Improvement of Atomization of High Viscosity Liquid through Injection Rate Modulation

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Abstract

The effect of injection rate modulation on the spatial dispersion of droplets of high viscosity liquid was investigated by using an electronically controlled accumulator type fuel injection system. The main experimental parameters were the modulation frequency, the modulation amplitude, the viscosity of the liquid, and the ambient pressure. The liquids used in this study were silicon oils with kinematic viscosities in the range of 10 to 30 cSt to simulate the viscosity of heavy fuel oil. The ambient pressure was varied from atmospheric pressure to 1.5 MPa. From the systematic experiments it is explored that applying injection rate modulation improved the atomization characteristics of a viscous liquid. The spray shape becomes wider and the spray angle becomes larger with increasing amplitude and frequency of the injection rate modulation. This tendency was observed at different ambient pressures, although the atomization was improved as the increase of the ambient pressure. The mechanism of this phenomenon is discussed based on the temporal movement of the droplets cloud visualized by the high speed camera. It is found that interactions between injected fuel droplets close to the nozzle played an important role in this effect.

Introduction

The improvement of atomization of high viscosity fuels such as heavy fuel oil is one of the most important issues in the field of marine diesel engines, since the quality of heavy fuel oil used in this field is becoming worse, whereas the requirements of cleaner exhaust emission is becoming more stringent. In the field of diesel engines for automobiles, fuel injection pressures have been increased up to 200 MPa to improve the atomization characteristics, which have successfully improved the combustion and emission performances of recent engines. However, it is difficult to use such high injection pressures in marine diesel engines as they will reduce the reliability of the injection pump and nozzles, which mainly originate from the low quality of the heavy fuel oil. Consequently, an alternative technique for improving the atomization other than the high pressure injection is required. Against this background, the authors are trying to improve the atomization characteristics of high viscosity liquids by employing high-frequency modulation of the fuel injection rate, i.e., periodical fluctuation of the injection rate.

In previous studies, the authors examined the effect of injection rate modulation on the spatial dispersion of fuel droplets and the inner structure of the fuel spray under atmospheric condition [1]-[4]. There are many studies concerning the effect of pressure modulation on PFI injector [5], the effect of velocity fluctuation on the disintegration process [6] and so forth. However, there are not so much studies which have investigated the effect of applying injection rate modulation for diesel-like injection conditions, i.e. rather high injection pressure and high injection velocity with a hole type injection nozzle except the author's studies. From these our studies it was found that the shape of spray becomes wider on modulating the injection rate at a modulation frequency larger than a specified value. Moreover, though not yet published, we have conducted a combustion experiment of fuel injection with diesel engine like injection period, 2 ms, and with 6.8 kHz of injection rate modulation under diesel engine like high pressure and high temperature ambient condition. From the results of this experiment, we have confirmed that the wider spray by injection rate modulation resulted in the promoted combustion, i.e., a shorter combustion period, a higher combustion temperature, and lower soot production in flame. Following on from these studies, the present study seeks to improve the atomization characteristics of high viscosity fuels such as heavy fuel oil by investigating the effect of injection rate modulation on the spray shape, spray angle, and inner structure of a spray injected by a hole nozzle.

Experimental Apparatus

The injection system used in the present study is an electronically controlled accumulator type injection system [7]. Figure 1 shows a schematic diagram of the injector and the inset shows a detailed internal view of the nozzle tip. The conventional injection nozzle for a diesel engine is used in this system; however, the pressure pin was extended to attach an actuator by which to control its movement directly. The actuator attached to the extended pressure pin controls the cross-sectional area of the flow passage by moving a needle valve, enabling an arbitrary fuel injection rate to be set. To realize a variable injection rate shaping, a multi-layer piezoelectric actuator was used as an actuator of our injection system since it has a fast response and good controllability.

Figure 2 shows a typical profile of injection rate examined in this study. As shown in this figure, a high voltage, 480V in this case, was applied to the piezoelectric actuator prior to injection to push the nozzle needle downward and to prevent the liquid from spilling. At the start of injection, the voltage to the piezoelectric actuator was reduced to open the needle valve and start injection. The voltage applied to the piezoelectric actuator was controlled during injection to obtain the desired nozzle needle lift and injection rate fluctuation. The injection rate was measured by the momentum method at atmospheric pressure and room temperature [8]. The injection rate modulation of 4 kHz in frequency was added to the quasi-steady injection of 4 g/s in the average injection rate. In this study, the injection pressure was set to a constant value, 30 MPa, and a spray with a modulation frequency of up to 6 kHz and a modulation amplitude of up to 75% of the average injection rate was examined experimentally. The injection nozzle used is a single hole type one with a hole diameter of 0.24mm and a length to diameter ratio, L/D, of 3. The liquids used in this study were silicon oils with kinematic viscosities in the range 10 to 30 cSt to simulate the viscosity of heavy fuel oil.

A schematic diagram of the experimental apparatus is shown in Figure 3. It consists of the electronically controlled injection system, a constant-volume high-pressure vessel, and an optical system [2]. The internal cavity of the constant-volume vessel is a circular cylinder of 160 mm in diameter, with two quartz observation windows of 110 mm in diameter. The ambient pressure was varied from atmospheric pressure to 1.5 MPa. The injection system was installed on top of the vessel and the tested liquid was injected downward into the vessel. To obtain images of the average spray shape, the spray was illuminated by light from a metal halide lamp and photographed by an ICCD camera with an exposure time of 2.5ms. To obtain instantaneous images of the spray, the ICCD camera was set to high-speed photography mode with an exposure time of 10 μs.

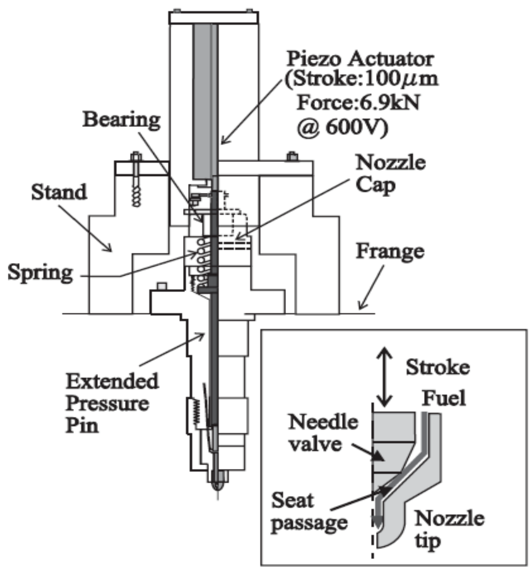
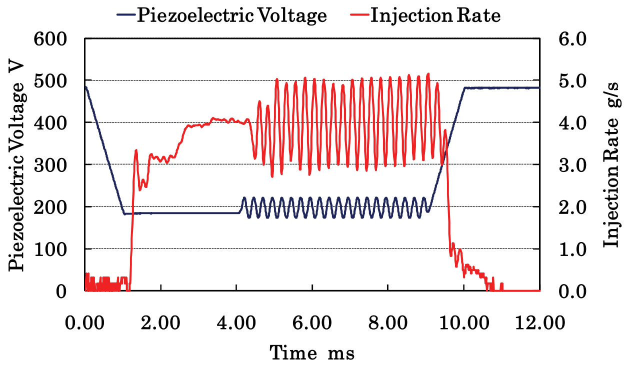


Fig.1 Schematic diagram of injector and piezoelectric actuator



Average injection rate: 4.0 g/s
Amplitude of injection rate: 1.0 g/s
Frequency: 4.0 kHz

Fig.2 Piezoelectric input voltage and injection rate

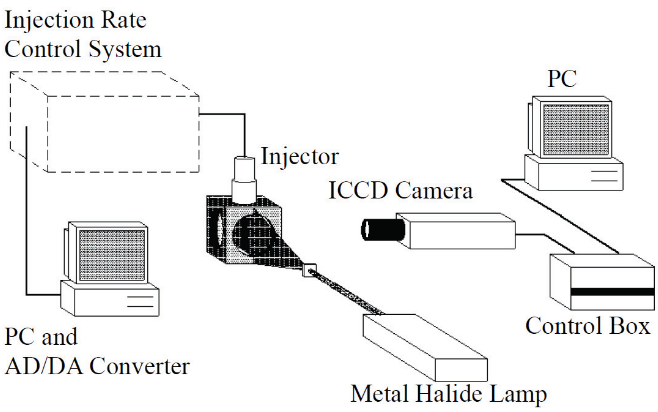


Fig.3 Schematic of experimental apparatus

Effect of Viscosity and Injection Rate Modulation on Spray Shape

Figure 4 shows typical images of a liquid spray injected with a constant injection rate of 4 g/s under atmospheric pressure. It shows the basic trend of the viscosity on the spray shape. These images were obtained with an exposure time of 2.5 ms so that they indicate the average shape of the spray. They show that the kinematic viscosity greatly affects the spray shape. The spray becomes narrower and the intensity of the images decreases with increasing kinematic viscosity, indicating that the atomization characteristics deteriorate with increasing kinematic viscosity. For silicon oil with a kinematic viscosity of 30 cSt, a liquid column is observed close to the nozzle exit.

Figure 5 shows the effect of injection rate modulation on the spray shape and the length of liquid column of spray of 30 cSt silicon oil. The average injection rate is 4 g/s and the modulation frequency is 2 kHz. These images reveal that the liquid column becomes shorter with increasing amplitude of the injection rate modulation. For an injection rate modulation amplitude of 3 g/s, the spray is fully developed from the nozzle exit and no liquid column is observed. The spray becomes wider with increasing amplitude of the injection rate modulation.

Figure 6 shows the effect of the kinematic viscosity of the silicon oil on the injection rate modulation. At a low modulation frequency of 2 kHz and a small amplitude of injection rate modulation of 1 g/s (Fig. 6(a)), although a short liquid column is seen in the spray of the silicon oil with a viscosity 30 cSt, the spray width and the average shape of the spray are almost the same for sprays of silicon oils with different kinematic viscosities. However, a slightly different tendency is observed at a higher injection rate modulation amplitude of 2 g/s and the same modulation frequency (Fig. 6(b)). The spray with silicon oil of 10 cSt has a conical shape and is similar to that obtained with an injection rate modulation amplitude of 1 g/s; however, sprays obtained using higher viscosity silicon oils are wider, especially in the upstream region near the nozzle. This tendency is similar to that at a small amplitude of injection rate modulation of 1 g/s and a higher modulation frequency of 6 kHz (Fig. 6(c)). The spray shape obtained using 30 cSt silicon oil is wider than those obtained with silicon oils with a lower kinematic viscosity.

To quantify and investigate this tendency in more detail, Figs. 7(a)–(c) show the effect of the amplitude of injection rate modulation and the viscosity of silicon oil on spray angle for modulation frequencies of 2, 4, and 6 kHz, respectively. The spray angle is defined as the angle of a triangle that approximates the spray shape between the nozzle tip and 40 mm downstream of the nozzle. The above discussion is quantified and clarified in these graphs. For steady state injection, 30 cSt silicon oil spray has a smaller spray angle than the lower viscosity silicon oil sprays. However, as the injection rate modulation amplitude is increased, the spray angle of 30 cSt silicon oil spray increases drastically; this effect becomes stronger with increasing modulation frequency. In contrast, injection rate modulation with an amplitude lower than 3 g/s and a frequency lower than 6 kHz has little effect on the spray angle of 10 cSt silicon oil spray. For 20 cSt silicon oil spray, the spray angle increases only at a high modulation frequency and a large modulation amplitude.

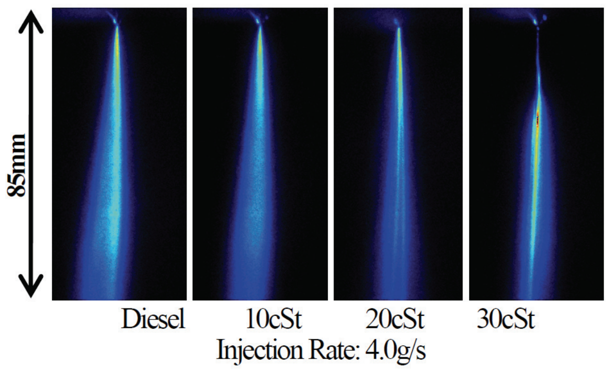


Fig.4 Effect of kinematic viscosity of liquid on average spray shape of quasi-steady spray

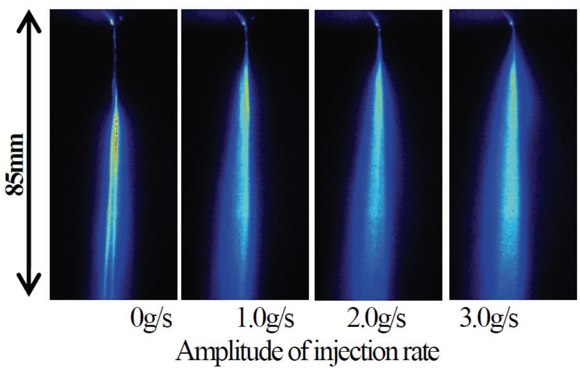
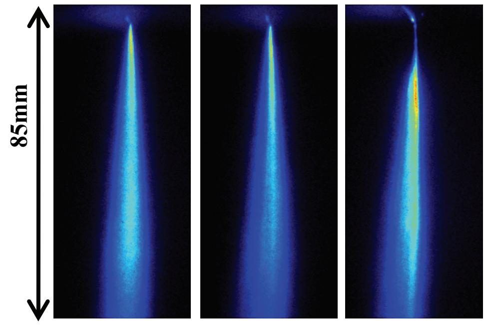
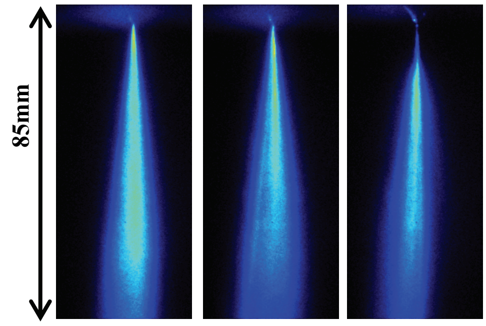


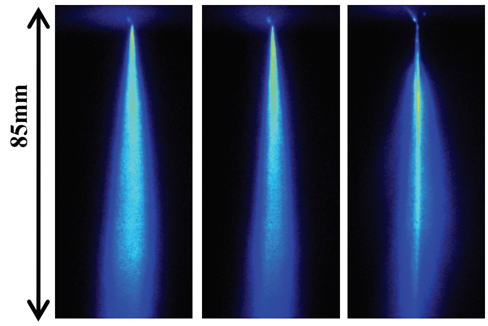
Fig.5 Effect of amplitude of injection rate modulation on average spray shape (Silicon oil 30 cSt, Average injection rate; 4.0 g/s, Frequency; 2.0 kHz)



(a)Frequency: 2.0kHz, Amplitude of Injection Rate:1.0g/s

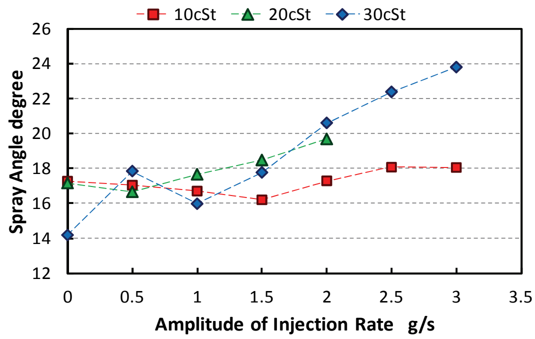


(b)Frequency:2.0kHz, Amplitude of Injection Rate:2.0g/s

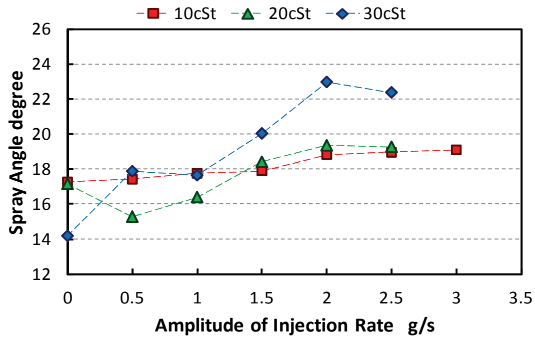


(c)Frequency:6.0kHz, Amplitude of Injection Rate:1.0g/s

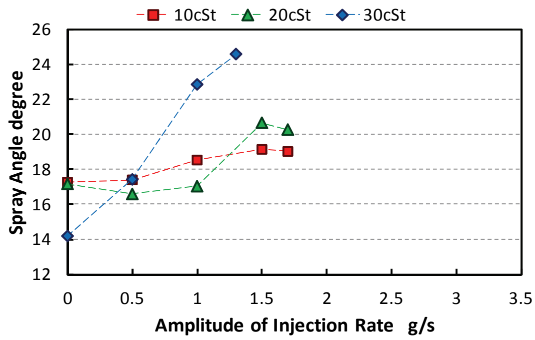
Fig.6 Effect of kinematic viscosity, amplitude of injection rate modulation and modulation frequency on average spray shape (Average injection rate; 4.0 g/s)



(a)Frequency: 2.0kHz



(b)Frequency: 4.0kHz



(c)Frequency: 6.0kHz

Fig.7 Effect of amplitude of injection rate modulation, kinematic viscosity and modulation frequency on spray angle (Average injection rate; 4.0 g/s)

Effect on Inner Structure of Spray

The results of the previous section indicate that injection rate modulation strongly affects atomization of a high-viscosity liquid; specifically, it shortens or eliminates the liquid column and widens the spray, especially in the upstream region of a 30 cSt silicon oil spray. To investigate the mechanism of this phenomenon, instantaneous high-speed images were obtained and analyzed.

Figure 8 shows high-speed images of a spray of silicon oil with a kinematic viscosity of 30 cSt. The modulation frequency is 3 kHz, the modulation amplitude is 2 g/s, and the average injection rate is 4 g/s. The time interval between each image is 0.03 ms. The time given below each image is the time from when the injection rate reaches a maximum during one modulation period. As shown in the images, a dense liquid cloud gradually forms after injection from the nozzle exit. This liquid cloud moves with an almost constant speed (as indicated by the red line) and it penetrates the spray. On reaching a certain distance from the nozzle exit, the liquid cloud expands perpendicular to the spray movement (as indicated by the red circle). These droplets expand continuously and form a wide spray, like that in the image obtained at 0.27 ms (as indicated by the red arrows).

Figure 9 shows high-speed images of the spray with a modulation frequency of 2 kHz and an average injection rate of 4 g/s. Figures 9(a) and (b) show images obtained for modulation amplitudes of 1 and 3 g/s, respectively. The time interval between each image is 0.05 ms. Similar to Fig. 8, a dense liquid cloud propagates with an almost constant speed. However, this movement is faster for a modulation amplitude of 3 g/s than for a modulation amplitude of 1 g/s, mainly due to the higher maximum injection rate. For injection rate modulation with an amplitude of 3 g/s, the spray expands perpendicular to the movement, which is similar to Fig. 8. However, this expansion occurs slightly closer to the nozzle exit and the spray is wider. In contrast, this expansion is not observed and the spray is conical when the injection modulation amplitude is 1 g/s.

These results indicate that the interactions among injected fuel droplets close to the nozzle (e.g., catching up and overtaking motions of the fuel droplets) affect the widening of sprays of high-viscosity liquids. The amplitude and frequency of the injection rate modulation are expected to be important parameters for this phenomenon since a large amplitude and a high frequency should result in large interactions. However, this widening of the spray may only affect a small portion of the injected fuel; a large amount of fuel may pass through the center of the spray. Therefore, the fuel distribution needs to be investigated in a future study.

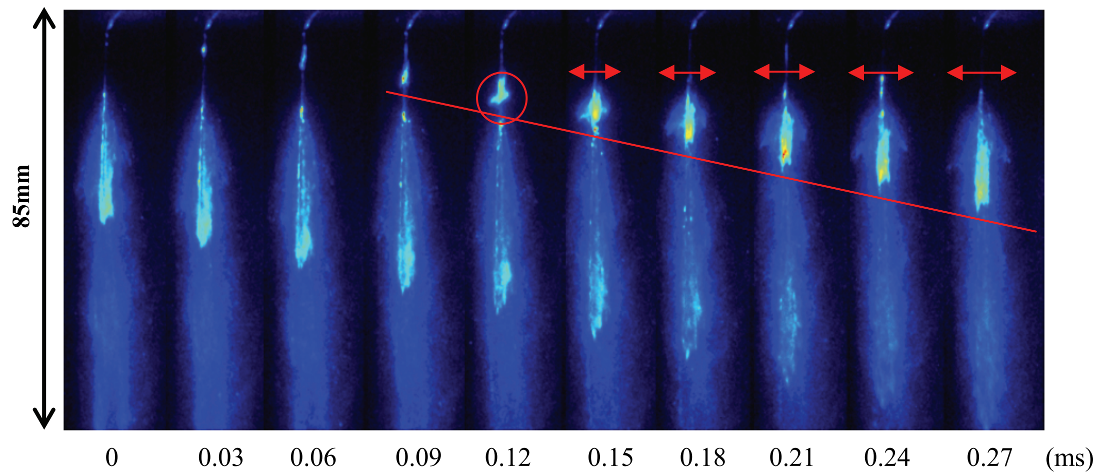
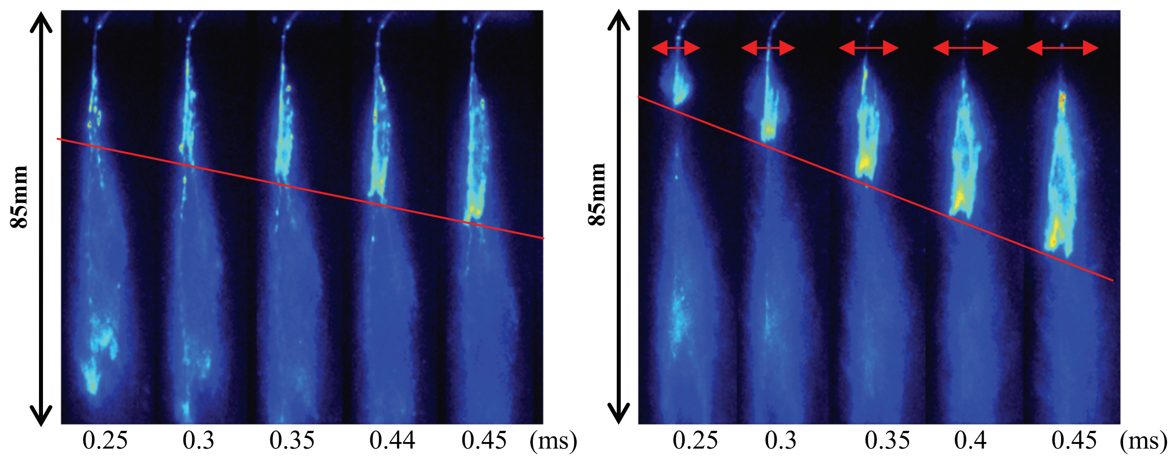


Fig.8 High speed images of spray with injection rate modulation (Silicon oil 30cSt, Average injection rate: 4.0 g/s, Amplitude of injection rate: 2.0 g/s, Frequency: 3.0 kHz)



(a) Amplitude of injection rate: 1.0g/s (b) Amplitude of injection rate: 3.0g/s

Fig.9 Effect of amplitude of injection rate modulation on temporal variation of spray structure (Silicon oil: 30cSt, Average injection rate: 4.0g/s, Frequency: 2.0kHz)

Effect of Ambient Pressure and Injection Rate Modulation on Spray Shape

From the results of former sections, it is found that injection rate modulation greatly affects the atomization of a high-viscosity liquid under atmospheric pressure. To confirm the potential of improving atomization at a higher ambient density similar to that in a cylinder of a diesel engine, experiments were conducted under an elevated ambient pressure. In these experiments, silicon oil with a kinematic viscosity of 20 cSt (which is approximately equivalent to that of heated heavy fuel oil) was used.

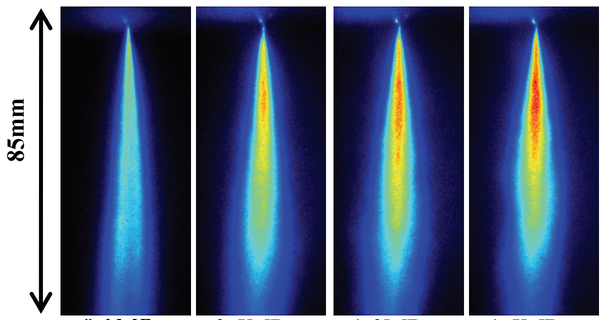


Fig.10 Effect of ambient pressure on average spray shape (Silicon oil: 20cSt, Amplitude of Injection Rate: 3.0g/s, Average injection rate: 4.0g/s, Frequency: 4.0kHz)

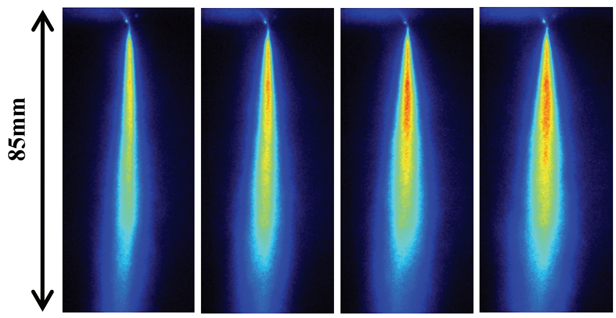


Fig.11 Effect of amplitude of injection rate on average spray shape (Silicon oil: 20cSt, Average injection rate: 4.0g/s, Frequency: 4.0kHz, Ambient pressure: 1.0 MPa)

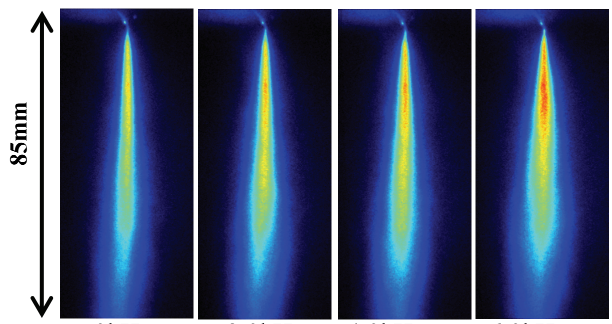


Fig.12 Effect of modulation frequency on average spray shape (Silicon oil: 20cSt, Amplitude of injection rate: 1.0g/s, Average injection rate: 4.0g/s, Ambient pressure: 1.0MPa)

Figure 10 shows the effect of the ambient pressure on the spray shape. The ambient pressure (i.e., pressure inside the vessel) was increased from atmospheric pressure to 1.5 MPa. The modulation frequency was 4 kHz, the amplitude of the injection rate was 3 g/s, and the average injection rate was 4 g/s. As shown in the images, the spray becomes wider and the intensity of the image increases with increasing ambient pressure, indicating improved atomization. Particularly, there is a large difference between the images obtained at atmospheric pressure and 0.5 MPa.

Figure 11 shows the effect of the amplitude of the injection rate modulation on the spray shape under an ambient pressure of 1.0 MPa. The average injection rate was 4 g/s and the modulation frequency was 4 kHz. The amplitude of 0 g/s indicates quasi-steady injection. As shown in the images, the spray becomes wider and the intensity increases with increasing amplitude. Figure 12 shows the effect of the modulation frequency on the spray shape. The amplitude of the injection rate was 1 g/s with an average injection rate of 4 g/s. Similar to the tendency in Fig. 11, the spray becomes wider and more intense and the difference with the quasi-steady spray becomes more pronounced with increasing modulation frequency.

The effects of the modulation amplitude and the modulation frequency are qualitatively similar to those observed under atmospheric pressure. To quantify these tendencies, Fig. 13 shows the effect of the amplitude of the injection rate and the ambient pressure on the spray angle for three different modulation frequencies. It shows that the spray angle increases with increasing modulation amplitude for all three modulation frequencies. This tendency is qualitatively similar at each ambient pressure. The spray angle increases with increasing ambient pressure, indicating that injection rate modulation is effective for improving the atomization characteristics at elevated ambient pressures.

Conclusions

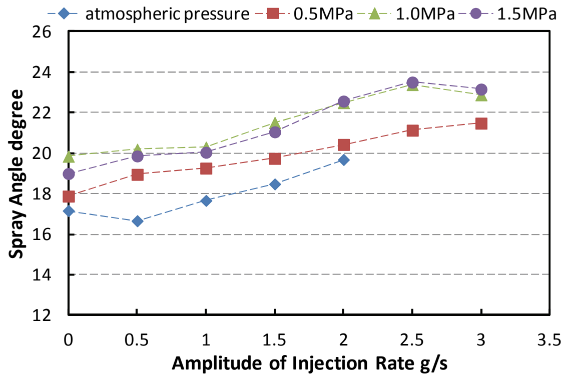
The effects of injection rate modulation on the shape and inner structure of a liquid spray were investigated using an electronically controlled fuel injection system. The main experimental parameters are the kinematic viscosity of the liquid (silicon oil in this study), the ambient pressure, the frequency, and the amplitude of the injection rate modulation. The following results were obtained:

(1) Injection rate modulation greatly affects atomization of a high-viscosity liquid.
(2) The width of the spray increases with increasing amplitude and frequency of injection rate modulation. The spray shape becomes wider and the spray angle becomes larger on applying modulation, especially for a high-viscosity liquid at atmospheric pressure.
(3) Improved atomization characteristics were obtained at higher ambient pressures.
(4) Injection rate modulation gave similar effects at atmospheric and elevated ambient pressures, indicating that it should be effective for improving the atomization of high-viscosity liquids.
(5) The interactions among the injected fuel droplets close to the nozzle generate expanding motion perpendicular to the spray movement, widening the spray.

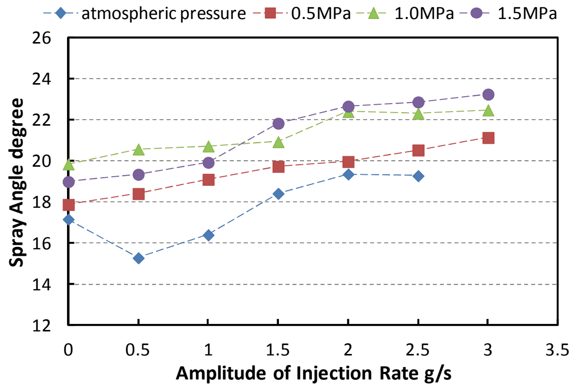
In the future, we intend to investigate the fuel distribution inside the spray and the effect of injection rate modulation on the atomization of high-viscosity liquids (including heavy fuel oils).

Acknowledgements

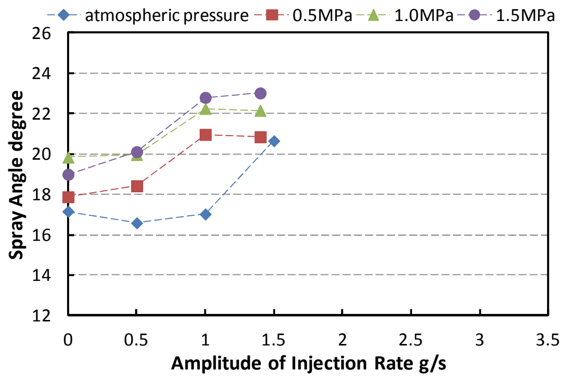
This study was partially supported by the grant from the Fundamental Research Developing Association for Shipbuilding and Offshore. The piezoelectric actuator and injection nozzle used in this study were supported by DENSO Corp.



(a)Frequency: 2.0kHz



(b)Frequency: 4.0kHz



(c)Frequency: 6.0kHz

Fig.13 Effect of amplitude of injection rate modulation, ambient pressure and modulation frequency on spray angle (Silicon oil 20cSt, Average injection rate: 4.0g/s)

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