

Article

Intrusive and Impact Modes of a Falling Drop Coalescence with a Target Fluid at Rest

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Abstract: The evolution of the falling drop substance transfer in a target fluid at rest was traced by high-speed video techniques. Two flow modes were studied: slow intrusive flow, when the KE of the drop was comparable or less than the available potential energy (APSE), and a fast impact flow, at a relatively high drop contact velocity. For the substance transfer visualization, a drop of alizarin ink solution at various concentrations was used. The use of transparent partially colored fluid allows tracing the drop matter motion in the bulk and on the fluid free surface. The traditional side and frontal view of flow patterns were registered and analyzed. In both flow modes, the substance of the drop partially remained on the free surface and partially went into the target fluid bulk, where it was distributed non-uniformly. In the intrusive mode, the drop substance partially remained on the surface, while the main mass of the drop flowed into the thickness of the target fluid, forming the lenticular colored domain. The intrusion was gradually transformed into an annular vortex. In the impact mode, the drop broke up into individual fibers during the coalescence, creating linear and reticular structures on the surface of the cavity and the crown. The flow patterns composed of individual fibers were rapidly rebuilt as the flow evolved and the splash emerged and decayed. The sizes of cavities and colored fluid domains were compared in different flow regimes as well. The total energy transfer and transformation impact on the flow structure formation and dynamics was revealed.

Keywords: fluid; drop impact; experiment; matter transfer; coalescence modes; dynamic; structure

MSC: 76-05



Citation: Chashechkin, Y.D.; Ilinykh, A.Y. Intrusive and Impact Modes of a Falling Drop Coalescence with a Target Fluid at Rest. *Axioms* **2023**, *12*, 374. <https://doi.org/10.3390/axioms12040374>

Academic Editor: Xi Deng

Received: 28 February 2023

Revised: 30 March 2023

Accepted: 4 April 2023

Published: 13 April 2023



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1. Introduction

The processes of a single free-falling drop, a sequence (“drop trains”), or groups of drops (rain models) merging with a target fluid at rest have been actively studied theoretically and experimentally due to the scientific value of the topic, the variety of technological applications, as well as the important role in the dynamics of atmosphere and hydrosphere. The expressive images of drop impact flows, which attracted the attention of writers, poets, musicians, artists, and jewelers from ancient times, became the subject of scientific research in the middle of the 19th century. The first results of visual observation of a vortex ring that appeared when a free-falling drop merged with a fluid at rest [1] was presented among different methods for producing compact vortices, which are the object of intensive scientific research. A few years later, the sizes of drops of various fluids (coconut oil and calcium chloride solution) were experimentally determined, and the surface area, volume, and mass of single drops and their sequences (“drop trains”) were calculated [2,3].

The use of a spark light source with a platinum wire and a cup with mercury, in a device for mechanically adjusting the duration of the flash delay, allowed researchers to trace from the sketches of the flow the motion and evolution of the ring vortex core shape generated by a falling drop in the target fluid [4]. Graphic images of the flows of miscible and immiscible fluids were used to identify the conditions for the formation of

rings in droplet flows, and to trace the transformation of a vortex into a system of loops with secondary vortices (splitting in the terminology of the authors [4]), which in turn formed a new tier of the vortices cascade. The influence of article [4] on the development of hydrodynamics, physics, biology, and philosophy of science brightly illustrates the success of the monograph [5], which, correspondingly, continues to be republished, studied, and discussed [6]. Reproducing the main results of [4], modern photographs of the vortex flows of the droplet impact, presented in Figure 1, allow us to trace of the flow geometry dependence on many factors—in particular, on the type of dye and the solution density [7]. Almost simultaneously with the study of the vortex wake [4], the oscillations of a free-falling drop were scrutinized experimentally [8]. The theory of volume oscillations, developed in [9], was supplemented by a study on the short capillary waves on the liquid sphere surface [10].

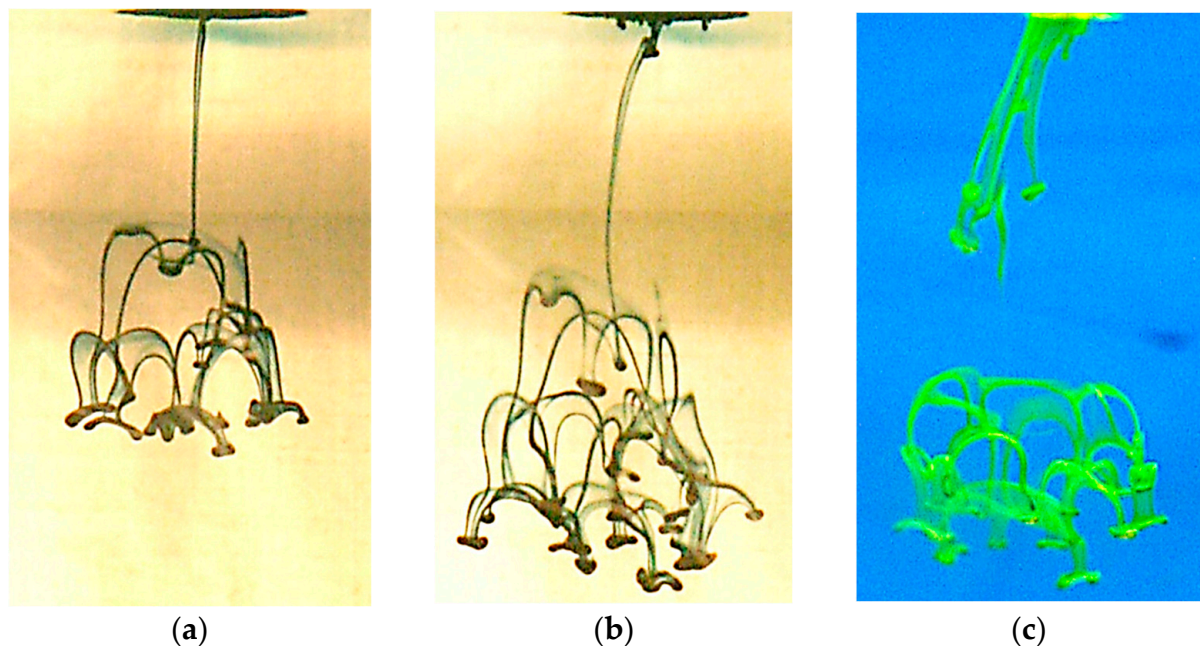


Figure 1. A cascade of vortices produced by dyed drop in tank with tap water: (a,b)—a drop of blue alizarin ink solution, $t = 12, 20$ s, respectively; (c)—a drop of uranine solution, $t = 16$ s.

The invention of new bright light sources and video recording instruments has had a significant influence on the development of the drop impact research. Photographic recording has enabled scientists to identify the main components of the drop impact flow, namely a cavity, a crown, sprays, a central jet (a splash), and annular capillary waves [11,12]. At the beginning of the 20th century, the registration of acoustic radiation from the impact of a drop began; initially, it took place in air [13], and with the invention of the hydrophone, in water as well [14]. The search for the mechanisms of acoustic signals emission by single-droplet impact [15], the mutual influence of hydrodynamic and physical phenomena [16], is actively continuing.

The information content of fast process images has noticeably increased with the use of controlled flash lamps, which has expanded the abilities of the stroboscopic visualization technique [17] (for clarity, the authors repeated the experiments [11] on the spreading of a water drop or a milk drop in diluted milk). The monograph was repeatedly republished, the expressive photographs of the crown and the splash were on greeting cards, and were reproduced in subsequent abundant publications [15].

The combination of bright light sources, filmography, and stroboscopy allowed scientists to get the first expressive images of the vortex rings at the top of a relatively thick jet during the pulsed extrusion of colored fluid from the nozzle [18] (here, 250 mg of Flu-

orescein $C_{20}F_{12}O_5$ and 300 mg NaOH were added to 200 mL of water for visualization). Due to the small difference in the densities of the solvent (water) and the colored liquid, the pigment was considered a passive admixture, visualizing the flow velocity. Repeatedly reproduced experiments [18] initiated an extensive cycle of theoretical and experimental studies on vortex ring formation.

The theory of vortex ring formation during the pulsed extrusion of a homogeneous liquid from a nozzle or a circular hole in a pipe plug, developed in [19,20], was analyzed in detail in [21] and in [22]. The results of experimental studies of the motion of laminar and turbulent vortex rings in a homogeneous liquid were also given in [23–26].

In a continuously stratified fluid, a horizontally moving vortex ring, which is contoured by a high-gradient shell, radiates attached internal waves [27], just like a uniformly moving solid sphere [28]. The braking effect of internal wave radiation is especially pronounced at the final stages of the ring motion, when the internal Froude number $Fr = U/ND$ becomes less than the critical value $Fr < 1$ (where D, U are the ring diameter and velocity and N is the buoyancy frequency of the medium [28]).

In the second series of experiments begun in [16], one of the methods for generating vortex rings, which was considered in [1], was reproduced at a new technical level: a drop of a dilute fluorescein solution was pinched off under the action of its own weight from a pipette installed at a short distance ($H = 1$ cm) above the water surface [29]. A drop falling on the liquid surface formed a slowly sinking vortex ring. G. Batchelor's decision to place one of the photographs [18,29] on the popular monograph cover [30] could be taken under the strong impression produced by the image of the stem vortex structure. At the same time, a systematic study of the drop flow geometry began. The dependences of the cavity dimensions and wave elevation on its wall on the time, momentum, and KE of the drop were determined; the streamlines were constructed based on the visualization data of the crown, cavity, air bubble, and particle motion [31].

The capillary in the drop dispenser [29] was replaced by a thorn with a hemispherical or conical tip, onto which a liquid slowly leaked and detached with the formation of a drop under the action of its own weight [32]. The new construction allowed the tracing of the conditions for the formation of a vortex ring, changes in its size, and descending velocity for a large number of liquids (water and solutions of salts, hydrocarbons) under room and cryogenic conditions. Further studies of the dependence of the size, structure, and velocity of the vortex ring on the energy of the falling drop, and assessment of the effect of oscillations that change the shape of the falling drop on the efficiency of vortex formation, began to be carried out using stroboscopy and video technology.

The researchers continued to work on the mode classification of the coalescence of a drop with a target fluid, the foundations of which were laid in [4], at the end of the last century, with high-speed filming of the flow pattern employing a Dynafax 350 camera (a rotating-drum camera with a shooting frequency of 1000 fps [33]). The experiments traced the formation of large gas bubbles, a sinking annular vortex, and a fast thin central jet with its own vortex ring at the top. Following [4], the boundaries of regions for the formation of an annular vortex and a splash were represented in the diagram “fall velocity—drop diameter” [33].

In subsequent experiments, the influence of the contacting drop shape, which oscillates during the fall, on the size and the forming ring vortex descending velocity was observed. A non-monotonic dependence of the maximum depth of the vortex ring immersion on the drop height (in fact, the contact velocity U [34]) was noted. The most stable vortex was formed at the boundary of the range when the oscillating drop changed its shape from spherical to vertically elongated [35]. The flow pattern visualization at the coalescence of a growing drop in contact with the water surface and the assessment of the effect of surface tension on vorticity generation were carried out in [36].

The theory of vortex formation in a layer of an ideal fluid, taking into account the effect of surface tension, was considered in [37]. Detailed studies of the free surface deformation by a merging drop, and the formation and subsidence of an annular vortex were carried

out by the direct shadows and laser fluorescence visualization in [38]. In the flow pattern, three stages of the determining influence of inertial, capillary, and viscous effects were distinguished, which manifested themselves in the stages of uniform, non-monotonic, and decelerating vortex motion. The increase in attention to the study of the motion of vortex rings of the drop impact [39] was facilitated by the observed structural similarity of the flow patterns in a small laboratory pool [29,40] to the shape of the nuclear explosion cloud produced in the atmosphere by blasts near the Earth's surface [41,42]. In the pattern of the flows of distinguished scales, an annular "vortex" is expressed at the top of a "thick stem" surrounded by a conical shell with separate vortex loops.

The development of research into the formation of air bubble processes by falling drops in the thickness of the target fluid was promoted by an interest in applied problems of actively developing marine hydroacoustics [14] and aeration of water pools. A detailed consideration of various mechanisms of sound generation by falling drops was carried out in [15,43]. Subsequent marine measurements showed that the sound radiation of raindrops, which is a significant part of the acoustic background of the ocean [44,45], makes it possible to remotely estimate the intensity of precipitation and wind in remote and hard-to-reach regions of the World Ocean [46]. The improvement of the theory of sound emission by falling drops [47] contributed to an expansion in the use of remote methods for estimating the intensity of precipitation in the ocean [48].

The determination of favorable conditions for the formation of individual gas bubbles, the dimensions of which prescribe the frequency of the emitted sound [15,44,49–51], became the main problem of hydroacoustics, along with the compilation of traditional maps of regimes, including the boundaries of coalescing and splashing drops [4,52].

The development of computer hardware and software, as well as video recording of fast processes, has expanded the study of drop impact flows. For the first time, comparisons of the calculated and observed patterns of flows began to be made, especially successful in the mode of large gas bubble generation in the target fluid thickness. The basis of calculations and experimental methods was the traditional system of Navier-Stokes equations for an incompressible homogeneous fluid [53], which included terms that took into account the surface tension effect [54].

To determine the position of the deformable free surface, additional assumptions about the shape of the cavity were used (usually assumed to be spherical [55]). The Volume of Fluid (VOF) approach [56] and various variants of the rapidly developing Level Set (LS) methods [57,58] were applied. Due to the complexity of describing fast multiscale processes, while simultaneously visualizing the flow pattern as a whole and determining the position of a thin boundary between media, calculations were carried out using programs with open codes (OpenFOAM v2212, Gerris 2, and others [59]). Since each of these methods has certain disadvantages (in diffuse VOF it is difficult to identify the true position of the sharp contact boundary, and in SL it is necessary to apply special efforts to support the fulfillment of the matter conservation law), various versions of the Direct Numerical Simulation technique (DNS) are being developed as an alternative [60–62].

The calculated patterns of axisymmetric vortices with a central jet and detached large gas bubbles [54] are in good agreement with the data of experiments performed and the calculations using other codes [63,64]. The agreement between the shapes of the calculated and observed basic flow elements, namely cavity, splash, secondary droplets, and splash, improved when the conversion of the available potential surface energy (APSE) upon the elimination and creation of a new water–air interface was taken into account [65].

The visualization of the crown and systems of drops emitted from the tops of spikes on their edge in a one-component system (the droplets of the target fluid falling) was carried out in [66]. Detailed calculations of the evolution of the axisymmetrical shape of the free surface and the dynamics of an annular vortex in a viscous fluid, which were based on the vorticity conservation equation, taking into account the mechanism of baroclinic generation of vortex motion, was presented. They also agree with the dye flow visualization data [67]. Observations of the thin gaseous layer between the merging drop and the target fluid

(which can form a central dent on the convex surface of the drop at the center of the flow or a toroidal cavity on the periphery), which broke up into sound-emitting gas bubbles, were given in [68] (the drops and the target fluid were silicone oil).

Careful measurements of the size and shape of the cavity, crown, splash, and secondary droplets emitted from its top during the merging of single drops or synchronously falling pairs of drops, as well as producing independently moving or merging vortices, were performed in [69]. A solution of instant coffee pigment was used for visualization. The data obtained are summarized in tables and interpolated for the convenience of further use. The processes of the development and collapse of a cavity and the formation of a central jet that splashed were experimentally studied in [70] in a wide range of parameters, including the formation of the splash itself and a subsequent streamer (a high thin jet on a wide pedestal), and a relatively short and thick splash.

In the flow patterns generated by an obliquely falling drop onto a flat liquid surface [71] or onto a rotating disk [72], the evolution of the shape and size of the cavity, as well as thin jets (spikes) that produce sequences of sprays, are traced at the edge of the crown. Additional studies have shown that the air medium affects the number and direction of droplet escape from the spikes on the edge of the crown on a rotating disk, and practically does not influence their size or the value of the horizontal velocity component [73].

At low and moderate air velocity in wind tunnel experiments, obliquely falling drops formed an asymmetric crown on the water surface, the spikes on which were located in the leeward part and the waves in the windward part of the crown. As the wind velocity and droplet size increased, the length of the spikes in the leeward part of the cavity increased, and gradually lost their symmetrical shape [74]. In a fluid at rest, patterns of the flow and capillary waves of the drop impact are axially symmetrical [75].

Traditionally, in most experiments with falling drops, observations are carried out “in the light” with the registration of contrasting black-and-white images. The droplet coloring pigment is considered to be a passive impurity visualizing the fluid velocity field. The vortex ring is the dominant component of the structure and the basis for the flow regime classification. An additional feature is air bubbles, which determine the acoustic radiation. The disadvantage of this technique is the strong dependence of the flow pattern information content on the physical properties of the contacting liquids, noted in [4]. The classical system of Navier-Stokes equations of continuity and transfer of momentum for a homogeneous fluid is used as the basis for describing flows. To simplify calculations, additional terms illustrating surface tension effects are included in the equation of motion. In a modern flow description extended system, equations including the equation of a substance transfer with physically based boundary conditions are used [53,76].

As it follows from the analysis of photographs of flow patterns with pigment, a slowly falling drop smoothly flows into the target fluid and forms a compact, uniformly colored volume. In this case, the movement of the free surface becomes more complicated, and a cavity is formed with a delay of $\Delta t_d = 10 \dots 13$ ms. The vortex ring itself begins to form and descend after the end of a series of fast processes [77].

The substance of a rapidly falling drop is distributed over the surface of the target fluid in the form of thin fibers that constitute regular linear and reticular structures on the surface of the cavity and crown [78,79]. The fibrous distribution pattern of the drop substance was observed for a long time in a deep [80] fluid at rest, in a shallow target fluid [81], as well as in the field of running gravitational-capillary waves [82]. The thin fibers of the substance of a freely falling drop form spiral structures on the surface and helical lines in the bulk of the liquid in a compound vortex, which is formed by a rotating disk installed on the bottom of an open cylindrical container [83]. A detailed analysis of the temporal variability of the pigment distribution pattern in different modes of droplets merging with the target fluid has not been previously performed.

In the process of structural rearrangement, new groups of capillary waves [75,76] and thin flows that are ligaments complementing the waves [84] appear in the flow pattern.

Waves and ligaments affect the formation and detachment of gas cavities, some of which emit sound packets [85].

To complete the description of the drop coalescence flow pattern, it is necessary to remark that fluid density has a complex nature, reflecting all its properties that are inertial, gravitational, and thermodynamic, caused by complex and variable atomic and molecular structures [68]. As a quantity of the thermodynamic nature, density, which is determined by the Gibbs potential derivative, is described by empirical equations of state [86–88].

In the traditional approach (which includes the continuity equations in the incompressibility approximation and the Navier-Stokes equation only), which is used to describe the droplet impact flows, the density is assumed to be constant. It is considered as a “passive impurity”, changes in the distribution of which can be used to visualize the velocity field. Separate equations for describing the transfer of physical quantities, such as the concentration of dissolved substances or temperature, which determine the density value, which were included in the complete system of fundamental equations of fluid mechanics [53], are excluded in [62]. Accordingly, in the experiments—the scientific basis of which is the system of continuity and Navier-Stokes equations—transparent homogeneous liquids (water, alcohol, and acetone) are mainly used. The domain of observation is illuminated “in the light”, when the flow contours are visualized [11,12,15,31,55,61,62]. The classifying sign is the structural features of the density distribution pattern, reproducing structural features in the fields of velocity. Accordingly, in experiments, the colored liquid is used to visualize the wave or vortex components of the flow [18,29,39–42].

In the modern definition of a fluid, density is treated as an independent physical quantity which is determined by the Gibbs potential derivative, and is described by empirical equations of state [86–88]. Accordingly, the topology and geometry of the fields of such independent quantities as velocity, momentum, and density can differ markedly. Of scientific and practical interest is the study of the evolution of the fine structure of the distribution patterns of the substance of a freely falling colored drop in a homogeneous transparent target fluid, which has not been systematically carried out before.

The aim of this work is a comparative analysis of the temporal variability of the drop substance distribution patterns and deformation of the liquid surfaces at the initial stage of flow evolution in two coalescence modes: an intrusive mode at low values and an impact mode at high values of the falling drop contact velocity. A free-falling drop of a uniformly colored dilute alizarin ink solution merging with water is used in the experiment. The scientific basis of the work is the complete system of fundamental equations of the mechanics of inhomogeneous fluids [76].

2. Basic Dimensional and Dimensionless Parameters of the Drop Impact Flow

The methodology of the experiments carried out is the system of fundamental equations, which describes the transfer of conserved physical quantities that are matter (density), momentum, and energy, which are treated as fluid flow measures [53,76]. A fluid or gas is defined as a continuous flowing medium with zero static friction, which is characterized by internal energy represented by the differential of the Gibbs potential $dG = -s_e dT + V dP + S_b d\sigma + \mu_i dS_i$ [53,86,87]. The derivatives of the Gibbs potential G determine thermodynamic quantities that are density ρ , specific volume $V = 1/\rho$, entropy s_e , pressure P , temperature T , concentration of dissolved substances S_i and suspended particles, surface tension coefficient σ normalized to the density of fluid $\gamma = \sigma/\rho$, and chemical potential μ_i of every dissolved component. Pressure, like density, has both a thermodynamic and direct mechanical meaning, determined by the equations of fluid flow.

The molecular transfer of momentum, temperature, and matter is characterized by the coefficients of kinematic ν or dynamic $\mu = \nu\rho$ viscosity, temperature conductivity κ_T , and diffusion κ_S . The medium is also characterized by the propagation velocities of waves (sound c_s , electromagnetic c_l), the charge transfer parameter (with a specific electrical conductivity η), and the refractive index of light n [88]. In practical oceanography, basic quantity values—density, sound velocity, or temperature—are measured directly and

calculated by algorithms containing data of various parameters. A comparison of these values is used to estimate the error of field measurements [89].

The fluid flow is defined as an inherent or forced joint transfer of momentum, energy, and matter. It is described by a scale-invariant system of fundamental equations of fluid mechanics. All equations were given in the first edition [53] of 1944 and were reproduced many times in subsequent treatises.

Basic physical quantities of the fluid flow that are density, momentum, and energy belong to the class of observable parameters, as the experimental technique allows estimating the error simultaneously with determining their values. The system is supplemented with physically justified boundary conditions (no-slip for velocity and no-flux for matter on solid walls), kinematic conditions, and dynamic conditions on the free surface [53]. The high heat capacity of liquids enables us to neglect temperature effects in a number of problems and to obtain experimentally accurate results for solving a simpler reduced system of fundamental equations.

Under natural and industrial conditions, a heterogeneous fluid is stratified under the action of gravity with acceleration $\mathbf{g} = (0, 0, -g)$. Light fluid volumes are located above heavier ones and form a stable density profile $\rho = \rho_0(z)$. The consideration is carried out in a Cartesian (x, y, z) or local cylindrical coordinate frame (ρ, φ, z) , and the axis z is directed vertically upwards. Depending on the magnitude of the density gradient, which is characterized by scale $\Lambda = |d \ln \rho / dz|^{-1}$, frequency $N = \sqrt{g/\Lambda}$, or buoyancy period $T_b = 2\pi/N$, fluids are called stratified (strongly at $N \sim 1 \text{ s}^{-1}$ or weakly $N \sim 10^{-2} \text{ s}^{-1}$), as well as potentially ($N \sim 10^{-5} \text{ s}^{-1}$) or actually ($N \equiv 0$) homogeneous.

The classification of the structural components of periodic flows is based on the analysis of complete solutions of linearized versions of the fundamental and reduced subsystems. It includes waves of various types (acoustic, inertial, internal, surface gravity, or hybrid) and accompanying thin flows that are ligaments, forming interfaces and fibers. Ligaments compose the fine structure of the medium [76].

From a consideration of the system of Navier-Stokes equations describing the motion of a low-viscosity, homogeneous fluid with a velocity $\mathbf{v} = (v_x, v_y, v_z)$,

$$\begin{aligned} \frac{\partial \rho}{\partial t} + \operatorname{div} \rho \mathbf{v} &= 0, \\ \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \nabla) \mathbf{v} &= -\frac{\nabla P}{\rho} + \nu \Delta \mathbf{v} - \mathbf{g} \end{aligned} \quad (1)$$

with kinematic and dynamic conditions on the free surface [53], it follows that infinitesimal periodic flows of the form $A = A_0 \exp(i\mathbf{k}x - i\omega t)$ with positive frequency ω and complex wave number vector $\mathbf{k} = \mathbf{k}_1 + i\mathbf{k}_2$ are characterized by the dispersion relation [90],

$$\begin{aligned} 2k(\omega^2 k_l - gk^2 - \gamma k^4 + 2i\omega \nu k_l(3k^2 - k_l^2)) - \\ - (k_l^2 + k^2)(\omega^2 - gk - \gamma k^3 + 2i\omega \nu k^2) = 0. \end{aligned} \quad (2)$$

The solutions of Equation (2) contain both regular roots with wave numbers k and singular roots with k_l . Here, t is the time, and ∇ and Δ are the Hamilton and Laplace operators.

The complete dispersion relation for waves and ligaments in a viscous exponentially stratified fluid was analyzed in [84]. Regular solutions of the linearized system (1) and relations (2) describe surface gravitational-capillary waves. Singular solutions characterize ligaments [76].

The transverse scale of the fibers δ that is the thickness of the ligaments in a stratified medium is determined by the kinetic coefficients and the buoyancy frequency: in the velocity field $\delta_N^v = \sqrt{\nu/N}$, in the density field $\delta_N^k = \sqrt{\kappa/N}$, as well as the frequency of the running wave value $\delta_\omega^v = \sqrt{\nu/\omega}$, $\delta_\omega^k = \sqrt{\kappa/\omega}$. In a flow, the thickness of the ligaments $\delta_U^v = \nu/U$, $\delta_U^k = \kappa/U$ is designated by the fluid velocity U [76]. All components, both large scale (vortices and waves) and thin ligaments, interact with each other, generate new harmonics [91], and degenerate under the influence of dissipative factors. The products of the nonlinear interaction of waves with each other and with ligaments complicate the evolving flow patterns [91].

In drop impact flows, the processes of internal energy transformation play an important role in the formation of ligaments. They accelerate flows in the immediate vicinity of the body, or in the regions where the free surface of the fluid is annihilated. Forming thin ligaments [16,76] contribute to the detachment of gas bubbles and the generation of acoustic packets [85].

The dispersion relation for sound waves in a homogeneous compressible fluid,

$$\left(\mathbf{k}^2 \left(1 - \frac{i\omega \tilde{\nu}}{c_s^2} \right) - \frac{\omega^2}{c_s^2} \right) (\omega + i\nu \mathbf{k}_l^2)^2 = 0 \quad (3)$$

contains a double singular root, as for waves in a viscous incompressible fluid [76]. Here, $\tilde{\nu} = \zeta + 4\nu/3$ is shear (first) ν and convergent (second) kinematic viscosity ζ . The complex wave number $\mathbf{k}$ corresponds to waves, $\mathbf{k}_l$ corresponds to ligaments, and c_s is the adiabatic sound velocity. The form of relations (2), (3) reflects the complex nature of periodic flows in a viscous fluid, all components of which can interact with each other.

The theory of fluid flows has been created and is being developed in the approximation of a continuous medium. Real fluids and gases are composed of atoms and molecules that form combinations of various associations. Different groups of elements are registered in fluids that are associates, complexes, clathrates, and voids with individual atoms, clusters, and others with physical and chemical bonds [92,93]. The linear scales of associations are in the range from 10^{-8} to 10^{-6} cm, and the lifetime ranges are from 10^{-12} s to tens of seconds. Each of the medium structure components has its own internal energy, which is accumulated during its formation and is partially transferred during destruction, providing the fluidity of liquids and gases.

The conversion of internal energy during the destruction of structural components, which ensures the formation of fast thin jets (rivulets, trickles, ligaments) in all types of flows, especially noticeably affects the fine structure of the drop impact flows inside the fluid contact area. In this domain, thin radial jets are formed [94]. The jets are accelerated by processes of APSE conversion at the contact line, forming the domain boundary [95].

The APSE is concentrated in a layer, with a thickness of the order of the molecular cluster size $\delta_c \sim 10^{-6}$ cm. Its release upon the annihilation of the free surface of merging liquids, which occurs quickly, in times of the order of $\tau \sim 10^{-8} \dots 10^{-9}$ s, and its accumulated during the formation of a free surface rather slow at $\tau \sim 10^{-2} \dots 10^{-3}$ s.

Consideration of the complete system of equations and boundary conditions [53,76,87,95] shows that the main dimensional parameters of the flows under study include the Gibbs potentials of the droplet G_d , the air G_a , and the target fluid G_t (the indices here and below denote the medium that the parameter characterizes), as well as densities $\rho_{d,a,t}$, kinematic and dynamic viscosities $\nu_{d,a,t}$, $\mu_{d,a,t}$, full σ_d^a , σ_t^a (and normalized to the density of the corresponding fluid), coefficients of surface tension $\gamma_d^a = \sigma_d^a/\rho_d$, $\gamma_t^a = \sigma_t^a/\rho_t$ cm³/s², diffusion coefficient of the pigment coloring the droplet in the target fluid κ_d , equivalent diameter D , surface area S_d , volume V , mass M , free fall height of the drop H and its contact velocity U , APSE $E_\sigma = \sigma S_d$, kinetic energy (KE) $E_k = MU^2/2$, and finally, the potential energy in a gravitational field with gravitational acceleration g .

The total energy of the falling drop $E_d = E_p + E_k + E_\sigma$ is the sum of the potential energy E_p , the extensive KE with the differential $dE_k = 0.5\rho U^2 dV$, and the APSE distributed in the near-surface layer with a thickness of the order of the molecular cluster size $\delta_\sigma \sim 10^{-6}$ cm and a mass of M_σ . The ratio of the KE and surface energy $R_E = E_k/E_\sigma$ under the conditions of these experiments varies over a wide range. At the same time, the surface energy density $W_\sigma = E_\sigma/M_\sigma$ (M_σ is the volume of the near-surface spherical layer with a thickness of the order of the molecular cluster size $\delta_\sigma \sim 10^{-6}$ cm) is always a large value. The ratio of the energy components densities is of the order of $R_W = E_\sigma M/E_k M_\sigma \sim 1000$.

The transfer time $\Delta t = D/U$ of the KE E_k and momentum $\mathbf{P}_d = M\mathbf{U}$ of the drop, which is determined by its diameter D and contact velocity $\mathbf{U} = (0, 0, U)$, is several milliseconds and is many orders of magnitude longer than the time of the free surface annihilation during

the surface fluid layer coalescence $\Delta\tau = \delta_\sigma/U \sim 10^{-8}$ s. Fast processes of transformation of APSE into other forms at the circular boundary of the fluid confluence region play a decisive role in the formation of thin jets and ligaments, and the generation of capillary waves in the target fluid [15,76,78,79].

Large scales determine the requirements for the measurement technique, in terms of choosing the size of the flow area observation, and small scales define the spatial and temporal resolution of instruments. The ratios of eigenscales define the dimensionless quantities used to describe droplet flows [53,76]. The traditional, incomplete set of dimensionless parameters includes the Reynolds $Re_d = UD/\nu_d$, Froude $Fr_d = U^2/gD$, Weber $We_d = U^2D/\gamma_d$, Bond $Bo = gD^2/\gamma_d^a$, Ohnesorge $Oh_d = \nu_d/\sqrt{\gamma_d^a D}$, and Schmidt $Sc = \nu_t/\kappa_t^m$ numbers.

Differences in the physical properties of the contacting media are characterized by dimensionless relationships, compiled by analogy with the Atwood number—the relative difference in densities $R_\rho = \frac{\rho_t - \rho_d}{\rho_t + \rho_d}$, surface tension coefficients $R_\sigma = \frac{\sigma_t - \sigma_d}{\sigma_t + \sigma_d}$, and dynamic viscosities $R_\mu = \frac{\mu_t - \mu_d}{\mu_t + \mu_d}$.

Fast atomic-molecular processes transform the APSE and transfer the KE of the drop. The severity degree of their action characterizes the ratio of the energy components $R_E = \frac{E_k}{E_\sigma}$ and their densities $R_W = \frac{E_k M_\sigma}{E_\sigma M}$. A large number of dimensionless parameters of the problem reflect the complexity of the spatiotemporal pattern of flows evolving under the influence of several simultaneously occurring processes.

The technique of experiments and data processing has been developed by taking into account the criterion for registering large-scale components of droplet flows—intrusions, caverns, crown, splash, capillary waves, and resolution of fine components that are primary sprays, spikes, and fibers.

3. Experimental Setup

The experiments were carried out on a modified stand for studying the fine structure of fast processes (FSP), which is part of the Unique Research Facility “HPC IPMech RAS” [96]. The flow pattern was formed in basin 1 filled with partially degassed tap water or other target fluid, shown in Figure 2. It was registered with an Optronis CR 300x2 video camera 2 (or photo camera). The flow domain was illuminated by two 3 and 8 Optronis MultiLED light sources with a luminous flux of 7700 lm, and a 4 Schott KL2500LCD fiber light illuminator.

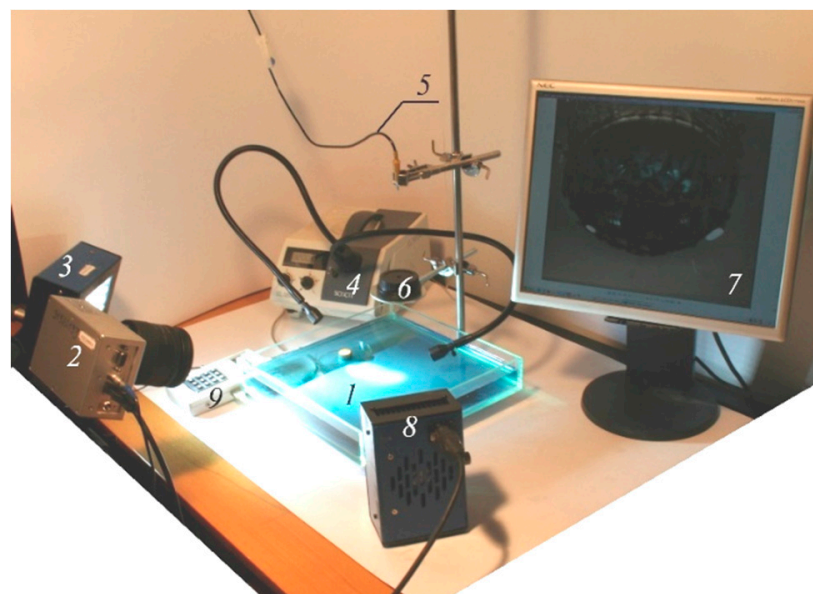


Figure 2. Experimental setup.

The drops fell from a dispenser 5 with a replaceable capillary installed at a chosen height above the basin 1. The countdown triggered a signal from the photodetector 6, which marked the overlap of the light beam by an incident drop, with an adjustable delay (time step 1 mks) set by control unit 9. The registered flow pattern was observed on the screen of experiment control unit 7. The central light spot in the pool in Figure 2 was created by a ReyLab Xenos spotlight, not included in the exposure.

To assess the influence of the pool dimensions on the flow pattern, experiments were carried out in basins of various sizes, $10 \times 10 \times 7 \text{ cm}^3$ and $30 \times 30 \times 5 \text{ cm}^3$ (shown in Figure 2). When preparing the experiment, attention was paid to the organization of the light flux to visualize the fine structure of the main flow elements that were the cavity, crown, splash, and capillary waves at all stages of the flow evolution. Before each experiment, a scale marker was registered.

In the experiments, after adjusting the equipment, a drop formed on the capillary tip, pinched off under the action of its own weight with the formation of a satellite [97], and then fell freely on the target fluid. Flying through the photodetector, the drop triggered the recording equipment. The drop velocity was estimated using the duration of the signal delay from the photodetector and the measurements of the drop position in the resulting video film frames.

4. Main Results

The experiments carried out showed that the observed patterns of the drop substance transfer in the target fluid are naturally divided into two groups. Drops approaching the surface at a low velocity at which the APSE exceeds the KE $E_\sigma > E_k$, smoothly flow in and form a compact colored volume in the thickness of the target fluid [77]. The surface of a fluid with a partially infused drop remains convex for some time. Rapid formation of a cavity starts with a delay of $\Delta t \sim 10 \dots 12 \text{ ms}$.

In the mode of the fast drop coalescence, for which $E_k > E_\sigma$, the cavity begins to form from the moment of initial contact. In this case, the substance of the drop is distributed over the surface of the target fluid in the form of individual fibers. They compose linear and reticular patterns on the surface of the cavity and crown [78,79]. The degree of expression of individual structural components of the flows depends on many dimensional or dimensionless parameters of the problem; in particular, the contact velocity of the drop at constant values of other physical quantities.

4.1. Flow Pattern Evolution in the Intrusive Mode of Drop Coalescence with a Target Fluid at Rest

A selection of frames from the video film recording the side view of the drop coalescence pattern at a low contact velocity, shown in Figure 3, illustrates the main features of the evolution of individual elements structure and the entire flow as a whole. In a short time of free motion (in these experiments, the distance from the capillary tip to the free surface is $H = 1 \text{ cm}$); the pinched off excited drop does not have enough time to assume an equilibrium shape and continues to change its form in the free fall. The central cylindrical part of the drop presented in the first frame is $D = 3.7 \text{ mm}$ in diameter and $h_d = 2.37 \text{ mm}$ high. Two end heads are expressed in the drop shape. The smoother forward head with $h_d = 1.06 \text{ mm}$ height is spherical with a radius of $R_d^f = 1.2 \text{ mm}$, while the back head with $R_d^b = 1.1 \text{ mm}$ height is conical (Figure 3, $t = -1.75 \text{ ms}$). The flattening of the upper and lower edges and some vertical compression of the drop during the time between frames of $\Delta t = 3 \text{ ms}$ (Figure 3, $t = 1.25 \text{ ms}$) serve as an indicator of intense droplet oscillations.

The primary contact of a slowly falling drop occurs without the formation of sprays and veils expressed in the fast drop coalescence [78,79]. The fluids are combined and the drop substance mainly enters the thickness of the target fluid, where it forms a colored lenticular intrusion, $d_i = 4.37 \text{ mm}$ in diameter and $h_i^l = 0.7 \text{ mm}$ high, with a convex base and a conical upper part ($h_i^u = 0.4 \text{ mm}$ high, Figure 3, $t = 3 \text{ ms}$).

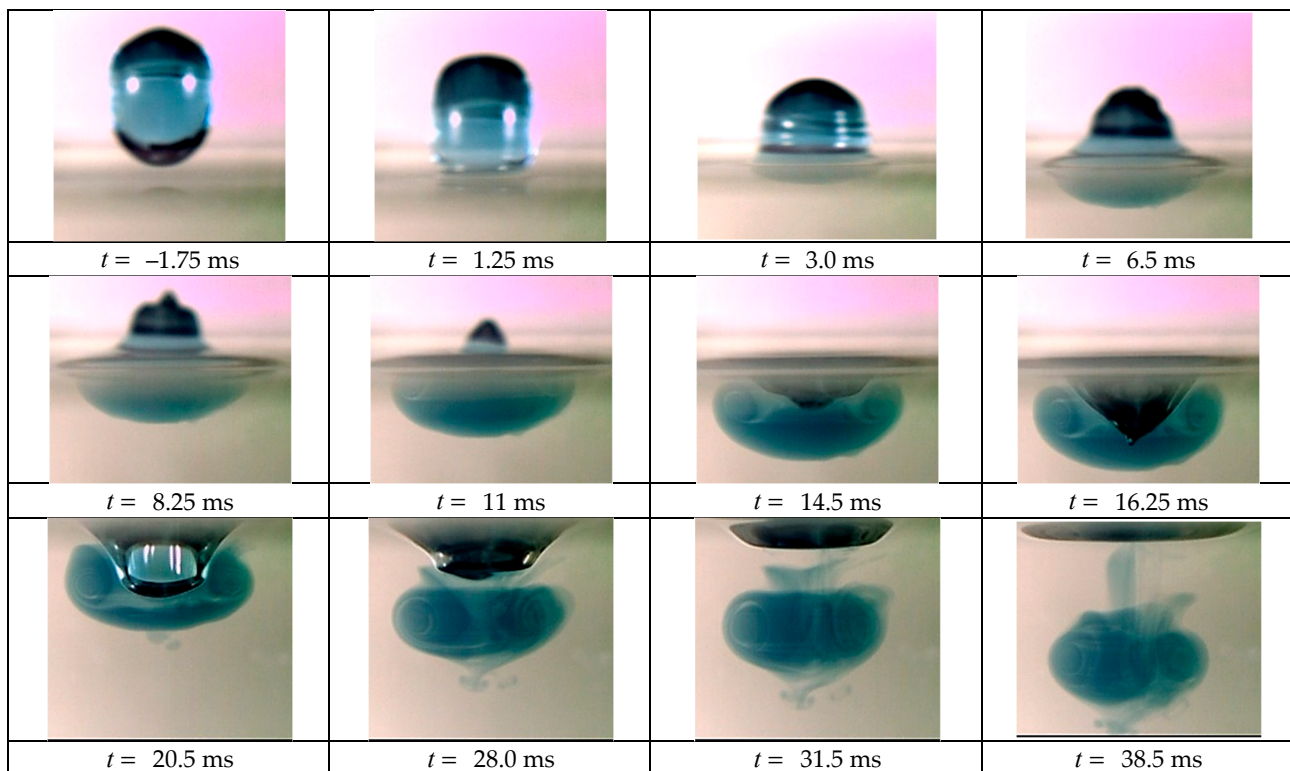


Figure 3. Side view of the flow produced by slow falling drop of an aqueous ink solution diluted at ratio 1:1000 ($\rho = 1.0 \text{ g/cm}^3$, $\sigma = 73 \text{ g/s}^2$, $\mu = 0.01 \text{ g/cm} \cdot \text{s}$ and in Figures below) coalescing with tap water ($D = 4.3 \text{ mm}$, $U = 0.34 \text{ m/c}$, $E_\sigma = 4 \text{ mJ}$, $E_k = 2.24 \text{ mJ}$, $Re = 1460$, $Fr = 2.8$, $We = 6.7$, $Bo = 2.5$, $Oh = 0.0018$, $R_E = E_k/E_\sigma = 0.57$, $R_w = 7.8 \times 10^{-7}$).

A joint free surface covering the target fluid and the inflowing drop remnant retains a convex shape. Annular capillary waves, with a length of $\lambda_d = 0.75 \pm 0.05 \text{ mm}$ and a span (doubled amplitude) of $2A_d = 0.15 \pm 0.05 \text{ mm}$, run from the contact line to the top of the drop remnant (Figure 3, $t = 3.0$ and 6.5 ms).

Waves and accompanying ligaments [76] noticeably distort the shape of the drop residue, in the upper part, of which a conical protrusion $h_d^u = 0.5 \text{ mm}$ high and $d_d^u = 0.7 \text{ mm}$ in diameter appear (Figure 3, $t = 8.25 \text{ ms}$). The dimensions of the dyed intrusion gradually increase and at $t = 11 \text{ ms}$ are $d_i = 6 \text{ mm}$ and $h_i = 1.9 \text{ mm}$. Further, the drop remnant above the free surface retain its conical shape (Figure 3, $t = 11 \text{ ms}$). The cavity, absent in this frame, appears in the field of view at $t = 13 \text{ ms}$ as a dark conical region in the center of the flow with a depth of $h_c = 1.1 \text{ mm}$ and a diameter of $d_c = 1.6 \text{ mm}$.

A rapidly growing cavity expanded into the fluid and pushes the intrusion away from the free surface, on which a part of the drop fluid remain, forming a spot of variable thickness (Figure 3, $t = 14.5 \text{ ms}$). In the bulk of the fluid, the formation of a vortex ring with an outer diameter of $d_r = 6.28 \text{ mm}$ start. The color density around the cavity decreases due to the inflow of the target fluid. The diameter and depth of the cavity grows rapidly: $d_c = 4.3 \text{ mm}$, the rate of its diameter growth is $u_h = dh_c/dt = 0.4 \text{ m/s}$, the depth decreases $u_h = dh_c/dt = 0.4 \text{ m/s}$ (Figure 3, $t = 16.25 \text{ ms}$). As the annular vortex, including the toroidal core and shell descends, its structure becomes more pronounced.

The cavity, which takes a conical shape with a rounded base, reaches its maximum depth $h_c = 2.66 \text{ mm}$ at $t = 20.5 \text{ ms}$ (diameter $d_c = 5.52 \text{ mm}$). Further, the cavity begins to intensively contract to the free surface. The rate of decrease in height reaches $dh_c/dt = -0.2 \text{ m/s}$.

The continued descending colored intrusion transforms into a spherical vortex at $t = 31.5 \text{ ms}$, which was first noticed in [2] and visualized in detail in subsequent works [1,7–9]. The cylindrical wake behind the vortex is surrounded by a painted “conical skirt”. The

toroidal vortex is ahead of a small trickle, with vortex heads of $h_j = 0.57$ mm height with a diameter of $d_j = 1.23$ mm.

The variability of the flow pattern at a low height of free fall of a drop is illustrated by frames from the video film of another experiment, shown in Figure 4. Here, a diluted at ratio 1:2500 alizarin ink was used for the visualization of the cavity shape, which still allows the tracing of the contours of the inflowing intrusion.

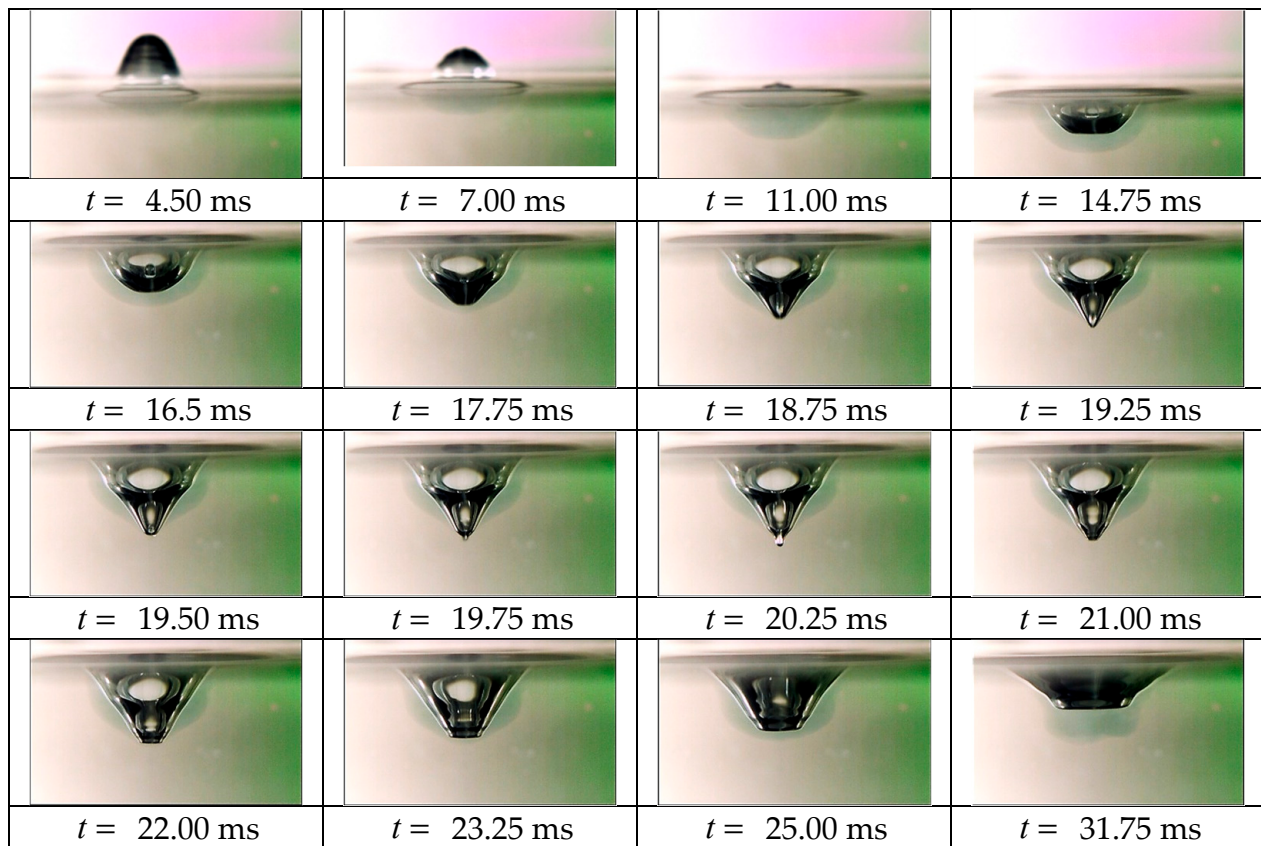


Figure 4. Side view of the flow produced by slow falling drop of an aqueous ink solution diluted at ratio 1:2500 coalescing with tap water ($D = 4.3$ mm, $U = 0.34$ m/c, $E_\sigma = 4$ mJ, $E_k = 2.24$ mJ, $Re = 1460$, $Fr = 2.8$, $We = 6.7$, $Bo = 2.5$, $Oh = 0.0018$, $R_E = E_k/E_\sigma = 0.57$, $R_w = 7.8 \times 10^{-7}$).

The substance of a partially infused drop forms an intrusion $d_i = 4.8$ mm in diameter and $h_i = 0.75$ mm depth in a time of $t = 4.5$ ms ($1/3$ of the drop height is lost). With further drop inflow, the sizes of the intrusion grow rapidly and at $t = 7.0$ ms they are $d_i = 5.2$ mm and $h_i = 1.2$ mm, respectively. The smooth inflow process continues for $\Delta t = 13$ ms. The flat cavity bottom appears in the field of view at $t = 11$ ms.

The shape of the growing cavity gradually changes. At $t = 14.75$ ms, the upper part of the cavity $h_c^u = 0.75$ mm high remains convex, while the lower part takes on a conical shape. Both wall shapes are retained with a further increase in the depth of the cavity. In this case, the colored intrusion forms a cavity shell with an almost uniform thickness of $\Delta h_i = 0.96$ mm. In the center of the cavity, there is a cylindrical column $d_d = 0.75$ mm in diameter, which is the residual of a drop deformed by waves running towards the top.

The upper part of the cavity shell remains rounded at $t = 16.5$ ms. In the center of the cavity bottom there is the remnant of a spherical drop $d_d = 0.65$ mm in diameter continuing to submerge on a cylindrical base $h_d = 0.85$ mm high. The thickness of the pigmented shell is $\Delta h_i = 0.94$ mm.

Further, the cavity takes a conical shape, and its bottom begins to deepen rapidly. Since the top of the droplet remnant that continues to sink moves slower than the cavity bottom, the height of the cylindrical base increases by $h_d = 1.02$ mm. Then, as the cavity

depth continues to grow rapidly, the movement of the droplet remnant accelerates, and at $t = 18.75$ ms the spherical tip of the droplet remnant reaches the cavity bottom. The solid angle at the top of the conical bottom is $\alpha_c = 74^\circ$. The top of the cone “pierces” the dye shell and transforms it into a ring of complex shape. As the bottom center keeps moving with acceleration, it leads to a decrease in the top angle, which at $t = 19.25$ ms is $\alpha_c = 68^\circ$. The colored fluid of the intrusion is accumulated in the transfer horizon vicinity from the convex part of the cavity to the conical one.

It should be noted that movement of the cavity bottom is complex and variable, and that it changes its shape. It becomes flat at $t = 19.50$ ms. After $\Delta t = 0.25$ ms, the bottom is broken by a rapidly growing cylindrical cavity (hole) with a diameter of $d_h = 0.27$ mm and a height of $\Delta h_c = 0.31$ mm, which grows for some time and becomes more noticeable at $t = 20.25$ ms ($d_h = 0.49$ mm, $\Delta h_c = 0.51$ mm). Then, the hole is rapidly drawn into the cavity, the bottom of which becomes flat again at $t = 21.00$ ms. The solid angle at the top of the cavity here is $\alpha_c = 76^\circ$. Dark horizontal stripes at the cavity in the last four and all subsequent frames are the crests of annular capillary waves running up the walls of the cavity.

The dyed drop fluid is still preserved at the fracture shape horizon of the cavity walls ($t = 22.00$ ms). A growing cylindrical splash with a spherical tip $d_s = 1.3$ mm in diameter and $h_s = 1.88$ mm high emerged once again in the cavity center at $t = 23.25$ ms. As the cavity shrinks to the fluid surface, its depth decreases ($h_c = 3.6$ mm, $d_c = 7.72$ mm at $t = 25.00$ ms). The colored intrusive fluid again flows under the cavity bottom. The cylindrical splash in the center of the cavity continues to grow and thicken and reaches a height of $h_s = 3$ mm at $t = 25.00$ ms.

The dyed drop fluid remains in a thin layer up to $\Delta h_i = 0.6$ mm thick around the side walls of the cavity and is accumulated under the moving bottom of the cavity, where a spherical vortex is formed ($t = 31.75$ ms).

Strong differences in the dynamics of formation and shapes of cavities in Figures 3 and 4, which illustrate the variability of the coalescence processes, are caused by the action of several factors. The volume of a drop pinched off the dispenser is not saved. A drop detached from the dispenser oscillates, and the modes of Rayleigh oscillations change in an un-controlled manner from experiment to experiment. Accordingly, the shapes of the head part of the drop surface at the time of primary contact, which can be both flat and pointed, are not saved. The intensity of oscillations, which can be both weak and active, is not conserved either. The coalescence pattern is affected by short capillary waves on the surface of the drop. The nature of the strong variability of the flow parameters at a low free fall height of the drop needs further study.

Additional details of the flow pattern are illustrated by a selection of frames from the video film in the frontal projection shown in Figure 5. The beginning of drop coalescence is accompanied by the formation of an axial capillary wave $\lambda_s = 0.42$ mm long and an annular colored area $d_i^s = 4.4$ mm in diameter and $\Delta r_i = 0.4$ mm wide (Figure 4, $t = 0.75$ ms) into which the drop material enters. As the droplet inflows, both the diameter and width of the colored region grow, the dimensions of which at $t = 3.5$ ms reaches $d_i^s = 5.52$ mm, $\Delta r_i = 0.78$ mm. Between the group of runaway capillary waves with a length of $\lambda_s = 0.83, 0.65, 0.43$ mm and the rest of the drop, a region of smoothed liquid with a diameter of $\Delta r_\lambda = 7$ mm is formed. Capillary waves run away from the contact line along the drop surface, the length of which at the top is $\lambda_d = 0.35$ mm.

With time, the diameter of the region of contact between the droplet and the target fluid liquid decreases and at $t = 5.75$ ms is $d_c = 3.12$ mm. The distribution of the light intensity in the colored area in a cell of size 34×34 mkm, moving along a semicircle with a radius of $r = 2.4$ mm, is shown in Figure 5. In the spatial spectrum of the illumination distribution, scales of $\Delta l_\varphi = 1.5, 0.78, 0.5, 0.3$ mm are distinguished.

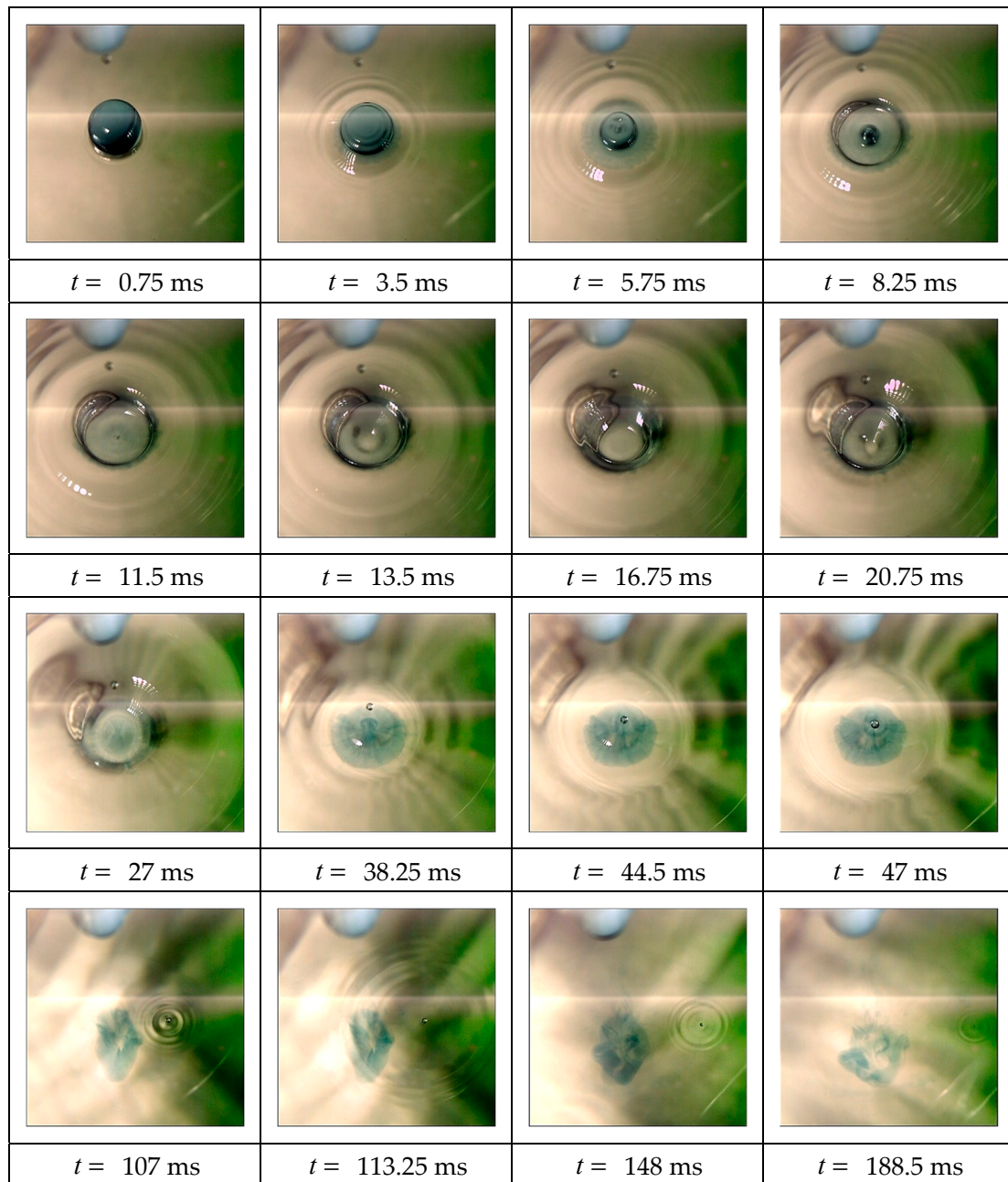


Figure 5. Top view of the flow produced by slow falling drop of an aqueous ink solution diluted at ratio 1:2500 coalescing with tap water ($D = 4.3$ mm, $U = 0.34$ m/c, $E_\sigma = 4$ μ J, $E_k = 2.24$ μ J, $Re = 1460$, $Fr = 2.8$, $We = 6.7$, $Bo = 2.5$, $Oh = 0.0018$, $R_E = E_k/E_\sigma = 0.57$, $R_w = 7.8 \times 10^{-7}$).

The outer diameter of the dyed area is $d_i^s = 6.24$ mm and the width of the quiet zone is $\Delta r_\lambda = 1.6$ mm (the leading edge advance velocity is $u = d(\Delta r_\lambda)/dt = 28$ cm/s). The minimum phase velocity of capillary wave propagation is $c_{ph}^{min} = 23.2$ cm/s for waves with length $\lambda_c = 1.74$ cm, the minimum group velocity is $c_g^{min} = 17.7$ cm/s for $\lambda_c = 4.4$ cm. The speeds of the inner boundary of the annular capillary wave domain expansion are shown in Table 1.

Table 1. Speed of the inner boundary of the annular capillary wave domain expansion.

t , ms	5.75	8.25	11.5	13.5	16.75
u , cm/s	38.71	34.76	33.04	35.10	33.95

The remnant part of a drop $d_d = 1.38$ mm in diameter is retained in the center of the colored confluence region of diameter $d_d = 6.8$ mm at $t = 8.25$ ms. The fluid surface loses its convexity when a cavity with a flat bottom $d_c = 4.9$ mm in diameter is formed.

At the same time, a bridge is detached from the mother fluid, which is formed during the detachment of a drop, which, after a series of oscillations [97], contracts into a spherical satellite $d_{sa} = 0.84$ mm in diameter, which begins free fall. At $t = 11.5$ ms, the drop residual almost completely merges with a deepening cavity $d_d = 7$ mm in diameter. Three annular capillary waves deform the side walls of the cavity.

Gradually, the remnant part of the drop pushes through the cavity bottom, and at $t = 13.5$ ms, a conical end with a base diameter of $d_c^c = 2.58$ mm begins to form in the center of the cavity. With time, the depth of the cavity increases, as well as the diameter of the conical region base, which is in contact with the rest of the flat cavity bottom. The distribution density of the pigment is uneven at the cavity bottom in a ring with a radius $6 < r_p < 7$ of 1 mm and a width of $\Delta r_p = 1.0$ mm. Gradually, the outer and inner boundaries of the annular region with an uneven distribution of colored fluid become more and more clearly defined. At $t = 20.75$ ms, a rapidly growing cylindrical depression $d_h = 1.3$ mm in diameter begins to form in the cavity center. The diameter of the outer edge of the intrusion is $d_i = 7.8$ mm.

Over time, the uniformity of the pigment distribution is disturbed; in the central part with a diameter of $d_c^i = 2.86$ mm, it is denser, and at the periphery of the bottom of the cavity, it is less dense ($t = 27$ ms). As the cavern is filled, the shape of the colored flow pattern changes; in the outer part of which, images of annular structures of diverging waves are expressed, as well as radial and oblique beams of capillary waves reflected from the walls of the pool ($t = 38.25$ ms). The diameter of the pigmented area here is $d_i = 6.16$ mm.

The non-uniform distribution of illumination in the center of the image along a semicircle with a radius of $r = 2.5$ mm is shown in Figure 6. The signal spectrum contains perturbations with a scale of $\Delta l_\varphi = 1.5, 1, 0.7, 0.6, 0.4$, and 0.3 mm.

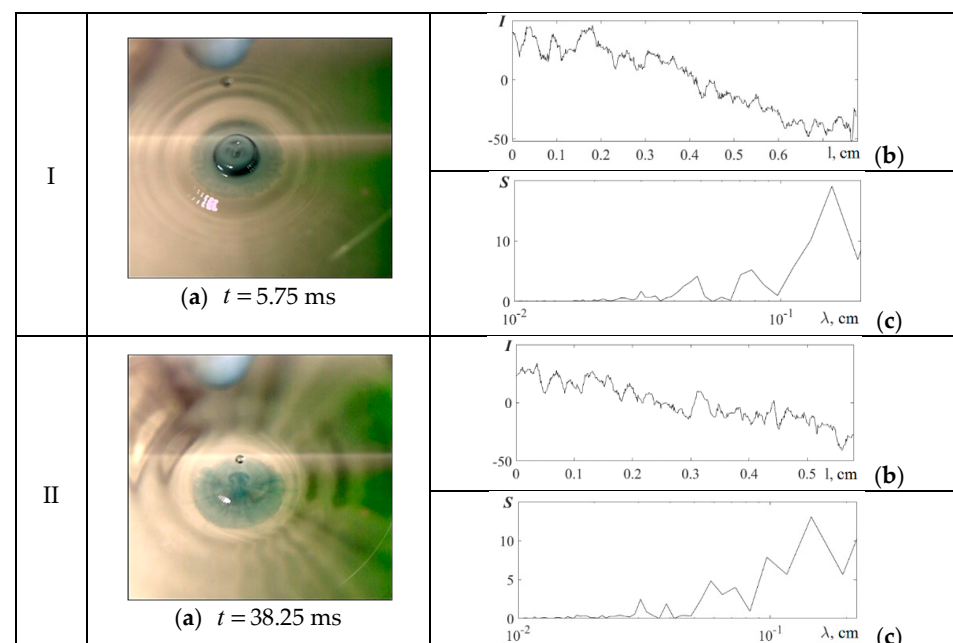


Figure 6. Azimuthally distributions of the colored area illumination of the drop coalescence patterns in selected frames I and II: (a)—frames at $t = 5.75, 38.25$ ms in Figure 5, (b)—illumination I , (c)—spatial spectra S .

A group of capillary waves is formed when the primary satellite, $d_s^p = 0.84$ mm in diameter, touches the liquid surface at $t = 47$ ms (to the upper right of the disturbance center). During $\Delta t_s^p = 60$ ms, the satellite located on the free fluid surface oscillates and

moves slowly. Then, at $t = 107$ ms, the satellite touches the fluid surface, loses part of its mass, and bounces off the fluid surface with the formation of a new group of annular capillary waves. The diameter of the rebounded satellite is $d_s^s = 0.47$ mm. Under the action of gravity, the satellite returns and forms a new group of annular waves at $t = 148$ ms.

Then the process is repeated. The satellite contacting with a certain delay loses part of its mass and is again thrown into the air. The next touch is observed at $t = 188.5$ ms. The process of rebounds of droplets drifting over the a target fluid surface was traced in more detail in [98].

4.2. Evolution of the Flow Pattern in the Transition Mode of Droplet Coalescence

With an increase in the height of free fall and the drop primary contact velocity, the rate of intrusion formation accelerates. In the first frame at $t = 3.5$ ms, the flow pattern shows the outer boundary of the intrusion region with a diameter of $d_i = 6.7$ mm, a growing cavity, side walls, and a cavity bottom with a diameter of $d_c = 6.06$ mm and a depth of $h_c = 0.68$ mm. The cavity is surrounded by a lenticular intrusion of inflowing fluid with a thickness of $0.1 < \Delta r_i < 1$ mm. The remnant of a submerging drop, $d_d = 1.9$ mm in diameter and $h_d = 1.73$ mm high, can be traced in the cavity center, protruding above the undisturbed level of the liquid surface. The colored fluid is unevenly distributed in the confluence area; its density is maximum in the center and on the outer boundary of the flow. The shape of the intrusion bottom shows a roughness of up to $\Delta r_i \sim 0.1$ mm.

As the flow develops, the flow pattern becomes more and more complex; at $t = 5.25$ ms, the remnant of a submerging drop $d_d = 0.7$ mm in diameter is located in its center, reaching the layer of capillary rise of the liquid. At a depth of $h_c = 1.4$ mm, there is a flat bottom of a cavity, $d_c = 6.54$ mm in diameter, surrounded by a lenticular intrusion ($d_i = 7.5$ mm, $h_i = 2.5$ mm). The intrusion thickness in the center of the flow reaches $r_i = 1.12$ mm. In the upper part of the flow, the fibrous structures are folded into separate skeins $d_v \sim 1$ mm in diameter (four skeins). As the intrusion depth increases, its lower surface becomes smoother.

A cavity with a flat bottom $h_c = 2.95$ mm deep and convex walls with a maximum diameter of $d_c = 7.42$ mm is surrounded by a fluid drop layer ($t = 9$ ms), with a maximum thickness of $r_i = 1.07$ mm in the center and on the walls of the cavity. The intrusion has a minimum thickness of $r_i = 0.28$ mm at the horizon of the cavity bottom.

As it deepens, the shape of the cavity bottom begins to approach a spherical one, and the colored fluid is more evenly distributed along its bottom and walls in a layer $0.25 < r_i < 0.67$ mm thick. Small-scale violations of the pigment distribution are observed in the center of the flow in the vicinity of the outer edge of the dyed fluid layer ($t = 11.5$ ms).

The caustics in the lower part of the cavern are evidence of a complex surface topography, in which sharp peaks and smoother depressions are expressed.

With further deepening, the cavity walls acquire a more complex and variable shape: the upper part is close to conical, and the lower part is a distorted hemisphere in which protrusions are pronounced at a depth of $h_c = 2.94$ and diameter $d_c = 6.04$ mm. Moreover, at the cavity bottom, the thickness of the colored layer is minimal, at $r_i = 0.1$ mm, and in the upper part a colored belt is formed with an uneven distribution of the pigment, with a maximum thickness of $r_i = 0.88$ mm ($t = 18$ ms). The formation of additional conical outer and inner boundaries of the cavity is associated with the features of light propagation in a partially colored transparent fluid with complex-shaped cavities.

The change in the shape of the cavity sections from convex in Figure 7 at $t = 11.5$ ms and concave at $t = 23.5$ ms illustrates the complexity of the flow pattern in the contacting fluids. The pigment is collected in a relatively narrow ring $\Delta h_p = 2.76$ mm high centered at a depth of $H_i = 4.4$ mm. The pointed cavity bottom is covered by its own painted shell, $\Delta r_i = 1.56$ mm thick.

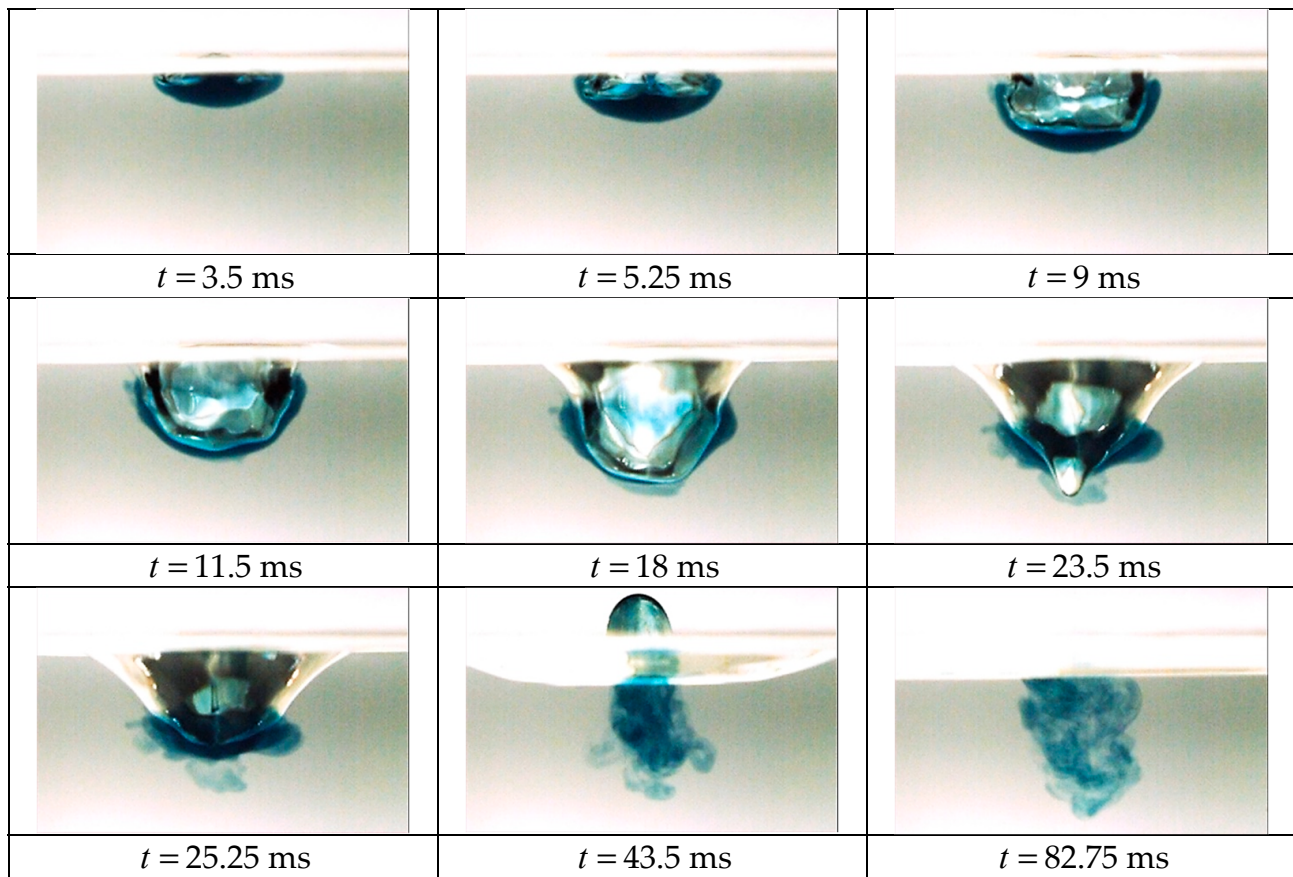


Figure 7. Side view of the flow evolution pattern in the transitional mode (drop of an diluted aqueous ink solution 1:800, $\rho = 1 \text{ g/cm}^3$, $\sigma = 73 \text{ g/s}^2$, $\mu = 0.01 \text{ g/cm} \cdot \text{s}$ is immersed in tap water: $D = 4.3 \text{ mm}$, $U = 1.0 \text{ m/s}$, $E_\sigma = 4.2 \text{ } \mu\text{J}$, $E_k = 20.8 \text{ } \mu\text{J}$, $\text{Re} = 4300$, $\text{Fr} = 24$, $\text{We} = 60$, $\text{Bo} = 2.5$, $\text{Oh} = 0.0018$, $\text{R}_E = E_k/E_\sigma = 4.95$, $\text{R}_W = 7.2 \times 10^{-6}$).

Over time, the region of the colored liquid continues to slowly descend, and the cavity bottom, due to collapse, approaches the free surface.

The pointed central protrusion at the cavity bottom rapidly retracts inward at $t = 25.25 \text{ ms}$. Gradually, the shape of the cavity is leveled and approaches the conical one, and the area of colored fluid is collected in a ring with an outer diameter of $d_r = 8.13 \text{ mm}$ in the belt around the lower cone of the cavity.

The cavity bottom becomes flat again at $t = 43.5 \text{ ms}$, when a splash appears above the free surface, and a narrow colored region surrounded by several jets with ring vortices at the tops remains in the fluid column. With time, the shape of the colored fluid region becomes more and more irregular; at interval $78 < t < 82.75 \text{ ms}$, fibrous structures are expressed under the flat cavity bottom, forming spots, spirals, and skeins.

4.3. Frontal View of the Flow Pattern in the Transition Mode

Samples from the video recording of the substance spreading pattern of a drop falling from a height of $H = 5 \text{ cm}$, observed through a free surface (the line of sight is deflected by an angle of 30° from the vertical), are shown in Figure 8. The primary contact of a drop with a fluid is not accompanied by the formation of noticeable sprays or a veil; the drop substance smoothly inflows into the fluid and is partially distributed on the free surface, forming a colored ring with a diffuse outer edge $\Delta r_i = 2.95 \text{ mm}$ wide.

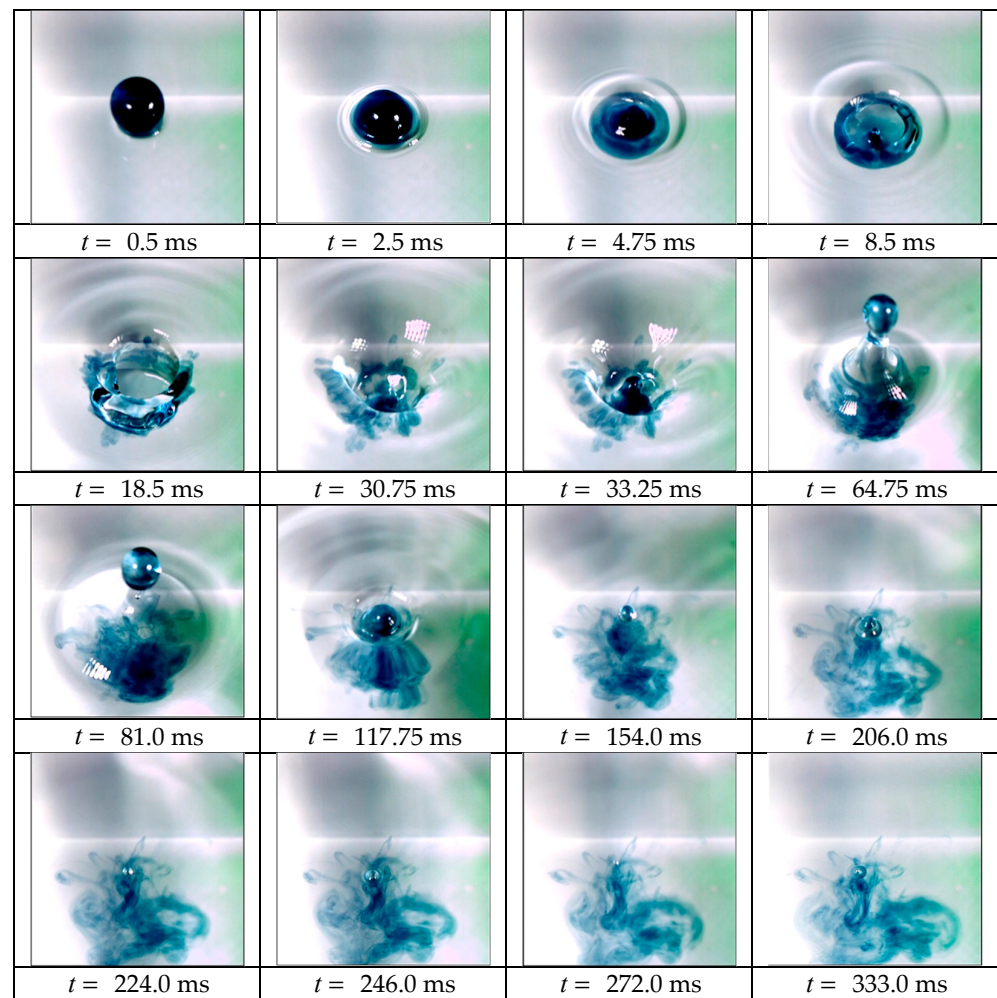


Figure 8. Top view of the flow produced by a slow falling drop of an aqueous ink solution diluted at ratio 1:800 coalescing with tap water in the transitional mode ($D = 4.3 \text{ mm}$, $U = 1.0 \text{ m/s}$, $E_\sigma = 4 \text{ mJ}$, $E_k = 20.8 \text{ mJ}$, $\text{Re} = 4300$, $\text{Fr} = 24$, $\text{We} = 60$, $\text{Bo} = 2.5$, $\text{Oh} = 0.0018$, $R_E = E_k/E_\sigma = 4.95$, $R_W = 7.2 \times 10^{-6}$, shooting rate is 4000 fps).

As the fluid inflows, the partially submerged drop is surrounded by an expanding protruding smooth rim $\Delta r_e \sim 0.5 \text{ mm}$ wide, which is a source of annular capillary waves $\lambda_s = 0.34$ and 0.5 mm length, $t = 2.5 \text{ ms}$. The consideration of the video film shows that at this stage, short capillary waves of small amplitude run along the drop surface. The top of the drop falls below the unperturbed free surface at $t = 4.75 \text{ ms}$. The drop substance unevenly covers the lateral vertical wall of the crown. Due to the partial shading of the image, the drop remnant is not clearly distinguished relative to the densely colored cavity bottom.

Capillary waves propagate in an annular layer of the width $\Delta r_\lambda = 1.56 \text{ mm}$, the inner boundary of which slowly moves away from the center of the flow. Gradually coalescing with time, the drop remnant takes a conical shape with a base diameter of $d_d = 2 \text{ mm}$, which is located at the bottom of a plunging cavity with a diameter of $d_c = 3.5 \text{ mm}$. The drop substance is non-uniformly distributed on the walls of the cavity. A smooth flow region adjoins the growing crown $\Delta r_s = 0.8 \text{ mm}$ wide, surrounded by the field of annular capillary waves.

Over time, surface tension forces unevenly contract the inner edge of the crown, the diameter of which becomes smaller than the diameter of the cavity (at $t = 8.5 \text{ ms}$ it is $d_c^a = 5.54 \text{ mm}$). The width of the intermediate region is $\Delta r = 1.63 \text{ mm}$ in the right part of the image. In the center of the flow, a cylindrical remnant of the submerging drop remains,

from the top of which capillary waves separate a spherical droplet with a diameter of 0.65 mm, which then smoothly merges with the target fluid within $\Delta t = 4$ ms.

The axial uniformity of pigment distribution is gradually disturbed, and individual dark and light spots on the crown as well as filaments up to $l_p = 1.45$ mm long and up to $w_p = 0.6$ mm wide in the liquid column are distinguished in the flow pattern. The outer edge of the colored fluid area is uneven. It has pronounced individual fingers on the top left. The inner edge of the crown has an irregular shape; a rib is expressed on it, with separate spots of liquid drops inside. The lateral surface of the cavity is covered with capillary waves $\lambda_s = 0.7$ mm long, visualized by the pigment distribution (Figure 8, $t = 18.5$ ms).

Gradually, as the cavity takes a conical shape (as in Figure 7, $t = 23.5$ ms), its diameter gradually increases: at $t = 18.5$ ms it is $d_c = 5.44$ mm, and at $t = 30.75$ ms it is $d_c = 7.16$ mm. In the drop substance distribution, individual fibers up to $\delta l_f = 0.8$ mm wide are expressed, which form a complex fibrous structure. Wedge-shaped depressions with sharp peaks appear on the walls and cavity bottom. The bottom cavity shape in the region of an appearing splash with a diameter of $d_s = 2$ mm is distorted by fine internal flows.

Further, a drop $d_d = 2.4$ mm in diameter at $t = 64.75$ ms begins to form at the top of a rapidly growing conical splash, $d_s = 2.9$ mm in diameter, at the cavity bottom. At the same time, the general structure of the pigment distribution on the rest of the crown is preserved. The splash growth at $t = 64.75$ ms is accompanied by a general change in the pigment distribution, in which ring structures appear. The splash height here is $h_s = 4.75$ mm, and the minimum isthmus diameter is $d_s^{\min} = 1.18$ mm.

A rapidly sinking splash leaves a drop $d_s^p = 2.7$ mm in diameter in the view field, under which there is a satellite $d_s^s = 0.37$ mm in diameter ($t = 81$ ms). In the pigment distribution pattern, individual fibers and smoother spots are expressed. The immersion of the splash top is accompanied by the generation of the next group of annular capillary waves.

Upon the contact of the returning splash drop on the free surface at $t = 117.75$ ms, a new group of capillary waves with a length of $\lambda_s = 0.4, 0.55$ mm is formed. The width of the spreading band, in which a significant part of the substance of the colored drop remains, is $\Delta r_i = 0.9$ mm. Separate vortex loops up to $l_l = 4$ mm long and up to $\delta w = 0.6$ mm wide adjoin the propagation region.

After the partial coalescence of the returned drop at $t = 117.75$ ms, a freely drifting drop $d_s^s = 1.2$ mm in diameter remains on the surface of the target fluid, which again comes into contact with the fluid at $t = 127.5$ ms and generates a new group of annular capillary waves. The distribution pattern of the pigment changes again, with radial streams and rings appearing in it. The drifting droplet again touches the surface at $t = 155.5$ ms and generates a new group of capillary waves.

In all phases of the process of secondary drops rebounds, a change occurs in the pattern of the drop substance distribution, in which large formations such as dipole jets with a tip, radial loops emanating from the flow center, and fibrous jets of complex geometry are distinguished. At the later evolution stages, in the right part of the flow, an elliptical annular vortex first appears in the pattern of the colored fluid (Figure 8, $t = 224$ ms), which gradually rounds off for $t = 246$ ms and forms an almost regular ring (Figure 8, $t = 272$ ms), which is deformed by background flows at $t = 333$ ms. Simultaneously, to the left of the degenerate ring, a new annular vortex is formed in the center of the frame.

The features of the colored drop substance distribution in the target fluid are illustrated by the graphs shown in Figure 9. The intrusion diameter increases monotonically and reaches its maximum value at $t = 17, 14$, and 16 ms (for curves 1, 2, 3, $a = 4.2, 3.7, 2.8$, respectively). Variations in the intrusion diameter on curve 2 are synchronized with the detachment of divergent lobes. The decrease in the intrusion diameter is consistent with the onset of a rapid transformation of the cavity central cylindrical part and the formation of a splash analog (Figure 7, $t = 25.25$ ms), when the annular vortex contracts into the vortex core.

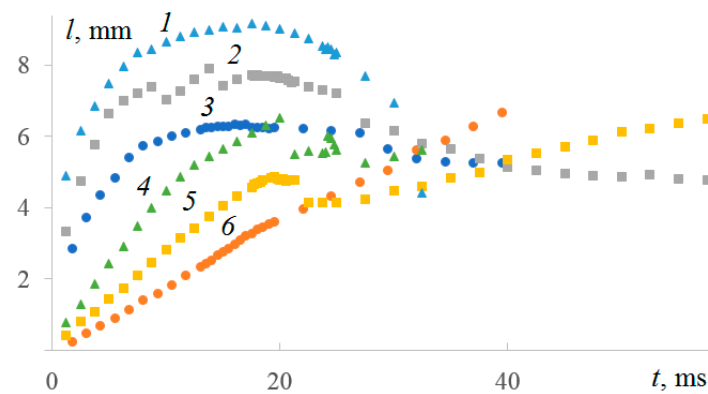


Figure 9. Evolution of intrusion dimensions at different values of drop contact velocity: curves 1, 2, 3—diameter, 4, 5, 6—intrusion height at $U = 1.0, 0.6$ and 0.34 m/s, respectively.

The position of the intrusion lower edge changes monotonously with time: at a high fall height over the entire observation interval, and at low heights, until the start of intensive collapse of the cavity adjacent to the intrusion surface.

4.4. Evolution of the Drop Material Distribution Pattern in the Target Fluid in the Impact Mode of Coalescence

The main features in the flow pattern at relatively high drop contact velocities are the ejection of small droplets from the tops of the spikes forming sprays [99] and the cavity formation from the moment of primary contact. Simultaneously, the continuum drop splits into thin jets on the contact line of the merging fluids [78], which leave wakes forming colored fibers in the target fluid [79]. Presented in Figure 10, frames from the video film illustrate the flow pattern evolution in the lateral projection of the coalescence impact mode, at a drop contact velocity $U = 3.1$ m/s. The colored strip in the target fluid, which begins to form from the moment of the initial contact of the drop (Figure 10, $t = 0.1$ ms), expands vigorously, and after $\Delta t = 0.5$ ms its depth reaches $h_i = 0.73$ mm (the velocity of the lower edge is $u_i = 1.1$ m/s). The boundaries of the colored fluid domain are irregular; individual fine jets are visible on them, separated by wider depressions at $t = 0.6$ ms.

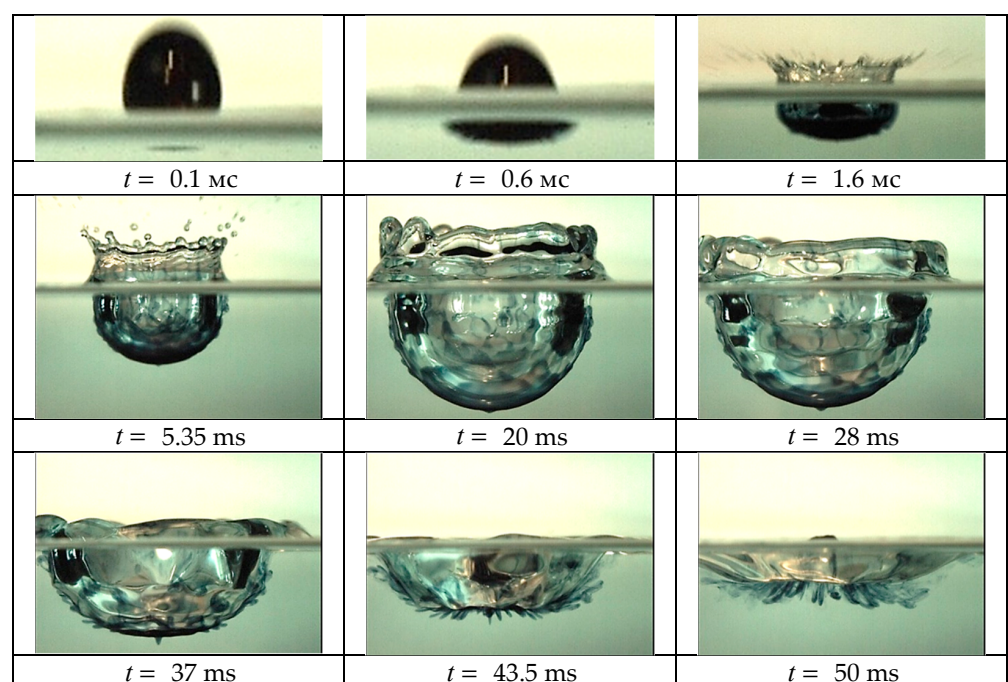


Figure 10. Cont.

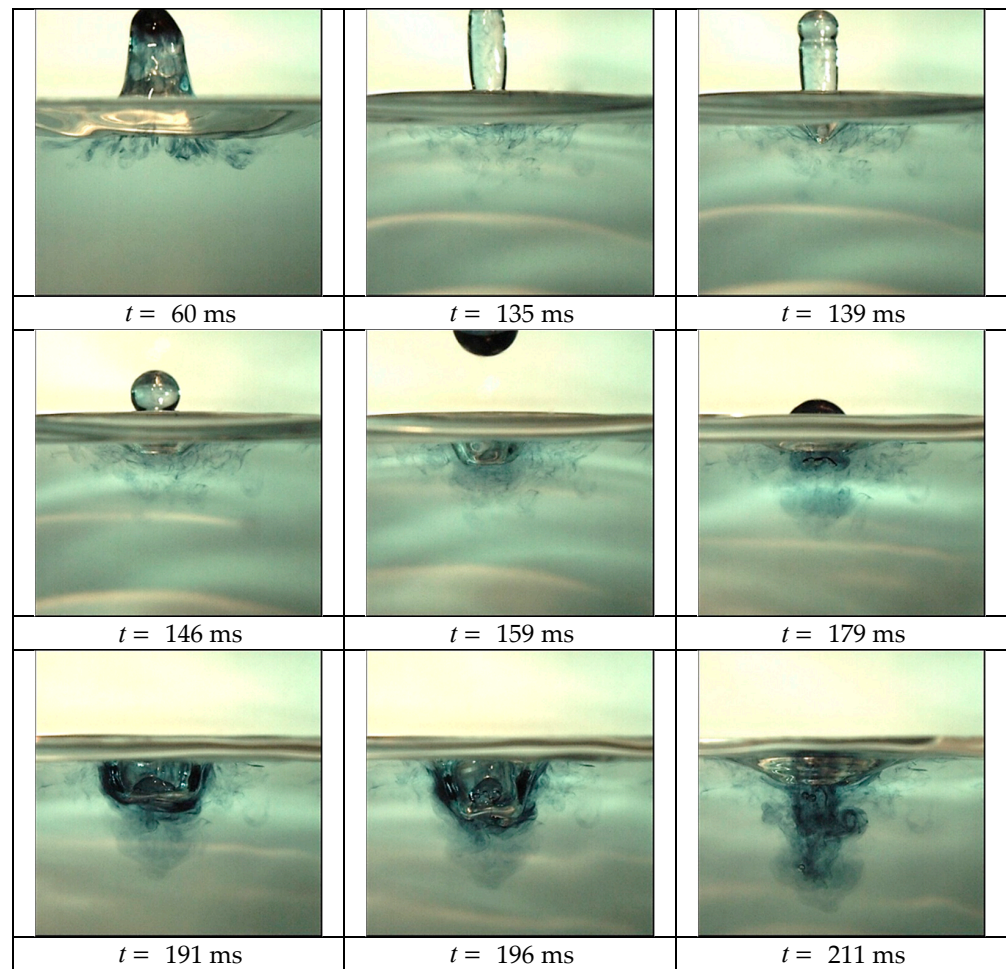


Figure 10. Side view of the impact flow produced by falling drop of an aqueous ink solution diluted at ratio 1:100 coalescing with tap water ($D = 4.3$ mm, $U = 3.1$ m/s, $E_\sigma = 4$ mJ, $E_k = 200$ mJ, $Re = 13,300$, $Fr = 230$, $We = 570$, $Bo = 2.5$, $Oh = 0.0018$, $R_E = E_k/E_\sigma = 50$, $R_W = 7 \times 10^{-5}$, shooting speed 4000 fps).

At the flat bottom center of a rapidly growing cavity $h_c = 2.2$ mm deep, at $t = 1.6$ ms one can see the remnant of a submerging drop $d_d = 4$ mm in diameter. The thickness of the colored fluid layer here is $h_i = 1.14$ mm. From the tops of the crown teeth, groups of small droplets fly out. Seven groups of jets in the left part of the figure are located at angles to horizon $15^\circ < \alpha < 42^\circ$. Droplets are also visible to the right of the cavity, but they are less pronounced in terms of the applied lighting conditions. The crown has a complex shape and thin jets are visible on its edge forming spikes up to $l_j = 2.27$ mm long. The drop substance is unevenly distributed over the cavity surface; individual fibers are traced, especially in the left part of Figure 10, $t = 1.6$ ms.

The beginning of the splash subsidence at $t = 5.35$ ms and a decrease in its expansion rate are accompanied by the generation of a capillary waves group and the emergence of a larger droplet. The drop substance is concentrated on the crown in thin dyed fibers $0.38 < \delta_f < 1.14$ mm thick. At the cavity bottom, the fibers form a reticular formation (mesh or network) with triangular cells about $l_n \sim 2$ mm in length. The edge of the bottom of the cavity is uneven; it contains individual protrusions up to $h_e = 0.4$ mm high.

The fall of the crown is accompanied by an increase in the amplitudes of the capillary waves running down along the wall from its edge; the distribution of the drop pigment becomes more complex. Separate vortices begin to penetrate into the fluid, which form along the nodes of the colored fibers reticular formation (mesh in Figure 10, $t = 20$ ms). During $\Delta t = 28$ ms, the upper edge of the splash leveled out, and separated colored layers

$h_l = 2.0\text{--}2.5$ mm high appear in the cavity. The tops of some vortices have separated from the cavity walls.

As the cavity begins to collapse, the height of the upper layer increases, the lower layers contract, and the vortices are elongated into loops ($t = 37$ ms), the length of which increases as the cavity depth decreases [100]. The appearance of a dark spot in the cavity center indicates the beginning of the splash formation, with a spherical tip and a narrow neck, $d_s^{\min} = 2.1$ mm. The length of the bottom loops reaches $l_l^b = 1.6$ and the side loops are $l_l^s = 4.8$ mm in length at $t = 43.5$ ms.

The diameter of a fully formed splash at $t = 50$ ms is $d_s = 2.9$ mm. The pigment is distributed unevenly along the walls of the cavity, which has taken a conical shape and forms fibrous structures in the fluid column. When the fluid adjacent to the cavity is drawn into the growing splash, the loop system is destroyed, leaving only wakes in the form of thin fibers in the fluid ($t = 60$ ms).

With time, the shape of the oscillating fluid surface in the impact region of the drop changes from concave to convex ($t = 135$ ms). In this case, the sinking splash forms a new cavity. The independence of the motion of the target fluid and the sinking surge leads to the formation of a complex flow geometry. Rapid growth of a cavity $h_c^s = 1.9$ mm deep and $d_c^s = 5.1$ mm in diameter, with a cone opening angle of $\alpha_c = 100^\circ$ at $t = 139$ ms, causes the thinning of a slowly sinking splash.

Then the cavity is quickly filled, and the wake of a drop fall with colored fibers remains in the fluid thickness. The picture of their distribution is distorted by a new growing cavity, shown at $t = 146$ ms. A droplet with a diameter $d_d^s = 4.6$ mm, which had previously ejected from the top of the splash, approaches to the cavity base.

The immersing drop forms a new cavity surrounded by a finely structured fluid, into which a densely colored drop, which has previously flown out from the top of the splash, enters it (Figure 10, $t = 159$ ms).

A partially submerged drop (Figure 10, $t = 179$ ms) forms a new cavity and causes the redistribution of the colored fluid left by the previous drop, $h_i = 2.4$ mm high and $d_i = 5.7$ mm in diameter (light bands in the frame are caustics of the wave running on the fluid surface).

The cavity bottom at $t = 188$ ms is flat and uneven; a group of bubbles gather near its wall, the positions of which quickly change. Then, a cylindrical protrusion is formed at the bottom of the growing cavity. The sinking rate of the cavity bottom is archived as $u_c^b = 0.22$ m/s.

The crossing of the fluid surface by the drop back edge is accompanied by the formation of a new densely colored cavity, on the flat bottom of which the remnant of the drop is visible (Figure 10, $t = 191$ ms). The cavity walls are distorted by groups of capillary waves. The remnants of the drop pigment form outlined vortex and jet patterns in the fluid thickness, consisting of individual more or less brightly colored fibers. Air bubbles remain in the center of the droplet remnant back edge, and then sink and connect with the cavity bottom at $t = 191$ ms. The cavity walls covered with capillary waves have a complex shape. The colored fluid on them forms a complex pattern with vortices and fibers (Figure 10, $t = 196$ ms).

The cavity collapses with the formation of a group of capillary waves with a length of 0.46, 0.62, 0.65 mm, and leaves in the fluid a cylindrical region of colored fluid with a vortex head and adjoining loops (Figure 10, $t = 211$ ms). The further evolution of the picture of the drop substance structured distribution in the target fluid was traced in [80].

4.5. Frontal Observations of the Drop Flow Pattern in Impact Mode

The primary contact of a diluted ink solution drop falling at a velocity of $U = 3.1$ m/s with a fluid at rest is accompanied by the formation of a system of thin radial jets with a thickness of no more than $\delta_w < 0.07$ mm. They are spaced from each other at a distance of $\delta l_\varphi \sim 0.1 \dots 0.2$ mm and protrude beyond the drop edge by no more than $\delta r_t \sim 0.4$ mm (Figure 11, $t = 0.1$ ms). In the center of the flow pattern at $t = 1.1$ ms, there is a drop

remnant. It merges with the target fluid. From the contact line of merging fluids, thin colored jets with thickness $\delta_w < 0.3$ mm placed with a step of $\delta l_\varphi \sim 0.6 \dots 0.7$ mm spread radially along the bottom and walls of the cavity.

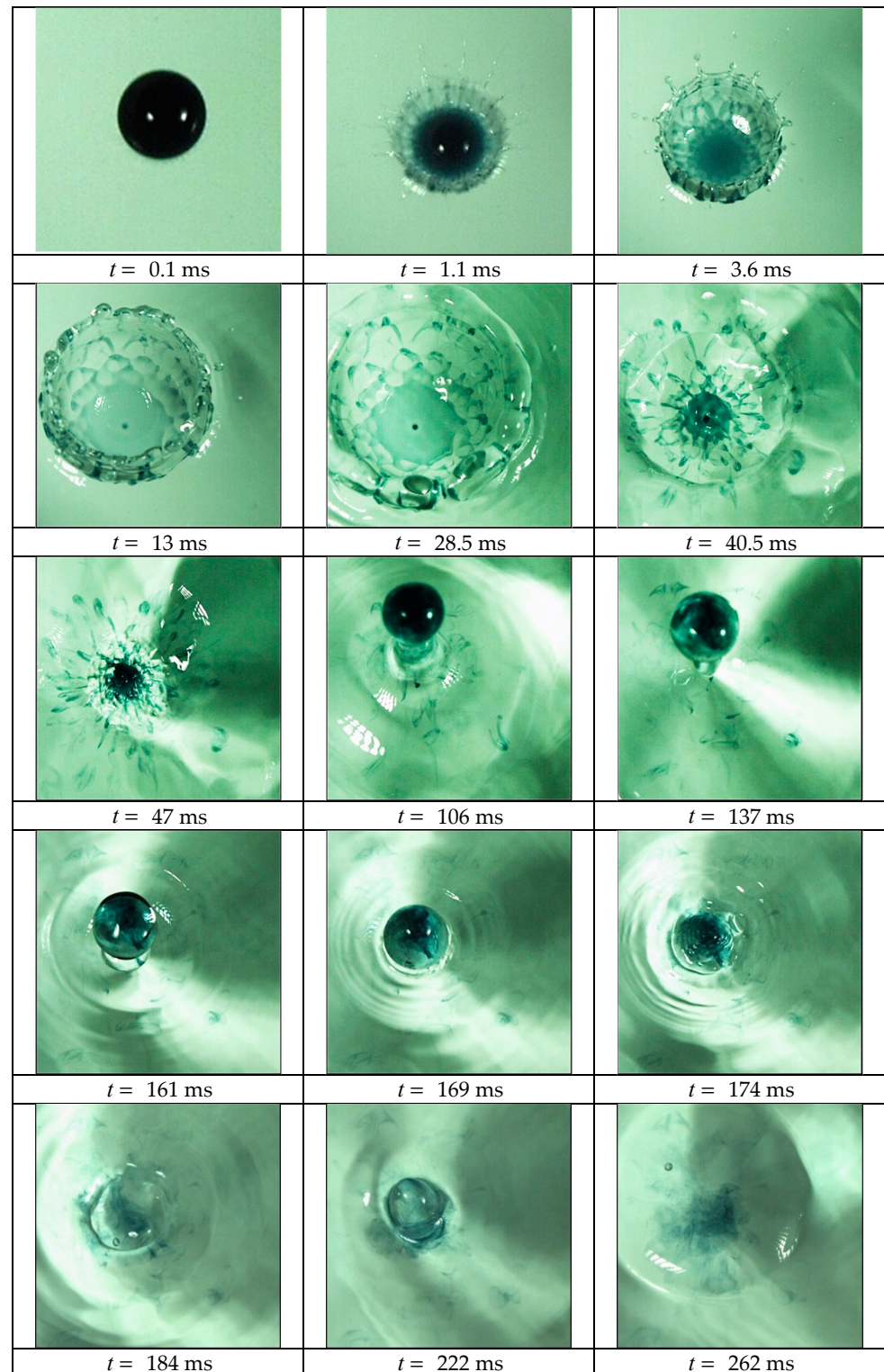


Figure 11. Frontal view of the impact flow produced by falling drop of an aqueous ink solution diluted at ratio 1:100 is coalescing with tap water ($D = 4.3$ mm, $U = 3.1$ m/s, $E_\sigma = 4.0$ mJ, $E_k = 200$ mJ, $Re = 13,300$, $Fr = 230$, $We = 570$, $Bo = 2.5$, $Oh = 0.0018$, $R_E = E_k/E_\sigma = 50$, $R_W = 7 \times 10^{-5}$).

Spectral analysis of the illumination pattern shown in Figure 11 at $t = 1.1$ ms allows us to distinguish the colored fibers with transverse dimensions of $\Delta l_\varphi = 0.23, 0.14, 0.12, 0.07, 0.06, 0.05$ cm in the axial pigment density distribution. Both the colored substance of the drop and the transparent target fluid penetrate into the spikes protruding from the crown of the cavity and into separated drops flying from their tops. Flow acceleration in contact line vicinity forming spikes and fast spray droplets, the velocity of which exceeds the velocity of the falling drop, indicates the influence of the internal energy conversion processes on both the structure and the dynamics of the fine flow components [101].

As the flow pattern evolves, the distribution pattern of the drop material along the cavity bottom becomes more complicated. On the crown wall, the radial distribution of fibers is preserved; at the cavity bottom, a reticular formation with triangular cells with pronounced annular boundaries with radii of $R_\varphi = 2.5, 3.5, 5.1$ mm is formed. On samples at $t = 1.1$ ms and at $t = 3.6$ ms, one can see the cyclical ejection of droplets from the tops of various spikes, which are located at a distance of $R_t = 6.2$ mm from the pattern center with a step of $\Delta l_\varphi = 2.3 \dots 3.3$ mm. The line distribution of the drop substances is clearly visible on the outer side in the lower part of the crown. In the spectral pattern of the density of the axial distribution of the drop material over the deformed surface of the target fluid at $t = 3.6$ ms, shown in Figure 11, local maxima are distinguished at scales of $\Delta l_\varphi = 0.23, 0.15, 0.11, 0.08, 0.07, 0.05$ cm.

As the size of the crown and cavity grows, the color contrast decreases due to the dilution of its concentration in the growing elements. In the images of individual teeth, point distributions of the droplet pigment are clearly visible. Around the crown, the first groups of annular capillary waves, $\lambda_s = 0.9, 1.1$ mm long, are visualized (Figure 11, $t = 13$ ms). The drop substance moves along the cell boundaries and collects at the nodes, under which colored streams are formed, penetrating the bottom of the cavity. With time, the length of capillary waves increases and at $t = 28.5$ ms reaches $\lambda_s = 1.55\text{--}2.0$ mm. Gradually, the brightness of the central dye spot color, $d_c^p = 0.6$ mm in diameter, which is the base of the growing vortex fibers, increases. The fibers can also be seen in Figure 10 at $t = 28$ ms. There are three tiers of pigmented spots with outer boundaries at a distance of $R_\varphi = 5.9, 8$ mm. On the edge of the crown, the centers of the depressions between the teeth are more brightly colored.

The growing splash distorts the shape of the cavity bottom and modifies the pattern of pigment distribution along the cavity bottom. Here, the central part with pronounced radial loops becomes brightly colored. The radial distribution of the drop material at the base of the emerging burst is characterized by transverse length scales of $\delta l_\varphi = 0.43, 0.19, 0.13, 0.1, 0.08, 0.07$ cm (Figure 11, $t = 40.5$ ms).

Inside the splash, the pigment is also distributed non-uniformly; it is concentrated in protrusions, $\delta d = 1.2\text{--}1.3$ mm in diameter, separated by transparent depressions. Previously, the complex structure of the splash surface was noted in [101]. A growing splash, at the top of which a drop $d_s^1 = 3.64$ mm in diameter is formed, surrounds a region with a perturbed liquid surface, in which a group of annular capillary waves with a length of $\lambda_c \sim 1$ mm is distinguished. In the pigment distribution pattern, vortex loops become the most pronounced elements. The most densely colored is the splash top, where a significant part of the pigment is collected (Figure 11, $t = 47$ ms).

The droplet diameter increases with the growth in the splash height, and at $t = 106$ ms it is $d_s^1 = 7.4$ mm. The lower part of the drop is less densely colored than the upper one, and the splash is almost transparent. The cavity bottom, which forms on the fluid surface, descends faster than the splash fluid, the base of which becomes thinner (as in Figure 10, $t = 135$ ms), and at $t = 137$ ms the splash breaks off. The liquid that continues to flow towards the drop increases its diameter to $d_s^1 = 8.4$ mm. The pigment inside the drop, as well as inside the splash, is distributed unevenly: large fibers and individual spots are distinguished.

The fibrous nature of the distribution of the drop pigment is retained when the droplet detaches from the splash and then falls at $t = 161$ ms. Ring lines on the surface of the

liquid separate the growing cavity from the region of calm fluid, which remains after the departure of capillary waves with a length of $\lambda_c = 2.54, 3.6$ mm.

The next falling drop comes into contact with the cavity walls and forms two systems of complex capillary waves: one system is on the fluid surface with a length of $\lambda_c = 0.87, 1.01, 1.18, 2.14$ mm, and another group of shorter waves on the surface of the drop. The flow at the outer boundary of the confluence area loses its regularity (Figure 11, $t = 169$ ms).

The pattern of capillary waves is even more distinct at $t = 174$ ms; their length on the rest of the drop is $\lambda_c = 0.58, 0.79$ mm. The width of the smooth area on top of the fluid is $\Delta R = 3$ mm.

The complete coalescence of the drop is accompanied by the formation of a complex-shaped cavity with an uneven wall. Trapped gas bubbles become a new element of the flow (Figure 11, $t = 184$ ms). In the subsequent complex axially asymmetric flow pattern (Figure 11, $t = 222$ ms), a new growing splash in the center is distinguished. Its lower part is adjoined by the remainder of the cavity, the walls of which are covered with capillary waves $\lambda_c \sim 0.3$ mm long. Separate colored fibers visualize the cavity walls and adjacent vortex flow structures.

Consideration of the video film shows that a floating gas bubble with a diameter of $d_b = 0.87$ mm, located at the lower wall of the cavity at $t = 184$ ms, is transported by the flow to the top of the growing splash and remains on the fluid surface at $t = 262$ ms. When it bursts at $t = 264$ ms, small droplets are thrown into the air.

Successive changes in the spatial structure of the drop substance distribution pattern in the target fluid illustrate the results of spectral processing results of the image samples presented in Figure 12.

The frames of videograms at $t = 1.1, 3.6, 40.5$ ms are taken for analysis (Figure 12(I–III)). Graphs 12b show the illumination dependences I in a window of 34×34 mkm moved along the upper semicircle with radii of $R_I = 3, 4.1, 4.3$ mm (for I, II, III, respectively). Narrow dark bands and lighter spaces between them are clearly distinguished along the line.

In the results of calculating the spatial spectrum S of the curve I , presented in Figure 12(Ic) at $t = 1.1$ ms, the scales $\Delta l_\varphi = 0.23, 0.14, 0.12, 0.07, 0.06, 0.05$ cm are distinguished. In the stage of splash formation at $t = 40.5$ ms, the spectrum becomes more contrasted, and its scales are $\Delta l_\varphi = 0.43, 0.19, 0.13, 0.1, 0.08, 0.07$ cm.

The sizes of the flow-selected structural elements depend on time, as it is shown in Figure 13. The cavity dimensions increase with the growth of the drop velocity. The diameter of the largest cavity is observed in the impact mode of the coalescence at $U = 3.1$ m/s it grows proportionally $h_c(t) = 2t^{2/3}$ up to $t = 20$ ms, then oscillates at $t > 22$ ms, and grows linearly at $t > 40$ ms.

The last section is consistent with the boundary movement of the region of capillary-gravity wave propagation. The cavity depth in the initial section increases monotonously $h_c(t) = 2t^{2/3}$, reaches its maximum value at $t = 21$ ms, and then decreases as $h_c(t) = -0.01t^2$ in the $21 < t < 50$ ms time interval.

In the transitional flow regime at a lower falling velocity $U = 1$ m/s, the cavity diameter grows non-monotonously in the initial section, at $t < 10$ ms (Figure 13, curve 3), and then linearly $d_c \sim 0.4t$. The depth of the cavity at $U = 1$ m/s increases linearly in sections of $t < 12$ ms, more slowly $h_c \sim 0.25t$ in the interval of $12 < t < 23$ ms, and further sharply decreases $h_c(t) = 9t^{-0.5}$.

The diameter of the cavity at a low speed $U = 0.34$ m/s grows linearly in the initial section $t < 9$ ms. The cavity depth is maximum at $t = 20$ ms and decreases linearly at $t > 20$ ms.

Noticeable differences in the images of drop flows are illustrated by a selection of contours of growing caverns, given in Figure 14, with an interval of $\Delta t = 0.5$ ms for $U = 0.34$ m/s in column 1 and with a step of $\Delta t = 1.25$ ms in the remaining columns of the Table 2. The flat cavity bottom of a slowly falling drop $U = 0.34$ m/s at $t > 5$ ms gradually transforms into a triangle one and the entire cavity takes a conical shape. The high rate of sinking of the central part of the cavity bottom persists during the entire time of its

growth, $t_c = 20.25$ ms. At the last stage of evolution, a narrow gas hole with a diameter of $d_h = 0.27$ mm is formed in the center of the bottom, which transforms into a cylindrical protrusion with a diameter of $d_h = 0.49$ mm for a short time of $\Delta t = 0.5$ m. Then, a dynamic analogue of a splash which does not arise above the free surface of the fluid forms at the cavity bottom. Violation of the smoothness of the outer boundary shape is observed at the horizon of the transformation of the cavity flat bottom into a rounded one.

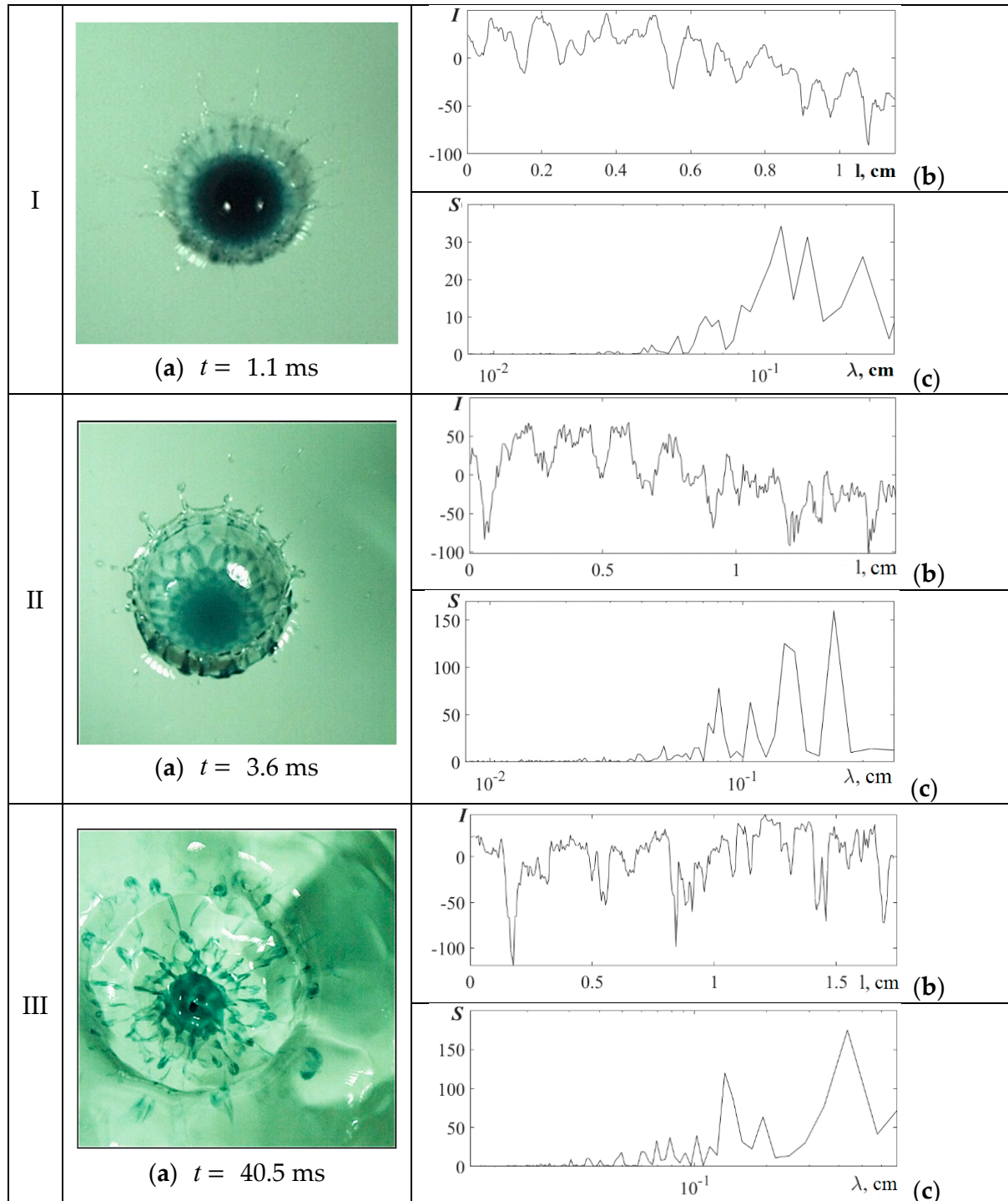


Figure 12. Azimuthally distributions of the colored area illumination of the drop impact patterns in selected frames I, II and III: (a)—selected frames at $t = 1.1, 3.6, 40.5$ ms in Figure 11. (b)—illumination I , (c)—spatial spectra S .

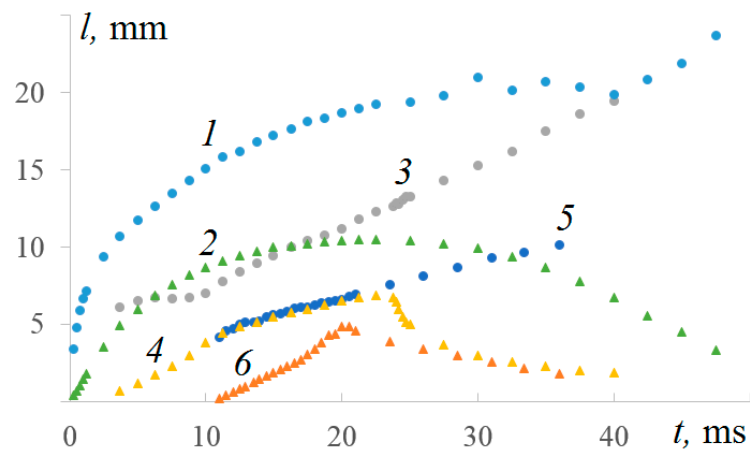


Figure 13. Evolution of cavern sizes at different droplet contact velocities: curves 1, 3, 5 are diameters; 2, 4, 6—cavern depths at $U = 3.1, 1.0, 0.34$ m/s; more detailed experimental data are given in the captions to Figures 3, 7 and 10.

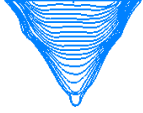
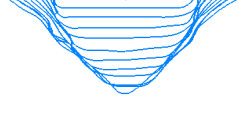
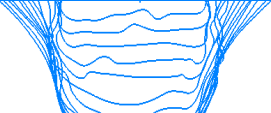
1	2	3	4
$U = 0.34$	$U = 0.6$ m/s	$U = 1$ m/s	$U = 3.1$ m/s
			
$H_c = 3.65$	4.64 mm	6.84 mm	10.4 mm

Figure 14. Sequences of external contours of cavities in different modes of drop coalescence: the second line shows the contact velocities of the drop, the last line shows the maximum depth of the cavity.

Table 2. The position of the regular protrusion on the left side wall of the cavity.

U , m/s	0.34	0.6	0.1	3.1
ϑ	35°	33°	29°	27°
$H_c^{\max}$, mm	1.23	1.9	2.22	4.6

At contact with a speed of $U = 0.6$ m/s, the cavity deepening time is $t_c = 23.5$ ms. The cavity wall has a smoothed shape at the initial stage of growth up to $t_c < 7.5$ ms. Regular change of the cavity shape occurs at a depth of $H_c = 3$ mm. The maximum cavity depth is $H_c = 4.64$ mm.

At the upper boundary of the transition mode interval of a drop coalescence at $U = 1$ m/s, the bottom of the cylindrical cavity, distorted by traveling capillary waves, retains a flat shape at $t < 4$ ms and then begins to round off. At the same time, the diameter of the cavity begins to grow rapidly, the value of which becomes comparable with the depth value.

In the impact mode, at a drop velocity of $U = 3.1$ m/s, the cavity flat bottom is retained only during the first $\Delta t = 5$ ms. Then, it begins to round off, approaching a spherical shape,

distorted by individual perturbations. At $t > 8$ ms, the upper part of the cavity has a shape close to cylindrical, while the lower part it is close to spherical. In the evolution of the cavity shape, large-scale deformations are observed, comparable in properties to the natural Rayleigh oscillations of the gas cavity, and relatively short capillary waves of $\lambda_c = 0.7 \dots 1.2$ mm, which are especially noticeable in the upper part of the cavity. On the left side of the cavity, repeating protrusions are traced on the contours, the tops of which are on the same straight line, inclined at an angle of $\varphi = 27^\circ$ to the horizon. The distances between the isolines illustrate the rate of change in the depth of the cavity, which increases with time in the intrusive mode at $U = 0.34$ m/s; remains almost constant at $U = 0.6$ m/s; slows down a little at the boundary transition mode at $U = 1.0$ m/s; and decreases quite quickly in the coalescence impact mode of $U = 3.1$ m/s. Instead of an oscillating section of the cavity bottom at $U = 0.34$ m/s in the intrusive mode, a regular formation of a central jet dyed by a drop pigment, sometimes with a vortex head, is observed at the cavity bottom (Figure 9, $t = 28$ and 37 ms).

In the intrusive mode, the cavity section has a triangular shape; in the transitional stage, vertical walls are present at the initial stage, and at the final stage, the cavity diameters grow faster than the depth. In the impact section, the cavity acquires a cylindrical shape with a spherical tip. At the initial stage, a flat section is expressed in the shape of the bottom of the cavity: for $U = 0.34$ m/s at $t < 5$ ms, for $U = 0.6$ m/s at $t < 15$ ms, and for $U = 1$ m/s the bottom and walls are strongly distorted by traveling capillary waves.

While maintaining the general trend in the evolution of the shape of the cavern section, one should note the variability of the shapes of even neighboring lines, both random, associated with the passage of individual three-dimensional capillary waves, and systematic, including the transformation of the bottom flat shape into a convex or concave one and the position of the protrusion formed on the left side of the caverns. The change in the depth of the protrusion and the value of the angle ϑ of the radius vector inclination drawn from the center of the cavity bottom to its top, to the horizon as well as the maximum cavity depth $H_c^{\max}$ are given in Table 2.

In the general case, in all flow regimes, the cavity does not have perfect axial symmetry supposed in [63] due to the superposition of various components of flows and waves that differ in their own sizes and time scales of variability. The drop substance distribution in a target fluid has an even more complex, asymmetric, and variable structure. It is formed as a result of the combined action of a number of factors. They are the difference between the changing shape of an oscillating drop [90] and an ideal stationary one, a variety of simultaneously acting mechanisms for the substance, momentum, and energy transfer [76], and the influence of conversion and accumulation of APSE processes. It is of particular interest to study the dissipative factors that influence the processes due to the difference in the coefficients of molecular momentum, substance transfer, and the smallness of dissipative coefficients in general. Their smallness ensures the long-term existence of thin fibers that are elongated by existing flows.

5. Results and Discussion

The developed technique for simultaneous video recording of the free surface shape and the pattern of the drop matter distribution during the coalescence of a free-falling dyed drop with a transparent fluid enables to distinguish two reproducible flow modes. At low contact velocities in the intrusive mode, the drop forms a compact lenticular intrusion inside the target fluid and a colored plane ring on its surface. Cavity formation starts with a delay after the drop begins to actively inflow into the target fluid thickness. Samples from flow patterns videograms are shown in Figures 3–5.

In the impact mode, the drop during confluence loses its continuity and breaks up into separate thin jets, the fibrous wakes of which form linear and reticular (mesh) structures on the surface of the cavity and crown (Figures 10 and 11). The formed fibrous components are conserved for a long time in the evolving pattern of the drop substance distribution in the target fluid.

In the absence of a complete mathematical description of the observed flows at present, it is of interest to discuss the physical model of the flow pattern evolution. Analysis is based on the general properties of the fundamental equations system with physically justified boundary conditions [76]. The system defines the fluid flow as the transfer of independent physical quantities—matter, momentum and energy—and includes the description of the internal energy transformation processes during the drop impact.

The contact with the target fluid drop is characterized by mass M , momentum $\mathbf{p} = M\mathbf{U}$, which in these experiments has only a vertical component, and total energy E_t , including kinetic and potential energy in the gravity field, as well as internal energy $E_t = E_k + E_p + E_i$, for which it is recommended to use the Gibbs potential [86,87].

The scheme of thermodynamic potentials distribution in a fluid is shown in Figure 15. Here, G_f is the Gibbs potential in the fluid thickness I, G_σ the Gibbs potential in the near-surface layer II, and G_s is the Gibbs potential on the contact surface III. It is usually assumed that in fluid thickness I shown in Figure 15a, the Gibbs differential has a simple form $dG_f = -sdT + VdP$. Here, s is entropy, T is temperature, $V = 1/\rho$ is specific volume, and P is pressure. The thermodynamic quantities are defined as derivatives of the Gibbs potential [87]. An additional term in the expression for the potential $dG_f = -sdT + VdP + dG_{st}$ is introduced because the supra-molecular internal structure of fluids [92,93] is rather complex and is continuously rebuilt.

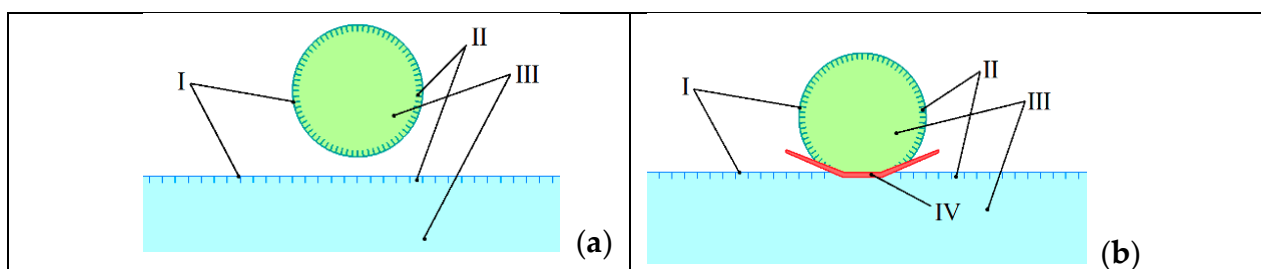


Figure 15. The scheme of the Gibbs potential distribution in the approaching drop and the target fluid as well as at the moment of primary contact, accompanied by the elimination of the contact surfaces of the merging fluids and the transformation of the APSE in other forms: (a) at the target fluid and approaching drop, (b) at the primary contact: I—surface layers of the target fluid and drop, II—sub-surface layers, III—interior fluid, IV—energy-saturated interface and its continuation.

The anisotropy of atomic-molecular interactions near the contact surface of the media creates an excess of energy, including APSE, chemical, and other forms of internal energy, which can be transformed into mechanical energy of fluid flows, as well as into perturbation of temperature and pressure, and perform the work of creating a new surface. The change in internal energy also leads to the redistribution and separation of substances and ensures the chemical reactions that change the composition of fluids.

Noticeable variations in the atomic and molecular structure of a substance are observed in a near-surface layer with a thickness of several molecular sizes $\delta_s \sim 10^{-7}$ [92], adjacent to the contact surface of droplet fluids, which is characterized by surface pressure and additional internal energy [102]. Accordingly, the differential of the Gibbs potential in the near-surface layer that is denoted by symbol II in Figure 14, takes the form $dG_\sigma = -sdT + VdP - S_\sigma d\sigma$ [87].

The greatest changes in the atomic-molecular structure of matter were recorded directly at the fluid-gas interface I, where fluids can decompose into ionic clusters with the formation of a surface charge. The difference of the density, dielectric constant, and dipole moment values in the fluid thickness and in a structurally isolated surface layer with a thickness of several molecular sizes $\delta_s \sim 10^{-7}$ was defined by methods of optical and X-ray reflectometry, and atomic force microscopy [103,104]. Here, the terms that depend on the chemical potential μ_n and the concentration differential of the cor-

responding components dN_n appear in the expression for the thermodynamic potential $dG_s = -sdT + VdP - S_b d\sigma + \mu_n dN_n$.

When an incoming drop merges with a target fluid at a velocity of 1 m/s, the fluid boundaries are eliminated in a time of the order of 10^{-10} s, and the near-surface layers merge in a time of the order of 10^{-9} s. When the free surface is eliminated, the energy components APSE $dG_s^a = -S_b d\sigma + \mu_n dN_n$ are converted into perturbations of temperature, pressure, and energy of mechanical motion. Simultaneously, the KE of the droplet, the density of which is noticeably less than the density of APSE in the near-surface layer, is transferred to the fluid.

The energy released during the merging of fluids remains in a thin double energy-saturated layer (DESL) with a thickness of the order of δ_σ cm. This is formed as the outer boundary of the region of merging of near-surface layers of fluids moves along the free surface of the target fluid over time τ_σ (layer IV in the scheme Figure 15b). In this part of the flow, the term $-S_b d\sigma$ vanishes in the expression for the thermodynamic potential, since the APSE is converted into other forms. The thickness of the resulting DESL grows under the action of the molecular diffusion of matter and momentum processes. In this case, the part of the APSE as well as KE captured in part of the drop is spent on the formation of a fast thin flow, which carries out the substance of the subsurface layers disappearing in coalescence with a thickness of the order δ_σ . The substance in the near-surface layers (i.e., eliminated parts of the free surface of the drop and the target fluid) enters the compound DESL.

At the initial contact of the low drop tip, the ejected double layer forms a thin veil IV in Figure 15b, which has been experimentally registered in a number of experiments [99]. As the descent progresses, an increasing part of the drop flows into the target fluid and transfers an increasing part of the KE, in proportion to the transmitted mass. Further evolution of the flow occurs according to different scenarios, depending on the drop velocity.

At low velocities, at the moment of primary contact of the fluids in the coalescence process, a thin surface layer splits off and forms a system of short thin jets, which can be seen in the photographs of the flow pattern shown in Figure 16. In this setting of the experiment, when the sight line is directed at an angle $\alpha = 2^\circ$ to the horizon, the drop edge and its reflection from the free surface, which is indicated by a weakly pronounced diffuse line in the center of the frame, is visible in the first frame.

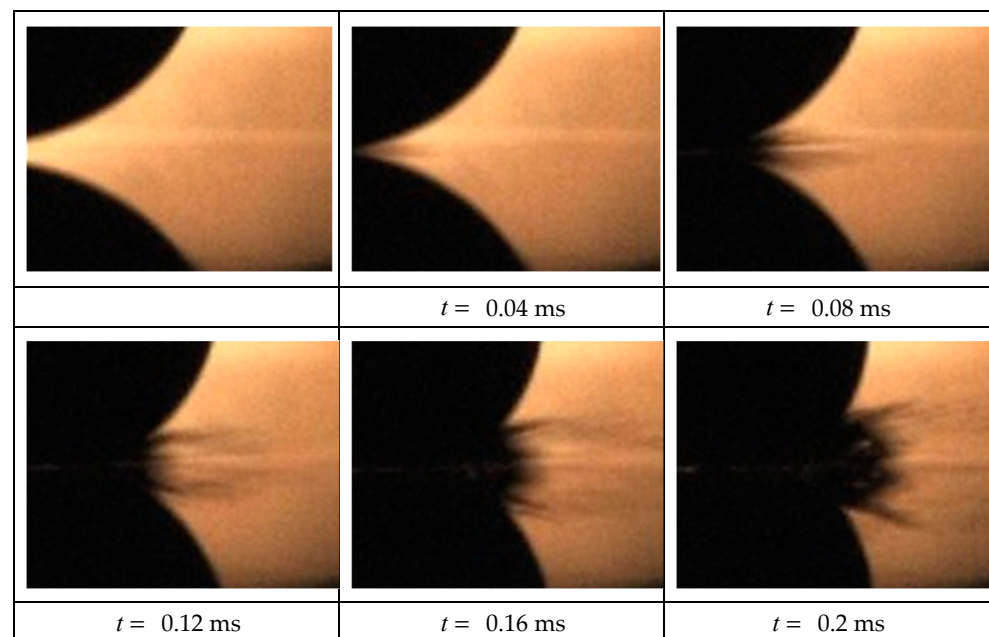


Figure 16. A fine structure of near-surface flows in intrusive mode of droplet coalescence ($D = 4.3$ mm, $U = 1.0$ m/s, ink solution diluted in ratio 1:200, shooting rate 25,000 fps, sight line directed at $\alpha = 2^\circ$ to the horizon).

At the initial contact, the surface of the target fluid begins to be colored with the drop pigment. At $t = 0.28$ ms, a small convexity $2A = 0.02$ mm high (i.e., the crest of the capillary wave running to the drop bottom) is separated from the contact surface, which becomes darker. At $t = 0.4$ ms, the crest height is $2A = 0.12$ mm. The increasing contrast of the surface and the thickening of the colored area near the moving contact line of the merging liquids in subsequent frames indicate that the fluid droplets enter both the thickness and the near-surface layer of the target fluid.

Dissipative effects in thin flows absorb the energy of the resulting jets, which cannot destroy the surface of the target fluid, and fly out into the air. At the same time, the interface between the coalescing fluids disappears in the contact spot of the media. The substance of the drop, which retains the initial vertical momentum, flows smoothly into the thickness of the target fluid, where it forms a lentil-like intrusion (see Figures 3 and 4). With a delay of about ten milliseconds, a rapidly deepening cavity is formed. Its initial bottom velocity is $u_c = 0.4$ m/s of the same order with the velocity of a drop $U = 1.0$ m/s. The rapid movement of the cavity bottom increases the duration of the process of drop coalescence.

The drop shape changes under the action of flows and annular capillary waves that run up from the contact line of the merging fluids. In particular, the time of crossing the initial position of the free surface of the target fluid by the drop upper edge is $t = 12$ ms. However, the complete coalescence of a dynamically changing shape of the droplet residue with a movable cavity bottom occurs much later at $t = 18 \dots 25$ ms.

The cross-section diagram of the emerging flow in the intrusive mode is shown in Figure 17. Here, thin surface I and thicker near-surface layers II of the target fluid and droplets, in the vicinity of the coalescence region, are displaced by an energy-saturated layer III.

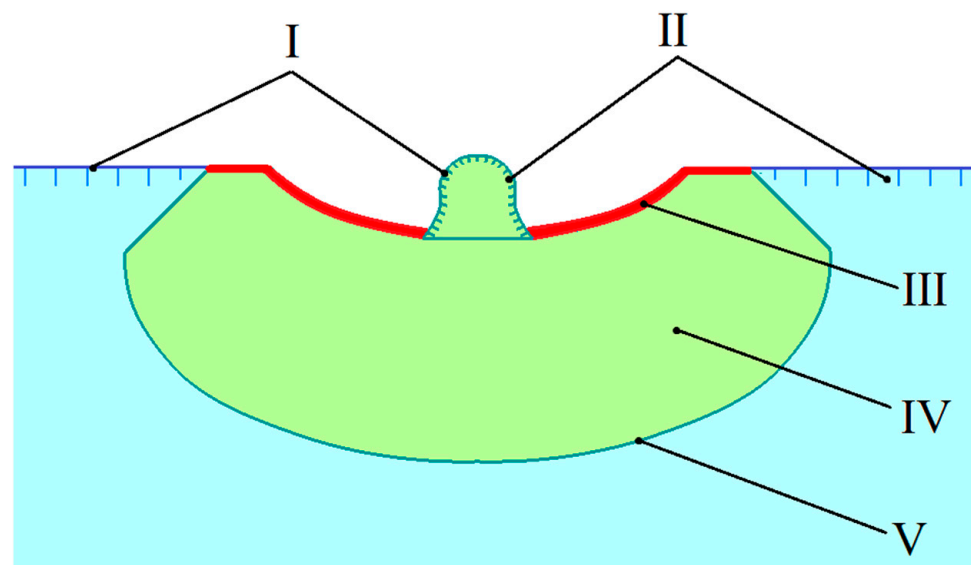


Figure 17. Scheme of drop merging with a target fluid in an intrusive mode: I—surface layers of the target fluid and drop, II—sub-surface layers, III—energy-saturated interface, IV—intrusion of the drop substance, V—boundary of the intrusion.

The extension of the layer III forms a colored ring around the intrusion region IV. Index V marks the boundary of the intrusion, illustrating the differences in pigment concentration and Gibbs potential in the inflowing and target fluids.

The difference in the thermodynamic potentials of the merging media is due to the presence of a pigment and the temperature diversity (not recorded in these experiments). It ensures the formation of a fairly clear boundary of the intrusion, which, however, is also not smooth. Small variations in the shape of the intrusion contour reflect the heterogeneity of the flow velocity and the presence of internal fast and slow thin jets, formed by non-

stationary ligaments [76]. The formation of ligaments is provided by the processes of restructuring the internal structure, the destruction of some elements (associates, clathrates, complexes, etc. [76,87,92,103,104]) with the release of internal energy E_{st}^i and the formation of other associates of physical and chemical nature with their own potential internal energy E_c^f , due to the loss of part of the mechanical energy.

The process of formation of a cavity that is a hole in the surface of the target fluid begins with a delay in the intrusive mode. In the course of further evolution of the flow, the intrusion transforms into a sinking vortex ring, which generates a cascade of secondary vortices [4].

At high contact velocities of the drop, the splitting off surface layer captures part of the drop material, and, as a result, the mass, momentum, and energy of the resulting fast jets increase sharply. The evolution of the emerging flow patterns can be traced in a series of frames shown in Figure 18. Already at the moment of the first contact at $t = 0.04$ ms, a thin veil emerges from the liquid at an angle of $\theta = 4^\circ$, and the angular position of which rapidly grows (width $\Delta r = 4.6$ mm at $t = 0.08$ ms).

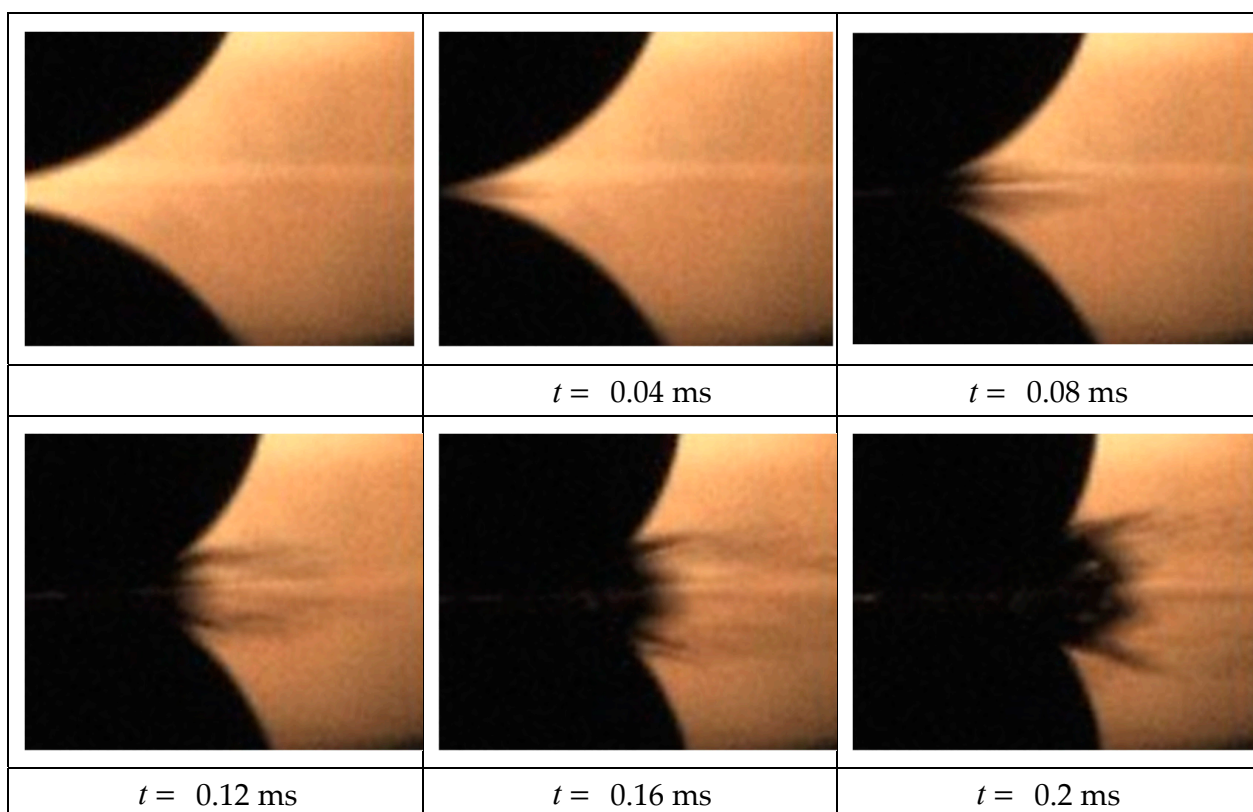


Figure 18. Ejecta veil and fast jets at the beginning of the droplet merging with the target fluid at rest in the impact mode ($D = 4.3$ mm, $U = 3.1$ m/s, ink solution diluted in range 1:200, frame rate 25,000 fps, sight line directed at $\alpha = 2^\circ$ to the horizon).

As it develops, the structure of the flow becomes more complicated; at $t = 0.16$ and 0.20 ms, new sprays appear, flying out at different angles from 4° to 15° to the surface and from the region of primary contact, and from the tops of spikes at the edges of the forming veil [99].

Over time, the pattern of pigment distribution continues to become more complicated, and the fibrous structure of ligaments is more pronounced. In the later of the flow patterns presented in Figures 5 and 6, you can see images of swirls and vortices with their own fine structure. During the further evolution of the flow, the intrusion transforms into a sinking vortex ring, generating a cascade of secondary vortices [4,7].

At the same time, the bottom and wall of the cavity are covered with thin flows [94], which accelerate in the vicinity of the rapidly expanding boundary line of the fluid contact domain [95]. The drop substance does not immediately fall into the thickness of the fluid.

The flow diagram at the initial stage of the drop coalescence is shown in Figure 19. The target fluid *I* and the drop remnant *V* at the cavity bottom are separated by a rapidly moving DESL *IV*, which creates a growing crown. Both the outer and inner walls of the crown are covered with fluids from both contacting layers *II* and *VI*. In this case, the target medium forms the basis, and the drop forms a system of thin invading jets that leave colored wakes. Faster colored jets, forming banded structures on the crown wall, create teeth on its upper edge with thin spikes at the top. Droplets (sprays) *III* fly out from the tips of the spikes. Annular capillary waves run from the contact line along the surface of the drop remnant, on which the sprays from the crown of the cavern can fall. The appearance of pigmented radial fibers of various thicknesses reaching the rib of the crown violates the axial symmetry of the flow.

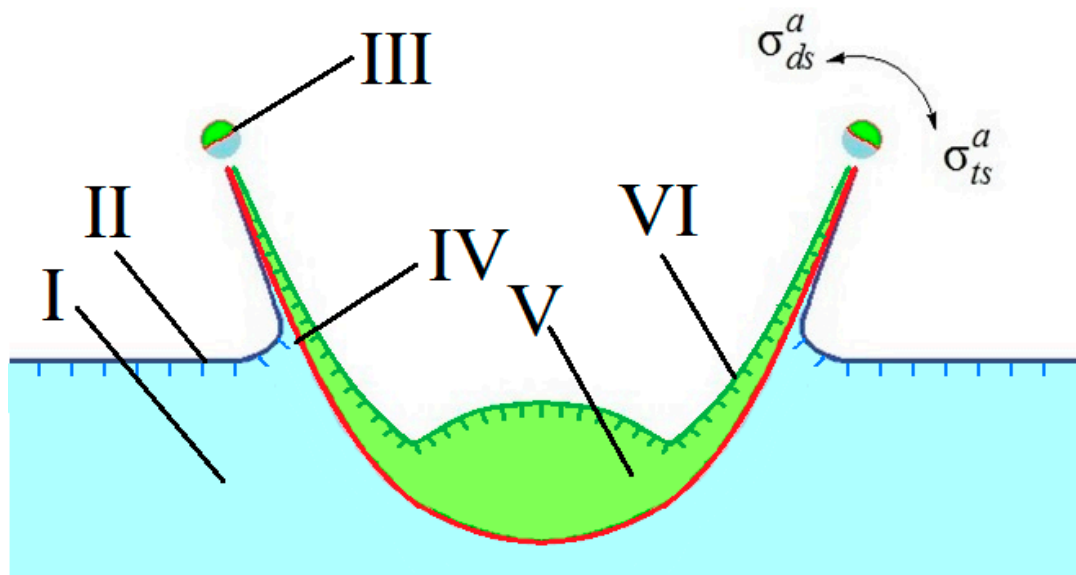


Figure 19. Cross-section scheme of the flow in the impact mode: *I* is the target fluid, *II* is the surface of the target fluid, *III* is the ejected droplet containing both merging fluids, *IV* is the double energy loaded layer is the contact area of the boundaries of the merging fluids, *V* is the droplet material, *VI* is the free surface of drop material.

As the observations show, both contacting substances fall into protruding spikes and flying droplets in the contact and coalescence of both miscible and immiscible liquids. Thus, a complex energy dynamic mechanism operates in the area of fluid coalescence in the impact mode. In one flow area, the conversion of APSE occurs, and fast jets (trickles) are formed, transferring the substance and energy of the drop into the DESL. In other areas of the flow, a new free surface is created when the liquid surface is deformed and ruptured. At the same time, other processes are actively going on in these areas—dissipation (damping of flows) and smoothing of the density gradient, changes in the medium temperature, and separation of matter. Chemical reactions that change the composition of the medium are also active here because the area of the media contact surfaces increases rapidly [105].

Further stages of the flow evolution (i.e., the formation of a cavity, a crown with teeth on the outer edge, a splash (Rayleigh jet or a cumulative one), secondary cavities, gas bubbles, capillary waves and sound packets) have been studied theoretically and experimentally in sufficient detail [11,12,17,22].

It follows from the analysis that several mechanisms of energy transfer with their own temporal and spatial scales are manifested in drop flows, both macroscopic processes (i.e.,

with flows and gravitational-capillary or acoustic waves) and microscopic ones of atomic-molecular and supramolecular nature (i.e., diffusion and rapid conversion of APSE into other forms). The effect of the conversion and restoration of APSE is the rather noticeable during the coalescence of existing surfaces and the formation of new free surfaces.

The difference in flow patterns in intrusive and impact modes is due to the peculiarities of the mechanisms of momentum and energy transfer in the vicinity of the mobile boundary of the contact spot (i.e., the area of elimination of the drop and the target fluid free surfaces). In the intrusive mode, homogeneous fast flows in a thin layer of the APSE conversion carry a small amount of fluid taken only from the near-surface layers into the ring covering the fluid coalescence domain. The energy of the flows is not enough to break the free surface. The momentum of the falling drop remaining in the fluid contains only one vertical component and ensures the formation of an intrusion in the thickness of a target fluid.

In the impact mode, at a higher rate of coalescence, the processes of APSE transformation into other forms capture thicker layers containing more KE and form both fast and slower jets (ligaments or trickles) inside the contact area of fluids [78,79,94]. Due to the conditions of formation, the jets (trickles) capture and transfer substances of both contacting media (indicated in red in the diagram Figure 19).

On the annular contact line limiting the spot of fluid coalescence, fast jets are additionally accelerated by the conversion processes of the APSE of the eliminated free surfaces, and distribute the substance and the drop momentum over the entire area of the cavity bottom. The uniformity in the distribution of the drop momentum vertical component is confirmed by the preservation of a flat shape of the cavity bottom at the initial stage of coalescence with the target fluid. Accordingly, the sharpness of the boundary separating the contacting liquids is preserved. Pigmented jets (trickles), leaving colored wakes, flow along the cavern bottom and the wall of the crown, and form teeth and spikes on their tops. Partial droplets (sprays) consistently fly out from the tips of the spikes.

Over time, as the cavity deepens and the height of the crown increases, the lengths of the jets grow, as well as the contact area with a slowly moving environment, which leads to an increase of their thickness due to the effects of momentum diffusion. Under the influence of inertial effects (i.e., an increase in the jet (trickle) thickness, and dissipative factors), the jets velocity (trickles) decreases. Accordingly, the thickness of the spikes and the size of the droplets flying from their tops are growing. At the same time, their velocity decreases as well. Eventually, when the bottom part of the drop begins to sink and the contact line contracts to the center of the flow, the jets (trickles) form a reticular pattern (mesh) at the cavity bottom. The structure of mesh also rapidly evolves under the action of several factors. As the cavity boundary area increases while it penetrates into the fluid thickness and decreases during its collapse, the linear and angular parameters of the mesh cells change accordingly. Capillary waves run along the walls of the cavity, descending from the rib of the crown, partially capturing the pigmented fluid. As a result, the pigmented fluid flows along the cavity boundary and is concentrated at the mesh nodes. A part of the initial drop momentum, carried by the pigmented drop fluid along the fibers, is collected at the nodes of a continuously changing mesh and pushes through the cavity wall. Small jets with vortex heads are formed in the places where the convexities are created. They gradually transform into loops [79,100].

A typical picture of the distribution of the drop substance in this step of the droplet coalescence process in the impact mode is shown in Figure 20. Most of the cavity wall is covered by tetragonal and pentagonal cells. On the uneven side walls, protrusions of growing vortices are visible. The cross-sectional area of the colored layer highlighted in the left part of the Figure 20 with white dotted lines is $S_t = 4.2 \text{ mm}^2$. The volume of the transition layer, as a rotation body of the left half of its section, is $V_t = 147 \text{ mm}^3$. Its ratio to the volume of the primary droplet makes it possible to estimate the entrainment coefficient of a target fluid, which is $\gamma = V_t/V_d = 3.5$ and is more than an order of magnitude higher than the entrainment coefficient for the jets of order $\gamma_j \sim 0.1$. Thus, in the intrusive mode, a large proportion of the substance and energy of the droplet is transferred directly into the

liquid thickness with a smoothly flowing jet, and in the impact mode, the substance and energy of the droplet remain in the vicinity of the deformable surface of the target fluid and enter the fluid thickness with a long delay in the form of thin fibers. In the process of further flow restructuring, the patterns of fiber distribution continuously change [80].

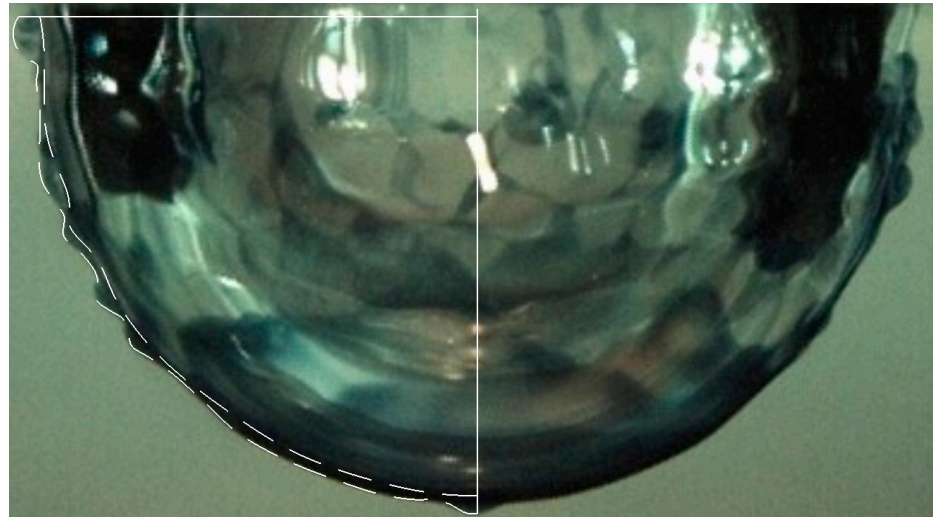


Figure 20. Spotty distribution of the drop substance over the surface of the wall and bottom of the cavity at $t = 21.25$ ms: a drop of ink solution diluted at ratio 1:100, with $D = 4.3$ mm and velocity $U = 3.1$ m/s merges with tap water, shooting rate 4000 fps.

6. Conclusions

The improved technique of observing the flows of transparent media allows us to simultaneously register the variable shape of the free surface and the fine structure of the substance transfer pattern of a free-falling drop in a fluid at rest. The evolution of the drop flow patterns in a wide range of defined dimensional and dimensionless parameters of the process is traced. Two modes of drop substance propagation in the target fluid at the initial stage of the coalescence process are distinguished. At low contact rates, when the drop KE is less than the APSE $E_k < E_\sigma$, a smoothly flowing drop forms a compact lenticular shaped intrusion in the fluid thickness and a colored ring on the free surface. The process of cavity formation (i.e., a hole in the target fluid surface) begins with a delay. In the course of the further evolution of the flow, a continuous lenticular shaped intrusion under the action of a rapidly growing cavern transforms into a sinking vortex ring, generating a cascade of secondary vortices.

At high contact speeds, when the drop KE is much larger than the APSE $E_k > E_\sigma$, the cavity begins to form from the moment of initial contact. In the area of media contact, the drop splits into fast jets (trickles). They spread in a thin layer in the vicinity of the wake of the destroyed contact surface along the bottom of the cavity and the wall of the crown. Fibrous wakes of jets form characteristic linear and mesh structures on the surface of the liquid. A continuously rearranging fibrous pattern of substance distribution remains in the thickness of the target fluid for a long time and is finally smoothed under the action of molecular processes.

In the formation of a flow structure, an important role belongs to the processes of transmission, rapid conversion, and dissipation of energy. A deep study of the processes of energy transfer and rearrangement of the distribution patterns of a free-falling drop substance in a target fluid can help to understand the nature of the flow structure evolution better, and to improve technologies in chemical, pharmaceutical, and other mass branches of industry.

Author Contributions: Conceptualization, Y.D.C.; methodology, Y.D.C. and A.Y.I.; experimental investigation, A.Y.I.; data curation, Y.D.C.; writing—original draft preparation, Y.D.C. and A.Y.I.; writing—review and editing, Y.D.C.; supervision, Y.D.C.; project administration, Y.D.C.; funding acquisition, Y.D.C. All authors have read and agreed to the published version of the manuscript.

Funding: The work was supported by the Russian Science Foundation (project 19-19-00598-P, “Hydrodynamics and energetics of drops and droplet jets: formation, motion, break-up, interaction with the contact surface”, <https://rscf.ru/en/project/19-19-00598-P/>, accessed on 3 April 2023). The experiments were performed at the stands of the Unique Research Facility, Hydrophysical Complex, Ishlinsky Institute for Problems in Mechanics, Russian Academy of Sciences.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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