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DROPLET BREAKUP REGIMES AND CRITERIA FOR THEIR EXISTENCE

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An analysis of experimental and theoretical studies of droplet breakup by a gas flow in shock tubes and nozzles is presented. A system of criteria defining droplet breakup regimes is developed.

When fuels are burned in various pieces of equipment it becomes necessary to analyze intermediate stages of preparation of the fuel mixture for ignition in the reaction zone. The processes of evaporation have been studied thoroughly and methods are available for their calculation, but the phenomenon of fuel atomization has been studied much less completely.

In the great majority of power devices production of useful work is accomplished by conversion of the chemical energy of the fuel into thermal energy, a process which usually occurs in a multiphase flow. The net velocity of the generally quite complex process of combustion of a liquid fuel is determined by the velocities of the elementary processes which occur: heating, evaporation, and atomization of liquid components, mixing and chemical reactions in the gas phase. For a proper description of the conversion process it is of extreme importance to know the principles by which these elementary processes operate.

One of the elementary acts having a great effect on the dynamics of the overall cycle is the process of droplet breakup in the gas flow. Acceleration of the two-phase flow, produced by geometric or thermal factors, leads to the appearance of a relative velocity between phases. Under the action of aerodynamic forces droplet deformation occurs, leading to droplet destruction [1-29]. The process of droplet and liquid jet breakup has been considered from such a position by many authors, beginning with Rayleigh [6, 8-11, 13, 21-23, 26-29]. In those studies it was shown that droplet and jet destruction occur under the condition that the Weber number exceed some critical value

$$W = \rho u^2 d/2\sigma > W^*, \quad (1)$$

where W* is the critical value of the Weber number.

It should be noted that the Weber number is not the unique criterion determining droplet behavior in a gas flow: depending on experimental conditions, its critical value varies over the range W* = 3-25 [6, 10-12, 16, 21, 22]. In the most general case W* depends on the liquid viscosity [10], droplet diameter [7], and also upon the time for which the gas flow acts upon the droplet [14].

When Eq. (1) is satisfied in energy devices with intense heat supply, it is possible for secondary fuel droplet breakup to occur [1-3]. In determining the critical Weber number, until recently little attention was paid to how droplet breakup and deformation occur. At

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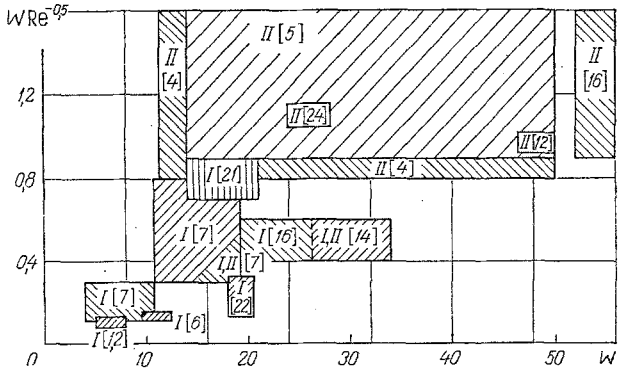

Fig. 1. Diagram of possible droplet breakup regimes: I, II) without and with tear-off of the surface layer; digits in brackets refer to reference cited.

the same time, a careful study of the process of droplet breakup in the Weber number range W = 3-25 will show the possibility of realizing several different types of breakup, differing from each other both in their external appearance, and in the spectra of secondary particles produced upon decay. Definition of the various breakup regimes is of principal importance, since small oscillations of the dynamic gas load can lead to transition from one regime to another.

Unfortunately, the character and possible varieties of droplet and liquid stream breakup in a gas flow have still not been studied sufficiently. An analysis of the experiments performed in [4-8, 11, 12, 14, 16, 17-19, 21, 22, 24-26] permits us to crudely distinguish two characteristic elements of the droplet destruction process: droplet deformation and formation of a shroud upon flow of the gas over the liquid. Depending on the Reynolds and Weber numbers in the two-phase flow, and the interaction time between droplets and gas flow the following types of breakup are possible: simple division of the droplet into approximately equal parts (usually not more than four); parachute-type destruction (in which the droplet, flattened in the direction perpendicular to the flow, forms a shroud extending along the direction of gas motion, after which the shroud breaks off, producing a group of fine droplets and leaving a liquid torus); chaotic destruction, in which several "parachutes" are formed from one droplet, which in the final stage produce groups of fine droplets and bands (open and closed) of liquid, directed up the gas flow and to the sides. Another form of breakup is "stripping," in which the gas flow tears shrouds away from the periphery of the flatted droplet (from the liquid boundary layer). These shrouds then rapidly transform into a cloud of fine droplets, after which the disk-shaped droplet reaches its critical deformation, perforates, and decomposes into several parts. Finally, there exists still one more type of breakup — explosive, or catastrophic, in which droplet breakup occurs so rapidly over the entire volume that practically no strips can be seen.

It was proposed in [4], and then confirmed in [5, 15, 16], that the criterion describing the conditions necessary for development of droplet breakup with removal of the surface layer is:

$$W\,Re^{-0.5} \geqslant 0.5, \tag{2}$$

where $Re = \rho u d \mu^{-1}$ is the Reynolds number. A relationship agreeing with Eq. (2) to the accuracy of a factor of the order of unity can be obtained from the condition of balance between the forces of surface tension and viscous friction in laminar overflow on the liquid—gas phase boundary.

In [17-19, 23, 24] it was shown that the explosive droplet breakup regime is related to the Rayleigh—Lamb—Taylor instability of the liquid surface on the windward side. The rate of instability development is connected with the droplet acceleration a, the criterion which describes this form of breakup being the Bond number

$$B = a\rho_f d^2 \sigma^{-1} \geqslant B^*, \tag{3}$$

where B* is the critical value of the Bond number.

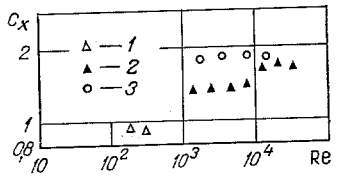

Fig. 2. Resistance coefficient versus Reynolds number.

It can easily be shown that the Bond number is proportional the the Weber number $B = 0.75c_xW$, where the proportionality coefficient is the droplet resistance coefficient c_x. It was shown in [17-19, [23, 25] that the critical value of the Bond number is $B^* \approx 5 \cdot 10^3$.

By analyzing the results of [4-19, 21-26, 30, 31] an observation diagram was constructed in the coordinates W, $WRe^{-0.5}$ (Fig. 1). The shaded regions of the figure correspond to the range of parameter variations in the studies cited. The citation number of the reference is shown in the various regions, while the Roman numerals denote the character of the droplet breakup observed. The experiments were performed with droplets of Newtonian liquids. Surface tension, liquid density, and droplet diameter varied over the ranges $\sigma = (15\text{-}300) \cdot 10^{-3}$ N/m, $\rho_f = 0.8\text{-}13.6$ g/cm^3, $d = 80\text{-}2000$ μm. The studies were performed in shock tubes, and Laval and Venturi nozzles at gas pressures of 0.1-50 bar and gas densities of 0.1-60 kg/m^3.

In a coarse approximation, in the plane of the parameters W, $WRe^{-0.5}$, we can distinguish three regions (which overlap partially at individual points), each of which corresponds to a unique droplet breakup regime:

$$\text{(I)} \begin{cases} 4 \leqslant W \leqslant 20, \\ 0.1 \leqslant W\,Re^{-0.5} \leqslant 0.8; \end{cases}$$

$$\text{(II)} \begin{cases} 10 \lesssim W \lesssim 10^4, \\ 0.5 \lesssim W\,Re^{-0.5} \lesssim 10; \end{cases}$$

$$\text{(III)} \begin{cases} 10^3 \lesssim W \lesssim 10^5, \\ 10 \lesssim W\,Re^{-0.5} \leqslant 10^2. \end{cases}$$

This classification is based not on the physical pattern of droplet breakup, but on the spectrum of the new droplets formed. Regime I is that in which the secondary droplets have dimensions which are close in order of magnitude to the size of the original droplets. This corresponds to division of the droplets into two or more parts, parachute-type breakup, and chaotic breakup. Regime II is that in which the surface layer is torn off the droplets (stripping), and in this case, together with droplets with linear dimensions comparable to the original ones, a significant fraction of very fine droplets appears. Regime III is explosive breakup of the droplets, in which the droplets formed are mainly of significantly smaller size than the original ones. Figure 1 does not show the region III or the parts of region II corresponding to large values of the numbers W, $WRe^{-0.5}$.

Droplet breakup of the parachute type [6-8, 10-12, 21, 16, 22] usually occurs at lower Weber numbers than chaotic breakup [7, 9, 11, 12, 16, 21]. These two regimes of droplet breakup are realized in a quite narrow range of flow parameters and are adjacent to the regime with droplet division into two or more parts. It should be noted that the breakup regime with decomposition into several parts is observed near $W = W^*$ and under specially created conditions. Droplet decay with tearing off of the surface layer (stripping) has been examined in many studies. Although stripping is an important breakup regime (because it produces fine atomization), nevertheless, in the majority of gases the major part of the liquid mass decomposes due to perforation of droplets by instability waves when the critical deformation is reached. All these variants are described in [16]. It is known that with a laminar flow regime the resistance coefficient $c_x \sim Re^{0.5}$. From this it can be shown that the criterion $WRe^{-0.5} > \text{const}$ is identical to the criterion $Wc_x > \text{const}$. However, as follows from Fig. 1 and [4, 5, 14, 16, 18], the Reynolds number in the experiments varies over a wider range than in a laminar flow regime, while region II encompasses Reynolds numbers at which the resistance coefficient is practically constant: $c_x = 1\text{-}1.5$.

A generalized dependence of resistance coefficient on Reynolds number for decomposing droplets is shown in Fig. 2. Points 1, 2, 3 are taken from [25, 30, 31], respectively. In region II for moderate Weber and Reynolds numbers the growth rate of Rayleigh—Lamb—Taylor

instability is low ($W \approx B < 10^3$). There is information [23] that at $B < 10^3$ the amplitude of perturbations increases linearly with time, while the growth rate changes little with increase in acceleration in the indicated region. In the deformation process the droplet transforms into an ellipsoid of revolution, on the surface of which instability waves develop simultaneously. The amplitude of these waves is smaller, the shorter their length, and the characteristic exponential growth time decreases with increase in acceleration. Since perforation of the flattened droplets usually occurs at an ellipsoid thickness significantly less than the original droplet radius, the droplet decay time in the range $W \approx B = 20\text{-}10^3$ is determined basically by the process of droplet deformation and comprises $(1.5\text{-}2)du^{-1}(\rho_f\rho^{-1})^{0.5}$. However, the dimensions of the droplets which are then formed depend strongly on the instability wave growth rate. For $B > 10^3\text{-}10^4$ fine waves develop so rapidly that the flattened droplet is perforated immediately at a large number of points, forming fine droplets. In this manner we can schematically describe explosive breakup. We note that this regime of droplet breakup probably often develops when powerful pressure and velocity pulses act on the two-phase medium (e.g., upon detonation or combustion of droplets in a supersonic flow).

Special attention must be given to the regime of droplet breakup with tearing off of the surface layer (II). Under certain conditions this regime may develop even earlier than droplet division [1], and is apparently realized in power equipment. Tearoff of the surface layer leads to an increase in total surface of the liquid droplets and the intensification of their heating and evaporation. An abrupt change in the rate of this elementary act may prove to have a strong effect on the net rate of conversion of fuel chemical energy into thermal energy in power equipment. It would be desirable to determine the characteristic time intervals corresponding to the development of each of these processes comprising droplet breakup, since those intervals determine both the possibility of realizing one or the other type of breakup, and the kinetics of liquid evaporation surface growth. The time for droplet deformation to the critical stage (i.e., the stage at which its perforation by instability waves commences) t_1 is defined quite well for the case of sudden loading by aerodynamic forces, e.g., behind a shock wave. The quantity t_1 is equal to $du^{-1}(\rho_f\rho^{-1})^{0.5}$. The characteristic droplet acceleration time is defined by the parameter

$$t_2 = 4\rho_f d/3c_x\rho u.$$

The characteristic boundary-layer establishment time on the droplet was defined in [30] and comprises

$$t_3 = 0.36du^{-1}(\rho_f\rho^{-1})^{0.5}.$$

Finally, the characteristic time for increase in perturbation amplitude on the liquid surface by a factor of $e(t_4)$ due to Rayleigh—Lamb—Taylor instability is of the order of magnitude of [20]

$$t_4 = du^{-1}(\rho_f\rho^{-1})^{0.5},$$

and according to the data of [25] the droplet destruction time in explosive decay is

$$t_4' = 10t_4 W^{-0.25}.$$

If we choose as a characteristic time scale the time t_1, then the dimensionless values of the remaining characteristic times can be represented in the form

$$t_1^* = 1, \quad t_2^* = 4(\rho_f\rho^{-1})^{0.5}/3c_x, \tag{4}$$

$$t_3^* = 0.36, \; t_4'^* = 10W^{-0.25}.$$

Here the values of the Weber number are determined from the gas flow parameters on the shock front. Since $c_x = 1\text{-}2$, and the value of $\rho_f\rho^{-1}$ at atmospheric pressure is greater than unity, it follows from Eq. (4) that under these conditions the droplet acceleration time is much greater than the deformation time. However, with increase in pressure the value of $\rho_f\rho^{-1}$ decreases, and the droplet acceleration time may become comparable with the deformation time. We will also present the relationship of the characteristic deformation time t_1 with the period of the droplet oscillations t_n for the mode with $n = 2$. In simplified form, t_n and t_1 are related as $t_n = t_1 W^{0.5}$. As is evident, at small Weber numbers $W < 10$ the value of t_n is also comparable to the deformation time. This coincidence in order of magnitude of the various characteristic times for elementary processes accompanying droplet breakup in gas flows is the cause of the phenomenon's complexity.

The favored development of one or the other droplet breakup regime is related to a reduction in the characteristic time of the corresponding elementary process under certain conditions. At moderate supercritical values of W the time for droplet acceleration by the gas flow and the development time of Rayleigh—Lamb—Taylor instability are larger than the droplet deformation time, which latter is close to the time for boundary layer establishment on the droplet (see Eq. (4)). Under these conditions decay of the entire droplet into two or more parts may occur due to its deformation up to the critical stage. For this case breakup conditions were established by Volynskii and Svetushkin, while droplet breakup with tearing off of the surface layer still can occur. Droplet decay into several parts is observed often when the time over which the flow acts on the droplet is brief. Thus, realization of one or the other breakup regime depends on the Weber and Reynolds numbers, and also the length of time for which the flow acts on the droplet.

In conclusion, we note that we have not considered the kinetics of droplet surface development and the rate of evaporation in breakup, both of which are most important for practical purposes. An evaluation of these questions should be performed separately, since each individual breakup and evaporation regime in a gas flow creates its own large set of kinetic gas liberation principles in the two-phase flow.

NOTATION

a, droplet acceleration; B, Bond number; c_x, resistance coefficient; d, droplet diameter; p, pressure; Re, Reynolds number; t, time; u, relative velocity of gas and droplet; W, Weber number; μ, gas viscosity; σ, liquid surface tension; ρ, gas density; ρ_f, liquid density.

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