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I. V. Samsonova, V. M. Boiko, S. V. Poplavski, et al.

Induction Time of Liquid Drop Breakup in an Accelerating Flow

I. V. Samsonova, V. M. Boiko[a], S. V. Poplavski[b], and A. A. Pivovarov

Khristianovich Institute of Theoretical and Applied Mechanics SB RAS,
Institutskaya str., 4/1, Novosibirsk, 630090, Russia

[a]Corresponding author: bvm@itam.nsc.ru
[b]s.poplav@itam.nsc.ru

Abstract. The temporal characteristics of the processes of deformation and disintegration of a freely falling drop of a low-viscosity liquid in an air accelerating flow are studied. The experiments were carried out under fast loading and in the regime of impulse-quasi-static loading of drops at moderate gradients of flow velocity. Experimental values of the interaction time and the induction time of the drop breakup are obtained.

INTRODUCTION

Getting into the gas flow behind the shock wave or into the confuse channel (nozzle), liquid drops are deformed, and internal flow appears inside it. The development of these processes leads to the disintegration of the drop (secondary breakup) and the appearance of fragments. The breakup process is complex and is determined by the ratio of the forces of surface tension, viscosity and inertia [1-2]. At present, the well-known classification of the types of breakup of single liquid droplets in gas flows is based mainly on the ranges of Weber numbers (We) taking into account the Reynolds numbers (Re) [1]. The breakup mechanism caused by the combined action of aerodynamic forces and Rayleigh-Taylor instabilities is taken as the main one for the breakup modes at low Weber numbers (We <30) [3]. Here it is appropriate to note the role of the internal flow, which can affect the mechanism of drop disintegration. Currently, information on this mechanism is insufficient and fragmentary. This range of Weber numbers includes typical breakup processes of the "bag" and "bag and stamen" modes. Numerical modeling of the drop breakup processes, which has been actively developing in recent years, reveals the need for a detailed study of deformation, drop acceleration, the size distributions of fragments formed at different stages of breakup process, as well as temporal characteristics. The possibility of high-speed filming in experiments makes it possible to determine the geometric parameters after image post-processing (for example, the stream-wise and cross-stream dimensions of a deformed drop, its middle area), as well as time characteristics that can be used in simulations of the deformation and gas-dynamic fragmentation of liquid drops in subsonic and supersonic flows.

The breakup process has a certain time scale, and does not occur instantly. The times of action of aerodynamic forces on the droplet, the delay (or induction) times of fragmentation, as well as the total time of the initial drop disintegration are always important. Another useful time is the period of natural oscillations of a liquid drop t_k, which is important when comparing time scales [1]. In order to compare the characteristics, dimensionless times are often used taking into account the characteristic time $t_0 = d_0/\Delta V_0(\rho_l/\rho_g)^{0.5}$, where d_0 is the diameter of the drop in the initial undeformed state, ΔV_0 is the initial relative velocity of the flow and the liquid drop, ρ_l/ρ_g is the density ratio of the liquid and gas. Dimensionless times will vary depending on the criteria and breakup modes.

The intensity of aerodynamic forces acting on a drop is determined by the Weber number. That is the time dependence of the We number determines the time of interaction between the drop and gas. When describing the process of drop breakup, one usually distinguishes between the deformation phase (before the appearance of the first fragments) and the fragmentation phase [4]. The deformation and the fragmentation phases can include several

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stages, characterized by their time ranges. Further in this work, in accordance with [4-7] the duration of the deformation phase is defined as the sum of the time from the beginning of the action of aerodynamic forces until the moment when critical conditions are reached (critical Weber number - $\mathrm{We}_{\mathrm{cr}}$) - t_{int} and the induction time - t_i, counted from the moment the critical Weber numbers are realized until the appearance of the first fragments. For the "bag" and "bag and stamen" modes of drop breakup, the deformation phase ends with the bag bursting. The sum of the duration of the deformation phase and the fragmentation phase determines the time of complete or total breakup (t_b or t_{tot}). It should be noted the differences in the definition of the phase duration and their measurements, which is emphasized by various scientists [5-7].

Despite a significant number of publications on the drop breakup study, this domain has not been completely investigated. Mainly, results are given on the dynamics of single drops and their atomization under shock waves or short-term drop-gas interaction. As for the drop breakup under conditions of a gradual increase in aerodynamic forces (quasi-static case), there are very few publications. As shown in [5-7] works, the rate of aerodynamic loading of drops can be different. Before onset of breakup, in the deformation phase, the times t_{int} and the times t_i are important, which can be determined experimentally. This work presents the results of studies of the temporal characteristics of the deformation and breakup of water drops in accelerating air flows in vertical converging channels in order to determine t_i. The conditions include both fast and quasi-static aerodynamic loading in the range $\mathrm{We} < 20$. The case of freely falling drops into a falling accelerating flow is considered. This experimental model is considered as the case of a rapidly changing flow, when the aerodynamic force can have the opposite direction at moderate gradients of the air flow velocity.

EXPERIMENTS AND RESULTS

Partially already reported on the results of studies for a similar setup of experiments for some modes of deformation and subsequent fragmentation of low-viscosity liquid drops that differ from those discussed in this work [8]. In the experiments discussed in this work, a single water drop with a diameter of $d_0 = 2.8 \pm 0.1$ mm with an initial velocity $V_0 = 1.8 \div 4.6$ m/s falls into a vertically positioned confuse channel of rectangular cross section with open access to the atmosphere in the upper part. Before entering the channel, the aerodynamic force is directed from bottom to top. In the channel, the aerodynamic force generated by the falling air flow has the opposite direction. The drop is accelerated depending on the flow velocity. The flow is formed as a result of air suction by a vacuum machine in one of two regimes through the outlet in the narrow lower part of the channel. The velocity field of the flow in the channel was calculated by the PIV method. When processing PIV data, the attention paid to the flow parameters on the channel axis along which the initial droplets and fragments move. In the middle and lower (converging) part of the channel, the increase in air velocity is $15 \div 22$ m/s (regime 1) and $20 \div 32$ m/s (regime 2). Thus, the experimental equipment made it possible to change the time of interaction of the liquid drop with the flow in the range of relative velocities $\Delta V = U - V = 9 \div 16$ m/s, where U is the air flow velocity, V is the drop velocity. The deformation modes and subsequent breakup observed both for unchanging or decreasing We numbers, and for cases of increasing We numbers. Thus, it is possible to realize various conditions for aerodynamic loading. It should be noted that the most systematic approach to determining temporal characteristics is described in the works of B. E. Gelfand with coauthors [5], as well as in articles by A. A. Schreiber, A. M. Podvysotsky, V. V. Dubrovsky [6, 7]. In [5] a comparison of the time scales of deformation and drop disintegration with the interaction time of the liquid drop and ambient gas is given. These scales are the deformation time and the period of natural oscillations. Depending on the ratio of these time scales, the types of aerodynamic loading are distinguished. In [6, 7] induction times t_i are counted from the moment the critical conditions ($\mathrm{We}_{\mathrm{cr}}$) are reached. In this work the interaction time t_{int} and the induction time t_i are defined similarly to [7]. The value of the critical number $\mathrm{We}_{\mathrm{cr}}$ was also estimated in accordance with the methodology in [7]. It is important to note that these authors separately take into account the interaction time and the induction time in comparison with many others authors.

It was found that in gradient flows it is rather difficult to establish the initial moment of the interaction of the drop with the flow. Apparently, this is also related to the way of the introduction of drops into the falling flow. Analysis of the data on secondary breakup of drops allows us to conclude that the beginning of the time counting corresponds to the beginning of the drop deformation. The deformation time characterizes the fundamental process – the development of the Rayleigh-Taylor instability [9, 10].

The visualization of the deformation processes and breakup of drops was carried out using a Phantom 310 digital camera. The high frame rate during registration (6500 fps) allows one to estimate with high accuracy the times of different stages of the process.

The relative Mach number is low (M~0.1).

Physical and chemical properties of water and air under normal conditions are taken from [11].

As noted above, the time characteristics depend on a number of dimensional and dimensionless parameters, which are difficult to take into account. Time characteristics depend on the initial conditions. It was found that with an increase in the droplet velocity V_0, deformation and secondary breakup processes occur faster. In this work the periods of natural oscillations t_k were measured experimentally and are shown in Fig.1 (filled symbols) together with data from other works (opened symbols [7, 12]). It is important to note that at different velocities V_0, even for the same d_0, t_k will differ. As can be seen from Fig. 1, t_k decreases with an increase in V_0 and with a decrease in d_0. It should also be noted that empirical expressions for t_k estimates are effective for a small number of oscillation periods, which corresponds to low V_0. This should be taken into account.

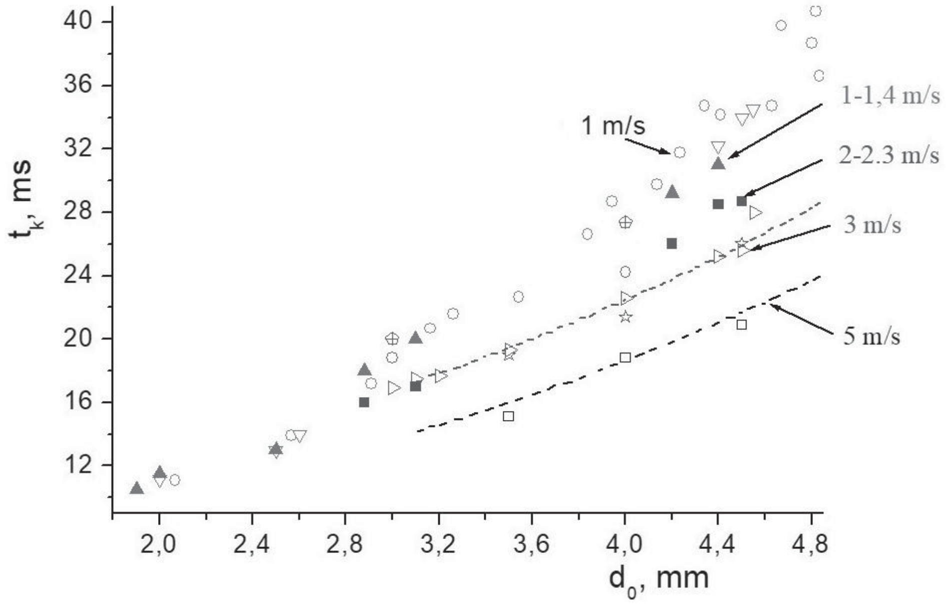
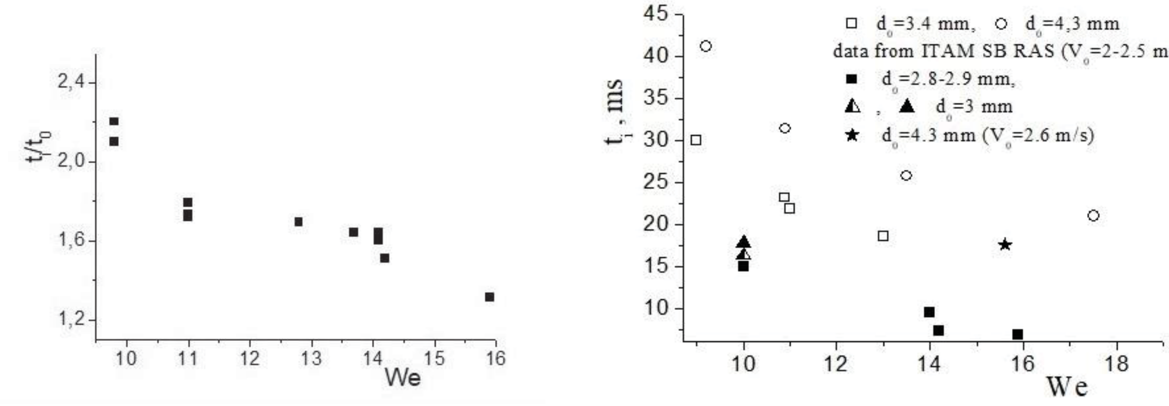


FIGURE 1. The period of natural oscillations of water drops (t_k) depending on the diameters of the initial droplets (d_0) and the initial velocities (V_0). Calculated and experimental data on t_k are given from [7, 12] (the opened symbols). Data obtained in this work presented by filled symbols

The experimental results showed that the destruction of droplets under quasi-static loading (in the narrowing part of the channel) is practically not achieved. That is, the breakup of drops occurs rather under impulse-quasi-static type of loading [5]. For water drops, the interaction times before critical conditions are reached is $t_{int} \approx 6.3 \div 7.1$ ms, and the induction times are $t_i \approx 7 \div 8.1$ ms, with the times for the appearance of the first fragments (i.e. the time of the onset of the bag bursting) $t = t_{int} + t_i \approx 13.2 \div 15$ ms. t_{int} may be bigger, but the count is from the moment of the development of irreversible deformation. The measured numbers We ≈ 8.8. Since the relative velocities are increasing, the We numbers are also increasing. In our experiments, a significant number of drop breakup processes are observed at We ≈ 12.8÷14. In this case $t = t_{int} + t_i \approx 13$ ms and even less. For dimensionless times $t_i/t_0 = 0.7 \div 1$, and $t/t_0 = 1.47 \div 1.58$, where $t_0 = 6.74 \div 8.1$ ms. In all cases $V_0 = 4.1 \div 4.5$ m/s. Apparently, when the drop moves in the narrowing part of the channel, the critical conditions corresponding to the initial stage and the stage at which the "bag" begins to breakup change. These are the features of flows with gradient sections of parameters. It was found that often the hybrid regimes of drop breakup appear under this type of loading.

In the upper part of the channel, the fast aerodynamic loading of drops is realized. Figure 2a shows the dependence of the dimensionless induction time on the Weber number for drops with $V_0 = 1.9 \div 2.5$ m/s and $t_0 = 5.2 \div 5.5$ ms. These conditions correspond to rather rapid increase of relative velocity, followed by a gradual decrease to the fragmentation time. The critical value $\mathrm{We}_{\mathrm{cr}} \approx 9$. For supercritical conditions $\mathrm{We}_{\mathrm{cr}}$ will be slightly higher. With an increase in We numbers to supercritical values, the dimensionless times t_{int}/t_0 decrease from 1.36 until 0.6. However, times t_i/t_0 are going down slightly in the We number range 12÷14.5. In addition, the ratio $t_i/t_k \approx 1$ is practically obtained in the Weber number range We<16. The obtained values of the t_i complement the data

[7] for larger drops (Fig. 2b). It seems that the obtained values of the t_i are somewhat lower than are given in [7]. Probably, this is due to the higher V_0 in our experiments than in [6, 7].



(a) (b)

FIGURE 2. The fast aerodynamic loading. (a) Dependences of the dimensionless induction time t_i/t_0 on the We number. (b) Summary graphs of the dependences of the induction time t_i on the intensity of aerodynamic forces. Filled symbols - data obtained in this work (ITAM SB RAS); opened symbols - data from [7]

CONCLUSIONS

In this paper, the new results on the measurements of the drop breakup induction time t_i in the gradient flows are presented. The obtained values of the t_i are lower than the values for the stationary breakup processes. It was found that the hybrid regimes of drop breakup appear at a moderate air velocity gradient. Further research on the hybrid breakup processes are needed to determine all temporal properties. Despite the fundamental nature of the problem and its applications, the full understanding is missing today.

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REFERENCES

1. B. E. Gelfand, J. Prog. Energy Combust. Sci. **22**, 201-265 (1996).
2. R. I. Nigmatulin, *Dynamics of Multiphase Media* (Nauka, Moscow, 1987).
3. D. R. Guildenbecher, C. Lopez-Rivera, and P. E. Sojka, Exp. Fluids **46**, 371-402 (2009).
4. W. - H. Chou and G. M. Faeth, Int. J. Multiphase Flow **24**, 889-912 (1998).
5. B. E. Gelfand, B. Vieilli, I. Gekalp, and C. Chauveau, J. Appl. Mech. Tech. Phys. **42**, 72-76 (2001).
6. V. V. Dubrovsky, A. M. Podvysotsky, and A. A. Shraiber, J. Appl. Mech. Tech. Phys. **5,** 87-93 (1991).
7. A. A. Shraiber, A. M. Podvysotsky, and V. V. Dubrovsky, Atomization and Sprays **6**, 667-692 (1996).
8. S. V. Poplavski, V. M. Boiko, O. A. Gobyzov, M. N. Ryabov, and A. V. Bilsky, “Experimental study of the breakup of microdrops and drop of natural size in gradient flows,” in *Proceedings of the XIX International Conference on the Methods of Aerophysical Research*, AIP Conference Proceedings 2027, edited by V. Fomin (American Institute of Physics, Melville, NY, 2018), pp. 020003.
9. T. G. Theofanous, G. J. Li, T. N. Dinh, and C. - H. Chang, J. Fluid Mech. **593**, 131-170 (2007).
10. T. G. Theofanous, Annu. Rev. Fluid Mech., **43**, 661-690 (2011).
11. H. Kuchling, *Physics. Reference book*, edited by E. M. Leikin (Mir, Moscow, 1983).
12. R. S. Volkov, A. O. Zhdanova, O. V. Vysokomornaya, G. V. Kuznetsov, and P. A. Strizhak, J. Engineering Phys. Thermophys., **87(6)**, 1351-1361 (2014).