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Experimental evaluation of the effect of emulsion stability on micro-explosion phenomena for water-in-oil emulsions

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HIGHLIGHTS

- Combustion of water/diesel fuel emulsion droplets was studied in a cell at 0.1 MPa.
- The combustion features were inferred by means of high speed backlight shadowgraphy.
- Emulsions of different stability were prepared by varying their internal parameters.
- A correlation between micro-explosion tendency and stability of an emulsion is found.
- Micro-explosions proceed by either coalescence or cooperative mechanisms.

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ABSTRACT

The combustion features of water-in-diesel fuel emulsions were studied in a single drop combustion chamber by means of high speed shadowgraphs, suspending emulsion drops to a thermocouple in order to follow their thermal history. Several emulsions were prepared by varying the internal parameters that affect their stability, such as water volume fraction, water particle size distribution and the amount of surfactant. It was found that the emulsion internal parameter which have influence on emulsion stability (water volume fraction and size distribution, quantity of surfactant) also influence the tendency towards micro-explosion.

1. Introduction

Water-in-fuel emulsions are generally recognized as a means of obtaining a cleaner combustion from liquid fossil fuels. The presence of water within the combustion system offers the interesting possibility of reducing simultaneously both nitric oxides and soot formation. Actually, the physical effect of diluting with water is to lower the flame temperature, hence reducing thermal NOx, whereas the chemical effect is to provide OH radicals, one of the main oxidizing species for soot and its precursor. Nevertheless, it is generally deemed that the most significant effect of introducing water in the combustion system in form of emulsion, rather than using other strategies, is due to the micro-explosion phenomenon. Micro-explosion of emulsion drops is due to the immiscibility and different volatility of the two liquid components and leads to secondary atomisation: the explosive boiling of the water inside the emulsion produces the disruption of the primary drops and the violent ejection of smaller drops into the combustion volume. Such secondary drops evaporate very quickly and are dispersed in a big volume, improving fuel/air mixing and the overall combustion efficiency. This mechanism is fundamental in reducing particulate emission in the combustion of medium and heavy oils [1].

However, different studies have shown that micro-explosion does not always occur, and that its occurrence depends on a number of parameters. An important factor affecting the occurrence of micro-explosion appears to be the coalescence or phase separation of the water droplets dispersed into the continuous phase. In this regard, Segawa et al. [2] argued that for a water-in-oil emulsion the disruption of the primary drop occurs when a fairly large droplet of water is formed inside the primary drop due to coalescence. Kimoto et al. [3] investigated the effect of the size distribution of water droplets on the micro-explosion phenomena on a hot surface for a water/heavy oil emulsion. They found that a fine and uniform size distribution (average diameter 1–2 μm) did not give rise to micro-explosion. In contrast, emulsion containing a wide size range of internal water droplets with some coarse sizes larger than 10 μm led to micro-explosion. They did observe effects due to the coalescence of the internal water droplets. Wang and Chen [4] studied the combustion characteristics of a series of

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water/n-alkanes emulsion drops freely falling in a furnace, with water droplet diameters smaller than 2 μm and a percentage of total surfactant of 4%, and did not observe micro-explosion for water/hexadecane emulsions. For micro-explosive drops (water/decane and water/dodecane emulsions), micro-explosions occurred only towards the end of the drop lifetimes and seemed more bound to the high concentration of surfactant that did not evaporate and finally incorporated the residual liquid. Watanabe et al. [5] examined water-in-kerosene emulsion drops suspended on a thermocouple and found a low occurrence probability of micro-explosion (0.23) for emulsions with a mean diameter of the internal water droplets of 1.1 μm, but a low quantity of surfactant (0.75%). The same authors [6] observed the milky-white emulsion drops becoming transparent before micro-explosion. They argued that the progress of coalescence of dispersed water droplets resulted in the formation of a transparent region inside the drop and outlined that micro-explosion followed the process of coalescence. On the other hand, Mura et al. [7] studied water-in-sunflower oil emulsions on a hot surface, with a large and coarse dispersion of the internal water droplets and a quantity of surfactant between 2.5% and 10%. They clearly observed phase separation within the drops, which micro-exploded. These emulsions were stable at most for some hours. Recently, Suzuki et al. [8] clearly observed coalescence, followed by micro-explosion, in water-in-kerosene emulsions using water colored with methylene blue, and found that water aggregation rate and micro-explosion occurrence probability increased with increasing mean diameter of the dispersed phase size distribution. In all these cases water volume fraction ϕ was comprised between 0.1 and 0.3.

All these studies indicates that coalescence and/or phase separation of the emulsion during heating is an important issue in the micro-explosion occurrence and bring about an indication of the role of emulsion stability on micro-explosion, in both homogeneous (free-falling droplet and hot plate experiments) and heterogeneous (suspended droplet) bubble nucleation regimes.

The stability of an emulsion depends on several factors, some of which are [9]:

1. Size distribution of the dispersed phase.
2. The volume fraction ϕ of the dispersed phase.
3. The type and quantity of the surfactant that primarily determine the repulsion forces between droplets of the dispersed phase.

During the heating of an emulsion, phase separation phenomena are accelerated because of the increased mass transfer, the decrease in viscosity of the continuous phase, and the loss of efficiency of the surfactant. If the emulsion is unstable enough, these phenomena can occur on the timescale of the evaporation and combustion of a drop, leading to coalescence and micro-explosion.

This experimental study is aimed to finding emulsion internal features, which influence micro-explosion frequency. For this purpose, a series of emulsions were studied, varying the above listed parameters that influence emulsion stability. Experiments were carried out on drops suspended on a thermocouple in order to infer the temperature of the droplet during the evaporation and combustion processes.

2. Materials and methods

2.1. Emulsion preparation

Emulsions were prepared using commercial Diesel oil No. 2 as base fuel. The preparation procedure involved mixing the surfactant Span 80 (from Sigma–Aldrich) with the base fuel under magnetic stirring until a clear solution was obtained. Afterwards distilled water was added drop by drop and the mixture was kept under magnetic stirring.

In order to investigate the effect of water volume fraction ϕ, two sets of emulsions were prepared with $\phi = 0.1$ and $\phi = 0.3$ respectively. To evaluate the effect of different size distributions, the stirring time and the high speed homogenization time were varied for each set of emulsions. Furthermore, emulsions with $\phi = 0.1$ were prepared also with different quantity of surfactant in order to evaluate the effect of low amount of the surfactant.

2.2. Measurement set up

Combustion experiments were performed in the single drop combustion chamber [10,11]. A diagram of the experimental set-up is illustrated in Fig. 1.

The chamber has four access windows to allow different experimental configurations. The drops, 700–1100 μm of diameter, were suspended on a K-type thermocouple of 76.2 μm diameter by means of a micro-syringe. The heating and ignition of the drops were attained by Joule effect using a high resistive coil placed below the drop. The evaporation and combustion processes were recorded in shadowgraphic configuration by means of high-speed digital imaging system (Motionscope by Redlake) with a maximum speed of 8000 frames/s. In all the tests the acquisition rate was set at 250 frame/s. The resolution of the images was 480 × 420 pixels, the exposure time 0.1 ms. This configuration allowed obtaining an appropriate time resolution (4 ms) to observe the fast micro-explosion process and an overall acquisition time (2 s) long enough to follow the whole drop lifetime. The acquisition was triggered by switching on the power supply of the coil. The signals from the thermocouple were acquired by a transient recorder. A PC was used to control the CCD system and store the captured image sequences.

The diameter of the drop during the whole process was inferred from the video by means of the National Instruments IMAQ Vision software.

Size distribution of the dispersed water droplets within the emulsions were obtained from micrographs of the emulsions, by means of an Olympus microscope with 100× magnification. Dispersed droplets smaller than 0.6 μm in diameter were not considered.

3. Results and discussion

Experiments were performed on water-in-diesel emulsions, varying the water volume fraction, percentage of surfactant and particle size distribution (through the homogenization procedure) to produce emulsions of different stability [12].

The most relevant samples studied are reported in Table 1, together with the main internal parameters that were varied. The size distribution of internal water droplets is expressed in terms of Sauter mean diameter d_{32}:

$$d_{32} = \frac{\sum n_i D_i^3}{\sum n_i D_i^2}$$

where D_i is the diameter of the water droplet measured by the optical microscope and n_i the number of droplets having the same D_i value. In the same table, the results of the combustion experiments in terms of micro-explosion frequency f and clearing of the drops during heating are reported, together with an indication of the emulsion stability. Micro-explosion was detected from the recorded frames as the complete disruption of the droplets. The micro-explosion frequency f represents the ratio between the number of drops