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Distribution of thermal energy of child-droplets issued from an optimal micro-explosion

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ABSTRACT

The micro-explosion phenomenon is involved in emulsified fuel droplets placed in a hot atmosphere, such as spray combustion. Droplets of water-in-sunflower oil emulsion are used, since they are representative of a class of emulsions used in practical applications of biofuels. Once the micro-explosion is triggered after a short delay, the rapid (⩽1 ms) vaporization of the inside water droplets and the subsequent disintegration of the emulsion droplet blow the fragmented droplets away. These fragmented droplets are called "child-droplets", and they are too small and fast for an on-the-fly infra-red imaging thermal characterization. The present study focuses on the thermal reaction of a thin plate when impacted by them. Thorough and detailed tests are carried out, to make sure that the plate and the acquisition system are collecting a data that is actually representative of the child-droplets thermal energy. A quantitative post-processing is applied to the transient temperature field on the plate. It leads to the thermal energy of the whole plate, and of representative samples of individual child-droplets. The results show that their thermal energy is governed by a log-normal distribution.

1. Introduction

In the field of emulsified fuels, micro-explosion and puffing are well known [1,2] as phenomena within spray combustion enabling significantly lower pollutant emissions.

Within a water-in-oil (w/o) emulsion droplet, the onset of puffing and/or micro-explosion is governed by heat and mass transfer, including coalescence and phase change [3,4] concerning the inside water droplets. Experimental data is useful to validate models of the spray combustion of a water-in-oil emulsified fuel, including the micro-explosion or puffing phenomena [3]. Indeed, they have already been recorded by optical means within spray combustion, showing a decrease by half of the mean diameter of droplets, compared to a non-emulsified liquid fuel [5]. Among a spray of droplets, the statistical effect of individual puffing or micro-explosion is called the secondary atomisation [1,5,6].

When an emulsified fuel drop undergoes an intense heat transfer, evaporation or combustion initiate. Under atmospheric pressure, the inside water and the oily fuel have widely different boiling points. As a consequence, the inside water can reach a liquid metastable state, at a superheat temperature. At the end of the waiting time since the initial heating, a rapid (⩽1 ms [1,7]) vaporization is then triggered by bubble nucleation, breaking up the emulsion droplet into child-droplets (see Fig. 1). Watanabe et al. [6] classify the subsequent disintegration as puffing or micro-explosion: In the case of puffing, the expanding vapor breaks up a part of the emulsion droplet. In the case of micro-explosion, the whole emulsion droplet is suddenly blown away into child-droplets. The occurence of one of these two phenomena depends on the properties of the emulsified fuels such as the surfactant [3] or the water content, and also on the experimental conditions.

Numerous studies have been carried out to investigate the vaporization and burning behavior of individual emulsion droplets undergoing puffing or micro-explosion [3,8]. The fine wire support technique is a cornerstone of that. It has brought a large amount of data including the temperature of the emulsion drop [9]. Another technique [7,10] is to deposit the emulsion drop onto a concave heated surface, where it slides upon its own vapor by means of

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Nomenclature

Variable	*Meaning and dimension*
A or da	area (m^2)
Bi	Biot number (–)
Cp	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
D	diameter (m)
D_{32}	Sauter mean diameter (m)
e	thickness of the plate (m)
$e\%$	gap (%)
E	thermal energy (J)
E^*	non-dimensional thermal energy (–)
h	convective heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
L	flight path (m)
m	mass (kg)
Nu	Nusselt number (–)
P (–)	probability (–)
Pr	Prandtl number (–)
Re	Reynolds number (–)
S	heat source ($W\ m^{-3}$)
t	time (s) or (ms)
T	temperature (K) or (°C)
T_N	nozzle upstream temperature (°C)
V	velocity ($m\ s^{-1}$)

Greek symbols	
ΔT	temperature decrease (K)
Δ_{xy}	Laplace operator (–)
$\Delta(-)$	mean relative difference (–)
ϵ	emissivity (–)
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
∇	gradient (–)
ρ	density ($kg\ m^{-3}$)
σ	log-normal parameter (–)
σ_{SB}	Stefan–Boltzmann constant ($W\ m^{-2}\ K^{-4}$)
$\sigma(-)$	standard deviation (–)
σ_{w-o}	water/oil interfacial tension ($mN\ m^{-1}$)
μ	log-normal parameter (–)

Subscripts	
a	ambient (–)
Al	aluminum (–)
d	droplet (–)

the Leidenfrost effect. This enables the emulsion drop to avoid any contact with a solid surface promoting heterogeneous nucleation, and offers a good probability to observe a sudden, unique and total disintegration, i.e. a micro-explosion (Fig. 1).

Previous kinematic studies about micro-explosion of w/o emulsions [7] were focusing on the size, number and velocities of the child-droplets. The next step to understand micro-explosion is the thermal behavior of the child droplets, i.e. their distribution of temperature and thermal energy. Little effort has been made so far to closely investigate the distribution of thermal properties among the child-droplets. Their distribution of thermal energy is related to the initial emulsion temperature field and to the disintegration that quickly happens within the parent emulsion drop. IR imaging could be used to measure the temperature of the child droplets [11]. However, the thermal measurement of a droplet moving at a velocity of $8\ m\ s^{-1}$ is very difficult to be practiced on-the-fly, also in case of a droplet as large as 400 μm and when typical parameters can be considered [7] as well as simplifying hypothesis, like a homogeneous temperature of the droplet, are assumed.

In the present work, an adapted experimental set-up is designed in this purpose. It is called the Thin Plate System (TPS). It consists in a thin conductive sheet able to capture the heat contained in the flying child droplets. In this way, the dynamic problem of measuring the heat content of a moving group of particles is transformed in a static one consisting in the analysis of the instationary heat transfer on a fixed system. The transfer of the problem from space to time domain permits reliable utilization of static infra-red imaging. Experiments are carried out to check the ability of TP to deliver a reliable transient temperature field on both sides. Over many repetitions of a mechanically optimal micro-explosion, the temperature data is used to calculate the thermal energy of the individual child-droplets. The obtained distribution of thermal energy is calculated, and compared to a theoretical log-normal distribution. The results are finally discussed, related to the existing knowledge about this optimal micro-explosion.

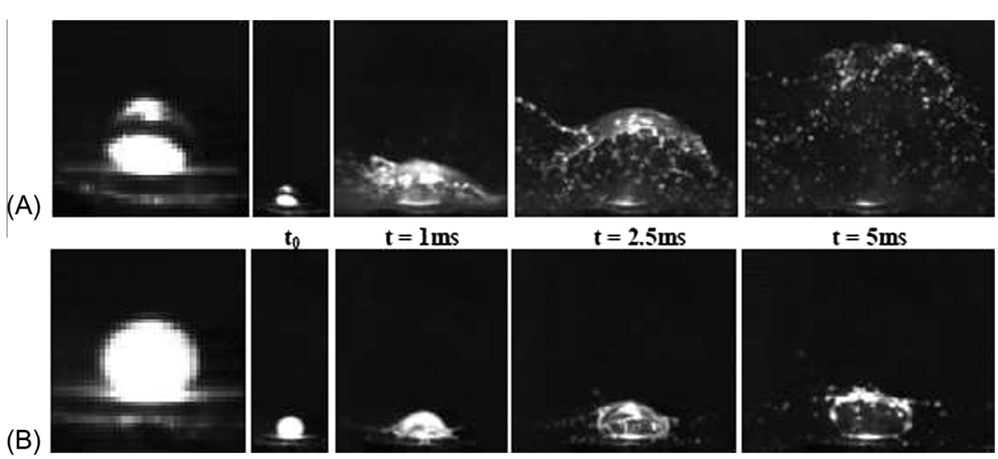

Fig. 1. Micro-explosion of two w/o emulsion droplets with diameter between 2.3 and 3 mm [7]: (A) D_{32} (H_2O) = 4.7 μm, (B) D_{32} (H_2O) = 17.4 μm. The emulsion droplet is undergoing Leindenfrost effect on a concave heated plate. The same experimental facility is used in the present study.