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COALESCENCE AND BREAK-UP OF DROPS IN TWO-PHASE FLOWS

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Abstract—The systematic experimental study of physical phenomena taking place at collisions of drops of water, water-glycerine solutions and transformer oil moving with moderate and high relative velocities has been carried out. The cases of drops interaction of one fluid and various fluids are considered. The regularities of drops collisions both in the quiescent and the moving gaseous medium have been studied. It has been stated that interaction is almost always accompanied by breaking a large drop with forming a certain amount of polydisperse fragments. The generalizing formulae are obtained for the parameter of coalescence and break-up Φ_{ji}, as well as for the function of fragments distribution by their size and initial velocity.

1. INTRODUCTION

Flows of two-phase mixtures consisting of liquid drops and the gas carrying them are widely spread in nature and engineering. They can be examplified by the motion of atmospheric aerosols, wet steam flow in the last stages of condensation turbines and in the blading of turbines of atomic power plants, processes in spray heat- and mass transfer units, mixers and diffusers with evaporative cooling and so on. One of the most important features of such flows are the numerous collisions of drops of various size which in the general case may result in redistribution of the substance between the fractions of the discrete component, i.e. may cause the change of its fractional composition. This phenomenon plays a very important role in determining both the local parameters of the flow and its integral characteristics (List & Gillespie 1976; Sternin *et al.* 1980; Young 1975). List & Gillespie (1976) consider the mass transfer at drops collisions to be the key to understanding the physics of clouds.

Brazier-Smith *et al.* (1972) give the following classification of interactions at collision of two drops: (a) mutual bouncing (the energy of impact is insufficient for displacement of the gas layer between the particles); (b) coalescence; (c) coalescence with subsequent separation into the original drops; (d) coalescence with subsequent separation and formation of small fragments; (e) break-up with formation of a considerable amount of fragments. From the practical point of view it is interesting to consider the case of comparatively high relative velocities of the colliding drops when one of the three latter types of interaction is realized. Numerous articles are published in the literature on this question. It is beyond the scope of this report to make a detailed analysis of all the known papers on the drops interaction. Here only a short analysis of the most interesting data published recently is presented. The results are conditionally divided into four groups.

(a) In the works published by Adam *et al.* (1968); Gunn (1965); Ryley & Bennet–Cowell (1967) and the others, qualitative considerations on the drops behaviour at high-speed interaction are presented together with some experimental facts. For example, they point out that at interaction of two similar water drops with the diameter of $\delta = 60\,\mu$m and the relative velocity $w_{ji} < 2.2$ m/s, all the collisions result in coalescence while at $w_{ji} > 2.2$ m/s fragments are formed. For the particles with $\delta = 5\,\mu$m the critical velocity increases up to 9.4 m/s.

Beard *et al.* (1979) have established that the efficiency of coagulation (the probability of coalescence) of freely falling water drops with $\delta_i = 81\,\mu$m, $\delta_j = 20\,\mu$m equals 0.45 ± 0.06. An interesting phenomenon has been investigated by Whelpdale & List (1971), and later a more detailed study has been carried out by Kolpakov & Kontush (1975): at $\delta_i \gg \delta_j$ there exists a relatively narrow range of angles of collision ψ† within which during the physical contact between the drops, 0.25–0.50 of the small drop mass overflows to a larger one under the influence of Laplacian pressure difference after which the drops separate.

(b) Substantial amount of work is devoted to establishing the boundaries between the regions of hydrodynamic conditions under which various types of interaction take place. Solovyov (1969) suggests that the regions of coagulation and break-up are separated by the critical value β_{cr} of the parameter

$$\beta_{ji} = \frac{m_i}{m_i + m_j} \frac{\delta_j \rho w_{ji}^2 \cos^2 \psi}{12\sigma} \quad (m_j < m_i), \qquad [1]$$

where m is the mass, ρ is the density, σ is the surface tension. According to the data of different authors and depending on the conditions and the experimental procedure $\beta_{cr} = 4 \ldots 20$. From [1] it follows that at large ψ (the impacts close to tangential ones) the coagulation region is substantially wider than at small ψ. At the same time the experiments by various authors show that in fact the dependence of the interaction result upon ψ is quite opposite.

Alemasov *et al.* (1971) have considered the problem of central ($\psi = 0$) impact of two drops at $\delta_j \ll \delta_i$ (these drops are called below "projectile" and "target"). Assuming that the kinetic and surface energies of the projectile are spent for overcoming the resistance at its motion inside the target, the formation of the cavity in the trace, the authors have obtained the condition of the drops coalescence

$$\mathrm{Re}_{ji}|_{\psi=0} < [4.7\Delta_{ji} + (12\mathrm{Lp}_i)^{1/4}]^2; \; \mathrm{Re}_{ji}|_{\psi\neq 0} = \mathrm{Re}_{ji}|_{\psi=0} \cos \psi, \qquad [2]$$

where $\Delta_{ji} = \delta_i/\delta_j$; $\mathrm{Re}_{ji} = w_{ji}\delta_j\rho/\eta$ is the Reynolds number, $\mathrm{Lp}_i = \delta_i\rho\sigma/\eta^2$ is the Laplace number, η is the dynamic viscosity.

Arkhipov *et al.* (1978a) have carried out a thorough cinematographic investigation of peculiarities of behaviour of colliding water drops ($\mathrm{Lp}_i \sim 10^5$) of commensurable size ($\Delta_{ji} = 1.1 \ldots 2.7$). It proved to be that the type of interaction (independent of ψ and Δ_{ji}) is determined by the value of Weber number $\mathrm{We}_{ji} = w_{ji}^2\rho\delta_j/\sigma$ ($\delta_j < \delta_i$): at $\mathrm{We}_{ji} < 1.5 \ldots 2$ bouncing is observed; at $\mathrm{We}_{ji} \in (2;\ 15)$ coagulation occurs; at $\mathrm{We}_{ji} \in (15;\ 50)$ coalescence takes place with the consequent separation, and finally at $\mathrm{We}_{ji} > 50$ fragments are formed. As to our opinion these conclusions are not of general character.

Brazier-Smith *et al.* (1972) on the basis of comparing the kinetic energy of rotation of the drop formed at coalescence, on one hand side, and the difference between the surface energies of this drop and the original ones, on the other hand, have obtained a formula for the critical value of the collision angle

$$\psi_{cr} = \text{arc sin}\left[\frac{f_1(\Delta_{ji})}{\mathrm{We}_{ji}}\right]^{1/2}; f_1 = \frac{4.8[1 + \Delta_{ji}^2 - (1 + \Delta_{ji}^3)^{2/3}](1 + \Delta_{ji}^3)^{11/3}}{\Delta_{ji}^6(1 + \Delta_{ji})^2} \qquad [3]$$

(at $\psi < \psi_{cr}$ complete coagulation takes place). The authors point out that [3] agrees perfectly with their experimental data for water drops at δ_i, $\delta_j \in (0.15;\ 0.75)$ mm, $w_{ji} = 0.3 \ldots 3$ m/s, $\Delta_{ji} = 1 \ldots 2.5$. At the same time the experiments carried out by Arkhipov *et al.* (1978b) with more viscous drops of water–glycerine solutions yielded a similar formula for ψ_{cr} in which however f_1 function is to be replaced by

$$f_2 = \frac{2.3(1 + \Delta_{ji}^3)^{13/6}}{\Delta_{ji}^3(\Delta_{ji} + 1)^2}. \qquad [4]$$

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†ψ is the angle formed by the line connecting the centres of particles at the moment of contact and the vector of their relative velocity.

At $\Delta_{ji} = 1$ the values of f_1 and f_2 differ almost by a factor of 2.5 ($f_1 \cong 6.3$; $f_2 \cong 2.6$), at $\Delta_{ji} = 3$ this difference is 9 times ($f_1 \cong 64.7$;† $f_2 \cong 7.3$). It should be noted that the values of the normalized momentum given by Brazier-Smith *et al.* (1972) (p. 405) agree much better with [4] than with [3].

Although we do not deny the usefulness of carrying out such studies it should be noted that application of their results in terms of [1]–[4] for calculating the evolution of fractional composition of aerosols is rather difficult since they do not give information about the quantitative relations of the process of break-up. Moreover, as the analysis of the experimental data shows, formation of a certain number of fragments in the region of coagulation is possible so that the concept of boundaries between the regions of coagulation and break-up is rather indistinct.

(c) In accordance with the recommendations by Sternin *et al.* (1980), it is expedient to carry out the calculation of the parameters of two-phase flow with the variable fractional composition using the "continuous" approach. For this calculation it is necessary to possess information about changes of the target mass at collisions as well as about the initial parameters of the fragments being formed. To characterize the first of the above values, the parameter Φ_{ji} (the work by Babukha *et al.* 1972) is used which presents the mathematical expectation of the ratio between the target mass changes during a certain time τ and the total mass of projectiles colliding with the target. On the basis of the experiments with "bombardment" of the fixed large drop by a stream of fast projectiles, the authors have obtained a formula

$$\Phi_{ji} = 1 - 0.115\,\mathrm{Re}_{ji}^{0.94}\mathrm{Lp}_i^{-0.36}\Delta_{ji}^{-0.88} \qquad [5]$$

in the range of $\mathrm{Re}_{ji} = 10 \ldots 435$; $\mathrm{Lp}_i = 0.1 \ldots 200$; $\Delta_{ji} = 2.3 \ldots 12$. Equation [5] characterizes the averaged effect of the drops interaction at equiprobable bombardment of the midship section of the target.

(d) The fractional composition of the fragments formed at the drops break-up is studied insufficiently. In the work by List *et al.* (1970) the functions of size distribution of new drops have been obtained with three maxima, two of which correspond approximately to the original particles diameters and the third one to substantially smaller drops (the average number of new drops is $N = 4.2$). McTaggart-Cowan & List (1975) have shown that the type of the distribution function and the number of new drops depend on the ψ-angles: at central impacts the curves have only one maximum most often ($N = 15.3$), at tangential impacts they have three maxima ($N = 7.1$), at intermediate values of ψ the curves have two maxima ($N = 9$). Spengler & Gokhale (1973) have stated that depending on the character of the target behaviour at collisions (formation of a "crown" at the point of impact, splash, thread-like spraying) the number of new drops can constitute 2.5–5.4 (4.3 on the average). Brazier-Smith *et al.* (1973) have obtained three nearly equal fragments with the total mass $0.12m_im_j(m_i + m_j)^{-1}$ (except the target and the projectile the mass of which can change a little due to collision).

The most thorough investigation into the process of fragments formation has been carried out by Bradley & Stow (1979). During the tests the water drops used had the size $\delta_i = 2 \ldots 3.5$ mm, $\delta_j = 1.15 \ldots 2.8$ mm at the relative velocity $0.9 \ldots 2.4$ m/s. It proved to be that the average size of fragments equals 200–300 μm and their distribution can be approximated by the Gaussian curve. Moreover the link of the number of fragments with the relative velocity and the Weber number We_{ji} has been found. As far as we know there is no data on the fragments initial velocity available in literature.

It should be noted that all the studies mentioned above have been carried out at collisions of drops of the same liquid; the question of interaction of drops with different physical properties is quite unknown as yet.

The drops destruction may be caused not only by collision but also by aerodynamic action

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†In the work by Brazier-Smith *et al.* (1972) an erraneous value of $f_1 \cong 18.2$ is cited.

of the carrying gas. Many works are devoted to studying the regularities of single drops break-up under the influence of the gas flow (Luna & Klikoff 1967; Dityakin *et al.* 1977; Reinecke 1978; Palatnik 1981 and others). It is generally accepted that basic parameter determining the drop behaviour is the Weber number $\mathrm{We}_i = \rho_G|\mathbf{u}_G - \mathbf{u}_i|^2\delta_i/\sigma$; the destruction condition can be expressed as

$$\mathrm{We}_i > \mathrm{We}_{cr} \tag{6}$$

(here u is the velocity, index G refers to gas). As to the simultaneous action upon a drop of aerodynamic and impulsive forces there are no experimental studies available in this field as far as the authors know. The only attempt to evaluate the combined effect of the factors mentioned above has been made by Aladyev (1974). He proposed to use the condition of the drop break-up similar to [6]

$$\mathrm{We}_i^0 > \mathrm{We}_{cr}, \tag{7}$$

where We_i^0 is the effective Weber number determined by the additive sum of pressures caused by impact and by blowing

$$\mathrm{We}_i^0 = \mathrm{We}_i + 8n_{ji}\mathcal{K}_{ji}/(\pi\delta_i\sigma) \tag{8}$$

(here $\mathcal{K}_{ji}$ is the change of the i-drop impulse at a single collision with a particle j, n_{ji} is the frequency of collisions). This approach seems to be too schematic and vaguely grounded.

Thus the information available in literature about the quantitative regularities of drops break-up and fragments formation is quite insufficient for development of reliable methods of calculation of two-phase flows with the variable fractional composition. The present paper is devoted to the systematic experimental study of physical phenomena which take place at collisions of drops at moderate and high relative velocities. Here not only interaction of particles in the quiescent gaseous medium but also the joint effect of collisions and aerodynamic forces has been considered.

2. EXPERIMENTAL STUDY OF DROPS INTERACTION

2.1 *Description of the experimental setup*

The experimental setup (figure 1) consisted of the following main components: (a) generator of monodisperse drops-projectiles; (b) generator of monodisperse drops-targets which are falling freely; (c) synchronizing device; (d) visualizer; (e) scanning device; (f) device for drops blowing; (g) instrumentation.

(a) The drum with the capillary rotating in the horizontal plane has been used as a generator of projectiles, the drum being driven by a three-speed asynchronous motor. The capillary diameter was chosen experimentally so that to provide the periodical separation of individual drops. It should be noted that monodispersion of drops formation as well as the spatial stability of the drops working trajectories was achieved with the help of a thin steel thread with the diameter of ≈0.2 mm which was tensioned beforehand. The thread was attached to the micrometric traversing device normally to the rotation plane of the capillary in the vicinity of its end (with the clearance 0...0.1 mm). At the moment of the capillary axis intersecting the thread the meniscus at the capillary end was cut away and immediately the formation of the main drop began at point A which drop separated at point B after a certain period of time and then followed the working trajectory BC. The drops formed afterwards during the rest of the revolution were not used; after colliding the protective cover they run off to the waste liquid receiver. Thus the formation of the projectile began and stopped (under the unchanged conditions of the experiment) at strictly fixed points A and B; the position of the working trajectory BC proved to be stationary and was determined by the thread position.

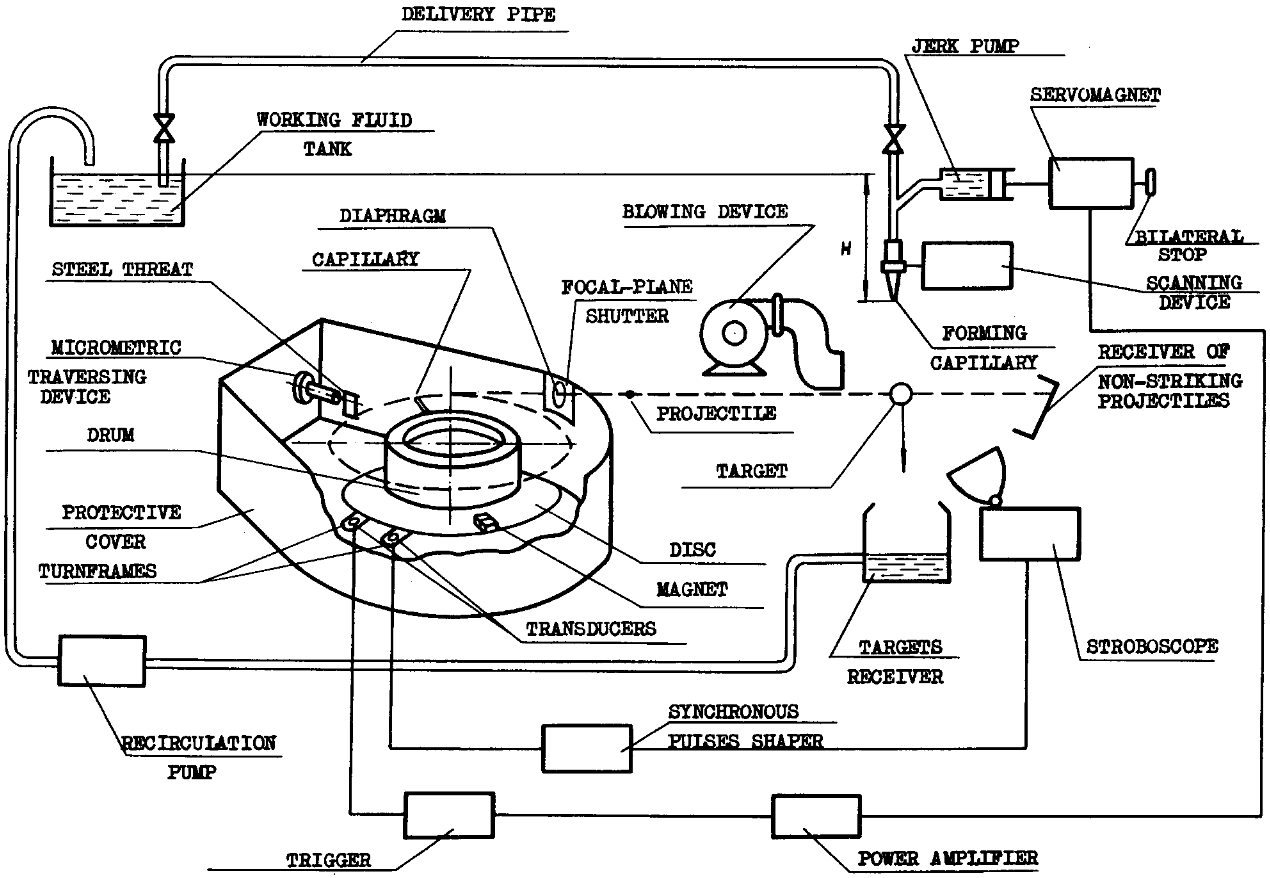

Figure 1. Experimental plant for investigation of drops interaction.

Despite careful balancing of the generator, a certain weak vibration resulted in the projectiles moving in the dissipation cone whose apex angle did not exceed 15–20 min under the most unfavorable conditions. In some cases the formation of drops—satellites took place which however followed the trajectory a little bit displaced relative to that of the main drops towards the drum rotation. In this connection it proved to be possible to intersect the motion of satellites beyond the cover by means of a diaphragm. The diaphragm was shut by a focal-plane shutter with an electric drive.

The drum generator has provided stable formation of monodisperse drops of water, water–glycerine solutions and transformer oil, those drops having the diameter of $\delta_j = 0.2 \ldots 1.05$ mm and moving with the initial speed $u_j = 7.5 \ldots 30$ m/s under the frequency of departure 12–24 Hz.

(b) The working fluid from the tank of the targets generator flowed through the delivery pipe under a certain static head H to the forming capillary. In the immediate vicinity from the capillary, the liquid was affected by pressure pulsations produced by the pump the piston of which was in a periodic reciprocating motion. Under those conditions, the jet running out broke into monodisperse drops separating with the frequency of pressure pulsations. The pump was driven by a servomagnet operated by a synchronizer (see below).

The size of targets being generated, other conditions being equal, depends on the diameter of the forming capillary, static head H, amplitude and frequency of the piston pulsations and on the physical properties of the working fluid. Since the process of formation of monodisperse drops is highly sensitive to the amplitude of the pulsations the piston stroke was controlled by means of a bilateral stop. The targets generator has provided stable formation of monodisperse drops of the liquids mentioned above those drops having the diameter of $\delta_i = 2 \ldots 5$ mm, under the frequency 12–24 Hz.

The large drops accumulated in the targets receiver from where the working fluid returned to the tank by means of the recirculation pump. Thus the continuous circulation of the liquid over the closed circuit of the targets generator was achieved. When there was no interaction with the projectiles and leakage from the targets generator circuit the mass of the liquid circulating in it (with the correction for evaporation) remained constant. The closed circuit of the targets generator had undoubtedly advantages over any other scheme since the error in calculation of the number of targets being generated did not affect the accuracy of determining the change in their mass due to interaction with the projectiles but rather caused a small error in determining the size (mass) of the drops being generated.

(c) To obtain the high probability of drops interaction the targets generator was connected with the projectiles generator by means of a synchronizing device. A magnet was attached to the disc which rotated together with the projectiles generator drum. The magnet passed close to the transducers (which were sealed contacts) located diametrically opposite each other on the turnframe. As soon as the transducers respond the trigger alternately changed from one stationary state to another and controlled the key power amplifier which supplied power to the servomagnet of the targets generator. Naturally the frequencies of targets and projectiles generation were the same as has been mentioned above. The turn of the frame changed the moment of targets initiation (phase shift); the optimal position of the frame was established by visual observation of the drops at the stroboscopic lighting.

(d) The process of drops collision was visualized by means of a stroboscope. For its synchronizing, electrical pulses were used which were generated by a shaper at the moment of transducers response at the magnet passing close to it. The transducer (sealed contacts, as before) was mounted on the frame whose turn could smoothly change the moment of visualization. In this way it proved to be possible to obtain a completely "frozen" non-drifting image of any phase of drop mutual approaching or interaction and of fragments formation.

One more scheme of visualization was used which permitted to obtain images of several phases of one and the same act of interaction. Figure 2 shows the block diagram of such a

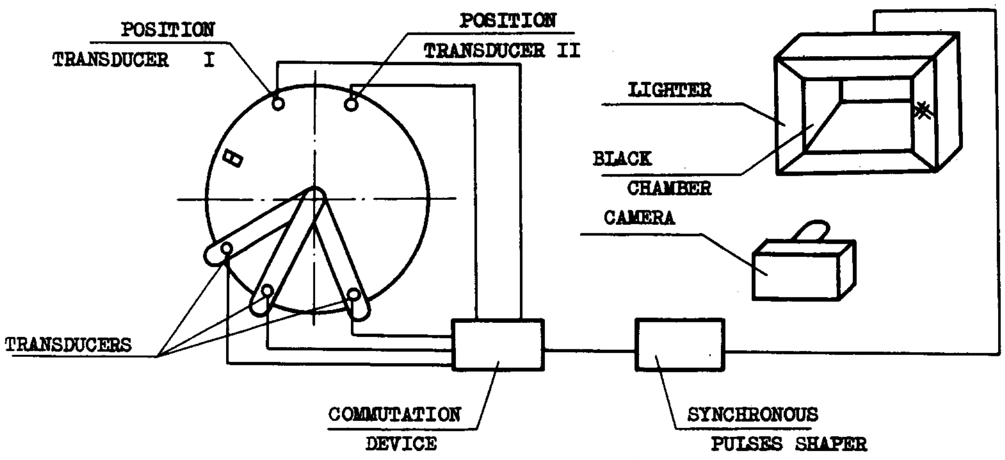

Figure 2. Apparatus for visualization of several phases of interaction.

device which yielded three flashes of the stroboscope lamp per each pair of colliding drops or one packet of three light pulses of much greater power. The method of obtaining some flashes at each revolution of the disc did not differ in principle from that described above with the only difference that three (or more) similar transducers were used to control the stroboscope operation. The time interval between the flashes could be varied by displacement of the transducers.

The packet of several powerful light pulses was generated if desired with the help of the commutation device. The flashes occured only after response of the position transducer I which provided unchangeable sequence of their occurence. The position transducer II disconnected the synchronous pulses shaper so that no flashes occured in the subsequent revolutions before the operator intervention.

By its construction, the lighter was an annular diffuser in the centre of which there was a black chamber. The light could not penetrate well deep into the chamber and was poorly reflected from its bottom. This excluded the exposure of non-elucidated spots at photographing the drops interaction.

(e) Since the outcome of the interaction depends considerably on the collision angle ψ the scanning device has been used to obtain directly from the experiment the results of the drops interaction averaged by the midship section of the target. The device provided slow travel of the forming capillary in two directions (which were mutually perpendicular) in the plane normal to the projectiles trajectory. The capillary travel was performed by two crank mechanisms with the adjustable length of the cranks. The amplitude of the capillary swinging was set somewhat greater than the sum of the interacting drops radii. If at the scanning device switched off, the probability of projectiles hit on the targets was equal to unity then introducing the swinging the probability of interaction decreased to the value of the order of 0.25...0.3. However this seemed to be sufficient for the experiment durability to be not too long and the target bombardment to be considered uniform. It should be noted that the speed of the capillary displacement can be considered (in the first approximation) constant only near the middle position of the elements of the scanning device. The uniformity of bombardment of the targets was verified by special tests in which a screen was bombarded this screen being installed at the point of drops interaction. The screen was displaced by means of the scanning device according to the same law as the capillary of the targets generator with sufficiently large amplitudes in both directions in order that the projectiles settled on the screen did not coalesce with one another and were quite distinct. The uniformity of bombardment was estimated by the number of projectiles entering the concentric zones of equal area. Further it would be shown that somewhat more dense bombardment of the peripheral zone of the target does not affect greatly the accuracy of determining the averaged effect of interaction (see section 3.2).

(f) The device for targets blowing contained a ventilator, flow rate controller and a nozzle. The nozzle was shaped so as provide typical for many applications continuous and gradual increase of aerodynamic forces acting upon the drop.

2.2 "*Weight*" *method of measurement*

During the experiment, measurements of changes of the liquid mass circulating in the target generator circuit were performed for a rather long period of time, the changes being caused by drops interaction. The total mass of projectiles colliding with the targets was also determined. The liquid mass change was measured by weighing a portion of the target generator circuit (receiver, recirculation pump, tank, see figure 1) before and after the test with two corrections being introduced. One of them took into account the temperature expansion of the unweighed portion of the circuit, the other (which is more important)—allowed for the liquid evaporation from the drop surface. The correction for evaporation was carried out by calibration which made it possible to evaluate the liquid mass change in the target generator circuit during the test without drops interaction. The calibration allowed also to correct for other factors which were not considered, for example possible leakage through the imperfect sealings of the jerk pump. Special verification has shown that evaporation of small drops during their motion and evaporation from the receiver of non-striking projectiles constitute a negligible value relative to the mass of projectiles colliding with the targets.

2.3 *Cinematographic and photographic methods of investigation*

The "weight" method described above for determination of the parameter Φ_{ji} was applied only for "mild" enough hydrodynamic conditions when drops break-up was not too great which allowed to separate quite well the fragments from the targets being bombarded. Under the "severe" hydrodynamic conditions the target trajectory proved to be unstable in the space. In order to capture all of the incident targets the dimensions of the receiver of the bombarded drops were to be substantially increased which did not exclude hitting it with the fragments formed. In this case filming and photographing methods were used.† Two methods of filming were applied: rapid filming (up to 4000 frames per second), and synchronous filming with stroboscopic lighting. With the latter method being used, the camera was actuated by the projectile generator through an electrical shaft (selsyn-transducer–selsyn-repeater). The camera shutter opened at each revolution of the generator. The moment of the visualization changed smoothly during the filming so that at the film being looked over an effect of rather slow development of the process was produced (successive phases of interaction of various pairs of colliding drops were displayed). It should be noted that while the synchronous filming decreased working hours of the study and consumption of the light-sensitive material it did not provide accurate measurement of the fragments initial velocity.

This limitation was not inherent to the method of photorecording: one frame recorded simultaneously several phases of the same interaction—the moment of the drops contact, the final stage of fragments formation and their removal from the target. Time intervals between the phases were easily determined by the frames position (see figure 2).

When using this technique, the scanning device was disconnected. Thus the local values of $\Phi^l_{ji}(\psi)$ were determined directly from the test. To find the averaged values of Φ_{ji} the functions $\Phi^l_{ji}(\psi)$ were numerically integrated by the target midship section.

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†Filming was used in the range of "mild" conditions as well for determining the fragments parameters.

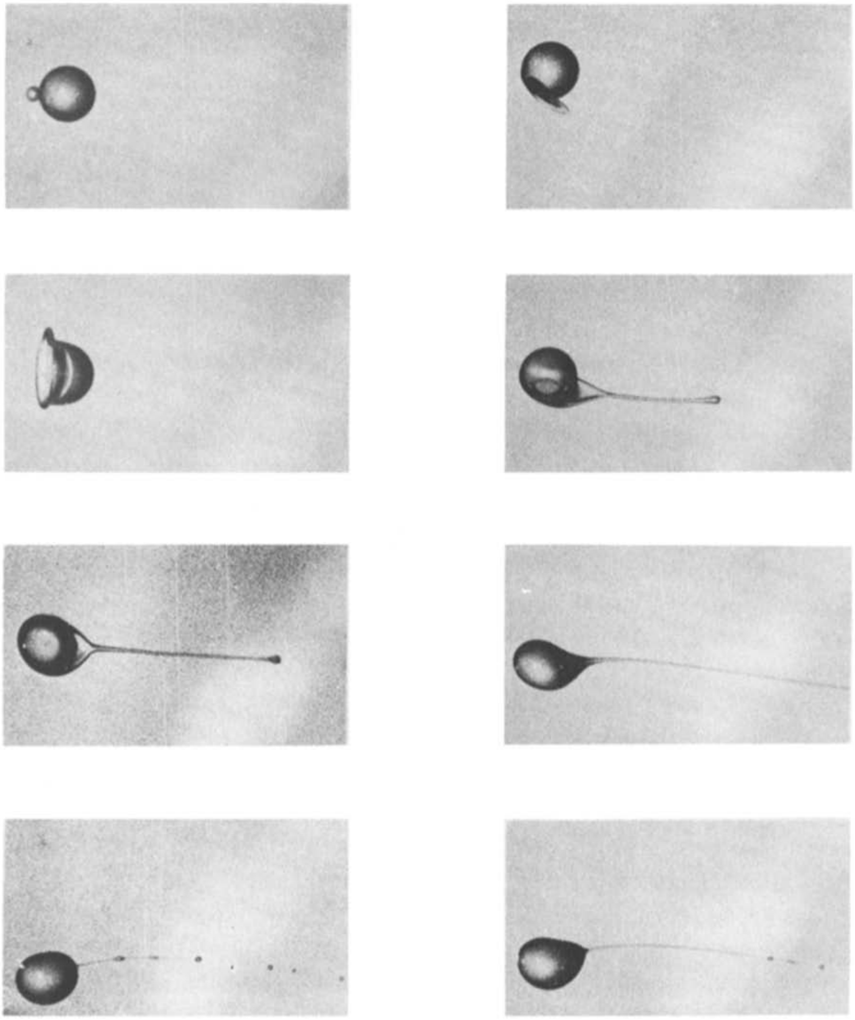
3. EXPERIMENTAL RESULTS

3.1 *Interaction of drops of one liquid*

Using the method described in section 2.2, more than 450 series of experiments were carried out in order to determine the values of the parameter of coalescence and break-up Φ_{ji} averaged over the midship section of the target. The measurements were made in the range $30 \leq \mathrm{Re}_{ji} \leq 6000$; $5 \leq \mathrm{Lp}_i \leq 3 \cdot 10^5$; $1.9 \leq \Delta_{ji} \leq 12$. We did not study the range of small relative velocities when the energy of collision was not sufficient to provide the reliable physical contact between the drops and the interaction was ended with the mutual bouncing.

As the experiments have shown in the most cases the colliding drops coalesce for a moment after which the aggregate breaks forming polydisperse fragments. Over the whole range studied, it has been stated that the value of the parameter Φ_{ji} decreases as the drops relative velocity and the projectile size increase, other conditions being equal. The effect of coalescence is more pronounced under the viscosity growth.

The drops behaviour at the central and tangential impacts is presented in figure 3. At the



(a) (b)

Figure 3. Phases of drops interaction in the quiescent gas medium at the central (a) and tangential (b) impact. $\mathrm{Re}_{ji} = 81$; $\mathrm{Lp}_i = 18$; $\Delta_{ji} = 4$.

Table 1. Parameters of drops interaction for typical hydrodynamic conditions

Mode No.	Re_{ji}	Lp_i	Δ_{ji}	Φ_{ji} by [9]	Φ_{ji} by [5]	We_{ji}	β_{ji} ([1])	Ψ_{cz} by [3]	Ψ_{cz} by [4]	Ψ_{cz} by [2]
1	30	50	2	0.444	0.626	36	1.33	44.5	18.8	81.6
2	30	50	3	0.503	0.738	54	2.17	90	21.5	85.3
3	30	50	10	0.644	0.909	180	7.5	90	35.4	89.4
4	400	250	2	-0.369	-1.39	1280	47.4	6.8	3.1	0
5	400	250	3	-0.222	-0.673	1920	77.2	10.6	3.5	30.1
6	2000	5 10	2	-0.585	-0.607	160	5.93	19.4	8.8	0
7	2000	5 10	3	-0.416	-0.124	240	9.64	31.1	10.0	0

† The values of β_{ji} correspond to $\Psi = 45^{\circ}$.

central impact, the target yields a fine jet at first which breaks afterwards into separate fragments. A certain part of the jet is drawn back into the target while the remainder moves in the form of fragments further along the impact path.

It should be noted that in some cases at impacts close to the central ones, the projectile is completely absorbed by the target which is subject to considerable deformation without fragments formation. Such situation is typical for low kinetic energy of the projectile and high viscosity of the liquid. At low viscosities and large relative velocities the liquid splashing is observed at the point of the drops contact with fragments outburst towards the projectile.

In the case of tangential impacts, at the point of interaction a sheet is formed which moves along the generatrix of the target and then extends into a tapered jet breaking into fragments. The most of the jet is consequently drawn back into the target. The direction of the fragments scatter at the tangential impact can differ substantially from that of the projectile motion.

The experimental data treatment by the least square method made it possible to get a correlation

$$\Phi_{ji} = 1 - 0.246\mathrm{Re}_{ji}^{0.407}\mathrm{Lp}_i^{-0.096}(\delta_i/\delta_j)^{-0.278}. \qquad [9]$$

About 85% of the experimental points deviate from relation [9] by less than 0.12, the mean square deviation being 0.087.

Some results of calculation of the drops interaction parameters by [9] and [1]–[5] are given in table 1. It should be noted that in the range of the target poor breaking (modes 1–3), [5] leads to too high values of Φ_{ji} while at vigorous breaking (modes 4 and 5)—these values are too low (modes 6 and 7 do not belong to the limits of [5]). These facts can be explained by different character of the effect of the target attachment (suspension) depending on the conditions of interaction (Babukha *et al.* 1972). At small kinetic energies of the projectile there appear weak vibrational disturbances of the target which are readily damped by the suspension. In this case, [5] overestimates the parameter Φ_{ji}. If however the kinetic energy is large enough not only to deform the target but also to impart it a considerable translational motion then the suspension which hampers such motion of the target, brings to intensification of its break-up due to energies redistribution, i.e. to Φ_{ji} decrease.

From table 1 it is evident that the values of We_{ji} and β_{ji} describe the result of drops interaction only rather approximately. For instance, mode 3 is characterized by rather poor break-up of the target (the mass of fragments is almost three times less than that of projectiles), while a rather vigorous break-up is typical for mode 6. At the same time the values of β_{ji} are similar. The expressions in section 1 for We_{ji} and β_{ji} can be rewritten in the form:

$$\mathrm{We}_{ji} = \mathrm{Re}^2_{ji}\Delta_{ji}/\mathrm{Lp}_i;\ \beta_{ji} = \mathrm{We}_{ji}\Delta^3_{ji}\cos^2\psi/[12(\Delta^3_{ji}+1)],$$

i.e. these criteria indicate more intensive break-up with growing ratio of the drops sizes Δ_{ji}, other conditions being the same. In accordance with [9], the dependence of the interaction result on Δ_{ji} proves to be contrary.

3.2 *Local values of parameters of coalescence and break-up*

The effect of the angle of collision on the value of the parameter of coalescence and break-up has been studied for interaction of drops of one liquid. The tests were carried out at the same apparatus. The experimental procedure differed from that described earlier (section 2.2) only in that the scanning device was not used and the drops interaction was arranged at the angles of collision which were constant throughout the test. The mutual position of the drops at the moment of contact was measured by means of optical devices in two mutually perpendicular planes.

It appeared that over the whole range studied, the local values of the parameter Φ^l_{ji} to be determined decreased monotonously with ψ growth—if at impacts close to the central ones coalescence prevailed, tangential collisions lead to formation of a substantial amount of fragments.

Treatment of the experimental data yields a formula:

$$(1-\Phi^l_{ji})/(1-\Phi_{ji}) = 1.32 - 1.2\exp(-3\psi^2) \equiv F(\psi), \qquad [10]$$

where ψ is the angle (rad.).

It should be noted that with the technique used by the authors, the accuracy of measurements of the angle and hence of [10] at the impacts close to the tangential ones is not high.

Equation [10] permitted to evaluate the effect of a certain non-uniformity of bombardment of the midship section of the target in the experiments on determining Φ_{ji} (see section 2.1, paragraph e). For this purpose, from each of the experiments the value

$$S = \int_0^R F(\psi)n(r)r\,\mathrm{d}r \Big/ \int_0^R n(r)r\,\mathrm{d}r$$

was determined where r is the distance of the given point from the "centre of bombardment" (the point corresponding to the central position of the scanning device elements), R is the circle radius which covers the given fraction P of the total number of projectiles ($r = R\sin\psi$), $n(r)$ is the number of projectiles per unit area of the screen (at $n(r) = \mathrm{const}$ S naturally equals unity). It appeared that at $P = 0.25\ldots0.3$ (just at this level the probability of interaction between targets and projectiles was maintained, see section 2.1) $S \approx 1.03$, i.e. the error in determining Φ_{ji} due to the bombardment non-uniformity at $\Phi_{ji} > (-0.4)\ldots(-0.3)$ does not exceed 0.04.

The results obtained ([9], [10]) show that with one of the determining parameters (Re_{ji}, Lp_i, Δ_{ji}, ψ) the value of Φ^l_{ji} changes smoothly so that the authors did not manage to find any sharp boundary between the regions of coagulation and break-up (see section 1). It should be noted that the values of ψ_{cr} calculated by [2]–[4] differ substantially from one another in some cases (table 1). It is interesting to state that according to [10] Φ^l_{ji} values which correspond to critical values of the angle of collision cited in table 1 are in the range from -0.17 to $+0.84$.

3.3 *Interaction of drops of different liquids*

While studying the interaction of drops with different physical properties, the divergence $\Delta\Phi_{ji}$ between the values of $\bar{\Phi}_{ji}$ for drops of different liquids, from one hand, and the values of Φ_{ji} corresponding to interaction of drops of one liquid (the target substance), from another, was determined. It appeared that the value of $\Delta\Phi_{ji}$ for low viscosities of the projectile substance ($H \equiv \eta_j/\eta_i < 1$) is always positive. At the same time at $H > 1$, positive $\Delta\Phi_{ji}$ correspond to high Lp_i (and Re_{ji}) while negative $\Delta\Phi_{ji}$ correspond to low values. It should be noted that at $H < 1$ the experiments were carried out only at relatively low Lp_i and Re_{ji}.

The other conditions being equal, the value of $|\Delta\Phi_{ji}|$ increases with H deviation from unity. At $\mathrm{Lp}_i \sim (4\ldots7)\cdot10^4$ and $\mathrm{Re}_{ji} \sim (2700\ldots3300)$ experimental values of $|\Delta\Phi_{ji}|$ are not high for all H; at very large or small Re_{ji} and Lp_i, the value of $|\Delta\Phi_{ji}|$ is substantially higher.

The experimental data is satisfactorily described by the formula

$$\Delta\Phi_{ji} = 0.0785|L|^{-1.05}|R|^{1.3}|\ln H|^{1.96}\Delta_{ji}^{-0.51}\operatorname{sgn} L \operatorname{sgn} R \operatorname{sgn}(\ln H);$$

$$L \equiv \ln(\mathrm{Lp}_i/5\times10^4);\ R \equiv \ln(\mathrm{Re}_{ji}/3150) \qquad [11]$$

at $\Delta_{ji} = 2\ldots6$; $H = 0.01\ldots250$ (the range of Re_{ji}, Lp_i changes is the same as before). The mean square deviation of the experimental points from [11] is 0.133.

3.4 *Interaction of drops in the moving gaseous medium*

Experiments with the moving gas have shown that aerodynamic forces can intensify (in some cases rather heavily) the target break-up. Such situation is examplified in figure 4. At drops collision in the quiescent gaseous medium (figure 4a) a small amount of fragments is formed (according to [9], [10] $\Phi_{ji}^{\,!} \sim 0.8$); "pure blowing" (figure 4b) results only in severe deformation of the target while the combined effect of the both factors causes vigorous break-up of the drop.

When treating the experimental data the effect of aerodynamic forces on the resulting drops collision was estimated by $\varphi_{ji} = \Phi_{ji} - \Phi_{ji}^0$ where Φ_{ji}^0 is the value of the parameter of coalescence and break-up under the conditions of gaseous flow action. It has been stated that aerodynamic forces contribution is determined by the parameter

$$A = \mathrm{Re}_{ji}^{0.285}\mathrm{Lp}_i^{0.2}\Delta_{ji}^{0.4}\mathrm{We}_i^{0.442}.$$

At small A ($A \leqslant 40.6$), blowing only insignificantly intensifies the target break-up.

At the same time at $A > 40.6$, φ_{ji} grows sharply with A reaching the value of $\varphi_{ji} \sim 20\ldots25$ at $A \sim 115$. The experimental data treatment allowed to get a formula

$$\varphi_{ji} = \begin{cases} 0.00446A, & A \leqslant 40.6; \\ 11.85(0.01A)^{4.64}, & 40.6 < A \leqslant 120 \end{cases} \qquad [12]$$

$$(30 \leqslant \mathrm{Re}_{ji} \leqslant 500;\ 8 \leqslant \mathrm{Lp}_i \leqslant 1000;\ 2.5 \leqslant \Delta_{ji} \leqslant 10;\ \mathrm{We}_i \leqslant 12.5).$$

At $A \sim 125\ldots130$ the target was destroyed completely with numerous fragments being formed. Naturally there is no sense in processing the experimental data in terms of Φ_{ji} or φ_{ji} within this range.

The analysis of the results obtained shows that Aladyev's (1974) approach (see [7], [8]) brings to distortion of quantitative dependences of drops interaction. For example, for mode 4 (see table 1), the second term in the right-hand side of [8] equals 10.6 (if the frequency of impacts n_{ji} is assumed equal to the reciprocal of the target relaxation time). In this case assuming that $\mathrm{We}_{cr} = 15$ one gets that at $\mathrm{We}_i = 4.4$ the target should be completely destroyed. At the same time from [9], [12] under these conditions it follows that $\Phi_{ji} \sim -0.37$, $\varphi_{ji} \approx 0.21$.

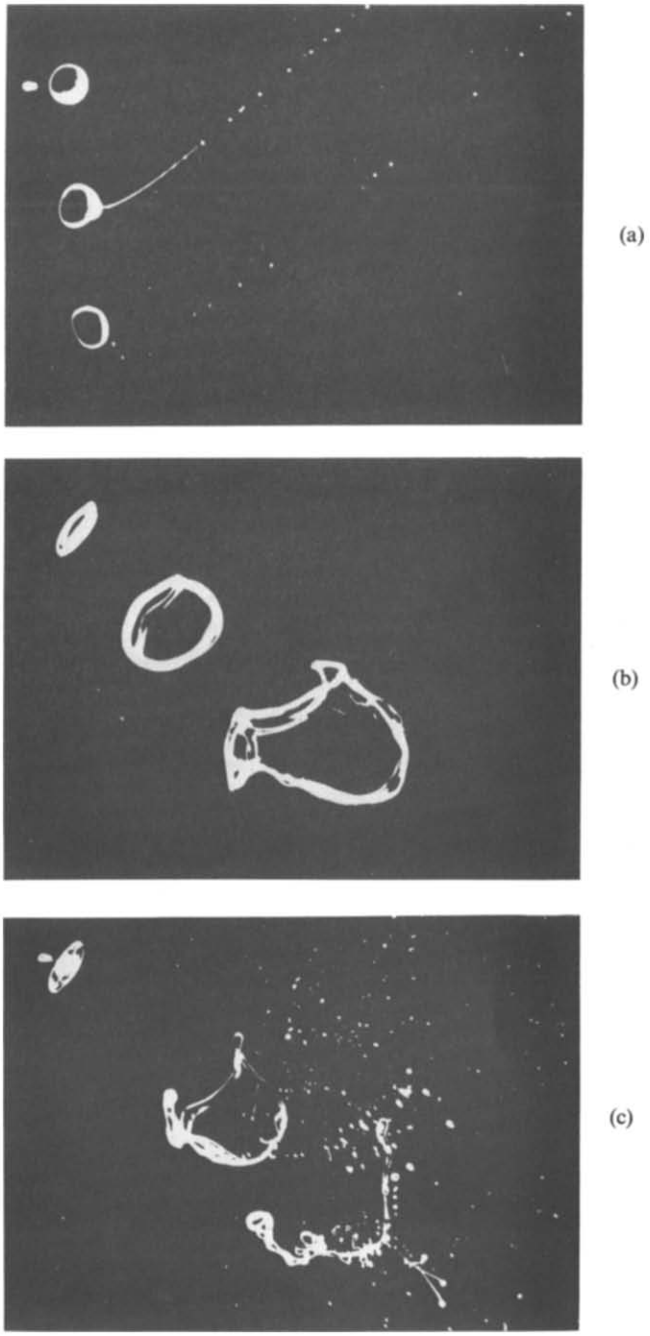


Figure 4. Phases of drops deformation and breaking in the quiescent gas (a), under the gas flow conditions (b) and at combined action of the both (c). $\mathrm{Re}_{ji} = 123$; $\mathrm{Lp}_i = 64$; $\Delta_{ji} = 4$; $\mathrm{We}_i = 12$.

3.5 *Fragments distribution by size and velocity*

The data treatment as to the fractional composition of the fragments δ_K being formed at drops δ_i, δ_j ($\delta_i > \delta_j$) collision has shown that this composition is well approximated in all the cases by a normally-logarithmic distribution

$$f(\epsilon) = \left(\sqrt{2\pi}\,\epsilon \ln \sum\right)^{-1} \exp\left[-\frac{(\ln \epsilon - \ln \bar{\epsilon})^2}{2\ln^2 \sum}\right] \qquad [13]$$

(here $\epsilon = \delta_K/\delta_j$, f is the counting differential function of distribution). Empirical formulae

$$\ln \bar{\epsilon} = -1.13\mathrm{We}_i^{0.08}\,\mathrm{Re}_{ji}^{0.65}\mathrm{Lp}_i^{-0.57}\Delta_{ji}^{-0.25};$$

$$\ln \sum = 0.61\mathrm{We}_i^{-0.15}\,\mathrm{Re}_{ji}^{0.11}\,\mathrm{Lp}_i^{-0.014}\Delta_{ji}^{-0.16} \qquad [14]$$

have been obtained for the parameters of [13].

The results obtained are in qualitative agreement with the data presented by Bradley & Stow (1979) (see section 1). At the same time a certain quantitative deviation is to be pointed out—[13], [14] predict on average somewhat larger fragments. This can be evidently attributed to the difference of the ranges studied.

While treating the data on the fragments initial velocity the value of $\beta = |\mathbf{u}_K| \cos(\mathbf{u}_K \hat{,} \mathbf{u}_j)/|\mathbf{u}_j|$ was determined where $\mathbf{u}_j$, $\mathbf{u}_K$ are the projectile and the fragment velocities in the system of coordinates moving together with the target. The values of β were averaged for each mode over all of the fragments recorded since in the calculation of the parameters of two-phase flows (Sternin *et al.* 1980) only average velocities of fragments are used. As a result an approximate formula is obtained:

$$\bar{\beta} = 0.08 + 0.016\,\mathrm{We}_i\;(\mathrm{We}_i \leqslant 12.5). \qquad [15]$$

4. CONCLUSIONS

The main results of the present work are as follows:

(a) At collisions of the drops of one liquid with moderate and high relative velocities in the quiescent gaseous medium ($30 \leqslant \mathrm{Re}_{ji} \leqslant 6000$; $5 \leqslant \mathrm{Lp}_i \leqslant 3 \cdot 10^5$; $1.9 \leqslant \Delta_{ji} \leqslant 12$) interaction is practically always accompanied by the target break-up and formation of a certain amount of polydisperse fragments. The material balance of interaction (the mathematical expectation of the target mass change) is described by [9], [10].

(b) No sharp boundary between the regions of coalescence and break-up has been discovered. It is shown that recommendations often encountered in literature as to determining this boundary (see section 1) provide only an approximate evaluation of the interaction result. Due to this and in order to get information convenient for use in calculation, it seems expedient to set an experiment in such a way that the unknown values be the parameter Φ_{ji} and the fragments characteristics.

(c) Difference in the physical properties of the target and the projectile for a certain range brings to a substantial correction of Φ_{ji} values as compared to the case of interaction of drops of one liquid.

(d) The gas flow action can considerably (several times) intensify the target break-up at collisions. It has been stated that the role of aerodynamic forces is determined by the value of parameter A (see section 3.4) with the complete destruction of the target at $A \sim 125 \ldots 130$. It is shown that the action of these factors is essentially non-additive so that for getting reliable information it is obligatory to carry out an experimental study of the combined proceedings of both phenomena.

(e) The fractional composition of fragments is well approximated by a normally-logarithmic distribution with the parameters corresponding to [14]. The fragments initial velocity is almost by an order of magnitude lower than that of a projectile and increases with the Weber number.

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