An early stage of the drop interaction with shock wave: airflow, deformation, destruction

S V Poplavski¹, A V Minakov² and A A Shebeleva²

¹ Cristianovich Institute of Theoretical and Applied Mechanics SB RAS, 630090, Novosibirsk, Russia
² Siberian Federal University, 660041, Krasnoyarsk, Russia

E-mail: s.poplav@itam.nsc.ru

Abstract. The work is devoted to experimental and computational modeling of the flow around water droplets behind an incident shock wave and its effect on deformation and decay. The structure of the flow near and in the wake of the drop, the evolution of the shape and breakup delay were investigated in the range of shock wave Mach numbers $M_s=1.109–1.34$ and Weber numbers $W_e=200–2200$. Comparison of calculations with experiments allowed constructing a phenomenological picture of the behavior of a drop in shock wave as a response to a rapidly changing flow field at an early stage of interaction.

1. Introduction

Aerodynamic dispersion of drops is used in various applications: energy, aviation and rocket engine, chemical industry, etc., and in this theme a special place is occupied by the problem of drop interaction with shock wave [1,2]. Since early works, these studies have evolved in two directions. First, it is the study of the ignition of hydrocarbon fuels in shock waves in relation to industrial explosion safety, advanced engines, etc. The process proceeds in two stages: 1. crushing of droplets in a shock wave; 2. ignition of the mixture and the flame front movement on the spray. The danger of an explosion increases in supersonic flows behind the shock front due to the increase in pressure and gas temperature during deceleration in suspension [3]. In the technogenic systems, the movement of droplets through the shock wave is realized also near the airframe parts of the supersonic aircraft when flying in the precipitation zone, but here the case is about water drops [1].

The breaking up proceeds in the same way for all low-viscosity liquids [2], and it can be studied on water. This second direction of studying droplets in shock wave is: the dynamics [4] and the mechanisms of droplets breakup when suddenly injected into the flow [2,5]. This is the most popular statement of experiments, since in the shock wave there is a certainty of the moment a drop hits the flow. Therefore, such experiments were repeatedly reproduced in many laboratories of the world in a wide range of modes, which increases the reliability of the data collected in a number of reviews [2,6]. There are also unsolved problems associated with the development of innovative technologies and the creation of new materials with complex rheology. Thus, the interaction of droplets with a shock wave is one of the fundamental problems of physical gas dynamics in the framework of the problem of heat and mass transfer in non-equilibrium heterogeneous systems, and computer simulation of these processes seems to be a relevant and promising direction. This paper is devoted to experimental and computer studies of the flow around a drop behind an incident shock wave, as a key factor determining the type of its deformation and the nature of destruction.
2. Physical mechanisms of droplet decay in shock waves and their numerical simulation

The movement of the liquid boundary relative to the initial surface of the drop due to the complex and changing distribution of external pressure creates the most bizarre forms on different modes of interaction. The connection of the deformation of the drop and the picture of the external flow was attempted to be established in earlier works with the simplified form of a drop as an ellipsoid of rotation [7]. This is possible for a flow around rain drops, and although the type of deformation in the flow behind the shock wave is different (Fig. 1), the model of the conjugate boundary layer in the liquid from [7] is still relevant for liquid jets, films and drops.

![Figure 1](image_url)

Figure 1. A typical series of shadow shots of water drop in incident shock wave; SW Mach number \( M_s = 1.144 \), Weber number \( \text{We} = 360 \), the interval between frames is \( 30 \times 10^{-6} \) s.

Aerodynamic fragmentation of droplets is divided into six modes according to the Weber criterion \( \text{We} = \rho u^2 d/\sigma \), two of them are implemented for the incident shock waves, and both are associated with the formation of a conjugate boundary layer in a liquid [2-6]. The first is the separation of the liquid boundary layer from a drop ("sheet stripping") \( 100 < \text{We} < 250 \). The second is the development of the Kelvin-Helmholtz instability in the liquid boundary layer with the formation of waves and their subsequent disruption ("wave crest stripping") \( \text{We} > 250 \). Numerical modeling of these processes is a challenging problem in which the only universal tool is direct numerical simulation (DNS). But, due to the huge computational cost, this can only be used for a narrow class of model tasks. It uses a technique...
that combines the VOF method for resolving the interface, the LES model for describing turbulent flows, and technology of adapted to the boundary moving grids. This approach, described in detail in [8], is less demanding of computational resources; it allows us to describe the behavior of a moving interphase boundary, but requires further development and testing.

The most reliable testing of numerical technology is the simulation of the same conditions as in the experiments, and a comparison of the results for the maximum number of parameters. The high-speed shadow visualization of the process based on a laser stroboscope was used as in the experiments of Fig. 1, as well as the gas-dynamic parameters of the flow of specific experiments with shock wave Mach numbers Ms = 1.109-1.34, Weber numbers We = 208–2260 [5]. In the calculations, the conditions of these experiments were simulated, and the first important result is a good agreement with experiments on the dynamics of the deformation of a drop behind a shock wave. (Fig. 2).

![Figure 2](image1.png)

**Figure 2.** The droplet shape at time points 110 μs (a, b) and 260 μs (c, d); calculation (a, c) and experiment (b, d), SW Mach number Ms = 1.144, We = 360, frames No. 5 and No. 10 of Fig. 1.

With an increase in the shock wave intensity from Ms = 1.109 to the maximum value in this series of experiments Ms = 1.34 (Fig. 3), a significant change occurs in the interaction mode of a drop by the Weber number (We = 208 - 2260). Although the deformation scenario does not change, there is a difference in the character of the erosion in Fig. 2c, d and Fig. 3c, d. In the first case, the daughter droplets get detached from the drop periphery, and in the second, they are observed in front of the windward surface, excluding, perhaps, the region adjacent to the critical point. This will be discussed below.

![Figure 3](image2.png)

**Figure 3.** The droplet shape at time points is 60 μs (a, b) and 90 μs (c, d); calculation (a, c) and experiment (b, d), SW Mach number Ms = 1.34, We = 2260.

The quantitative characteristics of the process have also shown good agreement with the experiments. Firstly, it is the induction period of the breaking up $t_i$, and it is indicative and available for comparison, and secondly, the time constant $t_0 = (d_0/u_2)(p_1/p_2)^{1.5}$ [2,6] as a generalized parameter of the droplet interaction mode with the flow. Here, $u_2$ and $p_2$ are the velocity and density of the gas behind the shock wave, and $p_1$ and $d_0$ are the density and size of the droplet. So in the calculations on all modes, it was possible to fix the beginning of the breakup $t_i$, (see, for example, Fig. 2c and Fig. 3c) and it is quite
consistent with the experimental data. The dimensionless time $T_i = t/t_0$ was $T_i \approx 0.36$, which also corresponds to the classical ideas about the delay in the destruction of droplets [2,5]. Thus, a comparison of numerical simulation with the experiments has shown agreement on the drop shape, strain dynamics, and decay delay, which indicates the high resolution of the computational algorithm.

3. Flow around a drop behind a shock wave and its effect on the deformation and decay

The shape of the drop at the time of the breakup onset, similar to Fig. 2 and Fig. 3, is characteristic of the entire range of Weber numbers $W_e > 200$. The mechanism of this kind of deformation has not yet been studied, although it is a key to understanding the behavior of a drop when it suddenly enters the flow. It is natural to consider the shape of a drop as the response of a liquid sphere to a change in the gas velocity field near it. Such data are not available yet, because the panoramic speed registration methods, for example, PIV, are not applicable in shock tubes due to speed limitations. Therefore, experiments with the droplet model in a stationary flow were performed in [5] with retention of the Reynolds number $Re \sim 10^3-10^4$, as in the SW. The studied body had the form characteristic of the stage of the onset of erosion (Fig. 2c, d, Fig. 3c, d). The features of the flow around such a body formulated in [5] can be also traced in numerical simulation (Fig. 4).

![Figure 4](image_url)

In general, the flow is nonstationary, but in it there are several gas-dynamic structures, which are constantly present near and in the wake of a drop. At the initial stage, the flow around a drop is close to the flow around a sphere at the Reynolds numbers $Re \sim 10^3-10^4$ with a separation near the mid-section (1). Later, a solitary toroidal vortex (2), a return flow (3) and two ring waves (4) and (5) are formed on the initially spherical drop. The first higher wave (4) originates with a spherical drop shape (Fig. 4) at the point of flow separation. Here, the gas velocity is maximum (red region), and the pressure is minimal. The surface of the fluid moves to the region of reduced pressure, which leads to the growth of the ring.
wave (4). Note that in this mode the gas velocity behind the shock wave is $u_2 = 60$ m/s, and in the droplet mid-point - more than 100 m/s. Behind the separation point, a recirculation zone is visible with a counterflow along the surface of the drop toward the mid-section (area 1). Naturally, in the conjugate boundary layer in the drop, the liquid also moves to the mid-section, which, along with reduced pressure in gas, contributes to its growth. Region (1) is present at all stages of the interaction of a droplet with a shock wave.

Figure 5 shows the calculated velocity field near the droplet at the Weber number $We = 2260$, where the same structures are visible as at $We = 208$. The flow pattern with the separation of the bottom flow into two vortices (1) and (2) is shown at the time of 70 μs. This flow structure was observed earlier on a solid model, and this feature can be explained by the return flow behavior in the wake.

The recirculation zone with a counterflow along the axis of the wake (region 3) is another constant gas-dynamic structure in the flow around a drop at an early stage of interaction with the incident shock wave. The pressure distribution at the bottom of the drop from this impact flow makes the surface flat. Here a second fracture of the generatrix is formed (5) due to the radial spreading of liquid in the conjugate boundary layer on the bottom surface of the drop. Spreading along the bottom surface, the gas flow is divided near the second wave (5), part of it penetrates into the first tear-off zone (1), and this happens along the drop surface, and the rest flows fall into the third permanent structure (2).

The structure (2) partially separates the previous two ones and is an isolated (solitary) toroidal vortex. Without interacting directly with the surface of the droplet, it originates at its bottom part ($t = 50-70\mu s$) and drifts into an aerodynamic wake ($t = 70-120\mu s$) at a speed much lower than the flow velocity. At $t = 170\mu s$, signs of the solitary toroidal vortex are still guessed, but after $t = 200\mu s$, the flow in the wake...
loses axial symmetry and breaks up into small nonstationary structures. They form a vast stagnant area with a low average speed of ≈50-60 m/s, comparable to the speed in the zone of flow inhibition in front of the windward surface of the drop. This stage of the process is not given here.

Comparison of drop shadow images at the time of onset of destruction with the external flow field has showed that the erosion occurs at the apexes of the waves - ring fractures of the generatrix (4) and (5), and they are formed at the flow separation points. This type of erosion corresponds to the mechanism of “sheet stripping”, and its signs are present in modes with the Weber number \( We = 208, 360, 650 \). In the regime with \( We > 2260 \), the morphology of the drop is similar to the previous examples, but the erosion of liquid occurs not only from the edges of two main waves. Earlier, the presence of products of destruction was noted in front of the windward surface of the drop when the number \( We = 2260 \) (Fig. 3, c,d), the origin of which is also the breakdown of wave crests, but the waves of different scale and nature. These are the Kelvin-Helmholtz instability waves on the windward surface of the drop, therefore the products of their destruction are observed in front of the drop. The signs of the collapse of the crests of the Kelvin-Helmholtz instability waves in Fig. 3, c,d ("wave crests stripping") is, perhaps, the only evidence of change in the destruction mechanisms obtained in the calculations in this range of modes described in [5].

Conclusion

Experimental and computational modeling has been performed for the water drop streamlining in a flow behind the incident shock wave as a key factor determining the type of its deformation and the nature of its destruction. The same conditions were simulated in experiments and calculations for droplets of “natural” size: shock wave Mach number \( Ms = 1.109-1.34 \) and Weber numbers \( We = 200-2200 \). The structure of the flow near and in the wake of the drop, the evolution of the shape and breakup delay have been studied. Comparison of calculations with experiments demonstrated good agreement on the main characteristics of the process, and allowed constructing a phenomenological picture of the behavior of a drop at an early stage of interaction with a shock wave as a response to a rapidly changing flow field.

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