HYDRODYNAMICS OF DETACHMENT, FREE FALLING AND IMPACT OF DROPS

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Abstract. The results of optical measurements of drop dynamics are presented. Oscillations and waves on its surface were traced. The pattern of the secondary droplets falls onto an immersed drop and the discrete distribution of the substance of a uniformly colored drop in the targeted liquid was visualized. The important role of energy transport processes, both fast — local atomic-molecular — and slow that are translational and dissipative, in the formation of flow patterns is highlighted. A system of fundamental equations of fluid mechanics with equations of state for the Gibbs potential and density is applied. Ligaments — thin trickles with scales from atomic-molecular and macroscopic sizes — are investigated. Their images in the family of intrinsic solutions of the fundamental system and drop impact phenomena are shown.

1. Introduction

A large number of theoretical, experimental and numerical studies are dedicated to the investigation of droplet phenomena that have a great impact on the energy transport and dynamics of processes in aircraft engines. The basis of this experimental study is a system of fundamental equations for the transport of matter (density), momentum and total energy [1], supplemented by empiric equations of state for the Gibbs potential and its derivatives, including density [2]. The explicit compatibility condition determining the rank of a nonlinear system, the order of the linearized version, and the degree of the characteristic (dispersion) equation was used to construct a complete solution of the system. The set of the structural components of a flow based on the constructed solution includes ligaments, waves, jets, wakes and vortices. The description of the fluid state takes into account that the internal energy in the bulk and in the surface layers of liquids has different forms due to the anisotropy of atomic-molecular interactions that create surface tension and even decay of molecules (in particular water) and ionization of fragments [3]. The experimental technique was developed taking into account the requirements for observing large components of flows, in particular, causing a change in the droplet shape during pinch-off, free fall, deformation of the free surface of the targeted fluid, and thin components — ligaments that are trickles in the bulk and on surface the fluid, spikes and sets of secondary small droplets [4].

2 Physical and spatio-temporal process parameters

The determining parameters of the problems of pinch-off and coalescence of a freely falling drop with a fluid at rest, which were studied in experiments, are the density of air \( \rho_a \) and water \( \rho_d \) (hereinafter \( \rho_{a,d} \)); kinematic \( \nu_{a,d} \) and dynamic \( \mu_{a,d} \) viscosity of media; full \( \sigma_d^a \) and normalized to the density of the liquid surface tension coefficient \( \gamma = \sigma_d^a / \rho_d \) cm\(^3\)/s\(^2\), acceleration of gravity \( g \), equivalent diameter \( D \), surface area \( S_d \), volume \( V \), mass \( M \), height \( H \) and droplet velocity \( U \) at the time of initial contact; available potential surface energy \( E_a = \sigma S_d \) and kinetic energy \( E_d = MU^2 / 2 \). The fraction of energy \( E_a \), stored in a near-surface spherical layer with a thickness of the order of the size of the molecular cluster \( \delta_a \sim 10^{-6} \) cm and mass \( M_a \), under the experimental conditions is about 1% of the kinetic energy of the droplet, but its density is much higher:
\[ R_w = \frac{E_o M}{E_d M_o} \sim 1000. \] The processes of converting surface energy into other forms plays a decisive role in the formation of thin trickles.

Physical processes determine length scales, including the capillary-gravitational parameter \( \delta_g = \sqrt{\gamma / g} \) included in the dispersion equation of short surface waves [1], dissipative-capillary \( \delta_\gamma = \nu^2 / \gamma \), \( \delta_\delta = \kappa^2 / \gamma \), capillary \( \delta_U = \gamma / U^2 \) and Prandtl’s scales \( \delta_U = \nu / U \) and \( \delta_U = \kappa / U \).

Groups of time scales include environmental parameters \( \tau_g = \frac{3}{\gamma / g} \), \( \tau_\gamma = \frac{3}{\nu^2 / \gamma} \), \( \tau_\delta = \frac{3}{\kappa^2 / \gamma} \) and the droplet size \( \tau_d = \sqrt{D^3 / \gamma} \), \( \tau_d = \kappa D / \gamma \), \( \tau_d = \nu D / \gamma \) and its velocity \( \tau_U = \frac{D / U}{\kappa / g} \), \( \tau_U = U / g \).

The frequencies of capillary \( \omega_c \) and acoustic waves \( \omega_s \) are associated with wave vectors \( k_c \), \( k_s \) and the corresponding wavelengths \( \lambda_c = 2\pi / k_c \), \( \lambda_s = 2\pi / k_s \), dispersion relations \( \omega_c^2 = g k_c + \gamma k_c^3 \) and \( \omega_s^2 = c_s^2 k_s^2 \), where \( c_s \) is the velocity of sound [1].

Experiments with photo and video recording of flows, measurements of acoustic signals are carried out at the test stand of the USF “HFC IPMech RAS” [5]. Installations and experimental procedure are described in detail in [6].

3 Visualization of fine flow patterns

The evolution of the flow pattern when the drop is separated from the sessile fluid is shown in Fig. 1. The pinch-off of water droplets is preceded by the formation of a “bridge” - a thin jet that connects the drop with the feeding source of water. Observations showed that the bridge becomes thinner and ruptures in the area of contact with the detached drop [7]. The bridge, which continues accelerated movement, is thinned in the area of contact with the feeding liquor and completely separates. Capillary forces pull the separated part of the bridge together in the linked set of oscillating droplets, which is transformed into one or two separated small oscillating satellites.

![Fig. 1. Transition of bridge in progress of a drop of water separation](image)

The rapidly retracting remnants of the bridge excite both low-frequency volumetric oscillations of the drop and the mother liquor, and traveling short capillary waves. The evolution of the shape of the detached drop is shown in Fig. 2.

![Fig. 2. Oscillations of a freely falling drop: D = 0.5 cm, a) - separation, b - d) – t = 11.5, 28.8, 40.2 ms, e) - droplet sizes variations: horizontal (1) and vertical (2)](image)
The oscillation frequencies of even large amplitudes are in satisfactory agreement with calculations using the Rayleigh formulas and modern concepts of the theory of capillary waves [8]. Along with oscillations and waves in the bulk of the targeted fluid, ligaments – thin trickles that play an important role in the evolution of the flow pattern and the generation of sound packets – are formed.

Improvement of optical instruments has helped to identify ever new stable structural components in droplet flows, the history of which has been studied for more than a hundred years. Recently, small cavities surrounded with short capillary waves have been recorded, showing the impact of small escaping spray onto the surface of an immersing drop of brine (dense sodium chloride solution) or water immersed in targeted water [9].

At the early stages of formation, the crown consists of separate layers. A fast inner layer contains a double energy loaded fluid, in which a high level of pressure, temperature, and flow velocity perturbations are saved. Inside this layer, the available potential surface energy contained in a thin surface layer of coalescence fluids with a thickness of molecular clusters of \( \delta \approx 10^{-6} \text{ cm} \) is transformed into other forms. The kinetic energy of the merged part of the drop is accumulated in this layer as well. The layer is split off from the crown and pulled together by capillary forces into a thin dome that loses stability and is crumpled into folds. At the ends of the folds, fine spikes form, from the tops of which small droplets fly out, falling onto the surface of the sinking drop.

Impact wakes that are small caverns, which are contoured by short capillary waves ahead of a moving source, are shown in Fig. 3. The number of droplet wakes and waves on the primary immersing droplet increases with an increase in the difference between the surface tension coefficients of the contacting media [9]. A mathematical model of the observed inversion of the horizontal velocity component of the spray droplets is under development.

![Fig. 3. Capillary waves on the surface of a drop immersed in water: a) – water, b) – brine (right part – fragments; marked scale - 1 mm)](image)

Depending on the size and velocity of the falling droplet at the moment of contact, the purity of the water surface and temperature, various types of interaction between the droplet and the targeted fluid are observed that are rapid coalescence with the formation of a cavity and a crown, hovering on the contact surface, rebound, as well as a core ejection with the spreading of the droplet shell into the targeted fluid.

In a fast spreading mode the material of a uniformly colored drop spreads over the surface of the cavity and the crown in separate filaments separated by thin layers of clean targeted fluid (Fig. 4.). In the center of the cavity individual strips form a net pattern composed of transparent tri-, quadruple, and pentagons with painted sides [10]. Examples of the discrete distribution of the substance of a uniformly colored drop in individual thin filaments separated by a clean fluid in the regime of fast spreading over the surface of the cavity and crown are shown in Fig. 4 [10].

Regular discrete patterns of droplet material are formed near the merging line of liquids and are transferred by forming fast trickles along the surface of the cavity and the inner wall of the crown up to its edge chevron [10]. In droplets flying out from the tops of the spikes, which end with the pointed cusps of the crown chevron, the presence of both contacting liquids is always noted.
Fig. 4. Striped patterns of the distribution of droplet material over the surface of the cavity and crown when a colored drop is immersed in water: a) – a solution of brilliant green, b) – a solution of alizarin ink: a cavity with the remnant of the drop, a crown with a set of ligaments, spikes and flying splashes.

The discrete pattern of the drop substance formed in the targeted fluid is saved at all subsequent stages of the flow evolution that are in the phase of the cavity and crown growth, the formation and spreading of the splash (the cumulative jet) in Fig. 5, and at subsequent stages, the attenuation of surface disturbances and the formation and decay of vortex rings.

The resulting double energy loaded layer, in which the fluid of the droplet, which in turn transports the kinetic energy of falling drop and the latent surface potential energy comes in contact with the targeted fluid. The transformed surface potential and kinetic energy has long existed as thin trickles that transport and break gas cavities. A double layer appears on the smoothed free surface in the form of a recurrence of fine structures after the degeneracy of surface perturbations, when it appears near the surface. In the flow pattern, the double layer manifests itself both in the wavy shape of the splash surface (Fig. 5 a, c) and in its filament texture (Fig. 5 b, d). Fine flows impact on formation, transport, rupture and oscillations of gas bubbles, accompanied by generation of acoustic signals [12].

Fig. 5. Visualization of the surface texture of the fluid:

a), b) – in the phase of a growing splash, c), d) – formed splash

The differences in the evolution of the pattern of surfaces of the cavity and of the crown are illustrated by the samples of videogram shown in Fig. 6. The crown chevron has the sharpest forms in the formation phase, when small droplets are ejected from the tips of spikes (Fig. 6, a). Over time, the teeth on chevron are smoothed, the diameters of the droplets increase, the crown enlarges monotonously (Fig. 6, b, c).

Fig. 6. Evolution of the surface structure of the crown and cavity (\( D = 0.6 \) cm \( U = 3.7 \) m/s):

\[ a - d \) – time \( t = 1.5, 43.2, 45.2, 47.7 \) ms

The shape of the smoothed bottom surface of the cavity is gradually distorted by capillary waves running from the walls of the crown (Fig. 6, b), then smoothed (Fig. 6, c) near the walls and again finely structured in the center under the influence of thin trickles previously hidden in the thickness of the liquid.
**4 Conclusion**

Detailed high-resolution observations give room to identify new groups of stably reproducible droplet impact processes, accompanying spatial structures that are traces of secondary droplets on the surface of an immersed droplet, fibrous patterns of the distribution of droplet matter in the thickness and on the surface of the targeted liquid, complex shapes, texture of the surface of flows, as well as generation of acoustic packets.

An important role in shaping the flow pattern is played by all energy transfer processes: both local fast ones - atomic-molecular on ligaments - and slow ones - translational and dissipative, forming thin fibers and interfaces, vortices, capillary, and acoustic waves.

A complete analysis of the system of fundamental equations of fluid mechanics, including the empirical equations of state for the Gibbs potential and density, which were performed taking into account the compatibility condition, gives room to systematize and characterize the observed phenomena in a unified way with a wide range of process parameters.

The experiments carried out far from cover all the structural features of impact drop processes, which substantially depend on all physical parameters, which in real conditions are subject to a wide range of changes.

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