Conditions for deformation and crash of liquid-drop aerosols

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Received January 18, 2006

Results of the experimental study of drop deformation and crash in the process of liquid-drop aerosol deposition by gravity are given for two regimes of flowing around: at moderate ($\mathrm{Re} \approx 10$–100) and small ($\mathrm{Re} \sim 1$) Reynolds numbers and Bond numbers close to the critical value: $\widetilde{\mathrm{Bo}}_{\mathrm{cr}} = 22.5$.

Aerodynamic breakdown of drops is one of the most essential processes determining the liquid-drop aerosol size distribution. Aerodynamic forces impacting a drop while flowing around can exceed surface tension forces, which results in the drop collapse followed by formation of smaller secondary drops. This process plays an important role in formation of the size spectrum of atmospheric precipitations,[1] gas dynamics of two-phase flows,[2] and in an assessment of environmental impacts caused by emission of fluid-propellant toxic components at launch vehicle damages.[3–5]

Processes of drop deformation and crash in a flow have been studied for many years by different researchers. Reviews on the problem are given in Refs. 6 and 7. In the majority of works, the Weber number

$$\mathrm{We} = (\rho|\mathbf{u}_{\mathrm{r}}|^2 D)/\sigma$$

is considered as the principal parameter determining the drop deformation and crash in a flow. Here $\mathbf{u}_{\mathrm{r}} = \mathbf{u}_{\mathrm{p}} - \mathbf{u}$ is the relative velocity of a D-diameter drop; $\mathbf{u}_{\mathrm{p}}$ is the drop velocity vector; $\mathbf{u}$ is the gas velocity vector; σ is the surface tension coefficient; ρ is the density of a medium (gas or liquid), in which the drop moves. The value of the Weber number $\mathrm{We}_{\mathrm{cr}}$, at which drop breaks, is referred to as critical; $\mathrm{We}_{\mathrm{cr}}$ varies widely ($\mathrm{We} = 12$–60) depending on the drop movement regime.[7]

Under certain conditions a drop can crash in accelerating flow due to the Rayleigh–Taylor instability, which occurs when the critical Bond number is reached[2,6-8]

$$\mathrm{Bo} = (\rho_{\mathrm{p}}\omega D^2)/\sigma,$$

where ω is the drop acceleration and ρ_{p} is the drop matter density.

The Bond and Weber criteria are connected by relation[2]

$$\mathrm{Bo} = \frac{3}{8}\frac{C_{\mathrm{D}}}{|1-\bar{\rho}|}\left(\frac{D_{\mathrm{M}}}{D_0}\right)^2 \mathrm{We},$$

where C_{D} is the resistance coefficient; $(D_{\mathrm{M}}/D_0)^2$ is the ratio of the oblate spheroid midsection to the equivalent sphere section; $\bar{\rho} = \rho/\rho_{\mathrm{p}}$.

In this work, the results of experimental study of deformation of a single initially spherical drop moving into another liquid under gravity are presented for two regimes of the flowing around: at moderate ($\mathrm{Re} \approx 10$–100) and small ($\mathrm{Re} \sim 1$) Reynolds numbers, small Weber numbers ($\mathrm{We} < \mathrm{We}_{\mathrm{cr}}$), and Bond numbers close to the critical value[2]: $\widetilde{\mathrm{Bo}}_{\mathrm{cr}} = \mathrm{Bo}_{\mathrm{cr}}(1-\bar{\rho}) = 22.5$.

The above regimes have been chosen because of the following causes. When studying the spheroid flowing around, the flow at $\mathrm{Re} \le 1$ or $\mathrm{Re} \gg 1$ is commonly considered:

$$\mathrm{Re} = \rho|\bar{u}_{\mathrm{r}}|D/\mu,$$

where μ is the dynamic viscosity coefficient of the flow.

The range of moderate Reynolds numbers, conventionally specified within $1 \le \mathrm{Re} \le 100$, is still insufficiently studied, though it is characteristic of the liquid-drop aerosol gravity deposition in atmosphere and, therefore, needs to be investigated in detail.

As it follows from the Hadamard solution for a drop falling down into a viscous liquid under gravity at small Reynolds numbers, the difference between normal stresses is stable all over the drop's spherical surface and does not tend to deform the drop.[8] In view of the above mentioned, Betchelor (Ref. 9) noted that if viscosities and densities of two liquids are such that small Reynolds numbers allow neglecting the inertial forces, then there are no restrictions on the liquid sphere size.

The performed linear analysis[2] for the problem of finding a critical set of parameters accounting for influence of the inner flow on a drop shape has shown that for arbitrary perturbations the existence of a solution for the nonuniform problem becomes questionable at $\widetilde{\mathrm{Bo}}_{\mathrm{cr}} = 22.5$. To study the behavior of a drop within the close-to-critical range of Bond numbers, we have investigated the second of the above flow regimes.

0235-6880/06/06 473-04 $02.00

Drop motion at moderate Reynolds numbers

In experiments with moderate Reynolds numbers, motion of an olive oil drop in the distilled water–ethanol solution was investigated. Varying ethanol concentration in the solution, it is easy to make $\bar{\rho} = \rho/\rho_p$ as close to unity as desired. Rates of drop fall or ascent can be varied in the process within certain limits beginning from zero.

Figure 1 shows the block-diagram of the experimental setup used for study of the drop motion and deformation.

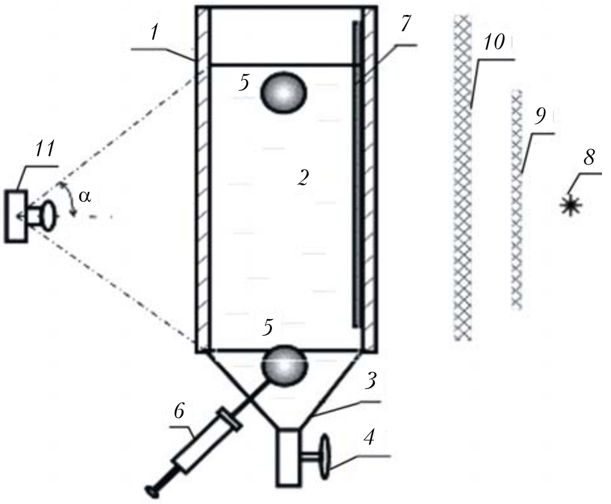

Fig. 1. Experimental setup for drop deformation study.

The setup consists of a cell with plane-parallel walls, device for drops producing, and flow visualization system. Cell *1* of 58×58×800 mm in size and 2.7 l in volume is made of 5-mm Plexiglas. It is set in upright position and filled with the solution of ethanol in distilled water *2*. Bleeding of the solution is carried out through funnel *3* glued in the bottom of the cell and valve *4*. Drops *5* are produced by pressing the oil through syringe *6* into either cell bottom (through the vacuum rubber pad) or top. To measure the drop speed and sizes, scale rule *7* with 1 mm division value is glued inside the cell. The visualization system includes backlight *8* of 1 kW power, two dull diffusers *9* and *10*, and movie camera "Convas-auto" *11* (picture size of 18×24 mm). The camera is mounted on a holder with a head allowing camera rotation angle of ±2α and hence shooting different phases of the drop motion.

While shooting the drop motion, the scale rule always was in the camera's field of viewing. The contrast of an olive oil drop in the solution is sufficient to obtain processable pictures (Fig. 2).

All experiments were performed at a temperature of 20°C. The drop diameters varied in a range 10–30 mm. Olive oil was preheated up to ~ 110°C before each experiment to evaporate the absorbed moisture. The drop motion in two directions: upward (ascent) and downward (fall) under gravity was studied.

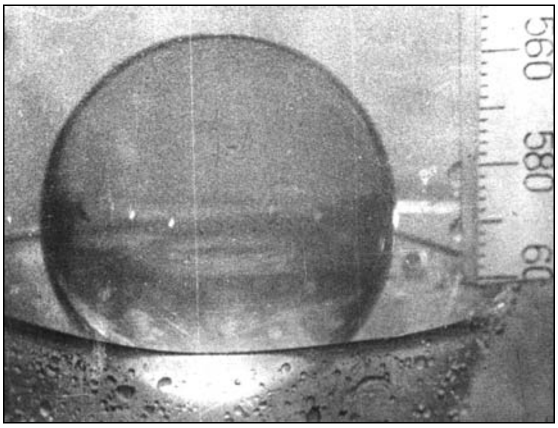

Fig. 2. The drop of olive oil in water–alcohol solution.

The experiment procedure was the following. Water–alcohol solution of the density close to the density of olive oil ($\rho_p > \rho$ for drop fall and $\rho_p < \rho$ for drop ascent) was prepared and filled into the cell. A preset volume of the oil was syringed into the cell top (fall) or bottom (ascent). A spherical sessile drop was formed at the end of the needle and then the needle was quickly taken away. To provide the drop motion, another portion of the water–alcohol solution of somewhat higher (for drop ascent) or lower (for drop fall) density as compared to the initial one was added into the cell in the point opposite to the initial drop position. The drop motion was shot in different sections of the cell. The camera was switched on 5–6 times during the period of drop fall (ascent), which took about 5 min in this series of experiments, at a shooting rate of 18 shots per second.

Analysis of pictures has shown that while moving, the drop takes a form of an oblate spheroid, the shorter axis of which is oriented along the drop motion direction (Fig. 3).

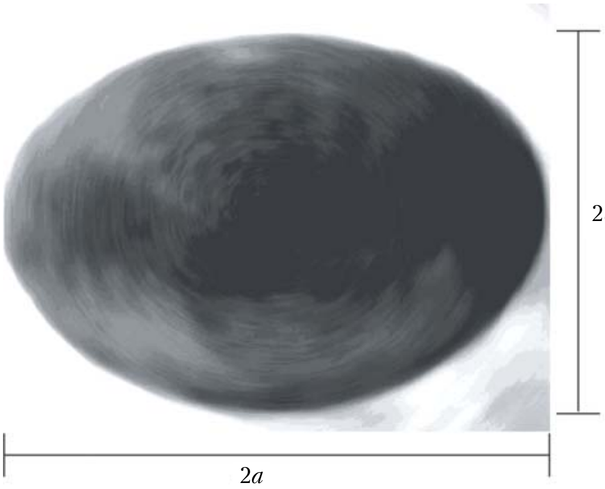

Fig. 3. The drop of olive oil moving in water–alcohol solution.

When pictures processing, sizes of longer (2*a*) and shorter (2*b*) axes of the spheroid, axial coordinates of its center of mass, and the drop speed were measured.

The diameter of the equivalent spherical drop (which has the same volume as the deformed drop) was calculated by the equation

$$D_0 = 2\sqrt[3]{a^2 b}.$$

Similarity parameters, i.e., Reynolds, Weber, and Bond numbers, were calculated based on the measured $|\mathbf{u}|$ and D_0.

Figure 4 presents experimental data on the degree of drop deformation as a function of the Weber number $\varepsilon = f(\text{We})$ in the range Re ≈ 10–100.

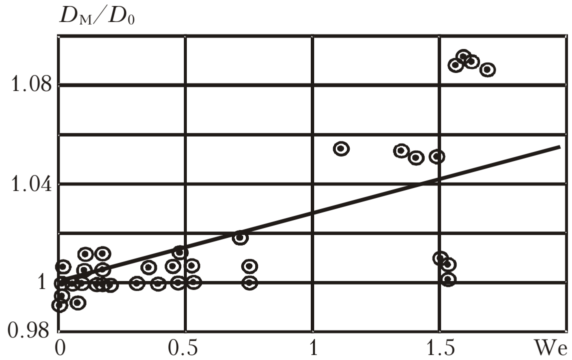

Fig. 4. The degree of drop deformation as a function of the We number.

The dependence

$$\varepsilon = D_M/D_0 = 1 + 0.027\text{We}$$

was obtained via approximation of results of the problem numerical solution.[10]

Drop motion at small Reynolds numbers

The drop motion at small Reynolds numbers was experimentally studied using the above described setup with another pair of model liquids (fall of a mercury drop in glycerin). The producing of large mercury drops turned out to be a serious problem in the experiment. Due to a high density and low viscosity of mercury, a standard capillary does not allow producing drops larger than 1–2 mm in diameter. A special device was used to produce mercury drops of 5–10 mm in diameter[11] (Fig. 5).

The device consists of a glass tube (capillary) *1* with receiving funnel *2* for mercury supply. Spiral section *3* of the capillary with high hydrodynamic resistance has been formed by means of twisting the glass tube heated to the viscoplastic state. Output cone *4* is soldered to the capillary end; the cone diameter is fitted experimentally within a range 5–10 mm. A mesh *5* of 1-mm grids, made of POC-40-solder tined cuprum, covers the cone. A hose *6* connects funnel *2* with rubber bulb *7*.

After filling up the funnel with a preset mercury portion, drop *8* is formed on the large-surface mesh; the drop shape is close to spherical. When pressurizing the capillary (using the rubber bulb) the drop grows in size, separates from the mesh and falls into the cell filled with glycerin, the temperature of which is recorded. Drop motion and deformation are shot.

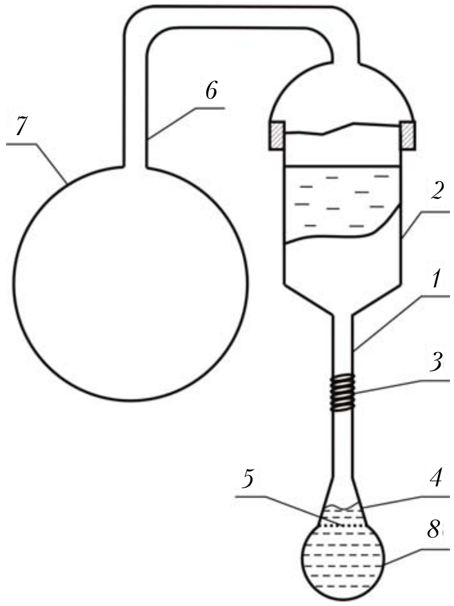

Fig. 5. The device for producing large mercury drops.

As was ascertained in the experiment, the drop is stable and keeps the spherical form while falling if the drop diameter is less than 8 mm; corresponding $\tilde{\text{Bo}}_{\text{cr}}$ equals to 6.4. If the drop diameter is about 10 mm, the drop is unstable and breaks down to fragments when moving; corresponding $\tilde{\text{Bo}}_{\text{cr}}$ is equal to 10.

It should be noted, that the shape of drops greater than 8 mm in diameter differs from spherical, which is connected with a difficulty to produce large spherical drops of a heavy low-viscosity liquid. Therefore, the experimentally defined critical $\tilde{\text{Bo}} \sim 10$ should be considered as an assessment of the bottom stability threshold over the $\tilde{\text{Bo}}$ number. To study the drop motion at $\tilde{\text{Bo}} \sim 22.5$, it is necessary to produce an initial spherical drop of about 15 mm in diameter. No modifications of the capillary-based device for drop producing gave positive results. However, results of the conducted experiments confirm the existence of the Bond number range 6.4–10, where the drop moving at small Reynolds numbers collapses and breaks down to fragments. A theoretically predicted $\tilde{\text{Bo}}_{\text{cr}} \sim 22.5$ qualitatively verifies the existence of the range.

Conclusions

The experimental setup to study deformation of drops moving in a viscous flow at moderate and small Reynolds numbers have been designed. The experimental dependence of the degree of deformation on the Weber number has been obtained in a range Re ≈ 10–100.

The device for producing large drops of a heavy low-viscosity liquid has been designed. Drop instability in the range of Bond numbers larger than 10 at small Re and We numbers has been verified experimentally.

Acknowledgments

This work was financially supported by the Russian Foundation for Basic Research (projects Nos. 05–03–32729 and 05–08–18237).

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