Droplet breakup in shock waves at moderate values of the Weber number

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Abstract. The object of this study was the physical mechanisms of aerodynamic fragmentation of droplets of low-viscosity liquids in shock waves in the region of existence of the shear breakup modes. New experimental data were obtained on the time induction of the droplets breakup depending on the gas flow velocity in the poorly studied range of Weber numbers We = 100 ÷ 2200.

1. Introduction
The aerodynamic breakup of droplets in a flow behind a shock wave in the range of Weber numbers We = 100 – 2200 is of interest for three sections of physical gas dynamics. Firstly, protection against drip erosion of supersonic vehicles and their engines during flight in the precipitation zone [1,2]. Secondly, high-speed gas-liquid flows as applied to nozzles and burners with a high consumption of liquid fuel. Thirdly, fire and explosion safety in the oil industry [3]. In order to establish the role of droplet breakup processes in specific circumstances and conditions, it is first necessary to have reliable data on a number of determining time parameters, such as the time of gas flow exposure, the scenario and the time of deformation of the droplets, the characteristic times of the onset and end of the process. Note that in the range of Weber numbers of interest to us, there are practically no experimental data on the time of the preparatory stage of spraying (the time of breakup induction $t_i$).

In widely cited works [1, 2], the main role in droplet destruction in shock waves (SW) is attributed to the formation of a boundary layer in a liquid under the action of friction forces and its subsequent separation. The main conclusion of [2] states that the induction time is directly proportional to the diameter of the droplet and inversely proportional to the velocity of the gas flow. To confirm the correctness of this statement, experiments are given in [2] for the water drops with $d = 2.7$ mm at the Mach numbers of the shock wave $M_s = 1.3, 1.5, and 1.7$. These modes, according to our estimates, correspond to the Weber numbers $We = 1500, 4600, 9500$ and are outside the considered range of $100 \leq We \leq 1000$.

We managed to find only one work [3], in which a series of experiments in a shock tube was carried out to determine the induction time for liquid streams breakup over a wide range of We, including the regime $We = 10^2 – 10^3$ of interest to us. Experiments on direct measurement of the induction time for spherical water droplets was not performed, but for water streams it was shown that the dimensionless induction time $t_i/t_0 = k = \text{const}$ and $k \sim 0.5$ only for $We \geq 1000$. In the range $100 \leq$
We $\leq 1000$, the value of $k$ is not constant and decreases from 2 to 0.5. There is no explanation of the observed phenomenon in the cited papers. Therefore, a large range of issues for the further accumulation and analysis of experimental data on droplet breakup in high-velocity flows remain relevant.

2. Experiments and discussion of the results

This paper presents the results of an experimental study of the processes of deformation and aerodynamic breakup of droplets of low-viscosity (Newtonian) liquids in shock waves in order to determine the type and characteristic time of the droplet fracture induction in the poorly studied range of Weber numbers $We = 100 \div 2200$. This range of Weber numbers $We$ has a maximum rate deformation of the drop, which significantly affects the dynamics of the drop at an early stage of interaction with the shock wave [4].

The working gas is air at atmospheric pressure. Before each experiment, the initial temperature and atmospheric pressure in the channel of the shock tube were measured. The flow parameters were calculated according to the theory of ideal shock waves from the measured velocity of the shock wave front $Vs$. Velocity $Vs$ was measured in two ways: 1 - from the shift of the shock front on two adjacent frames of shadow images; 2 - from the travel time of the shock front of a known distance (270 mm) between two pressure sensors. The relative measurement error is $\delta Vs/Vs \sim 1\%$. Using the measured velocity and initial parameters of the air, the Mach number of the shock wave $Ms$ was determined and the velocity $U$ and the density of the gas $\rho_g$ were calculated.

The dynamics of the processes of interaction between the droplet and shock wave were recorded by the method of shadow visualization with high-speed filming (figure 1).

![Figure 1](image)

**Figure 1.** Three consecutive frames of high-speed filming illustrating the beginning of the process of interaction of a shock wave with a drop of water; intervals between frames $\Delta t = 30$ $\mu$s, exposure time $\tau \leq 50$ ns, the image size in grayscale is 9.56 Mpix.

The basic element of the diagnostic complex was the stroboscopic ruby laser light source with periodic Q-switching by the Kerr cell developed at the Institute of Theoretical and Applied Mechanics
of the Siberian Branch of the Russian Academy of Sciences. The images were recorded by a high-speed camera in standby mode with rotating mirror polyhedron onto a high-resolution film 35 mm wide. The film sector for each experiment has dimensions of the 24x260 mm² and contains up to 20 frames. For reasons of space-time resolution optimization, the number of frames and the intervals between frames were selected taking into account the calculated duration of constant parameters behind the shock wave front ~ 600 µs in these experiments. In the present work, the following parameters of the laser strobe were set: exposure time \( \tau \leq 50 \) ns, interval between the frames \( \Delta t = 30 \pm 0.1 \) µs.

In all the original photographs (figure 1), there are two rows of points of the coordinate grid on the glass (scale 10 mm), successive positions of the shock front, position, size and shape of the droplet are clearly visible [4-6]. To obtain quantitative data, the informative area of each frame was selected and digitized (figure 2), and then a digital image was stylized with tracing of particle outlines and grid points (figure 3).

The morphological features of the windward surface determined the type of drop destruction. The moment of manifestation of crushing products in the droplet trail was taken as the onset of breakup. The fracture induction time \( t_i \) was determined from the moment the shock wave front intersects the windward boundary of the droplet until crushing products appear as, for example, in figure 2 frame 4. The absolute accuracy of these data is limited by the half-interval between adjacent frames and in this experiment is \( \approx 15 \) µs.
The measured delays $t_i$ depending on the flow velocity are shown in figure 4. The data are presented in logarithmic coordinates and are approximated with a high accuracy by a straight line. The slope of line determines the powermode function of dependence of the time of the breakup beginning of the drop on the flow velocity:

$$t_i = 10^{5.4}U^{-1.5}$$

(1)

Figure 4. Dependence of the induction time of water drop breakup on the air flow velocity behind the front of a shock wave.

3. Summary
The results of an experimental study of the processes of deformation and aerodynamic fragmentation of droplets of low-viscosity (Newtonian) liquids in shock waves are presented with the aim of determining the type and characteristic time of the droplet breakup induction in the range of Weber numbers $We = 100 \div 2200$. The obtained experimental data shows that the droplets destruction induction time depends on the gas flow velocity to the degree of $-3/2$ instead of $-1$, predicted by the A. Ranger on the basis of his simplified model.

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