EXPERIMENTAL INVESTIGATION OF DROP FRAGMENTATION BY AERODYNAMIC FORCES

V. V. Dubrovskii, A. M. Podvysotskii, and A. A. Shraiber

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The mechanisms of deformation and breakup of "clean" drops and two-component particles (drops with solid inclusions) by aerodynamic forces are studied. An experimental apparatus and a method of measurement are described. Drop breakup for critical and transcritical Weber numbers We is investigated. The time characteristics of drop deformation and breakup processes are studied. It is established that the rate of growth of the external perturbation has a significant effect on the critical Weber number We*. A new, for the types of problems studied here, similarity number G is proposed for estimating the character of the changes in the aerodynamic forces. Generalized empirical formulas are obtained for We_*, the induction time, and the parameters of the fragment size distribution.

1. Formulation of the Problem. Description of Experimental Apparatus. Two-phase flows consisting of a carrier gas with liquid drops suspended in it are widespread in nature and technology. In many cases the behavior of the drops is strongly affected by their deformation and fragmentation by aerodynamic forces. In spite of the significant number of publications concerning it, this topic has not been adequately studied and generalized.

It has been established that the most important parameters determining drop stability and breakup are $We = (u_g - u)^2\delta\rho_g/\sigma$ and (in the case of quite viscous liquids) the Laplace number $Lp = \delta\rho\sigma/\eta^2$ (u is the velocity, δ is the diameter of an undeformed drop, ρ is the density, σ is the surface tension, and η is the coefficient of dynamic viscosity; quantities containing an index g refer to the gas and unindexed quantities refer to the drop). Information about the effect of other parameters (Reynolds, Mach, Bond, etc. numbers) is fragmentary or nonexistent. In [1-6] breakup regimes are classified as a function of the intensity of the action of the aerodynamic forces and data are given for determining the boundaries between the regions where one or another regime is realized. Detailed analysis [3, 6] shows that three types of loading of a drop must be distinguished.

A. The relative velocity increases rapidly and then decreases evenly up to the moment of breakup.

B. The load increases evenly (quasistatically).

C. The relative velocity first increases evenly and then decreases.

Analysis of the experimental results [1-3, 5-9] indicates that there is a large spread in the values of We_* (from 1-1.5 to 60-80). There are apparently two reasons for this spread.

1. In some works (for example, in [5]) We_* is taken to be the local value of We corresponding to the moment of breakup. Often, the method used to determine We* is not described; but, it can be conjectured that We_* also was calculated at the point of breakup. The gave too high a value of We_*, if the breakup occurred with increasing $(u_g - u)$, or too low a value of We_* in the opposite case.

2. A qualitative description of the loading of a drop without a quantitative estimate of the rate of change of the aerodynamic forces is, by itself, probably insufficient to judge unequivocally the effect of this factor on the conditions of breakup. It is considered [3, 7] that when the external action changes evenly (loading of the type B or C) the values of We_* are approximately two to three times larger than in the case of type-A loading. At the same time, in [10] the opposite dependence of We_* on the rate of change of aerodynamic forces was obtained (no generalization of the data was made). Thus the important, from our

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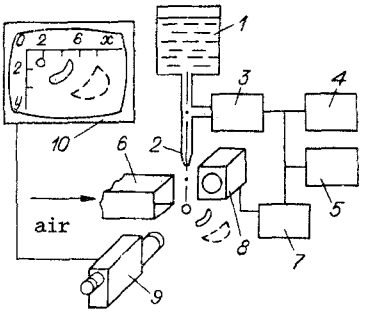

Fig. 1

point of view, question of the effect of the rate of change of aerodynamic forces on the critical conditions of drop breakup remains unresolved.

One aspect of the problem to which adquate attention has not been given is the determination of the characteristic times of the breakup process. Results of measurements of different characteristic times are presented in [2-4]: the effect of flow on a drop, the attainment of the critical stage of deformation, induction (i.e., delay of breakup) τ_i, complete breakup τ_d, etc. These times are usually referred to the scale

$$\tau^0 = \delta(u_g - u)^{-1}(\rho/\rho_g)^{0,5}. \tag{1.1}$$

The time response for type-A loading have been studied in greatest detail. According to [3], in the regime of vibrational breakup

$$\tau_d \approx \tau_i \approx \tau^0 + \tau_{osc} \tag{1.2}$$

where τ_{osc} is the period of characteristic oscillations of a drop.

The time characteristics of the processes under conditions of even loading have hardly been studied. We call attention to [11], according to which in the case of fragmentation in the zone where the perturbation changes very little $\tau_i \approx \tau_{osc}$.

Fragmentary information is available about the size fraction composition of the fragments formed in the process of fragmentation [12]. We note that virtually no information has been published on the mechanisms of deformation and fragmentation of two-component particles.

In the present paper we present the results of an experimental study of the critical conditions of the breakup of drops and two-component particles, the time characteristics of the process, and the size fraction composition of the fragments formed. The experiments were performed on the experimental stand shown in Fig. 1. The working liquid (water–glycerine solutions of different concentrations) was fed from the reservoir 1 under a static head into the forming capillary 2, out of which the liquid flowed. Pressure pulsations were applied to the liquid near the capillary with the help of a pump 3. In the process, the jet was atomized into monodispersed drops, which were detached with the frequency of the applied pulsations. In order to obtain two-component particles a suspension with different concentrations of solid inclusions was prepared in the reservoir. The pulsational pump was controlled with a specially developed electronic unit 4, which regulates the frequency of detachment of freely falling drops in the range 4-30 Hz and forms the controlling signals for the visualization apparatus and the electronic counter 5. A transverse jet of air, flowing out of interchangeable nozzles, was directed onto the falling drops. The nozzles made it possible to form flows which differed both by the time interval during which the flow acted on the drop and by the character of the increase in the aerodynamic forces. Special measures were taken to reduce to a minimum the turbulent pulsations in the flow incident on the drop.

Different phases of drop drformation and breakup were studied with the help of photography as well as methods for visualizing the process with pulsed illumination. For this we developed and built an electronic-digital unit 7 which enabled repeated visualization and made it possible to generate packets of light pulses with a repetition frequency that is a

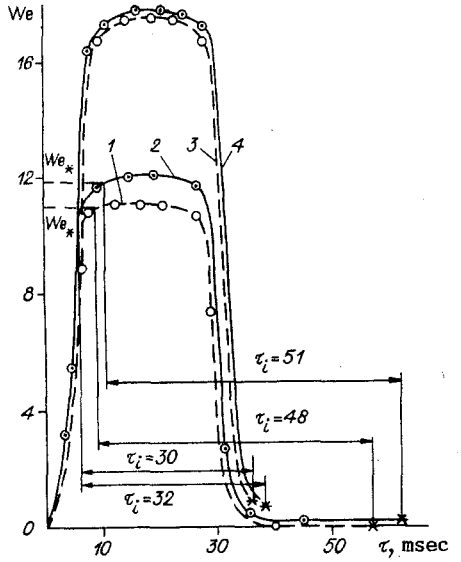

Fig. 2

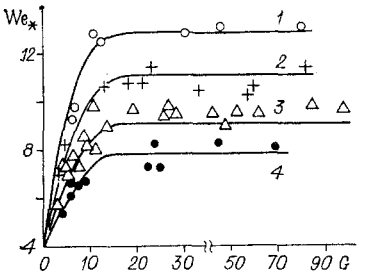

Fig. 3

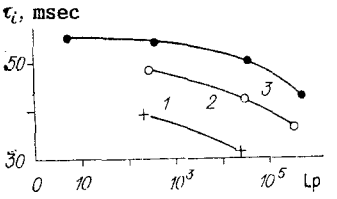

Fig. 4

multiple of 1 msec. This made it possible to observe visually and record on film simultaneously several phases of drop deformation and fragmentation separated by predetermined time intervals. The generated pulses were employed for synchronizing the stroboscope 8 or powerful flashlamps. These method of visualization made it possible to obtain a "frozen" image of up to three stages of drop drformation and breakup simultaneously as well as to measure the time interval between phases with the high accuracy characteristic of digital devices having a quartz-stabilized reference generator.

The coordinates of a drop moving through the gas flow were determined with the help of a video camera and a TV monitor. A coordinate grid, seemingly superposed on the plane of motion of the drop, was placed directly on the screen of the monitor. The grid helped to record the trajectory of a drop and to measure the velocity field in the flow incident on the drop. An enlarged (by a factor of six) image of a drop was obtained on the TV screen; this made it easier to observe the qualitative picture of the process. The number of free drops generated was calculated with the help of a counter connected to control device.

The diameter of the clean monodispersed drops generated was determined from calibrations with respect to the number of drops and their total mass; the diameter of the two-component particles was determined from the number of particles and their total volume. A calibration curve was used to find the volume concentration V of solid inclusions in a drop. In the experiments the value of V was varied from 0 to 17%. Experiments with two-component particles were performed using as solid inclusions of quartz sand with size fractions of 160-315 μm and density ρ_s = 2774 kg/m³.

2. Critical Conditions of Breakup. In the experiments on the determination of the critical conditions of breakup the intensity of the gas-flow effect on the drops or two-component particles was gradually increased up to values at which drop fragmentation was first observed. The largest measured value of We along the trajectory of the drops was taken as We_*. We note that here We_* is not the local value of We, corresponding to the moment of drop breakup, as many investigators assume, but rather the minimum value of We for

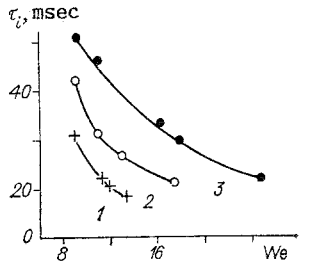

Fig. 5

which drop breakup always occurs with some delay under the given conditions. As mentioned above, if We_* is taken to be the local value of We at the point of breakup, then a definite systematic error (which can be very significant) is introduced into the experiment.

In our experiments with $We \approx We_*$ vibrational breakup into two (less often three) approximately equal fragments occurs. Fragmentation is preceded by growing oscillations of the drop; immediately preceding breakup the drop often assumed a dumbbell shape. For more intense action of the aerodynamic forces (critical values of We) the oscillatory process in the drops did not occur. The drops rapidly assumed a disk shape, and after some time interval a crater (characteristic "pit") was observed on the front surface on the side of the incident flow. At even higher intensities the drop was blown into a "bag" after which it broke up into polydispersed fragments. We note that depending on the conditions of the experiment, drop breakup was observed in the zone of constant relative velocities, in the zone of decreasing aerodynamic forces, and even outside the effective field of the gas flow. The experiments show that the qualitative picture of the process of deformation and fragmentation by aerodynamic forces is identical for both clean and two-component particles and the same sequence of phases is observed in both cases, but the characteristic time intervals of the process are somewhat different.

Figure 2 shows as an example the character of the change in We in time along trajectories of clean drops and two-component particles (lines 1, 3 and 2, 4) for critical and transcritical (lines 1, 2 and 3, 4) breakup conditions (τ is the instantaneous time). For a clean drop and for a drop with impurity $We_* = 10.9$ and 11.8 (curves 1 and 2).

Careful measurements confirmed the assumption that the rate of growth of the external action significantly affects the critical conditions of drop breakup by a gas flow. In order to estimate the character of the change in the aerodynamic forces we introduce the similarity number $G = dWe/d(\tau/\tau_{osc})$. According to our measurements, $\tau_{osc} = 0.83(\rho\delta^3/\sigma)^{0.5}$.

Figure 3 shows We_* for clean drops as a function of the rate of growth G of the aerodynamic forces for Lp = 5.3, 250, $2.32 \cdot 10^4$, and $3.48 \cdot 10^5$ (lines 1-4). Characteristically, for $G > 15$ (the experiments were performed in the range G = 3-97) the values of We_* are self-similar relative to G in a wide range of values of Lp. As the viscosity of the liquid increases drop breakup was observed at increasingly larger values of We; this agrees qualitatively with the data of [10]. For $G < 15$ the values of We_* decreased sharply with increasing time of interaction of the gas flow and the drop (i.e., with decreasing G). The effect of the rate of change of the aerodynamic forces is strongest for viscous liquids (curve 1). In the case of slow growth of aerodynamic forces, for example, under near quasistationary ($G \to 0$) conditions of drop fragmentation, when a drop deforms sowly, the role of viscous forces decreases appreciably and the curves 1-4 approach a common limit ($We_* \approx 4$). Characteristically, the lower limit of self-similarity corresponds to the situation when We_* is reached within a time equal to approximately half the period of the characteristic oscillations of the drop.

In experiments with two-component particles We_* increased with the impurity content of the drops. This is probably connected primarily with the increase in the dynamic viscosity of the suspension due to the presence of solid inclusions (compare Fig. 2). Einstein's correction was used to determine the coefficient of dynamic viscosity η_m of the mixture of the liquid with the solid particles (for solid spherical inclusions $\eta_m = \eta(1 + 2.5\,V)$). If for drops with an impurity Lp is calculated from the density and viscosity of the suspension, then, as the measurements showed, the values of We_* for clean and two-component particles agree satisfactorily with one another in a wide range of experimental conditions.

The obtained experimental data were approximated by the dependence

$$\begin{gathered}\mathrm{We}_* = 13{,}5 - 0{,}44P - (9{,}5 - 0{,}44P)\exp[(0{,}005P - 0{,}25)G], \\ P = \ln \mathrm{Lp}\end{gathered} \tag{2.1}$$

for G and Lp in the ranges $3 \leq G \leq 97$ and $5.3 \leq \mathrm{Lp} \leq 3.5 \cdot 10^5$. The largest deviation of the experimental points from the dependence (2.1) does not exceed 1.25, and the rms deviation is equal to 0.509.

Thus the experimentally established dependence (2.1) refutes the widely held opinion that in the case when the aerodynamic forces increase slowly We_* is several times larger than in the case of rapid change. The parameter G makes it possible to take into account the dynamics of the change in the aerodynamic forces as the drops break up. The spread in the experimental data of [1-3, 5-9] is apparently partially explained by the fact that this factor was not taken into account in detail.

3. Time Characteristics of the Process. The stand shown in Fig. 1 was also used for measuring the time τ_a during which the gas flow acted on the drop (from the moment at which the action of the aerodynamic forces begins up to the moment corresponding to critical conditions) and the induction time τ_i. We note that the concept of τ_i is not celarly defined in [2, 3, 6]. In [11] τ_i is measured from the moment at which the drops become disk-shaped. However the concept of disk shape is imprecise, since the degree of drop deformation in the form of a disk can fall within wide limits. It is virtually impossible to measure τ_i from any stage of drop deformation, since at the present time there are no reliable data on the conditions under which a drop assumes one or another form. In addition, our experiments established that a drop does not necessarily always break up after it becomes disk shaped. From our standpoint, for all cases of drop fragmentation by a gas flow (both critical and transcritical) τ_i must be measured from a fixed value of We, namely, from the moment when the critical value is reached for given specific conditions of interaction with the flow before the first fragment appears. Thus in Fig. 2, τ_i = 48 and 51 msec for clean and two-component particles (lines 1 and 2) with the maximum value of $\mathrm{We} \approx \mathrm{We}_*$ along the trajectory of the drop. For transcritical conditions of fragmentation τ_i decreases to 30 and 32 msec for clean drops and for drops with solid inclusions (lines 3 and 4), respectively.

Our investigation of the process of drop deformation and breakup under critical conditions established that for $G < 15$, i.e., for relatively low rates of growth of aerodynamic forces, when We_* depends on the gradient G, $\tau_a \geq 0.5\tau_{osc}$ and the drop broke up within one period ($\tau_i < \tau_{osc}$). If, however, the drop deformed under conditions of rapid growth of the relative velocity ($G > 15$, We_* does not depend on G), then $\tau_a < 0.5\tau_{osc}$ and drop breakup started later than one period of the characteristic oscillations ($\tau_i > \tau_{osc}$).

The experiments showed that under conditions when the values of We do not exceed We_*, with sufficiently rapid change of the aerodynamic forces the delay in drop fragmentation decreases with increasing Lp (Fig. 4, δ = 3.4, 4.3, and 5.3 mm — lines 1-3). In all cases the presence of a solid impurity in the drops (even at low volume concentrations) led to some increase of the induction time, since solid inclusions increase the viscosity of the liquid. The value of τ_i for otherwise equal conditions decreases with decreasing drop size.

Figure 5 illustrates the dependence of τ_i on We for transcritical conditions (the nomenclature is the same as in Fig. 4). The induction time τ_i decreases with increasing intensity of the aerodynamic flow.

In order to generalize the experimental data, in our opinion, it is best to refer the characteristic periods of the process of deformation and fragmentation to the period of characteristic oscillations of the drops. It is inconvenient to use τ^0 (see (1.1)) as the scale, since in many cases $(u_g - u)$ changes significantly druing the process, and in order to calculate τ^0 it is necessary to use a specific value of the relative velocity (for example, the initial value, as done in [4]). This makes the results less general. Analysis of the experimental data led to the expression

$$\frac{\tau_i}{\tau_{osc}} = \begin{cases} T, & We = We_*, \\ T\exp\{(8{,}4\cdot 10^{-4}\,Re - 3{,}44)\,[(We - We_*)/We_*]\}, & We > We_*, \\ T = 4{,}32 - 8{,}5\cdot 10^{-4}\,Re - (0{,}15 - 4\cdot 10^{-5}\,Re)\ln Lp \end{cases} \tag{3.1}$$

in the range $2790 \leq Re \leq 3620$; $5.2 \leq Lp \leq 3.92\cdot 10^5$; $G > 15$. Here $Re = (u_g - u)\,\rho_g\delta/\eta_g$ is calculated for the critical conditions of breakup.

The calculations showed that the expression (3.1) predicts a value of τ_i of the same order of magnitude as (1.2). For example, for $\delta = 5.3$ mm, $\rho = 1100$ kg/m^3, $u_g - u = 10$ m/sec, $\eta = 0.00375$ Pa·sec, and $\sigma = 0.069$ N/m ($Re = 3530$, $Lp = 28600$, and $We_* = 9.3$) the ratios $t \equiv \tau_i/\tau_{osc}$ are equal to 1.22 and 1.4, respectively (we recall that, according to [11], $t \approx 1$). The small discrepancies are probably caused by the difference in the reference time from which the induction time is measured as well as by the conditions of the experiment, in particular, the character of the change in the external action.

It is also evident from the experiments that τ_i depends only on the previous history, i.e., on the character of the change in the external action preceding the critical conditions and not on how the action on the drop changes after this moment. In other words, the induction time is the same, irrespective of whether the drop is in the field of constant external forces, which vary to a greater or lesser extent, or at the moment of actual breakup the drop is located outside the range of action of the gas flow.

4. Fraction Composition of Fragments. The fraction composition of the fragments was determined by the method of photographing in pulsed illumination with fragmentation of initial clean drops with diameter 3.2-5.9 mm in the range of viscosities $\eta = 0.00375$-0.0365 Pa·sec. Analysis of about 14000 fragments established that for $We_{max} = 9$-30 the distribution function of fragments over sizes δ_0 is described well by a log-normal law

$$n(\varepsilon) = \frac{1}{\sqrt{2\pi}\varepsilon\ln\Sigma}\exp\left[-\frac{(\ln\varepsilon - \ln\bar{\varepsilon})^2}{2\ln^2\Sigma}\right], \quad \varepsilon = \frac{\delta_0}{\delta}.$$

Average values were obtained in the investigated region of values of the parameters of the distribution ($\ln\langle\bar{\varepsilon}\rangle = -2.2$, $\ln\langle\Sigma\rangle = 0.66$).

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APPARATUS FOR INVESTIGATING THE LIQUID-NITROGEN DISTRIBUTION IN THE SPRAY CONE OF A JET FLOWING OUT OF A NOZZLE INTO AN AIR FLOW

A. S. Bushmin, A. A. Galenko, and L. M. Dmitriev

UDC 533.6.071

In systems which cool the flow in cryogenic wind tunnels liquid nitrogen is injected into the flow through spray nozzles. In using this method it is of interest to have information about the distribution of liquid in the flow, the penetration depth of the drops into the flow, and the evaporation time of the drops. Optical methods are widely employed for studying these processes [1], but often the accuracy of these methods is too low.

In the present paper we present data on an apparatus for measuring the amount of liquid nitrogen present in a two-phase flow. The operation of the apparatus is based on the extraction of a sample of the liquid. The construction and the measurement system were made so that the sample is analyzed in the dynamic regime. The apparatus was employed for studying the spraying and evaporation of liquid nitrogen out of a spray nozzle perpendicular to the flow in the working part of a cryogenic wind tunnel. The mass of the liquid nitrogen entering the receiver is measured with an accuracy of ±5%.

A diagram of the apparatus and the system of measurements is presented in Fig. 1 (a: 1 – feed path of the liquid nitrogen, 2 – nozzle, 3 – Pitot tube, 4 – adapter for extracting liquid from a gas–liquid mixture, 5 – feed path of helium, 6 – regulator, 7 – variable hydraulic resistance, 8 – calibration tube, 9 – flowmeter orifice, 10 – thermocouple; b: 1 – input slit of adapter, 2 – helium inflow, 3 – mixture of helium and evaporating nitrogen, 4 – flow of nitrogen drops, 5 – jet of excess helium; DF – direction of air flow).

The inner channel of the nozzle used for injecting liquid nitrogen has a smooth profile and the output diameter of the nozzle is equal to 1.5 mm. The attachment was constructed in two variants. In the first variant, a jet of helium, blocking the path of the air flow into the adapter, is injected into the receiving channel (through a 1 × 10 mm slit) perpendicular to the direction of the incident flow. Because helium has a low density the drops of liquid pass through the zone of the helium jet and evaporate in the cavity of the adapter in a helium atmosphere. The mixture of evaporating nitrogen and helium is extracted through a path in which the density and flow rate of the mixture and thereby the amount of liquid entering the adapter are measured. The volume flow rate of the helium jet is set at a value 1.5-2 times greater than the volume flow rate of the mixture through the channel.

In the second variant the adapter consists of a tube with an inner diameter of 4 mm and an outer diameter of 5 mm into which helium is introduced. A 0.7 × 7 mm input slit is cut in the tube 60 mm from the point of helium entry. At the location of the slit the tube is flattened to an oval cross section with inner dimensions of 1.5 × 5 mm. The slit is oriented along the generatrix of the tube and is located on the crest of the flattened section. The mechanism of the processes occurring in this adapter is the same as in the first adapter.

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