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Combustion of a single emulsion fuel droplet in a rapid compression machine

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ABSTRACT

The autoignition and combustion characteristics of a single water/*n*-decane emulsion droplet were examined using a rapid compression machine. A specific volume ratio of water was added to the *n*-decane, and a water-in-oil emulsion was formed by ultrasonication. The emulsion droplet was suspended at the tip of a fine thermocouple and placed at the center of the reaction chamber. The time evolutions of droplet temperature and diameter were observed. Droplet combustion was classified into four stages, and the characteristics of each stage varied little with the water volume ratio. Ignition delay increased monotonically with initial droplet diameter and water volume ratio. Increasing the water ratio boosted the intensity of micro explosions, while the rise in droplet temperature was hindered by the specific heat and latent heat of the water. The average burning rate was elevated when the initial droplet diameter increased. However, the burning rate was not affected much by the water volume ratio.

1. Introduction

An emulsion is a mixture of liquids that are normally immiscible. In emulsions, additives are spread out in the base liquid in the form of tiny droplets [1]. Because of their distinctive characteristics, emulsions are widely used in various industries, including mechanical, medical, and chemical and biological engineering fields. In the field of combustion, emulsion fuels have been considered an alternative fuel form that could boost combustion efficiency while reducing pollutant emissions, such as NO_x and PM (particulate matter). Currently, emulsified fuel is used widely in various spray combustion systems such as internal combustion engines, turbines, and furnaces [2]. Mixing water with a base fuel is a well-known method for fabricating emulsion fuels. These are divided into W/O (water-in-oil) and O/W (oil-in-water) emulsions, depending on the relative concentrations of each liquid.

The main characteristic of emulsion droplets during evaporation and combustion entails disruption of the droplet, referred to as ‘fragmentation’ or ‘micro-explosion’ [3]. The main cause of these phenomena is the sudden explosion of fine water droplets that are superheated within the base droplet. The occurrence of micro-explosions atomizes the fuel droplet into smaller droplets, increasing the contact area between fuel and air. This improves combustion efficiency and decreases pollutant emissions. However, it is also known that water content in the fuel decreases the flame temperature by absorbing much heat for vaporization, and it decreases the combustion efficiency [4]. Stability issues are another weak point of emulsified fuels [2]. Because of the pros and cons of emulsion fuels, optimal conditions for their use are needed.

Various studies have examined micro-explosions and the combustion characteristics of a single emulsion fuel droplet under different experimental conditions. Jackson and Avedisian [5] conducted an experimental study of the combustion behavior of water in *n*-heptane in a convection-free environment. The results showed a three-stage burning process: burning of *n*-heptane, of both *n*-heptane and water, and finally, burning of the surfactant. Moreover, the addition of water content reduced flame luminosity, soot formation, and the burning rate of the droplet. In research by Mura et al., [6] micro-explosion analysis of emulsified droplets was conducted with two different experimental approaches: suspension and Leidenfrost techniques. The results showed that the effects of the separation process, such as coalescence and creaming, influenced the micro-explosion efficiency markedly for both methods. The influence of the thermocouple in their experimental conditions was negligible. The heat transfer process was

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fundamental to determining the metastability of the emulsion fuel droplet. Watanabe et al. [7] observed micro-explosion phenomena of emulsion droplets using a suspension method with a ceramic fiber and thermocouple. Temporal variation in droplet temperature was recorded via the thermocouple and was analyzed by matching with the droplet image accordingly. They also proposed a mathematical model to calculate the mass of water vapor generated in micro-explosions. Law et al. [8] carried out numerical research on the combustion characteristics of water-in-oil emulsion droplets. They postulated various combustion modes of emulsion droplets, considering the relative volatilities and concentrations of water and oil. Their results showed differences in droplet temperature and droplet radius-squared history, depending on the numerical models. Experiments were also performed for confirmation; the results agreed with the postulated combustion modes.

Spray ignition and combustion of emulsion fuels in various devices have been studied by several researchers. Lin and Wang [9] applied W/O and O/W/O emulsions to diesel engines, and reductions in exhaust gas temperature and NO_x were achieved. Compared with a W/O emulsion, the O/W/O emulsion had higher exhaust gas temperature and lower CO and NO_x emissions, but the differences in O_2 and CO_2 emissions were not significant. Watanabe et al., [10] conducted numerical research on spray ignition with a W/O emulsion fuel. Their results showed that consideration of puffing and micro-explosion was necessary for a precise analysis even when the combustion reactions had almost terminated. They also proposed a new mathematical model for puffing and micro-explosions, which agreed well with the experimental results. In the study by Ballester et al., [11] a water/heavy oil emulsion was applied to a laboratory-scale furnace, and the effects of water addition were analyzed. Addition of water to heavy oil significantly accelerated the evaporation and process in the flame and reduced the flame temperature.

Previous research on emulsions was conducted mostly under steady-state conditions, where the ambient pressure and temperature conditions were fixed. Under these conditions, consideration of the transient behavior of emulsified droplets would be insufficient, although it is an important factor in micro-explosion phenomena. Moreover, it is not possible to observe single droplet behavior in a spray combustion system due to difficulties in the optical observation of droplets and the effects of neighboring droplets. The observation of emulsion droplet combustion under transient conditions would provide additional understanding of the processes involved.

The main goal of this study was to observe the ignition and combustion characteristics of an emulsion droplet experimentally under transient conditions using a RCM (rapid compression machine). A suspended single droplet was installed at the tip of a thermocouple, and temporal variation in the droplet was observed via sensors and a high-speed camera. For this purpose, *n*-decane was designated as the base fuel, and specific volume ratios of pure water and 2% surfactant were added to prepare the emulsion fuel, which was homogenized ultrasonically using an ultrasonicator so that fine water droplets were dispersed into the base fuel.

2. Experimental set-up

A schematic of the experimental apparatus is shown in the Ref. [12]. The experimental set-up is roughly divided into an RCM, sensors, and the optical observation system. An ultrasonicator was also used.

2.1. RCM

The RCM is an experimental device for simulating a single compression stroke. It is composed of driving chamber, reaction chamber, and piston that compresses air inside the reaction chamber. The RCM used for the present study was pneumatically driven. Compressed air is supplied to RCM via reservoir tank, and it is used for controlling the RCM operation with several valves. Before each experiment, piston is fixed by the compressed air in front of driving piston, and the experiment starts by draining the compressed air fast with the solenoid valve. The step-shaped clearance stops the driving piston without damage by absorbing the momentum of the piston. A creviced piston design was used in the reaction chamber because the crevice shape reduces corner vortices inside the RCM [13]. Optical access to the droplet was provided via a 10-mm-diameter quartz window pair in the reaction chamber wall. The detailed specifications of the RCM are described in a previous article [14].

Under room temperature conditions, the autoignition diameter range of W/O emulsion droplets was quite narrow because of the low volatility of *n*-decane and the suppression of vaporization under the high-pressure conditions. To address this, a heating jacket was applied to the wall of the reaction chamber. This increased the initial air temperature inside the reaction chamber and expanded the ignitable droplet diameter range. In the present study, the initial air temperature inside the reaction chamber was maintained $50 \pm 0.5\ ^\circ C$.

2.2. Thermocouple and pressure transducer

In the present study, a fine thermocouple was used to install the single droplet and to measure the transient bulk droplet temperature. A Cr–Al-sheathed K-type thermocouple (Omega Engineering, Inc.) was used for droplet suspension. The cover tip of the thermocouple was removed, and an approximately 100-μm bead was formed by welding the two 50-μm inner wires. A tiny amount of ceramic adhesive was applied on the bead to avoid detachment of the droplet during combustion so that the lifetime temperature of the droplet could be observed. From the information of manufacturer, standard error limit of thermocouple was greater of 0.75%. The temperature of droplet was properly calibrated by following the procedure of the previous research [15]. The thermocouple was installed so that the tip was placed at the center of the reaction chamber. A pressure transducer (Sensys, Inc., PMS) was used to measure the pressure inside the reaction chamber. Further explanation of the set-up of sensors and data acquisition is provided in our previous report [14].

2.3. Optical observation setup

Images of the droplet were taken with a high-speed CCD (charge coupled device) camera array at 500 frames per second. The initial droplet diameter and the temporal variation in the droplet diameter were observed in post-processing procedures [14]. Optical observation of the droplet was conducted from the start of experiment to the extinction of the flame. Ignition of the droplet was judged by observing a luminous yellow flame in the droplet image. A LED (light-emitting diode) backlight with a filter was used as a background light source.

2.4. Preparation of emulsion fuel

The *n*-decane was selected as the base fuel of the W/O emulsion because it has a higher boiling temperature than water. Fixed volume ratios of distilled pure water were added to the *n*-decane base. In the present experiment, 10%, 20%, and 30% vol. of water were set as experimental conditions. Sorbitan Monooleate (SPAN 80: $C_{24}H_{44}O_6$) was chosen as the surfactant. It is suitable for making W/O emulsions due to its lipophilic properties