



Autoignition and combustion behavior of emulsion droplet under elevated temperature and pressure conditions

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ABSTRACT

In this study, experiments were conducted to investigate the combustion characteristics of an water-in-oil W/O emulsion droplet under elevated temperature and pressure conditions. The base fuel used was n-decane, and total volume ratios of 10, 20, and 30% of distilled water were mixed for producing the emulsion fuel. Span 80 with a volume ratio of 2% was added as a surfactant, and the emulsion fuel was homogeneously mixed via ultrasonication. The combustion process of an emulsion droplet was divided into five stages: droplet heating, classical combustion, puffing, secondary classical combustion, and surfactant combustion. The ignition delay decreased with elevated ambient temperatures, whereas an increase in the ambient pressure and water volume ratio resulted in longer ignition delays. The droplets did not ignite in 500 °C or 600 °C conditions at 1 bar because of the significant Stefan flow of fuel vapor. After droplet ignition, the droplet combustion process, including classical combustion, puffing, and surfactant combustion, followed. The average burning rate increased with ambient pressure, but it was insensitive to ambient temperatures and water volume ratios. After flame extinction, a secondary flame reappeared because of the combustion of surfactant and residues.

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1. Introduction

Numerous researchers dedicated to improving energy efficiencies and decreasing pollutant emissions of conventional fossil fuel. Researches were conducted in total direction because it is urgent matter for sustainable nature and humanity [1–4]. Nevertheless, there were unavoidable limitations to the amount of improvement when conventional fossil fuels were used. Especially, it may be reached the limit in reducing several pollutants matter during combustion such as particulate matter (PM), nitrogen oxide (NOx), and carbon monoxide (CO), which are harmful for environment and human health [5,6].

In the reasons above, emulsion fuel has received particular attention as an alternative fuel for reducing pollutant emissions and improving combustion efficiency. When the emulsion fuel is combusted, superheated water vapor is generated inside the fuel droplet and it explodes at the surface of the droplet; this is known

as “micro-explosion” or “puffing.” Several researchers have reported that the puffing process induces fuel atomization, and therefore, high combustion efficiency and low pollutant emission can be achieved without any additional apparatus or cost [7,8]. For the above reasons, several researchers have conducted studies on emulsion fuel combustion.

Ithnin et al. [9], experimentally studied the combustion of water-in-diesel emulsions under various engine load conditions. They reported that emulsion fuel containing 20% water had a maximum cylinder pressure and pressure increase rate comparable to other cases. In addition, emulsion fuel exhibited lower NOx and PM emissions, whereas CO and carbon dioxide emissions increased under low- and high-load conditions compared to the pure diesel case. Ochoterena et al. [10], conducted a study on the spray development and combustion of water-in-diesel emulsions and micro-emulsion fuels. Spray development, droplet break-up, vapor penetration, and combustion processes were observed optically. They reported that an emulsion fuel droplet penetrated further than a conventional fuel droplet, and atomization of emulsion fuel decreased the soot concentration and flame temperature compared to regular diesel fuel. Deng and Zhou [11] experimentally examined

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the combustion of a coal tar/water emulsion. In their study, a longer ignition delay of the emulsion droplet was observed, but the peak temperature of the droplet was achieved considerably earlier than ordinary coal tar. This indicated the potential of soot reduction and the extent of burnout of cenospheres when using emulsion fuel. Gong and Fu [12] observed ignition delay times for oil-in-water emulsion droplets with various fuel compositions. They reported that the ignition delay time can be decreased by adding more volatile component fuel to the emulsion, and it was notably decreased when the proportion of the volatile component was 10–20%. The effect of this volatile component was not evident at higher concentrations.

The distinctive combustion characteristics of emulsion fuels led previous researchers to conduct a number of experimental and theoretical studies, as discussed above. A study of the combustion of a single liquid fuel droplet under high temperature and pressure conditions is the primary approach for investigating the basic phenomena of spray combustion [13,14]. Although several studies dealt with emulsion fuel droplet, no studies have been conducted regarding a single emulsion droplet under high temperature and pressure conditions. Therefore, there is lack of studies and data regarding emulsion fuel droplet combustion under elevated pressure conditions [15,16]. Considering that numerous combustors are operated under high-temperature and high-pressure conditions, observation of the autoignition and combustion behaviors of emulsion fuel under these conditions are essential. This study could provide fundamental knowledge on emulsion fuel during the combustion process.

This study focuses on the combustion characteristics of a water/n-decane emulsion fuel droplet under elevated temperatures and pressures. The water volume ratios in the emulsion fuels were set to 10%, 20%, and 30%, and 2% vol. of Span 80 was added in all cases for obtaining a stable suspension. The combustion characteristics of an emulsion fuel droplet under various temperature and pressure conditions were observed, including ignition delays and burning rates. The results obtained under each experimental condition were compared.

2. Experimental setup

The experimental setup comprised a high-pressure combustion chamber, an optical observation system, and measuring sensors. Various ambient pressure and temperature conditions could be investigated with this experimental setup.

2.1. Experimental setup

Fig. 1 is a schematic diagram of the experimental apparatus that has been verified and used in previous studies [17,18]. The inner diameter and height of the cylindrical stainless-steel combustion chamber employed in this study were 150 mm and 800 mm, respectively. A single emulsion droplet of $900 \pm 100 \mu\text{m}$ was suspended at the tip of a K-type thermocouple wire (Omega Engineering, Inc.). The shield of the thermocouple was removed, and the two wires in the thermocouple were welded for droplet installation. The diameter of the inner wire was $50 \mu\text{m}$ and the welded bead size was $100 \mu\text{m}$. The droplet temperature could be measured while the droplet was suspended at the tip of the thermocouple during the experiment. This droplet installation method was widely used for several researchers due to its simplicity and accuracy of droplet temperature measurement [19]. Refer to the thermocouple manufacturer (Omega Inc.), the standard error limit of thermocouple was greater of 0.4%

The target ambient temperature could be achieved by heating the electric furnace within an error range of $\pm 5^\circ\text{C}$ measured by the

K-type thermocouple inside the furnace. The side of the rectangular parallelepiped shape of the electric furnace was 100 mm and its height was 185 mm. The inner part of the electric furnace was encased by a ceramic board for heat insulation and a small 20-mm hole was drilled in the bottom for the thermocouple insertion where a droplet was suspended. When the temperature inside the electric furnace reached the experimental temperature, it was moved to the experimental position, and the experiment was started, as shown in Fig. 1. During the experiment, droplet images were recorded by a high-speed camera at 200 frames per second. A history of the droplet diameter was acquired using an image processing program that was validated in previous studies [20,21]. In the post-processing of the images, errors smaller than 3.12% were found; therefore, the experimental errors were in good agreement with those obtained in previous studies.

2.2. Emulsion fuel

Distilled water and n-decane were used for producing water-in-oil (W/O) emulsion fuel. The thermophysical properties of water and n-decane are presented in Table 1. Volume ratios of water of 10%, 20%, and 30% were mixed in the n-decane, and 2% vol. of Span 80 was added as a surfactant. As Span 80 has lipophilic characteristics (HLB value: 4.3), it is a representative surfactant that can be used in W/O emulsion. The emulsification process was performed using an ultrasonicator (Sonics & Materials, Inc.). It was operated for 10 min in pulse mode (5 s ON & 5 s OFF) to prevent a rapid increase in the emulsion temperature. The experiment was conducted within an hour of the preparation of the emulsion fuel to prevent errors due to phase separation of the emulsion fuel.

The boiling temperature of water and n-decane across the wide pressure range could be calculated as follows:

$$\ln(p_{kPa}) = A \cdot \ln(T_{boil}) + \frac{B}{T_{boil}} + C + D \cdot T_{boil}^2 \quad (1)$$

The coefficients for water are $A = -7.34297$, $B = -7276.39$, $C = 67.0245$, and $D = 4.16191 \times 10^{-6}$, and for n-decane $A = -7.76881$, $B = -8163.33$, $C = 69.7646$, and $D = 2.62033 \times 10^{-6}$ [22]. The boiling temperatures at different experimental pressures are presented in Table 2.

2.3. Experimental conditions

The experiments were conducted under various temperature (500, 600, and 700°C) and pressure (1, 5, 10, and 15 bar) conditions, with an initial droplet diameter set to $900 \pm 100 \mu\text{m}$. The experiment was conducted under each temperature and pressure condition with different water/n-decane fuel ratios. Each experiment was repeated a minimum of five times under identical conditions for consistency of the results. The chamber was purged with dry air after each experiment to remove the combustion residue.

The ignition delay was the time between the start of the experiment and the droplet ignition. Droplet ignition was defined when a yellow flame first appeared in the image of the droplet, and the droplet burning time was calculated by counting the numbers of frames from droplet ignition to flame extinction.

The burning rate constant (K_b) is widely used for examining the combustion phenomena of a single droplet. Burning rate is defined as the temporal change in the squared droplet diameter (d^2), and is calculated as follows [23]:

$$K_b = \frac{d}{dt} (d^2) \quad (2)$$

Unlike droplet evaporation, the observation of a droplet during

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