Explosion of heterogeneous water droplet in a high-temperature gaseous region

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Abstract. Using high-speed video recording tools (up to 10^5 frames per second) and «TEMA Automotive» and «Phantom Camera Control» software packages the experimental features of explosive disintegration, boiling and evaporation of water droplets with comparably sized solid inclusions heated in high-temperature (more than 650 K) gaseous region were determined. The necessary and sufficient conditions of explosive vapor formation achievement with the next heterogeneous water droplet disintegration were found.

1. Introduction

The technologies of use of the heterogeneous and multiphase flows in power engineering, chemical and petrochemical applications are applied enough in recent years [1-4]. These technologies primarily mean the presence of solid inclusions (solid phase) in a flow. Most often these solid inclusions are added artificially [1-4]. Thus, the phase change mechanisms at the «solid inclusion – liquid droplet» interfaces are of interest. The research of vapor bubble occurrence, growth and movement processes [5, 6] near solid inclusions in a heterogeneous flow attracts special interest. Uninvestigated heat exchange features of different phases in a flow determine one of the main unsolved fully problems – mechanism determination of liquid droplet phase changes with solid inclusions in gaseous (especially high-temperature) region taking into account the optical and thermal-physical particle material properties.

One of the main applications of multiphase heterogeneous gas-vapor-droplet flows is the forest fire extinguishing by using the water atomization. Both the theoretical [7, 8] and experimental [8-10] investigations in the given branch show that the addition of typical solid metallic and nonmetallic inclusions (particles of different shapes and sizes – from 50 μm to 500 μm) in extinguishing liquid increases significantly the efficiency factor. An experimental investigation of an impact of solid inclusions comparably sized with a liquid droplet on the evaporation and boiling rate in the combustion area and possible explosive vapor formation conditions are of interest.

The pulverization of extinguishing agent droplets by probable explosive vapor formation will increase the flame coverage area by the vapor-droplet cloud. In this case, it seems advisable to determine necessary and sufficient conditions whereby the phase change (evaporation and boiling of liquid, explosive vapor formation) differences of water droplets with solid inclusions can be identified.

The aim of the present work is to determine the explosive vapor formation conditions of a heterogeneous water droplet heated in a high-temperature gaseous region corresponding to combustion products of the typical petroleum products.

2. Experimental setup and methods of investigation

During experimental investigations the setup (figure 1) similar to the one used in the tests [9, 10] was applied.

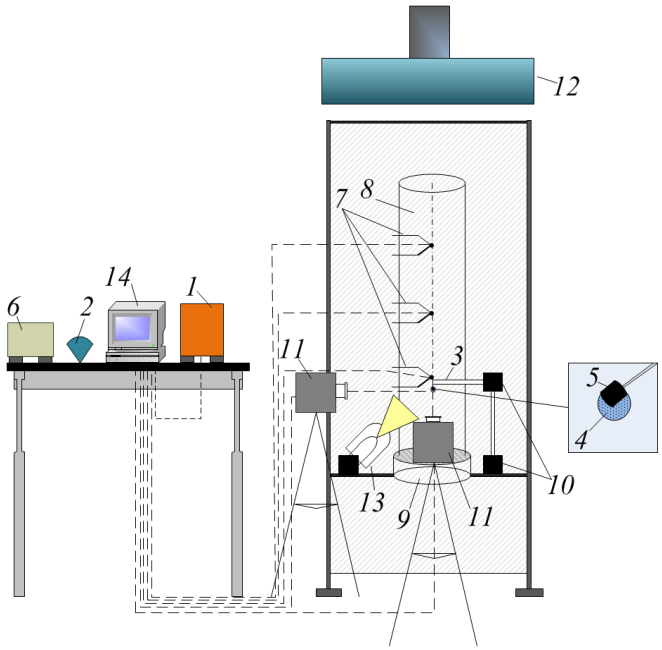

Figure 1. Scheme of the experimental setup:

1 – analytical weighing system,
2 – electronic dosing devise,
3 – rod (holder for inclusion),
4 – droplet,
5 – inclusion,
6 – manufacture of inclusions,
7 – thermocouples,
8 – cylinder of quartz glass,
9 – burner/heat gun,
10 – moving mechanisms,
11 – high-speed cameras,
12 – air flow system,
13 – spotlight,
14 – personal computer (PC)

Droplets moved through a high-temperature region in the experiments [9, 10]. In this work a heterogeneous water droplet was fixed on the rod *3*. Figure 2 illustrates the typical configurations of heterogeneous liquid droplets.

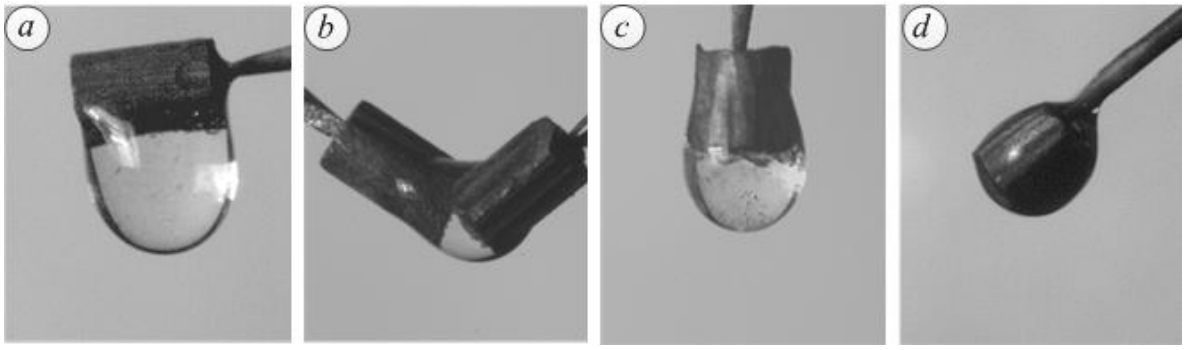

Figure 2. Typical variants of heterogeneous liquid droplets: *a* – water droplet (volume is 15 μl) hangs from the horizontal inclusion in the parallelepiped shape and covers only one inclusion edge; *b* – water droplet (volume is 15 μl) is between two inclusions in the parallelepiped shape, inclusions are in contact; *c* – water droplet (volume is 15 μl) hangs from the vertical inclusion in the cylindrical disk shape and fully covers the inclusion; *d* – water droplet (volume is 5 μl) fully covers the inclusion in the parallelepiped shape with the formation of almost uniform in thickness film.

The decision on the heterogeneous droplet fixation on the rod was accepted according to the results of the primary tests illustrated the regular partial protrusion of inclusions out of the droplet surface during their motion through a high-temperature gaseous region.

High-speed video recording of the heterogeneous droplet evaporation on the ceramic rod *3* was performed. Two high-speed (up to 10^5 frames per second) video cameras («Phantom V411» and «Phantom Miro M310») *11* were used during this process. A heterogeneous water droplet was fixed into the quartz cylinder *8* (height is 1 m, inside and outside diameters – 0.2 m and 0.206 m). This volume contained the temperature-controlled combustion products. The processing of the videograms was provided by «Phantom Camera Control» and «TEMA Automotive» software packages.

The burner *9* was at the bottom of the cylindrical channel *8*. Industrial alcohol used to generate high-temperature gases was in the burner *9*. The chosen industrial alcohol as a combustible liquid produces less smoke than kerosene as used in previous experiments [9-11]. With such configuration, the droplet images had sufficient contrast to be analyzed.

The temperature of the gaseous region in the cylinder *8* was controlled by the chromel-alumel thermocouples *7* (measuring temperature range 273–1373 K, measurement error ± 3.3 K). The temperature was registered at heights 0.3 m, 0.5 m and 0.7 m relative to the bottom of burner *9*. Three holes were drilled the cylindrical channel *8* for these purposes. The hole at height 0.7 m was also used to insert the ceramic rod *3* with a fixed heterogeneous droplet into the channel (after measurement of gas area temperature).

The experiment included several steps. The droplet of fixed mass was lowered on the graphite inclusion *5* by using the dosing device *2*. Then the droplet was inserted into the hole at height 0.7 m. After insertion of the droplet in a high-temperature gaseous region the video recording of droplet evaporation was activated. The obtained video materials were processed on PC *14* by using the «Phantom Camera Control» and «TEMA Automotive» software packages: the sizes of droplet (d), liquid film thicknesses (δ) and the characteristic time of heating (τ_h) until explosive disintegration or complete water evaporation were determined.

The experiment of the radiation energy impact assessment on the heating and phase changes of heterogeneous liquid droplet was carried out by using the same setup, but instead of burner *9* was installed the heat gun of fixed motion speed (3 m/s) and temperature (up to 1000 K) of air flow. Also, the preliminary investigations included the tests using the household multi-fuel burner where the types of fuels were industrial alcohol and gas mixture (butane, propane). The video recording, processing of water droplets and solid inclusions during the preliminary tests correspond above mentioned procedure.

Errors on measurements of inclusion, water droplet sizes (d) and film thickness (δ) did not exceed 0.01 mm. Random (characterize the measurement repeatability) errors of d and δ determination were not more than 7-10 %. The error on time of heating τ_h did not exceed 1 ms.

3. Results of experiments and discussion

It was found that the intensive boiling and vapor formation of a heterogeneous liquid droplet heated in a high-temperature gaseous region are carried out much faster when a heat flux is supplied to an inclusion. Then a heat flux begins to heat a droplet.

To check this phenomenon the control experiments with two droplets and one inclusion were carried out. Figure 3 shows that the phase changes of the second water droplet in relation to the air flow direction were realized moderately until fully evaporating the first droplet. Then the intensive formation of the vapor layer at the «solid inclusion – water droplet» interface and the liquid boiling were observed. It is worth to note that the explosive vapor formation did not record during the tests in the hot air. It proves the fundamental importance of the radiation energy to achieve conditions of the process under investigation.

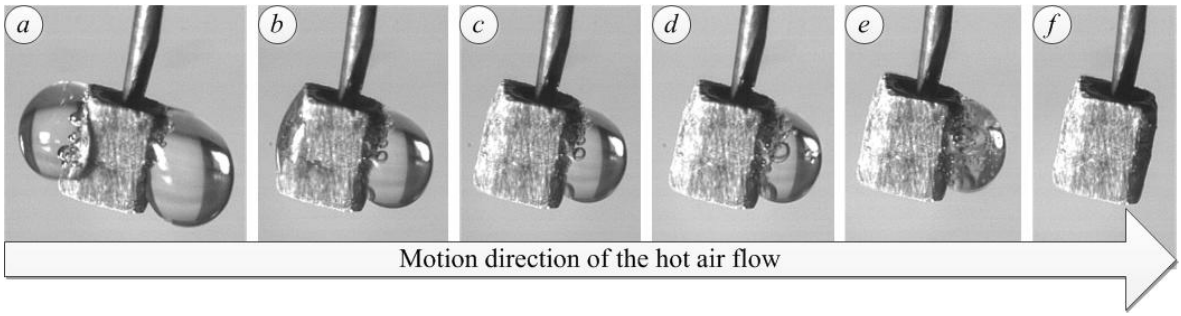

Figure 3. Typical video frames of two water droplets (the initial droplet volume is 7 μl) during evaporation and boiling at the graphite inclusion surface (the characteristic size is 2 mm) in various time points (the temperature of the air is 623 K): *a* – 6 s; *b* – 14 s; *c* – 15 s; *d* – 16 s; *e* – 18 s; *f* – 22 s.

Also, the increase of a heat exchange surface (for instance, a heterogeneous droplet consists of two inclusions) is one of conditions to intensify phase changes. «Water droplet – two inclusions» case (figure 4) showed that such processes as intensive boiling and onset, joining of bubbles take place during the first second of heterogeneous droplet heating in a gaseous region. Figures 4, *b* and 4, *c* show the bubble joining at the interface and single bubble growth with increase of a heterogeneous droplet size in relation to the initial size. When exceeding the vapor pressure of a critical value of the pressure caused by forces of surface tension and outside environment the explosion of a heterogeneous liquid droplet takes place. Figure 4, *d* shows the water droplet after the collapse (explosion) of single vapor bubble. The consequences of explosive vapor formation can be different (formation of a small droplet group or large liquid agglomerates, collapse of vapor bubbles without water droplet disintegration). In this case (figure 4) the water droplet disintegration on the small droplet group or large agglomerates was not observed.

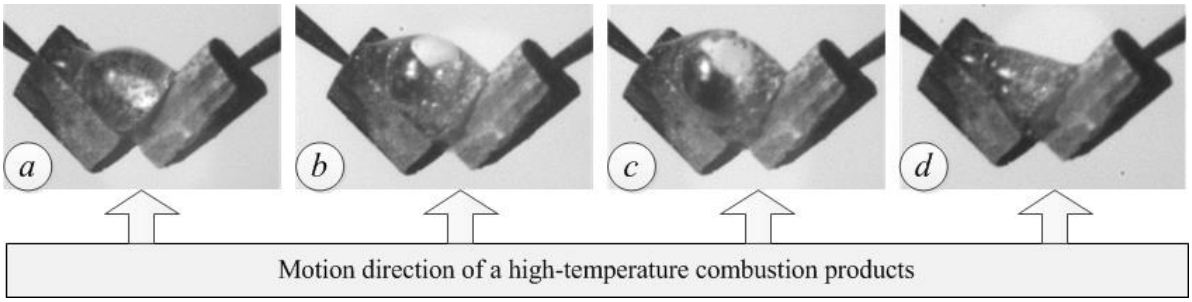

Figure 4. Typical video frames of the heterogeneous droplet consisting of the water droplet (the initial volume is 15 μl) and two graphite inclusions (the characteristic size of each inclusion is 3 mm) during evaporation and intensive vapor formation in various time points (the temperature of industrial alcohol combustion products is about 650 K): *a* – 0.33 s; *b* – 3 s; *c* – 3.45 s; *d* – 4 s.

It was revealed that an explosive vapor formation can continue for a long period (figure 5). The liquid evaporation from free surface of a water droplet takes most of the heating time. Figure 5, *b* illustrates the significant decrease of the water droplet size in relation to the initial size (figure 5, *a*). The significant increase of heterogeneous droplet size was recorded during the onset, growth and joining of the vapor bubbles (figure 5, *c*).

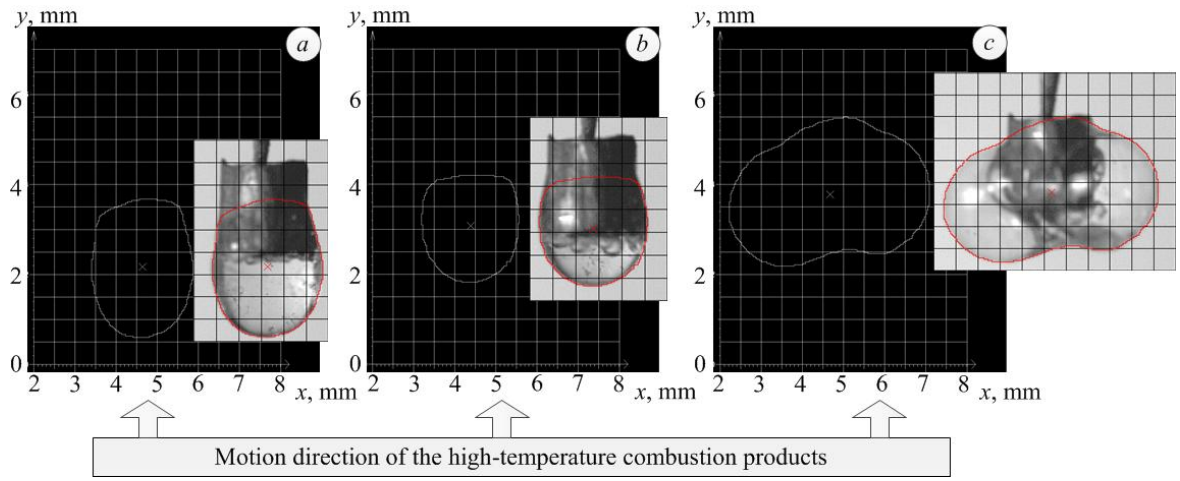

Figure 5. Typical video frames of the heterogeneous droplet heated in the industrial alcohol combustion products with the indication of change in water droplet (the initial volume is 15 μl) sizes during the explosive vapor formation in various time points: *a* – 0.01 s; *b* – 9 s; *c* – 12.175 s.

The obtained results allowed revealing the conditions of explosive vapor formation achievement. A temperature of gaseous region and radiation energy are the most important. The carried out control tests showed that the shape, material, sizes of inclusion (inclusions) and position of a heterogeneous droplet in relation to a motion direction of a gaseous flow.

The carried out experimental investigations showed that the explosion of a heterogeneous water droplet 3-4 mm in size at the outside gaseous region temperatures of not less than 650 K occured during several seconds (1-3 s). It is worth noting that the processes of long duration (up to 12-13 s) are also possible. If we tell about heterogeneous droplets with such sizes [11], then the existence times at the same conditions, as a rule, are not less than 10 s. The intensive evaporation from the outside surface and the bubble onset near the inside interface was observed during all experiments at the temperatures of not less than 650 K. Such phase change mechanism is characterized by large existence times of droplets (30-40 s).

4. Conclusions

It was found that the explosive vapor formation conditions of heterogeneous droplets 3-4 mm in size are possible at the gas temperatures of more than 650 K. So, the existence times till breaking up the droplets, as a rule, were several seconds. The phase change features of heterogeneous water droplets were recorded. It was revealed the significant impact of radiation energy on the considered process. Therefore, the explosive disintegration conditions of heterogeneous water droplets heated in combustion products of petrochemicals are realized during a short time versus hot air at the same temperatures.

5. Acknowledgement

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