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SHOCK-FREE BREAKUP OF DROPLETS. TEMPORAL CHARACTERISTICS

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In the present paper, we consider the shock-free breakup of droplets in their encounter with a layer (sheet) of a moving gas in the absence of pressure perturbations when the droplets are affected by a short U-shaped pulse of aerodynamic forces. Under a high pressure of the ambient gas medium $p_0 = 20$–80 *bar, the droplets (ethanol or liquid oxygen) have a chance to break up after stay in a thing (2–5 mm thick) gas layer (jet) moving with a velocity of* 1–10 m/sec. *A distinctive feature of the process is that the characteristic time of droplet deformation and the period of natural oscillations coincide with the residence time for the droplets in the region of their interaction with the gas stream. Empirical formulas are proposed for determination of the total breakup time and the duration of the droplet disintegration stage in shock-free breakup.*

Usually, droplet breakup in gas flows is associated with the appearance of pressure perturbations (pressure or depression waves or shock or explosive waves) in the gas near droplets, which cause relative motion of the droplets and the gas. A description of the principal modes of droplet breakup due to passage of pressure waves in a two-phase system "gas–droplets" is given in [1].

It is known that droplet breakup can occur in a continuous medium that is not disturbed by pressure waves. Droplet breakup in an isobaric medium will be called shock-free breakup. Shock-free droplet breakup (SFDB) occurs, in particular, in the following cases:

1) breakup of free-falling droplets;

2) injection of liquid droplets (jets) across a gas flow that has the form of a rectangular sheet of finite width or a cylindrical jet of finite diameter;

3) breakup of droplets of a heavy liquid with density ρ_f distributed in a flow of a lighter incompressible liquid.

Some of the above-enumerated cases of SFDB are of practical importance. For example, the second case is significant for the preparation of fuel mixtures in the combustion chambers of liquid-propellant rocket engines or Diesel engines. This case of SFDB, in particular its temporal characteristics, has been studied insufficiently, especially for high initial gas pressure $p_0 > 10$ bar. Some experimental data are contradictory because the gas parameters under a smooth increase of aerodynamic forces were not fixed. For example, many results of [2, 3] were obtained within the errors reported in those papers and are of little use for quantitative estimates.

For a reliable description of the SFDB process and determination of the parameters, it is necessary to synchronize the observed behavior of particles with the initial and current conditions of relative motion of the gas and the droplets. Only a special procedure for measuring the gas flow parameters near droplets of ethanol and liquid oxygen in an isobaric medium [4, 5] made it possible to obtain reliable data on the conditions of implementation and temporal characteristics of SFDB when droplets encounter a moving thin

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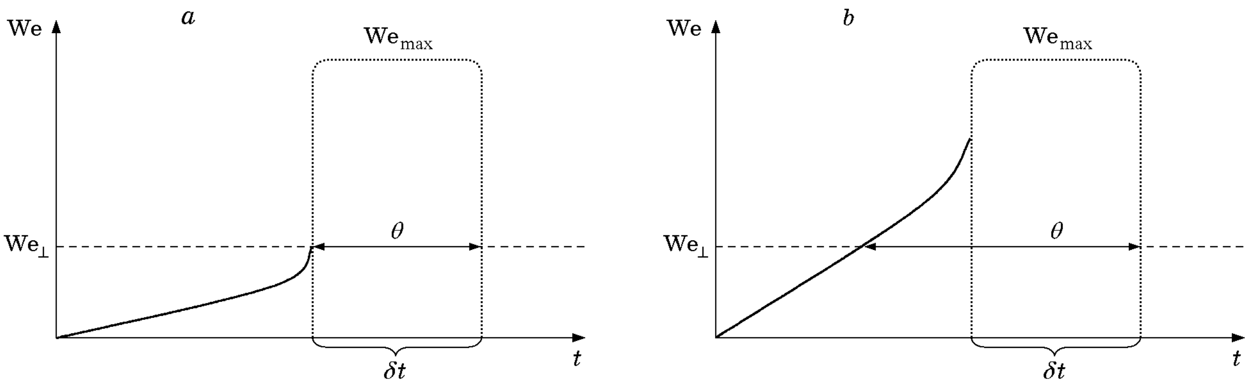

Fig. 1. Qualitative time dependence of the Weber number in the SFDB process for $\theta \approx \delta t$ (a) and $\theta > \delta t$ (b): solid and dashed curves refer to $\mathrm{We}_\perp$ and We_m, respectively.

layer of gas. The experimental data of [4–6] supplement the results of observations reported in [7–9]. It follows from these data that the SFDB process depends on the residence time for the droplets inside the gas sheet (jet): $\delta t = \Delta / w_\perp$. Here Δ is the width (diameter) of the moving gas sheet, and $w_\perp$ is the velocity of motion of the droplets across the gas layer.

For a better understanding of the process considered better, it is reasonable to determine the time variation of the aerodynamic forces acting on a droplet. We characterize the magnitude of these forces by the Weber number $\mathrm{We} = \rho_{\mathrm{g}} u_r^2 d/\sigma$. Here $\rho\mathrm{g}$ is the gas density in the sheet (air or helium [4, 5]); $u_r = (w_\perp^2 + v^2)^{0.5}$, v is the velocity of the gas, and σ is the surface tension of the liquid. An analysis of experiments similar to the experiments of [4–6] shows that the liquid droplets are subjected to the action of an U-shaped jump of aerodynamic forces, whose main forms can be described by the Weber number as a function of time t (Fig. 1). In the experiments of [6–10], at the time when the droplets approached the moving gas jet, the Weber number was equal to $\mathrm{We}_\perp = \rho\mathrm{g} w_\perp^2 d/\sigma \ll \mathrm{We}_m = \rho\mathrm{g} v^2 d/\sigma$. However, in real engine operation and in experiments with liquid oxygen under high pressure [4, 5], $\mathrm{We}_\perp \approx \mathrm{We}_m$. When $\mathrm{We}_\perp \ll \mathrm{We}_m$ (Fig. 1a), a droplet is exposed to an U-shaped action of aerodynamic forces with amplitude $\mathrm{We}_{\max}$ and duration $\theta \approx \delta t$. When $\mathrm{We}_\perp \approx \mathrm{We}_m$ (Fig. 1b), the simple U-shaped form of the jump of aerodynamic forces is distorted because the Weber number increases during motion of the droplets in the motionless gas before encounter with the jet, and in this case, $\theta > \delta t$.

Thus, besides the magnitude of aerodynamic forces (determined by the Weber number), an analysis of the SFDB process must take into account the ratio of the time during which they act θ to the time scales of the droplet breakup process. According to [1], these time scales are given by the time of particle deformation $\tau_1 = d u_r^{-1} (\rho_f \rho\mathrm{g}^{-1})^{0.5}$ and the period of natural oscillations $\tau_2 = 0.785 \rho_f d^3 \sigma^{-1} \approx 0.785 \tau_1 \mathrm{We}^{0.5}$.

The time of onset of intense droplet breakup τ_i and the duration of the disintegration process τ_b for SFDB were determined in [4, 5]. The total breakup time is $\tau_\Sigma = \tau_i + \tau_b$. None of the above-mentioned experimental values was compared with τ_1 and τ_2 and with the residence time of the droplets in the field of aerodynamic forces θ. Figure 2 shows the function $\tau_i(\mathrm{We})$ for various values of the initial gas pressure p_0. The experimental data were obtained for liquid oxygen droplets with a size of $d = 0.7$–1.4 mm.

As shown in Fig. 2, $\tau_i \geqslant \theta$ for We $\leqslant$ 20–30 and $\tau_i \leqslant \theta$ for We $\geqslant 30$. There are similar relations between the period of oscillations τ_2 and the time θ: $\tau_2 \geqslant \theta$ for We $\leqslant 15$ and $\tau_2 \leqslant \theta$ for We $\geqslant 30$. For We $\approx$ 15–30, it was found that $\tau_2 \approx \tau_i$. In most experiments (see [4, 5]), $\tau_\Sigma \geqslant \theta$. The experimentally revealed complex interaction between the processes characterized by the times τ_1, τ_2, and τ_Σ and the time of action of breaking loads complicates the analysis of experimental data and determines the peculiar features of the phenomena observed.

Usually, one distinguish three types of disintegration of a target (droplet) under the action of a load (aerodynamic force) [11].

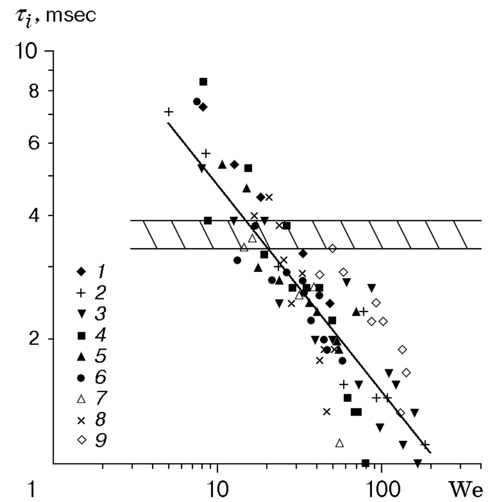

Fig. 2. Time of onset of droplet breakup versus Weber number (the shaded area represents the residence time for the droplets in the region of action of supercritical aerodynamic forces $\mathrm{We}_1 > 10$) for $p_0 = 2$ (1), 5 (2), 10 (3), 20 (4), 30 (5), 40 (6), 50 (7), 60 (8), and 70 bars (9); the solid curve refers to calculation and points refer to experiment.

1. For $\theta \gg \tau_2$, a quasistatic breakup of droplets occurs, which depends on the magnitude of the applied load (Weber number) [6, 10].

2. For $\theta < \tau_2$ (see [7–9]), a pulsed breakup of droplets occurs. In this case, not only the magnitude of the load but also the duration of its action are important.

3. For $\theta \approx \tau_2$, a quasistatic-pulsed droplet breakup occurs. In this case, the breakup process depends on the dynamic characteristics of the load: $\mathrm{We} = \mathrm{We}(t/\theta)$ (see [2–5]). Resonance phenomena due to the equality of the residence time of the droplets and the period of natural oscillations were observed [2, 3]. From this and the experiments of [4, 5], one can determine the dimensionless time of onset of intense droplet breakup $\tau_i^* = \tau_i/\tau_1$ and the breakup duration $\tau_b^* = \tau_b/\tau_1$ as functions of the Weber number. Accordingly, $\tau_\Sigma^* = \tau_\Sigma/\tau_1 = \tau_i^* + \tau_b^*$.

Figure 3a and b shows the total breakup time τ_Σ^* and the duration of the breakup stage τ_b^* versus the Weber number. For the case of shock-induced breakup of droplets by short-time pressure perturbations, Gel'fand et al. [12] proposed the empirical relation $\tau_\Sigma \approx \tau_1 + \tau_2 = \tau_1(1 + 0.785\chi \mathrm{We}^{0.5})$, i.e., $\tau_\Sigma^* \approx 1 + 0.785\chi \mathrm{We}^{0.5}$ ($\chi \leqslant 1$ and $\tau_i^* = \tau_i/\tau_1 \approx 1$). The solid curve in Fig. 3a corresponds to this relation with $\chi_1 = 0.9$ and is in satisfactory agreement with the experimental data of [4, 5]. Thus, the total droplet breakup time is the sum of the time of particle deformation to the critical stage and the period of natural oscillations of the particles. For $\mathrm{We} < 100$, the duration of the particle breakup itself is close to $\tau_b^* \approx \tau_\Sigma^* - 1 = 0.785\chi_2\,\mathrm{We}^{0.5}$, where $\chi_2 = 0.8 \pm 0.2$.

Figure 3b shows the calculated dependence $\tau_b^* = 0.785\chi_2\,\mathrm{We}^{0.5}$ (solid curve) and the experimental data of [4, 5]. The satisfactory agreement between the calculated and experimental data implies that the breakup time and the period of natural oscillations of droplets have close values. Pilch and Erdman [13] also observed a paradoxical behavior of the function $\tau_\Sigma^* = \tau_\Sigma^*(\mathrm{We})$ in the range of Weber numbers $18 < \mathrm{We} < 45$, where the dimensionless time of droplet breakup past shock waves grows with increase in Weber number. This behavior of droplets is typical of situations where the forced oscillations of the particles still contribute to the breakup process. For $\mathrm{We} > 100$, the period of droplet oscillations $\tau_2 \gg \tau_1$. In this case, the breakup process is related to oscillations of the droplet shape to a lesser extent and, therefore, $\tau_\Sigma^* \neq \tau_\Sigma^*(\mathrm{We})$ and the value of τ_Σ^* tends to a constant, approximately equal to 5 ± 1.

Thus, the main distinctive feature of the SFDB process in the case of droplet motion through a sheet (jet) of a moving gas in an isobaric medium is pulsed or quasistatic-pulsed breakup of the particles under the action of aerodynamic forces. This is due to the equality of the duration of the load θ and the characteristic times of droplet deformation τ_1 and natural oscillations τ_2. As a result, the total droplet breakup time is close to the sum of the deformation time and the period of natural oscillations. After attainment of the

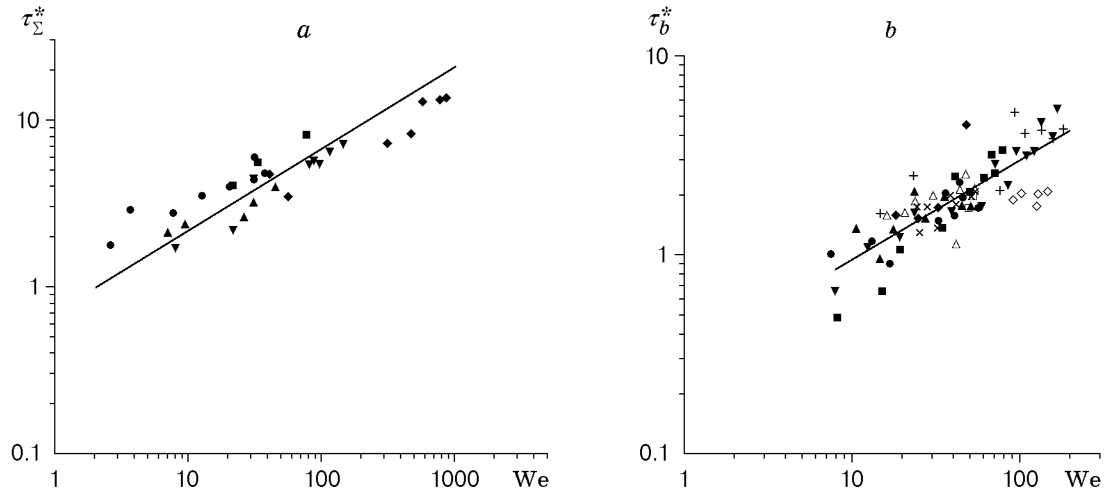

Fig. 3. Dimensionless total breakup time (a) and dimensionless duration of the droplet disintegration stage (b) versus Weber number (the notation is the same as in Fig. 2).

critical deformation stage, the duration of the droplet breakup process is comparable to the period of natural oscillations of the droplets. For $\theta \gg \tau_1$ and, hence, for $\theta \gg \tau_2$, the temporal characteristics for the SFDB process and for the droplet breakup process in the presence of pressure waves coincide.

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