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Interaction of Water and Suspension Droplets during Their Collisions in a Gas Medium

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Abstract—The results of the experimental studies of collisions of water and water suspension droplets in a gas medium using high-speed video recording and specialized software for tracking the initial droplets and the resulting fragments were presented. Videograms that illustrate the typical drop collision modes (bounce , separation, coalescence, and disruption) were given. The effects of droplet collisions under free fall conditions in air at ambient temperature (20°C) and during their motion in the counter-flows of heated air (500°C) and combustion products (800–850°C) were considered. A statistical analysis of collision modes was performed. The dependences of their occurrence on some factors (size, rate, collision angle, and criterial expressions that include the dimensionless linear and angular interaction parameters) were presented. The ranges of fluid surface area during fragmentation and separation of droplets due to collisions in gas media with different temperatures were determined.

Keywords: water, suspension, drops, interaction, collisions, coalescence, bounce, fragmentation, separation, disruption

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INTRODUCTION

Coalescence, disruption, and fragmentation of liquid droplets during their interaction in a gas medium have attracted the attention of researchers for many years. The importance of this area of scientific research is due to several factors. The main factors are the constraints that hinder the development of promising gas-vapor-drop technologies [1–6]: thermal and fire treatment of water and other liquids from unspecified impurities; heat transfer technologies of evaporation and condensation in tracks, blocks, and units of heat power equipment; creation of heat carriers from flue gases, water vapors, and drops; and ignition of composite fuels excluding nozzle clogging and torch extinction in combustion chambers. The high potential of these and many other gas-vapor-droplet technologies is dictated by the possibility of varying the group of basic characteristics of the corresponding multiphase and multicomponent flows in wide ranges (much wider than in liquid or gas flows). The advantages of using mixed gas-vapor-droplet flows for intensification of fuel ignition were considered in [4–6]. Microdispersion of droplets due to overheating can significantly reduce the ignition inertia and minimize the required energy, time, and resources. Major changes can also concern the reduction of anthropogenic emissions and the completeness of fuel burnup [4–6].

The tendencies of formation and rearrangement of multiphase and multicomponent gas-vapor-droplet flows during fire and thermal cleaning of liquids (in particular, water) from unspecified solid and liquid impurities were described in [7]. The peculiarities of the dispersion of the heated droplets of complex composition and the effect of this process on the characteristics of multiphase and multicomponent gas-vapor-droplet flows in heat exchangers were highlighted in [8–10]. The typical trajectories of the motion of liquid droplets in flows corresponding to the above technologies were demonstrated in [7]. It was shown that the properties and structure of liquid droplets can significantly change during vigorous heating [11]. These aspects can accelerate the droplet evaporation and the changes in the composition and structure of gas-vapor-droplet flows. The influence of the dispersion and fragmentation of droplets on the characteristics of multicomponent and multiphase gas-vapor-droplet fuel flows with emphasis on combustion dynamics was shown using suspension fuels with a complex composition as an example in [12–14].

An analysis of [15–17] led us to conclude that the unpredictable and uncontrollable changes in the characteristics (primarily, the rates, with inclusion of the laminar, transient, and turbulent modes of motion) of multiphase and multicomponent gas-vapor-droplet flows due to coalescence, disruption, and dispersion

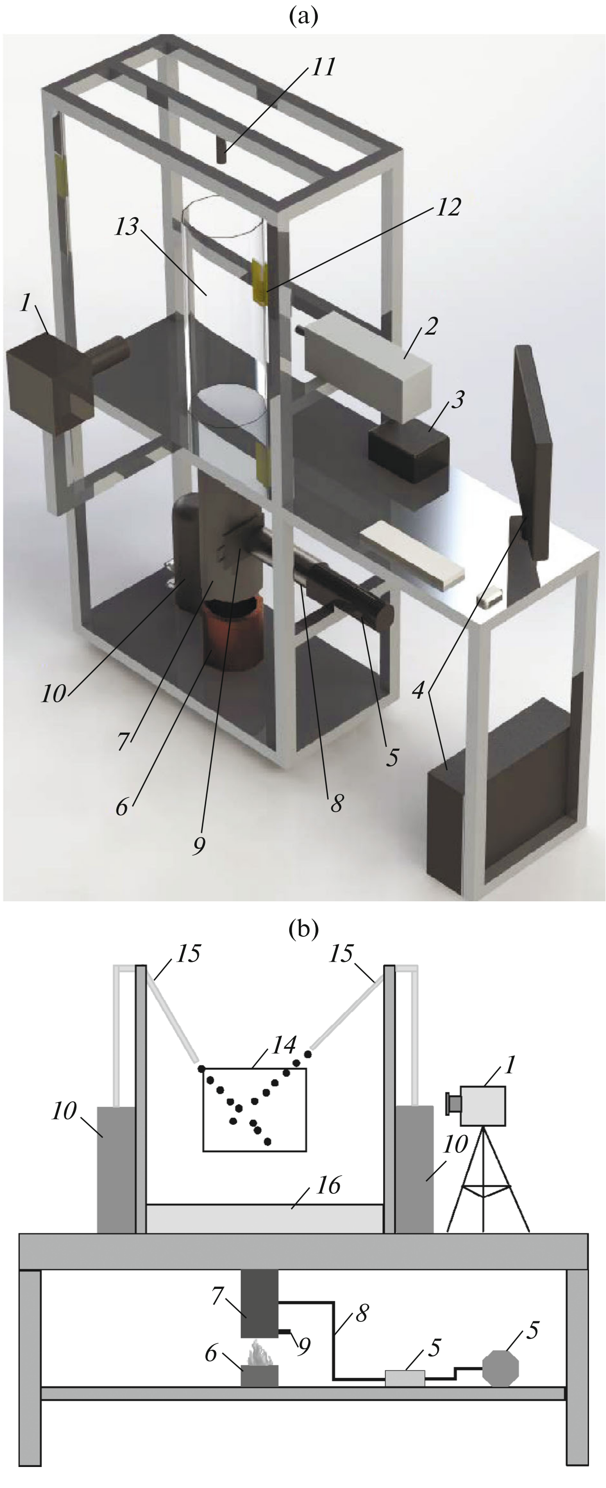

Fig. 1. Diagram of the test stand for experiments with (a) aerosol and (b) two colliding droplets: (*1*) high-speed video camera, (*2*) laser radiation generator, (*3*) synchronizer, (*4*) personal computer, (*5*) air heater and blower, (*6*) burner device; (*7*) groove for supply of combustion products, (*8*) heated air flow supply route, (*9*) gate (necessary for separate supply of combustion products and heated air), (*10*) water tank, (*11*) spray device, (*12*) projector, (*13*) quartz glass cylinder, (*14*) recording area, (*15*) liquid supply capillary, and (*16*) droplet collection reservoir.

of droplets and their entrainment and evaporation are far from being completely explored.

Previously, the interactions of liquid droplets in a gas medium were studied experimentally using two approaches (phenomenological and statistical), namely, collisions of the elements of a droplet aerosol (a large set of droplets) [18] in a flow of combustion products; and coalescence, disruption, and fragmentation of water droplets in air [19]. There were no experimental data on the characteristics, conditions, and modes of collisions of substantially inhomogeneous droplets of liquids, in particular, suspensions. In accordance with the conclusions of [20], it can be assumed that the main reason is high requirements for recording devices, especially under conditions of active phase transformations and chemical reactions, for example, in a heated air flow or during the motion through combustion products.

The goal of this study was to experimentally investigate the modes, conditions, and characteristics of collisions of droplets of typical suspensions in a gas medium (in comparison with water without any solid impurities).

TEST STAND AND METHODS OF INVESTIGATION

Two test stands were used in the experiments. The first test stand (Fig. 1a) allowed the recording of conditions for tens and even hundreds of collisions of droplets in each experiment (recording time 5–10 s) due to the mixing of aerosol and gas flows (statistical approach). The second (Fig. 1b) was designed for recording single collisions of two droplets in each experiment (phenomenological approach). The necessity of using two test stands was dictated by the fact that each of these had both advantages and limitations on the conditions and complexity of research. The use of both approaches affords much more experimental data, which are more reliable. Both methods correspond to the two main trends in studies of droplet interactions [18–20]. This is especially important for heterogeneous droplets as they have not been studied in any of the recording schemes.

The procedures for generating the heated air and combustion product flows and the main techniques for control of parameters in the gas phase used in the experiments were described in detail in [18]. The scientific novelty of this study was that either two aerosol generators or two droplet dosers were used simultaneously. One of these generated water droplets, and the other formed suspensions (Fig. 2). In some experiments, the two generators formed only water or suspension droplets. The practical importance of these experiments lies in the possibility of simultaneously recording the separation of inhomogeneous and homogeneous droplets. These interactions are characteristic of many multicomponent and multiphase gas-vapor-droplet flows [7]. It is important not only to determine the required and sufficient conditions of coalescence, disruption, and separation of homogeneous and substantially inhomogeneous droplets, but also to record the characteristic consequences of droplet collisions, in particular, the number and size of the secondary fragments of the liquid. This will allow us to evaluate the total surface area of the liquid before and after the interaction of droplets, which is especially important for heat and mass transfer gas-vapor-droplet and typical spray systems (generally designed for breaking the droplets to the smallest possible sizes).

Figure 2 shows the video frames with images of the objects of study in six possible modes of droplet collision, as shown in [19]. A series of frames were used to study the mechanisms of interactions of water and suspension droplets (Fig. 2). The experimental parameters were varied in the following ranges: droplet radius (R_d) 0.1–5 mm, rate of motion (U_d) 0–10 m/s, collision angle (α_d) 0–$\pi/2$, relative concentration in aerosol (γ_d) 0.001–0.002 m^3 of liquid droplets in 1 m^3 of gas, temperature (T_g) of combustion products 800–850°C and of air flow 20–500°C, rate of air and combustion products (U_g) 0–10 m/s, and relative mass concentration of graphite particles (with a size of 50 μm) 0–5% (at higher concentrations of the dispersed phase, it is difficult to ensure the stability of suspensions, i.e., to slow down the separation, and hence to perform a series of experiments with stable conditions of injection of inhomogeneous droplets by generators). The choice of graphite as a material of solid particles in droplets was dictated by several reasons: (i) Graphite provides a fairly uniform composition of the generated fragments of suspensions. (ii) Its main physical properties are well defined and close to those of the majority of solid fuels and additives. (iii) The surface transformation of moving droplets and large unsprayed arrays containing such particles was studied earlier [5].

In experiments with aerosol, the optical particle image velocimetry (PIV) method was used to control the gas flow rate (U_g). The particle tracking velocimetry (PTV) technique was used to control the liquid droplet rate (U_d). The droplet size R_d was measured by interferometric particle imaging (IPI) used to record the sizes of spherical and droplet-shaped bodies according to the average radius or diameter. The error of U_g and U_d did not exceed 3.4%; the error of R_d was up to 2.1%. All the methods were integrated based on Actual Flow software. In experiments with two drops, special drop tracking algorithms in the recording area (within the Tema Automotive complex) were used.

For statistical analysis of the characteristics of the interaction of liquid and suspension droplets in an aerosol mixed with the counter-gas flow, we used a technique for calculating the number of collisions in one of four modes to the total number of collisions. In this case, the relative occurrences of coalescence, separation, disruption, and bounce of drops $P_1...P_4$ were calculated. When analyzing the effect of the group of main factors on the $P_1...P_4$ values, at least 100 droplet collisions under identical conditions were considered.

During the criterial processing of the experimental results, the Weber numbers for (missile and target) droplets were calculated using the well-known and widely used equation for the relative flow rate $U_{rel} = (U_{d1}^2 + U_{d2}^2 - 2\cos(\alpha_d)|U_{d1}U_{d2}|)^{0.5}$ [18, 19]: $We = 2\rho R_d U_{rel}^2/\sigma$. The densities and surface tensions of water and suspensions were taken in accordance with the known reference data taking into account the temperature dependence.

RESULTS AND DISCUSSION

When processing the experimental data, we calculated $P_1...P_4$ for droplet collisions and the transient values of Weber numbers for each collision mode (bounce, coalescence, separation, and disruption). Figures 3 and 4 present the main experimental data including the effects of the key variable parameters (size, motion rate, and droplet attack angle) on the conditions and characteristics of the surface transformation of the colliding fragments of the liquid in the statistical (with aerosol) and phenomenological (two individual drops) approaches.

The effects of droplet size and rate illustrating an increase in P_2 and P_3 and a decrease in P_1 at the maximum attained R_d and U_d values are quite obvious and agree well with the data of other authors, in particular, [19]. The P_4 values are high (sometimes exceed 0.5) only in the range of small Weber numbers (below 2), or, accordingly, at low droplet rates and sizes. If we analyze the effect of collision angles, it was poorly defined by other authors because of the high complexity of studies (it is necessary to control the trajectories of droplet motion using at least two high-speed video cameras). This effect was first studied in the experiments reported in [18]. In the present study, it was found (Fig. 3) that coalescence dominated at small (0°–10°) α_d values; disruption dominated at large values (80°–90°); and three variants (separation, disruption, and coalescence) were recorded in the range of medium α_d values. The bounce was found under conditions of droplet interaction at different attack angles, but the most typical conditions (with maximum P_4 values) were recorded for droplets moving in the same direction.

An analysis of the results of experiments using a typical technique, which involves the calculation of Weber numbers (Fig. 4) for missile and target droplets, revealed significant differences in the transition boundaries between the dominant bounce, coalescence, separation, and disruption, especially if the analysis took into account different positions in collisions of water and suspension droplets (i.e., if missiles

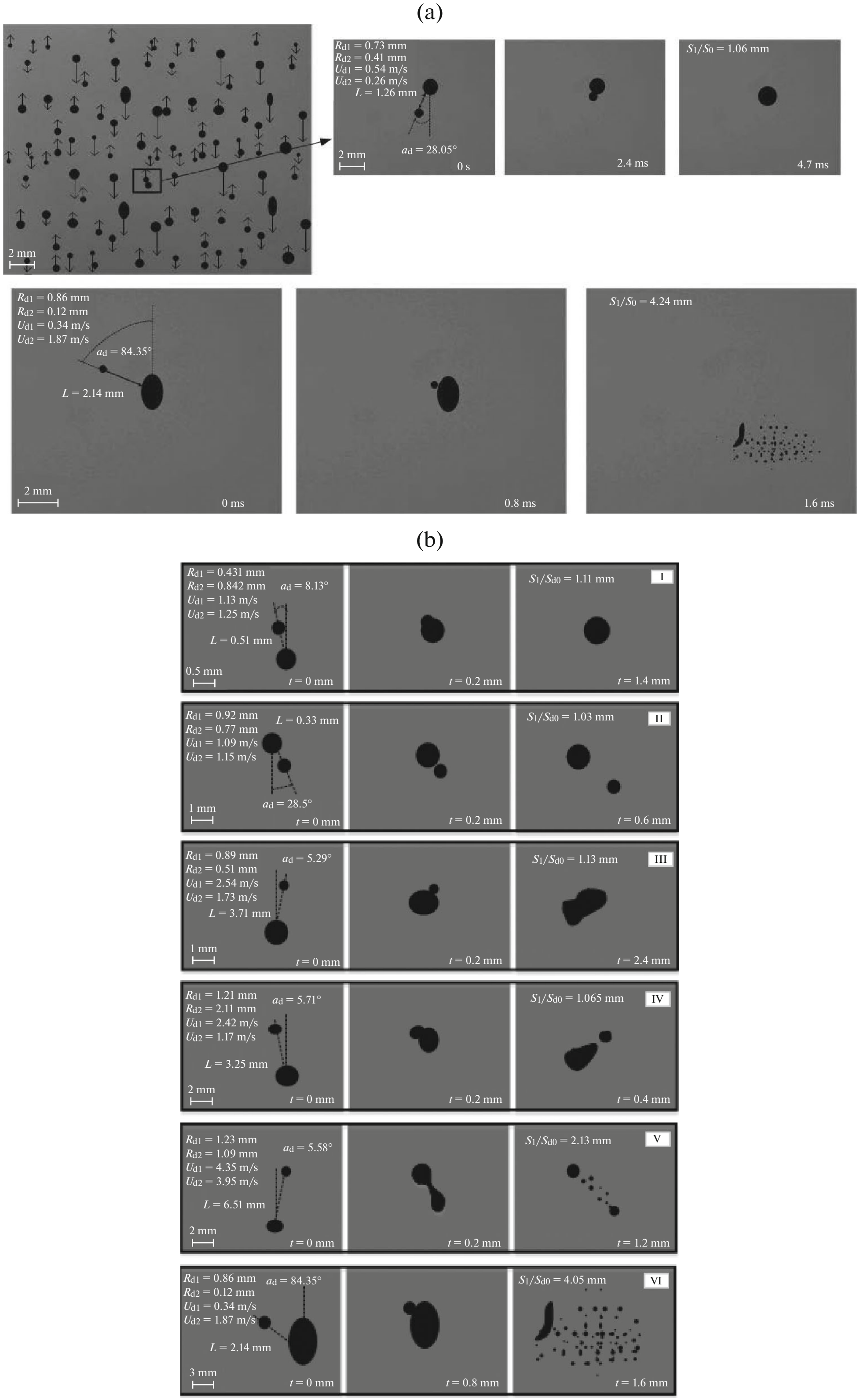

Fig. 2. Typical frames of experiments with (a) aerosol and (b) two drops, illustrating the different modes of their collisions in a gas medium (the names of modes are given in accordance with the terminology of [17–19]): (I) merging (coalescence) of droplets due to surface tension forces, (II) bounce, (III) merging (coalescence) of droplets, (IV) short-term coalescence of droplets with further scattering, (V) droplet disruption through neck formation, and (VI) disruption with formation of an aerosol cloud.

and targets alternated). It was found that the higher the temperature of the gaseous medium, the greater the difference between the conditions of separation or coalescence of water and suspension droplets. This is caused not only by the difference in the surface tension of water and suspensions on heating, but also by the complexity of agglomeration of solid particles in inhomogeneous droplets.

Based on the obtained experimental data, it is reasonable to consider the group of factors that determine the differences in conditions and characteristics (the Weber numbers of both droplets at the moment of collision and droplets that formed during collisions) of the interaction of water droplets and typical suspensions.

Surface tension and its variation during the heating of droplets. According to the known reference data (given in [17–20]), under normal conditions, the differences between the surface tension coefficients of water and water suspensions with a relative mass concentration of solid particles less than 5% differ by no more than 4–7%. At higher concentrations of the dispersed phase, the surface tension increases significantly, and high energy is seemingly required to destroy the droplet. As shown by our experiments, however, the higher the concentration of solid inclusions in a suspension droplet, the greater the surface transformation of the latter. This illustrates the influence of other forces (not only of those related to surface tension), in particular, inertia and internal friction because of the nonuniform distribution of dispersed phase particles in the droplet. The surface tension of water and water suspension substantially decreases (two- or threefold) during the heating. This should lead to active transformation of the droplet surface. However, the experiments showed a slightly different result. In the flow of combustion products, the droplet shape changed insignificantly from spherical (compared with that in an air flow at similar rates without heating). This can be explained by the formation of a buffer vapor layer around the droplet. The higher the temperature and the gas flow rate, the greater the deceleration of aerosol droplets in the flow due to their evaporation and diminishing. As a result, again not all characteristics of the transformation of the droplet surface are determined by the surface tension of the liquid.

The presence of solid particles in droplets, their size, and concentration. Agglomeration factor. Most likely, it is exactly agglomeration of solid particles that leads to droplet instability. This effect on the surface transformation of the liquid mass was analyzed in detail in [5]. The videograms showed that the larger the size and number of solid particles in the droplet, the higher the occurrence of aggregation of solid particles and their protrusion beyond the droplet surface (due to the difference in densities) [5]. It is noteworthy that the integrity of a droplet is most likely affected by the hydrophilic and hydrophobic properties of the material of solid particles. When the particles are wetted to

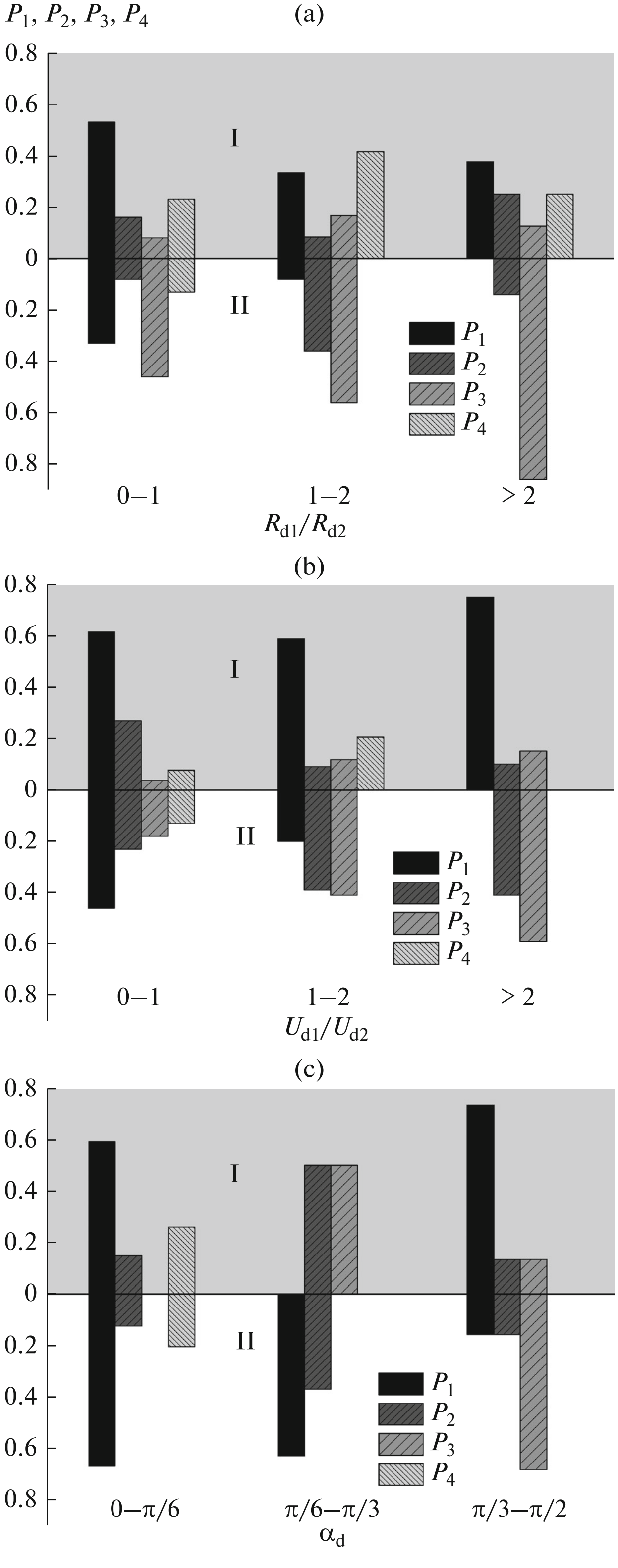

Fig. 3. Relative occurrences of droplet collision modes ((I) water, and (II) graphite suspension at a relative mass concentration of the dispersed phase of 5%) in a gas medium at different (a) droplet size ratios, (b) relative rates, and (c) attack angles.

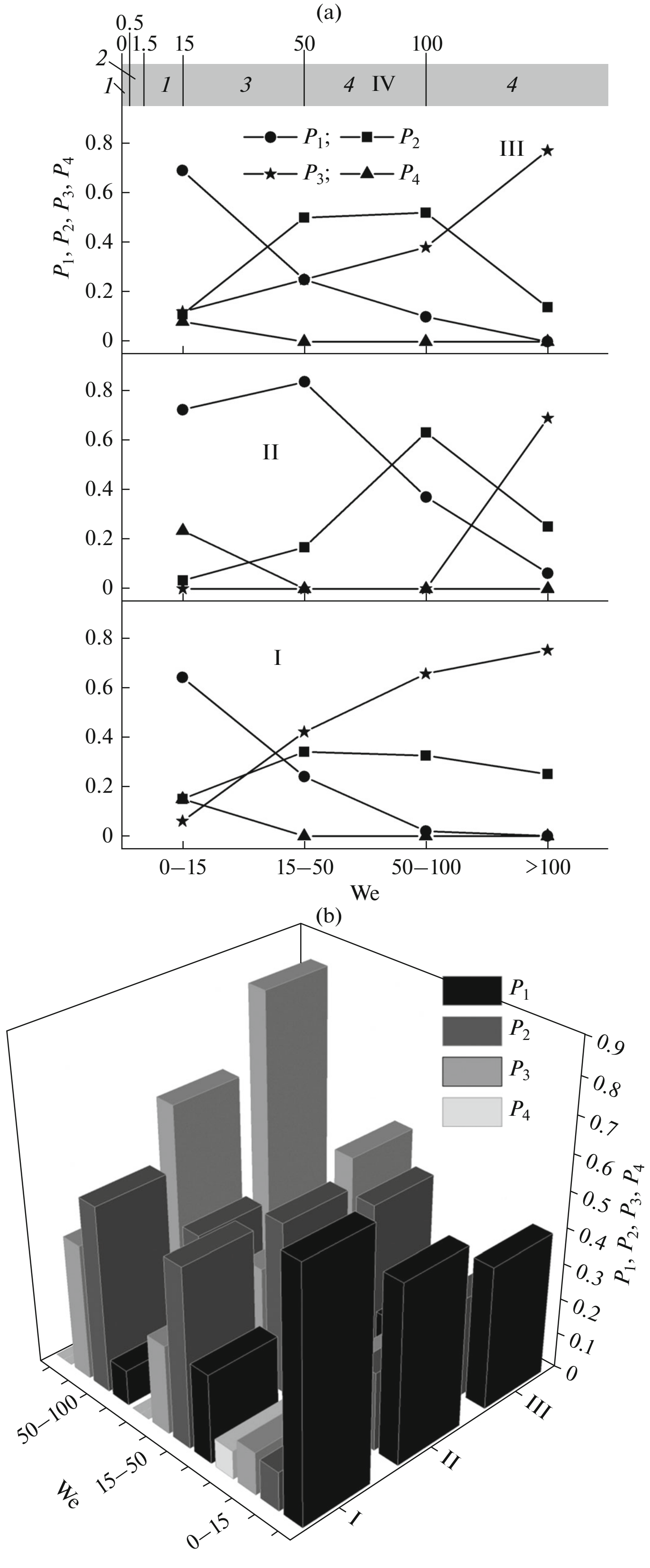

Fig. 4. (a) Differences in the characteristics of collisions of water and suspension droplets (at a relative mass concentration of the dispersed phase of 5%) in a gas medium (20°C) according to Weber numbers: (I) water droplets as missiles and suspension droplets as targets, (II) water, (III) suspension, and (IV) data of [19] ((*1*) coalescence, (*2*) bounce, (*3*) separation, and (*4*) disruption). (b) Additional data illustrating the role of the gas medium temperature on the characteristics of the interactions of suspension droplets in the form of diagrams with three groups of columns ((I) for air at 20°C and (II) 500°C; and (III) for combustion products at 800–850°C).

a greater extent, the effects of droplet surface transformation are expected to be weaker. The videograms showed that the contact of a water droplet with a deformed suspension droplet led to a separation of both in all the recorded instances. As might be expected, the agglomeration increased with the concentration of solid particles.

Collision of water droplets with different parts of suspension droplet (substantially heterogeneous system due to separation), i.e., contact with a water fragment or a mass of thick gel-like composite. When solid particles are added to a drop, its average (or so-called effective) density increases significantly. This leads to a decrease in the limiting rates and sizes of droplets sufficient for their separation on contact with other droplets. The result is quite obvious because the difference between the densities of interacting droplets increases. However, it is noteworthy that at small sizes of suspension droplets and low rates of motion, the approaching water droplets did not collapse on contact (during collision), but scattering occurred; i.e., a denser suspension droplet passed through a water droplet.

Viscosity and density of suspensions and water. When hydrophilic materials are used for the dispersed phase, the viscosity and density of suspensions can increase significantly. The carbon particles showed fairly good hydrophilic properties. Therefore, the conditions for the separation of "dehydrated" solid particles from the surface of the droplet during its flight were not recorded. The elements of the dispersed and liquid phases separated only at high rates of collision.

Droplet shape, impact parameter, and attack angle. An analysis of the video frames showed that the droplet shape of suspensions was not spherical because of particle agglomeration. Ellipsoid, parachute, and even pancake shapes were recorded most frequently. The contact of a spherical water droplet with droplets of these shapes generally led to separation and disruption; coalescence and bounce were recorded less frequently. The attack angle had a critical effect. For example, at interaction angles from 0 to 10°–15° (i.e., during co-directional movement of the liquid and suspension fragments), coalescence and bounce were dominant (the higher the relative rate, the higher the frequency of coalescence). The attack angle of 70°–90° led to disruption. In the medium range of interaction angles, the surface configuration of both drops played an important role. For sphere–sphere or sphere–ellipsoid interactions, separation and coalescence were mostly recorded; in the case of pancakes and parachutes, disruption was dominant. Only when the centers of mass of the colliding droplets coincided or their sizes differed many times, separation was recorded. These effects determine the form of the maps of interaction modes obtained using the angular and linear parameters of collisions (Fig. 5). By varying the β and B parameters from 0 to 1, we can study the effects of all possible collision schemes on the consequences of interaction and conditions of a definite mode.

Difference between the interaction conditions of droplets in aerosol and under ideal contact conditions of two drops. According to the videograms, the droplets continuously transform due to active interactions when moving in an aerosol (especially at high relative concentrations of liquid fragments in a gas medium). We can conclude that the droplets have a synergistic effect on the conditions of their motion in the gas flow. This factor enhances the interaction of the latter. As the attack angles, sizes, and rates of motion vary within wide ranges, certain differences (scatter of values) of the key collision characteristics were recorded (a statistical base was formed based on the experiments). There were significant differences not only in the collision dynamics, but also in the typical consequences even under identical flight conditions within aerosol and when recording collisions of individual drops. For motion within aerosol, conditions of more significant surface transformation were observed, most likely due to continuous contacts with other neighboring drops.

The limiting values of Weber numbers required for the separation of a droplet during its accelerated motion should generally be significantly higher than the corresponding values for droplet collisions. This effect was expected to be most significant for mixed droplets due to the rather complex nonspherical shapes in a wide range of main parameters. The thermal protection factor should also show itself during vigorous heating of droplets due to the formation of a vapor layer around the droplet. The experiments showed that these differences are noticeable only for droplet disruption (for coalescence and scattering, the Weber transition numbers did not differ significantly for drops of water and suspensions). In particular, we can conclude from the well-known studies of the transformation of moving droplets [15–17] that the dynamics of droplet separation during the flight depends on the limiting Weber numbers. At $10 < \mathrm{We} < 15$, disruption of the vibrational or rotational type takes place [17]. A small number of liquid fragments with different sizes can form. The scattering of droplets during collisions occurs in the same range (liquid fragments also form in small numbers). At $20 < \mathrm{We} < 40$, "parachutes" form from moving droplets and separation with formation of a cloud of small jets and chains [17]. At $50 < \mathrm{We} < 70$, "parachutes with a stream" are formed. At $10^2 < \mathrm{We} < 10^3$, the conditions of break-away or shear of the surface layer appear. At $10^3 < \mathrm{We} < 5 \times 10^4$, the conditions of explosive (or "catastrophic," as it is often called [17]) disruption of moving droplets are typical. In this case, the droplet separation dynamics is substantially related not only to the critical Weber numbers, but also to Reynolds numbers that characterize the gas flow mode [15–17]. The processing of the experimental data showed that the formation of a cloud of small fragments of liquid

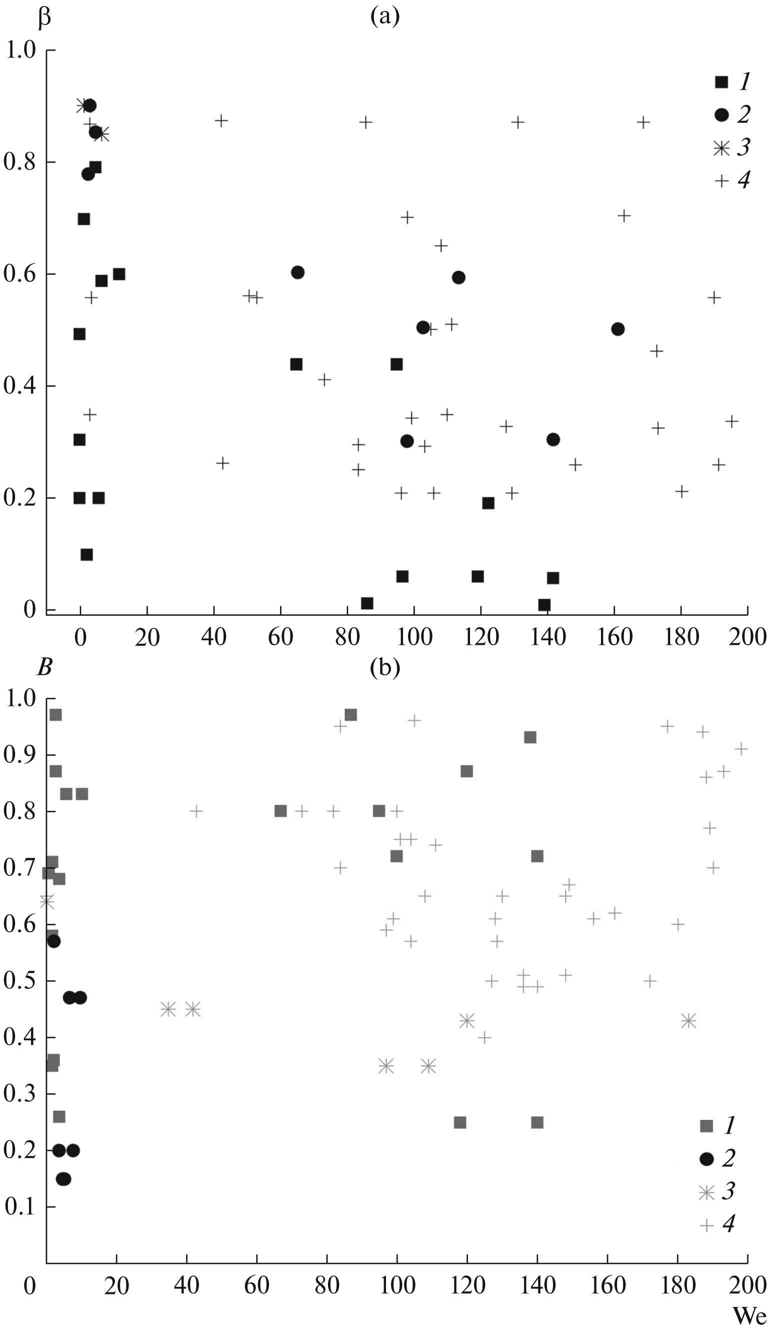

Fig. 5. Maps of collision modes ((*1*) coalescence, (*2*) bounce, (*3*) separation, and (*4*) disruption) of the water–graphite suspension droplets (at a relative mass concentration of the dispersed phase of 5%) including the (a) angular and (b) linear interaction parameters and Weber numbers.

during the interaction of droplets does not require that We > 100. Collisions with formation of a cloud of small drops take place even at 50 < We < 80. A comparison of water and suspensions showed that these minimum We values for droplet disruption of suspensions can be 7–15% lower depending on the concentration of the dispersed phase. The mixing of heterogeneous and homogeneous droplet flows generally leads to more active disruption of liquid fragments.

Gas medium temperature. The experiments showed that this factor was especially significant in intensifying two of the four droplet interaction modes: bounce at low rates and small droplet sizes and disruption at high values of these parameters. The contribution of this factor to the structural changes of the aerosol cloud due to bounce and disruption is clearly shown in Figs. 4 and 6. The intensification of the bounce is associated with a significant increase in the evapora-

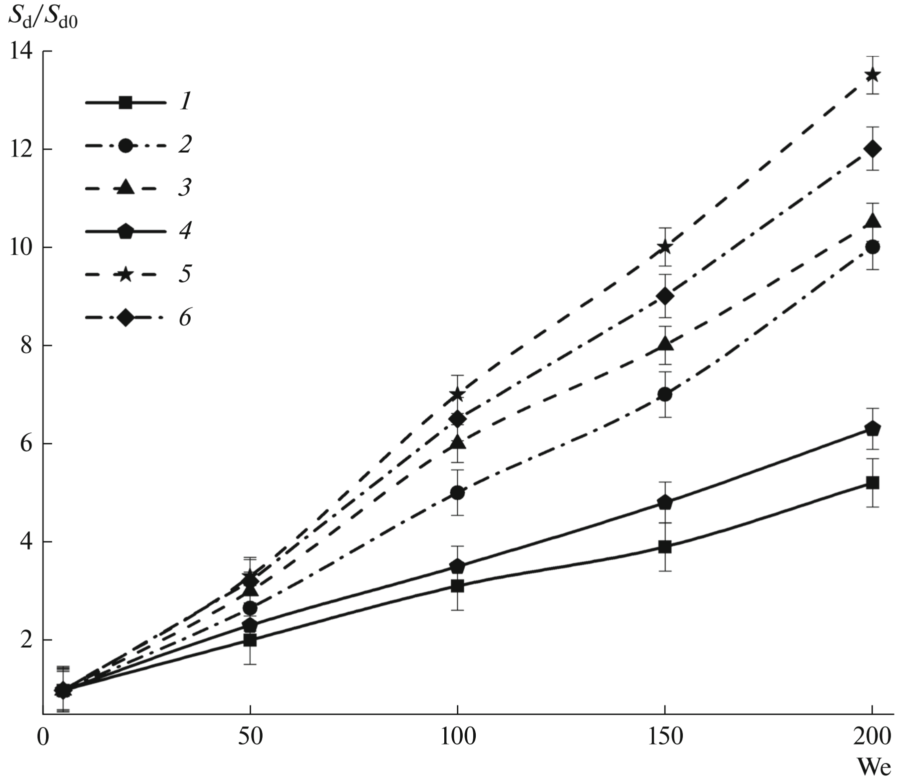

Fig. 6. Results of evaluation of the potential increase in the number of droplets and their total surface area during collisions of parent droplets ((*1*–*3*) in air at 20°C and (*4*–*6*) in the flow of combustion products at 800–850°C): (*1*), (*4*) water; (*2*), (*5*) suspension–water; and (*3*), (*6*) suspension. The data of all experiments with suspensions at relative mass concentrations of the dispersed phase of 0–5% were summarized.

tion rates of water and suspension droplets, especially at increased temperatures (the exponential dependences of these parameters are well known). The corresponding expressions and experimental data for their substantiation were given in [7]. The heating of droplets is intensified in the presence of solid inclusions due to their higher thermal conductivity and significantly lower heat capacity compared to the same parameters of water. Therefore, water in a suspension droplet is heated to higher temperatures. As a consequence, the rates of transformation increase. Reasonably powerful steam flows from the droplet surface form under these conditions. The linear outflow rates of vapor at gas temperatures of 500–900°C can reach 0.05–0.3 m/s (based on the data [7], these parameters can be calculated with allowance for the relationship between the linear outflow rate of vapor and the mass rate of vaporization in terms of the ratio of the latter to the vapor density). As the droplet bounce at 20–30°C occurred under conditions of droplet approach at a relative travel rate of up to 1–1.5 m/s, the contribution of vapor injection with calculated outflow rates to droplet deceleration can be considered significant. Therefore, at high gas temperatures, the bounce was also recorded at initial relative droplet rates of up to 2.3 m/s. The intensification of disruption of suspension droplets at high temperatures is explained by three factors. The first factor is associated with a decrease in the surface tension of water. The second is the weakening of bonds in the surface layer due to vaporization. The third is accumulation of solid particles in the surface layer of the droplet and their release due to water evaporation.

The most valuable result of these studies is that attempts to generalize the experimental data using the Weber numbers led to a large dispersion of the characteristics of droplet coalescence, separation, bounce, and disruption ($P_1...P_4$). An analysis of the data of [19, 20] showed that even when using the maps of droplet collision modes in coordinate systems that include the angular ($\beta = \cos(\alpha_d)$) and linear ($B = L/(R_{d1} + R_{d2})$) interaction parameters and the Weber numbers, the probabilistic nature (significant scatter of experimental data in both the collision mode parameters and consequences) is preserved (Fig. 5). The experiments revealed that this effect was especially noticeable when comparing water and suspension with emphasis on the change in the role of droplets (missile or target) (the collision mode maps are similar to those shown in Fig. 5 except that one or two, or even three collision modes in the identical ranges of β, *B*, and We were recorded). Anyway, higher We values were recorded

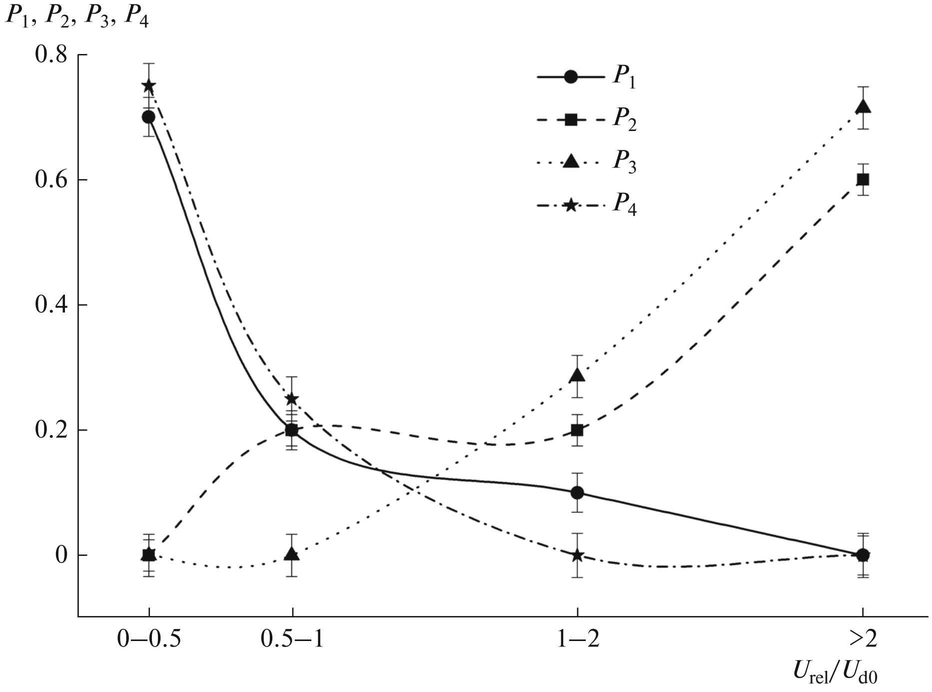

Fig. 7. Differences in the characteristics of the collisions of suspension droplets (at a relative mass concentration of the dispersed phase of 5%) while varying their relative rate. To make the rate dimensionless, the scale corresponding to 1 m/s was taken into account.

for the shell than for the target because it is commonly accepted that the missile is a droplet moving at a higher rate. When comparing water and suspension droplets, more dynamic interaction conditions (i.e., with a larger number of small fragments of liquid) were recorded during collisions of the missile droplets of suspensions with the target droplets of water. This is due to the higher density and viscosity of the former (they break the water droplets they encounter).

It was found that the higher the concentration and size of the elements of the dispersed phase in the droplet, the higher its integrity. An important role is played by the surface layers of interacting droplets. In particular, during collision with a definite region (e.g., the lower part) of a droplet containing an agglomerate of solid particles, the scattering was recorded with a rather slow subsequent separation of the remaining fragments containing solid particles. Only at high droplet rates (above 5–7 m/s) collision of a water droplet with the agglomerate led to the formation of a finely dispersed aerosol. If the water droplet interacted with the upper part of the suspension droplet with a low concentration of solid particles, the conditions of separation or coalescence corresponded well to experiments with water without inclusions. At high rates, the collision led to a separation of the lower part of the suspension droplet and its strong twisting. Due to the high concentration of solid particles in this fragment and high rotational rate, all subsequent collisions of water droplets with it led to a separation or disruption of the elements of the liquid aerosol. Each subsequent collision led to an increase in the number of rotating elements in the aerosol and intensified the collisions.

To obtain the dependences presented in Figs. 6 and 7, a specialized algorithm was developed for calculating the number of droplets and their total surface area (based on the Tema Automotive and Mathematica software systems). It involves the marking of the approaching liquid fragments; determination of their contours and surface areas from the difference in luminosity compared with the background image; calculation of the sizes, rates, interaction angles, the number of the resulting liquid fragments, their size, and total surface area; and comparison of the latter parameter with the same parameter before the interaction.

The results of the experiments are of great interest for some chemical, petrochemical, and heat and mass transfer applications in the field of sputtering of liquids, solutions, emulsions, and suspensions (especially at high gas temperatures), for example, in heat treatment chambers of liquids, contact heat exchangers, and fuel composite systems. Despite the justified prospects of such systems, however, their development is limited by the lack of experimental data on the hydrodynamic processes occurring in them. It is worthwhile to note secondary atomization (disruption) systems, which can be created by varying the size of liquid droplets directly in the process chambers after injection. An analysis of the literature (for example, [1–7]) and the experiments shows that effective secondary (additional) atomization of a liquid is possible due to various mechanisms: thermal (overheating of the low-boiling component of inhomogeneous droplets, growth of bubbles, and their subsequent collapse), dynamic (disruption due to acceleration), and contact (scattering or disruption during collisions). The experimental data shown in Figs. 6 and 7 indicate that the latter factor can lead to a substantial disruption of droplets. For heterogeneous droplets, the area ratio increased more significantly. Therefore, a hypothesis can be formulated: the potential synergistic effect most likely ensures the conditions for multiple increase in the surface area of the liquid due to the disruption of the colliding heated inhomogeneous droplets. Unfortunately, this hypothesis cannot be verified on the developed test stand (Fig. 1) because of the low residence times of droplets in the recording area (disruption processes can continue even after the droplets have left the video recording area). The inhomogeneous droplets can be overheated to the conditions of fragmentation of the low-boiling component either by providing high heating temperatures or by increasing the hovering time of colliding droplets before the interaction. The formulated problem is very promising for future research, judging from the results of this study and the data of [17–20].

CONCLUSIONS

The experimental results of the comparative analysis of the characteristics of interaction of homogeneous (water) and inhomogeneous (suspensions) droplets during collisions at different heating temperatures of the gas medium were obtained using two approaches (phenomenological and statistical). They provide an opportunity to study the interaction of single droplets or a large group of aerosol elements by calculating the corresponding characteristics of the processes. The first approach allowed us to study the differences between the main physical processes of interaction; the second, to determine the characteristics of coalescence, separation, and disruption for typical gas-vapor-droplet applications.

An analysis of the videograms of the experiments and criterial processing of the experimental data led us to conclude that even the main features of interaction of inhomogeneous droplets can hardly be described using only the Weber, Laplace, or Stokes numbers. For future development of the corresponding models, it is important to formulate generalized criteria that take into account all the factors studied in experiments: size, rate, interaction angle, droplet composition, their roles (target or missile), temperature, and gas flow rate. A promising problem is the construction of the spatial fields of variation of the key parameters to illustrate the conditions of bounce, separation, disruption, and coalescence of homogeneous (e.g., water) and substantially inhomogeneous (suspensions and other varieties of mixtures) droplets.

In collisions of water and suspension droplets, the effective surface area of liquid fragments can be increased on the average more than fivefold. At increased gas temperature, the consequences of collisions of droplets can change due to active evaporation and a decrease in the size before collisions. This leads to the formation of a greater number of small drops; as a result, the total surface area of the sprayed liquid can increase even tenfold or more. These effects are especially pronounced in studies of interactions of inhomogeneous droplets. If we take into account the results of a multiple increase in the number of generated fragments during the explosive disruption of boiling inhomogeneous droplets, we can formulate a hypothesis about the potential synergistic effect of collisions of the latter in high-temperature gas flows.

FUNDING

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NOTATION

B	dimensionless linear interaction parameter
L	impact parameter (the distance between the centers of droplets used for calculating the linear interaction parameter of the latter), mm
P_1, P_2, P_3, P_4	relative occurrences of coalescence, separation, disruption, and bounce of droplets
R_{d1}, R_{d2}	radii of interacting droplets, mm
S_{d0}, S_d	total surface area of droplets before and after the interaction, m^2
U_{d0}	nominal rate used as a scale factor for reducing the results to the dimensionless form, 1 m/s
U_{d1}, U_{d2}	rates of interacting droplets, m/s
U_{rel}	relative rate of droplets, m/s
U_g	gas (air) flow rate, m/s
α_d	attack angle, deg
β	dimensionless angular interaction parameter
ρ	density, kg/m^3
σ	surface tension, kg/s^2
We	Weber number

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