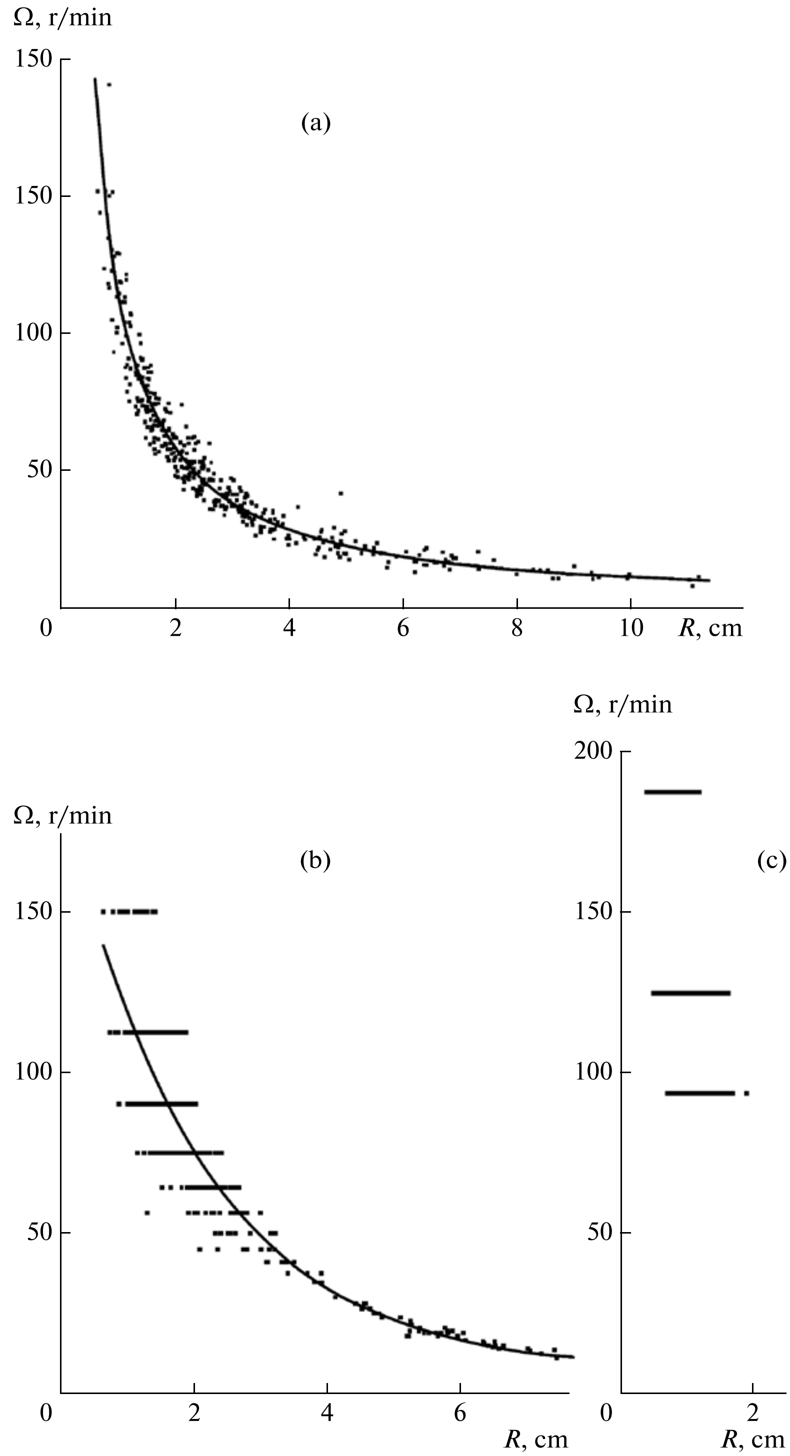

Fig. 7. The distribution of the angular velocity Ω at a marker height of 4 cm, depending on the distance between the center of the marker and the center of the vortex *R*. The velocity of the rotation activator: a) 500 r/min, b) 650 r/min, c) 900 r/min.

tion of the container walls. As it moves, the marker rotates around the center, as well as around its own axis.

3. The instantaneous center of rotation of the flow pattern is shifted relative to the center of the container symmetry.

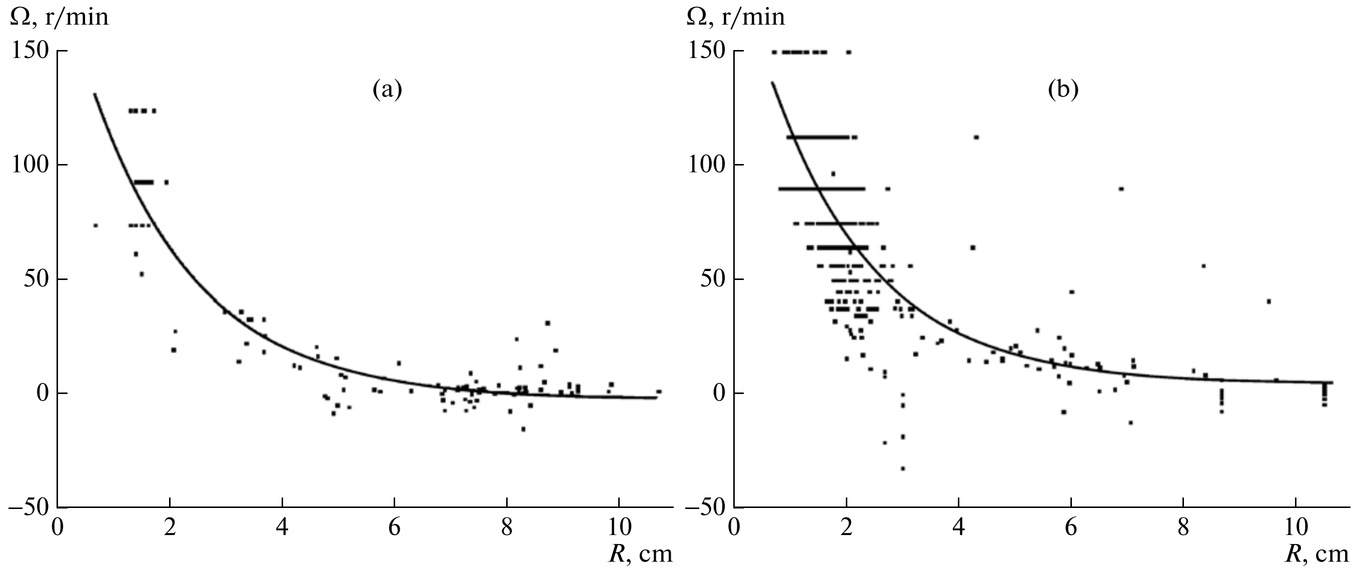

Fig. 8. The distribution of the angular velocity of the marker Ω, depending on the distance between the center of the marker and the center of the vortex *R*. The velocity of the activator rotation is 650 r/min. The height of the marker is a) 3 cm, b) 4 cm.

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Fixes and typos:

Fig.8. should be replaced by:

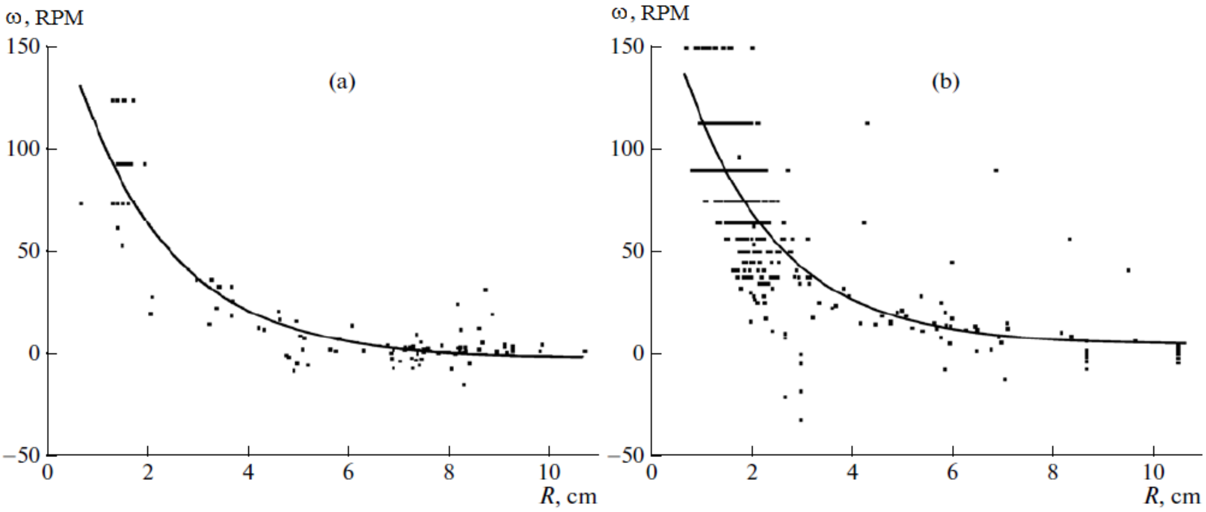

Fig. 8. The distribution of the angular velocity of the marker ω, depending on the distance between the center of the marker and the center of the vortex *R*. The velocity of the activator rotation is 650 r/min. The height of the marker is a) 3 cm, b) 4 cm.