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Temperature and velocity fields of the gas-vapor flow near evaporating water droplets

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ABSTRACT

Experimental studies of unsteady temperature and velocity fields of the gas-vapor flow in the immediate vicinity of evaporating water droplets were performed in the interests of developing high-temperature (over 300°C) gas-vapor-droplet applications. The formation time of virtually homogeneous (temperature variations of under 2–3°C) temperature fields of evaporating water droplets was established using Particle Image Velocimetry, Laser Induced Phosphorescence, Planar Laser Induced Fluorescence. We observed highly inhomogeneous and unsteady temperature and velocity fields of the gas-vapor mixture and determined the lateral and transversal dimensions of the aerodynamic and thermal traces of evaporating water droplets. The degree of impact of several parameters on the latter was evaluated: initial temperature (20–500 °C) and velocity of the incoming flow (0.5–5 m/s), as well as the initial droplet size (1–2 mm). The role of evaporation and convective heat exchange between a droplet and gases in forming of thermal and aerodynamic trace was analyzed. The heat flow density was found to vary nonlinearly with time (in the immediate vicinity of an evaporating droplet), and the impact of droplet trace temperature and velocity on the heat flow density was evaluated. Both advantages and limitations of the used techniques are established in terms of reliable plotting of unsteady temperature and velocity fields of gas-vapor mixture in the trace of evaporating water droplets, considering the heating lag of the latter.

1. Introduction

Convective heat exchange of liquid, solution, emulsion, and slurry droplets moving in gases have been studied extensively for many years [1–6]. The high interest in the topic comes from a wide range of practical applications in two-phase and heterogeneous systems. Particularly complicated and yet the most interesting to study are the high-temperature (300–1200°C) gas-vapor-droplet applications: thermal and flame water cleaning from unspecified hard and liquid impurities; production of hydrogen and syngas with the required component composition by heating wet condensates; production of heat carriers based on flue gases, vapor, and water (waste-heat recovery); thermally loaded surface treatment and cleaning; defrosting of loose media by gas-vapor-droplet flows; firefighting using water mist and polydisperse flows of water slurries and emulsions. Traditionally, one of the main tasks in experimental and theoretical studies (e.g. [1–6]) of heat and mass transfer near the *liquid – gas* interface is the analysis of convective heat exchange or phase changes. This kind of studies is crucial for finding the energy-efficient conditions of heat and mass transfer in all of the applications mentioned above. It is difficult to conduct reliable experimental measurements at high temperatures of the gas (over 300°C) due to rapid droplet heating and vaporization (complete evaporation time can be as short as several seconds). At such conditions, the droplet surface distorts and transforms substantially, with a possibility of boiling and breakup [7]. This is the reason why there are still no adequate models of high-temperature heat and mass transfer that could be used to reliably evaluate the convective heat exchange or phase change when determining the thermal balance at the *liquid – gas* interface. To solve this problem, it is reasonable to develop an experimental technique for measuring at least the basic parameters (vapor temperature and velocity) near the interface by visual tracing [8]. There have been several attempts to develop such a technique over the past several years. For instance, some experimental studies [9–11] can be mentioned, where optical recording techniques were used to evaluate the droplet temperature field, water vapor concentration, convective flow velocity, and other parameters. The requirements for measurement instruments are strict in terms of speed, since the temperature grows exponentially near the interface, while the events to be recorded are only a couple of seconds to last. The video capture resolution also has to be high enough to provide for the adequate analysis

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of the interface position variation over time.

High-temperature heating may lead to the generation of a buffer vapor layer near the *liquid – gas* interface, decreasing the heat flow from the gases to the droplet surface [12–14]. This buffer layer appears due to the rapid generation of water vapor that is cold (maximum temperature is equal to that of boiling water) in comparison to the incoming gas flow [12]. When the distance between droplets is shorter than their typical size, water vapor ejected from the surface of one droplet will significantly affect the temperature near the surface of other droplets. This conclusion is based on the results of thermocouple measurements [13,14]. However, in many scenarios, a significant inhomogeneity and instability of temperature fields near the *liquid – gas-vapor mixture* interface is evident. Experimental study would require several dozens of thermocouples, and each will interfere significantly with the temperature of the generated gas-vapor mixture, being a heat sink. Using non-contact optical techniques and high-speed video capturing instruments may become a reasonable solution to this problem.

It is only viable to use Particle Image Velocimetry (PIV) [15] and Laser Induced Phosphorescence (LIP) [16] to study the velocity and temperature fields of the gas-vapor mixture around a water droplet. To reliably analyze the thermal conditions of the interaction between the gas flow and evaporating droplet, we need to study the unsteady temperature field of the latter. For that we can use Planar Laser Induced Fluorescence (PLIF) [17]. A combination of PIV, LIP and PLIF allows us to evaluate the impact of convective heat exchange and vaporization on the generation of thermal and aerodynamic traces of evaporating water droplets. It is particularly important to carry out this analysis for the gases temperature of over 300 °C. The upper limit of the gas temperature range should be defined based on the complete droplet evaporation time and the limitations of PIV, LIP and PLIF techniques in terms of speed and accuracy.

The purpose of this research is to experimentally evaluate the unsteady temperature and velocity fields of gas-vapor flow near the evaporating water droplets, using PIV, LIP and PLIF techniques.

2. Experimental setup and procedure

2.1. Scheme and elements of the setup

Fig. 1 shows the scheme of the experimental setup used in our study. All the main elements can be divided into two groups: *technical*: elements required to maintain the defined operating conditions – air flow temperature and velocity, seeding density of tracer particles, relative positions and dimensions of droplets under study; *instrumental*: hardware and software required for PIV, LIP and PLIF measurements.

The *technical* group consisted of an air heater, fan, compressor, voltage converters, and a motorized manipulator. The air heater was a 1-m high hollow ceramic cylinder (60 mm in outer diameter and 52 mm in inner diameter), with six independent coils of 0.3 mm nichrome wire located on its exterior, one coil per 0.2 m of the ceramic tube. The overall maximum consumed power of nichrome coils was 9 kW. Nichrome coils were thoroughly braided on the outside with a 5-mm diameter nonflammable asbestos rope to avoid heat loss. The air flow was generated by the air fan, attached to the lower end of the heater tube by the aluminum corrugated pipe. The air flow velocity U_a inside the cylinder ranged from 0.5 to 6 m/s. A monophase thyristor controller Shuft SRE 2.5 was used to adjust the air fan rotation rate. The air velocity was measured using PIV [15]. The air flow temperature (T_a) at the exit of the heater (the upper opening of ceramic tube) was varied from 20 to 500 °C by controlling the voltage on nichrome coils in the range of ~50–250 V. Two laboratory-grade step-down voltage converters were used (Fig. 1), with three coils of the heater connected parallel to the output of each one.

An air compressor (24 l reservoir, 1.2 MPa maximum pressure) was used for seeding the air flow with tracer particles. The type of particles is dependent on experimental conditions described in subsections 2.2 and 2.3. Tracer particles were placed into an elbowed input duct of the air fan (tracer placement is shown in Fig. 1). Next, the air from the compressor under the pressure of 200 kPa was fed to the air fan input for 5 s, so that all the tracer particles were completely injected into the air flow. The mass of the tracer particle batch injected into the air flow was approximately 1.5 g for each burst. This is the experimentally defined mass, sufficient for uniform seeding of the air flow. Each experiment involved 2–3 consecutive bursts. At a distance of 100 mm from the upper portion of the heater, an air extraction duct was placed, 150 mm in diameter, provided with a fine-mesh filter, able to absorb particles as small as 0.1 μm. Thus, the heated air flow from the heater was collected by the extraction fan, and the tracer particles were absorbed by the filter.

To generate a droplet of the required volume, we used a Finnpipette Novus dispenser with a pitch variation of 0.1 μl. The initial droplet volume V_d varied from 5 μl to 25 μl. This corresponded to the variation of the initial droplet radius R_d from 1 to 2 mm. A water droplet was attached to the tip of the holder – a steel wire 0.8 mm in diameter. The holder was a hollow cylinder with the wall thickness of 0.1 mm. Before selecting the material for the holder, we conducted some trial experiments with solid bars made of copper, aluminum, and ceramics, as well as a hollow steel bar. The experiments showed that, with the same droplet and holder contact area, the longest droplet evaporation times are typical of hollow metal and ceramic holders, with a difference of 1–3%. For an aluminum holder, the evaporation times were 15–18% shorter and for a copper one, 35–40% shorter. Thus, in further experiments, we chose to use a hollow metal holder, as its impact on droplet heating and evaporation is minimum. A ceramic holder was not an option, because the material is brittle: when heated to high temperatures, the holder developed cracks in the area of rapid water evaporation.

The holder was fixed to a 4 mm diameter copper tube section attached to the motorized manipulator mount. The manipulator was controlled via the Motomaster software to provide the positioning of the droplet in the hot air flow. After the droplet was attached to the holder, it was introduced into the hot air flow zone. The speed of the droplet positioning into the observation area was 0.15 m/s. When the droplet was positioned on the central axis of the ceramic cylinder heater, 30 mm above its upper opening (Fig. 1), the manipulator stopped. The experimental observation area was located in the upper part of the setup, including the space from the ceramic heater output to the air extractor. After that, we determined the characteristics of aerodynamic and thermal traces.

The *instrumental* group of the setup consisted of three cross-correlation digital cameras, two solid-state Nd:YAG lasers, thermal voltage converters, analog input module for thermal sensors scanning and sending a temperature signal to a PC, as well as software to manage the measurement tools. Solid-state Nd:YAG lasers were supplied with optical collimator to transform a laser beam into a planar light sheet and were mounted in the upper portion of the experimental setup (Fig. 1), so that the air flow would be scanned vertically. The section of the light sheet was located directly on the central axis of the droplet positioned in the air flow. The optical axis of the recording CCD cameras was directly perpendicular to the light sheet plane. Two chromel/alumel thermocouples with a temperature range of –50–1200 °C, systematic error ± 3 °C, and response time no more than 0.5 s were used for temperature measurement. Thermocouples were positioned in two locations on the central axis of the ceramic heater, at a height of 10 mm and 90 mm from its upper opening. This way the mean temperature of the air flow was registered for the whole observation area. Thermocouple readings were transferred to and stored on a PC via the analog input module. The maximum random error of the air flow temperature measurement did not exceed 15 °C. All the details on the instruments involved, experimental techniques used, and experimental data processing methods are given further in sections 2.2–2.4.