ISSN 1063-7850, Technical Physics Letters, 2017, Vol. 43, No. 6, pp. 558–561. © Pleiades Publishing, Ltd., 2017.
Original Russian Text © M.V. Piskunov, P.A. Strizhak, 2017, published in Pis'ma v Zhurnal Tekhnicheskoi Fiziki, 2017, Vol. 43, No. 12, pp. 34–41.

Growth of the Surface Area of Separated Liquid Fragments during High-Temperature Fragmentation of an Inhomogeneous Liquid Drop

M. V. Piskunov* and P. A. Strizhak

Tomsk Polytechnic University, Tomsk, 634050 Russia

**e-mail: piskunovmv@tpu.ru*

Received January 19, 2017

Abstract—We have experimentally studied the formation of a droplet cloud during intense heating and subsequent explosive fragmentation of an inhomogeneous liquid drop. The experiments were performed with water drops containing graphite particles, which were heated in a flow of combustion products at a temperature varied from 600 to 1100 K. Three regimes of fragmentation of the inhomogeneous liquid drops have been observed, which are characterized by different total areas of liquid phase surface in aerosol clouds. Dependence of these regimes on the water/inclusion volume ratio and the amount of supplied heat has been determined.

DOI: 10.1134/S1063785017060256

Increasing the surface area of liquid phase is among most commonly accepted approaches to intensification of the heat exchange in gas–vapor–liquid-droplet systems for various applications [1–3]. The presence of a dispersed phase leads to the intensification of phase transformations [4–6]. The scale of this intensification can be very large, which is important for promising advanced high-tech applications in fields such as thermal and flame cleaning of liquids, creation of new heat-transfer agents based on flue gases and water drops and vapor, as well as production of syngas from various solutions.

Previously, it was established [6] that inhomogeneous (water containing nontransparent solid inclusions) drops that were intensely heated in a flow of high-temperature combustion products exhibited explosive evaporation with fragmentation. The physical backgrounds of these processes and main effects were explained [6]. The term "explosive fragmentation" was used [6] (in accordance with accepted concepts [7–9]) in order to illustrate high rates of heating and detachment of liquid fragments from the drop surface. This process essentially represents aerosol formation as a result of the collapse of intensely heated and "swelled" (vapor-filled) inhomogeneous drops. A topical, yet unsolved problem consists in determining a key parameter of this process—the ratio of liquid surface areas before and after the explosive fragmentation of inhomogeneous liquid—and establishing conditions under which the process can be treated as stable and reliably reproducible.

The present work was aimed at experimental determination of the conditions and characteristics of growth of the surface area of liquid phase during explosive fragmentation of intensely heated inhomogeneous water drops.

The experiments were performed in a setup described previously [6]. Thermal chamber comprised a hollow vertical silica-glass cylinder (of 1-m height and 0.2-m internal diameter) with special holes for introducing thermocouples and inhomogeneous drops and performing high-speed video monitoring. A flow of gaseous combustion products with controlled temperature (T_g) and velocity (U_g) was created by burning kerosene. This choice of this fuel instead of technical ethanol used in previous work [6] was determined by the higher temperature of gaseous combustion products, T_g, and its longer retention period. By controlling the parameters of supply system, gas-flow temperature T_g and velocity U_g could be varied within 700–1100°C and 0.5–2 m/s, respectively. The temperature was monitored simultaneously by three chromel–alumel thermocouples (273–1373 K, ±3 K) arranged in the cylinder. Reliable determination of the flow velocity was ensured by using the particle image velocimetry (PIV) technique with a cross-correlation system [10].

Inhomogeneous liquid drops were formed as described in [6]. Water drops were generated using a batcher with minimum and maximum volumes of 5 and 50 μL at a step of 0.1 μL, so that the liquid-film thickness around a solid inclusion varied within

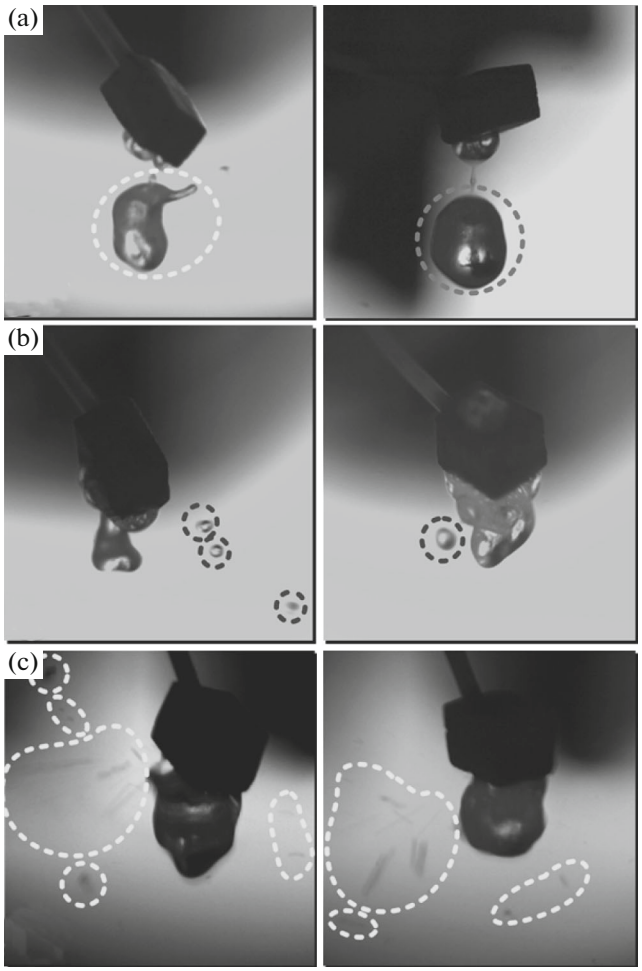

Fig. 1. Video images of fragments separated from the initial inhomogeneous water drop in (a) first, (b) second, and (c) third regime of explosive fragmentation.

0.2–1.5 mm. A weighed water drop was taken from the substrate in the balance by the batcher tip and kept in the discharge channel. Solid inclusions (graphite particles) of parallelepiped shape with dimensions of 2 × 2 × 1, 2 × 2 × 2, and 2× 2 × 3 mm were prepared using a special device [6]. Each particle had a central hole 0.15 mm in radius and 0.3 mm in depth, which was used to mount and fix the particle on a ceramic rod having a length of about 0.25 m. The rod was mounted in a positioner mechanism and could be moved by motor drives in two coordinates (along and perpendicular to the axis of cylinder), which allowed the drop with inclusion to be introduced at a 90° angle relative to the gas flow. The liquid drop was discharged on the particle from the batcher tip so as to fully envelope the inclusion [6]. The process of inhomogeneous liquid-drop evaporation and fragmentation was monitored using two high-speed video cameras.

The dimensions of initial inhomogeneous drops (maximum sizes in three coordinates and calculated average size d) and liquid fragments separated during fragmentation (radii R_d and calculated total surface areas S_{out}) were determined by processing video recordings using the Tema Automotive program package. The error of determining the dimensions of liquid drops and their fragments did not exceed 0.01 mm.

Based on the obtained experimental data, three regimes of explosive fragmentation of inhomogeneous water drops have been established, which are characterized by different process parameters including the heating time, number of fragments, and their surface areas. Figure 1 shows typical images of objects observed in these regimes. The first regime represents breakage of the initial inhomogeneous drop into several (up to three to five) liquid fragments with characteristic dimensions R_d within 1–1.5 mm. The second regime is characterized by detachment of 5–10 liquid fragments with dimensions from 0.5 to 1 mm. the third regime corresponds to the conditions of formation of a large set (up to several dozen or even several hundred) of small droplets ($R_d < 0.5$ mm). These regimes of fragmentation of the inhomogeneous drops studied were established based on the results of processing of numerous experimental video records with the aid of special algorithms and tools of Tema Automotive program package, including Airbag, Advanced Airbag, and Distance. Synchronous records of two cameras were used to monitor the detachment of fragments, determine their dimensions in three coordinates, and estimate the total surface areas. The high-speed video monitoring established that separated liquid fragments were inhomogeneous (contained water vapor and air) and, hence, exhibited subsequent boiling and fragmentation.

Figure 2 shows plots of the ratio of total surface area (S_{out}) of liquid fragments formed upon breakage of inhomogeneous liquid drop to its initial surface area (S_{in}), which characterizes the intensity of this heating-induced fragmentation process for various ratios of the initial volumes of inclusion (V_{inc}) and liquid (V_{liq}) (and, hence, various thicknesses of the liquid film surrounding the solid particle). As can be seen, the smaller the V_{liq}/V_{inc} ratio, the more significantly the third regime of fragmentation predominates. The first regime becomes predominant when V_{liq} is several times as large as V_{inc}, while the second regime is mostly realized for V_{liq}/V_{inc} ratios varying within 1–2.

Analysis of the results of experiments with variable temperature and velocity of the flow of combustion products allowed limiting conditions to be established under which one regime of fragmentation predominates over the other two. In particular, at a flow velocity of $U_g < 1$ m/s and combustion-product temperature $T_g > 900$ K, the third regime (i.e., fine-dispersed aerosol formation) predominated (observed in 8 of 10 experiments) over the first and second regimes. As the flow velocity was increased ($U_g > 1$ m/s), the second regime was more frequently observed, which was

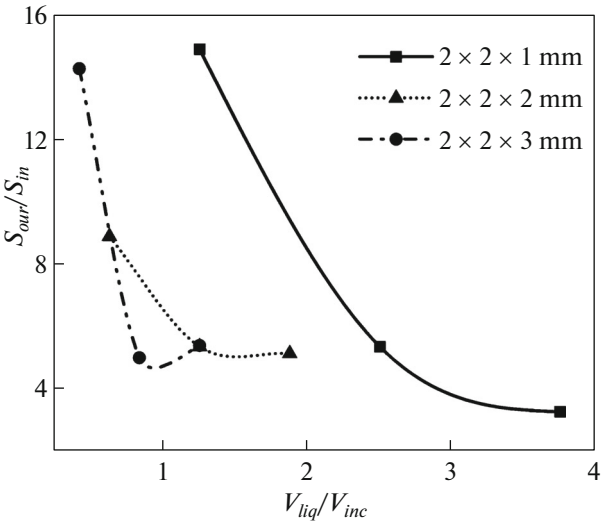

Fig. 2. Plots of the ratio of total surface area of liquid fragments upon explosive fragmentation of an inhomogeneous liquid drop (S_{out}) to the initial water-drop surface area (S_{in}) vs. water/inclusion volume ratio (V_{liq}/V_{inc}) for water drops with inclusions of various dimensions.

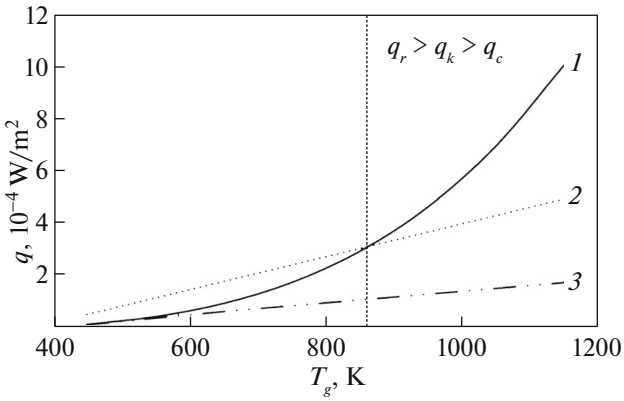

Fig. 3. Densities of (*1*) radiative (q_r), (*2*) convective (q_k), and (*3*) conductive (q_c) heat fluxes for inhomogeneous liquid drops heated in the flow of combustion products at various temperatures T_g.

caused by the separation (breakage) of some fragments under the action of aerodynamic forces. Due to viscous properties of the liquid, the separating fragments had various dimensions (R_d = 0.5–1 mm). At high flow velocities (U_g > 1.5 m/s) but relatively low combustion-gas temperature (800–900 K), the first regime predominated, which was caused by significant radiative heat flux from the gas to the liquid-drop surface.

Figure 3 presents plots of the densities of convective heat flux $q_k = \alpha(T_g - T_s)$ (for heat transfer coefficient α = 40–70 W/(m^2 K), liquid surface temperature T_s = 370 K), conductive heat flux $q_c = \lambda(T_g - T_s)/\delta$ (for thermal conductivity coefficient of gas–vapor mixture λ = 0.028–0.045 W/(m K), buffer vapor-layer thickness δ = 0.001–0.002 m), and radiative heat flux $q_r = \varepsilon_w\sigma(T_g^4 - T_s^4) + \varepsilon_v\sigma T_g^4 + \varepsilon_g\sigma T_g^4$ (for silica-wall emissivity of thermal chamber ε_w = 0.9, water-vapor emissivity ε_v = 0.01, and combustion-gas emissivity ε_g = 0.12 and Stefan–Boltzmann constant $\sigma = 5.67 \times 10^{-8}$ W/(m^2 K^4)) in the "inhomogeneous water drop–flow of gaseous combustion products" system studied. All initial parameters for calculations were selected with allowance for the temperature dependence of the thermal properties of substances and for the modern notions about processes under consideration. The vertical dashed line in Fig. 3 indicates the temperature boundary above which the aforementioned three regimes of fragmentation take place. The greater q_r, the more intense the process of fragmentation of an inhomogeneous water drop. This circumstance confirms a previously formulated hypothesis [6] that explosive fragmentation of an inhomogeneous liquid drop takes place, which is based on the assumption of intense heating of the surface of inclusion up to temperatures corresponding to the boiling of liquid. The greater radiative component of heat flux results in faster heating of the inclusion surface and more rapid formation of evaporation centers, growth of vapor layer, and "swelling" (vapor filling) of the drop. Increased convective component of the heat flux leads to more intense mixing of the heated (near the surface of inclusion and the free surface of a liquid drop) and unheated (in volume of the film surrounding the inclusion) layers of water. These processes lead to somewhat slower heating of the surface of the inclusion, so that the nucleation and growth of vapor bubbles on this surface become less developed (predominating radiative heat transfer leads to accumulation of a greater energy at the surface of inclusion and more intense nucleation of vapor bubbles). As a result, fragments with various dimensions can separate instead of the short-term formation of fine-dispersed aerosol (i.e., a transition from the third to the second and first regime takes place). The third regime of fragmentation was characterized by process times below 1–1.5 s, while in the second and first regimes this time increased to 5–8 s. The ratio of the total surface area S_{out} of fragments formed upon breakage of the initial drop to its initial surface S_{in} reached 14–17 in the third regime, 5–7 in the second regime, and 1.5–3 in the third regime.

In concluding, these experimental investigations allowed us to estimate for the first time the scale of increase in the liquid phase surface area as a result of intense evaporation on the internal interface and the subsequent explosive fragmentation of inhomogeneous drops. The obtained results provide a fundamental basis for the development of promising high-temperature gas–vapor–liquid-droplet technologies in the fields of thermal cleaning of liquids, fire extin-

guishing, creation of new-generation heat-transfer agents, etc.

Acknowledgments. This work was supported in part by the Presidential Program of Grants for Young Scientists in Russia, project no. MD-1221.2017.8.

REFERENCES

1. V. V. Yagov, *Heat Exchange in One-Phase Media and at Phase Transformations* (Mosk. Energet. Inst., Moscow, 2014) [in Russian].
2. V. I. Terekhov and M. A. Pakhomov, *Heat Mass Transfer and Fluid Dynamics in Gas-Drop Flows* (Novosib. Gos. Tekh. Univ., Novosibirsk, 2009) [in Russian].
3. O. V. Vysokomornaya, G. V. Kuznetsov, and P. A. Strizhak, *Evaporation and Transformation of Drops and Large Liquid Masses Moving through High Temperature Gases* (Sib. Otdel. RAN, Novosibirsk, 2016) [in Russian].
4. A. Yu. Varaksin, High Temp. **52**, 752 (2014).
5. A. V. Minakov, A. S. Lobasov, V. Ya. Rudyak, D. V. Guzei, and M. I. Pryazhnikov, Tech. Phys. Lett. **40**, 562 (2014).
6. I. S. Anufriev, G. V. Kuznetsov, M. V. Piskunov, P. A. Strizhak, and M. Yu. Chernetskii, Tech. Phys. Lett. **41**, 810 (2015).
7. E. J. Hopfinger and J. C. Lasheras, Phys. Fluids **8**, 1696 (1996).
8. C. A. Stan, D. Milathianaki, H. Laksmono, et al., Nat. Phys. **12**, 966 (2016).
9. S. D. Allen, Nat. Phys. **12**, 899 (2016).
10. R. S. Volkov, G. V. Kuznetsov, and P. A. Strizhak, Tech. Phys. **60**, 1310 (2015).

Translated by P. Pozdeev