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

P.A. Strizhak [a], R.S. Volkov [a], G. Castanet [b], F. Lemoine [b], O. Rybdylova [c], S.S. Sazhin [c,*]

[a] National Research Tomsk Polytechnic University, 30, Lenin Avenue, 634050 Tomsk, Russia
[b] Université de Lorraine, CNRS-UMR 7563, CS 25233, France
[c] Sir Harry Ricardo Laboratories, Advanced Engineering Centre, School of Computing, Engineering and Mathematics, University of Brighton, Brighton BN2 4GJ, UK

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ABSTRACT

The results of a series of experiments focused on investigation of the heating and evaporation of suspended water droplets in a hot air flow (at temperatures up to 800 °C) are described. The temperatures inside droplets were estimated based on Planar Laser-Induced Fluorescence (PLIF) imaging. The advantages and limitations of this method are investigated. Typical distributions of temperatures inside droplets at the initial stages of their heating and evaporation are presented. These distributions at various cross-sections are compared. They are shown to be strongly inhomogeneous during the whole period of observation. A new model for heating and evaporation of a suspended droplet, taking into account temperature gradient and recirculation inside the droplet and the effect of a supporting rod, is suggested. It is assumed that the heat transferred from the rod to the suspended droplet is homogeneously distributed inside the droplet; its effect is modelled similarly to the effect of external thermal radiation, using the previously developed model for droplet heating in the presence of this radiation. It is shown that a reasonable agreement between the model predictions and experimental data can be achieved if the reduction of the ambient gas temperature due to the presence of an evaporating droplet is taken into account. The effect of the rod on droplet heating is shown to be most significant for ambient gas temperature equal to 100 °C and becomes negligibly small when the gas temperature reaches 800 °C.

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 Abramzon 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

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* Corresponding author.
E-mail address: s.sazhin@brighton.ac.uk (S.S. Sazhin).

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Nomenclature

$B_{M(T)}$	Spalding mass (heat) transfer number
c	specific heat capacity
d_h	diameter of the rod
D	diffusion coefficient
f	function introduced in Eqs. (18) and (19)
h	convection heat transfer coefficient
h_0	parameter introduced in Eq. (9)
k	thermal conductivity
L	specific heat of evaporation
Le	Lewes number
$\dot{m}''_d$	evaporation mass flux
Nu	Nusselt number
p_n	parameter introduced in Eq. (8)
P	source term in Eq. (4)
Pe	Peclet number
Pr	Prandtl number
q	heat rate
$\dot{q}_d$	heat spent on rising droplet temperature
q_n	parameter introduced in Eq. (8)
R	distance from the droplet centre
R_d	droplet radius
Re	Reynolds number
Sc	Schmidt number
S_c	contact area of the droplet and the rod
Sh	Sherwood number
t	time
T	temperature
U	velocity
υ_n	eigenfunctions
V_d	droplet volume
Y	mass fraction

Greek symbols

κ	thermal diffusivity
κ_R	parameter introduced in Eq. (8)
λ_n	eigenvalues
μ_0	parameter introduced in Eq. (8)
ρ	density
χ	coefficient defined in Eq. (3)

Subscripts

a	air
c	centre
d	droplet
eff	effective
l	liquid phase
p	constant pressure
s	surface
sup	support (rod)
total	total
v	vapour phase or per unit volume
0	value at the beginning of a time step or initial value
∞	ambient

Superscripts

$*$	modified Sherwood or Nusselt number
—	average

spherical; some attempts to generalise the previously developed models to non-spherical droplets are described in [24].

This study focuses on the effect of convective heating of water droplets. Planar Laser-Induced Fluorescence (PLIF) will be used to characterise the temperature inside the droplets. In parallel, previously developed modelling tools [3,4] will be adapted to the specific configuration encountered in the experiments, i.e. a stationary droplet suspended from hollow fibres (rods). In contrast to the models described in [3,4], in the model described in this paper, the effect of these rods will be taken into account. The effect of radiative heating of droplets will be ignored at this stage, as the ambient gas temperature in our experiments did not exceed 800 °C, with maximal temperatures of the walls of the enclosure being even less than this. As shown in our previous papers (see [3] and the references therein), the effects of radiative heating for these ambient gas and external wall temperatures are expected to be small for Diesel fuel droplets [3]; one would expect a similar conclusion for water droplets. Transient temperature fields of evaporating droplets for various ambient gas temperatures and velocities and initial droplet radii will be established experimentally and these experimental results will be compared with the predictions of the model. The results of these investigations are expected to be primarily used in designing efficient water based fire extinguishers, although their relevance to a wider range of engineering and environmental application is anticipated.

2. Experimental setup and measurement technique

2.1. Experimental setup and air flow measurement

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.

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. TiO_2 particles sized between 0.5 and 5 µm were used to follow the gas motion. To prevent particle clustering, the TiO_2 powder was dried in a 'Nabertherm' muffle tubular furnace at temperature 100 °C for 150 min. This ensured homogeneous seeding of trace TiO_2 particles 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)