ISSN 1063-7850, Technical Physics Letters, 2015, Vol. 41, No. 9, pp. 840–843. © Pleiades Publishing, Ltd., 2015.
Original Russian Text © R.S. Volkov, G.V. Kuznetsov, P.A. Strizhak, 2015, published in Pis'ma v Zhurnal Tekhnicheskoi Fiziki, 2015, Vol. 41, No. 17, pp. 53–60.

Statistical Analysis of Consequences of Collisions between Two Water Droplets upon Their Motion in a High-Temperature Gas Flow

R. S. Volkov, G. V. Kuznetsov, and P. A. Strizhak*
Tomsk Polytechnic University, Tomsk, 634050 Russia
**e-mail: pavelspa@tpu.ru*
Received February 12, 2015

Abstract—Consequences of collisions between two water droplets upon their motion in high-temperature (about 1100 K) gases are analyzed statistically. The initial radii and motion velocities of the droplets varied within 0.1–0.25 mm and 0.5–5 m/s, respectively. The velocity of the counterflowing gas was 1.5 m/s. Using panoramic methods and tools of high-speed and cross-correlation video recording, conditions corresponding to different consequences (coagulation, decomposition, or breakup) of collisions between droplets are determined.

DOI: 10.1134/S1063785015090126

Processes of coagulation, breakup, and deformation of liquid droplets play an important part [1–3] in a wide spectrum of gas–vapor–droplet applications [5–8]. However, almost all conclusions about the regularities of such processes were made based on results of studying the motion of small groups (two, three, or five) droplets. When implementing technologies [5–8], droplets move in the turbulent regime and their density in the flow can reach several thousand droplets per 1 m^3; their dimensions can vary from tens micrometers to several millimeters [5–8]. It is of interest to analyze regularities in collisions of droplets having significantly different dimensions and motion velocities.

The least understood are processes of liquid droplet motion through high-temperature gases [9–12]. Analysis of results from [9–12] (on deformation of water droplets during their motion through gases, evaporation in high-temperature gases, and effects of motion velocities and droplet dimensions on characteristics of these processes) shows that processes of water droplet motion through a high-temperature gaseous medium are characterized by an intense and continuous variation in the trajectories of their motion and collisions. Results of direct investigations of droplet collisions and their consequences in high-temperature gases have never been published. Videograms [10, 11] show that consequences of droplet collisions are suitable to be studied using the statistical approach. Different consequences of collisions under conditions of joint action of a group of factors are possible with a certain probability of the result.

The aim of this work is to distinguish consequences of collisions between two water droplets in a flow of high-temperature gases according to results of experimental investigations.

When performing the experiments, a setup [10, 11] with a complex of registering equipment was used: a video camera with a picture format of 1024 × 1024 pixels and frame rate of up to 10^5 fps; a cross-correlation camera with a picture format of 2048 × 2048 pixels and minimal interframe gap not more than 5 μs; a double pulsed solid-state laser with a wavelength of 532 × 10^{-9} m, a pulse energy of not less than 70 mJ, a pulse duration of up to 12 ns, and a repetition rate of not more than 15 Hz; and a synchronizing processor with signal sampling of less than 10 ns.

By analogy with experiments [10, 11], images of water droplets were recorded in the process of their motion through high-temperature kerosene combustion products in a hollow cylinder (with a height of 1 m and inner and outer diameters of 0.2 and 0.206 m) made of heat-resistant translucent glass. Dimensions of each video frame in the region of high-temperature gases were chosen according to the characteristic length of trajectory intervals of two droplets colliding in the experiments.

The temperature of combustion products in the experiments amounted to 1070 ± 30 K. The measurements were performed by three chromel-alumel thermocouples (the range of measured temperatures is 273–1373 K, the error is ±3.3 K). The initial temperature of water droplets introduced into the gaseous medium temperature was maintained near 300 K with use of heating chambers [13].

Velocity u_g of the gas motion along the considered cylindrical channel was measured using particle image velocimetry (PIV) [14]. By analogy with [9–12],

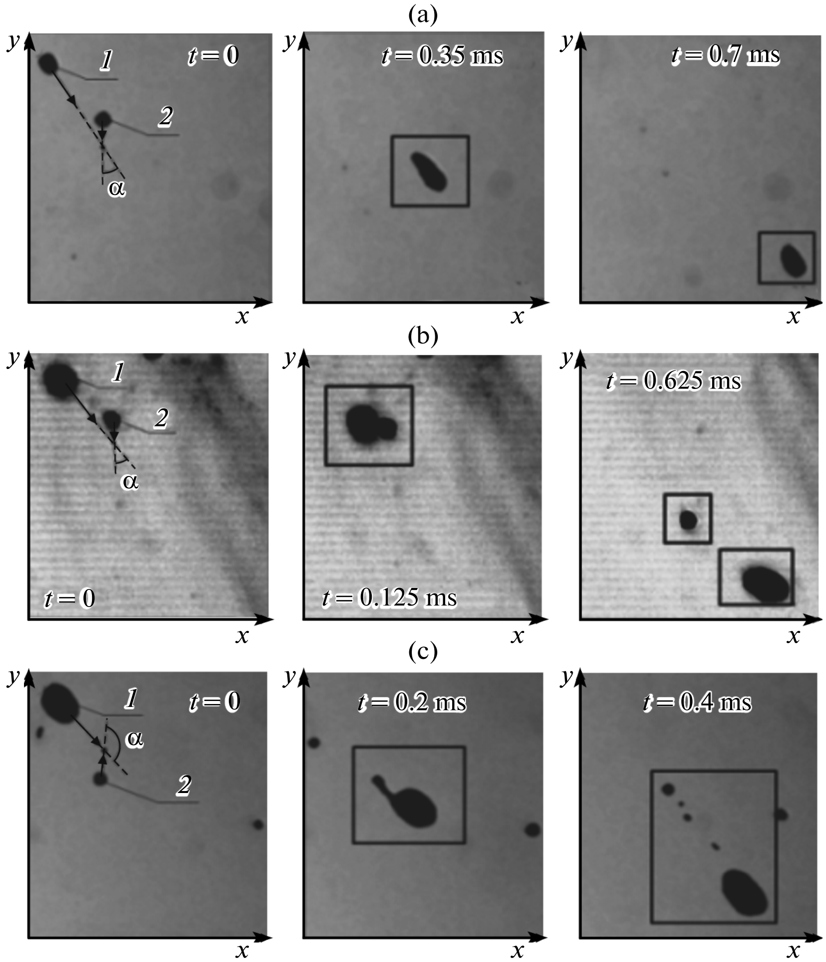

Fig. 1. Videograms of experiments with the implementation of three consequences of droplet collisions: (a) coagulation and motion of the merged droplet, (b) merging and decomposition into close (in the initial size) droplets, and (c) breakup into smaller droplets.

"tracers" (TiO_2 particles) were introduced into the gaseous medium before carrying out experiments with droplets. Their velocities and, correspondingly, that of the gas motion were maintained near 1.5 m/s.

Similarly to experiments in [9–12], investigations were carried out for droplets of a polydisperse water flow. Their initial sizes (radii) varied in the range $0.1 \leq r_m \leq 0.25$ mm. The relative volume density was maintained to be 0.001–0.0012 m^3 liquid droplets per 1 m^3 of gas. Sizes r_m and velocities u_m of droplets were measured using interferometric particle imaging (IPI) [15] and PIV [14]. Systematic errors in the determination of r_m, u_g, and u_m by use of PIV and IPI, as well as by an appropriate video recording facility [11, 12], did not exceed 1.6 and 2.1%. The maximum random errors amounted to 2.1% for r_m and 3.4% for u_g and u_m. Videograms of the experiments were also processed using a specialized software and parametric grid on the videograms with the aim to determine angles α at which motion trajectories of the droplets intersect at the instant of their collision.

As a result of the statistical analysis of the obtained experimental data, it was found that a collision can be followed by three variants of the further development of the process: coagulation and motion of a merged droplet (Fig. 1a); the droplets merge, but then the conglomeration (for a very short period, less than 0.1μs) decomposes into two droplets with close initial dimensions (Fig. 1b); and breakup into several (from three to ten) small droplets (Fig. 1c). The different consequences of a collision between two droplets allow conclusions to be drawn according to the results of experiments [9–12] on droplet coagulation in high-temperature gases. In particular, three coagulation regimes were established [9–12]: the droplets moving in the trace overtake foregoing ones; the droplets reverse the direction of their motion and coagulate with those going in the trace after them; and, due to the implementation of phase transformations, the droplets coagulate with those moving parallel at a certain distance from them (due to the decrease in the

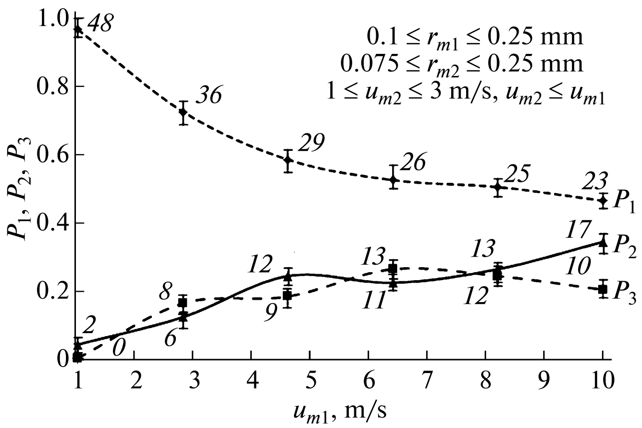

Fig. 2. Typical values of the criteria P_1, P_2, and P_3.

static pressure between droplets moving parallel in the process of their evaporation, the droplets converge).

In addition, using results of analysis of videograms obtained in the performed experiments, one can explain the existence of one of the known [12] regimes of droplet deformation during the motion in a gas flow. It was found [12] that droplets can either be sequentially deformed and take "ellipsoid–sphere" shapes (with their typical expansion and compression with respect to the motion direction) or rotate around the center of mass (but with a change in dimensions) with the preservation of the ellipsoidal shape. In polydisperse flows, the second deformation regime was revealed [12], and the regime is caused by rotation of droplets due to collisions and nonstationary shift of the center of mass.

Investigations in a wide variation range of the droplet size and velocities of their motion showed the statistics on the consequences of collisions between two droplets under the considered conditions. Coagulation, breakup, or decomposition of droplets occurred at any values of r_m and u_g. However, the frequencies of occurrence for each of the events were significantly different.

Figure 2 presents values of criteria P_1, P_2, and P_3 characterizing the frequency of occurrence for one of three events after collisions between two droplets for different size ($0.1 \le r_m \le 0.25$ mm) and velocities ($1 \le u_m \le 10$ m/s). Values of P_1 (coagulation), P_2 (scatter), and P_3 (breakup) were calculated after processing of 300 collisions (50 collisions for each value of velocity u_{m1} of the first droplet; values of the number of consequences with the corresponding variant of the result are presented near each "characteristic point" of the dependences).

Values of P_1, P_2, and P_3 were calculated by the formulas

$$P_1 = N_1/(N_1 + N_2 + N_3), \quad P_2 = N_2/(N_1 + N_2 + N_3),$$
$$P_3 = N_3/(N_1 + N_2 + N_3),$$

where N_1, N_2, and N_3 are numbers of collisions resulting in the implementation of the first, second, and third variants of consequences (for each value of u_{m1}, 50 collisions were considered; numbers in Fig. 2 correspond to the number of collisions resulting in the implementation of one of the three corresponding variants).

The dependences in Fig. 2 illustrate the effect of the difference between velocities of colliding droplets in a gas flow on consequences of the collisions. The motion velocities of first (among the number of observed pairs) droplets before the collision amounted to $1 \le u_{m1} \le 10$ m/s. The motion velocities of second ones varied within the range of $1 \le u_{m2} \le 3$ m/s. At the same time, the motion velocity of the second droplet in the analyzed collisions did not exceed that of the first droplet (the condition $u_{m2} \le u_{m1}$ was satisfied at all points in Fig. 2). One can note that, at small ($u_m <$ 3 m/s) and comparable motion velocities of droplets, the highest frequency of collision consequences corresponds to coagulation. The distinguished regularity can be noted for a wide range of the droplet size variation, $0.1 \le r_m \le 0.25$ mm. With an increase in the difference between motion velocities of colliding droplets, P_2 and P_3 significantly increase (Fig. 2). Here, in general, one can note comparable values of the criteria. The revealed effect illustrates the fact that the frequency of collisions with a breakup or scatter of the droplets significantly increases with an increase in the difference between droplet velocities. This is related most probably with the fact that an increase in the droplet motion velocities is accompanied by an increase in the effect of inertial forces as compared to forces of viscosity and surface tension. As a consequence, in the presence of an "obstacle" in the way of droplets, they either scatter or disintegrate into smaller ones. With an increase in the motion velocity of one droplet with respect to another, the frequency of consequences of collisions with a breakup exceeds the analogous parameter for the scatter.

One can suppose that the result of a collision between two droplets must be determined not only by their dimensions and motion velocities but also by the angle α of intersection of their motion trajectories. Figure 2 presents statistical data on collisions between droplets as the angle α varies in a wide range (20°–150°). Since the dependences of frequencies P_1, P_2, and P_3 are almost monotonic, one can draw the conclusion that a rather moderate part of angle α plays a role in determining the variant of collision consequences. At the same time, one can note that using 3D images is suitable for a complete study of the effect of angle α on characteristics of the droplet collision because the droplets can leave the cross section recorded by a high-speed camera. In this case, droplets from other cross sections of the flow can cover the recorded region (Fig. 3). In the experiments performed, a small region before a droplet collision was recorded to exclude the effect of this factor.

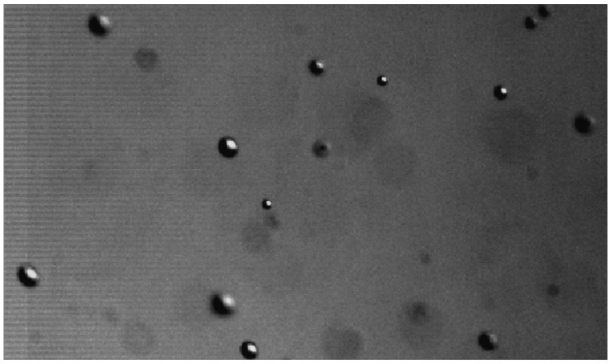

Fig. 3. Videogram with a collection of droplets in a flow of high-temperature gases in the process of 3D recording.

The obtained values of criteria P_1, P_2, and P_3 can be used as estimating values when choosing operation parameters of the equipment for the implementation of a large group of technologies with gas–vapor–droplet high-temperature flows (thermal cleaning of liquids, gas–vapor–droplet heat carriers, and polydisperse firefighting).

Acknowledgments. This work was supported by the Russian Science Foundation, project no. 14-39-00003.

REFERENCES

1. A. L. Gonor and V. Ya. Rivkind, Itogi Nauki Tekh., Ser.: Mekh. Zhidk. Gaza **17**, 86 (1982).
2. J. Eggers and E. Villermaux, Rep. Prog. Phys. **71**, 79 (2008).
3. V. I. Terekhov and M. A. Pakhomov, *Heat and Mass Transfer and Hydrodynamics in Gas-Droplet Flows* (NGTU, Novosibirsk, 2009) [in Russian].
4. I. G. Zhidov, E. E. Meshkov, N. N. Nevmerzhitskii, I. G. Pylev, and E. A. Sotskov, Tech. Phys. Lett. **28**, 87 (2002).
5. Yu. V. Alekhanov, M. V. Bliznetsov, Yu. A. Vlasov, V. I. Dudin, A. E. Levushov, A. I. Logvinov, S. A. Lomtev, and E. E. Meshkov, Tech. Phys. Lett. **29**, 218 (2003).
6. A. Yu. Varaksin, High Temp. **51**, 377 (2013).
7. G. V. Kuznetsov and P. A. Strizhak, Tech. Phys. Lett. **40**, 499 (2014).
8. O. V. Vysokomornaya, G. V. Kuznetsov, and P. A. Strizhak, Fire Saf. J. **70**, 61 (2014).
9. R. S. Volkov, O. V. Vysokomornaya, G. V. Kuznetsov, and P. A. Strizhak, Tech. Phys. Lett. **41**, 128 (2015).
10. R. S. Volkov, G. V. Kuznetsov, and P. A. Strizhak, Tech. Phys. **59**, 959 (2014).
11. R. S. Volkov, G. V. Kuznetsov, and P. A. Strizhak, Int. J. Heat Mass Transfer **79**, 838 (2014).
12. R. S. Volkov, A. O. Zhdanova, O. V. Vysokomornaya, G. V. Kuznetsov, and P. A. Strizhak, J. Eng. Phys. Thermophys. **87**, 1351 (2014).
13. G. V. Kuznetsov and P. A. Strizhak, *Ignition of Condensed Substances upon Local Heating* (Siberian Branch, Russian Academy of Sciences, Novosibirsk, 2010) [in Russian].
14. J. M. Foucaut and M. Stanislas, Meas. Sci. Technol. **13**, 1058 (2002).
15. N. Damaschke, H. Nobach, and C. Tropea, Exp. Fluids **32** (2), 143 (2002).

Translated by A. Nikol'skii