Heating and evaporation of suspended water droplets: Experimental studies and modelling

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1. Introduction

The importance of experimental studies and modelling of droplet heating/cooling and evaporation in engineering and environmental applications is well known [1–4]. The experimental studies of these processes have mainly focused on the application of non-intrusive laser-based techniques such as Particle Image Velocimetry (PIV) [5], Stereo Particle Image Velocimetry (Stereo PIV) [6], Interferometric Particle Imaging (IPI) [7], Laser-Induced Fluorescence (LIF) [8], Particle Tracking Velocimetry (PTV) [9], Shadow Photography (SP) [10], and Laser Induced Phosphorescence (LIP) [11]. High-speed video-recording allows one to study these processes with a high level of time resolution [12,13]. An approach to estimating the droplet evaporation rate has been described in [19]. Among previously-mentioned technical approaches, LIF can be used to measure the temperature of heated and evaporating droplets [11,14]. In particular, a two-colour version of LIF, based on the detection of the fluorescence signal on two separate spectral bands, was devised to measure the volume-average temperature of droplets in monodisperse streams [17] and sprays [38]. In [15,18], this approach was extended to the characterisation of the temperature distribution inside moving droplets, which highlighted the importance of internal liquid transport and the Marangoni effect in the heating process of combusting droplets [16].

Experiments on the heating and evaporation of droplets have focused either on stationary droplets supported by fibres [20] or on tandem of droplets [21]. These experiments are essentially complementary. The main difficulty in interpreting the first set of experiments is in the need to model the effects of fibre, while in the case of the second set of experiments the effects of interaction between droplets need to be accounted for [18].

One of the most advanced modelling approaches to the analysis of droplet heating and evaporation is based on the Abramzov and Sirignano model [22] for the gas phase and the analytical solutions to the heat transfer and species diffusion (in the case of multi-component droplets) equations for the liquid phase [3,4]. In contrast to most models used in commercial and in-house Computational Fluid Dynamics (CFD) codes, the effect of thermal radiation on droplet heating and evaporation has been considered not as a surface but as a volumetric processes [23]. Most of the models have been based on the assumption that droplets are...
This setup is designed to perform PLIF with the aim of measuring engineering and environmental application is anticipated. Fire extinguishers, although their relevance to a wider range of applications is anticipated, is primarily used in designing efficient water-based systems. The results of these investigations are expected to be primarily used in designing efficient water-based systems. The results of these investigations are expected to be primarily used in designing efficient water-based systems.

The temperature field inside suspended droplets, which are heated by forced convection. The experiment was performed inside a transparent, heat-resistant (up to a maximal temperature of 1800 °C) cylindrical quartz pipe. The height of the pipe was 0.3 m, while its inner diameter and thickness were 0.1 m and 2.5 mm, respectively. Three holes were drilled in the wall of the cylindrical pipe at the same height and at relative angles of 90°, in order to insert a droplet, to illuminate it by a laser and to take photographs/images. A flow of heated air was produced by the air heater (Leister LE-5000 HT; range of temperatures 50–1000 °C) and the air blower (Leister CH-6060; air velocities in the range 0–5 m/s). The air heater was connected to the lower part of the quartz pipe via a metallic pipe, in which a fine metallic net (with cell size 0.7 mm) was inserted to generate grid turbulence and eliminate possible swirls. This ensured that the flow remained uniform. To control the air flow temperature, a type K thermocouple was placed inside the quartz pipe in the vicinity of the water droplet. It was shown that the deviations of this temperature from preset values of the air flow generated by air heater and blower did not exceed 5 °C.

PIV was used to characterise the air flow in the quartz pipe [5]. Our approach is similar to the one described in [28, 10] in terms of sizes of trace particles, geometry of the measurement volume, configurations of the injection of trace particles, and the optics used. TiO₂ particles sized between 0.5 and 5 μm were used to follow the gas motion. To prevent particle clustering, the TiO₂ powder was dried in a 'Nabertherm' muffle tubular furnace at temperature 100 °C for 150 min. TiO₂ particles were injected into the flow. Using an air compressor, trace particles were injected into hot air. The flow was illuminated using a double impulse Nd:YAG laser Quantel EverGreen 70 (@532 nm, 10 Hz repetition rate, 30 mJ pulse energy). PIV images were captured by an ImperX IGV-B2020M camera (2048 × 2048 pixels, 20 fps, 8 bits).

2. Experimental setup and measurement technique

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A general view of the experimental setup is presented in Fig. 1. This setup is designed to perform PLIF with the aim of measuring the temperature field inside suspended droplets, which are heated by forced convection. The experiment was performed inside a transparent, heat-resistant (up to a maximal temperature of 1800 °C) cylindrical quartz pipe. The height of the pipe was 0.3 m, while its inner diameter and thickness were 0.1 m and 2.5 mm, respectively. Three holes were drilled in the wall of the cylindrical pipe at the same height and at relative angles of 90°, in order to insert a droplet, to illuminate it by a laser and to take photographs/images. A flow of heated air was produced by the air heater (Leister LE-5000 HT; range of temperatures 50–1000 °C) and the air blower (Leister CH-6060; air velocities in the range 0–5 m/s). The air heater was connected to the lower part of the quartz pipe via a metallic pipe, in which a fine metallic net (with cell size 0.7 mm) was inserted to generate grid turbulence and eliminate possible swirls. This ensured that the flow remained uniform. To control the air flow temperature, a type K thermocouple was placed inside the quartz pipe in the vicinity of the water droplet. It was shown that the deviations of this temperature from preset values of the air flow generated by air heater and blower did not exceed 5 °C.

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