Effect of Injection Rate Modulation on the Spatial Dispersion of Fuel Droplets and the Inner Structure of Fuel Spray Injected by a Hole Nozzle

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The effects of injection rate modulation, i.e., periodical fluctuation of injection rate, on the spatial dispersion of fuel droplets and the inner structure of fuel spray were investigated using an electronically controlled fuel injection system. Through systematic experiments, it is confirmed that the shape of spray with injection rate modulation becomes wider from a specific modulation frequency. The value of this frequency depends mainly on the average injection rate and the amplitude of modulation. As the average injection rate becomes lower and as the amplitude of modulation becomes larger, the value of frequency becomes smaller. However, the changes of L/D ratio of nozzle hole and ambient pressure show small effect on the value of this frequency. Through the investigations of the visualized images and the computational results of a simplified model, it was estimated that the motions of droplets inside the spray, such as catching up and taking over, and interaction during this period played an important role in the formation of inner structure of spray and the improvement of spatial dispersion of fuel droplets.

1. Introduction

The injection rate, especially the average injection rate, is a key factor in combustion systems, such as in diesel engine, since it is a major parameter which determines the heat release rate. Therefore, though the injection rate has a strong effect on the fuel spray, i.e., droplets dispersion, droplet diameters, temporal evolution of spray and so on, it could not be changed arbitrarily.

The aim of our study is to develop a new controlling technique for the distribution of fuel droplets with the average injection rate unchanged. As a first step for this purpose, we examined the effect of injection rate modulation, i.e., periodical fluctuation of injection rate, on the spatial dispersion of fuel droplets and the inner structure of fuel spray [1]. There are many studies concerning the effect of pressure modulation on PFI injector [2], the effect of velocity fluctuation on the disintegration process [3] and so on. However, there are not so much studies in applying the injection rate modulation to diesel like injection conditions, i.e. rather high injection pressure and high injection velocity with hole type injection nozzle. In this study, we investigated the effect of injection rate modulation on spray shape, spray angle and inner structure of spray injected by a hole nozzle. The examined parameters are modulation frequency, modulation amplitude, average injection rate, L/D of nozzle hole and ambient pressure, i.e., ambient density.

2. Experimental apparatus and procedure

The fuel injection system used in the present study is an electronically controlled accumulator type fuel injection system [4]. A schematic diagram of the injector and a detailed internal view of the nozzle tip are shown in Fig. 1. In this system, we used an ordinary injection nozzle, however, the pressure pin was extended so as 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 fuel flow passage by moving a needle valve, enabling the fuel injection rate to be set arbitrarily. In order to realize variable injection rate shaping, a multi-layer piezoelectric actuator was selected as an actuator of our injection system for its ability of fast response and controllability.
A typical injection rate shaping examined in this study is shown in Fig. 2. The fuel injection rate was measured by the momentum method under atmospheric pressure and room temperature. The injection rate modulation of 6.8kHz in frequency was added to the quasi-steady injection of 6g/s in the average injection rate. In this study, the spray with the modulation frequency up to 7 kHz and the modulation amplitude up to 25% of average

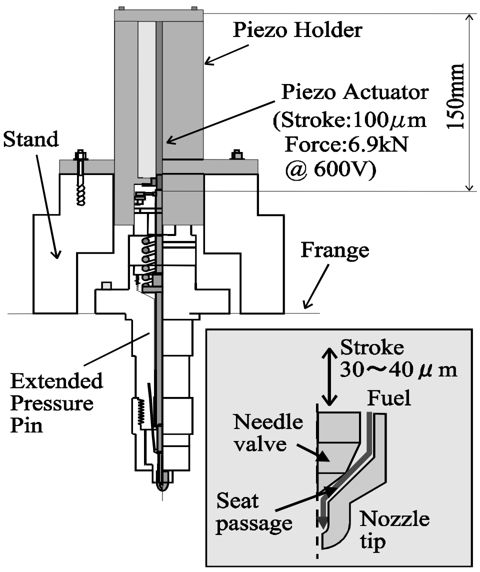


Fig.1 Schematic of injector

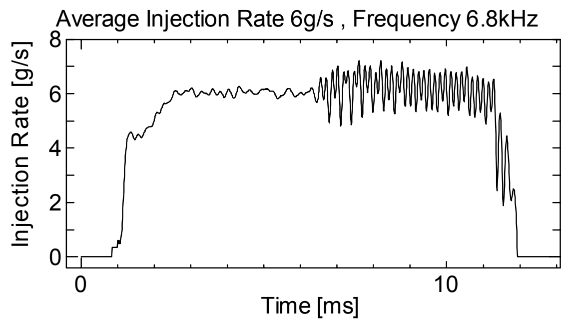


Fig. 2 Typical injection rate shaping

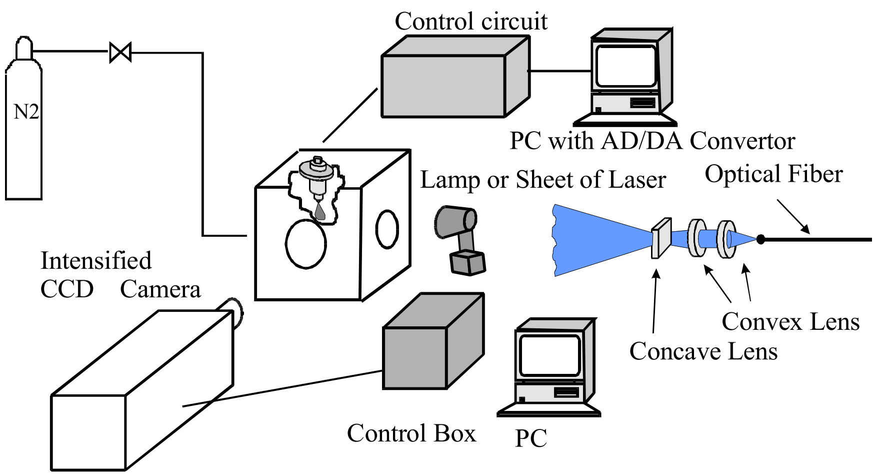


Fig.3 Schematic of experimental apparatus

injection rate were examined experimentally. The injection nozzle used is a single hole type one with a diameter of 0.28mm. The majority of the experiments were conducted using a nozzle with a length to diameter ratio, L/D, of 4. The fuel used in this study was JIS No.2 diesel oil.

A schematic diagram of the experimental apparatus is shown in Fig. 3. The experimental apparatus consisted of the electronically controlled fuel injection system, a constant-volume high-pressure vessel, and optical systems. The internal cavity of the constant-volume vessel is a circular cylinder of 80 mm in diameter, with two quartz observation windows of 80 mm in diameter. The fuel injection system was positioned on the top of the vessel, and fuel was injected downward into the vessel. To obtain the images of averaged spray shape, the spray was illuminated by a tungsten lump and photographed by an ICCD camera with exposure time of 2.5ms. To visualize the sectional image of spray, the spray was illuminated by a light sheet of Ar laser of 488nm in wavelength along the spray axis. In this case, the ICCD camera was set to the high-speed photography mode with exposure time of 10μs.

3. Results and discussion

3.1. Effects of injection rate modulation on spray angle

Figure 4 shows typical photographs of fuel spray with exposure time of 2.5ms, indicating the average shape of fuel spray. The average injection rate was around 6g/s. As shown in these photographs, the modulation frequency affects the spray shape. The spray becomes wider, especially at the modulation frequency of 7kHz, compared with the spray without injection rate modulation.

In order to investigate this tendency in more detail, Fig. 5 shows the effect of modulation frequency on spray angle in three ambient densities. It is clearly shown that the spray angle increases gradually with the increase of frequency, and it increases remarkably from a specified frequency, around 6kHz under the conditions of 6 g/s in the average injection rate and 0.75 g/s in the modulation amplitude. It is also shown this specified frequency does not change with ambient density, though the spray angle becomes larger at elevated ambient densities.

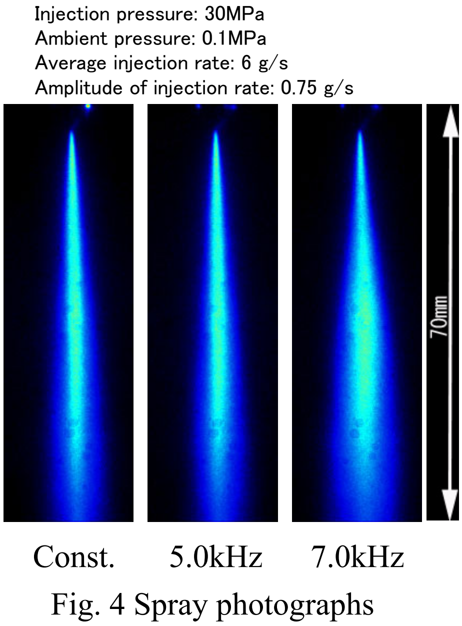


Fig. 4 Spray photographs

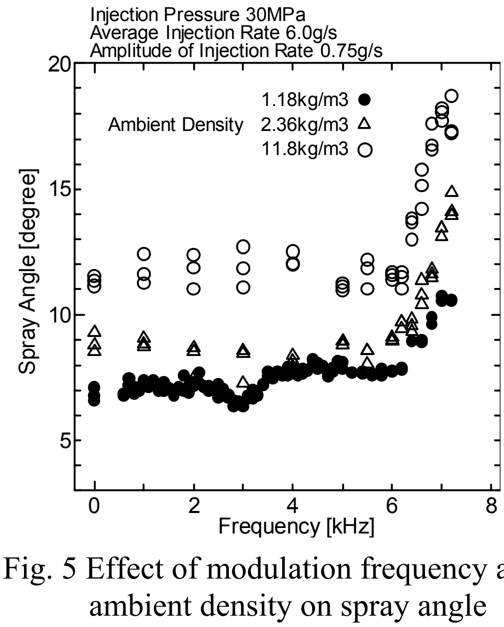


Fig. 5 Effect of modulation frequency and ambient density on spray angle

Figure 6 shows the effect of L/D on the trend of spray angle vs. modulation frequency. Though the variation of L/D is not so large, from 4 to 5, it shows small effect on the value of this specified frequency. From these results, it can be inferred that the ambient conditions and the phenomena occurred inside the nozzle give small effect on the specified frequency, which spray becomes wider beyond this modulation frequency.

Figure 7 shows the effect of average injection rate and amplitude of injection rate modulation on spray angle. Compared to the data in Fig. 5 the average injection rate was reduced from 6g/s to 4g/s. It can be found that the spray becomes wider from 6kHz at the modulation amplitude of 0.5g/s, 5kHz at 0.75g/s and 4kHz at 1.5g/s. Comparing with Fig. 5, it can be summarized that the spray becomes wider from lower frequencies as the average injection rate becomes lower and as the amplitude of modulation becomes larger.

To investigate the effect of modulation amplitude in detail, Fig. 8 shows the relationship between the modulation amplitude and the spray angle in two modulation frequencies. The spray angle becomes larger as the modulation amplitude increases in both frequencies.

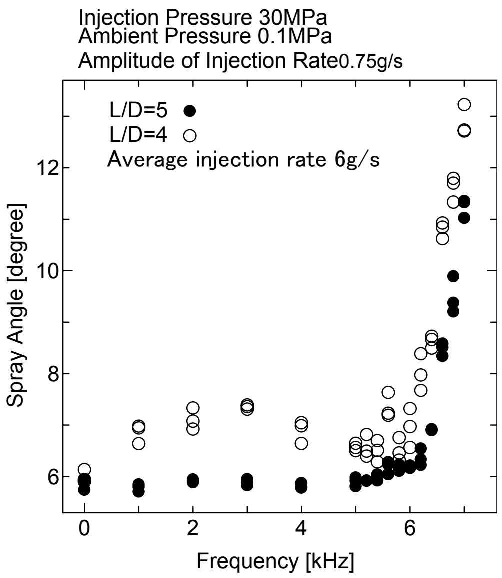


Fig. 6 Effect of modulation frequency and L/D on spray angle

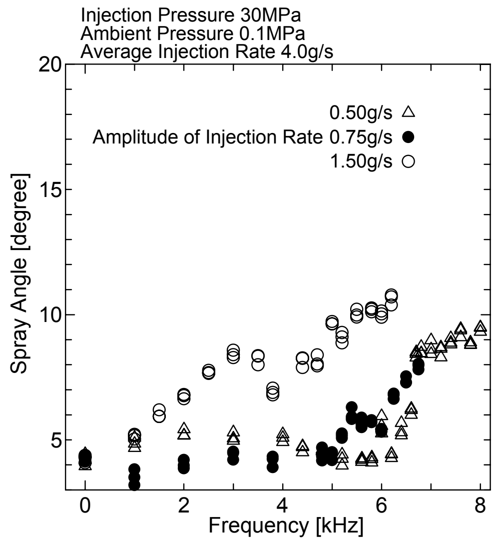


Fig. 7 Effect of modulation frequency and modulation amplitude on spray angle

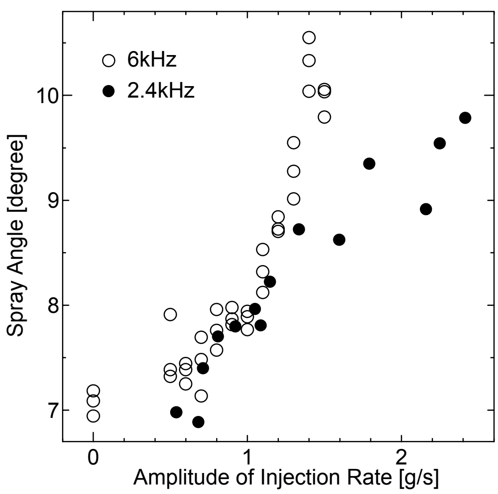


Fig. 8 Spray angle vs. modulation amplitude (Average injection rate: 6g/s)

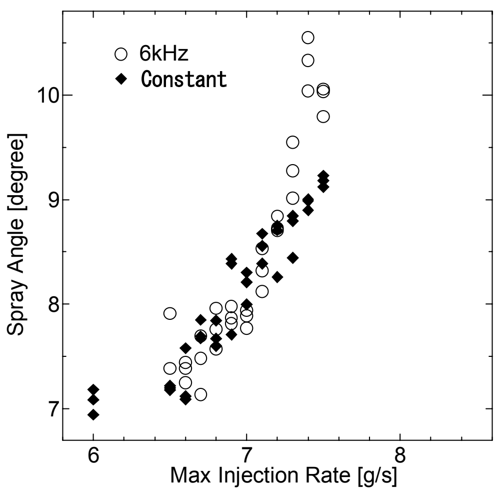


Fig. 9 Spray angle vs. maximum injection rate

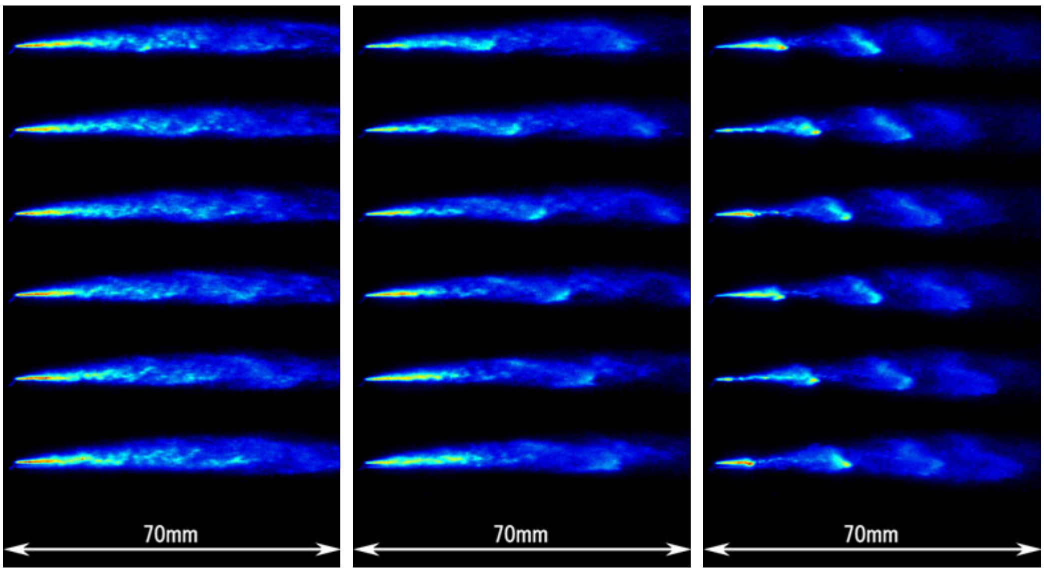
However, in the case of 6kHz, the spray angle increases remarkably beyond the amplitude about 1g/s.

In the experiment of Fig. 8, though the average injection rate was constant, the maximum injection rate changed with the change of the modulation amplitude. To investigate this effect, the spray angles of the spray with various amplitude of modulation at average injection rate of 6g/s and modulation frequency of 6kHz are compared with the spray angle of the spray without modulation but with same maximum injection rate in Fig. 9. In the region of smaller modulation amplitude, the spray angle of the injection rate modulated spray corresponds well with the spray angle of the spray with same maximum injection rate but without modulation. However, in the region beyond the maximum injection rate of 7g/s, i.e., the modulation amplitude of 1g/s, the injection rate modulated spray exhibits a remarkable increase in spray angle. From these results, the increase of spray angle with the modulation amplitude in 2.4kHz should be due to the increase of the maximum injection rate. However, in the case of 6kHz, there should be other mechanisms for the remarkable increase in spray angle. From above observations, it could be concluded that the phenomena occurred in the region rather close to the nozzle exit have the important role in the remarkable increase of spray angle.

3.2. Effects of injection rate modulation on the inner structure of fuel spray

Figure 10 shows the high-speed sectional images of spray in three modulation frequencies at the modulation amplitude of 0.75g/s. Six images per one period of injection rate fluctuation were captured in the spray of 4kHz modulation and three images per one period of injection rate fluctuation were captured in the spray of 6.8kHz modulation. In the images of spray with injection rate modulation, it seems like that a large cloud of droplets was ejected from the dense liquid core and the spray at 6.8kHz, the spray with larger spray angle, shows the liquid core of very short length.

From the high-speed sectional images, the velocities of spray development were analyzed and plotted against the distance from the nozzle exit in Fig. 11. The velocities close to the nozzle



Constant(200 μ s/frame) 4kHz(83.3 μ s/frame) 6.8kHz(49 μ s/frame)

Average injection rate; 6g/s, Amplitude of injection rate; 0.75g/s, Ambient pressure; 0.1MPa

Fig. 10 High-speed sectional images of spray for three modulation frequencies exit, marked by ● and ■, indicate the growth speed of the liquid core. On the other hand the velocities marked by ○ and □ indicate the velocity of the droplets cloud. As shown in this figure, the growth speed of liquid core increases as the distance from the nozzle exit becomes larger and reaches to the maximum just before a large cloud of droplets was detached from the liquid core. This velocity increase corresponds well with the injection rate fluctuation and, therefore, catching up and taking over of the succeeding fuel plays an important role in this region. After this detachment, the cloud of droplets penetrates along the spray axis decreasing its velocity and diffuses rapidly.

Figure 12 shows the high-speed sectional images of spray in three modulation amplitude at the same modulation frequency of 2.4kHz. Six images per one period of injection rate modulation were captured. Same feature to Fig. 10, i.e., a large cloud of droplets was ejected

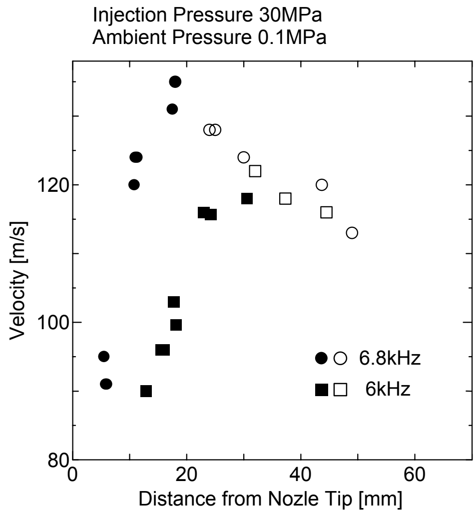
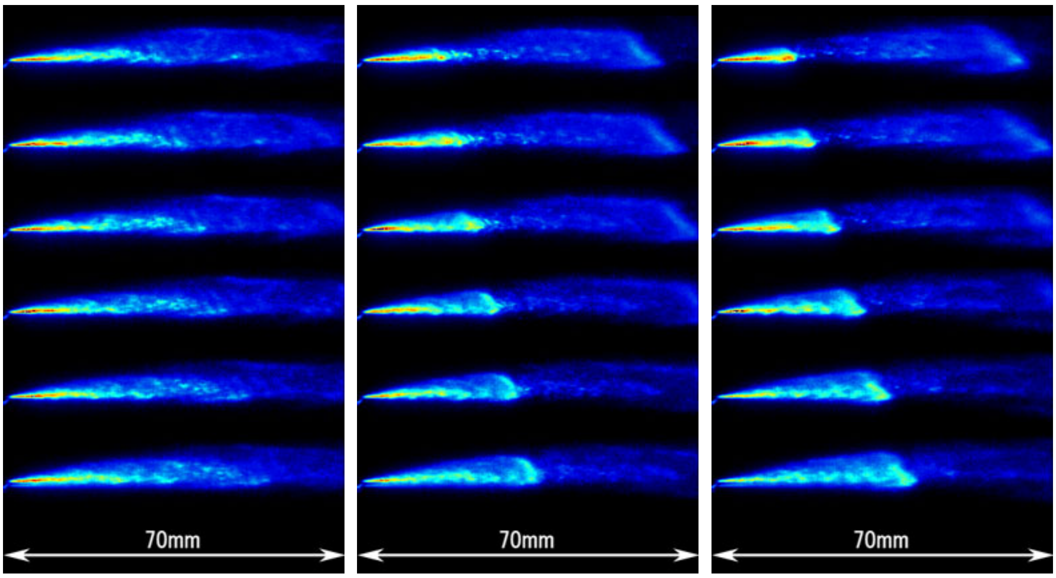


Fig. 11 Velocity vs. distance from nozzle tip

(Average injection rate; 6g/s, Modulation amplitude; 0.75g/s)



Amplitude of injection rate; 0.45g/s

Amplitude of injection rate; 1.5g/s

Amplitude of injection rate; 3.0g/s

Frequency; 2.4kHz (34.7 μ s/frame), Average injection rate; 6g/s, Ambient pressure; 0.1MPa

Fig. 12 High-speed sectional images of spray for three modulation amplitude from the dense liquid core, is shown in these images. The distance between the dense liquid core and the cloud of droplets becomes larger as the amplitude of modulation increases, and it can be inferred that the maximum injection velocity has strong effects on this phenomenon.

3.3. Analysis of the effects of injection rate modulation on the inner structure of fuel spray

To analyze the effects of injection rate modulation on the movement of droplets and the distribution of fuel, the computations based on the simplified model were performed. The computational results of the flight traces of fuel are indicated in Fig. 13. In the computations, the injection period was subdivided into small period and the fuel injected during each small period was assumed to move along the spray axis with constant velocity calculated from the injection rate. It is shown in this figure that the flight traces converge to a point, around 35mm downstream from the nozzle in this case, which implies the movement of catching up and taking over of the succeeding fuel.

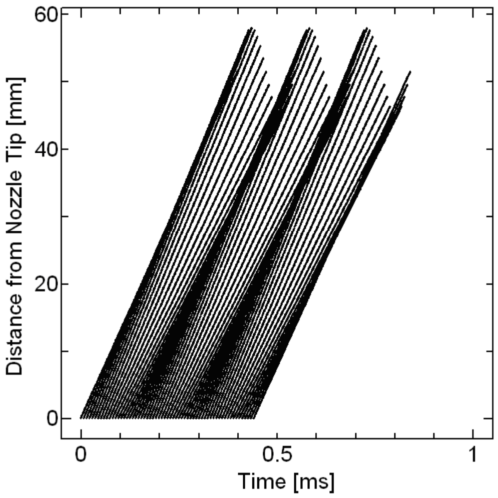


Fig. 13 Calculated flight traces of fuel
(Average injection rate; 6g/s, Amplitude; 0.75g/s, Frequency; 7kHz)

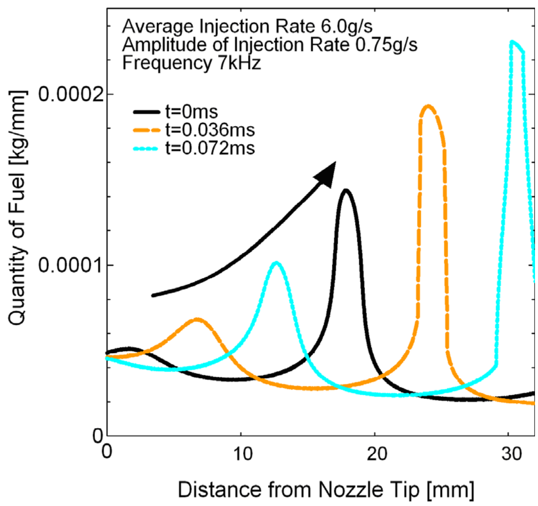


Fig. 14 Temporal change of one-dimensional fuel distributions

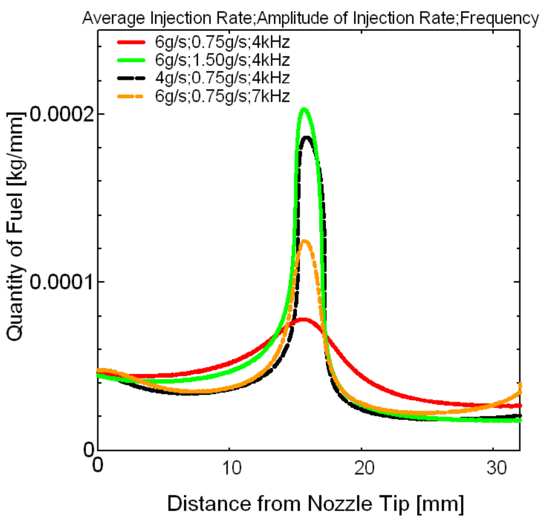


Fig. 15 Calculated one-dimensional fuel distributions

From these results, one dimensional fuel mass distribution was calculated and indicated in Fig.14 for three timings. As the spray develops with time, the region with higher fuel concentration moves to downstream and its concentration becomes distinctive. From the results of parametric computations, as shown in Fig. 15, the fuel concentration close to the nozzle becomes higher as the increase of modulation frequency and modulation amplitude, and as the decrease of average injection rate. This tendency correspond well with the experimental results, and it can be concluded that the interactions among the injected fuel close to the nozzle, such as the movement of catching up and taking over, have the important role in the improvement of fuel dispersion of spray with injection rate modulation.

4. Concluding remarks

The effects of injection rate modulation, i.e., periodical fluctuation of injection rate, on the spatial dispersion of fuel droplets and the inner structure of fuel spray were investigated using an electronically controlled fuel injection system. It is confirmed that the spray with injection rate modulation becomes wider from a specific modulation frequency. The value of this frequency depends mainly on the average injection rate and the amplitude of modulation. As the average injection rate becomes lower and as the amplitude of modulation becomes larger, the value of this frequency becomes smaller. However, the changes of L/D ratio of injection nozzle and ambient pressure show small effect on the value of this frequency. The mechanism of having a wider spray beyond specific frequencies cannot be explained by the increase of the maximum injection rate. It was estimated that the motions of droplets inside the spray, such as catching up and taking over, and interaction during this period played an important role in the formation of inner structure of spray and the improvement of spatial dispersion of fuel droplets.

5. References

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