Microscopic Observation of Primary Spray Structure of High-Pressure Swirl Injector for Gasoline Direct Injection Engine

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Experimental investigations of primary spray structure very close to nozzle of practical high-pressure swirl injector, which is used in gasoline direct injection (GDI) engine, were carried out. Visualizations of primary spray structure were demonstrated using a high-speed video camera with a long-distance microscope. Evaluation of system performance was investigated. Three kinds of light source, such as metal-halido lump, laser beam and laser sheet of Ar-ion laser were applied. Strong intensity of the light source is needed to obtain the image with very high camera speed. Moreover, initial state and development of the spray of the swirl injector were discussed. It has been shown that the liquid fuel column without swirl motion was injected as a compact jet at the beginning of the injection. During the injection period, the spray indicates the quasi-steady state mode. However, the length of the liquid sheet, which is produced from the nozzle exit, indicates the fluctuated motion. Liquid sheet from the nozzle exit has a ligament structure. Using Ar-ion laser sheet and high-speed camera, length and thickness of the liquid sheet can be measured.

1. Introduction

Gasoline direct injection (GDI) engine [1-3] have been developed for improving fuel economy and reduction engine-out emissions. In GDI engines, fuel is directly injected into cylinder therefore the spray characteristics and mixture formation are of primary importance. Fuel injection systems for GDI engine provide both late injection for stratified charge combustion at part load, as well as early injection during the intake stroke for homogeneous-charge combustion at full load [3, 4]. The method of internal mixture formation in GDI engine requires a broad spray angle for early injection and a small spray angle for late injection. Moreover, The GDI injector should be designed to provide a highly atomized fuel spray having an SMD of less than 25 μm for all operating conditions. Therefore, the hollow-cone spray with swirl motion is commonly used in GDI engines under moderately high injection pressures. Swirl motion imparted on the fuel droplets has been effectively utilized for spray penetration reduction while maintaining adequate atomization.

Requirements of GDI injector spray are as follows; shorter fuel spray penetration, the spray shape controllability due to the ambient pressure, well-atomized spray, and so on. Many experimental investigations of gasoline direct injection sprays using several measurement techniques like laser sheet method with high-speed camera [3, 5], laser-induced (exciplex) fluorescence (LIF) [6], laser and phase Doppler anemometor (LDV/PDA) [7, 8], particle image velocimetry (PIV) [9] have been carried out for better control of spray and combustion characteristics. These results provided the detailed information about spray tip penetration, spray cone angle, distribution of the liquid/ vapor phase, or droplet velocity and diameter. However, one of the key processes affecting spray behavior is atomization process. Experimental investigations of atomization process were restricted due to high-speed and very small region phenomena. Although scale-up models have been used to study the primary spray structure, it is impossible to match Reynolds, Weber, and cavitation numbers and time scales in practical high-pressure swirl injector. Microscopic investigation of primary spray structure of practical swirl injector is needed.

Microphotography systems with pulsed laser illumination were conducted in diesel sprays [10-12]. Lai M.-C. et al. [10] used a long-distance microscope with pulse-laser in order to visualize the spray structure very close to the nozzle exit. Chang and Farrell [11] applied a high-speed solid state camera with a high magnification catadioptic lens and Copper-vapor laser to common rail DI diesel injector. Fath et al. [12] developed a 2D measurement technique on basis of Mie scattering using a pulsed Nd:YAG laser and long-distance microscope. The high-magnification images from these studies indicate spray breakup process at or very near the nozzle exit. Recently Schmitz et al. [13] applied measurement system of A. Feth [12] to a high-pressure swirl injector, which is used in GDI engine. Their system could not detect a liquid sheet at the nozzle exit. Gavaises et al. [14] used high resolution CCD camera in order to investigate spray angle at nozzle exit of swirl-pressure atomizer.

On the other hand, numerical simulations [15-17] have been conducted for better understanding of spray formation process. These researches indicated qualitatively good agreement, but the initial conditions, such as liquid sheet thickness and break-up length, were not accurate since break-up process of the liquid sheet from swirl injector has not been examined. In numerical simulation of spray behavior, a sub-model for atomization phenomena is very important. Therefore detailed knowledge of the primary atomization process and the break-up process of liquid sheet play an important role.

In this research, experimental investigations of primary spray structure very close to nozzle of practical high-pressure swirl injector were carried out. Visualizations of primary spray structure were demonstrated using a high-speed video camera (max. 1Mfps) with a long-distance microscope. Evaluation of system performance was investigated. Primary spray structure and behavior of liquid sheet at nozzle exit were discussed using obtained images.

2. Experimental apparatus

2.1 Swirl Injector and experimental set-up

The gasoline engine pressure-swirl injector used in this study is prototype that was fabricated specifically for research use [18]. This injector has a 60° nominal cone angle. Dry-solvent was used as a fuel instead of gasoline. The injector has an inwardly opening needle. A swirl tip is located at the upstream of the injection hole shown in Fig. 1. The diameter of nozzle exit is ϕ 1.0 mm. Fuel is guided round the needle axis by tangential slots generating a controlled swirl flow at the nozzle. Spray symmetrically distributed across the spray axis. This injector produces the hollow cone spray with very small amount of the sac spray (so-called initial spray). It is believed that the swirling fuel forms a very thin liquid sheet around the needle in the swirl injector (Fig. 2). At the exit of the nozzle, the spray becomes a hollow cone, and the kinetic energy of the spray causes an increase of the droplet surface tension and thereby the droplet atomization.

A whole spray images from the swirl injector are shown in Fig. 3. Injection period was 0.75 ms. t_e denotes the elapsed time from the injection start signal. The start of injection delayed from the injection start signal. Delayed time was almost 0.230 ms. It can be seen that the sac spray has very small amount. The main spray indicates the hollow cone spray and generates the large-scale vortices at the upper part of the spray.

Figure 4 shows schematically the experimental set-up for investigation of the primary spray structure of high-pressure swirl injector. The closed vessel used was a steel cylinder, 180 mm in diameter and about 350 mm long. The swirl injector is mounted on the upper end plate of the closed vessel. The closed vessel has three quartz windows for the optical access. The ambient pressure inside the vessel can be changed by an air-compressor. The swirl injector is controlled with an electric injector driver, requiring a high voltage power source and external trigger input for injector pulse width control. Nitrogen gas was used to pressurize the fuel supply system and provides adjustable fuel delivery pressure up to 7MPa. The experiment was performed with an injector pressure of 5 MPa in a closed vessel at atmospheric pressure.

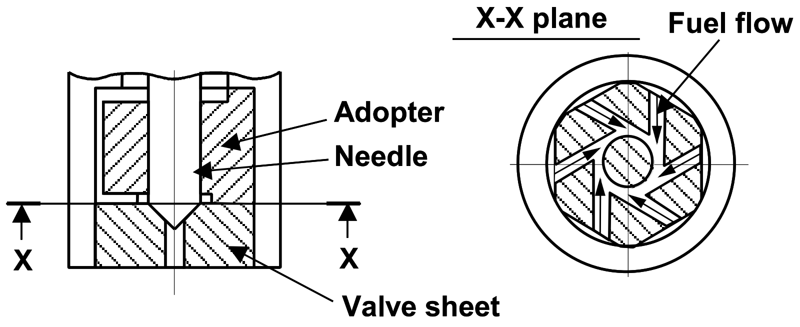

Fig.1 Detail of the nozzle of the swirl injector

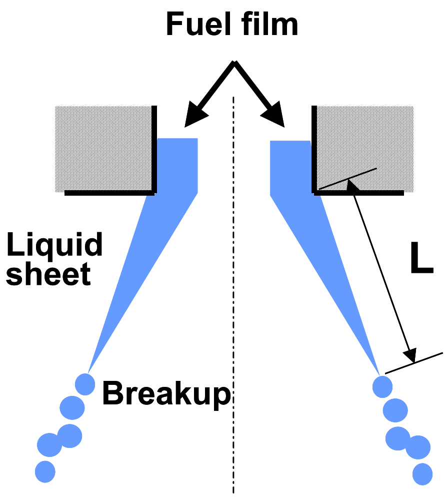

Fig. 2 Schematic image of liquid sheet

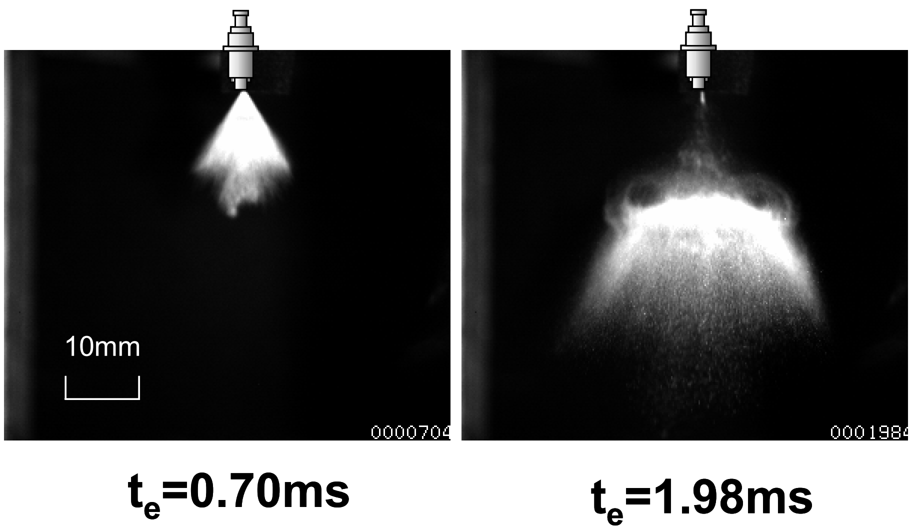

Fig. 3 The whole spray images of the swirl injector

2.2 Measurement technique

A high-speed video camera (maximum speed: 1Mfps, Shimadzu Hyper Vision HEX-108) was used with high resolving long-distance microscope. This high-speed camera has a resolution of 316 x 260 pixels. The transient spray atomization process at the nozzle exit was recorded. The magnified images provided qualitative information of detail spray structure, as well as quantitative information of the injection angle, liquid sheet thickness and droplet break-up length. The transient spray atomization process very close to the nozzle exit could be recorded. The investigated measurement plane has a size of approximately 3.0 mm x 3.0 mm.

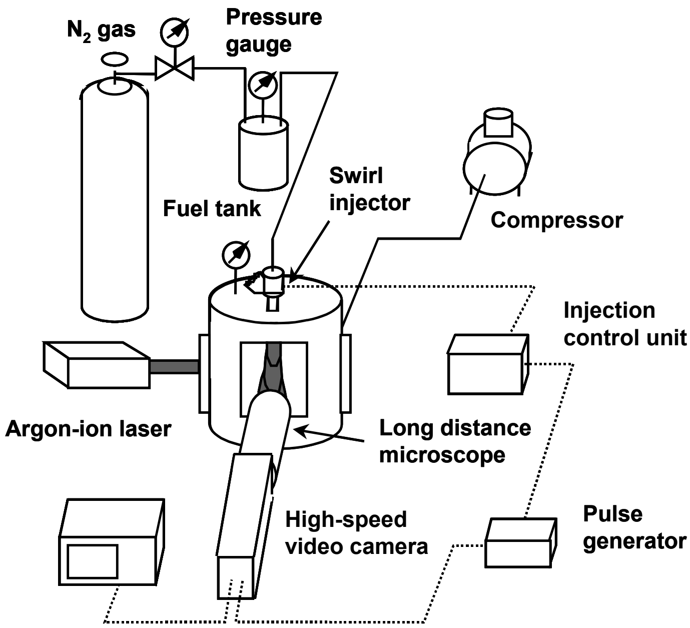

Fig. 4 Experimental set-up

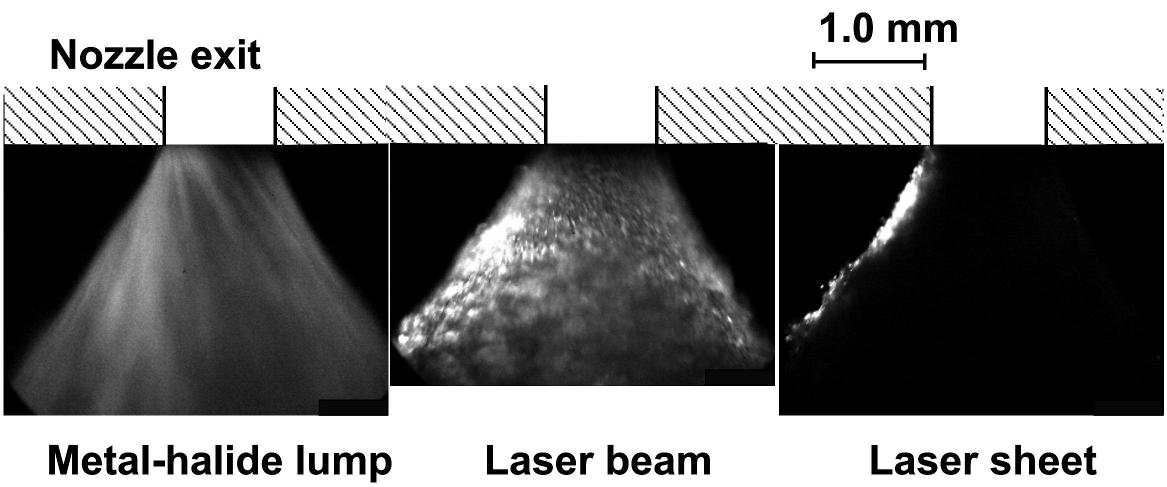

Fig. 5 Effect of the difference of light source on captured images

Three kinds of the light source were used, such as metal-halido lump, laser beam and laser sheet of Ar-ion laser with output power of 6W. At first, metal-halido lump was used, however high-speed camera could not obtain the images at high camera speed (e.g. 500 kfps, 1Mfps) due to lack of light intensity. Therefore, Ar-ion laser was used as the light source. Laser beam of Ar-ion laser was used in order to capture the spray surface at high camera speed. Laser sheet was used for the liquid sheet thickness and length measurements. Captured images using three kinds of light source were indicated in Fig. 5. In this diagram, the image on the left is images obtained using metal-halido lump, in the center is using laser beam of Ar-ion laser, and the one on the right is using laser sheet of Ar-ion laser. Image using metal-halido lump was captured at 63 kfps. Due to the lack of speed of camera, instantaneous image cannot be obtained. Generally speaking, spray droplet velocity has almost 100 m/s at the exit of the nozzle under the condition of injection pressure 5 MPa [16]. When the camera speed is not high even at 63 kfps, it is difficult to obtain the instantaneous image of spray at the nozzle exit. Effect of camera speed on captured image will be discussed in the next section.

Using laser beam of Ar-ion laser, images can be captured at 1 Mfps. This image indicates the surface of hollow cone spray at the nozzle exit. However, the lower part of image is out of focus due to the short focal depth of the long-distance microscope. The swirl injector has a 60° nominal cone angle so that effects of focal depth should be considered. Captured image using laser sheet of Ar-ion laser (camera speed: 1Mfps) indicates a cross-section of the fuel spray at the nozzle exit. Laser sheet thickness and laser power were optimized. Liquid sheet length and thickness can be discussed using laser sheet image with high-speed camera.

3. Experimental results

In order to find out the development of spray very close to the nozzle exit, the temporal sequence images obtained at the camera speed of 63kfps are shown in Fig. 6. These images were captured in one experimental run. Light source is metal-halide lump. Upper part of these images indicates the nozzle exit hole. Three stages in the development of spray can be identified: (1) the initial stage (t_e=0 ~ 0.400 ms); (2) the quasi-steady state (t_e=0.400 ~ 0.750 ms); (3) the post-injection stage. During the initial stage of spray, the spray is shaped like a liquid column as the leading edge region. Thereafter, the spray develops into an asymmetric shape about the central axis of the nozzle exit. From t_e=0.320 ms after the injection start signal, the cone angle of the spray becomes larger. The spray indicates the swirling motion. From t_e=0.400 ms until t_e=0.900 ms, the spray indicates quasi-steady state and the cone angle close to the nozzle shows no variation. The surface of the spray is not smooth and neat. They indicate inhomogeneous surface of the spray due to the tangential slots. After the end of injection, the cone angle of the spray decreases. At t_e=1.104 ms, large droplets can be seen in the image. Using the long-distance microscope, the spray structure at the nozzle exit of the swirl injector can be observed in detail.

Figure 7 shows the laser sheet images in order to understand the initial state and development of spray of the swirl injector. These images indicate the cross-section of the spray very close to the nozzle exit and were obtained at the camera speed of 1Mfps. At first, a liquid fuel column without swirl component comes out. The swirl injector used in this research was designed with very small sac volume inside the nozzle exit so that initial spray cannot be observed. From t_e=0.388 ms, the spray becomes a hollow-cone shape. At t_e=0.452 ms, the spray forms quasi-steady state mode. The liquid film sheet from the nozzle exit can be seen and these surfaces are not smooth and neat due to the ligaments structure. The atomization process can be observed. During the quasi-steady state of the spray, the length of the liquid sheet indicates the variation. These variations of the liquid sheet length will be described in the next paper.

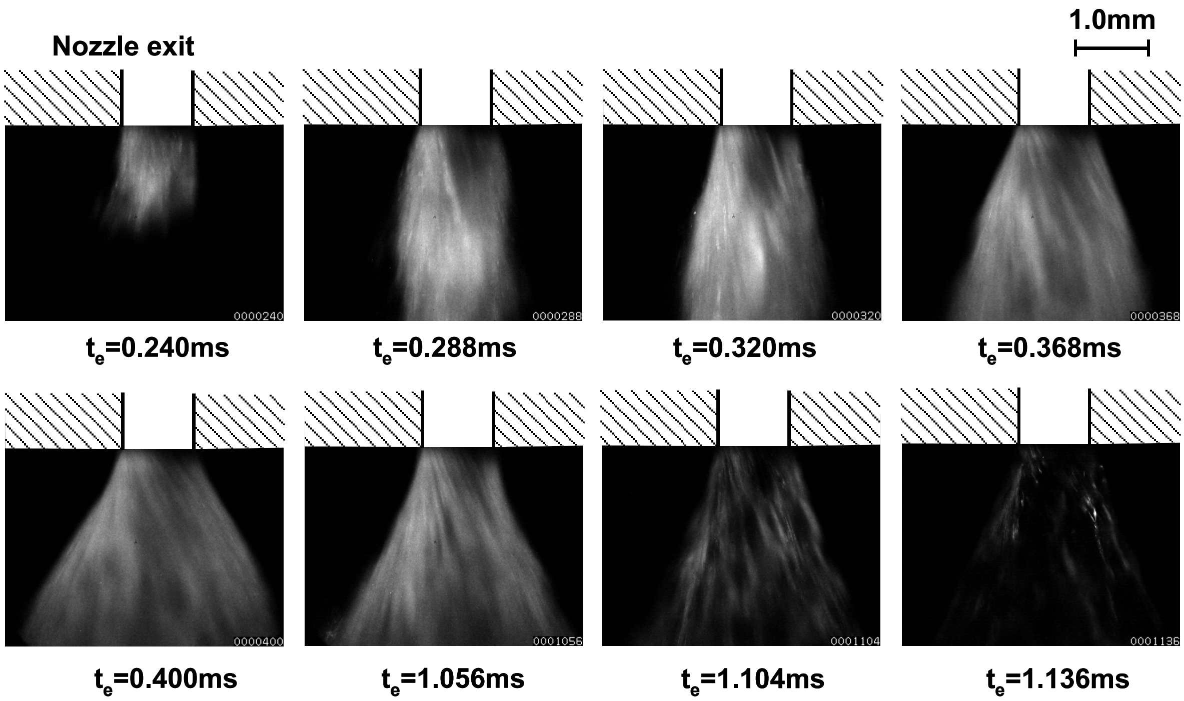

Fig. 6 Temporally resolved primary structure near nozzle exit (P_{inj}: 5.0 MPa, P_a: 0.1 MPa)

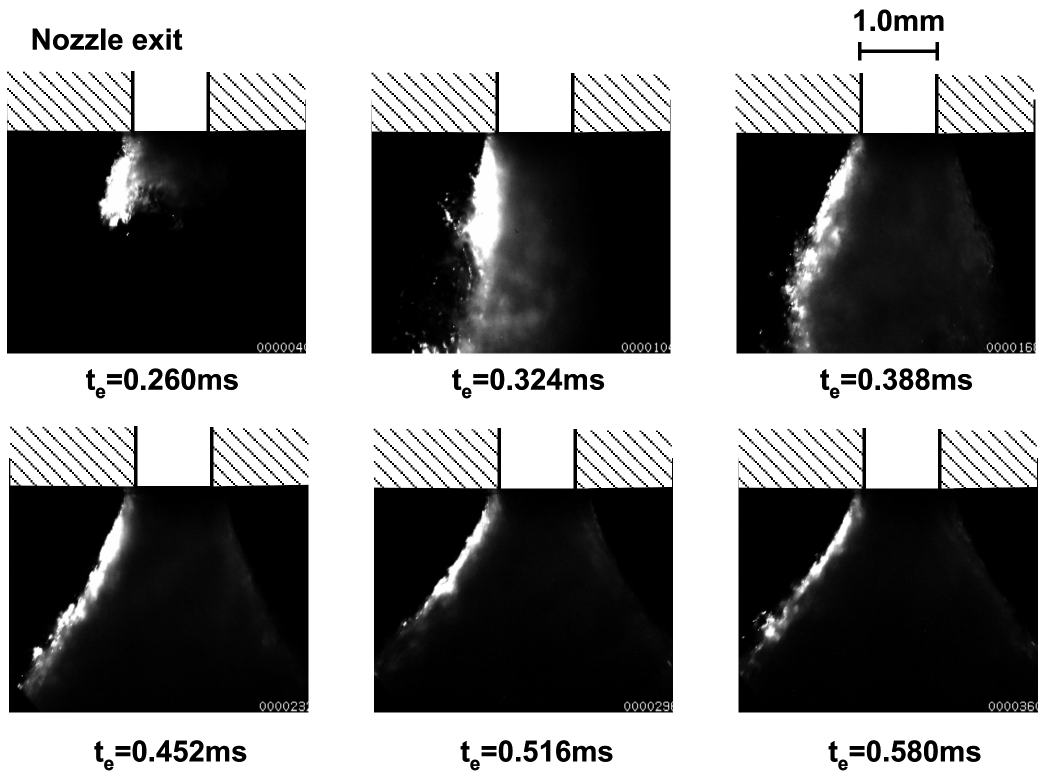

Fig. 7 Initial state of the spray

Using the laser sheet image, length and thickness of the liquid sheet were measured. The effect of camera speed on the measured value was investigated. Captured images at camera speed of 125kfps and 1Mfps were shown in Fig. 8. Enlargement parts of these images were indicated in the same figure. In the case of camera speed of 125 kfps (Exposure time: 0.008 ms), the droplet's movements were observed. If the spray velocity is assumed at approximately 100 m/s, the spray can move at almost 10 pixels during this exposure time. These 10 pixels mean that the length of the movement is 97 μm. Therefore, when the camera speed is relatively low, the length of the liquid sheet includes these the spray movements. Captured image at the camera speed of 1Mfps is indicated at the right side of the figure. In this case, instantaneous image can be captured due to the high camera speed. Therefore, the camera speed of 1Mfps (Exposure time: 0.001 ms) is needed to evaluate the length and thickness of the liquid sheet at the nozzle exit.

Here, the measurement method of liquid sheet length and thickness is explained. Captured images obtained at the camera speed of 1 Mfps with Ar-ion laser sheet were used. These images have the distribution of the intensity as the gray-scale data. In order to clear the edge of the liquid sheet, these images were changed to black and white images using the certain threshold level. Black and white image of captured image is shown in Fig. 9. Length

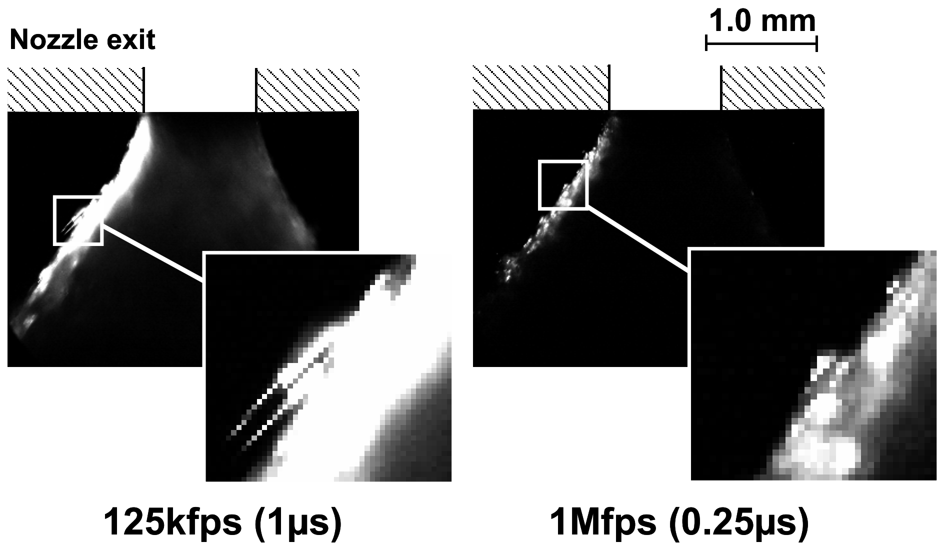

Fig. 8 Effect of camera speed on captured images

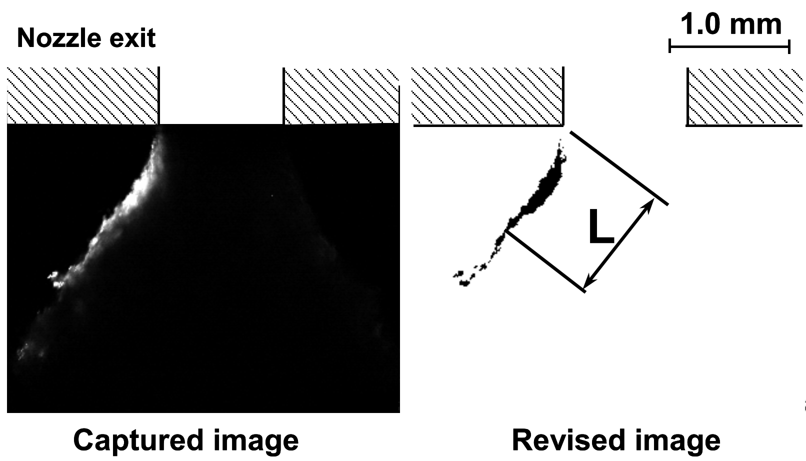

Fig. 9 Definition of the length of the liquid sheet

of the liquid sheet was defined as the continuous part from the nozzle exit. Liquid sheet has a ligament structure so that thickness of liquid sheet has variations. Here, average value of the thickness was discussed. Using this method, the length and thickness of the liquid sheet are 760 μm, and 69 μm respectively. However, the length and thickness of the liquid sheet have temporal and spatial variation. Detail results of the liquid sheet will be described in the next paper.

Detail structure and variation of liquid sheet very close to the nozzle exit of the swirl injector used in GDI engine can be observed using high-speed camera with camera speed of 1Mfps (Exposure time: 0.001 ms) and long-distance microscope.

4. Conclusions

The primary spray structure very close to nozzle of practical high-pressure swirl injector used in GDI engine has been investigated. Visualizations of primary spray structure were demonstrated using a high-speed video camera (max. 1Mfps) with a long-distance microscope. It has been shown that the liquid fuel column without swirl motion was injected as a compact jet at the beginning of the injection. During the injection period, the spray indicates the quasi-steady state mode. However, the length of the liquid sheet, which is produced from the nozzle exit, indicates the fluctuation motion. Liquid film sheet has a ligament structure. Using Ar-ion laser sheet and high-speed camera, length and thickness of the liquid sheet can be measured.

5. References

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