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Analysis of the Water Droplet Evaporation Features with a Solid Nontransparent Inclusion in High-Temperature Gas Environment as a Part of University Research Work

Maxim Piskunov*, Anastasia Shcherbinina, Pavel Strizhak

National Research Tomsk Polytechnic University, 30 Lenin Avenue, Tomsk, 634050, Russia

Abstract

This paper examines the features of the heating and evaporation of heterogeneous liquid (water) droplets (with the initial radius from 1.5 to 2.5 mm) in the combustion products of typical liquid combustible substances (acetone, technical ethanol, butane-propane gas mixture) and heated air explored as a part of university research work. The investigations have been performed by means of high-speed video recording and software "TEMA Automotive" and "Phantom Camera Control". The gas temperature varied from 300 to 850 K in the experiments. The characteristic times of droplet existence (complete evaporation) have been determined. The influence of radiative, convective and conductive heat transfer has been defined.

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Keywords: Evaporation; water droplet; solid inclusion; evaporation rate; high-temperature combustion products; radiative heat transfer; heat transfer enhancement.

1. Introduction

Nowadays, more and more attention is paid to improving the efficiency of fire extinguishing by increasing the area of flame covering by water vapor-droplet cloud. For this purpose, investigations have been performed that

* Corresponding author.
E-mail address: piskunovmv@tpu.ru (M. Piskunov).

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examine the features of the phase changes of sprayed liquid compositions. Such investigations are based on the approaches to reduce the size of droplets and increase their concentration in the flow (Försth & Möller, 2013; Joseph, et al., 2013; Tang, et al., 2013; Yao & Cong, 2012). However, recent experimental studies (Volkov, et al., 2014a; Volkov, et al., 2014b; Volkov, et al., 2015) showed that small droplets were likely to be taken away from the fire area under the influence of combustion products. Thus, it is advisable to determine the optimum droplet size for fire extinguishing by sprayed quenching composition. One of the key points is also to increase the evaporation rate in the flame zone. This helps to accelerate droplet heating up. Efforts to intensify significantly droplet vaporization have succeeded in the study (Volkov, et al., 2014a) by adding impurities and inclusions (metallic and non-metallic) to the droplet. In this case, the heating of heterogeneous droplets (a water droplet with a proportionate inclusion or inclusions much smaller than the droplet) is caused by a complex mechanism of phase changes. First of all, it is of interest to study phase changes at the internal boundaries between the media (inclusion/liquid) (Volkov, et al., 2015). In this case, the following processes can be distinguished: bubble boiling, the relevant processes of nucleation, growth and merging of vapor bubbles, and particularly the "explosive" vaporization of a liquid droplet. According to the theoretical analysis of the experimental data (Volkov, et al., 2015), it is expected that the effect of "explosive" vaporization may improve significantly the efficiency of water use in firefighting. This is due to the disintegration of liquid droplets into smaller droplets. Thus, the flame covering zone increases.

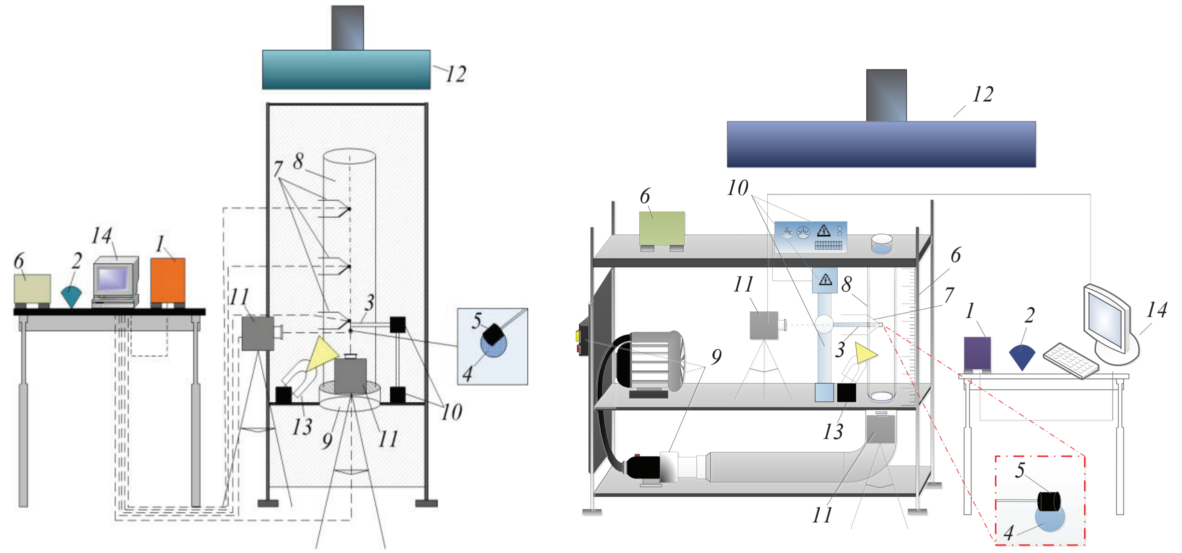
Fire involving oil and petroleum products is characterized by several fundamental differences: a high temperature in a combustion zone, the formation of incomplete combustion products (Volkov, et al., 2014b; Volkov, et al., 2015). These factors complicate the formation of vapor-droplet flows, change the conditions of phase transitions at the internal and external boundaries of heterogeneous droplets. Therefore, it is of particular interest to study the effect of high temperature environment (generated by burning different fuels) on complete liquid evaporation from the exterior surface of the heterogeneous droplet, as well as vaporization at internal boundaries (inclusion/water).

Among the scientists involved in the study of the designated problem, there is professor P.A. Strizhak, postgraduate students M.V. Piskunov, A.A. Shcherbinina and others, who work at the Department of Heat and Power Process Automation of the Institute of Power Engineering at the National Research Tomsk Polytechnic University. The team works within the educational direction "Thermal Engineering and Heat Engineering" during the 2014/2015 academic year. Scientific results obtained during this period of time were applied in academic disciplines "Modern problems of power engineering, heat engineering and heat technologies", "Experimental studies of heat and mass transfer and gas-dynamic processes".

The aim of this work is to investigate experimentally the evaporation features of heterogeneous liquid droplets in various high-temperature gas environments. Experiments were carried out to define the basic laws of the explosive vaporization occurrence of heterogeneous water droplet flaws during their motion in high-temperature gas environment.

2. The experimental setup and methods

Fig. 1 shows the schemes of experimental setups, where investigations were performed. The first experimental setup (Fig. 1, *a*) was used to study the evaporation and boiling of a heterogeneous water droplet in the combustion products of industrial alcohol, acetone and the liquefied hydrocarbon gas mixture (butane, propane). A burner *9* was chosen depending on the type of fuel burned. The second facility (Fig. 1, *b*) was used to study the same processes in heated air flow with a controlled temperature. The main tools of our experimental setup were similar to that used in studies (Volkov, et al., 2014b; Volkov, et al., 2015; Volkov, et al., 2014c; Vysokomornaya, et al., 2014), but here we implemented high-speed video recording of heterogeneous droplet evaporation. The droplet was fixed on a rod *3* made from an insulating material (ceramic). Video recording was carried out using two high-speed (up to 10^5 fps) video cameras *11* ("Phantom V411" and "Phantom Miro M310"). We performed video processing by means of a computer *14* and software "TEMA Automotive", as in experiments described in the paper (Janiszewski, 2012). We also used software "Phantom Camera Control" that enabled the visualization of investigated processes and the mode control of video recording.



a b

Fig. 1. Schemes of (a) the first and (b) second experimental setups: *1* – analytical balance, 2 – electronic pipette, *3* – rod (inclusion holder), *4* – droplet, *5* – inclusion, *6* – complex to produce inclusions, *7* – thermocouples, *8* – quartz cylinder, *9* – burner/high-pressure blower, *10* – motorized sliding mechanisms, *11* – high-speed cameras, *12* – air flow system, *13* – spotlight, *14* – personal computer.

The experiments involved several stages. In the first (preparatory) stage, water droplets were weighted using an electronic analytical balance *1*. The mass of liquid varied from 5 to 15 mg. All manipulations with water droplets were carried out using an electronic pipette *2*. Solid graphite inclusions were produced with the help of a set of needle files *6*. The inclusion was fixed on the rod through a special drilled hole (diameter 0.6 mm, depth 0.3 mm). Our preliminary experiments showed that the parallelepiped inclusion is the most appropriate by several criteria. Firstly, this shape provides the more stable enveloping of inclusion. Secondly, it minimizes the impact of the rod on the heating conditions of the heterogeneous droplet (no contact between water and the rod). The produced inclusion *5* was covered with liquid using the electronic dosing device *2*. Thereby, the heterogeneous droplet was formed. The ceramic rod *3* with the fixed heterogeneous droplet was introduced into the high-temperature environment with the help of motorized sliding mechanisms *10*. A spotlight *13* was installed to improve the image contrast required for the correct operation of software “TEMA Automotive”.

The second stage of studies is to conduct experiments in the setup, shown schematically in Fig. 1, *a*. The investigations of the evaporation and boiling of the heterogeneous water droplet in the combustion products of technical ethanol, acetone and the gas mixture (propane, butane) had a number of features. The investigations were performed as follows:

– the burner *9* was used in the case of generating high-temperature gas environment by burning technical ethanol and acetone; a multi-fuel burner with an adjustable flow was used when burning the liquefied hydrocarbon gas mixture.

– the heterogeneous water droplet was inserted into one of the three holes of cylindrical channel *8* by the motorized sliding mechanism *10* and the rod *3*; holes were drilled at a height of 0.3 m, 0.5 m and 0.7 m relative to the base of the burner;

– three chromel-alumel thermocouples were installed to measure the temperature of combustion products in the cylinder *8*; the temperature varied by setting an air flow system *12*;

– the change in the droplet size and the liquid film thickness of the inclusion *5* was monitored during the video recording of droplet evaporation in each experiment;

– the times of the complete evaporation of liquid from the inclusion surface τ_h were recorded in software “Phantom Camera Control”;

– the maximum droplet diameters in three dimensions were measured in software "TEMA Automotive"; it was necessary to determine the average droplet size (*d*) and the liquid film thickness δ (on each face of the inclusion) of the inclusion 5;

– the initial temperature of water droplets *4* and inclusions *5* was equal to the ambient temperature in our laboratory (about 290 K).

The third stage of studies is to perform experiments in the setup (Fig. 1, *b*). The main points of experimental methods for investigated processes in heated air were similar to that implemented in the second stage (manipulation with heterogeneous droplets, video recording of processes, video and data processing). However, the third stage had a number of distinctive features:

– a high-pressure blower *9* was the source for generating high-temperature environment; we set the desired temperature using the control unit of the high-pressure blower for the current series of experiments (5 experiments for each temperature)

– the air temperature inside the cylinder *8* varied from 323 to 723 K in increments of 100 K; the heater of the high-pressure blower maintained the temperature at a predetermined level; the fan of the high-pressure blower *9* provided the rate of the heated air flow (4 m/s);

– the air flow system *12* was used as an exhaust channel for heating air; it was switched off.

Systematic errors in measuring the size of the inclusion or the water droplet, and the film thickness did not exceed 0.01 mm. Random errors in determining *d* and δ did not exceed 7–9 % relative to the average value for the series of experiments under identical initial conditions. These parameters characterized the repeatability of measurement results. Errors in determining times τ_h did not exceed 1 ms.

3. Results and discussion

The first feature established in the experiments is that there are several mechanisms of enveloping the inclusion by water: partial enveloping of the inclusion (the most common case), full enveloping (it is usually implemented at a small amount of liquid).

The second feature is quite obvious (in terms of the physics of the processes): phase transitions occur simultaneously on the outer surface of the liquid droplet and at the internal boundaries between the media (inclusion/water). In the vast majority of experiments, the rate of the complete evaporation of liquid from the outside (free) surface is higher than the rate of phase changes at the interface.

The comparative analysis of experimental results was performed for the case of heating air and the combustion products of liquid fuels. The analysis suggests a significant role of the radiant (radiation) heat flow during the evaporation and vaporization of liquid (Fig. 2 and 3). It should be noted that there is a significant difference in the times of droplet heating to the conditions of complete evaporation from the inclusion surface in considered high-temperature environments. We observed the moderate formation of vapor bubbles, their subsequent growth and merging to larger bubbles at the internal boundaries inclusion/water in the experiments with heated air, as well as in the experiments with the combustion products of liquid fuels. Bubble formation is mainly due to the absorption of gas radiation energy by water with subsequent energy accumulation. This phenomenon was observed in the experiments conducted in the flow of the combustion products of liquid fuels. Phase transitions at internal boundaries stopped at the stage of the formation of larger vapor bubbles, because the liquid droplet became commensurate with bubbles at this point.

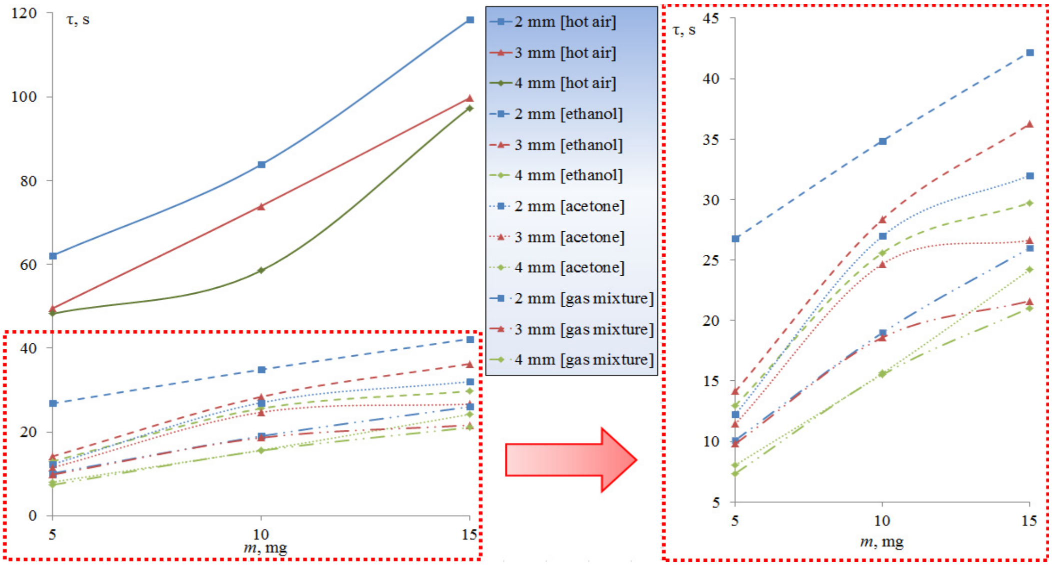


Fig. 2. Times of existence (complete evaporation) of water droplets with solid inclusions of different sizes when increasing the temperature of air and combustion products of liquid fuels, and varying water mass.

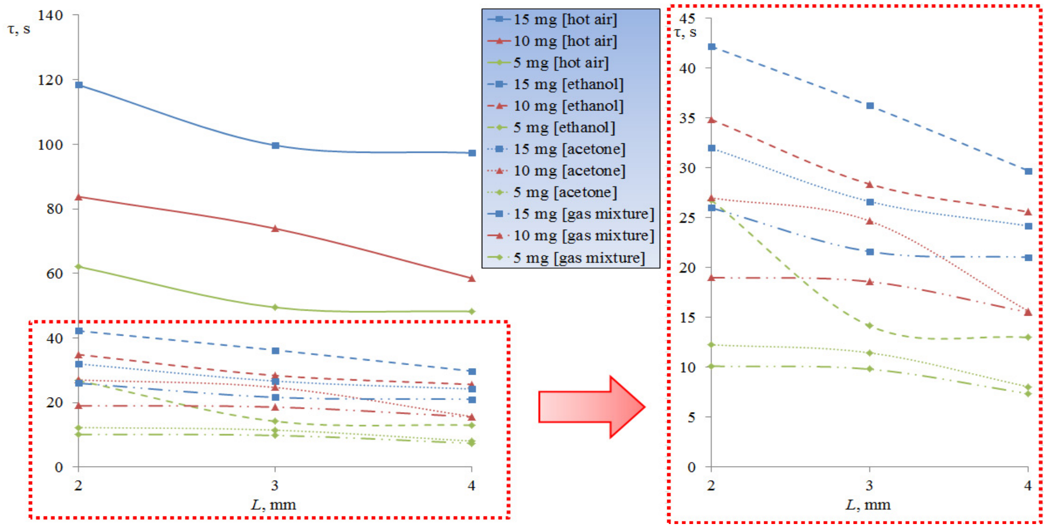


Fig. 3. Times of existence (complete evaporation) of water droplets of different mass with solid inclusions when increasing the temperature of air and combustion products of liquid fuels, and varying the size of inclusion.

Fig. 2 shows the dependencies of the times of the complete evaporation of liquid droplets with inclusions of different sizes when varying the ambient temperature and the mass of enveloping liquid. When the surface area of the solid inclusion increases, phase transitions intensify at internal boundaries; this reduces the lifetime of the liquid droplet (Fig. 3). Essentially nonlinear dependence (Fig. 2 and 3) can be explained, first of all, by the nonlinear dependence of the evaporation rate on the temperature (Avdeev & Zudin, 2012). Changing the inclusion size and the liquid mass leads to the increasing of this nonlinearity. It is obvious that when the mass of the enveloping fluid increases (Fig. 2) and the inclusion size decreases (Fig. 3), the time of the complete evaporation of heterogeneous droplets increases.

It should be noted that experiments demonstrated the intensive evaporation of liquid droplets with their subsequent disintegration (implementation times – up to 5 s) in addition to the mechanisms of evaporation from the outer surface and vaporization at the internal boundaries.

Highlighted features and mechanisms of the phase transitions of heterogeneous droplets can be used in the development of firefighting technologies, as well as in energy and chemical industries (thermal water treatment, granular media defrost by heterogeneous vapor-droplet flows, and others.).

4. Conclusion

The results demonstrate the effect of radiant (radiation) heat transfer on the conditions of the phase transitions of heterogeneous water droplets in high-temperature gas environments. The experimental studies suggest that there are three simultaneous mechanisms of phase changes during the heating of heterogeneous droplets: the evaporation from the free surface, vaporization at the internal boundaries (inclusion/liquid) and the "explosive" vaporization of a liquid droplet. A comparative analysis of the characteristics and times of the complete evaporation of liquid from the inclusion surface may improve and complete modern technologies based on heterogeneous vapor-droplet flows.

Moreover, the implementation of investigations presented in this work allowed participants to develop a research base, which enabled publication of three articles in journals indexed by the leading database of scientific publications. We took part in two international conferences and established scientific contacts with scientists from the USA, Japan and Belgium working on a similar subject, which is an important part of continuous professional development among academic staff.

Acknowledgements

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