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# Experimental research of radiative heat transfer in a water film

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ABSTRACT

The paper presents results of experimental research into the transmission of infrared radiation through water film. Experiments substantiate a hypothesis about the considerable role of radiative heat transfer when heating heterogeneous water drops containing opaque solid particles in high-temperature gases. We measure the temperatures of water film surface, the bottom of a cylindrical plastic cuvette and a graphite substrate. During the experiments, the typical thickness of the water film, the bottom of the plastic cuvette and the graphite substrate is 1 mm. The temperature measurements are implemented for carbonated, distilled and tap water. Results of a comparative analysis of these measurements are presented as well. The hypothesis is formulated about a significant variation in the optical properties of water under temperature fluctuations. This assumption is based on the hydrophobic properties of amphiphilic molecules. Importantly, the experimental data enable the study of rapid evaporation of a liquid at internal and external interfaces of water drops containing solid opaque particles with a further explosive fragmentation of water film. This mechanism relies on heating of the particle surface above the boiling point of water.

## 1. Introduction

For the first time, the phenomenon of the explosive vaporization of water droplet under rapid heating by laser radiation was described in [1,2]. Scientific works with the analysis of the given phenomenon started to appear as early as in 1960s [1]. A large number of studies within this topic was carried out in 1970–80s [3–5].

Note that numerical (for example, [3]) and experimental (for example, [4]) investigations of the explosive breakup of water droplets exposed to intensive laser radiation were performed in the USSR. Explosions were classified into (1) fragmentation as the hydrodynamic disintegration of the droplet into small droplets with local heat release; and (2) gas-dynamic explosion, which involves high temperature and pressure spreading almost throughout the entire droplet and highly depends on heating conditions, namely on quasi-uniform and detonation-like heating modes. Study [4] reports that the fragmentation and gas-dynamic explosion of near-surface layers of a liquid, i.e. a surface explosion or a disruption of a liquid film, occur in the case of large drops. Experimental conditions in [4] include the application of $CO_2$-lasers. The size of the water droplets varies in a range of $\sim 5–10^3$ μm. Sources of the laser radiation operate in the pulsed and continuous modes with radiative flux in the operating range of $10^2–10^9$ W/cm$^2$. The wavelengths of radiation are 10.6 μm, 2.36 μm, 1.06 μm, and 0.69 μm.

There are theoretical research findings on the explosive breakup of droplets under high-temperature pulsed laser heating [6,7]. In [6,7], the authors studied the hydrodynamic reaction of a single droplet in an aerosol to an intense external irradiation. This phenomenon is known as EMR-droplet interaction. The authors assumed that the droplet was heated instantaneously and uniformly.

Experimental studies [8,9] were performed using small droplets with a radius from 5 μm to 25 μm. The source of heating was a 10.6-μm laser pulse. These experiments mainly focused on estimating the energy balance of the process under study and studying the disturbance waves arising from the explosive vaporization of a liquid, as well as expansion rates of the heated air. According to experimental results [9], the pulsed laser heating (with a radiative density up to 10 MW/cm$^2$) of $\sim$20-μm drops caused vaporization at the front surfaces followed by the explosive boiling at the rear surfaces. In contrast, smaller droplets less than 12 μm in radius are heated throughout their entire volume. Experimental data [9] are in good agreement with theoretical results [10], which also introduced a criterion of the explosive vaporization of the droplet. Under this criterion, the density of the absorbed power should be higher than the pressure caused by the surface tension of water.

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**Nomenclature**

| | |
|---|---|
| $C$ | heat capacity, J/kg K |
| $h_g$, $R_g$ | height and radius of the graphite substrate of cylindrical shape, mm |
| $h_s$, $R_s$ | height and radius of the plastic cuvette of cylindrical shape, mm |
| $(L–\delta)$ | water film thickness ($L–\delta = 0.001$ m) |
| $q$ | infrared radiation flux at the surface of water film ($\sim$0.7 kW/m$^2$) |
| $T$ | temperature, K |
| $t$ | time, s |
| $T_{wg}$ | water film temperature in the experiments with the graphite substrate, K |
| $T_{ws}$ | water film temperature in the experiments with the plastic cuvette, K |
| $T_g$ | surface temperature of the graphite substrate, K |
| $T_s$ | temperature of the plastic cuvette bottom, K |
| $V_0$ | initial water volume in the cuvette, μl |
| $x$ | coordinate, m |
| $\delta$ | thickness of the graphite substrate ($\delta = 0.001$ m) |
| $\rho$ | density, kg/m$^3$ |
| $k$ | thermal conductivity, W/m K |

*Indices*

| | |
|---|---|
| 1 | graphite substrate or cuvette bottom |
| 2 | water film |

In [11], the author describes the main parameters affecting the heating and, consequently, the explosive vaporization of a fluid. Primarily, among these were the wavelength and intensity (density) of radiation as well as the size of water droplets. Study [11] reports that most of the theoretical research into the radiative heating and evaporation of water droplets do not take into account the inhomogeneity of distribution of the energy absorbed by the fluid and, consequently, do not consider regions with the highest concentration of the energy in a droplet.

Up to date, one of the fullest descriptions of the theory of thermal radiation in disperse systems is given in monograph [12]. This study includes the discussion of such problems as the thermal radiation of two-phase combustion products in rocket engines, spectral radiative properties of advanced thermal insulations, microwave thermal radiation of disperse systems on the sea surface, and thermal radiation in a multiphase medium formed in the case of a hypothetic severe accident of a nuclear reactor. The authors developed the theoretical models mainly based on the Mie theory for the radiative properties of single particles and approximate methods for the radiation transfer in anisotropically scattering media. Research [13] analyzes if the radiative transfer theory is applicable for calculating the thermal radiation emitted by a spherical particle made from a semitransparent material. This investigation provides numerical examples for large particles, which illustrate the transition from the dominant radiation of the central region of the particle to the surface layer emission. Moreover, theoretical study [14] presents calculation results of a nonuniform distribution of the absorbed radiation power for typical polydisperse water-based aerosols and droplets of diesel fuel. This research also includes approximate analytical relations for the distribution of absorbed radiation power inside a particle.

In addition to the data on the influence of the radiative heat transfer on the explosive breakup of droplets of fluids, there exists a group of the experimental investigations dealing with the rapid phase transformations of the droplets when heated on hot substrates (for instance [15]). In these investigations, water droplets contained an insignificant amount of surfactant impurities. These surfactants, as experimental results show, contribute to reaching the conditions for the sharp explosion of a droplet levitating above the heating surface because of a stable vapor film under this droplet (the Leidenfrost effect). The sharp explosion of such a droplet occurs after a relatively long period of steady evaporation. Under identical experimental conditions, the lifetime of the water droplet is considerably shorter. In study [15], the authors believe that an increase in the lifetimes of a fluid in the experiments occurs due to the presence of a surfactant, sodium dodecyl sulfate.

For the first time, the explosive breakup of water drops containing opaque nonmetallic and metallic inclusions when heated in high-temperature gases above 800 K was described in [16,17]. In these experiments, high-speed video recording provides a detailed analysis of the evaporation behavior of water at the *solid/liquid* interface under the condition that this interface accumulates thermal energy. The authors of [16,17] assume that the explosive fragmentation of water drops with inclusions occurs owing to the infrared radiation transmitted through the water film and because the inclusion surface is heated above water temperature in the drop. According to this assumption, such heating leads to water boiling at the *solid/liquid* interface. In this case, vapor bubbles nucleate, grow, and coagulate. Then, the heterogeneous drop is filled with vapors. When each vapor bubble begins to collapse, the fragmentation of water film occurs. As a result, a group of droplets containing vapor microbubbles is formed. However, according to [18,19], water is generally almost opaque to infrared radiation. Nevertheless, there are opposite opinions, namely [20,21].

Thus, it is fair to assume that the presence of an impurity in water influences the characteristics of its phase transformation. Phase transformation scenarios become difficult to predict. In other words, without experimental data on the evaporation of droplets of heterogeneous liquids it is impossible to predict precisely which mode of phase transformations will occur: the explosive breakup of the droplets, their convective evaporation, or a moderate vaporization at their internal interfaces during an intensive high-temperature heating [16,17]. It is necessary to note that the conclusions mentioned above, for instance, in studies [1–11], were drawn based on classical concepts about the intensive evaporation of a homogeneous fluid, water in particular, in the case of the domination of radiative heating. It is difficult to use them in respect of the heterogeneous droplets for a range of reasons. Primarily, the presence of the impurity in water, as a rule, influences not only its optical and thermophysical properties, but also molecular ones. However, as noted in [11], the main parameters that affect the heating and explosive breakup of the droplets, i.e. the wavelength and radiation density, as well as droplet size, are general and typical of investigations with the heterogeneous water droplets.

Since 1970–80s studies of the optical properties of water have been instrumental for calculating the passing of radiation through layers of atmosphere containing droplets of water and other aerosols of various dispersity, as well as oceans, which are actually hydrosols (i.e. colloidal systems) [20]. As a result, such sciences as meteorology, hydrology, hydrometeorology, hydrophysics, hydrometry significantly evolve. At the same time (1970–80s),