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The balance between surface and kinetic energies within an optimal micro-explosion

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ABSTRACT

Micro-explosion is caused by the sudden vaporization of water drops inside water-in-oil emulsion. Past studies have shown an optimal diameter for dispersed water. This optimal micro-explosion produces the largest number of secondary droplets, i.e. the largest interfacial area among the resulting spray. Such an increase in the interfacial area within the spray causes a better and less polluting combustion process. By using an infra-red camera, the present experiments can measure the size and planar velocity of secondary droplets issued from an optimal and also a non-optimal emulsion. The distributions of kinetic energy and surface energy among the spray are then calculated and discussed. Among the secondary droplets, it results that the optimal micro-explosion favors surface energy over kinetic energy.

1. Introduction

Micro-explosion of a fuel drop emulsified with a proportion of water [1] is due to the rapid (≤1 ms [2]) vaporization of the water phase, disrupting the emulsion drop into so-called “secondary droplets”, also referred to as child-droplets [3]. It is also called secondary atomization [4]. Evaporation duration of drops is considered as proportional to their squared initial diameter [5]. And drop vaporization is known as the rate-controlling factor in spray combustion, because it is the slowest phenomenon among many interconnected phenomena [6]. For these reasons, the decrease of diameter due to secondary atomization is a significant improvement for mass transfer and efficiency within a spray combustion [7]. Environmental improvements were actually recorded at the exhaust, especially concerning solid carbonaceous residue [8].

Mura [2] has found the existence of an optimum dispersion of water by investigating micro-explosion of individual emulsion drops (Fig. 1). Investigating this optimal micro-explosive behavior, Tarlet [3] found that its distribution of thermal energy among secondary droplets is log-normally distributed. The size of the inside water droplets exerts an influence on the observed coalescence, i.e. the separation of oil and water prior to a micro-explosion [2,9,10]. The middle-size water droplets are small enough to be heated for a long time, and large enough for efficient coalescence, hence referred to as the optimal.

The time from the beginning of heating to the micro-explosion is a few seconds, using oily fuel in the present experimental conditions [10]. The dependence of t he micro-explosion delay on both intrinsic and external parameters of the emulsion drop heating were experimentally investigated by Gollahalli [11] and compared to numerical results by Tarlet et al. [12].

In the timeline until micro-explosion, Shinjo [13] considers two successive steps: (i) phase separation during heating over a long time scale $O(1\,s)$, and (ii) boiling phase from the moment of rapid vapor growth by nucleation [14–17] which triggers disruption of the emulsion drop [18].

Using a simple experimental procedure, the present letter focuses on the distribution of mechanical energy of secondary droplets. These investigations are aimed at the energetic balance within the micro-explosion, at the moment of the disruption of the emulsion drop.

2. Experimental set-up

Fig. 2 shows the heated plate, that was used in past investigations [2,3,18]. The heated plate is a piece of aluminium that is 10 mm long, with a diameter of 5 mm. It is actually heated by a customized soldering iron regulating temperature at the value of

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1290-0729/

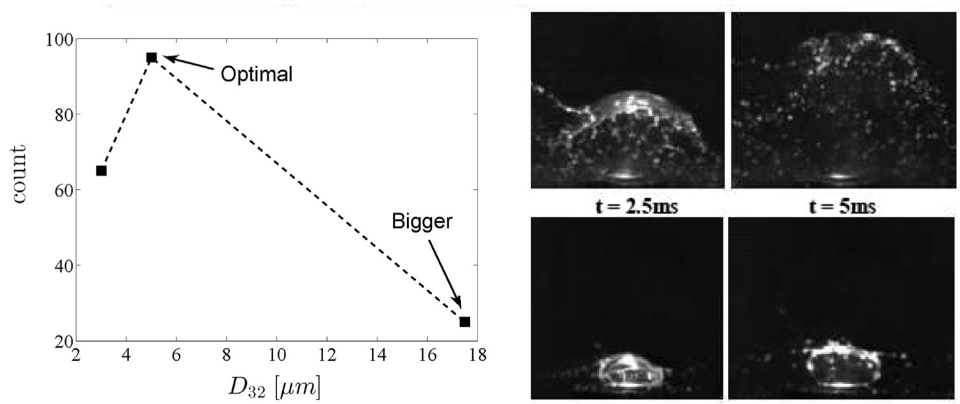

Fig. 1. On the left: the count of secondary droplets -reproduced from [2]- along the Sauter (D_{32}) mean diameter of inside water droplets under the same conditions as in the present work. An optimum of atomization was noticed for $D_{32} = 4.7$ μm. After a micro-explosion, the resulting secondary droplets were counted by means of an optical, fast camera, as can be seen in the photographs on the right. At the same instants (2.5 ms and 5 ms from micro-explosion), the top images are the optimal case, the bottom images are the non-optimal case with a worse atomizing behavior.

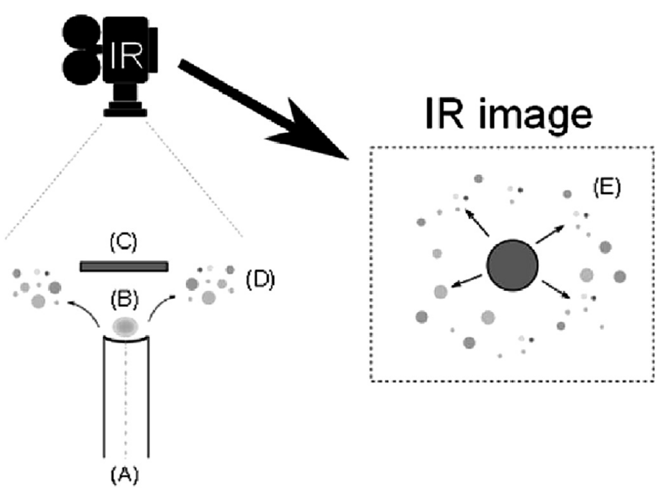

Fig. 2. Scheme of experimental set-up - (A) Heated plate, (B) Emulsion drop undergoing micro-explosion, (C) Infra-red opaque covering of the heated plate, (D) Launched secondary droplets in the field depth of the FLIR SC-7500 infra-red camera, (E) Scheme of the acquired Infra-red image.

375°*C*. A 12 μL emulsion drop (diameter 2.8 mm) is released on the top surface of the heated plate. The oily fuel is filtered sunflower oil, with physical properties detailed in Table 2. Viscosity was measured by a LAMY RM-200 rheometer, having 1% uncertainty and surface tension was measured by a KRÜSS K-12 tensiometer having 5% uncertainty. The emulsification process consists in: (i) First, mixing the SPAN 83 surfactant and the filtered sunflower oil during 2 min at a moderate rotating speed (50 rotations per minutes) in the stirrer; (ii) Secondly, with a higher rotating speed (400 rotations per minute) adding distilled water drop by drop using a syringe and keeping the mixer rotation during one hour. Once it is completed, this process ensures stability of the dispersed diameter during 50 min. The emulsion drops are picked up for micro-explosion during this time by a pipettor (VWR "Signature") with 3% volume accuracy.

The diameter of the dispersed water is measured by means of an optical microscope, with +/− 0.25 μm uncertainty and over a large enough sample. The emulsion with a Sauter mean diameter of dispersed water $D_{32} = 5$ μm is called the optimal one [2], and another with $D_{32} = 10$ μm is called the bigger, i.e. non-optimal one. "Optimal" here means producing the largest number of secondary droplets, i.e. mechanically optimizing the disintegration of the emulsion drop (Fig. 1). The micro-explosion is considered as optimal in this case, because the initial diameter of the emulsion drop is 2.8 mm, as it was tested by Mura et al. [2]. In the present experiments, testing an optimal case and a non-optimal case called the "bigger" enables a deeper investigation of the optimal features.

An emulsion with a smaller diameter, i.e. with $D_{32} \leq 5$ μm, was tested to deliver bigger secondary droplets [2]. This effect is due to a too small and homogeneous water dispersion [2,10], reducing the differences in Laplace pressure that would promote coalescence. As a consequence, the optimal emulsion is not compared to a smaller one in the present study.

Once it is on the heated plate, the emulsion drop undergoes a Leidenfrost effect [3,10,18] due to intense vaporization in its bottom part. It is lifted up by the vapor film and slides upon the concave heated surface during a few seconds until a micro-explosion is triggered. Consequently, any contact with a solid surface is avoided during the delay prior to the micro-explosion. The Leidenfrost effect on one hand, and the suspended droplet technique on the other hand, are the two main techniques used for micro-explosion of individual emulsion drops so far. The experimental parameters met in the literature are reported in Table 1. Numerical studies [13], literature reviews [1] or spray combustion experiments [4,7] are not concerned by this survey.

The Leidenfrost effect enables to get rid of heterogeneous nucleation [1] and to obtain a sudden, unique disintegration together with a sharp bursting noise characteristic of a proper micro-explosion. The present results correspond to such cases. Puffing was not observed in this situation. In Fig. 3, the emulsion drop stands still 0.7 ms before frame 1 that is considered as the beginning of the micro-explosion.

In this work, the spray of secondary droplets resulting from micro-explosion is observed from above by an infra-red camera (FLIR SC-7500). The infra-red 640 × 512 CCD captor has the advantage of its higher sensitivity in the 3 to 5 μm range compared to a visible wavelength CCD. The CCD captor has a sensitivity of 20 mK over the whole range from − 30 °C to 3000 °C, and a precision of ±1 °C according to the manufacturer NUC calibration. The resolution of 210 μm per pixel enables to detect the smallest secondary droplets (Sauter mean diameter of 400 μm [2]) due to high thermal sensitivity. The field depth of the camera is adjusted to catch the objects between the two planes perpendicular to the line of sight, intersecting the points B and C in Fig. 2. Objects become blurred when out of field depth after a significant time of free fall at