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Full Length Article

Evaporation of a single emulsion fuel droplet in elevated temperature and pressure conditions

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ABSTRACT

The evaporation characteristics of water/n-decane emulsion droplet at various temperatures and pressures were experimentally observed. Emulsion fuel was made by adding pure water to the base n-decane fuel with a volume ratio of 0.2. Span 80 was used as a surfactant, and ultrasonification was conducted for the mixing process. The temporal variation of the droplet diameter was optically observed by using a high-speed camera, and the changes in droplet temperature were also measured. The evaporation process of emulsion droplets was divided into three stages, namely, droplet heating, inflation/puffing, and pure evaporation. As the ambient temperature increased, the behavior of droplet inflation shifted to puffing during the inflation/puffing stage. A decline in the inflation/puffing incidence rate was noted at high-pressure conditions. The evaporation rate during the pure evaporation stage and the overall droplet lifetime were affected by the ambient temperature but not by the ambient pressure. The inflation of the droplet mostly occurred at relatively lower temperature and pressure conditions; it changed to puffing, however, at higher temperature and pressure conditions.

1. Introduction

Recently, emulsion fuel has received attention for its application in heat engine systems owing to its distinct combustion characteristics and lower pollutant emission. An emulsion fuel is a mixture of conventional hydrocarbon-based fuel with additive liquids, which are immiscible with the base fuel. Usually, water is used as the additive liquid to make a water-in-oil (W/O) emulsion fuel. The structure of emulsion fuel consists of tiny water droplets that are distributed into the base fuel. It is known that several factors including the type of surfactant and means of mixing influence the quality of the fuel [1,2].

Because of its distinctive characteristics, emulsion fuel has been widely studied by several researchers. The most remarkable characteristic during the combustion of emulsion fuel is micro-explosion or puffing. When the temperature of an emulsion droplet increases above the boiling point of water, tiny water droplets inside the droplet superheat and start to evaporate rapidly. In this circumstance, 'micro-explosion' or 'puffing' is initiated. Micro-explosion is defined as the breakup of a whole droplet, whereas puffing is defined as a relatively small blowout at the droplet surface. When these happen, a portion of the base fuel detaches from the droplet surface, a process called 'atomization' [3]. Atomization of the base fuel increases the contact area between the base fuel and the air, boosts the combustion efficiency, and suppresses particulate matter (PM) emission. Moreover, a lower flame temperature owing to the latent heat of water decreases thermal NO_x [4]. However, the lower heating values of emulsion fuel are one of its critical weaknesses. Water itself does not release heat, but it does absorb a great amount of heat when it evaporates. It also decreases the overall heating value and the thermal efficiency of emulsion fuel. Corrosion of the metal parts in a combustor by the residue of the water is another problem [4].

Notwithstanding the pros and cons, a number of researchers have investigated the behavior of emulsion fuel in evaporation and combustion conditions. Gong and Fu [5] examined the ignition delay time for oil–water emulsion with droplets of various additional liquid fuels with higher volatility. They found that the addition of more volatile components significantly reduced the ignition delay time. Ignition delay notably decreased with a volatile component portion of 10–20%; however, the effect decreased with higher concentrations. In the study of Calabria et al. [6], the combustion characteristics of diesel/pyrolysis oil emulsion were observed. A single droplet was suspended at the tip of a thermocouple to measure the droplet temperature. The results showed that the main characteristics of emulsion droplet combustion were between pure pyrolysis oil and diesel; however, the micro-explosion of diesel/pyrolysis oil emulsion was ineffective in destroying the droplet. Tanaka et al. [7] investigated the effect of ambient pressure on the

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micro-explosion of emulsion droplet on a hot surface. In their research, the waiting time for the onset of micro-explosion was correlated with a wear-out type that could be represented by a Weibull distribution. Moreover, the phase separation of emulsion fuel was observed at ambient and high-pressure conditions. The occurrence of puffing between carbonated emulsion fuel and degassed emulsion fuel was compared in the study of Watanabe et al. [8]. They found that the mean waiting time and superheat temperature, when puffing occurred, decreased when the emulsion fuel was saturated with CO_2 gas. Moreover, experimental results were compared with the equation, and a good agreement was found between the two. A correlated equation was obtained for the case of carbonated emulsion fuel. Besides the single droplet behavior, the bulk combustion performance of emulsion fuel in an internal combustion engine was experimentally investigated by Saravanan et al. [9] They concluded that NOx and PM can be suppressed by applying emulsion fuel to a compression-ignition engine since the addition of water to diesel fuel lowers the peak combustion temperature and enhances the atomization performance. These previous research studies focused on discovering the evaporation and combustion characteristics of emulsion fuel in various conditions.

In addition to the previous research studies, it would be valuable to observe the evaporation characteristics of W/O emulsion fuel droplets in elevated temperatures and pressure conditions because none of the previous studies dealt with the detailed evaporation and micro-explosion or puffing behavior of emulsion fuel in high-temperature and -pressure conditions. Moreover, the changes in droplet temperature during the evaporation process could give additional information about the behavior of emulsion fuel in a combustor.

The main goal of this research was to evaluate the evaporation and puffing characteristics of a single W/O emulsion fuel in various temperature and pressure conditions. n-Decane was chosen as the base fuel, and 20 vol% water and 2 vol% surfactant were added to it to produce a stable emulsion fuel. It was ultrasonically mixed for emulsification. The change in droplet diameter was observed via a high-speed camera, and the temporary change in droplet temperature was measured by a thermocouple used for suspending the droplet.

2. Experimental setup

The experimental setup was composed of a test chamber, an optical observation system, and measuring sensors. Fuel was emulsified by using an ultrasonicator.

2.1. Test chamber

A schematic of the test chamber with the name of each part is shown in Fig. 1. A test chamber is a device for conducting single droplet evaporation and test experiments. Several research experiments have been performed using a test chamber because it makes it easy to change the experimental conditions and enables to observe a single droplet [10].

The test chamber for the present study has been used by several previous researchers, and a detailed specification and explanation of the device are shown in Refs. [11,12]. The test chamber is composed of a pressure vessel and an electric furnace inside the vessel. As shown in Fig. 1, the experiment started by dropping the electric furnace from the initial position (solid line) to the experiment position (dotted line). Once the electric furnace was in the experiment position, the droplet was then exposed to a high-temperature condition. The temperature controller shown in the Fig. 1 measured the furnace temperature by using K-type thermocouple which is built-in the furnace (No. 9 in the figure), and kept the furnace temperature constant during the experiment.

A single droplet was installed at the tip of a fine thermocouple to measure the droplet temperature during the experiment. The detailed procedure for the thermocouple installation and calibration is identical to that used in a previous study conducted by the authors [13]. For the optical assessment of the droplet, a 70-mm quartz window pair was installed by the pressure vessel wall. The Experiments in each case were conducted at least 5 times to observe the reproducibility.

2.2. Droplet installation

The suspension of a single droplet at the tip of a thermocouple for droplet experimentation has several advantages including the ability to measure the droplet temperature [13]. A Cr–Al, K-type thermocouple (Omega Engineering, Inc.), which has a 50-μm inner wire diameter, was used. The fuel droplet was suspended at the tip of the thermocouple, and the droplet temperature was measured. It would be reasonable to consider the measured droplet temperature as a 'transient bulk temperature' of inner droplet, because the location of thermocouple bead in the droplet was slightly changed during the experiment. A tiny amount of ceramic adhesive was applied to the tip of the thermocouple, as in our previous research experiment [4]. This increased the adhesion force between the thermocouple tip and the droplet, which greatly reduced the detachment of the droplet during testing. The detailed description of the thermocouple can be found in the previous study conducted by authors [13].

2.3. Optical observation setup

Droplet images were obtained by using a high-speed CCD camera array at 200 frames per second. The images were used to investigate the change in droplet diameter via the post-processing procedure [13]. The image processing program recognized droplet boundary by detecting dark pixels in the image, and the area of the droplet was determined by counting the number of pixels inside the boundary. The actual droplet area was deduced by multiplying scale factor that is ratio of the real subject and the magnified image, and the diameter of the droplet was achieved by assuming the droplet as the circle with identical area. Optical observation was started when the droplet appeared in the center of the furnace window. Droplet inflation and puffing were also observed by droplet imaging. A light-emitting diode (LED) was used for the background light.

2.4. Emulsion fuel

n-Decane was designated as the base fuel because it has a higher boiling temperature than water, which makes it suitable for producing W/O emulsion. Twenty volume percent pure water was mixed with n-decane, and 2 vol% Span 80 was added as a surfactant. Span 80 has lipophilic properties (hydrophilic–lipophilic balance value of 4.3), enabling it to be widely used for making W/O emulsions. The boiling temperature of n-decane and water in experimental pressure conditions (1, 5, 10, and 15 bar) was calculated by using Eq. (1), and the results are shown in Table 1 [14].

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

The coefficients for water were $A = -7.34297$, $B = -7276.39$, $C = 67.0245$, and $D = 4.16191 \times 10^{-6}$, whereas those for n-decane were $A = -7.76881$, $B = -8163.33$, $C = 69.7646$, and $D = 2.62033 \times 10^{-6}$ [14]. In the self-verification test, it was discovered that addition of 2 vol% of Span 80 increased boiling temperature of n-decane about 2 °C.

Fuel was ultrasonically homogenized by using an ultrasonic processor (VCX-130, Sonic & Materials Co.). The diameter of the processor tip is 6 mm, and 30 W of power was applied during the mixing process. A water bed was applied, and an ultrasonicator was operated in pulse mode (5 s on and 5 s off) to prevent a rapid increase in fuel temperature during the mixing process. The experiment was carried out within an hour of making the fuel to minimize any errors related to phase