Proceedings for the 5th International Fire Behavior and Fuels Conference
April 11-15, 2016, Portland, Oregon, USA
Published by the International Association of Wildland Fire, Missoula, Montana, USA

Conditions for Intense Vapor Formation of Heterogeneous Liquid Droplets with Their Explosive Disintegration

Maxim Piskunov
National Research Tomsk Polytechnic University, Tomsk, Tomsk Region, Russian Federation, piskunovmv@tpu.ru

Pavel Strizhak
National Research Tomsk Polytechnic University, Tomsk, Tomsk Region, Russian Federation, pavelspa@tpu.ru

Introduction

Nowadays, the state-of-art fire-fighting equipment and well-organized elimination of consequences of natural disasters are insufficient to solve forest-fire problem. Deep knowledge is required to explain regularities of origination, spreading and growth of forest fires, as well as processes of fire extinguishing associated with the intense heat exchange in the flame zone.

Investigations of large forest fire as a phenomenon, preventative measures and consequences of this natural disaster are a field of research with particular difficulties and restrictions [1, 2]. The known and persistent problems in firefighting practice are, for example, the effect of wind, interaction between wind and convective column, entrainment of firebrands of forest fuel materials with further ignition of another forest area [1]. In addition, each of these factors is difficult to take into account in case of mathematical and physical simulation of process.

However, the detail discussion on phase transition mechanisms of droplets of extinguishing liquid when interacting with high-temperature flame is of strong interest. Nevertheless, there are some restrictions as for instance the lack of experimental base about boiling and evaporation of droplets of the extinguishing agents under intense heat exchange that is typical for large forest fires.

Over recent years, the cycle of experimental and theoretical research [3–5] was performed to study the deformation of large (3–6 mm) single liquid droplets, deceleration and entrainment of droplets (0.05–0.35 mm in size) when evaporating spray flows in the counter flow of combustion products. In these experiments, the temperature conditions (about 1000 K) conform to typical large forest fires. Moreover, in the papers [6, 7] at the same temperature conditions, the significant enhancement of heat and mass transfer took place owing to the addition of solid non-metallic inclusions (from several dozens of micrometers to several millimeters).

Crucially, in the research [7], the phenomenon of intense vapor formation of liquid occurred at the internal interfaces of heterogeneous droplets. The rapid development of this mechanism contributed to the explosive breakup (disintegration) of heterogeneous liquid droplets during short time (2–6 s). As a result, small droplets (groups of droplets) detached from the liquid layer. We believe that when extinguishing forest fire using flows of the heterogeneous droplets such phenomenon will contribute to the formation of cloud consisting of the small-sized droplets and vapor. Finally, the formed cloud can cover larger area of flame and, moreover, limit the oxidizer supply in the burning area. Furthermore, the significant saving water resources can be reached by the explosive breakup. In the paper [7], the authors tried to explain the physical nature of such phenomenon, to reveal conditions for its origination and to determine system parameters that can vary during experiments. Taking into account a large amount of these parameters and difficulties to consider each of them, only several conditions of the intense vapor formation with the explosive disintegration were specified definitely. Among these are, primarily, the temperature of gas area that surrounds a heterogeneous droplet, as well as the material of inclusions and their physical parameters.

During the following research (for instance, [8–10]), other conditions to enhance heat transfer in the system under consideration are determined. Owing to these conditions, at least boiling took place.

In the paper, to combine the established regularities and conditions of the revealed novel physical phenomenon is appropriate. Afterwards the development of practical recommendations for use of the results when extinguishing large forest fires will become possible.

The purpose of the present work is to investigate, by experiment, the conditions for intense vapor formation of heterogeneous liquid droplets with their explosive breakup when heated at the temperatures that are typical for the large forest fires.

Materials and Methods

To perform the experimental research, we used the multifunctional laboratory setup equipped by high-speed camera *1*, as well as the devices to provide the optical diagnostics of combustion product flow *5*, *6* and to produce high-temperature areas *2–4*. The latter includes hot air blower *3*, muffle furnace *4* and cylindrical channel (with burner at the bottom) filled in combustion products of typical fuels *2*. Figure 1 illustrates the scheme of the setup. The red circles show the regions to insert heterogeneous liquid droplets in high-temperature area (see inset of Figure 1). The devices to heat heterogeneous droplets enable to take into account the influence of combustion product flow, the variation of the heated air velocity and the convective heating. According to the main steps, the experimental technique is similar to the one applied in research [6, 7]. However, in this paper, we will briefly present the main technical tips and explanations.

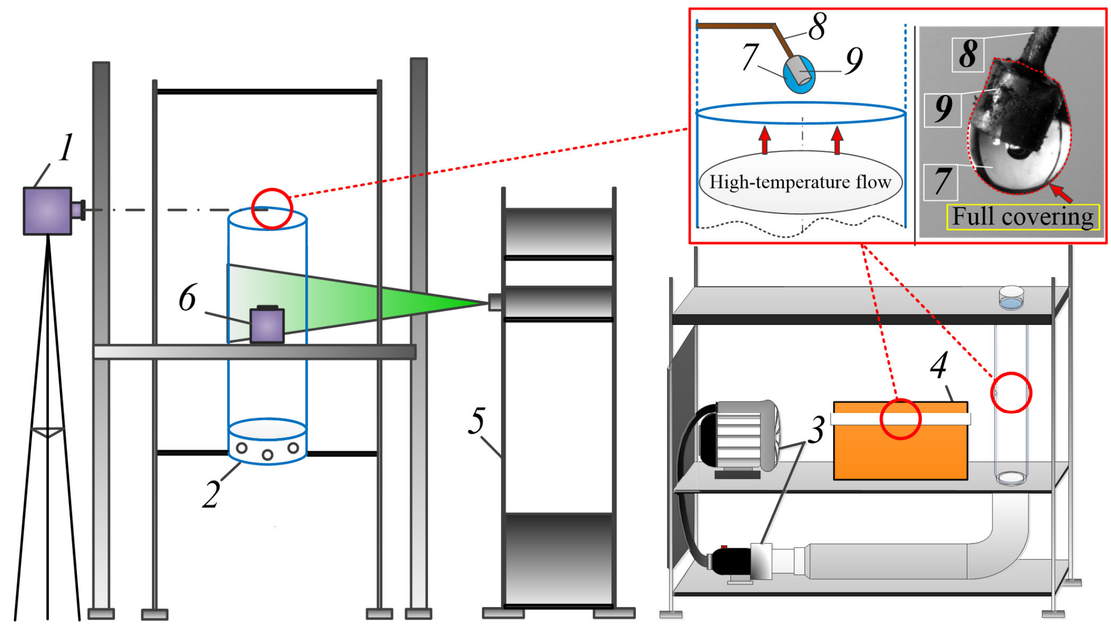

Figure 1. Scheme of experimental setup: *1* – high-speed camera; *2* – burner with cylindrical channel; *3* – hot air blower; *4* – muffle furnace; *5* – optical diagnostics of combustion products rate; *6* – cross-correlation camera; *7* – liquid droplet; *8* – ceramic rod; *9* – solid inclusion

Creation of Heterogeneous Droplets

The research performed with the heterogeneous liquid droplets fixed on ceramic rod *8* (see inset of Figure 1). The heterogeneous liquid droplet is a single solid inclusion inside the liquid droplet. The pure graphite was chosen as a material of inclusions. The size of inclusions was from 2 mm to 4 mm. The shapes of inclusions were a cylinder, cube, parallelepiped, sphere and polyhedron. Errors on measurements of solid inclusion size did not exceed 0.05 mm. The inclusions were fixed on ceramic rod *8* mechanically. The analytical balance measured the mass of inclusions. The dosing device took liquid of the required volume out of the vessel to cover the inclusion. The volume of liquid in the experiments varied in the range from 5 μl to 15 μl. The mandatory requirement for each test was a full covering of solid inclusion *9* by liquid droplet *7* (see inset of Figure 1). This condition was possible by dipping inclusion *9* in the vessel with liquid (at ~298 K) during several seconds before each experiment. Additionally, the inclusion is cooled down to the initial temperature. In the experiments, the following liquids were used: distilled water, solutions of distilled water with wetting agent, aerated water.

High-speed recording and PIV measurements

By using high-speed recording, we determined the lifetimes of heterogeneous liquid droplets in high-temperature areas and specified the regularities of their phase transitions. Errors on lifetime determination were 0.01 s.

PIV (Particle Image Velocimetry) technique was applied to monitor combustion product flow rate in the cylindrical channel. The procedure of similar measurements is presented in [6].

Temperature recording in high-temperature area

The temperature monitoring in high-temperature areas was performed by type K thermocouples fixed near the heterogeneous liquid droplets.

Method of procedure

(1) Using the moving mechanism operated by PC, a heterogeneous liquid droplet was introduced in high-temperature area.
(2) When moving droplet in the focusing point, the video recording became active.
(3) After evaporating liquid, solid inclusion was moved back from high-temperature area.
(4) Cooling and preparing next liquid droplet; determining lifetimes of droplet according to the recorded video track and temperature of area during the test.
(5) Repeating (1)–(4) points.

Under identical conditions, we performed the three series of experiments consisting of six tests for each variant of heterogeneous liquid droplet.

Results and Discussion

Figure 2 shows the typical frames of the considered physical phenomenon.

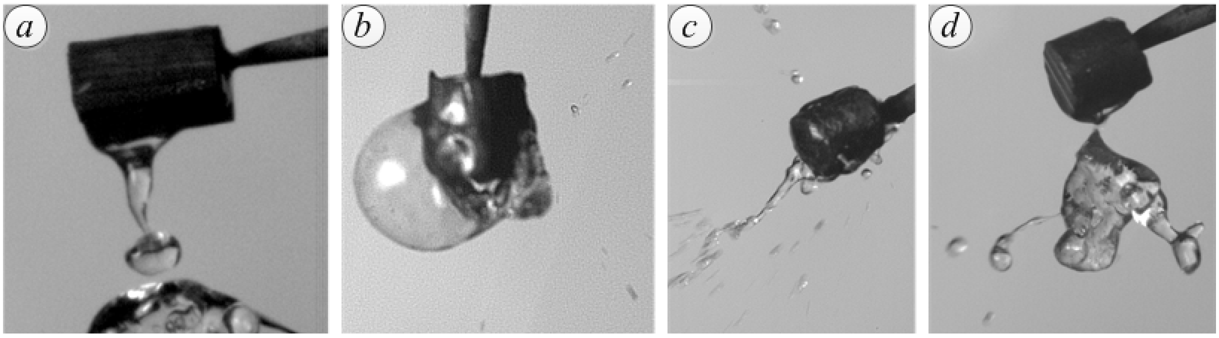

Figure 2. Examples (*a–d*) of heterogeneous droplet breakups [7]

The explosive breakup of droplet is due to the intense formation of vapor bubbles at the surface of solid inclusion. The growth of vapor bubbles at the interface of inclusion surface / liquid layer and their further evolution including the coalescence and detachment from the interface lead to filling droplet by vapor and thinning liquid film [7]. In the experiments, we observed most often from several successive explosions of large vapor bubbles to several dozens. In addition, every time the groups of small liquid droplets were detached from the liquid layer.

The conditions that contribute to intense vapor formation with explosive breakup of heterogeneous liquid droplet are as follows:

1. Heating temperature;
2. Using large (~3–5 mm) heterogeneous droplets;
3. The material of inclusion is a pure graphite; the shape of inclusion is a polyhedron (including such artificial irregularities of surface as the roughness and porosity);
4. Decreasing surface tension force of water by the addition of wetting agents with certain concentration;
5. Using aerated water as a liquid in heterogeneous droplet.

The main condition is to reach the temperature of area contributing to the formation of vapor bubbles at the interface of liquid layer / inclusion surface. In this case, the growth rate of vapor bubbles must significantly exceed evaporation rate of liquid from the surface of droplet. Furthermore, the growth rate of vapor bubbles and their further evolution mainly influence the duration of processes (explosions) that was specified in [7]. Also, using the pure graphite with high thermal conductivity is critically important. The preliminary experiments with the similar materials did not reveal any prerequisites to the nucleate boiling. The shape, as the experiments [7] showed, also play the important role to enhance heat transfer. It is obvious that the edges, irregular shape of inclusions, roughness and pores increase the heat-exchange surface area. Thus, the amount of heat supplied to the liquid layer from the inclusion grows.

In the investigations [8–10], other authors studied how to enhance heat transfer in a different way and to initiate vapor formation at the internal interfaces. As a result, using the solutions with the addition of wetting agents and the carbonation contribute to the formation of vapor bubbles at the surface of inclusions.

The solutions with the addition of surfactants and the aerated liquids are intensively used in state-of-art firefighting technologies. Therefore, the following practical recommendation can be stated to extinguish forest fires:

- The intense vapor formation with the breakup of single droplets and the further formation of vapor-droplet cloud can occur by the large (up to 4 mm) and rough (edges, pores etc.) graphite particles that are added in the flow of typical extinguishing liquid with the certain concentration. The temperature in immediate proximity to the flame zone will provide the conditions for the considered mechanism at the internal interfaces. Moreover, the mass of the formed heterogeneous flow will be higher than the one of homogeneous flow. Thus, the convective column will entrain less droplets.

The findings expand the experimental base of the research on heat transfer enhancement in the heterogeneous systems. We believe that the further study is crucial to develop the possible ways to initiate the intense vapor formation with breakup of the liquid layer of heterogeneous droplet. The performance of the experiments with the group of droplets (flow of heterogeneous droplets) in a laboratory environment and by the standardized fire sources is also recommended.

Conclusion

We stated the revealed conditions of the intense vapor formation with explosive breakup for the heterogeneous (with single large graphite inclusions) liquid droplets when heated at the temperatures that are typical for the large forest fires. In addition, to develop the future technology of the firefighting, the practical recommendation was specified.

Acknowledgements

This work was supported by the grant of the President of the Russian Federation (MD-2806.2015.8).

References

1. Wang H-H (2011) Analysis on downwind distribution of firebrands sourced from a wildland fire. *Fire Technology* **47**, 321-340.
2. Viegas DX, Simeoni A (2011) Eruptive behaviour of forest fires. *Fire Technology* **47**, 303-320.
3. Strizhak PA, Volkov RS (2016) The integral characteristics of the deceleration and entrainment of water droplets by the counter flow of high-temperature combustion products. *Experimental Thermal and Fluid Science* **75**, 54-65.
4. Volkov RS, Kuznetsov GV, Strizhak PA (2015) Water droplet deformation in gas stream: Impact of temperature difference between liquid and gas. *International Journal of Heat and Mass Transfer* **85**, 1-11.
5. Volkov RS, Kuznetsov GV, Strizhak PA (2016) Influence of droplet concentration on evaporation in a high-temperature gas. *International Journal of Heat and Mass Transfer* **96**, 20-28.
6. Volkov RS, Piskunov MV, Kuznetsov GV, Strizhak PA (2016) Water droplet with carbon particles moving through high-temperature gases. *Journal of Heat Transfer* **138**, Article ID 014502.
7. Kuznetsov GV, Piskunov MV, Strizhak PA (2016) Evaporation, boiling and explosive breakup of heterogeneous droplet in a high-temperature gas. *International Journal of Heat and Mass Transfer* **92**, 360-369.
8. Jeong YH (2008) Wettability of heated surfaces under pool boiling using surfactant solutions and nano-fluids. *International Journal of Heat and Mass Transfer*. **51**, 3025–3031.

9. Agogo H (2011) Spreading and evaporation of surfactant solution droplets. *Progress in Colloid and Polymer Science*. **139**, 1–6.
10. Power IM, Harrison AL, Dipple GM, Wilson SA, Kelemen PB, Hitch M, Southam G (2013) Carbon mineralization: From natural analogues to engineered systems. *Reviews in Mineralogy and Geochemistry*. **77**, 305-360.