EXPERIMENTALLY DETERMINING THE EFFECTS OF WATER DROPLETS COLLISION WHEN MIXING AEROSOL WITH GAS FLOW AT DIFFERENT HEATING TEMPERATURES

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The article presents the results of experimental studies of the collisions characteristics for water droplets in an aerosol at its entry into the air counter flow. The temperature of the latter ranged from 20 °C to 500 °C. Experiments were also carried out with the flow of combustion products having a temperature of 800–850 °C. The initial dimensions (radii) of the droplets in the aerosol were 50–1000 μm. Visualization of the droplet motion in the counter flow of air and combustion products required the use of a hollow cylinder made of quartz glass with a height of 1 m and an internal diameter of 0.15 m, a cross-correlation complex and optical methods (Particle Image Velocimetry, Particle Tracking Velocimetry, Interferometric Particle Imaging). The characteristics of the droplet interaction (size, velocity, total surface area of the liquid before and after) were controlled using a high-speed video camera and tracking algorithms in the Tema Automotive software package. The main modes of drops interaction have been identified: bounce, coagulation, scatter, and breakup. The statistical information database has been obtained to describe the interaction modes using diagrams, taking into account the ratio of the sizes of colliding drops, velocities of their motion, and an angle between trajectories of motion. The influence of gas temperature on the probabilistic criteria of droplet collisions, as well as the integral criterion characterizing the change in the liquid surface area due to the intensification of droplet collisions in the gas medium has been established.

Key words**:** *water droplets; high temperature gases; collisions; interactions; coagulation; scatter; breakup.*

1. Introduction

The world scientific community has relied on multiphase and multicomponent gas-vapour flows in a large group of technologies [1–3]. This approach is quite justified, since it contributes to higher environmental, energy and technical and economic characteristics of the relevant devices, blocks, units and systems as a whole. For example, one can distinguish a group of technologies where the aforementioned characteristics increase by 20–60% when using the multiphase and multicomponent gas-vapour flows [4]: thermal and flame cleaning of water and other liquids from unspecified impurities; heat transfer technologies of evaporation and condensation in heat power paths, nodes, blocks and units; coolants from flue gases, vapours and drops of water; composite fuels ignition without effects of nozzle clogging and flame extinction in combustion chambers; time and space distributed supply of specialized gas-vapour mixtures to the fire zone for its effective localization and entire suppression. However, the main problem of wide application of multiphase and multicomponent gas-vapour flows is still [4] their component composition and structure that is difficult to predict. Droplet distribution by velocity, trajectories, size and concentration varies due to the effects of coagulation, breakup (complete disintegration of parent droplets) and puffing (separation of liquid fragments with different sizes and volumes from the surface) of droplets [5, 6]. There are yet no adequate models reliably describing the droplets motion in multiphase and multicomponent gas-vapour media or the one taking into account the effects of droplets interaction [7–15].

The review articles [11–15] present experimental data for the last 70-80 years on the characteristics of the two drops collision for different liquids (water, glycerine, various oils, milk, fuels, etc.). They served as a basis for the formation of modern ideas about the characteristics and modes of droplet interaction in the gas medium. Unfortunately, such ideas about the processes of bounce, coagulation, scatter, breakup and complete disintegration of liquid droplets are not sufficient to predict the structure of the gas-vapour flow at heating. In accordance with the review articles [11–15], the relevant experiments have not been conducted yet. There are several main reasons for this. *First*, they require much more complicated experimental techniques and additional equipment to control the temperature in the zone of droplet interaction. *Second*, the dependences of different liquids properties (viscosity, density, and surface tension) on temperature are known. Using these dependences, one may very tentatively estimate to what extent the characteristics of droplet collisions can change. *Third*, at droplet heating the properties of the gas medium significantly change due to vaporization. It is difficult to reliably control the parameters of the gas medium at high rates of vaporization. These parameters can significantly affect the collision characteristics. The numerical values of the heated droplets interaction characteristics have not been identified yet for the conditions of promising gas-vapour technologies [1–6].

There are available experimental data [7, 8] obtained by high-speed (up to 100 000 frames per second) video recording, cross-correlation software and hardware complexes (based on the Actual Flow software) that implement optical high-precision and low-inertia methods of recording the speed, temperature, dispersion and size of the elements, as well as the droplet collisions consequences in the aerosol. However, so far, data are known only for the conditions of intensive evaporation in the flow of combustion products at maximum temperatures (up to 1000 °C) [7, 8]. In this regard, an experimental study of the conditions, characteristics and consequences of collisions of liquid droplets moving in gas media with different temperatures is of interest to determine the vaporization effect.

Based on the analysis of experimental data [7–10], the following hypothesis has been formulated. The breakup and scatter of intensively evaporating droplets are complicated due to the formation of a vapour buffer zone around them. It contributes to a decrease in the rates of convergence and, as a consequence, can lead to the dominance of droplets bounce and coagulation. It is necessary to perform statistical analysis of droplet collisions to justify or refute this hypothesis. The most valuable results may be obtained by bringing the experimental conditions to the real gas-vapour applications considered in article [4].

The aim of this work is to define differences in schemes, conditions and characteristics of the water fragments interaction by mixing the aerosol and gas stream at different temperatures by means of the statistical analysis of collisions for aerosol droplets in the air flow of variable temperature and combustion products.

2. Experimental methods and setup

Analysis of the references on this scientific problem (in particular, [1–5, 7–15]) shows that to date, several experimental methods have been developed to study the interaction of colliding droplets in the gas medium. In general, all known methods can be divided into two groups. The first includes techniques based on experiments with two individual drops, i.e. with the exception of the influence of the third and other drops. For example, articles [9, 10] show a typical stand where the first drop (target) was generated by a rotational capillary and moved along the same trajectory, and the second drop (slug) was formed using a vibrating capillary. This allowed directing the slug at different angles of attack relative to the target. Similar research methods often involve fixing one of the drops on the threads or other holders and generating droplets-slugs to hit the target. The main advantage of these methods is the controlled droplet interaction under different conditions. The main drawback is high complexity of experiments due to the need to use a large number of devices and systems to approach the conditions of droplet interaction to real applications. In addition, it is quite often hypothesized that idealized conditions of droplet collisions in accordance with such techniques are very far from real gas-vapour applications. For these reasons, actively developing is the second group of techniques based on the statistical analysis of conditions and characteristics of liquid droplets interaction at aerosol generation, i.e. by sampling frames with a large number of collisions. For example, researches [7, 8] present methods implying the study of high-speed video recording frames and the sampling of frames with collisions. This analysis serves to calculate the relative probabilities of collisions with bounce, coagulation, breakup, scatter and other consequences of droplet interaction in the gas medium. Since this work involves the analysis of droplet interaction in gas media with a wide range of temperature variation, it is advisable to use techniques from the second group.

In general, the method of experimental studies in this paper is similar to that used in experiments [7, 8]. In contrast to articles [7, 8], the experiments are carried out not only with the turbulent flow of combustion products, but also with the laminar flow of heated air. Temperature is varied from 20 °C to 500 °C and velocity ranges from 0 to 10 m/s. The main elements of experimental setup: the compressor and the gas flow heater, a cylinder made of quartz glass, where the gas flow is formed, the aerosol generator, the registration area and the hardware-software tracking system. Similar to the methods in articles [7, 8], experiments are additionally performed to generate the flow of kerosene combustion products under control of their temperature (800–850 °C) and velocity variation (from 0 to 10 m/s). For this purpose, the burner device presented in articles [7, 8] is used instead of the heater and the air blower. In contrast to the experiments [7, 8], the system of air supply to the burner was modified to vary the combustion products velocity in the above range. Gas temperature is controlled using three low-inertia thermocouples (chromel-alumel, range of 50–1200 °C, and systematic error of ± 1.5 °C, and junction diameter of 0.3 mm) and input-output board, National Instruments 9213. The relative concentration of 0.001–0.002 m^3 of liquid droplets in 1 m^3 of gas is maintained in all experiments to allow comparing data with earlier results [7, 8] and complying with the average for real ranges in spray applications.

Experiments on registration of the coagulation, breakup and disintegration effects for water droplets are performed with pulsed (1 s) injection of polydisperse water aerosol: sizes (radii R_d) of droplets from 0.05 to 1 mm and velocity (U_d) from 0 to 10 m/s. To control the gas flow velocity (U_g), the optical method of Particle Image Velocimetry (PIV) [16] is used, and for liquid droplets (U_d) Particle Tracking Velocimetry (PTV) method [17] is applied. The droplet size R_d is measured using the Interferometric Particle Imaging (IPI) [18]. Errors in determining the values of U_g and U_d do not exceed 3.4%, and for R_d they are no more than 2.1%. All methods are integrated on the basis of the Actual Flow software. Methods of application of PIV, PTV and IPI are described in detail in the earlier article with experimental data obtained with the flow of combustion products [6].

For marking and tracking the moving drops, specialized algorithms of the Tema Automotive complex [5, 6] are used. The reason is that the cross-correlation registration has a limit on the number of frames per second due to the synchronous operation of the laser, cameras and personal computer. Therefore, the above optical methods allow obtaining the average values of velocities and sizes of droplets. For a detailed study of the interaction of each specific pair of drops, it is advisable to use the previously developed tracking algorithms in the Tema Automotive (used in the processing of the experimental results [7, 8]). It serves to specify the size R_d, shape, velocity U_d, angles of attack α_d of the drops, the surface area S_d (under the assumption of a spherical configuration the expression $\pi R_{d1}^2+\pi R_{d2}^2$ was used) and to register new liquid fragments, formed at collisions, and their parameters (R_d and S_d). The spray systems were arranged for varying the values of α_d in the entire possible range – from 0 to $\pi/2$. Permissible errors in determining the parameters of approaching droplets at choosing scale factors in videogram processing were: U_d – 1.8%, R_d – 1.1%, and α_d – 2.3%.

The registration area represents the zone at the cylinder exit similar to the method [6] to ensure accurate imaging of droplet interaction: bounce – droplets interaction through the gas layer without direct contact, because of insufficient kinetic energy to overcome the repulsive forces; coagulation – merger; scatter – collision, in which the initial and final dimensions of the interacting fragments are almost identical; and breakup – puffing, i.e. disintegration with the formation of several or a large number of small drops. It should be noted that the method of calculating the ratio of the collisions number with one of the four consequences variants to the total number of collisions was used in the statistical analysis of the water droplets interaction characteristics in the aerosol mixed with the gas flow [7, 8]. In this case, the values of relative probabilities of coagulation, scatter, breakup and bounce of drops were calculated: P_1, P_2, P_3, P_4. When analyzing the influence of a group of main factors on the values of P_1, P_2, P_3, P_4, at least 50 collisions were considered under identical conditions. In total, several thousand interactions of droplets have been studied to provide reliable statistics.

Weber numbers for droplets (slug and target) was calculated taking into account the widely used expressions and values of water properties (used in experiments [7–10]): $We=2\rho R_d|U_d|^2/\sigma$. In the case of co-directional motion of droplets, their velocities were subtracted, in the countermotion they were added, and in the case of a side collision, the value of one velocity corresponding to the slug or target, respectively, was taken into account.

3. Results and Discussion

The analysis of video frames resulting from the experiments allows concluding that the modes of droplet interaction and the data obtained during the experiments with two approaching individual droplets are generally satisfactory [9–15]. In particular, in the air flow with room temperature (about 20 °C) at characteristic (for targets and slugs) Weber numbers from 0 to 150, six schemes (modes) of their interaction have been determined. At low Weber numbers, the conditions of merger (stable coagulation) of droplets ($We<0.5$) or their bounce ($0.5<We<2$) (interaction of liquid fragments through the gas layer without their direct contact) were recorded. By high-speed video recording, the bounce was found to occur during intensive swirling of the drops and formation of the vacuum zone in their wake, i.e. a significant drop in velocity and pressure of the gases. Coagulation was recorded at droplet surface transformation, i.e. deviation of their shape from the spherical one. Under such conditions (especially at non-central collision) the droplets stuck together due to surface tension forces. In the case of a spherical form, drops often bounced from each other. In the experiments, the results of which are analyzed in articles [9–15], such conditions were explained by the formation of a gas layer between the droplets, whose kinetic energy was not sufficient to overcome such a layer. Most likely, this hypothesis is valid, since the probability of droplet bounces significantly increased with increasing air temperature (especially many collisions were recorded in experiments with combustion products having a temperature of 800–850 °C). However, even with the use of high-speed cameras, optical recording methods and the Schlieren method, it is not possible to establish the parameters of gas and vapour shells around intensely heated and evaporating water droplets of small size. On the basis of experimental and calculated data comparison [19], it was established that the characteristic thickness of such shells does not exceed 1 mm at high temperatures of convective heating of droplets. The statistics of collisions with drop bounce established in the present work may serve to substantiate hypotheses on bounces, presented in the articles [9–15].

At $2<\mathrm{We}<15$ and at room temperature, coagulation (merger) of droplets dominates. The kinetic energy of the latter is sufficient to squeeze out the gas and vapour layer between the droplets (and for their subsequent merger). The collision process ends with the formation of a single drop with an intensely oscillating surface and even its rotation. After passing the distance of 10–15 R_d in the gas medium the formed drop takes the shape close to spherical or tear, and continues to move steadily.

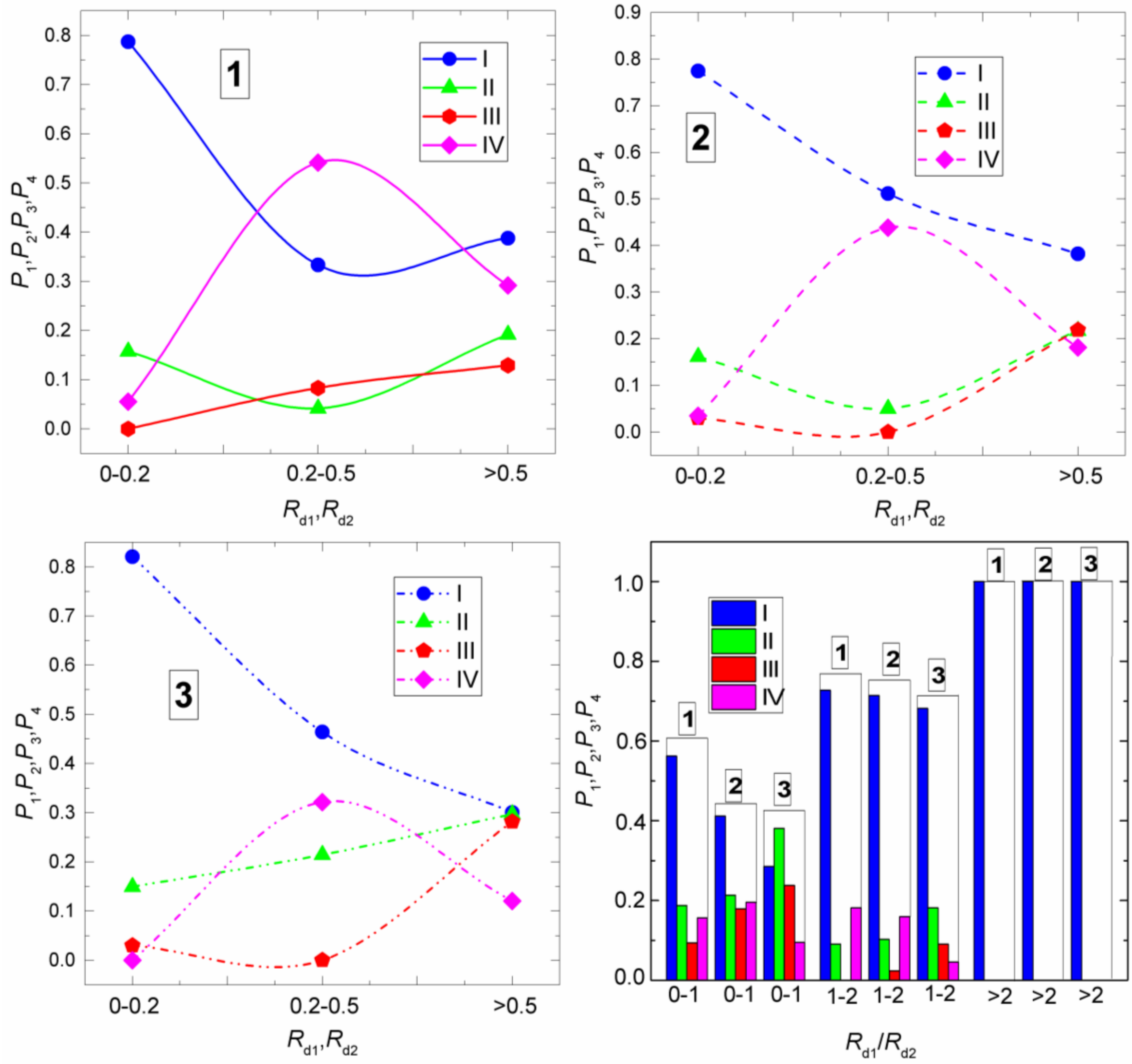
In the range of $15<\mathrm{We}<50$ it was possible to record the dominance of the droplet interaction effects in the scatter mode, i.e., the collisions, in which the sizes of the two participating droplets correspond well to the two newly formed droplets. When $\mathrm{We}>50$ the scatter of droplets also dominated, but it was slightly different than at $15<\mathrm{We}<50$. In particular, it was found that with increasing Weber numbers, the scatter occurred in the mode of breaking through the drop-target. In general, two large liquid fragments with sizes corresponding to the initial size remained after the collision, but in addition, several small fragments were formed. The physical reasons for such differences, taking into account the forces of surface tension, viscosity, inertia, and friction, have not been established yet. Hypotheses [9, 10] were formulated more than 30–40 years ago, but to date there have been no experiments to justify or refute them. This paper has obtained experimental results that justify the ideas from articles [9, 10], but only for the room temperature of the air flow. When the gas medium is heated, the conditions, characteristics, and effects of droplet interaction vary considerably. Further, using Figs. 1 and 2 the main revealed regularities will be elucidated.

At $\mathrm{We}>100$, the conditions of droplet breakup with the formation of a droplet cloud dominate. In this case, the colliding droplets disintegrate. The disintegration characteristics (the number of new drops, their size, and trajectory) significantly depend not only on the size and velocity of the parent drops, but also on the angles of attack and their shapes. In particular, high-speed video recording has shown that the maximum number of the formed liquid fragments with minimal dimensions correspond to the central collision of non-spherical drops (for example, discs, ellipsoids, and parachutes). If the droplets with such shapes collided, for example, tangentially or in the lateral part, rather than along the central axis, the disintegration is partial and only the contact zone is completely destructed. The conditions of cavitation interaction of droplets considered in articles [9, 10] have not been registered in the experiments.

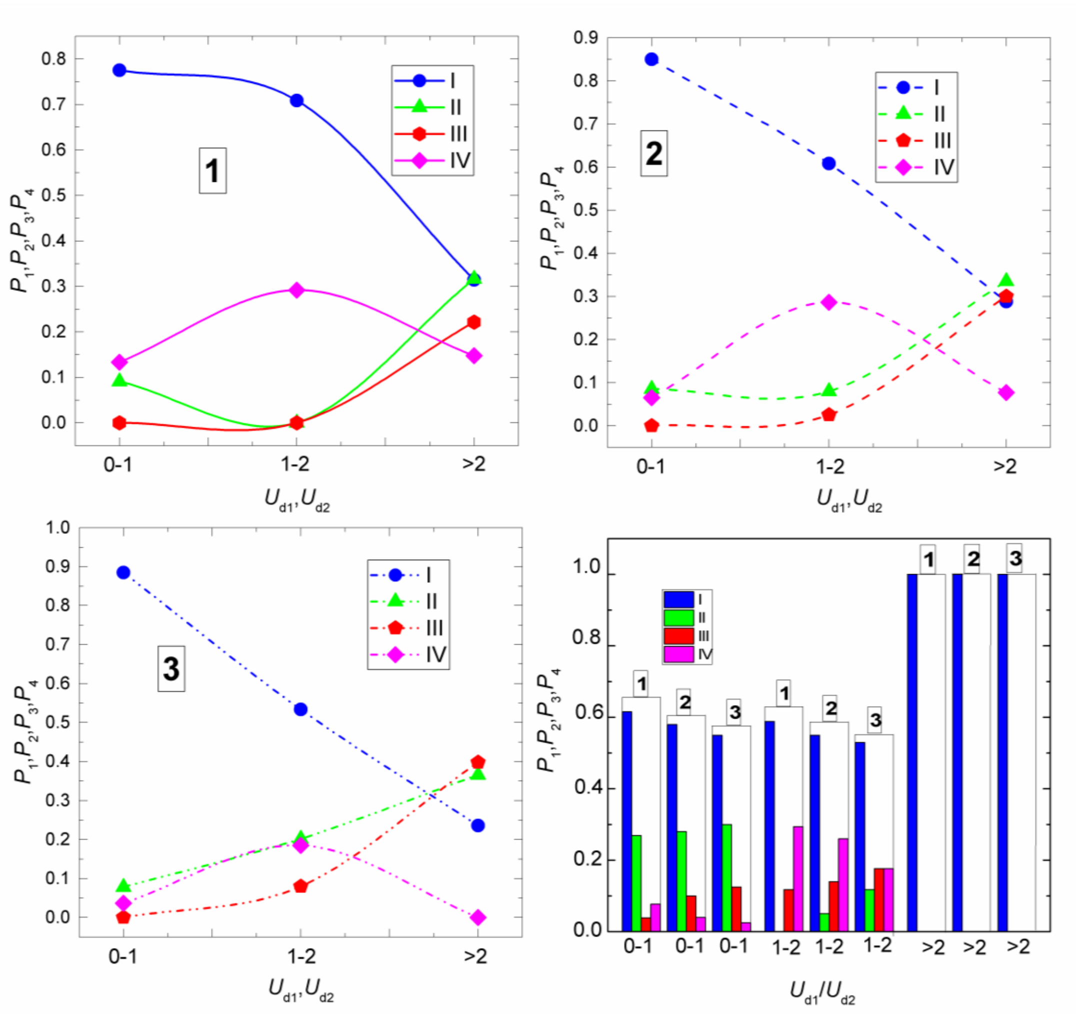
When the temperature and velocity of the gaseous medium increased, only three (of the four main) of the six variants of droplet interactions discussed above were recorded: coagulation, scatter, and breakup. The bounce conditions were specific only for the co-directional motion of small (up to 0.5 mm) droplets with a low relative velocity (up to 2 m/s). Intensive evaporation of droplets (experiments using contactless methods, i.e. Planar Laser Induced Fluorescence (PLIF) [19] have shown that the surface temperature of such droplets will reach 60–80 °C for 1.5-3 seconds at air temperature from 300 to 800 °C) allows creating a stable vapour shell, but at high velocities the thickness of the shell becomes small. As a result, the bounce practically did not take place. Estimates of experimental data on evaporation rates [14] bring to a conclusion that they can reach 0.05–0.15 $kg/(m^2s)$. Hence, the maximum linear velocity of vapour outflow, taking into account its density of 0.6–0.9 kg/m^3 will reach 0.08–0.25 m/s, which is much lower than the relative velocities of droplets in the gas medium (for example, at 2–4 m/s). Therefore, the bounce was not realized, and coagulation dominated. It may be also noted that the vapour shell formed around the droplets due to heating and evaporation compressed the latter. This significantly slowed down the surface transformation of the droplets, and their shapes were close to spherical. Consequently, collisions at high velocities (over 7–8 m/s) and maximum sizes (0.4–0.5 mm) of droplets resulted in complete disintegration (scatter). In the range of medium sizes and velocities of droplet motion the conditions of stable droplet scatter were realized.

Figs. 1 and 2 provide typical values of the calculated probabilities of drops collisions for different conditions of the air flow and combustion products heating with illustration of the transitional values of the Weber number (between bounce, coagulation, scatter and breakup in accordance with the data of experiments [9, 10]). In addition, Fig. 2 presents data from early experiments carried out by other authors. It was found that even under room temperatures, the boundaries of transitions between bounce, coagulation, scatter and breakup of droplets (in accordance with data of experiments [7–10], as well as results of theoretical and experimental studies [11–15]) can be considered only as conditional. This is due to the fact that only the size and velocity of colliding droplets are taken into account when calculating Weber numbers. As shown in Fig. 1, the determining influence is exerted not only by the absolute values of dimensions or velocity of the droplets, but especially by their ratio. It is the analysis of the correlation data that serves to substantiate the importance of independent accounting of the influence of R_d and U_d, since each of these parameters has a significant and essentially different effect on the critical (transitional between interaction modes) Weber numbers. In addition to these two parameters, there is a governing influence of the angle of attack (Fig. 2,*c*). In the range of average values for interaction angles (from $\pi/4$ to $3\pi/4$) almost equal probabilities of all four collision outcomes were recorded. At small angles of attack coagulation dominated and at large ones (closer to $\pi/2$) breakup and scatter prevailed. This influence, as well as that of the real shape (relative to the sphere) has not yet been mathematically described. In addition, the values of transition Weber numbers for droplets, slugs and targets, were also significantly different (Fig. 2). This factor was not taken into account in the experiments [7–10], since the authors limited themselves to considering the parameters of droplets-slugs. In articles [11–15] this effect was taken into account (due to the use of the so-called interaction parameters, i.e. the angular β and the geometric or linear I), but under idealized conditions of two drops collisions, i.e. with the use of stands and models excluding the influence of a large number of adjacent drops on the conditions of their motion and interaction in the gas medium. The influence of the droplets attack angle (and respective differences in their trajectories) presented in Fig. 1*c* on the collision characteristics at room temperatures correlates well with the conclusions of articles [11–15] on the influence of β and *I*, especially on the conditions of transition from stable coagulation to scatter and breakup. At elevated gas medium temperatures, experimental data have been obtained for the first time.

The experiments have shown that the larger is the temperature of the gas medium, the higher is the probability of not only a bounce (the reasons are analysed above and associated with an intense outflow of vapour from the surface of the liquid), but also of the droplets coagulation. This non-obvious result is due to different conditions, including the counter mixing of aerosol with heated gas flow, that are considered in this paper. High-temperature gases significantly inhibit droplets moving in the front. All subsequent drops catch up with the ones in front and coagulate due to low relative velocities (as a rule, no more than 2 m/s) of interactions. The increase in the gas temperature contributes to droplet heating and reduces surface tension several times. In addition, the evaporation weakens the strength of the near-surface layer of droplets.



(a)



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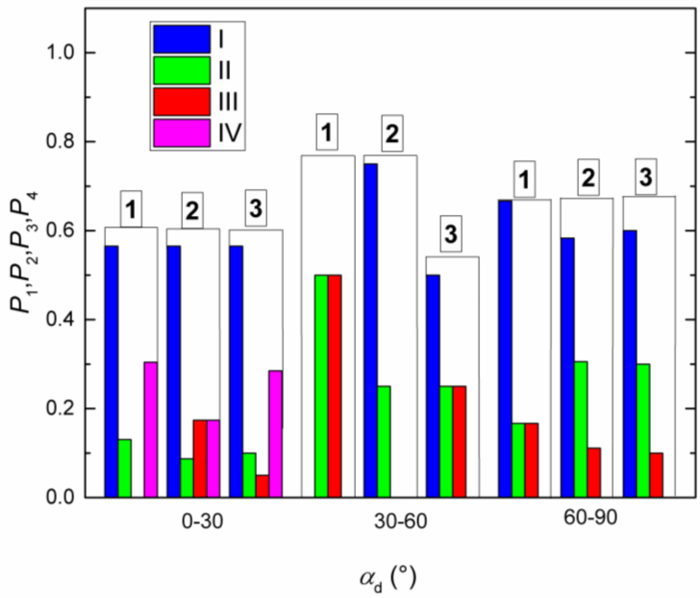
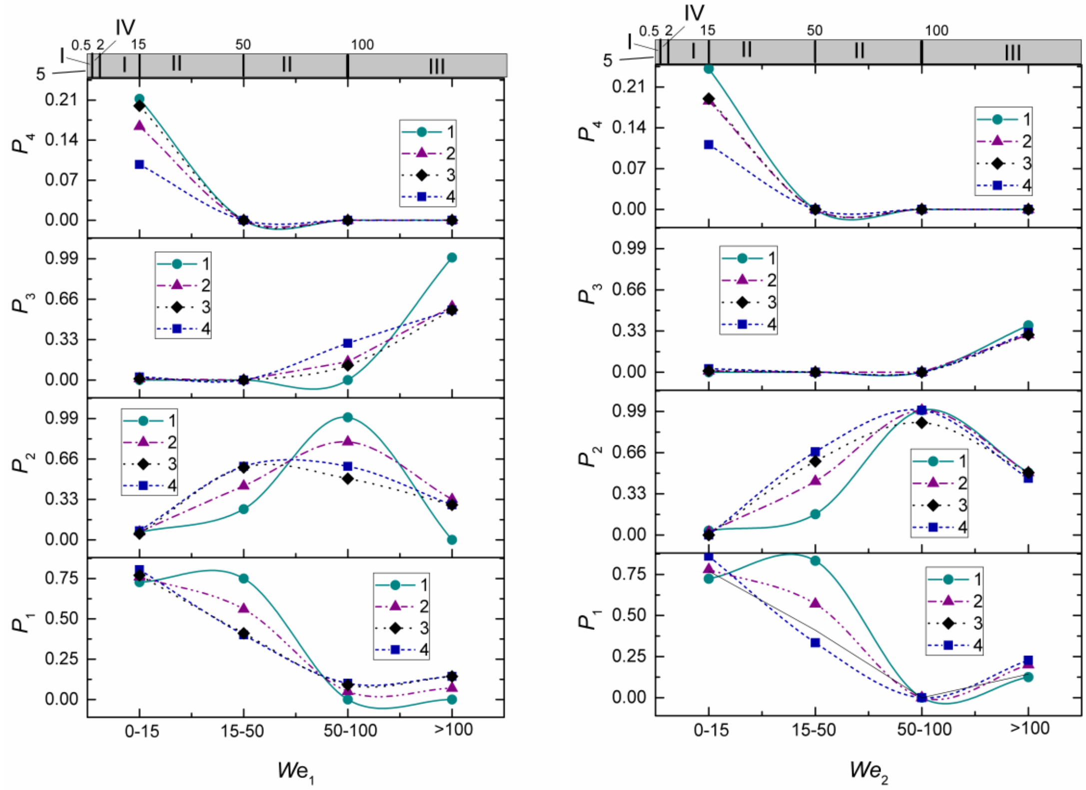


(c)

Figure 1. Probabilities of collisions consequences for aerosol droplets depending on the ratio of sizes (a) velocities (b) and the angle between the trajectories (attack) (c) of the latter in a gaseous

medium with variable temperature (1 – T_a=20 °C, 2 – T_a=200 °C, 3 – T_a=500 °C): I – coagulation; II – scatter; III – breakup; IV – bounce.

The established relative probabilities P_1, P_2, P_3, P_4 correspond well to the experimental data [7–15] in terms of realization of different collisions consequences in a wide range of Weber numbers. However, if analysing the numerical values of P_1, P_2, P_3, P_4 at different gas heating temperatures, the difference may be significant in the entire range of We changes (this is the main scientific result of the experiments). This is very important for correct prediction of changes in the structure and component composition of the gas-vapour flow during heating. For example, Fig. 3 demonstrates the calculated values of the total area of the free surface of the liquid (water) due to the interaction of droplets at different values of Weber numbers and heating temperatures. With their use, it is possible to estimate to what extent the values of relative areas increase at a breakup of colliding droplets, as well as S_d values remain during the bounce, merge or scatter of the latter.



(a) (b)

Figure 2. Probabilities of consequences of collisions of aerosol droplets depending on the Weber number for targets and slugs (a) and targets (b) in a gaseous medium with variable temperature 1 – T_a=20 °C, 2 – T_a=200 °C, 3 – T_a=500 °C); 4 – experimental data [9, 10]; 5 – combustion products. Where P_1 is the probability of coagulation; P_2 is the probability of scattering; P_3 is the probability of breakup; P_4 is the probability of bounce; I – coagulation; II – scatter; III – breakup; IV – bounce.

In the analysis of Figs. 1 and 2 it may be noted that there is a generally satisfactory agreement with the experimental data [11–15] on the effect of the velocity and size of colliding droplets (expressed through Weber number), as well as the interaction parameters (I and β), taking into account the distance between the droplets in comparison with the sum of their size and the angle of attack. A series of experiments and calculations considered in articles [11–15] served to determine the ranges of Weber number, in which the bounce, coagulation, scatter and breakup occur steadily. The ranges determined in this work and described above differ (being wider) from the data [11–15] on average by 18–32%. At that, similar to experiments [11–15], different variants of the consequences of droplet collisions under identical flow conditions were recorded proving the probabilistic nature of these processes. The main reasons are due to the simultaneous influence of too many factors and effects that cannot be described by one criterion, for example, by the number of Weber. Experimental data [11–15] may be used to compare only the Weber numbers, since in these works a generalization is made for liquid droplets and solid particles. In general, it may be concluded that it is necessary to develop modern physical and mathematical models of droplet interaction taking into account the influence of a wide group of factors and effects (heating, mixing schemes) considered in the experiments [11–15].

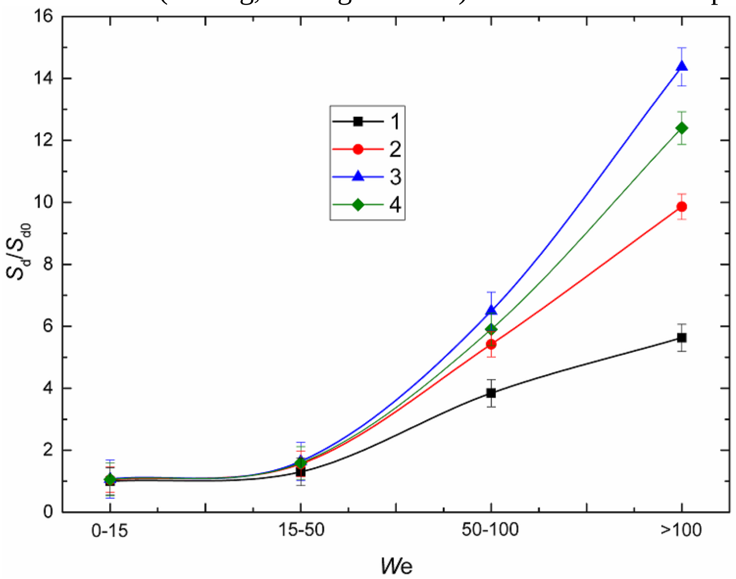


Figure 3. Possible number and total surface areas of droplets after collisions under different heating conditions in the entire range of We for the investigated droplets (slugs and targets): 1 – T_a=20 °C, 2 – T_a=200 °C, 3 – T_a=500 °C, 4 – combustion products.

It should be noted that this paper considers the conditions of short-term mixing of aerosol and gas flows, in which the droplets are heated for no more than 2–3 seconds and then are entrained from the mixing area. In real technologies, the lifetime of droplets in a heated gas medium may be different. The most interesting development of this work is to study the effect of time of the droplet aerosol heating on the conditions of its elements interaction. Under such conditions, it is possible to consider in detail the effects of droplets vaporization with the simultaneous use of optical methods, Planar Laser Induced Fluorescence (PLIF) and Laser Induced Phosphorescence (LIP), which allow controlling the temperature of gases and liquids [19]. Under such conditions, it will be possible to take into account a group of simultaneous processes that affect the probability of collision outcomes, in particular, the reduction in size and the number of droplets at evaporation.

4. Conclusion

The experiments have shown that the interaction of droplets in the aerosol when mixed with the gas medium under the conditions of temperature variation of the latter cannot be fully described and predicted on the basis of the known experimental information, obtained in the generalization of the results of experiments with two colliding droplets at room temperatures. That is, classical ideas about the transition values of Weber number are not enough for reliable prediction of the structure and component composition of gas-vapour flows. In particular, it has been found that the decisive influence may be exerted by vaporization, intensifying collisions of droplets, reducing their size and increasing the probability of partial or even complete disintegration. The obtained experimental data serve as a basis for further development of ideas about the so-called regime maps of liquid droplets interaction in heated multicomponent and multiphase flows [20], taking into account a large group of parameters traditionally considered in the processing of experimental data: the ratio of size, velocity, angle of attack, numbers of Weber, Reynolds, Onezorge, Laplace, and linear and angular interaction parameter.

Acknowledgments

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Nomenclature

I – linear parameter of interaction equal to $L/2(R_{d1}+R_{d2})$;
L – distance between centres of mass of drops [mm];
P_1, P_2, P_3, P_4 – relative probability of coagulation, scattering, breakup, bounce;
R_{d1}, R_{d2} – radii of the first and second drops [mm];
S_{d0} – total area of droplets before interaction [m^2];
S_d – total area of formed droplets after the interaction of initial ones [m^2];
U_{d1}, U_{d2} – velocities of the first and second drops [m/s];
U_g – gas flow velocity [m/s];
We_1, We_2 – Weber numbers for the first and second drops;
α_d – angle of attack [°];
β – angular parameter of droplet interaction equal to $\cos(\alpha_d)$;
ρ – density [kg/m^3];
σ – surface tension [kg/s^2].

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