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Abstract

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SECOND SERIES OF GROUND-BASED EXPERIMENTS WITH WEIGHTLESS LIQUIDS

The first series of our experiments ([1]) was arranged in order to detect disturbances that can greatly complicate the behavior of a weightless liquid in comparison with the elementary theoretical scheme ([2]). In the second series, well-purified liquids were tested: mercury, bidistilled water, and bromobenzene. The internal motion-picture equipment of the freely falling projectile was the same as before. As before, the scales of the photographs may be judged by assuming that the diameter of the chronoscope dial corresponds to 30 mm.

To ensure complete cleanliness of the underlying surface, not wetted by the liquids, and to exclude completely the transfer of any impurities from this surface into the liquid, instead of the paraffin cuvette we used (on the advice of A. A. Trapeznikov) a cuvette made of fluoroplastic, bounded above by a spherical surface with radius of curvature 470 mm.

Of particular interest are the results obtained in two experiments with pure mercury (the two numbers given correspond to the two experiments). The amount of mercury taken was 140–118 g. The "flat drop," with disk diameter 55–46 mm, in the first stage after the onset of weightlessness took the form of a toroid (Fig. 1a). Over the course of 0.1 sec the height of the toroid rapidly increased, its diameter decreased, and finally the ring closed–transforming it into a truncated sphere of diameter 33–31 mm. In the motion-picture frames one clearly sees the cumulative effect that gives rise to a sharp peak above the sphere (Fig. 1b). This peak rises upward with an initial velocity of more than 80 –75 $cm \cdot sec^{-1}$, and, following it, ever new masses of mercury are drawn upward.

At 0.125 sec after the onset of weightlessness, the rate of growth of the peak begins to decrease noticeably, and at this moment a droplet of mass about 0.1 g detaches from its tip. After another 0.025 sec, a second droplet detaches, with mass 1.5–1.0 g. They move upward with constant velocities: the first at 62–45 $cm \cdot sec^{-1}$, the second at 25–27 $cm \cdot sec^{-1}$. In Fig. 1c the first droplet is visible above the chronoscope hand, and the second above the peak.

The shape of the main body of rotation changes strongly, reaching its greatest rise above the bottom of the cuvette at 76–64 mm. In Fig. 1d one can see the characteristic belts that arose in both experiments. Unlike an unduloid, characterized by constancy of the pressure of the surface layer at all its points, here an inequality of pressures is produced, which we established by measuring in the photographs the principal radii of curvature (of alternating sign): at the top the pressure of the surface layer is 1700 dyn/cm^2; on the surface of the first narrowing, 680 dyn/cm^2; on the convex surface lying lower, 830 dyn/cm^2; on the second narrowing, 540 dyn/cm^2; at the height of the greatest transverse section, 620 dyn/cm^2; and at the very bottom, 1300 dyn/cm^2. Thus pressure gradients arose, causing the motion of the mercury during the subsequent phases of oscillation, predominantly in the direction from both ends of the body of rotation toward the center of mass. As a result, not only does the height of the column decrease, but its base becomes rounded and even detaches from the surface of the cuvette; the entire mass of mercury hangs in the air. This is seen in Fig. 1e, where one of the extreme phases of the oscillatory cycle is shown. There is no doubt that after the oscillations die out the mercury will assume the form of a truncated sphere of diameter 33–31 mm, of the type shown in Fig. 1b but without the peak, or of the type shown in Fig. 2a in article ([1]).

Let us try to explain the very stable wavy form of the profile of the body of revolution, which is preserved both before the phase of Fig. 1 g and after it.

We shall investigate the propagation of annular waves on the surface of a weightless liquid cylinder along its axis z. Distances from the axis in the direction of the radii will be denoted by x. For the velocity potential φ we write Laplace' s equation

$$\frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial z^2} + \frac{1}{x}\frac{\partial\varphi}{\partial x} = 0 \tag{1}$$

and integrate it under the following conditions: the oscillations are harmonic, with cyclic frequency ω; the derivative $\partial\varphi/\partial x$ vanishes on the axis of the cylinder. The integral is represented in the form

$$\varphi = AI_0(kx)\sin(kz - \omega t), \qquad k = 2\pi/\lambda;\ \omega = 2\pi/T, \tag{2}$$

where λ is the wavelength and T their period.

In a first approximation it is admissible that the amplitude of the radial oscillations is small in comparison with the radius of the cylinder r, and therefore one of the principal radii of curvature of the surface is constant, equal to r. Then the contribution of the quantity σ/r to the surface pressure may be regarded as constant, adding it to the external atmospheric pressure. The pressure of the surface layer will change only as a result of changes with time (and along z) of the second principal radius of curvature: in the meridional plane of the body of revolution.

Thus, in addition to (2), it is necessary to write the equation used in the theory of purely capillary waves:

$$\frac{\partial^2\varphi}{\partial t^2} - \frac{\sigma}{\delta}\frac{\partial^3\varphi}{\partial x\,\partial z^2} = 0. \tag{3}$$

Substituting the function φ and its derivatives into (3), on the basis of (2), we find for the cyclic frequency the expression

$$\omega^2 = \frac{\sigma k^3}{\delta}\frac{I_1(kr)}{I_0(kr)}. \tag{4}$$

Substitution of the numerical values from measurements on the photographs into (4) gives $\omega = 8.0$ and, consequently, $T = 0.78$ sec. It is now clear that the motion-picture photographs recorded standing waves on the surface of the body of revolution: in a quarter-period, near the upper end, the phase which produced the point was replaced by a phase characterized by a drop-like thickening, visible in Fig. 1 *g* and in many other frames of the motion picture. In reality the waves arise not on the surface of a cylinder, but on the surface of the highly elongated ellipsoid shown in Fig. 2 of paper ([2]). Thus, as one moves upward, r continuously decreases in the arguments of the cylindrical functions. As a result, the velocity of wave propagation, determined from the relations $c = \omega/k$ and (4), decreases, i.e.

$$c = \sqrt{\frac{\sigma k}{\delta}\frac{I_1(kr)}{I_0(kr)}}. \tag{5}$$

This thereby causes an increase in the amplitude of the radial oscillations as one approaches the upper end of the body of revolution—in full agreement with Fig. 1 *g*.

Thus, in accordance with our elementary theoretical scheme ([2]), the mercury, having instantaneously lost its weight, passes through a state of static equilibrium (Fig. 1 *b*, without the peak), possessing excess kinetic energy; this energy is completely exhausted in the phase of Fig. 1 *g*. But, in contrast to the scheme ([2]), the motion is complicated by standing waves superposed on the surface of the elongated ellipsoid of revolution. This is natural, since the arguments put forward, for example, with respect to pulsating drops ([3]), proceeded from the assumption of only small deviations from spherical form. The period of oscillations of mercury, calculated by formula (6) from ([2]), as applied to the two experiments described, is respectively 0.84-0.80 sec. In reality it proved to be 25% larger. Measurements on strongly enlarged motion-picture photographs of the type of Fig. 1 *g* made it possible to compute the surface of the body

rotation in the limiting phase, when the kinetic energy is reduced to zero. It turned out that it only very slightly exceeds the initial surface of separation of mercury—air in the "flat drop." This means that the greater part

Fig. 1

Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

Fig. 2

of the surface energy at the mercury–fluoroplastic interface was expended owing to losses during the deformation of the mercury from the "flat drop" to the body of revolution, Fig. 1 *g*. Obviously, the greatest amount of energy is damped in the cumulative effect, Fig. 1 *b*. It would be very important to investigate the hydrodynamics of this phenomenon, which presents the greatest difficulties. Further deformation–on the path from Fig. 1 *b*, *v* to Fig. 1 *g*–proceeds considerably more simply.

There is reason to believe that at the mercury-fluoroplastic interface the losses due to hysteresis of the contact angle are small.*

By contrast, extremely large hysteresis losses were found in experiments with bidistilled water and especially with bromobenzene.

As is known, water does not wet the surface of fluoroplastic. The experiments were carried out with various amounts of water introduced into the cuvette: 10, 20, and 40 g. The initial contact angle for the "flat drop" was always about 95°. Particularly interesting results were obtained in the first variant: during the free fall of the projectile it was possible to record on motion-picture film more than two successive cycles of oscillations. In Fig. 2a the state of the water is shown 0.09 sec after the onset of weightlessness. The shape of the surface is very remarkable: the contact angle became acute, as in the case of liquids wetting a solid surface; it is 35° on the left and about 30° on the right. Higher up, the surface of revolution becomes flatter, up to a peculiar belt, above which a hemisphere has formed. Here hysteresis manifested itself sharply: the molecular forces retard the motion of the circular water-fluoroplastic boundary toward the axis of the body of revolution. At the same time, in accordance with the known schemes ([4]), water flows from the "flattened" –peripheral–part into the hemispherical part. As a result, the system passes through the phase of static equilibrium (in the form of a truncated sphere) and acquires a greater curvature at the axis of symmetry. This is seen in Fig. 2b, corresponding to 0.22 sec after the onset of weightlessness. Even here there still remains a residual trace of the lower "tier" that existed in Fig. 2a, although now the contact angle has acquired its initial value–about 95°. Measurements of the principal radii of curvature showed that the pressure of the surface layer is 130 $\mathrm{dyn \cdot cm^{-2}}$ at the top, at the axis of symmetry, and 74 $\mathrm{dyn \cdot cm^{-2}}$ below, at the remnant of the belt. After the phase of Fig. 2b, the apex of the body of revolution begins to descend, and at the moment corresponding to 0.37 sec the water assumes the form shown in Fig. 2c. Here again, though more weakly, hysteresis of the contact angle made itself felt. Now it retarded the motion of the water edge in the opposite direction—away from the axis of symmetry. Precisely for this reason the contact angle on the left reached almost 120°, and on the right about 100°.

The period of oscillations, calculated for 10 g of water by (6) from ([2]), is 0.57 sec. Consequently, the phase of Fig. 2b should have occurred after 0.28 sec. In fact, it occurred 23% earlier. Thus, even the retardation caused by hysteresis played a smaller role than the additional energy at the water–fluoroplastic surface, not taken into account in (6) from ([2]). This energy appeared still more clearly at other stages of the oscillations: the time interval separating the phase of Fig. 2b from the next similar phase is 0.4 sec. Consequently, here the period of oscillations proved to be 30% smaller than that calculated by (6) from ([2]).

We shall not dwell here on the results of the experiments with bromobenzene, during which hysteresis losses did not allow interesting phases to develop within the free-fall time so far available. In general, although the unexpectedly large role of hysteresis created additional difficulties for future hydrodynamic investigations of the process, it also revealed a new application of experiments with weightless liquids to important questions of molecular physics. If the first steps in the physics of weightless liquid suggest ever new applications of it, then the fundamental interest of investigations will increase still further after the creation of a hydrodynamic theory of the deformation of a weightless liquid mass.

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* Signs of angle hysteresis are visible in Fig. 1a on the left.

Note: Figure translations are in progress. See original paper for figures.