SPECTRUM OF SECONDARY DROPS WITH IMPULSIVE BREAKUP OF A LARGE SINGLE DROP

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1. An experimental and theoretical study of the interaction of a single drop with a moving solid surface is presented in a number of works (see, for example, [1-7]). Most such works concern primarily the problems of interaction of a solid surface with a moving drop without investigation of the quantitative behavior characteristic of the processes of collapse of the fluid itself, and the dispersed composition of the drop is not adequately studied. Up to now, no clear theoretical laws have been proposed relating the dimensions of secondary drops, the structural parameters of the atomizing system, and the physical properties of the fluid. In some works (see, for example, [6]), it is asserted that at the present time it is generally impossible to construct a clear model of the collapse of a drop even in a gas flow. For this reason, the quantitative laws governing the breakup of a fluid are most often described by criterional equations for the average diameter of the secondary drops.

In describing many of the laws governing the breakup of drops in the impulsive load regime, it is possible to use the hypothesis [8, 9] that with such a load the drop manifests brittle properties, stemming from the flow of comparatively long duration relaxation phenomena inside the drop. Such a model of the collapse of a drop requires the use of not only the usual quantities characterizing the fluid as such, but also physical characteristics, describing solid bodies when they fracture, in particular, elasticity and strength [8, 10].

2. Impulsive collapse of large single drops was studied experimentally on a setup whose scheme is shown in Fig. 1. The generator of drops 1 forms drops with a definite size, which move toward the impact plate 2. The repetition rate of the drops is set by the generator 3. In order to form monodispersed drops without accompanying drops, an appropriate operational regime is chosen for the drop generator. The studies were carried out with monodispersed drops with diameters of 0.7, 1.0, 2.0, and 3.0 mm.

The solid plate 2 is fixed on a rotating disk 4. As a result of the impact of the drop against the reflecting plate 2, a cloud of secondary drops is formed. The velocity of the impact plate is stabilized and can be maintained in the range from 10 to 120 m/sec. The experimental setup also provides for the presence of a special synchronizing system, not shown in Fig. 1, for pulsed photographing and studying of the pattern of the collapse of a single drop directly from the photographs.

In order to study the spectrum of secondary drops, the technique of capturing drops by a trap 5, filled with a special immersion fluid, was primarily used. The trapped drops were photographed simultaneously with a scale on a microphotographic system. The number of drops was computed and their dimensions determined after the film was developed on a 5PO-1 setup. Figure 2 shows one of the photographs of the captured drops with a scale, permitting exact measurement of the drop dimensions.

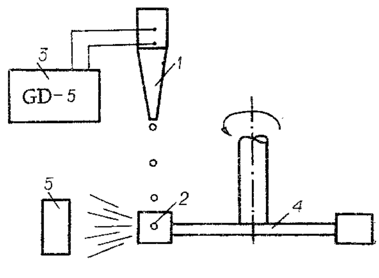

Fig. 1

Sumy. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 64-70, May-June, 1981. Original article submitted May 6, 1980.

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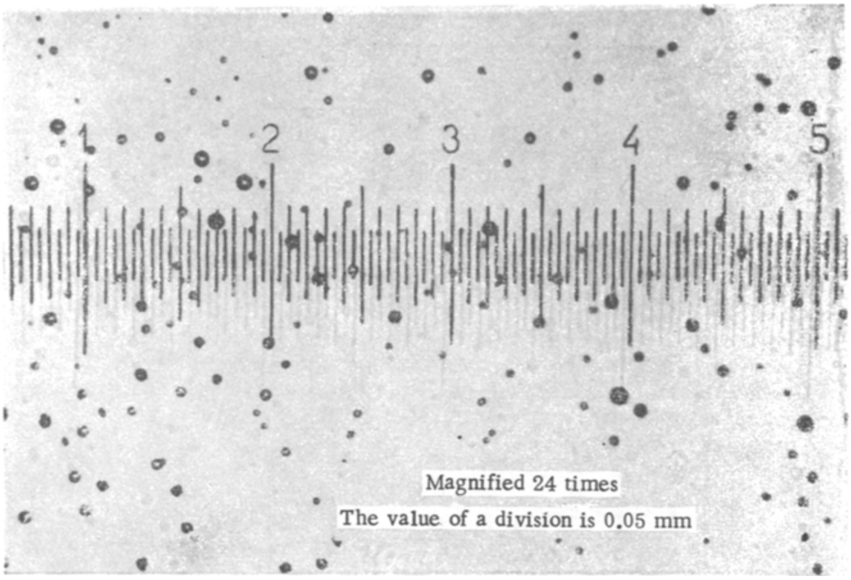

Fig. 2

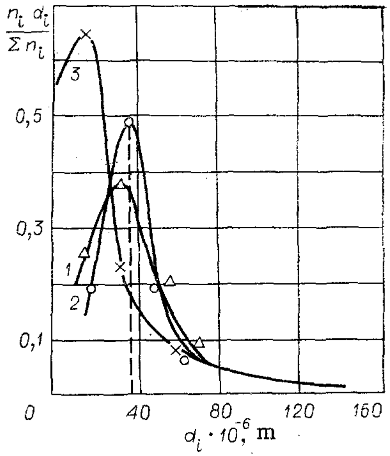

Fig. 3

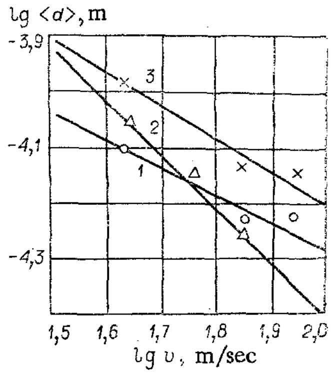

Fig. 4

The numerical values of the parameters entering into the criterional equation were determined with standard techniques for measuring velocities, surface tension, viscosity, density, and the diameters of the primary drops. A computer was used to process the data.

3. Typical size distributions of secondary drops with impulsive breakup of large primary drops are shown in Fig. 3 for three rheologically different fluids (curves 1-3, respectively): distilled water, representing a Newtonian fluid, aqueous glycerine solutions, representing a non-Newtonian fluid, and emulsions (milk, mixtures of ultradispersed drops of oil and water, another example of a non-Newtonian fluids), with identical relative velocities of the impact plate v = 60 m/sec and primary drop diameters d_0 = 2.0 mm. For the glycerine solutions, the shape of the curve showing the size distribution of the secondary drops is almost Gaussian.

Figure 4 shows log <d> as a function of log v with a constant primary drop size (d_0 = 2 mm), where <d> is the average volume-surface diameter of the secondary drop; v is the velocity of a drop relative to the impact plate (curves 1-3 relate to distilled water, aqueous solutions of glycerine, and emulsions, respectively). Figure 5 shows log <d> as a function of log E for constant v = 75 m/sec and d_0 = 2 mm, where E is the modulus of elasticity. The behavior of log <d> as a function of log d_0 with constant v = 80 m/sec is shown in Fig. 6, where curves 1-3 characterize, respectively, distilled water, aqueous glycerine solutions, and an emulsion.

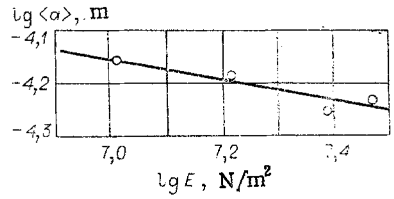

Fig. 5

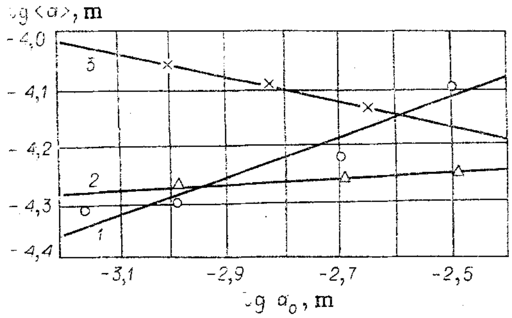

Fig. 6

The results obtained show that <d> depends on the rate of deformation of the drop, on the size of the primary drop d_0, and on the elastic (strength) properties of the fluid. An inverse dependence on the velocity of the impact plate (Fig. 4) exists for all fluids studied. This indicates the fact that the rate at which the impulse is transferred, which determines the rate of deformation, is one of the main components for impulsive breakup of primary drops. The behavior of the average diameter of secondary drops as a function of the elastic moduli is characterized by a weak inverse dependence (Fig. 5) and is a more complicated function of the primary drop diameter (Fig. 6). For Newtonian fluids (Fig. 6, curve 1), it is expressed more clearly: As the size of the primary drop increases, the average diameter of the secondary drops increases. For certain non-Newtonian fluids (Fig. 6, curve 2), the diameter of secondary drops is almost independent of the size of the primary drops. For emulsions (Fig. 6, curve 3), this dependence has a completely unexpected character: As the size of the primary drops increases, in a certain size range, the average diameters of the secondary drops decrease.

The dispersive composition of secondary drops represented as a function of a number of factors (Figs. 4-6) gives the possibility of constructing standard phenomenological criterional equations.

The breakup process is mainly affected by the velocity of the drops relative to the plate, the diameter of the primary drop, the elastic and usual properties of the fluid. Starting with these assumptions and assuming that the viscosity of the fluid is constant during the breakup process, the average diameter of secondary drops can be represented as a function of the following basic physical quantities:

$$d_* = f(v, \mathrm{E}, \sigma, d_0, \mu_l, \rho_l).$$

Let us assume that this function is a product of the quantities being examined:

$$d_* = K v^{b_1} \mathrm{E}^{b_2} d_0^{b_3} \sigma^{b_4} \mu_l^{b_5} \rho_l^{b_6},$$

where d_* is the average diameter of secondary drops, m; d_0 is the diameter of primary drops, m; v is the relative velocity of a drop and the plate at the moment of impact, m/sec; E is the modulus of elasticity (which is proportional to the strength [8]) of the fluid, $\mathrm{N/m^2}$; σ, μ_l, ρ_l, are the surface tension, dynamic viscosity, and density of the fluid; b_1 through b_6 are some numbers.

Transforming the last expression [11], we find the criterional equation for the average diameter of secondary drops

$$d_* = K \left(\frac{\mu_l^2}{\rho_l \sigma}\right) \left(\frac{\sigma}{v \mu_l}\right)^{K_1} \left(\frac{\mathrm{E}\mu_l^2}{\sigma^2 \rho_l}\right)^{K_2} \left(\frac{d_0 \sigma \rho_l}{\mu_l^2}\right)^{K_3}.$$

Introducing the notation for the complexes, we have

$$d_* = K \mathrm{M} \mathrm{Ch}^{K_1} \mathrm{U}^{K_2} \mathrm{Lp}^{K_3}. \tag{3.1}$$

This equation excludes not only the gravitational force, thermal characteristics of the fluid (heat capacity, thermal conductivity), as being unimportant for the given method of breaking up drops, but also the characteristics of the gaseous medium which are often introduced in describing the dispersion of fluids. As we have established, the dispersed composition of secondary drops of oils and molten metals is not distinguished in a vacuum and in a gaseous medium has no important effect on the spectrum of secondary drops in this method for breaking up drops. This is understandable: The forces, acting in this case on the fluid elements from the side of the solid body, are many orders of magnitude greater than the corresponding forces on the side of the gaseous medium.

Equation (3.1) contains three dimensionless criteria: the numbers $\mathrm{Ch} = \frac{\sigma}{v\mu_l}$, $U = \frac{E\mu_l^2}{\sigma^2\rho_l}$, the Laplace criterion Lp [6], and the coefficients K, K_1, K_2, and K_3.

The metrical criterion $M = \mu^2_l/\sigma\rho_l$, consisting of quantities that determine the properties of the fluid, has a simple physical meaning. This is the characteristic size of the regions formed from groups of molecules of the given fluid.

The criterion U, characterizing the elastic and brittle properties of the fluid, was varied in the experiments over the range 100-34,000. Rewriting it in the form $U = E/(\sigma^2\rho_l/\mu^2_l)$, we obtain the dimensionless elasticity (strength): the ratio of the modulus of elasticity (or strength) of the fluid E to the characteristic stress inside the fluid in the absence of a load. In some works [5], the concept of an internal negative pressure p_*, whose dimensions coincide with E, $p_* = \alpha c v \rho_l$, where c is the velocity of sound and v is the relative velocity of the drop and the solid surface, is used. The negative pressure is a variable quantity and, for fixed values of the density of the fluid and velocities, is identical for all fluids, i.e., it does not reflect the individual properties of a fluid. For this reason, it makes sense to introduce instead of this quantity a characteristic directly taking into account the individual nature of each fluid, in particular the strength. Using the terminology of the concept of negative pressure, the strength can be interpreted as the limiting pressure, below which the liquid does not break up with the impulsive method.

The criterion $\mathrm{Lp} = d_0\sigma\rho_l/\mu^2_l = d_0/M$ in this case can be viewed as the ratio of the size of the primary drop to some characteristic size of a closed group of molecules. Laplace's criterion was varied in the experiment over the range 300-100,000.

The criterion Ch, characterizing the breakup method, can be formally expressed in terms of the known classical criterion Ch = Lp/Re. The use of the latter ratio does not reflect the properties of the process described. Indeed, $\mathrm{Re} = d_0 v\rho_l/\mu_l$ characterizes the ratio of inertial forces to forces manifested with viscous flow, i.e., it determines the degree of turbulence (the nature of the motion) inside the continuous liquid, for example, with motion in pipes. The fluid drop behaves with impulsive breakup qualitatively differently: At the moment that the impulsive load is applied, viscosity is not manifested in the drop (or almost not manifested). For this reason, there is no reason to introduce Re, characterizing the fluid as a continuous medium. The criterion Ch was varied over the range 0.2-5.

According to the results of the measurements, more than 40 particular equations of the type (3.1) were constructed, characterizing the behavior of the volume-surface diameter as a function of the initial drop size, relative velocity of the impact plate, and the physical properties of the fluid. For each type of fluid, the average values of the coefficients in equations of the type (3.1) were computed. The equations, determining the volume-surface diameter of secondary drops $\langle d \rangle$ for distilled water, aqueous solutions of glycerine, and emulsions (milk), have the following form, respectively:

$$\langle d\rangle = M_1\mathrm{Ch}^{0.464}U^{1.021}\mathrm{Lp}^{0.198}; \quad (3.2)$$

$$\langle d\rangle = 1.272M_2\mathrm{Ch}^{0.683}U^{0.394}\mathrm{Lp}^{0.169}; \quad (3.3)$$

$$\langle d\rangle = 2.09M_3\mathrm{Ch}^{0.58}U^{1.25}\mathrm{Lp}^{-0.14}, \quad (3.4)$$

where $M_1 = 0.012\cdot10^{-6}$ m, $M_2 = 0.713\cdot10^{-6}$ m, and $M_3 = 0.516\cdot10^{-6}$ m are the metrical numbers for water, 1:1 aqueous solutions of glycerine, and milk, respectively.

The coefficients in the criteria Ch and Lp were also found directly from Figs. 4-6. They are compared with computer-generated values in Table 1, from which follows the comparatively good correlation of the coefficients K_1 and K_3. The presence of some errors is explained by the fact that the computer processed a mass of equations using the method of least squares, taking into account the least total error of the mass of equations, while in determining the coefficients from Figs. 4-6, the effect of other parameters was not taken into account, since

TABLE 1

Fluid studied	K_1		K_3	
	computer	experiment	computer	experiment
Distilled water	0,464	0,48	0,198	0,25
Solutions of glycerine in distilled water	0,683	0,79	0,169	0,15
Emulsion (milk)	0,58	0,68	−0,14	−0,15

they are assumed to be constants. The complex U showed the greatest spread in the exponents (up to 25% for each fluid). This is explained, apparently, by the comparatively high inaccuracy in the values of the elastic moduli of the fluids, which were taken from the literature and are valid for pure degassed fluids, while the results obtained concern commercial fluids with a spread in this parameter even for the same fluid. Controlled checks, carried out for drops having different sizes and for different types of fluids with variable dynamic loads, showed that the diameters of the secondary drops, computed theoretically from Eqs. (3.2)-(3.4), differ from the experimentally determined values with a maximum error of 10%.

4. It is evident that for the impulsive breakup of large single drops, the structural characteristics and the rheology of the fluid affect to a large extent the dispersed composition and average size of secondary drops. If an attempt is made to construct for these conditions a generalized criterional equation, a single equation for all types of fluids, agreeing well with experiment, then the criterion must include additional functional dependences, in particular, the structural characteristics of the fluid state. The equations become considerably more complicated.

As the sizes of the primary drops decrease, all features of the behavior of viscous and structural forces become the same for different types of fluids. For this reason, for such drop sizes, it is already possible to construct a single criterional equation, which describes well the results of impulsive breakup of drops of different fluids.

Investigations of the dispersion composition of secondary drops with impulsive breakup of a single large drop are only now beginning to lead to an explanation of the mechanism of high-speed breakup of fluids. Many aspects of this mechanism must still be studied. First, it is necessary to study the dependence of the effect of physical properties of the fluids on the formation of groups of molecules (complexes), as well as on the breakup time with impulsive loads. This would give the possibility of relating in a unified way many properties of fluids, including structural, brittle-elastic, and plastic, factors on whose behavior the breakup of fluids under impulsive loads primarily depends. Second, it is interesting to relate the elastic criterion U to the relative phenomena occurring in the fluids. In fact, judging from the magnitude of the exponents in U, its role in the process of impulsive breakup is significant.

The results obtained for impulsive breakup of a large single drop of fluid are important in connection with the problem of low-energy atomization and can be useful for future theoretical studies, as well as for developing impact reflective atomizers of liquid media.

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