Droplet diameter measurement near a nozzle exit of a common-rail Diesel injector using PDA

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Abstract
The purpose of this study is to measure the droplet diameter distribution very close to the nozzle hole of a common-rail Diesel injector using a phase Doppler anemometer (PDA). Experimental investigations of atomization process were restricted due to very high-speed and very dense spray region phenomena in the case of the spray from the common-rail injection. In this experiment, droplet diameter and axial velocity in spray formed by one hole of the common-rail Diesel injector were measured with HiDense PDA system to investigate atomization characteristics near the nozzle exit of the common-rail Diesel injector. HiDense PDA system permits accurate measurements in spray with extremely high particle concentrations, and it is the only PDA system available that provide high quality measurements in the core region of the spray cone. Optimization of optical set-up and measurement condition of signal processor were carried out to measure the accurate droplet diameter distribution very close to the nozzle exit under higher injection pressure conditions. It is possible to measure the droplet diameter distribution at the 10mm from the nozzle exit under 100MPa as the injection pressure. Radial distributions of droplet velocity were measured using HiDense PDA system. At 10 mm from the nozzle exit, there are strong shear layer between the surround air and injected spray. Narrower droplet distribution can be seen at 10 mm from the nozzle exit.

Keywords
Phase Doppler anemometry, Common-rail Diesel injector, Droplet diameter, Break-up

Introduction
In recent years, the fuel injection pressure in diesel engines has been increased to improve atomization, and to achieve high efficiency under high supercharging and high EGR conditions [1]. The problem with the compression ignition (CI) engine is emissions of nitrogen oxides (NOx), and particulates (PM). It is very important to control the fuel injection from higher injection pressure and to obtain better fuel mixing inside combustion chamber [2-4]. Many strategies have been developed to control the in-cylinder combustion process, in addition to the use of exhaust after-treatment devices. The in-cylinder control parameters include injection pressure, number of injections, shape and timing, EGR, and swirl ratio. Understanding of the atomization process can contribute to improving the performance of diesel engines.
In order to understand the spray characteristics formed by the common-rail diesel injector, investigations of diesel injection sprays using several measurement techniques like laser sheet method with laser-induced (exciplex) fluorescence (LIF), phase Doppler anemometor (PDA) [5], particle image velocimetry (PIV) have been carried out for better control of spray and combustion characteristics [6]. Atomization process of liquid jet is categorized in three regions, (1) cavitation inside nozzle, (2) primary break-up of liquid ligament, and (3) secondary break-up of larger droplets [7]. Experimental investigations of atomization process of the common-rail injector used in Diesel engine were restricted due to very high-speed and very

dense spray region. 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 simultaneously in practical high-pressure common-rail injector. There are some research results to try to measure the droplet velocity and diameter distributions very close to the nozzle exit of DISI or the common-rail diesel injector. Crua et al. tried to visualize the jet break-up process of the common-rail diesel injection using ultra-high speed imaging with the long-range microscope [8]. They tried to measure the droplet diameter distribution very close to the nozzle exit [9]. Zama, Y. et al. measured the velocity distributions very close to the nozzle exit of DISI injector using ultra-high speed PIV method [10]. Maximum velocity of the spray was estimated from the fitting analysis of the spray velocity distribution in radial distribution by Goertler solution. Consequently, the region where the spray velocity on center axis of the spray was constant appeared near the nozzle exit such as potential core region well-known in a turbulent jet. Ballistic imaging is more powerful tool to visualize very dense spray [11, 6]. X-ray phase-contrast imaging has been used to capture the spray morphology very close to the nozzle exit [12]. They showed that the higher injection pressure had led to earlier breakup closer to the nozzle at lower needle lift. Kastengren et al. tried to measure the droplet diameter of the common-rail diesel injection sprays using ultra-small-angle x-ray scattering (USAXS) [13, 14]. In our previous research, droplet diameter and axial velocity in spray formed by one hole of multi-hole injector were measured with HiDense PDA system to investigate atomization characteristics near the nozzle exit of the DISI injector under 20MPa as the injection pressure [15]. Effects of laser power at the measurement location on detection of smaller droplets were considered in PDA measurement. Atomization process very close to the nozzle exit of the real common-rail diesel injector is strongly needed.

The purpose of this study is to measure the droplet diameter distribution very close to the nozzle exit of a common-rail Diesel injector using a phase Doppler anemometer (PDA). In this experiment, droplet diameter and axial velocity in spray formed by single hole of the common-rail Diesel injector were measured with HiDense PDA system to investigate atomization characteristics. HiDense PDA system permits accurate measurements in spray with extremely high particle concentrations, and it is the only PDA system available that provide high quality measurements in the core region of the spray cone. Optimization of optical set-up and measurement condition of signal processor were carried out to measure the accurate droplet diameter distribution very close to the nozzle exit of the common-rail injector under higher injection pressure conditions up to 100MPa as the injection pressure. Radial distribution of droplet diameter and velocity were measured using HiDense PDA system in comparison with the ultra-high-speed visualization using high-speed camera.

Experimental apparatus

Figure 1 shows schematically the experimental arrangement for investigation of the primary spray structure of high pressure common-rail injector. The common-rail injector is controlled with an electric injector driver, requiring a high voltage power source and external trigger input for injector pulse control. Electrical pump and the common-rail were used to pressurize the fuel supply system and provides adjustable fuel delivery pressure up to 100 MPa. The common-rail injector has single hole nozzle with 0.125mm as the nozzle diameter.

For droplet diameter and velocity measurements near the nozzle exit of the common-rail injector, HiDense phase Doppler anemometer (57x50: Dantec Dynamics) was used as shown in Fig. 1. The configuration of this application was equal beam separations of 38 mm for the 514.5 nm wavelengths from OPSL laser. The Dantec 57x80 receiver optical system had a scattering light collection lens with focal lengths of 310mm. The receiver was positioned at a scattering angle of 68 degrees to collect the light scattered due to refraction. The scattered light is focused through a unique spatial filter (slit) and is collimated to a segmented lens. Each part of this lens guides the light in a multimode optical fiber. The width of the spatial filter (25; 50; 100 and 200 μm) can be selected by the mean of a slit selector. The part of the image which falls on the slit itself corresponds to the probe volume. Only the light from the probe volume is passed by the optical fiber to the photo-multipliers. Because PDA is based on single-particle scattering theory, and it is necessary to measure relative smaller droplet under 10 μm in diameter accurately and to treat high-density particle sizing with high spatial resolution, decreasing the measurement volume is often necessary to achieve highly accurate results under dense-particle conditions. Filter of width 25 μm is used in this experiment. The signal processor (Dantec BSA-P80) was used in this work. The operational characteristics of the former processor and its performance with regard to velocity and size measurements in fuel injected spray are discussed in details by Lading (1988) [16]. The processor is based on multi-bit burst detection and multi-bit FFT signal processing. Doppler signal frequencies of up to 180 MHz and frequency bandwidths up to 120 MHz can be accommodated [17]. 10,000 validated droplets were measured at each point. Measurement locations were 10 and 20 mm from the nozzle exit as shown in Fig. 2. Especially, droplet diameter distribution at 10 mm from the nozzle exit was focused to consider the measurement accuracy. Phase-locking method was used to analyze the time-series of droplet behavior from start of injection signal using HiDense PDA system. In this research, droplet diameter and axial velocity distributions during the quasi-steady state of transient injection spray were focused. Experimental conditions were shown in Table 1.

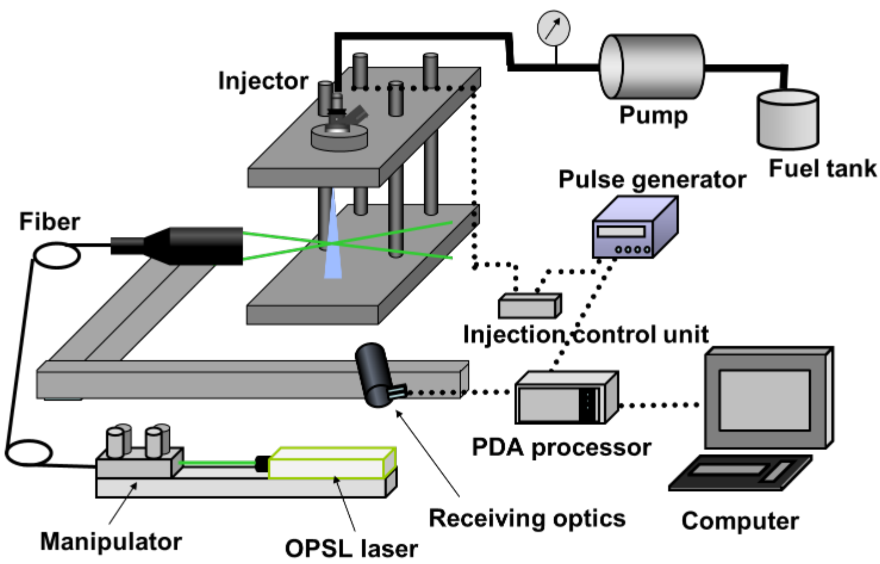


Figure 1. Experimental setup

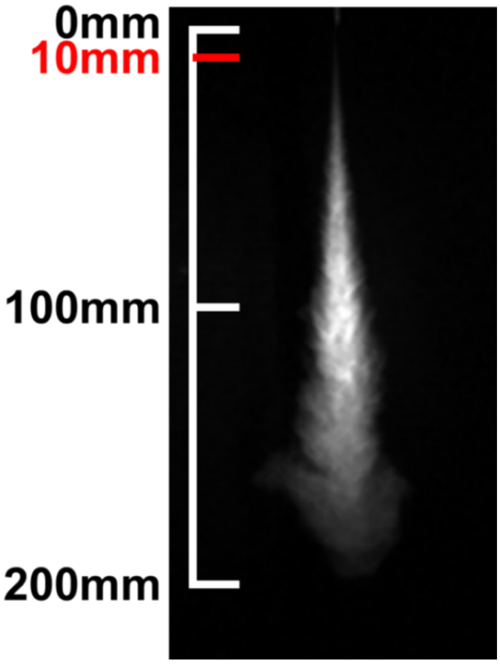


Figure 2. Measurement location of the single hole common-rail injector

Table 1 Experimental conditions

Fuel	n-Dodecane
Injection pressure	100MPa
Injection duration	3ms
Laser power	200mW
Wavelength of laser beam	514.5nm
Axial distance	z=10mm
Number of samples	10000
Range of velocity, m/s	$0 \leqq V \leqq 504.61$

Optimization of PDA system

For droplet diameter and velocity measurements near the nozzle region, HiDense phase Doppler anemometer (57x50: Dantec Dynamics) was used in one-dimension (1-D) configuration. HiDense PDA system permits measurements in spray with extremely high particle concentrations. Applying one dimensional configuration decreases the measurement time further and allow more of the dense spray regions to be probed, since the probability of only two beams forming a measurement volume must be higher [5].

At first, the measured droplet velocity distribution were considered in the case of 100 MPa as the injection pressure. Using LDA system, without droplet diameter measurement, the maximum axial droplet velocity was 500 m/s at the 10 mm from the nozzle exit. Therefore the range of droplet velocity was changed from the previous setup [15].

Secondary, the optimization of receiving optics and signal processor setup were carried out. The example of the effects of signal processor setup on measured droplet velocity distributions was shown in Fig. 3. Optimal settings for the photodetector by changing the Signal gain and

Sensitivity were tried. Signal gain is the gain of the signal in the photomultiplier, and sensitivity is the voltage applied to the photomultiplier. According to the results of previous studies [15], the optimum setting was checked by increasing the sensitivity and decreasing the signal gain in order to increase the sensitivity of the detected droplet. As a result, at a fuel injection pressure of 100 MPa, the lowest error data and the highest mean flow velocity were obtained when the sensitivity was 600 V and the signal gain was 0 dB, as shown in Fig. 3. Fig.4 indicates the droplet diameter distribution and relationship between the measured droplet diameter and droplet axial velocity. Compared with the previous conditions [15] of 500V sensitivity and 2dB signal gain, the error data was decreased. In the case of 500V as sensitivity and 2dB as gain, larger droplets with lower velocity were measured, therefore mean diameter was larger. In this research, 600V sensitivity and 0dB signal gain as the signal processor setup were used for the droplet diameter measurements very close to the nozzle exit of the common-rail injector with 100 MPa as the injection pressure. It is quite important to check the optimal setup of the transmitting and receiving optics and the signal processor setup on detection of very higher droplet velocity with smaller droplet diameter.

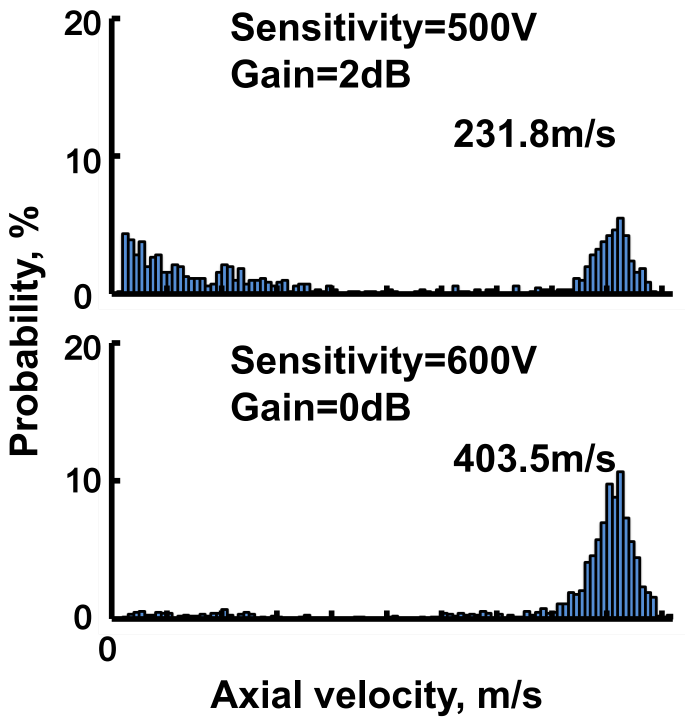
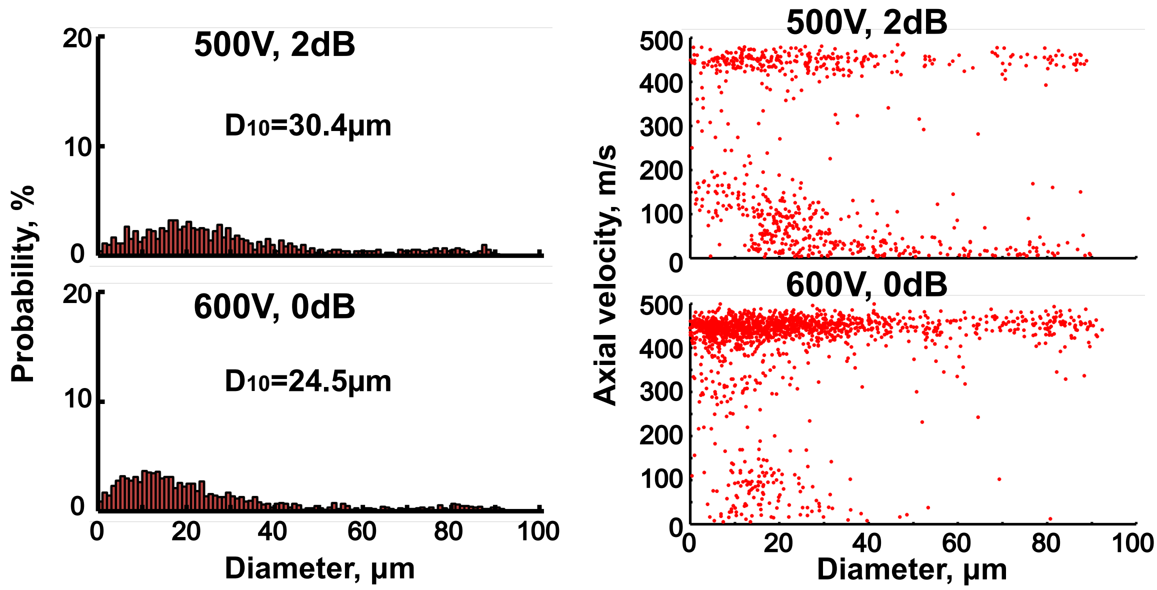


Figure 3. Effects of signal processer setup on obtained droplet velocity distribution.



(a) Droplet diameter distribution (b) Relationship between droplet diameter and velocity

Figure 4. Effects of signal processer setup on obtained droplet diameter distribution.

Results and Discussion

The purpose of this study is to measure the droplet diameter distribution very close to the nozzle hole of the common-rail injector using HiDense PDA system under higher injection pressure conditions. In this experiment, droplet diameter and axial velocity in spray formed by single hole of the common-rail injector were measured with HiDense PDA system to investigate atomization characteristics very close to the nozzle exit of the common-rail injector. Figure 5 shows the axial velocity and droplet diameter distributions at Z=10 and 20mm from the nozzle exit under 100 MPa as injection pressure. Mean axial velocities and SMD were shown in these figures. Mean axial velocity at Z=10mm under 100 MPa as injection pressure indicates over 450m/s. As it goes to the down-stream, mean axial velocity and SMD decreases due to drag force under 100 MPa as injection pressure. Droplet diameter distribution at Z=10mm shows the good distribution under even 100 MPa as injection pressure. It is possible to obtain droplet diameter and velocity distribution very close to the nozzle exit of the common-rail injector using HiDense PDA system with optimization of optical set-up. The atomization process of the spray can be discussed in this research. HiDense PDA system permits accurate measurements in spray with extremely high particle concentrations, and it is the only PDA system available that provide high quality measurements in the core region of the spray cone. It is possible to measure the droplet diameter distribution at the 10 mm from the nozzle exit under 100 MPa as the injection pressure, under the conditions with optimization of optical set-up and measurement condition of signal processor.

Fig. 6 indicates the radial distribution of mean droplet velocity and diameter at the 10 mm from the nozzle exit under 100 MPa as injection pressure. Mean droplet velocity is almost 400 m/s at the central axis of nozzle exit. The mean droplet velocity is decreased as the radial distance is increased up to 1.0mm at 10 mm from the nozzle exit. The mean droplet diameter is 19.8 μm at the central axis of nozzle exit. Detected sample number is larger than the case of spray edge region due to the dense spray region at the central axis. The mean droplet diameter and measured sample number are decreased as the radial distance is increased. At the edge of spray region, it is difficult to detect droplets due to the shear layer. Here, ultra-high-speed visualization of the spray from the common-rail Diesel injector was carried out using ultra-high-speed camera with 10Mfps as frame speed. Fig. 7 shows the ultra-high-speed image obtained near 10 and 20 mm from the nozzle exit. At 20 mm from the nozzle exit, wider droplet distribution can be seen using ultra-high-speed visualization. At 10 mm from the nozzle exit, there are strong shear layer between the surround air and injected spray. Therefore the narrower droplet distribution can be seen at 10 mm from the nozzle exit.

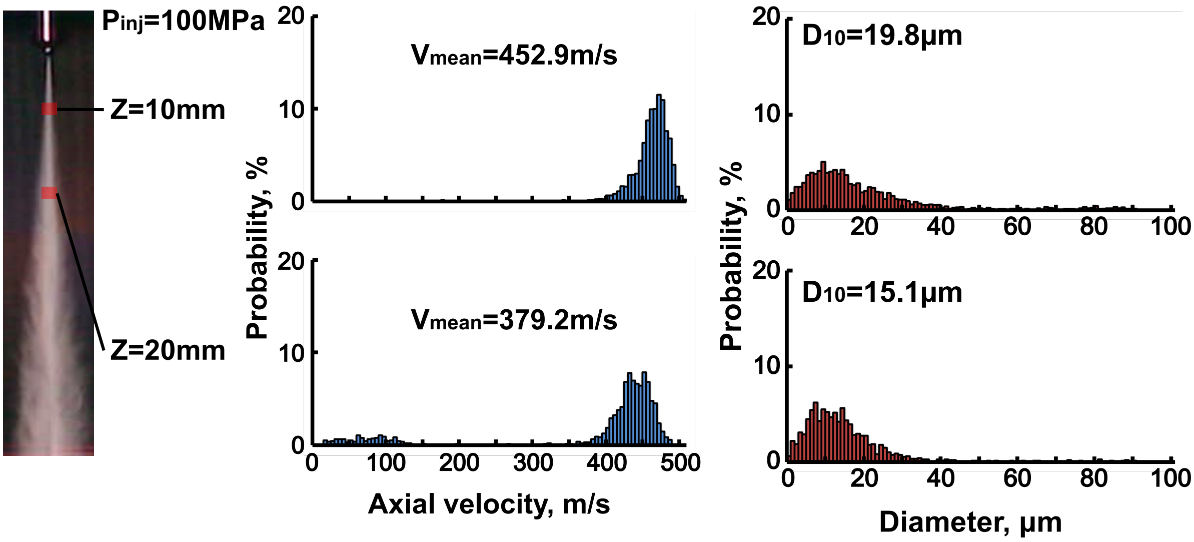


Figure 5. Measured droplet velocity and diameter at the 10 and 20 mm from the nozzle exit under 100 MPa as injection pressure

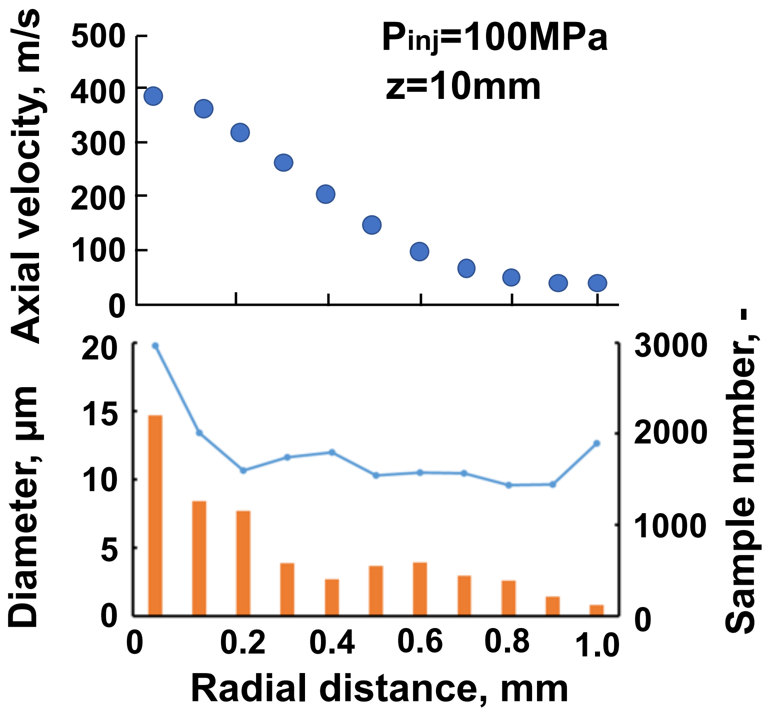


Figure 6. Radial distribution of mean droplet velocity and droplet diameter at the 10 mm from the nozzle exit under 100 MPa as injection pressure

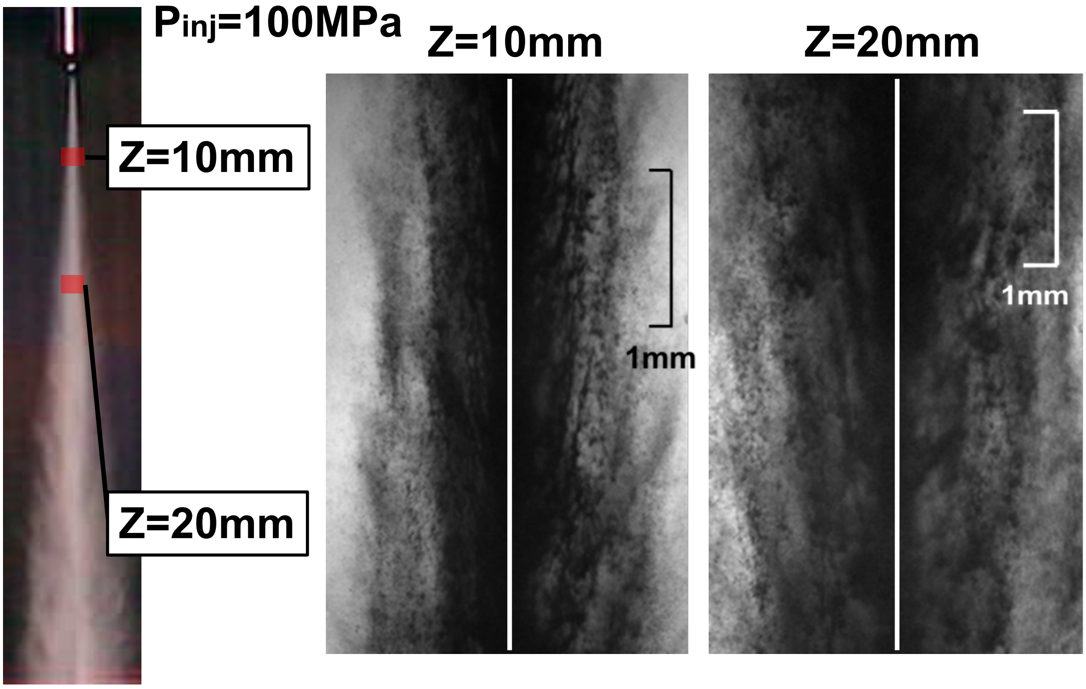


Figure 7. Ultra-high-speed visualization of higher dense spray near the nozzle exit of the common-rail injector

Conclusions

In this experiment, droplet diameter and axial velocity in spray formed by single hole of the common-rail injector were measured with HiDense PDA system to investigate atomization characteristics. The results obtained from this study can be summarized as follows:

(1) HiDense PDA system permits accurate measurements in spray with extremely high particle concentrations, and it is the only PDA system available that provide high quality measurements in the core region of the spray cone. It is possible to measure the droplet diameter distribution at the 10 mm from the nozzle exit under 100 MPa as the injection pressure using appropriate optical configuration.

(2) Radial distributions of droplet velocity were measured using HiDense PDA system. At 10 mm from the nozzle exit, there are strong shear layer between the surround air and injected spray. Narrower droplet distribution can be seen at 10 mm from the nozzle exit.

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