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Evaporation, boiling and explosive breakup of heterogeneous droplet in a high-temperature gas

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ABSTRACT

Experimental investigation of evaporation and boiling was carried out on fixed water droplet containing a single nontransparent solid inclusion and placed in gaseous environment at high-temperature (500–1100 K). We carried out experiments with water droplets (diameters 3–5 mm) containing graphite inclusions of different shapes (sphere, disk, cone, parallelepiped and polyhedron) with sizes between 2 and 4 mm. These droplets were in the hot flux on top of combustion of industrial ethanol. The behavior of the droplets was recorded by high-speed (up to 10^5 frames per second) video cameras "Phantom" and "TEMA Automotive" software. Conditions for intensive vaporization at solid/liquid interface inside droplets were determined. A phenomenon of explosive disintegration occurred when heating some of the heterogeneous droplets. Time of heating until an explosive disintegration and complete evaporation was recorded. Influence of gas temperature and inclusion sizes were measured.

1. Introduction

Nowadays, one of the most important directions of development in the field of fire extinguishing technologies is the improvement of heat exchange between extinguishing liquid and combustion products in flame zone and in its close vicinity [1–7]. The traditional approach of droplet breakup when spraying extinguishing liquid received a lot of criticisms [1–7]. In the case of fires in large open spaces, it concerns mainly the entrainment of small droplets (sizes less than 0.5 mm) from flame zone by gas fluxes (combustion products). Indeed, in real practice the droplets of extinguishing liquid coalesce during their motion through flames. These effects complicate the problem of selection of initial droplet sizes and their control during the motion in order to speed up their evaporation on top of flaming zone and to absorb the fire energy as well as to expel both the oxidant and flammable combustion products.

Besides the breakup of droplets, improvement of heat exchange can be obtained by specific admixtures and inclusions in extinguishing liquid. In the recent years a lot of approaches in this direction were proposed [8–10]. The main emphasis is on the increase of liquid evaporation rate in flame by the addition of two-phase, multiphase and even heterogeneous gas–vapor-droplet mixtures. Experimental and theoretical investigations [10–12] substantiate the possible intensification of evaporation by addition of admixtures and solid nontransparent inclusions into the extinguishing liquid (water and different emulsions on its base). However, reported experiments [10–12] indicate that the heating of heterogeneous (with inclusions) droplets at high temperatures corresponding to flames of real fires is accompanied by rather complicated phase changes, heat and mass transfer. Let us note that evaporation of homogeneous liquid droplets is also complex [13–15] when they are in hot gaseous environment (at more than 1000 K). Experiments [10–12] concluded that solid inclusions in water droplets increase the heating rate and evaporation not only on the outside (free) surface of the droplet, but at the inside liquid/inclusion interfaces too. This can lead to boiling and breakup of the liquid film accompanied by growth and motion of bubbles. This effect can also be used to accelerate the phase changes in the flames during fire extinguishing, but it is underexplored up to now. The conditions for boiling and breakup (disintegration) of heterogeneous droplets containing small size inclusions (less than 0.5 mm, as in [10–12]) can occur only with extended heating (up to several dozens of seconds). Such conditions cannot be reached with experiment setup similar to the facility used in reference [10–12]. Droplets with inclusions were evaporated more intensively than without particles, but they did not disintegrate because their motion in high-temperature gas cannot be recorded for more than about 1 s). During fire extinguishing actions the motion of liquid droplets through the flames (including forest ground and crown fires) does not exceed several seconds (as a rule, less than

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Nomenclature

c	heat capacity, J/(kg K)
$H(R)$	density of a heat flux, W/m^2
k_λ	coefficient of energy adsorption by water
Q_e	heat of a vapor formation, J/kg
R	radial coordinate, m
R_1	radius of a solid inclusion, m
R_2	radius of a water droplet, m
T	temperature in numerical solution domain, K
T_0	initial temperature in numerical solution domain, K
T_f	gas temperature, K
V_0	initial volume of a liquid droplet, µl
W_e	evaporation rate, kg/(m^{2}s)

Greek symbols

T	time, s
τ_h	time of complete liquid evaporation from surface of inclusion, s
τ_e	time of explosive breakup of a heterogeneous liquid droplet, s
ρ	density, kg/m^3
ε	emissivity factor
σ	Stefan–Boltzmann constant, W/(m^2 K^4)
λ	thermal conductivity, W/(m K)
ΔR	relative difference of droplet sizes before and after a flame zone

Subscripts

1	solid inclusion
2	liquid

5–7 s). Therefore, experiments with droplets containing 1 mm size nontransparent nonmetallic inclusions are appropriate.

The purpose of the present work is, based on our experimental results, to investigate the features of evaporation, boiling and explosive breakup of water droplets containing a nontransparent inclusion when immerged in gaseous environment at high temperatures corresponding to typical fires.

2. Experimental setup and research methods

Experiments were performed in the setup shown on Fig. 1. It is a version adapted to the present problem of our standard system [10–12]. The stationary heterogeneous droplets were fixed on the rod ***3*** (Fig. 2). They model the heterogeneous droplet but in a different way than in [10–12] the droplets are fixed in the high-temperature gas flow. The rod ***3*** has to be a very poor heat conductor in order not to disturb the heat and mass transfer linked to the evaporation.

The heterogeneous droplet shapes allow comparison with the previous results obtained with the same diagnostic system. The additional experiments with heterogeneous water droplets moving (free falling) through high-temperature gases showed that the position of solid inclusions can be very different but the partial protrusion (Fig. 3) of inclusion from its surface are systematic.

We used two high-speed (up to10^5 fps) video cameras ("Phantom V411" and "Phantom Miro M310") *11* to record evaporation of a heterogeneous droplet. It was necessary to obtain 3D images of a heterogeneous droplet during the process. It allowed determining the droplet 3D sizes at any time and to control the time of complete evaporation or breakup of droplets. In [10–12] the heterogeneous droplets moved through high-temperature gases, and panoramic optical methods (PIV [16–18], PTV [19,20], Stereo PIV [21,22], IPI [23,24], SP [25–27]) were used. It was evident for us to choose to use our efficient high-speed video recording and software "TEMA Automotive" [28,29] with fixed droplet configuration.

Three type K thermocouples (***7*** on Fig. 1, temperature measurement range 273–1373 K, error ± 3.3 K) were used to control the temperatures of combustion products in cylinder ***8*** (material: quartz, height 1 m, inside and external diameters – 0.2 m and 0.206 m). Three holes were drilled in the cylindrical channel ***8*** at heights 0.3 m, 0.5 m and 0.7 m relative to the base of burner ***9*** this allows to insert the thermocouples ***7*** into cylinder ***8*** and to insert the rod ***3*** with a heterogeneous droplet into the cylindrical channel. Temperatures of combustion products were set in the range 500–1100 K depending on air flow in burner ***9*** and to the adjustment of air flow controller ***12*** The flow velocity of combustion products was generally about 1.5 m/s [10–12].

Distilled water was taken out of a bottle by an electronic dosing devise ***2*** ("Finnpipette Novus": minimum volume – 5 µl, maximum volume – 50 µl, variation step – 0.1 µl)). The mass of droplets was tested by the analytical weighing system ***1*** ("VIBRA AF 225DRCE": maximum weight – 220 g, minimum weight – 0.001 g, error – less than 0.5%). The mass of used liquid droplets were in the range 5–15 mg adjusted by setting the dosing device ***2***.

The manufacture of inclusions ***6*** by using broach files and bench grinder allowed getting solid nontransparent inclusions (material – graphite) of different shapes (sphere, disk, cone, parallelepiped, polyhedron) and sizes (2–4 mm). The mass of inclusions varied in the range of 16–22 mg. The graphite density (about 2100 kg/m^3) was measured using "Shinko AFDK" device. A very narrow hole (diameter and depth are about 0.3 mm) was drilled in the solid inclusion ***5*** along the symmetry axis. This hole is used to fix the graphite inclusion ***5*** on the rod ***3*** (the rod end was inserted into hole). The length of rod ***3*** is about 0.25 m to allow to position a heterogeneous droplet at the symmetry axis of channel ***8***.

There are several reasons for choosing the method of heterogeneous droplets fixed in high temperature gas flow on low thermal conductivity rod ***3***. To investigate the conditions for explosive breakup of moving free falling heterogeneous droplets long channels are necessary. The rough estimations showed that the length of such channels should be at least 7–10 m long. To follow falling drops along such a distance with high speed camera is not reachable for us presently. Therefore, the research was carried out with stationary droplets in gas flow and fixed on the rod ***3*** (it is an identical condition from physical standpoint). Moreover, preliminary tests showed that inclusions inside droplets were continuously moving during their free fallings. This feature does not allow to study vaporization at the solid liquid internal interfaces (to distinguish stages, determine their life times and etc.).

The developed experimental procedure included several steps. Before carrying out the high-speed video recording the weighing of the distilled water droplet was performed. Then, we took it from the base of weighing system ***1*** and lowered on the inclusion fixed on the rod ***3*** by the dosing device. After completing the coating of inclusion by liquid (it was a mandatory control before each experiment) the heterogeneous droplet was inserted by using the rod ***3*** into one of the three holes in the channel ***8***. During each experiment all sides of inclusion were covered by water film. The movement of rod ***3*** was performed in two coordinates: along the symmetry axis of cylinder ***8*** and perpendicular to the axis when inserting droplets into high-temperature gases in the cylinder ***8***.