

Influence of surface roughness and porosity of inclusion in water droplet on heat transfer enhancement

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Abstract. Using high-speed camera, the experiments were performed to research evaporation of 10 μl water droplets containing 2 mm solid inclusions in the shape of cube, when heated (up to 850 K) in combustion products of technical ethanol. Adding solid inclusions in water droplets allowed considerably decreasing (by 70%) their evaporation times. Also, the artificial irregularities (roughness and porosity) at the surfaces of solid inclusions were manufactured to increase heat transfer area. Such approach enabled to decrease evaporation times of heterogeneous liquid droplets in high-temperature gases by 40% (when comparing inclusions with artificial irregularities and smooth surface).

1 Introduction

The experimental investigations on approaches to enhance heat and mass transfer present the broad list of possible ways discussed in scientific papers (for example, [1–3]), published over the last 150 years. In particular, existing methods to enhance heat transfer between liquid and heating surface can be divided into two types. The first one includes various changes in liquid. Among these are an addition of solid insoluble particles of different sizes and concentrations (preparation of suspensions), use of surfactants (wetting agents, plasticizers etc.), binary liquids, salt solutions and more. The second type involves mechanical change of heat-exchange surface (for example, finning well-known in thermal engineering and other artificial irregularities contributing vapor formation at the “liquid – heating surface” interfaces).

In research [4, 5], we revealed some conditions of intense vapor formation at the internal “solid inclusion – water” interfaces of heterogeneous (inhomogeneous) liquid droplet. Moreover, under such conditions, the explosive disintegration of droplets occurred. We believe that when changing geometry of heating surface, the lifetimes of heterogeneous droplets established in [4, 5] will reduce. Furthermore, the change of heat-exchange surface can be one of the key factors to reach the rapid elimination of heat. Thus, in the present research, to determine the influence of surface irregularities on heat transfer under experimental conditions as in [4, 5] is appropriate.

The purpose of the research is to establish experimentally influence of artificial irregularities of graphite inclusion inside water droplet on its lifetimes (evaporation times) in high-temperature combustion products of technical ethanol. In addition, we expect that the increase of heat flux in water layer can contribute to reach conditions of the intense vapor formation with explosive disintegration of heterogeneous liquid droplet.

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2 Experimental setup and research methods

To perform the experimental research, the setup as in [4, 5] was used. Fig. 1 illustrates the scheme of the setup.

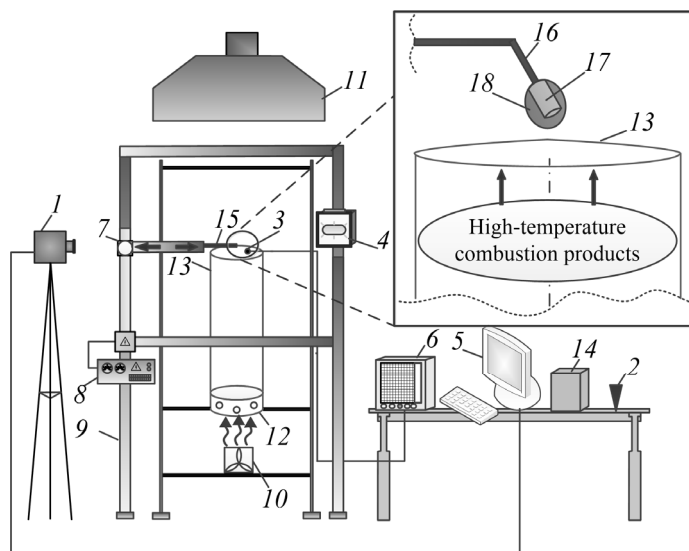


Figure 1. Scheme of the experimental setup: 1 – high-speed camera, 2 – electronic dosing devise, 3 – thermocouple, 4 – spotlight, 5 – personal computer (PC), 6 – temperature registration, 7 – moving mechanism, 8 – power supply to moving mechanism, 9 – mount, 10 – fan blower, 11 – air flow system, 12 – burner, 13 – metallic cylinder, 14 – analytical balance, 15 – guideway to fix a ceramic rod, 16 – ceramic rod, 17 – solid inclusion, 18 – water droplet

The main steps of experimental technique are similar to ones stated in [4]. Therefore, when describing the technique of the research, we will note only the significant differences and brief the necessary steps.

Recommendations and explanation of choice of such approach to fix and move heterogeneous droplets (see inset of Fig. 1) in high-temperature gas area are discussed in [4]. When experimenting, the inclusions made of pure graphite in the shape of cube (size of inclusions is $l_{in}=2$ mm) were used. To reach the purpose of the research, the following types of surface irregularities were manufactured:

1. Roughness (on each side of inclusion, depth – 0.15 mm, shape – cylindrical, random distribution of lines along surface with intercrossing, number of lines in 1 mm^2 – not less than 12);
2. Pores in the shape of holes (depth – from 1 mm to 1.5 mm, diameter – 1 mm, number on one side of inclusion – 1).

To perform each test, the important conditions were as follows:

1. Regulation of initial temperature of inclusion before each test;
2. Full covering of inclusion by water droplet.

These conditions were provided by dipping inclusion in a vessel with water (~ 298 K) during several seconds. After this procedure, water droplet of required initial volume was supplied on inclusion. Moreover, liquid mass remaining on inclusion after dipping was considered when processing the results. Experiments were carried out using the distilled water, which was taken out of a vessel by dosing device 2.

Using high-speed recording allowed solving the following problems:

1. Determining lifetimes τ_h of heterogeneous water droplets in high-temperature combustion products;
2. Finding peculiarities of phase changes of water droplets with graphite inclusions.

To provide high-temperature area in cylinder 13, we burnt technical ethanol.

The main steps of the experimental research are as follows:

1. By using moving mechanism 7, heterogeneous liquid droplet (10 μl water droplet with graphite inclusion) was introduced into the gas area; then, video recording was carried out; after water evaporation, an inclusion was removed from the gas area.
2. Cooling and full covering of an inclusion; the formation of the next heterogeneous droplet; repeat of the first step.
3. Computing lifetimes τ_h of heterogeneous water droplets in the gas area.

Errors on lifetime τ_h are less than 10^{-2} s. Errors on measurements of solid inclusion sizes l_{in} do not exceed 0.05 mm.

3 Results and discussion

Fig. 2 presents research results that indicate the influence of addition of solid inclusions and irregularities at their surfaces on the evaporation time τ_h of heterogeneous droplets. The addition of solid inclusions in water droplets enabled to considerably decrease (by 70%) the evaporation times τ_h . Moreover, the significant decreasing (by 40%) the evaporation time τ_h of heterogeneous droplets occurred owing to manufacturing the artificial irregularities at the surfaces of solid inclusions (see Fig. 2, *a* and *b*).

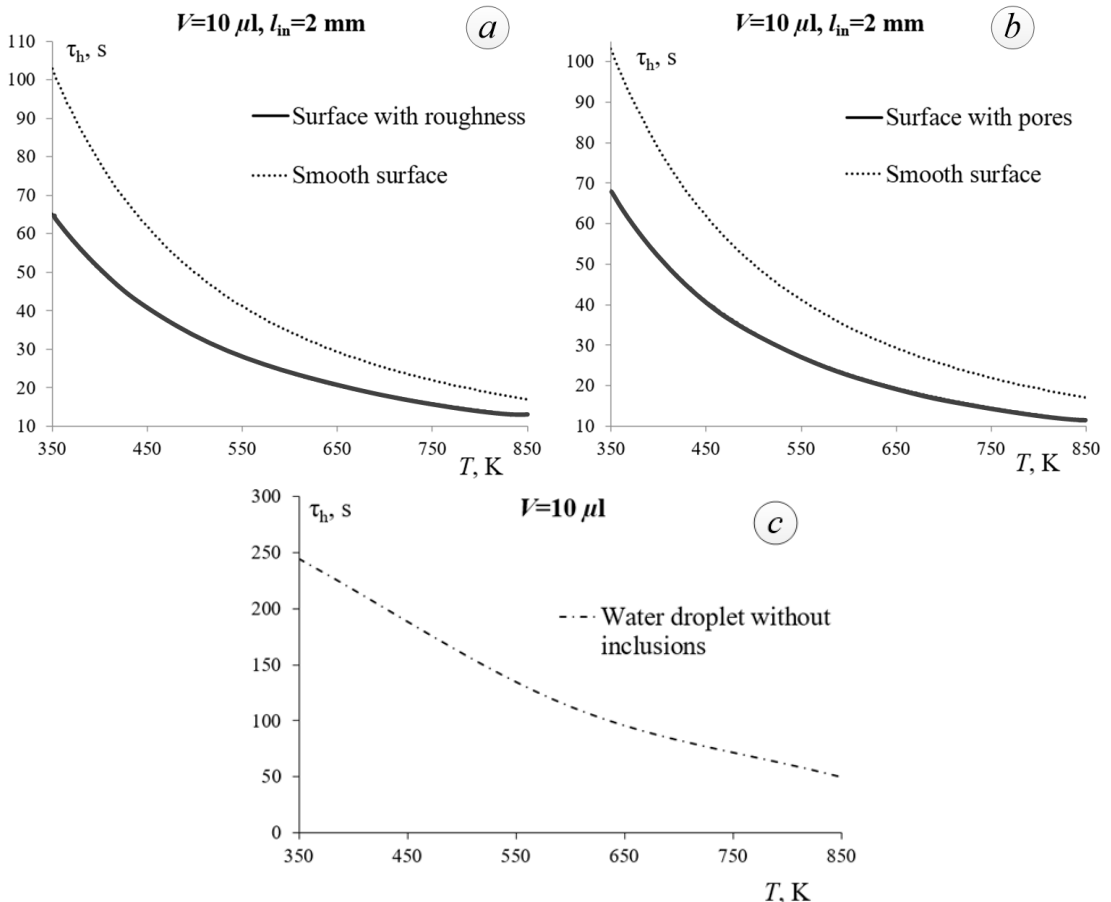


Figure 2. Comparison of lifetimes τ_h of 10 μl water droplets without (*c*) and with (*a*, *b*) solid inclusions with smooth and irregular (rough and porous) surfaces, when heated in high-temperature combustion products

The remarkable thing is that the influence of shallow and numerous roughness (Fig. 2, *a*), as well as single pores (Fig. 2, *b*) on the heat transfer enhancement is almost similar.

In the research [4], the detailed description is presented for the mechanism of phase changes in the heterogeneous droplets when heated in high-temperature gas area. Moreover, the addition of solid inclusion significantly enhanced the heat transfer in the high-temperature gases – heterogeneous liquid droplet system [4]. Such phenomenon is mainly due to the intense heat outflow from the inclusion to the water layer. Thus, all other things being equal, in the heat transfer equation $Q=kF\Delta T$ (k – heat transfer coefficient, W/m^2K , F – heat exchange surface area, m^2 , ΔT – temperature difference, K) for the present research, the heat flux Q (from the inclusion to the water layer) will increase by the growth of heat exchange surface area F . Then, the enhancement of heat outflow to the water layer quantitatively influenced the lifetimes τ_h of heterogeneous liquid droplets (Fig. 2, *a* and *b*).

In the performed experiments, only the evaporation of liquid from the surface of heterogeneous droplet occurred. At the internal interfaces, the nucleation of vapor bubbles was not observed. From the above reasoning, adding solid inclusions and manufacturing artificial irregularities on their surfaces (increasing the heat exchange surface area inside heterogeneous droplet) contributes to the significant increasing the evaporation rate of liquid when heated. However, the used approach does not provide the necessary conditions for the intense vapor formation at the internal interfaces.

The revealed peculiarity of evaporation of heterogeneous liquid droplets can be the theoretical basis to develop recommendations for improvement of the effectiveness of waste and industrial water treatment.

4 Conclusion

Owing to manufacturing the artificial irregularities at the surfaces of 2 mm solid inclusions, evaporation time τ_h of heterogeneous droplets decreased by 40% (when comparing inclusions with artificial irregularities and smooth surface). Furthermore, adding solid inclusions in water droplets enabled to decrease evaporation times τ_h by 70% (when comparing water droplets with and without solid inclusions with artificial irregularities).

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