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INTERACTION OF DROPS WITH BOUNDARY LAYER ON ROTATING SURFACE

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The interaction of a drop with a boundary layer on the surface of a rotating disk is investigated experimentally.

Theoretical and experimental investigations of a two-phase current flowing around a fixed plate [1, 2] have shown that the boundary layer has a significant effect on the type of motion observed and the settling out of moisture.

The interaction of moisture with the boundary layer of a moving surface, although it is a subject of some importance, has yet to be adequately studied.

In the present paper, the interaction of a single drop with the boundary layer on the surface of a rotating disk is considered.

A diagram of the experimental apparatus is given in Fig. 1. Disk 1 is rotated by a dc motor about an axis perpendicular to its plane. A generator 2 feeds a series of drops (d_d = 0.3-4.0 mm; v_d = 0.1-10 m/sec) normally to the disk surface [4]. The processes of interaction of the drop with the boundary layer and the change in velocity and diameter of the drops were recorded using a fast-exposure SKS-1m-16 cine camera (Fig. 1a) and photography by a Zenit-3m camera (Fig. 1b). In the first case, the light source was a DPSh-250 mercury lamp, in the second case an ISSh-15 strobe lamp with a flash length of no more than 10^{-5} sec. The flash frequency could be varied in the range 5-500 Hz.

It is considerably simpler to study the interaction of a drop with a disk surface rotating in an infinite space, since in this case the Navier—Stokes equation for the boundary layer has an accurate solution [3]. Analysis of this solution shows that the axial velocity components in the boundary layer are small in comparison with the other components; the maximum value of the radial velocity component is an order of magnitude less than the azimuthal. Thus, the behavior of the drop in the boundary layer is determined mainly by the gradient of the azimuthal velocity component.

The upper part of Fig. 2 shows strobograms of the drop trajectory for collision with the surface of a disk rotating with frequency ω. It is evident that in the region of contact with the disk the drop is deformed and then immediately reflected at an angle α to the disk surface; the drop trajectory is close to parabolic. After reflection from the disk, the deformed drop begins to rotate with frequency ω_d.

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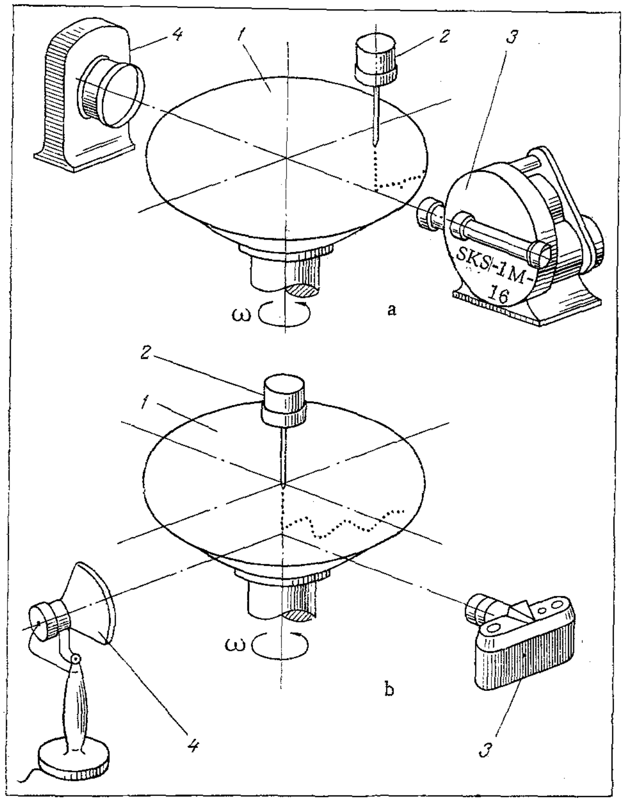

Fig. 1

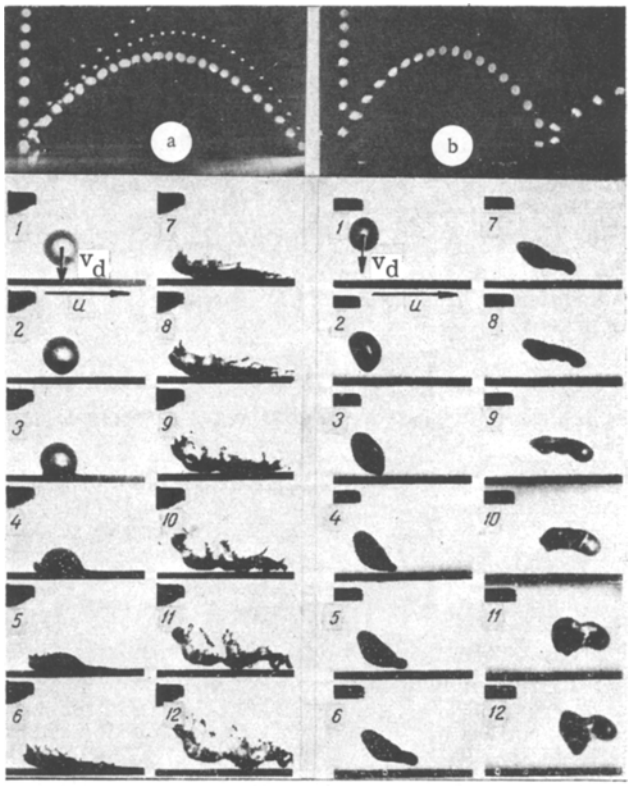

Fig. 2

Fig. 1. Diagram of apparatus: a) for rapid cine photography of collision process: 1) rotating disk; 2) drop generator; 3) cine camera; 4) mercury lamp; b) to photograph drop trajectory: 1) rotating disk; 2) drop generator; 3) camera; 4) ISSh-15 strobe lamp.

Fig. 2. Drop trajectory and cine-film frames for collision of drop (d_d = 2 mm, v_d = 1.2 m/sec) with surface of rotating sphere: a) for u = 30 m/sec; b) 60 m/sec.

In the experiments, three types of interaction of the drop with the disk could be distinguished: 1) The drop is captured by the disk on contact and spreads out over its surface; 2) the drop enters the boundary layer of the disk, is slightly deformed, and is partially spread out over the surface and partially reflected from it; 3) the drop is strongly deformed in the boundary layer and, without touching the surface, is reflected away from it.

The first form of interaction (no reflection from the surface) corresponds to a low azimuthal velocity u. The drop passes through the boundary layer and, still undeformed, enters into contact with the surface, gradually spreading out in the direction of rotation of the disk.

At higher values of u (for the same drop velocity v_d), a second type of interaction is observed; in this case, part of the drop is reflected from the surface (Fig. 2a). As it approaches the disk, the drop is slightly deformed; the lower part of the drop contacts the disk surface and is carried along with it, but the upper part is hardly displaced in the direction of rotation (frames 1-3). Similarly to the case of collision with a fixed surface, the bottom part of the drop is spread out in the region of contact. The motion of the disk promotes the spreading of the contacting part of the drop, but not the rearward portion. As a result of the velocity gradient in the boundary layer, a wedge of air forms under the drop, which begins to rise (frames 4-8). Then the lifting force separates the drop from the disk surface (frames 9-12) and projects it beyond the limits of the boundary layer; the drop then moves in a parabola toward a second collision with the surface.

Further increase in u leads to total reflection of the drop on interaction with the boundary layer of the rotating surface (Fig. 2b). In this case the drop is significantly deformed as it enters the boundary layer (frames 2 and 3), as a result both of the dynamic pressure difference exerted on the drop by the flow gradient and also of the reduction in static pressure close to the surface of the rotating disk. The lower part of the disk is displaced in the direction of rotation of the surface, and under the action of the increasing lift force begins to rise above the surface. The drop takes a streamlined form (frames 4-7). The center of application

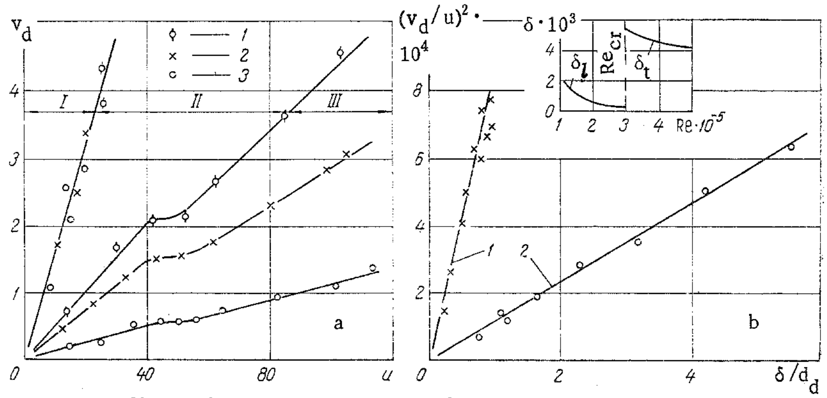

Fig. 3. Effect of parameters on reflection of drop from disk: a) velocity ratio: 1) drop diameter d_d = 0.3 mm; 2) 0.8; 3) 4; I) region of complete adherence; II) partial reflection; III) total reflection; b) $(v_d/u)^2 \cdot 10^4$ as a function of δ/d_d; 1) laminar flow; 2) turbulent; v_d, m/sec; $\delta \cdot 10^3$, m; u, m/sec.

of the aerodynamic force (the pressure center) does not coincide with the center of mass of the drop, which leads to spatial rotation of the drop (frames 8-12) at some angular velocity.

The drop—surface interaction conformed to a similar pattern for all the drop sizes investigated: $0.5 < d_d < 4.0$ mm. The boundaries between the observed types of collision for drops of various dimensions are shown in Fig. 3a. The boundary between interactions of types I (complete "adherence") and II (partial reflection) is practically independent of the drop size. In the experiments, type-I collisions were observed over the whole range of d_d when $v_d/u < 0.15$. The position of the boundary between types II and III (complete reflection) is determined by the drop size. For all values of d_d, the boundary curve has a discontinuity at $u \approx 40$ m/sec, caused by the transition from laminar to turbulent flow of the gas around the rotating disk, i.e., in this region $Re_D = wR^2/\gamma \approx Re_{cr}$.

The dimensionless lift-force coefficient is written in the form

$$C_w = \frac{F_L}{S\,\dfrac{\rho u^2}{2}} .$$

The time that the drop is subjected to the lift force is determined by the time that it spends in the boundary-layer region. If it is assumed that within the boundary layer the drop moves with constant deceleration under the action of the lift force, then the deceleration of the drop may be determined as $a = v_d^2/2\delta$. Then the lift-force coefficient, taking into account the mass of the drop and its frontal area, may be written in the form

$$C_w = \frac{2}{3} \cdot \frac{\rho_d}{\delta} \cdot \frac{d_d}{\delta}\left(\frac{v_d}{u}\right)^2 = 5.9 \cdot 10^2\,\frac{d_d}{\delta}\left(\frac{v_d}{u}\right)^2 .$$

For constant physical properties of gas and liquid (ρ/ρ_d = const), $C_w = f[d_d/\delta;\ (v_d/u)^2]$. By plotting the boundary between the types of interaction in the coordinates $[d_d/\delta;\ (v_d/u)^2]$, the value of C_w characterizing the transition from partial to complete reflection of the drop from the disk surface can be determined (Fig. 3b). In the case of laminar flow of the gas, $C_w^l = 0.52$; for turbulent flow, $C_w^t = 0.068$. This means that, when all other conditions are equal, the lift force at which total reflection is established is approximately 8 times smaller for turbulent flow than for laminar flow. This difference may be explained both by the change in the velocity curve and by the increase in thickness of the boundary layer δ_t (Fig. 3b), which leads to increase in the time that the drop is in the gradient flow.

The shape of the drop and the rate of its deformation are among the most important parameters affecting the interaction of the drop with the boundary layer. It is necessary to distinguish between the deformation of the drop in the boundary layer and deformation of the drop on impact with the surface.

The trajectory of the reflected drop (or part of a drop) is determined by the initial velocity v_d^{refl} and the angle of reflection α. In addition, as already noted, the reflected drop rotates with some frequency ω_d.

In Fig. 4a, the velocity-retention coefficient $K = v_d^{refl}/v_d$ (1), the angle of reflection α (2), and the frequency of rotation of the drop ω_d (3) are shown as a function of C_w for laminar flow ($Re_D = 2 \cdot 10^5$). It should be

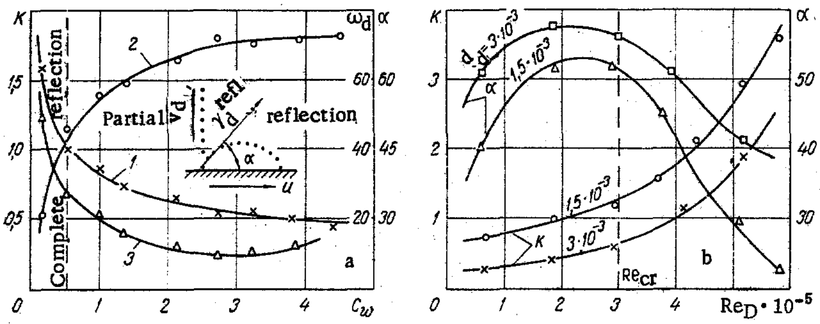

Fig. 4. Basic characteristics of motion of reflected drop: a) as a function of C_W for $Re_D = 2 \cdot 10^5$; b) as a function of Re_D for d_d = 3 and 1.5 mm; ω_d, sec^{-1}; α, deg.

noted that the value K = 1 is reached at the boundary between the cases of partial and complete reflection. The rotational frequency of the drop in the experiments reached $\omega_d = 100\ sec^{-1}$, which corresponds to $n \approx 950$ rpm. At high rates of rotation, breakdown of the drop is observed.

As is evident from Fig. 4b, the type of flow in the boundary layer has a significant effect on the values of K and α. The comparatively narrow range of variation of Re_D in the dependences shown is the result of breakdown of the reflected drop for $Re_D > 6 \cdot 10^5$ when $d_d > 1.5$ mm.

The observed features of the interaction of the drop with the boundary layer of a rotating surface appear again in the case of incidence of the drop on a rotating cylinder. Here also there are three types of interaction but, because of the differences in the gas flow close to a disk and a cylinder, the boundaries between the types of collision are shifted toward higher values of v_d/u. It is obvious that similar results would also be expected in the case of translational motion of the surface.

It is also necessary to note that the presence of a liquid film on the disk significantly affects the behavior of the drop. In experiments with the supply of a liquid film to the disk, it is impossible to achieve even partial reflection of the drop; in all conditions the drop is adsorbed by the film. Apart from this, the interaction is very similar to the first case for the dry disk. The drop is practically undeformed as it approaches the surface of the film and, after contact with the film, is uniformly carried away by the liquid layer. The gas flow reaches its maximum value at the boundary between the phases; this value is significantly lower than the azimuthal velocity of the disk, on account of which the lift force acting on the drop is also less. However, for very small ratios $v_d/u < 10^{-3}$, it is possible to achieve reflection of the drop from the surface coated by the film.

NOTATION

d_d, drop diameter; v_d, drop velocity; ω, rate of rotation of disk; u, azimuthal velocity of disk; R, disk radius; ν, kinematic viscosity; C_W, lift force coefficient; F_L, lift force; S, frontal area of drop; ρ, density of gaseous medium; ρ_d, density of drop; δ, boundary-layer thickness; ω_d, rate of rotation of drop; v_d^{refl}, velocity of drop reflected from disk; α, angle of reflection of drop.

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