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Full Length Article

Secondary atomization and spray flame characteristics of carbonated W/O emulsified fuel

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HIGHLIGHTS

- Secondary atomization and spray flame of carbonated emulsified fuel were studied.
- Shadow imaging clearly visualized the spray droplets during secondary atomization.
- Compact luminous flames were formed in the carbonated emulsified fuel.
- Carbonation of emulsified fuel improved the spray flame characteristics.

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ABSTRACT

The secondary atomization behavior and spray flame characteristics of carbonated W/O emulsified fuel were studied. The dissolved CO_2 in the carbonated emulsified fuel was able to reduce the bubble nucleation energy needed for secondary atomization. First, the spray characteristics of carbonated fuels were studied in a N_2 environment at 923 K, using high-magnification shadow imaging of the spray droplets. This allowed the spray droplets to be clearly visualized during secondary atomization. The dissolved CO_2 was shown to enhance secondary atomization by decreasing the bubble nucleation energy, resulting in the production of finer spray droplets. The spray flame characteristics of *n*-dodecane, emulsified fuel, and carbonated emulsified fuel were then studied in a laminar counterflow burner. Direct photography of the flame using a color high-speed video camera and magnified shadow imaging using a monochrome high-speed video camera were used. Compared the ignition point of luminous flames in *n*-dodecane, an ignition delay was found in the emulsified fuel, which was not found in the carbonated emulsified fuel. Compact luminous flames were also formed in the carbonated emulsified fuel. In the magnified flame images, bright spots of higher luminosity than the surrounding area were observed in both the emulsified fuels. These proved to be a useful marker for secondary atomization. In the carbonated emulsified fuel, the bright spots appeared earlier, indicating that the dissolved CO_2 reduced the droplet temperature at which secondary atomization occurred. This effect countered the ignition delay caused by water addition in the emulsified fuel. A higher frequency of bright spot occurrence was also found in the carbonated emulsified fuel. It was demonstrated that carbonation of emulsified fuel improved the spray flame characteristics through the enhancement of secondary atomization.

1. Introduction

Spray combustion has widespread applications. However, the emissions from spray combustion, such as NO_x and soot, present serious global problems. Water-in-Oil (W/O) emulsified fuel is a possible alternative that could reduce the emission of pollutants [1–3]. Secondary atomization by the rapid evaporation of the dispersed water is the widely accepted explanation for the decrease in CO and soot emissions. Secondary atomization in emulsified fuel mainly consists of micro-explosion and puffing [4]. In a micro-explosion, the entire droplet bursts into smaller droplets. In puffing, water vapor is blown out from the droplet surface with fine droplets. Because of the interest in puffing and micro-explosion, they have been frequently studied using single droplet experiments [4–7].

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Recently, secondary atomization has been extensively studied in spray flames [8–10]. Our previous studies visualized the secondary atomization of spray droplets in a N_2 environment [11,12] and in spray flames [13] using magnified shadow imaging.

One technical issue holding back the use of emulsified fuel in a practical system is ignition delay [14], mainly caused by water addition. To reduce ignition delay, secondary atomization must be enhanced in the low temperature upstream region. The dissolved gas in the emulsified fuel decreases the bubble nuclear energy needed for secondary atomization [4]. In our previous study, we proposed a carbonated emulsified fuel containing dissolved CO_2, and showed the dissolved CO_2 decreased the droplet temperature at which secondary atomization occurred by using a single droplet experiment [4]. The eruption of CO_2 from a droplet of carbonated emulsified fuel also improves secondary atomization. Carbonation of emulsified fuel therefore offers the possibility of solving the ignition delay in emulsified fuel, and improving the spray flame characteristics. The characteristics of gas-dissolved diesel fuel spray using *n*-tridecane and liquefied CO_2 have been described [15], but, the use of carbonated emulsified in spray droplets and spray flames has not been well studied.

This study investigates the secondary atomization behavior and spray flame characteristics of carbonated emulsified fuel. First, secondary atomization and the size distribution of spray droplets were studied in a high temperature N_2 environment using high-magnification shadow imaging. The impact of dissolved CO_2 in the fuel on spray droplets is discussed. Then, the spray flame characteristics of the carbonated emulsified fuel were studied in a laminar counterflow burner.

2. Experiment

2.1. Preparation of the emulsified fuel

Sorbitan Monooleate (Emasol O-10V, Kao Corp. HLB = 4.3) was used as an emulsifying agent to prepare the W/O emulsified fuel. The water content of the emulsified fuel was 10 vol%, with 0.75 vol% of surfactant. The W/O emulsified fuel was prepared by adding the water and the emulsifying agent to *n*-dodecane and stirring the mixture in a mechanical homogenizer (Omni Homogenizer, GLT-115, Yamato Science, Japan) at a rotation speed of 9000 rpm. After 20 min mixing, the W/O emulsified fuel formed. To prepare the carbonated fuel, the procedures for degassing and dissolving CO_2 were carried out using the fuel tank and stirrer shown in Fig. 1.

First, degassing was performed to eliminate any previously dissolved gas in the emulsified fuel. The initial pressure in the fuel tank was set to 50 kPa using a vacuum pump, and the pressure in the tank was maintained constant for 10 min. After the degassing procedure was completed, CO_2 (95%) was introduced into the tank. Fuel was supplied to two different facilities by different spray nozzles. When the carbonated fuel was supplied to the pressure atomization nozzle in the apparatus (Fig. 2), the pressure in the tank was set to 0.82 MPa. When the fuel was supplied to the ultra-sound atomizer equipped with a counterflow burner (Fig. 3), the pressure was set to 0.12 MPa. More details of Figs. 2 and 3 are given below. Since the pressure in the fuel tank decreased as the CO_2 dissolved into fuel, the pressure kept constant with suppling CO_2 until the amount of dissolved CO_2 reached 9.1 g/L-fuel at 0.82 MPa and 1.0 g/L-fuel at 0.12 MPa, respectively. The dissolved CO_2 was estimated from the pressure change. The carbonated fuel was then supplied to the nozzle by CO_2 pressure feeding. Assuming that the Henry constant of *n*-dodecane is the same as that of decane ($C_{10}H_{22}$) [4], the equilibrium values of dissolved CO_2 in emulsified fuel are 18.2 g/L-fuel at 0.82 MPa and 2.6 g/L-fuel at 0.12 MPa, respectively. Thus, the dissolved CO_2 in the emulsified fuel would be 50 wt% and 39 wt% of equilibrium values at 0.82 MPa and 0.12 MPa, respectively. To supply the emulsified fuel or *n*-dodecane, N_2 pressure feeding was used. The number mean diameter of the dispersed water droplets in the emulsified fuel was 2.0 μm after injection from the pressure nozzle [11], and 5.1 μm after injection from the ultra-sound atomizer [13]. Although the size distribution of dispersed water droplets in the carbonated emulsified fuel prepared at 0.82 MPa CO_2 was difficult to measure, our previous study showed that the size of dispersed water droplets of the carbonated emulsified fuel prepared at 92 kPa CO_2 was similar to that of the original emulsified fuel [4]. Thus, the impact of dissolved CO_2 on the size of dispersed water droplets is supposed to be insignificant in this study.

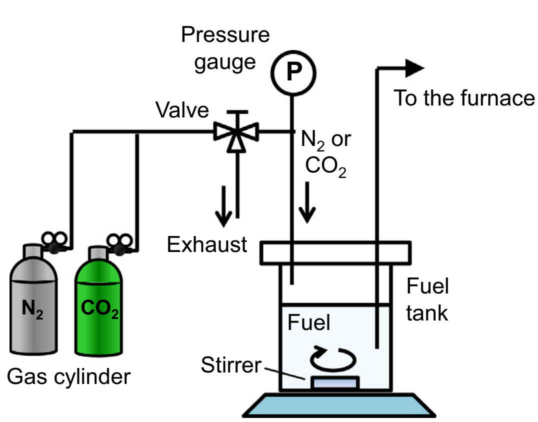

Fig. 1. Schematic diagram of experimental apparatus for dissolving gas.

2.2. Observation of spray droplets in N_2

Fig. 2 shows a schematic diagram of the experimental apparatus to visualize the secondary atomization of spray droplets in high-temperature N_2. An inert gas, N_2, was introduced at a flow rate of 1.0 L/min into the furnace through a pre-heating furnace with a current plate. During measurement, the furnace wall temperature was set at 923 K and the gas temperature was 813 K. Emulsified fuel, carbonated emulsified fuel, *n*-dodecane, and carbonated *n*-dodecane were used as fuel, and were sprayed into the furnace after passing through a water-cooled probe. The spray pattern was hollow-cone, and the flow rate was 2 L/h. The dissolved CO_2 has two effects on secondary atomization: a decrease in bubble nucleation energy, and CO_2 eruption from the droplet. Leaving aside the decrease in bubble nucleation energy, the effect of the dissolved CO_2 was analyzed by comparing the *n*-dodecane and carbonated *n*-dodecane spray flows. The amount of dissolved CO_2 in the carbonated *n*-dodecane was set at the same level as that in the carbonated emulsified fuel.

A high-magnification shadow imaging system was used to record the secondary atomization process and to measure the droplet sizes. A stainless electrically heated furnace with two quartz windows was used for shadow imaging. Spray droplets and secondary atomization behavior were visualized in a high temperature N_2 environment in which the ignition did not occur and the gas temperature was well controlled. This allowed the effects of secondary atomization on the size distribution of the spray droplets to be analyzed in detail. A high-speed video camera (FASTCAM-SA4, Photron) with a frame rate of 125,000 fps and 3× zoom lens to record the shadow and a metal halide lamp for light source were positioned opposite to each other. The spatial resolution was 6.5 μm/pixel (192 × 96 pixels). Spray droplets smaller than 10 μm were excluded from the digital image processing because of experimental uncertainties. Fig. 2(b) shows the