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EXPERIMENTAL INVESTIGATION OF THE INTERACTION OF COLLIDING DROPLETS

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Information concerning the coalescence and disruption of colliding droplets is needed for solving a number of problems of two-phase flow dynamics. A considerable number of studies have been devoted to droplet collision [1-8]; so far, however, in calculating flows with allowance for particle coagulation and disruption, approximate hypotheses and empirical formulas for the droplet coalescence probability have been used. Below we present the results of a cinematographic investigation of the collision of free-flying droplets in air. As distinct from the authors of [2, 3], we investigated not averaged mass collision effects, but the behavior of individual interacting droplets in relation to the criteria determining the result of the collision.

The apparatus consisted of two generators producing continuous counterflows of monodisperse droplets which we shall agree to call targets (the larger-diameter droplets) and projectiles. In order to obtain target droplets $(0.6-1.2) \cdot 10^{-3}$ m in diameter we used a generator of the "vibrating capillary" type in which vibrations with a frequency of 20-100 Hz were produced by an electrodynamic transducer. Projectile droplets $(0.3-0.8) \cdot 10^{-3}$ m in diameter were obtained in a generator of the "rotating capillary" type. Liquid from a tank mounted on the shaft was supplied to the capillary through an intermediate tube. On rotation, a droplet was cut off by a metal thread $50 \cdot 10^{-6}$ m in diameter placed near the end of the capillary at right angles to the plane of rotation. This ensured the separation of droplets at a certain point on the periphery at a frequency of 5-200 droplets per second. The droplet collision velocity $u = 1-5$ m/sec. The collision process was recorded with an SKS-1M high-speed motion-picture camera at the rate of 1500-3000 frames per second. The experiments were conducted with distilled water [whose density, dynamic viscosity, and surface tension were, respectively, $\rho = 10^3$ kg/m^3, $\eta = 10^{-3}$ kg/(m·sec), and $\sigma = 72.88 \cdot 10^{-3}$ kg/sec^2 at a temperature of +20°C].

The interaction of droplets with a given diameter ratio (in our experiments $\gamma = D_2/D_1 = 1.9 \pm 0.8$) is determined by the collision angle θ (the angle between the droplet collision velocity vector and the straight line connecting the centers of the droplets at the moment of contact) and the Weber number $W = \rho u^2 D_1/\sigma$. For water droplets the viscosity forces are negligibly small compared to the surface tension and inertia forces; accordingly, the effect of the criterion containing η (for example, $Lp = \rho\sigma D_2/\eta^2 \sim 10^5$) is unimportant. Under our experimental conditions the value of θ was not determined, and the results obtained represent averages over all possible values of the collision angle $\theta = 0 - \pi/2$. On the interval $W = 0.1-120$ qualitatively different types of interaction were observed, depending on the value of the Weber number.

1. At $0 < W < 0.5$ we observed coalescence of the droplets under the influence of surface tension forces (Fig. 1a). The interactions at small values of W were obtained as a result of droplets from the same generator overtaking each other. Droplet coalescence at low collision velocities can be attributed to vibration of the surface of the droplets and a reduction of pressure in the gap between them [7] or to saturation of the atmosphere with vapor [1, 6]; however, there is no generally accepted opinion on this point.

2. In collisions at W from 0.7 to 1.5 the projectile droplet was observed to rebound from the target droplet (see Fig. 1b). The probable cause of rebound is the presence of an intervening gas layer between the droplets [1, 7]. It may be assumed that the impact of the colliding droplets is insufficient to displace the gas and achieve physical contact. In [8] rebound is attributed to the elastic properties of the surface layer of the droplets; coalescence is possible only after considerable deformation of the droplets, when the kinetic collision energy is comparable with the free surface energy. This assumption is contradicted, however, by the observed

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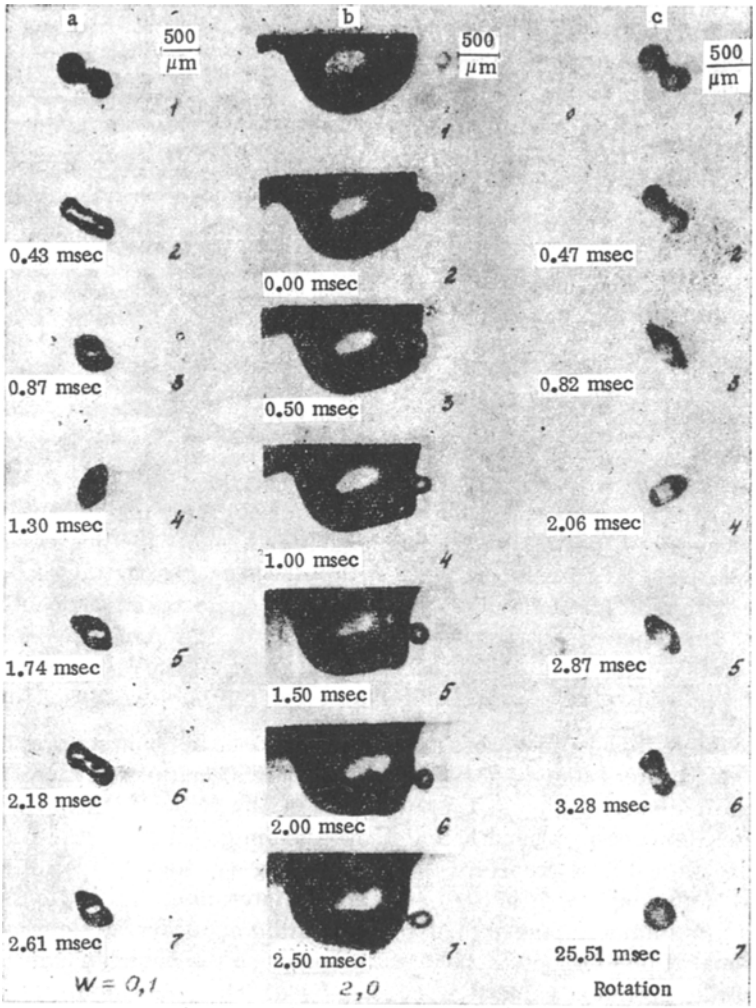

Fig. 1

coalescence of the droplets at near-zero collision velocities (see Fig. 1a).

3. At values of W from 2 to 15 stable coalescence of the droplets was observed (see Fig. 1c). In this case the kinetic energy of the droplets is sufficient to displace the intervening air layer, and the droplets enter into physical contact. The coalescence process is accompanied by complex motions of the droplet formed: rotation and various modes of vibration.

4. At $W > 15$ collision leads to temporary coalescence of the droplets with subsequent disruption of the coalesced droplet (Fig. 2a). In this case two droplets, of approximately the same size as the colliding droplets, are formed. One possible cause of the disruption of the initially formed droplet is the rotation resulting from noncentral impact. If the momentum of rotation Ω reaches a certain value Ω_*, the droplet may be disrupted by the action of the centrifugal forces. In [5] it was shown theoretically that, as a body topologically equivalent to a sphere, a droplet will exist at values of the dimensionless momentum $\omega = \Omega/\sqrt{\rho\sigma}V^{7/6} < 2.38$ (V is the volume of the droplet formed as a result of coalescence). The relation between ω and W is given by the expression $\omega = 0.565\sqrt{W}[\gamma^3(1+\gamma)/(1+\gamma^3)^{13/16}]\sin\theta$, whence for $W_* = 15$-30 we obtain $\omega_* = 5.4$-7.6 (for $\gamma = 1.9$), i.e., about twice as great as the calculated value. For $\sin\theta$ we took the mathematical expectation of that quantity ($\langle\sin\theta\rangle = 2/3$) calculated on the assumption of a uniform distribution of the points of intersection of the collision velocity vector and the normal plane.

5. With further increase in W the interaction picture changes sharply. For central impact at $W > 50$ we observed "penetration" of the target droplet. At the moment of coalescence the diameter of the target increases by 10-15%; then a droplet of approximately the same size as the projectile separates from the back of the target (see Fig. 2b). In this process a neck about $0.1D_1$ in diameter and $4D_1$ long is formed between the droplets; this neck breaks down with the formation of four or more accompanying droplets up to $0.2D_1$ in diameter.

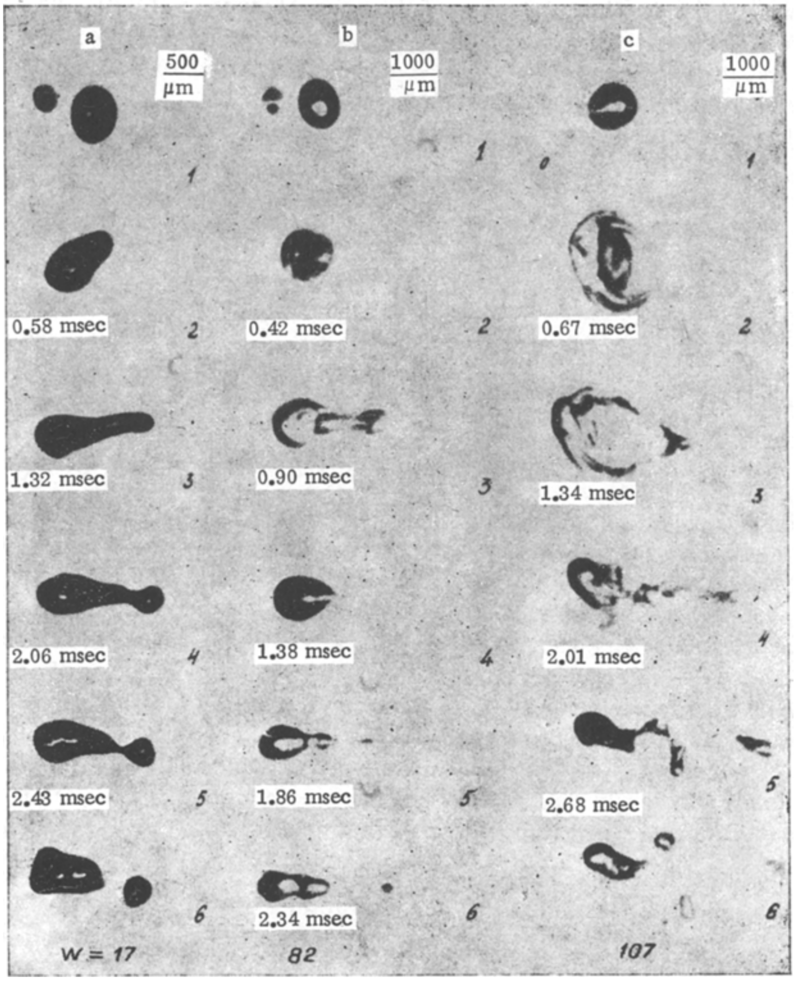

Fig. 2

6. At W > 100 we observed the severalfold expansion of the target droplet with retention of its spherical shape and wave-structure surface perturbations. This was followed by the explosive disruption of the droplet with the formation of a large number of fragments expelled radially from the interaction zone (see Fig. 2c). It is probable that at a certain value of W the droplet interaction takes place in the cavitation mode.

Thus, the interaction of colliding droplets may have any of six possible outcomes depending on the value of the Weber number. We have experimentally determined the range of numerical values of this criterion corresponding to each mode of interaction: coalescence at low collision velocities, rebound, stable coalescence, disruption of the coalesced droplet owing to rotational or vibrational instability, penetration of the target, and cavitational disruption of the droplet.

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NONSTEADY SHOCK WAVES IN GAS – LIQUID MIXTURES OF BUBBLE STRUCTURE

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In recent years many theoretical and experimental reports have been published on the investigation of shock waves in liquids containing gas bubbles [1-11]. The reports on the experimental level are devoted to the investigation of the structures of compression waves in mixtures with rather large bubbles (~1 mm) [4-6, 9]. Because of the considerable lengths of the relaxation zones for waves in such mixtures (~1 m), comparable with the lengths of the shock tubes, the waves observed in [4-6, 9] were nonsteady, as a rule. This was first noted in [8], where the necessity of enlisting the nonsteady theory in the analysis of experimental data was pointed out (up to then only steady wave configurations were studied in the theoretical reports [1, 3-5, 8, 9]). The propagation of a weak nonsteady wave was first studied in [7] on the basis of the Burgers–Korteweg–de Vries model equation. The report [10] is devoted to a description of the general approach to the investigation of nonsteady waves in bubble media. In the present report principal attention is paid to questions of the concrete definition of the model of the dynamic behavior of the medium and to a discussion of recent results.

§1. To describe the nonsteady motions of mixtures of liquids and gas bubbles we use the methods of the mechanics of a continuous medium, assuming that the characteristic linear scales of the flow are much larger than the sizes of the bubbles and the distances between them. We construct the model of the dynamic behavior of the mixture with the following simplifying assumptions:

1. The viscosities and thermal conductivities of the phases are important only in processes of interaction between the phases.
2. The bubbles are spherical and monodisperse.
3. Breaking up, collisions, and coagulation of bubbles are absent.
4. The velocities of the macroscopic motions of the phases coincide.
5. The density and temperature of the liquid are constant.

Let us discuss assumptions 4 and 5, which are of fundamental interest from the point of view of simplicity of the solution of concrete problems, in more detail. In sufficiently weak waves the difference in the velocities of the phases is small and viscous dissipation in the relative translational motion of the liquid and bubbles is barely noticeable against the background of the dominant thermal dissipation [8]. In stronger waves, when the noncoincidence of the velocities of the phases is significant, the bubbles break up, as a rule [12]. This leads to a sharp decrease in the slipping of the phases and to a corresponding decrease in the dissipation due to the relative motion. With allowance for the effect of the breaking up of bubbles, one can also study rather strong waves within the framework of the one-velocity approach.

The assumption of constancy of the liquid temperature is fully justified from the physical point of view, since the heat capacity of the liquid (per unit volume of the mixture) considerably exceeds the heat capacity of the gas. The assumption of constancy of the liquid density is applicable if the volume content of bubbles in the mixture is high enough and the compressibility of the mixture is practically determined by the deformation of its gaseous component.

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