Deformation and acceleration-induced fragmentation of the liquid drops in the gradient air flow

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Abstract. The regimes of aerodynamic destruction of a falling drop of a low-viscosity liquid in a falling accelerating air flow were experimentally studied. This model formulation allows us to study the behaviour of a drop when the direction of the aerodynamic force is reversed. The experiments showed a large deformation and rather high instantaneous drop acceleration at a moderate velocity gradient. The results confirmed that a change in the sign of aerodynamic force increases the effect of Rayleigh-Taylor instability.

1. Introduction
The study of liquid drops breakup was and remains actual problem in gas dynamics. Aerodynamic atomization is used in various technologies where it is necessary to maintain high performance nozzle requirements and the fragment size dispersion of sprays. It should be noted that the variety of the gas flow velocity regimes and geometries of used channels and nozzles allows detecting transition and hybrid modes of drop breakups that are still understudied today. Also, the liquid drop breakup in the gradient flows is not sufficiently studied.

Comparing to shock wave drop breakup, where gas flow parameters are constant, there is much fewer information about drop breakup in gradient flows [1-5]. The difficulty is that the gas flow parameters can vary at characteristic lengths of velocity relaxation, deformation and breakup of a drop. Understanding of the breakup physics is important for the numerical simulations of the aerodynamic atomization of liquid drops in the low Weber number range and for different aims of the spray formation and optimization, where the time-resolved breakup features and fragment size distributions are required.

The present work aims to study the deformation and breakup of water drops falling in an accelerating falling air flow as a limiting case of the flow fast change when the direction of the aerodynamic force can be even reversed at the moderate gas velocity gradient. This problem is being solved for the first time. In addition to academic value, the results are of interest in creating industrial air strainers, large-scale systems of the dispersion and cooling of liquids, etc.

2. Experimental part
A freely falling drop enters in the vertically positioned channel with rectangular cross-section open to the atmosphere [3]. Before falling into the channel, an aerodynamic force acts from the bottom to the top; in the channel, the aerodynamic force from the falling flow is directed from above. The drop is accelerated in the air flow created by suction by a vacuum machine through the lower outlet of the channel (figure 1). Depending on critical conditions defined by the Weber criterion, it is unstable and
the secondary breakup may occur in an upper or a middle part of the channel. It should be noted that some periodic drop deformations are usually observed before the channel entrance. This kind of the deformation is characteristic for the freely falling drops. The deformation periods $t_k$ (figure 1, (a)) for water drops with different initial spherical diameters $d_0$ estimated from image sequences after post-processing procedures are in good agreement with experimental and predicted data [6]. The most important parameter is relative velocity $\Delta V$ between drop $V_l$ and air flow $V_{flow}$ in main flow direction: $\Delta V = V_{flow} - V_l$. $V_{flow}$ in the channel is regulated by convergence angle of channel walls and by the air pumping rate (3 regimes). The velocity profiles obtained from PIV measurements. One of the $V_{flow}$ profiles is shown in figure 1, (b). In the experiments always maintains the condition $V_{flow} > V_l$. In the gradient flows, there is an uncertainty in the start moment of interaction drop-air which do not allow to precisely measure the time characteristics of the process, unlike the shock wave disturbances. Thus, the induction time of breakup $t_i$ is defined as the time between the visual drop deformation (the beginning) and an appearance of the first fragments during the initial drop destruction (i.e. the bag bursting). Experimentally observed times $t_i$ are typically made non-dimensional using the characteristic interaction time: $t_0 = d_0(\rho_l/\rho_g)^{1/2}(\Delta V)^{-1}$. Here $\Delta V$ is the initial relative velocity, $\rho_l/\rho_g$ is the liquid-to-ambient gas density ratio. For the experimental curves the non-dimensional time $t_i/t_0$ is usually calculated. For example, the water drops with $d_0 = 2.7-2.9$ mm and velocities in the entrance to the channel $2.5-2.8$ m/s have $t_i \approx 14-16$ ms. The ratio $t_i/t_0$ is practically obtained and $t_i > t_0$, where $t_0$ is about 5.5-6 ms. All these times are typical for the secondary breakup regimes in the low values Weber number range ($We < 20$).

![Figure 1](image_url)

**Figure 1.** (a) The deformation period ($t_k \approx 28.5$ ms) of the freely falling drop with $d_0 = 4.4$ mm and $V_l \approx 2.3$ m/s; (b) Schematized configuration of breakup regime study, video registration and post-processing of the images.

The test conditions are summarized in table 1. The liquid and air properties were obtained from [7].

| Table 1. Test conditions. |
|---------------------------|
| parameter                | range          |
| liquid                    | water          |
| initial droplet diameter, $d_0$ (mm) | 2.7 - 4.5 |
| air velocity, $V_{flow}$ (m/s) | 12 - 32 |
| water-air density ratio, $\rho_l/\rho_g$ | 840 |
| Reynolds number ($Re$) | 960 - 2670 |
| Weber number ($We$)      | 6 - 14         |
| Ohnesorge number ($Oh$) | 0.0012-0.0024  |
Reynolds number range is higher to one for the regimes when the gas (air) viscosity effects on the liquid drop drag. For this range, the drag coefficient of a solid sphere is about 0.4-0.5. The Mach number is low ($M \approx 0.1$).

3. Results and discussion

It is obtained that the periodic drop deformation over the channel entrance does not considerably affect the breakup mechanism. The images of the main stages of the typical secondary breakup in one process are presented on figure 2, (a).

![Image of drop breakup](image)

**Figure 2.** Drop breakup in falling accelerating air flows; the high-speed registration (Phantom, 6500 fps); (a) the secondary bag breakup: 1-3 deformation (0; 9.23; 14.46 ms), 4-7 breakup (17.69; 18.15; 19.69, 24.3 ms), $d_0 = 2.9$ mm, $t_0 \approx 5.6$ ms, $We \approx 4-10$; the third breakup on the transition bag-and-stamen mode of the fragment with $d_0 \approx 1.9$ mm, $t_0 \approx 4.6$ ms, $We \approx 3-14$; 1-5 deformation (4.64; 5.87; 6.1; 6.48; 6.63 ms), 6-8 fragmentation (7.1; 7.71; 8.02 ms) (b).

Note after image filtration procedure there are no small fragments (less than 0.4 mm). The distinguishing characteristic of experiments is that there is the third breakup in the lower part of the channel (Figure 2, (b)). The third breakup (bag or transition bag-and-stamen breakup) is possible because there is the continuous air flow, and $We$ numbers may exceed critical condition. After the secondary big drop breakup namely the big fragments (node-droplets and some ring-droplets) are involved in the third breakup.

It is known [8,9], that the drop deformation significantly affect the drag. In addition, to estimate the instantaneous drag coefficient, it is necessary to have experimental information about time dependence of the deformation. Besides, to estimate the instantaneous drop acceleration, experimental data about the drop velocity are required.
Accordingly, the time dependencies of the drop velocity and the deformation are given as an example (figure 3 and 4). Moreover, figure 4 represents the velocity profile of the drop along the channel length. The details of calculations and estimations are not discussed in this paper.

As shown by figure 3, the drop of a greater diameter \( d_0 \) needs more time for the deformation and the further fragmentation. In this case, inertial forces increase. It bears mentioning that the “internal flow” effects are not considerable in the range of parameters under study.

\begin{figure}[h]
\begin{center}
\includegraphics[width=\textwidth]{figure3.png}
\caption{Deformation dynamics of drops; \( d_0 = 3.1 \) mm (\( t_0 \approx 6.4 \)ms) and \( d_0 = 4.4 \) mm (\( t_0 \approx 10.2 \)ms): 1, 2 - expanding of the cross-stream diameter \( d_{\text{cro}} \) until the bag bursting; 3, 4 - evolution of the total stream-wise diameter \( d_{\text{str}} \) until the bag bursting; 5, 6 - \( d_{\text{str}} \) of the liquid ring until its rupture beginning.}
\end{center}
\end{figure}

\begin{figure}[h]
\begin{center}
\includegraphics[width=\textwidth]{figure4.png}
\caption{Dependence of the drop velocities on the channel length and dimensionless time \( (d_0 = 2.8 \) mm, \( t_0 \approx 5.5 \) ms): velocity measurements at the forward edge (1) and back edge (3), until the liquid ring rupture beginning; at the drop bag end (2) until its bursting.}
\end{center}
\end{figure}

As it is mentioned above, the breakup process starts when the drop enters in the channel and is subjected to an ambient flow field. Deformation is caused by an unequal pressure distribution over the surface of the drop. There are liquid drop expanding in cross-flow direction \( d_{\text{cro}} \) and compressing in the stream-wise direction \( d_{\text{str}} \). So, when the stage of flattened drop is obtained, which is characterized by the disk-like drop deformation, a flow separation and a wake formation begin. The difference between forward and rear pressure areas is a consequence of the flow separation. This leads to the formation of the drop bag and its growth. From the beginning up to this stage the drop velocity increases and the drop acceleration increases too. At the flattened drop stage (\( d_{\text{cro}} \) is maximal) the instantaneous drop acceleration is the biggest. Later, when the hollow bag is formed, the drop velocity change is slow and the acceleration falls down. After the bag bursting the toroidal liquid ring moves with a slow increasing of the velocity until its rupture. At this stage the pressure difference vanishes. The droplet acceleration is not very high. The results of the different point velocity measurements are shown at figure 4. There is difference between the velocities, which is associated with the bag mode. Instantaneous parameters estimations at different stages are given in table 2.
Table 2. Estimations of the instantaneous parameters for the water drop with \(d_0=2.9\) mm.

| Dimensionless time, \(t/t_0\) | Channel length, \(h\), mm | \(V_{flow}\), m/s | \(We\) | Drop acceleration, \(a\), m/s\(^2\) | Bond number, \(Bo\) |
|-----------------------------|------------------------|-----------------|--------|-------------------|------------------|
| 0.81                        | 11.6                   | 16              | 9.1    | 99-130            | 12-15            |
| 1.56                        | 25.8                   | 16.9            | 8.8    | 277-522           | 33-62            |
| 2.7                         | 56.3                   | 17.6            | 7.7    | 190-230           | 23-28            |
| 3.16                        | 73.5                   | 17.1            | 6.3    | 150-185           | 18-22            |

It is noteworthy that, in our experiments, “bag” breakup of droplets occurs at Weber numbers \(We<9\), while in stationary flows this mode occurs at Weber numbers 14-50. Some unsteady effects of the ambient air flow should be noted at the fragmentation stages. For the third breakup process, these effects appear too but the quantitative data are not presented. So, more experiments are needed.

For the “bag” mode, the drop acceleration at the flattened drop stage can be estimated by the length of Rayleigh-Taylor instability wave. For the water drop with a diameter \(d_0=2.9\) mm (for example, figure 2, (a), stage 2) and the maximal cross-stream diameter \(d_{cro} \approx 5 - 6.4\) mm, \(\lambda = d_{cro}\) in the case with two nodes. Thus, the drop acceleration \(a \approx 274 - 440\) m/s\(^2\).

4. Conclusions
In this paper, the deformation and breakup regimes of a falling drop in a falling accelerating air flow have been investigated for the first time. Such experiments models the behavior of a droplet when sudden changing the direction of aerodynamic force. The presented results show that a change in the sign of the aerodynamic force enhances the effect of Rayleigh-Taylor instability and leads to a significant decrease in the critical Weber number for this breakup mode.

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