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Using Planar Laser Induced Fluorescence to explain the mechanism of heterogeneous water droplet boiling and explosive breakup

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ABSTRACT

Over the recent years, the research community has taken an increasing interest in high-temperature gas-steam-droplet systems. This promotes emerging technologies in thermal or flame water cleaning from unspecified impurities, and firefighting by water slurry aerosols. Unfortunately, these technologies have yet to become mainstream, although they have been regarded as extremely important and promising for several years already. The fact is that there are too few experimental data on the physical processes intensifying the evaporation of water slurries in hot gaseous media. The results of such experiments with temperatures over 1000 °C are virtually impossible to find. These data are so evasive due to fast-paced processes and difficulties in measuring the temperature in evaporating heterogeneous water droplets. The typical durations of high-temperature heating and evaporation do not usually exceed several seconds. In this work, we conduct experiments using a heterogeneous water droplet with a single nontransparent solid inclusion to determine the unsteady temperature field of the latter. We use an optical diagnostic technique, Planar Laser Induced Fluorescence, to study the conditions, mechanism, reasons and characteristics of water boiling leading to an explosive breakup (disintegration) of water slurry droplets. Rhodamine B acts as a fluorophore. The typical temperatures are determined in the depth of a droplet, near its free (outer) surface, and at the interface. The water temperature at the water – solid inclusion interface is shown to be higher than at the outer surface of a droplet. Furthermore, we compare the temperature fields of a homogeneous and heterogeneous water droplet under identical heating conditions.

1. Introduction

Water slurries are widely used for extinguishing fires of different complexity [1–3]. Adding solid nontransparent particles (of clay, sand, silt, soot, etc.) to water intensifies the suppression of flaming combustion and thermal decomposition of various materials. Adding solid particles to water provides different fire suppression mechanisms [1–3]. Water slurries and specialized solutions may have fire-retardant, wetting and other capacities necessary for effective fire extinguishing.

Volkov et al. [4] present an approach to producing water slurries with fine solid particles to enhance vaporization in the flaming combustion zone. The rates of heating and evaporation of water slurry droplets are shown to be much higher than for homogeneous water droplets without solid particles [4]. Consequently, the temperature in the combustion zone lowers significantly faster in the experiments with water slurries [4]. The authors also formulate a hypothesis [4] that with a particular concentration of solid particles in heterogeneous droplets, water may overheat significantly, reaching the values above the water boiling temperature. In these conditions, the droplet surface transforms considerably and the droplets disintegrate to produce a cloud of much smaller droplets than the initial ones. Unfortunately, the authors failed to confirm this hypothesis when injecting water slurry aerosol into the flame [4].

To develop the insights in [4] and to substantiate the above-mentioned hypothesis, Kuznetsov et al. [5] studied experimentally the heating and evaporation of a single water droplet with a solid nontransparent particle in a flow of high-temperature combustion products. Similarly to experiments in [4], the authors used two types of inclusions in [5]: carbonaceous and graphite particles. A size of droplets (i.e. their mean diameters) ranged from ~3 mm to ~5 mm. The one water droplet of 5 µl, 10 µl or 15 µl in volume contained a single inclusion of defined shape (sphere, disk, cone, parallelepiped or polyhedron) with a size from ~2 mm to ~4 mm [5]. Note that a droplet of water fully covered the inclusion. Experiments in paper [4] were carried out using the water droplets ranging in size from ~1 mm to ~5 mm containing the inclusions with a size from ~0.05 mm to ~0.5 mm at a weight concentration from 0 to 0.01. The hypothesis of possible explosive breakup of a heterogeneous water droplet when moving through a high-

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temperature gaseous medium [4] was confirmed [5]. The research [5] shows that solid particles with a high infrared absorption coefficient included in droplets make the liquid heat up more rapidly. This leads to the formation and further growth of vapor bubbles at the inner (inclusion-water) and outer (gas-water) interfaces. Vapor bubbles rapidly fill the heterogeneous droplet. Due to higher vapor pressure within the droplet as compared to the surface tension pressure, the heterogeneous droplet breaks up into a large group of smaller droplets. Thus, the water evaporation surface area increases severalfold and occasionally even more than ten times [5]. This process lasts for 1–3 s and the videographed images [5] remind of droplet explosion. With this in mind, the authors [5] used the term *explosive breakup* to denote the rapid evaporation and boiling of a droplet followed by its overheat and destruction.

Presumably [5], vapor bubbles alter the conditions of convective, conductive, and radiative heat transfer in heterogeneous droplets. In particular, liquid and vapor partially absorb the radiative heat flux, which heats the inclusion surface. The temperature of this surface exceeds the boiling temperature of the liquid. The authors developed physical and mathematical models [5] to forecast the temperature fields of water droplets before their breakup. No experimental data, either confirming or disproving these conclusions [5], have been obtained so far on the temperature fields of heterogeneous droplets of water slurries. It is extremely difficult to make such measurements even using fast-response miniature thermocouples, since thermocouples may significantly affect the heating and, therefore, the temperature field of a liquid, slurry, solution, or emulsion droplet. Thus, measuring the temperature of an evaporating heterogeneous droplet of water requires contactless methods.

The recent years have seen the rapid development of optical methods of high-speed measurement used to obtain key parameters of gaseous, fluid and even heterogeneous media [6], such as temperature, speed, consumption, particle size, concentration, etc. Such contactless methods include Particle Image Velocimetry (PIV) [7], Particle Tracking Velocimetry (PTV) [8], Stereo Particle Image Velocimetry (Stereo PIV) [9], Interferometric Particle Imaging (IPI) [10], Shadow Photography (SP) [11], Planar Laser Induced Fluorescence (PLIF) [12], and Laser Induced Phosphorescence (LIP) [13]. PLIF is the method of choice to determine the unsteady temperature field of an evaporating heterogeneous droplet of water. In [14–17], the authors outline the key benefits and barriers to the use of PLIF when determining the temperature fields of liquids. Study [17] reports the main stages of water droplet temperature measurement with using the PLIF technique. This technique is based on a natural laser-induced fluorescence of molecules of an organic dye (fluorophore). Dye concentration is taken to be rather small, and, therefore, during passing the light through a solution, a reduction of its intensity can be neglected. For some dyes, the quantum yield depends on temperature. This property allows measuring instantaneous temperature distributions in a flow. To illuminate the cross section of stream during field measurements, the pulse laser is used to form the light sheet. Since the fluorescence occurs at higher wavelength than the absorption, then the light emitted by dye is separated from the laser radiation by color filter and recorded by digital camera. When using the PLIF technique, experiments are performed, as a rule, according to the three stages. *The first stage* includes the recording of a series of the background images, i.e. without laser emission. The averaging of a series allows removing background noise. The one series consists of 100 images. The mean background image is obtained after averaging these images. When changing background illumination with time it is necessary to record the background before each series of measurements. *The second stage* is a recording of the images for several given working fluid temperatures constant throughout measuring area, i.e. *the second stage* is a calibration. Given temperatures cover all a temperature range within the measuring area during the experiment. To plot the calibration curve to a high precision, it is recommended to measure not less than the five values of temperatures. For each temperature, by analogy with the previous stage, the series of images is recorded, and then it is averaged. *The third stage* is a measuring. All the described operations should be performed without changing laser and camera parameters, under the constant properties of the working area and fluid, background illumination, relative position of devices and the working area.

The preliminary analysis has shown that using PLIF for measuring the temperature field of an evaporating droplet will provide the missing experimental information on the temperature gradient from the center to the surface of a droplet as well as from the latter to the *inclusion – liquid* interface. This information will help to substantiate or adjust the conclusions in [5] on the physics of overheat, boiling, and explosive breakup of heterogeneous water droplets under high-temperature heating. Reliable experimental data will make it possible to develop adequate physical and mathematical models. These, in turn, may change the current perceptions of the optical properties of liquids (e.g., water and water-based solutions [18,19]) under heat exchange with a radiating gaseous medium.

Experimental results [17,20,21] support the applicability of contactless optical techniques for solving research tasks with the intense heating-up of the heterogeneous water-based suspensions. In particular, study [21] offers solutions of the two main problems of imaging two-phase flows by Laser Induced Fluorescence (LIF): the large fluorescence intensity difference between the two phases and the subsequent effect of halation. In this case, the problems are solved by using the LIP technique eliminating any halation interference at the *liquid-vapor* interface. Thus, this boundary is clearly visualized during the phase transformation. Moreover, by calibration of the vapor phase phosphorescence signal, *Charogiannis and Beyrau* [21] measured the vapor concentration around an evaporating droplet stream. The vapor profiles obtained by using LIP are in good agreement with those found in the literature. Note that in study [21], the LIF measurements significantly overpredict the estimated values of acetone vapor concentration near the interfacial boundary. However, under such conditions the LIP technique also has some limitations of which the most critical one is an applicability in oxygen-free environments only. Even trace quantities of oxygen fully quench the vapor phase phosphorescence emission. Markides et al. [20] simultaneously applied the PLIF technique and infrared thermometry to study unsteady conjugate heat transfer in harmonically forced liquid film flow falling under the action of gravity over an inclined heated-foil substrate. This approach allowed them to estimate the liquid film thickness, film free-surface temperature, temperature on the interfacial *substrate – liquid film* boundary, local/instantaneous heat fluxes. Based on the obtained data, local and instantaneous heat-transfer coefficients were found. Note that the computational results revealed significant heat transfer enhancement relative to steady-flow predictions in the thinner film regions. Thus, it is necessary to pay attention to the numerous benefits of mentioned optical techniques and their applicability for phase transformation study of fluids when heated.

Experimental information on patterns of heat and mass transfer in heterogeneous water droplets under high-temperature heating will enable us to not only vary the parameters of firefighting systems in a wider range but also make thermal liquid purification more effective. The latter consists in the evaporation or burning of impurities. Other applications are also possible, e.g., defrosting of loose media by gas-vapor-droplet flows, cleaning of power engineering equipment surfaces by gas-vapor-liquid mixtures, as well as production of power-efficient heat carriers based on flue gases and vapor-droplet mixtures. All these technologies require knowledge of the characteristics of high-temperature heating and evaporation of heterogeneous droplets of solutions, slurries, and emulsions. The same data are necessary on the evaporation of liquid fuel droplets [22].

The purpose of this work is to determine experimentally, using an optical diagnostic technique, the temperature fields of heterogeneous droplets under high-temperature heating.