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Atomization and combustion characteristics of a fuel-water rapid internal mixing injector

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Abstract

In this study, we investigated the atomization characteristics of rapid internal mixing injector (RIM injector) developed in our laboratory. RIM injector successfully emulsifies base fuel without any surfactant just before fuel injection. The diameter of droplet discharged from RIM injector was evaluated based on processing of shadowgraph images. It was found that Sauter mean diameter (SMD) of droplet is determined by the gas to liquid ratio (GLR) and viscosity of emulsified fuel. The increasing GLR decreases SMD value. As water content ratio is increased, the inner structure of droplet changes to W/O type emulsion. The emulsification increases its viscosity, which deteriorates the atomization characteristics. We proposed an empirical formula as functions of GLR and Reynolds number reproducing the deterioration resulting from increasing viscosity. The formula successfully predicts the SMD variation with respect to GLR and water content ratio. Finally, we examined the effect of atomization air ratio on NOx and PM emissions. The quantity of atomization air significantly influences the PM emission because the increasing air improves the mixing of fuel vapor with combustion air.

1 Introduction

In recent decades, combustion technology based on water emulsification has been studied [1]. Micro-explosion is characteristic phenomena that flash evaporation of water particles dispersed in fuel droplet generates fine fuel droplets, which promotes the evaporation of fuel as a result of the increase in total surface area of droplets [2]. In addition, the micro-explosion also promotes the mixing of fuel vapor and combustion air, resulting in the reduction of soot emission [3][4]. On the other hand, water contained in emulsified fuel decreases flame temperature of emulsified fuel combustion. This is due to latent heat, and dilution of combustible mixture with water vapor. The lower flame temperature reduces NOx emission [5].

In contrast, it was reported in the previous studies that emulsified fuel has some drawbacks. First, the emulsification needs expensive surfactant to mix oil with water. Second, although the surfactant is doped to emulsified fuel, the quality of the emulsified fuel temporally deteriorates [6]. Third, excessive water in emulsified fuel often induces unstable combustion due to heat sink resulting from latent heat [7]. To overcome the drawbacks, we have developed a fuel injector (Rapid Internal mixing injector, RIM injector) incorporating a small mixing chamber [8]. Water, fuel and atomizing air are separately introduced into the RIM injector, and then the three fluid are mixed in the mixing chamber, resulting in emulsification of fuel with water. The emulsified fuel made is discharged though holes drilled on the mixing chamber into a furnace. By using our injector, we can make emulsified fuel without any surfactant just before combustion in a furnace, and adjust its water content in response to thermal condition in furnaces.

In our previous study [8], we have investigated the droplets discharged from RIM injector, and demonstrated the successful emulsification in the wide range of water content. Emissions from the laboratory-scale furnace with our RIM injector has been also examined, which proved the simultaneous reduction of NOx and soot emission as when using conventional emulsified fuels.

The aim of this study is to investigate the detail of atomization characteristics of RIM injector when high viscosity fuel such as vegetable oil is used. We measured Sauter mean diameter (SMD) of droplets discharged from RIM injector using the processing of spray images captured by high-speed shadowgraph method, and investigated the effects of gas to liquid ratio (GLR) and viscosity on SMD. From these results, we proposed an empirical formula predicting SMD based on GLR and Reynolds number reproducing effect of viscosity. Finally, the effects of atomizing air ratio on NOx and PM emissions were examined by combustion test using a laboratory-scale furnace.

2 Experimental setup

Figures 1(a) and 1(b) shows cross-sectional and exploded-view diagrams, respectively, of RIM injector used in the experiments. The injector consists of a main body, a swirler, a mixing chamber, and a cover clamping the mixing chamber onto the main body, all of which are made of brass. The length of the mixing chamber is 33 mm, and the inner diameter is 12.6 mm.

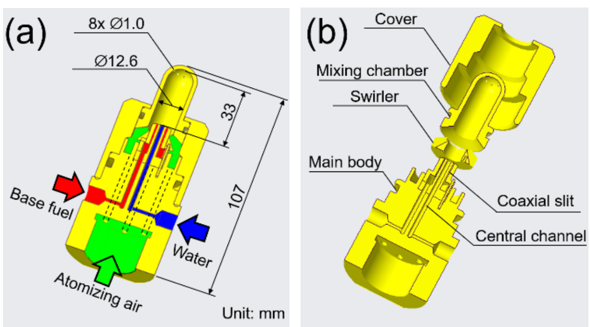

Figure 1: (a) Cross-sectional and (b) exploded-view schematics of proposed fuel–water RIM injector

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The base fuel, water, and atomizing air are respectively introduced into the mixing chamber through a coaxial, a central channel, and a four-slit swirler, generating rotational flow within the chamber. The introduced fuel and water are mixed by the swirling air, resulting in the emulsification of the fuel within the chamber. The emulsified fuel is subsequently discharged through eight holes of 1.0 mm in diameter arranged in a circular pattern in the upper section of the chamber. Each injection hole is inclined by 45° relative to the vertical direction.

In this study, we investigated Sauter mean diameters (SMDs) and inner structure of droplets under cold conditions. In addition, we measured NOx and soot emission during hot combustion tests. The experimental apparatus used in this study are same as those in our previous study [8]. Here, we will briefly introduce the apparatus used. The SMDs of droplets in sprays discharged from the injector were evaluated using shadowgraph images. Figure 2 shows a schematic of the shadowgraph system, which consists of a spray chamber and an injector as well as a nano-spark photography unit [9] and a digital camera (Nikon D7000). The chamber has two optical windows composed of silicate glass on opposing lateral sides to allow parallel light emitted by a light source to pass through and illuminate the spray in the chamber for short durations of 30 ns. The spatial resolution of shadowgraph images is 4.1 µm/pixel. The diameters of droplets were evaluated through the image processing based on the luminosity gradient around the droplets.

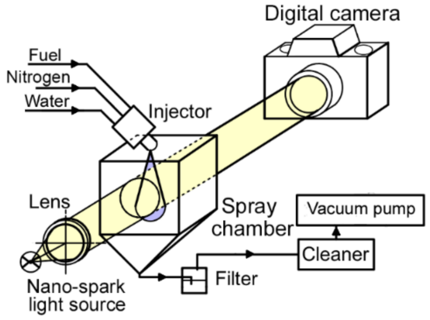

Figure 2: Experimental apparatus for droplet size measurements using shadowgraph method

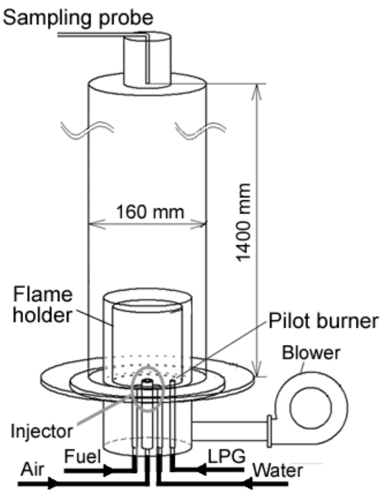

Figure 3: NO_x and soot emission measurements

To examine the fuel emulsification resulting from the mixing in the chamber, the internal structure of the droplets discharged from the injector was investigated using an immersion method. During the droplet sampling trials, blue coloring agents were added to the water in the injector to allow for the easy identification of water and oil droplets in the microscopic images.

The combustion test was carried out on the laboratory-scale furnace. Figure 3 shows a schematic of the combustion test apparatus, which consists of a combustion furnace and an injector as well as a NO_x and soot measurement system. RIM injector was mounted on the center of a flame holder. Secondary air flows into the holder through holes on the bottom. A probe was installed from the exit of the combustion furnace to sample flue gases. NOx concentration was measured by a gas analyzer (Horiba, PG-250). PM in the flue gas was collected on a piece of filter paper, and the weight of the PM on the paper was determined using an electronic scale.

During the assessment of the spray and emulsification characteristics, the mass flow rate of base fuel M_f was varied from 0.48 to 1.61 kg/h while atomizing gas flow rates M_a were set to 3.94 kg/h and 5.40 kg/h. The accuracies of the rates were respectively ± 0.02 kg/h in fuel mass flow, and ± 0.07 kg/h in atomizing gas. Soybean oil was used as fuel, and nitrogen was the atomizing gas rather than air for safety reasons. In the present study, the extent of water introduction is represented by the water content ratio $Y_w = M_w/(M_f + M_w)$, where M_w is mass flow rate of water. During the experimental trials, this ratio was varied from 0 to 0.7 with a maximum error of ±2.0%. Gas to liquid ratio (GLR), which is used as a measure of atomization, is defined as GLR = $M_a/(M_f + M_w)$.

During the measurements of NO_x and soot emissions, the total air flow rate M_t (sum of atomizing air and secondary air) was maintained at 15.42 kg/h. The atomizing gas flow rate M_a were set to 3.94 kg/h (M_a / M_t = 0.26), and 5.40 kg/h (M_a / M_t = 0.35). The fuel mass flow rates were 1.13 kg/h and 1.31 kg/h, which correspond to an equivalence ratio ϕ of 0.9, and 1.05, respectively. The rich condition simulates the combustion conditions in a conventional furnace operating under high-load conditions.

3 Results and discussion

3.1 Spray characteristics of RIM injector

Figure 4 shows probability profiles of droplet diameter evaluated by the shadowgraph method. During the measurements, GLR was set to a constant of 2.47.

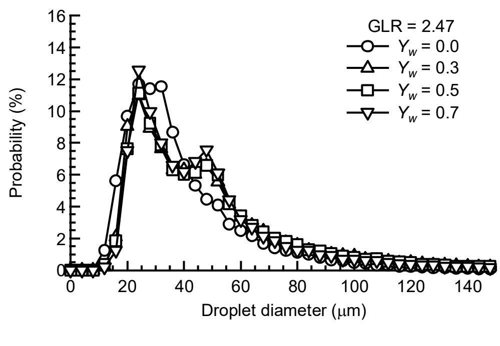

Figure 4: Probability profiles of droplet diameter at conditions with various water content ratios

When pure fuel was only applied (Y_w = 0), the probability shows the peak value at a diameter of approximately 25 µm. However, there are some huge droplets with a diameter beyond 100 µm even though its probability is much lower. In our previous study [8], to investigate the mechanism of the huge droplets formation, we observed flow pattern appearing in the mixing chamber using a high-speed camera. The flow pattern in the mixing chamber is classified as annular flows that the liquid film flows on the side wall of the chamber. When thick film reaches the hole of the chamber, the huge droplets is discharged because the quantity of the liquid increases. As the water content ratio increases, probabilities of droplets with diameters over 40 μm increase. Figure 5 shows the variation of SMD of droplet with water content ratio. At Y_w = 0, SMD value is approximately 80 μm, which is greater than the mode value shown in Fig. 4. This is due to the appearance of the huge droplets. With increasing water content ratio, SMD value increases, and subsequently reaches 130μm at Y_w = 0.5. However, a further increase in water content ratio decreases SMD value at Y_w = 0.7.

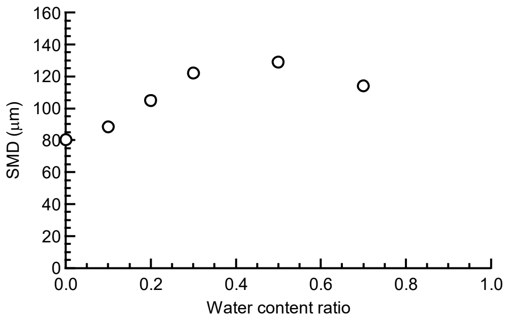

Figure 5: Variation of SMD with water content ratio

The trend of the SMD variation shown in Fig. 4 and Fig. 5 has been already reported in our previous study [8], in which it was found that the increase in SMD with water content ratio in the range of 0 < Y_w < 0.5 results from changing inner structure of droplets. Figure 6 shows the droplet sampled by immersion method. At Y_w = 0, we can observe transparent droplets in this image, which corresponds to pure fuel droplets. On the other hand, emulsified fuel containing small water particles appears at Y_w = 0.5, which demonstrates that the structure of droplets discharged is classified as W/O type emulsified fuel.

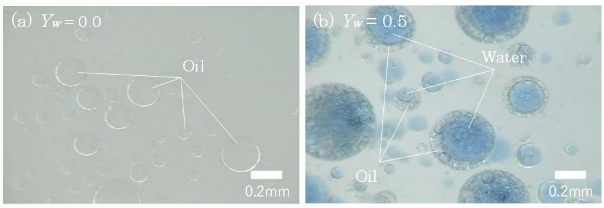

Figure 6: Microscopic images of emulsified fuel droplets sampled by immersion method at (a) Y_w = 0, (b) Y_w = 0.5

Yaron and Gal-Or [10] have proposed complicated expression representing the variation of viscosity with water content ratio. Assuming that continuous phase is soybean oil, we can estimate the viscosity of emulsified fuel using their expression. Figure 7 shows the variation of the viscosity with respect to water content ratio. The viscosity of emulsified fuel increases as the water content ratio is increased. Li et al. [11] discussed the effect of viscosity on the primary atomization, and concluded that high viscosity result in the production of much larger droplets. From these results demonstrated in the previous studies, the increase in SMD value shown in Fig.5 is due to the increase in the viscosity resulting from the changing structure from pure fuel to emulsified fuel.

In the range of Y_w > 0.5, SMD value decreases with the increase in water content ratio. Under this condition, our injector incompletely emulsifies base fuel because of large amount of water. Therefore, pure water with lower viscosity remains in the mixing chamber, and it is subsequently discharged as smaller droplets. The existence of small droplets decreases SMD value shown in Fig.5.

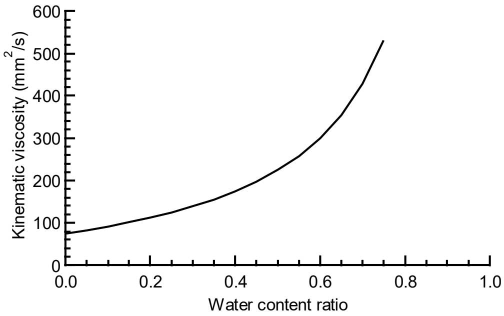

Figure 7: Variation of viscosity with water content ratio

To investigate effects of GLR on SMD value, we varied GLR while keeping water content ratio constant. Figure 8 shows the probability profile of droplet diameter at Y_w =0.3. As GLR increases from 2.47 to 3.35, the probability of smaller droplets increases. Figure 9 shows the relation between GLR and SMD value under conditions with different water content ratio. The result shown in this figure includes those shown in Fig. 5. At each water content ratio, SMD value decreases with GLR.

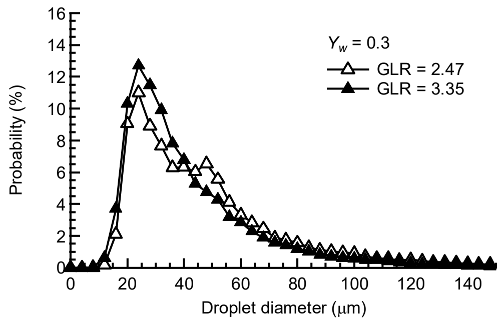

Figure 8: Probability profiles of droplet diameter at conditions with different GLR

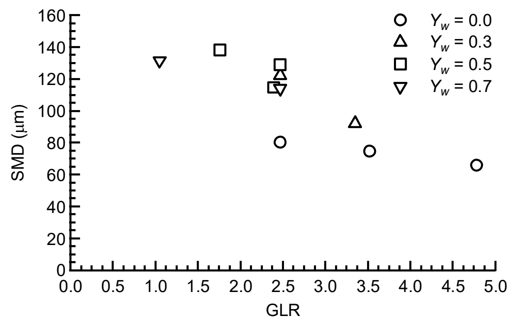

Figure 9: Variation of SMD with GLR

In the previous study [12], the effects of atomizing air velocity, surface tension, and viscosity are expressed using empirical formula. In this study, we focus on viscosity (see Fig. 5) and GLR (Fig. 9) to express the SMD value of droplets discharged from our injector. The effect of viscosity is represented using Reynolds number based on the estimated viscosity (see Fig. 7) and velocity of atomizing air. The empirical formula proposed in this study is shown as follow;

$$SMD = 2421\left(GLR(Re^2)\right)^{-0.21} \quad (1)$$

In above equation, unit of SMD is μm. Figure 10 shows the prediction of SMD value using Eq.1, in which plots are experimental results shown in Fig. 5 and Fig. 9, and solid line is prediction obtained from Eq.1. The SMD predicted shows a good agreement with experimental results, which demonstrates that viscosity and GLR are dominant parameters for the SMD value of droplets discharged from our injector.

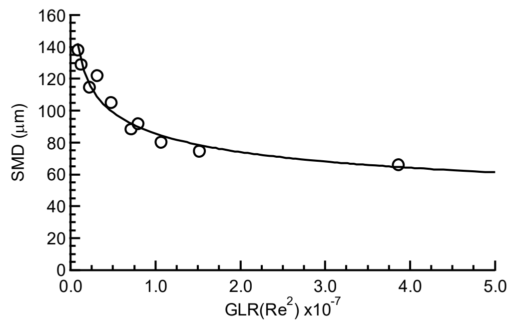

Figure 10: Prediction of SMD value using Eq. 1

3.2 Emissions

Figure 11 shows the NOx emission index (EINOx) with respect to the water content ratio under conditions with equivalence ratio ϕ = 0.9. The $EINO_x$ values were estimated according to a definition proposed by Turns and Myhr [13]. As shown in Fig. 11, NOx emission is reduced by water addition. This is likely due to lower flame temperatures resulting from the latent heat of the added water [5] and the pure dilution effect from the increase in the concentration of water vapor [14] and the increase in OH radical [15]. Although M_a/M_t is increased, which corresponds to conditions shown in Fig. 8, NOx emission is kept a constant.

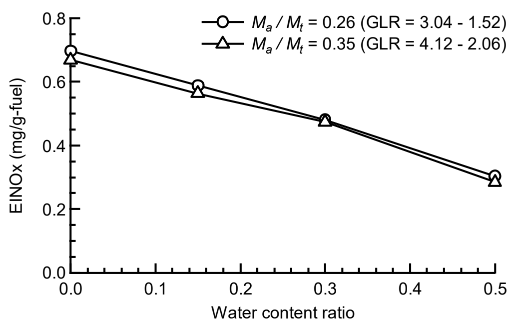

Figure 11: NO_x emission as a function of the water content ratio

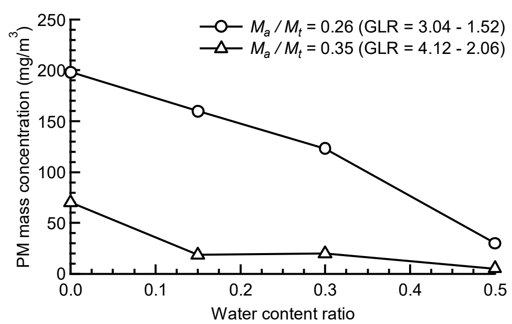

Figure 12: Mass concentrations of PM as functions of the water content ratio

Figure 12 shows the PM emission with respect to water content ratio. PM concentration significantly decreases with increasing water content ratio. This is attributed to the improved mixing of fuel vapor and combustion air. Nazha and Crookes [3] reported that the high-equivalence-ratio region that is present in emulsified fuel spray disappears as a result of the improved mixing of fuel vapor with combustion air, which suppresses soot formation. Tsue et al. [4] also reported that the enhanced mixing caused by the puffing behavior decreases the volume of the sooting region. When M_a/M_t is increased, PM emission is significantly reduced. This is because the high velocity of atomizing air improves the mixing of fuel vapor with combustion air.

4 Conclusions

In this study, we investigated the atomization characteristics of our RIM injector enabling the emulsification of a base fuel without any surfactant. The mean diameter of droplets discharged from RIM injector is determined by the GLR and Reynolds number. The Reynolds number represents the variation of viscosity resulting from the change of inner structure of droplet from pure fuel to W/O type emulsified fuel. A simple expression based on GLR and Reynolds number is proposed, and successfully predicts SMD value of droplets. Finally, we examined the effect of atomizing air ratio on NOx and PM emissions. Under the conditions during experimental trials, the increasing atomizing air significantly reduces the PM emissions because of the improved mixing of fuel vapor with combustion air.

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