Effect of High Ambient Pressure on Behavior and Structure of Diesel Spray

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Abstract
Characteristics of diesel spray depend on various conditions such as injection pressure, diameters of nozzle hole, and ambient temperature. Recently, boost pressure and EGR ratio are increased in DI (direct injection) diesel engine to improve engine performance. Consequently, pressure in cylinder become high compared with conventional one, and it is considered that the high pressure affects the behavior of diesel spray. Therefore, it is necessary to understand the effect of high ambient pressure on diesel spray. In this study, behavior of diesel free spray in a high pressure vessel was investigated experimentally. Moreover, tomographs of spray were taken using laser light sheet of Nd:YAG laser in order to investigate the internal structure of free spray. The distribution of excess air ratio in a spray was estimated from the video image. In the view point of spray shape, the side periphery of free spray was straight in a low ambient pressure condition. On the contrary, in a high ambient pressure condition, it was suddenly expanded at the middle spray part corresponding to the end of low excess air ratio area. This sudden expansion of spray was more obvious at higher ambient pressure and higher injection pressure conditions. From laser tomographs obtained in this study, a wavy motion of high density spray zone was clearly found in high ambient pressure condition. It seems that the wavy motion affected the development of free spray and was associated with the effect of ambient pressure on spray formation. As for the formation mechanism of wavy motion, we speculated that the earlier injected part of spray stagnated when the spray developed to some extent, and then the later injected part of spray developed with avoiding the stagnated spray, or the earlier injected part of spray blocked the later injected part of spray, therefore, the later part bent like backling.

Introduction

In DI (direct injection) diesel engine, combustion and emissions characteristics are greatly influenced by the atomization of fuel, in particular by the formation of air-fuel mixture in a combustion chamber. The mixture formation depends on various conditions such as injection pressure, diameter of nozzle hole and ambient temperature. Many researchers have investigated the effects of various conditions on diesel spray characteristics [1-8]. Recently, boost pressure and EGR ratio are set to increase for improving engine performance. Consequently, pressure in cylinder become high compared with conventional one, and it is considered that the high pressure affects mixing behavior of diesel spray and air. Therefore, it is necessary to understand the effect of high ambient pressure on diesel spray.

In this study, behavior of diesel free spray in a high pressure vessel was investigated experimentally. Moreover, tomographs of spray were taken using laser light sheet of Nd:YAG laser in order to investigate the internal structure of free spray. Spray spreading behavior and structure were optically observed and the effect of high ambient pressure on free spray was reported here.

Experimental Methods

A schematic view of experimental apparatus and experimental conditions are shown in Fig.1 and Table 1, respectively. The fuel was injected from a single-hole nozzle into a pressure vessel filled with nitrogen gas. Images of free spray were taken using a high speed video camera (Photron, FSTCAM-512PCI). The frame rate was set at 8000 frames/s. A metal halide lamp placed on the axis of camera and spray, and shadow images were taken. A gray scale was placed in a pressure vessel. This scale image was taken together with the free spray, and an intensity of spray image was adjusted by using the scale image. The internal structure of free spray was taken with a laser light

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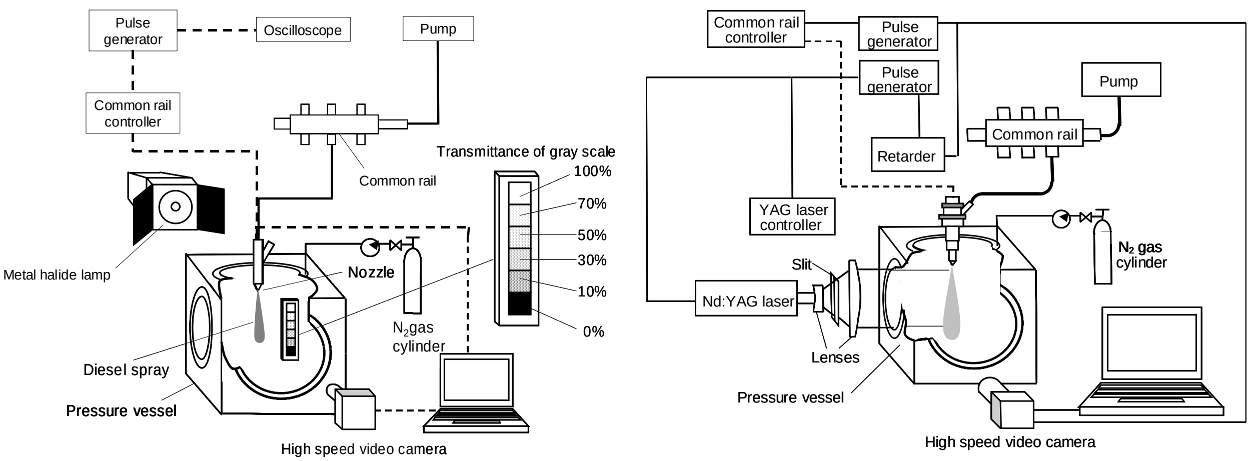

(a) Experiment for observe spray behavior (b) Experiment for observe spray structure

Figure 1. Experimental apparatus

Table 1. Experimental conditions

Hole shape	Circular hole		
Injection pressure P_{inj} [MPa]	90, 150		
Injection mass M_{inj} [mg]	10.5		
Size [mm]	Diameter		
	0.17		
Hole area [mm^2]	0.0227		
Ambient temperature [K]	300		
Ambient pressure [MPa]	1.0	3.0	5.0
Ambient density [kg/m^3]	11.6	34.8	58.1
Fuel oil	Diesel fuel (JIS No.2)		

sheet of Nd:YAG laser (wavelength 532mm). In order to make a laser sheet, two cylindrical lenses and a slit were used. The width and thickness of the laser sheet were 100mm and 0.5mm, respectively.

In this experiment, a single shot spray injected from a single-hole nozzle with common rail system was observed. The fuel injection mass was 10.5mg for one injection. To keep injection mass constant at both injection pressures, injection period was set at 1.2ms when injection pressure was 90MPa and 1.0ms when injection pressure was 150MPa.

Results and Discussion

Photographs of free spray are shown in Fig. 2. t_{inj} indicates the elapsed time from injection start. It was clear that spray development became slow with an increase of the ambient pressure P_a. As for the sprays of P_a = 1.0MPa and 3.0MPa, slender spray was observed and widths of sprays were narrow compared with that in P_a = 5.0MPa. In the case of P_a = 1.0MPa, further, dilute spray was observed around the spray tip. In the case of P_a = 5.0MPa, higher spray density was observed, because the spray development was slow. Moreover, the disturbed spray shape was found around the spray tip. Earlier injected part of spray seemed to block penetration of later injected part of spray. It was considered that, therefore, the disturbed spray shape was formed.

In order to obtain information about the formation of air-fuel mixture, spray density was estimated and was evaluated by a local excess air ratio λ. From the photographs of free spray, it could be seemed that axisymmetric model was applicable for spray shape. Therefore, the particle number density was estimated by the light extinction theory [9] with the axisymmetrical approximation and the Sauter mean diameter [3]. Sauter mean diameter was caluculated by Eq. (1) and Table 2 was obtained for the test sprays. Moreover, the excess air ratio was calculated from mass of ambient gas and fuel per unit volume.

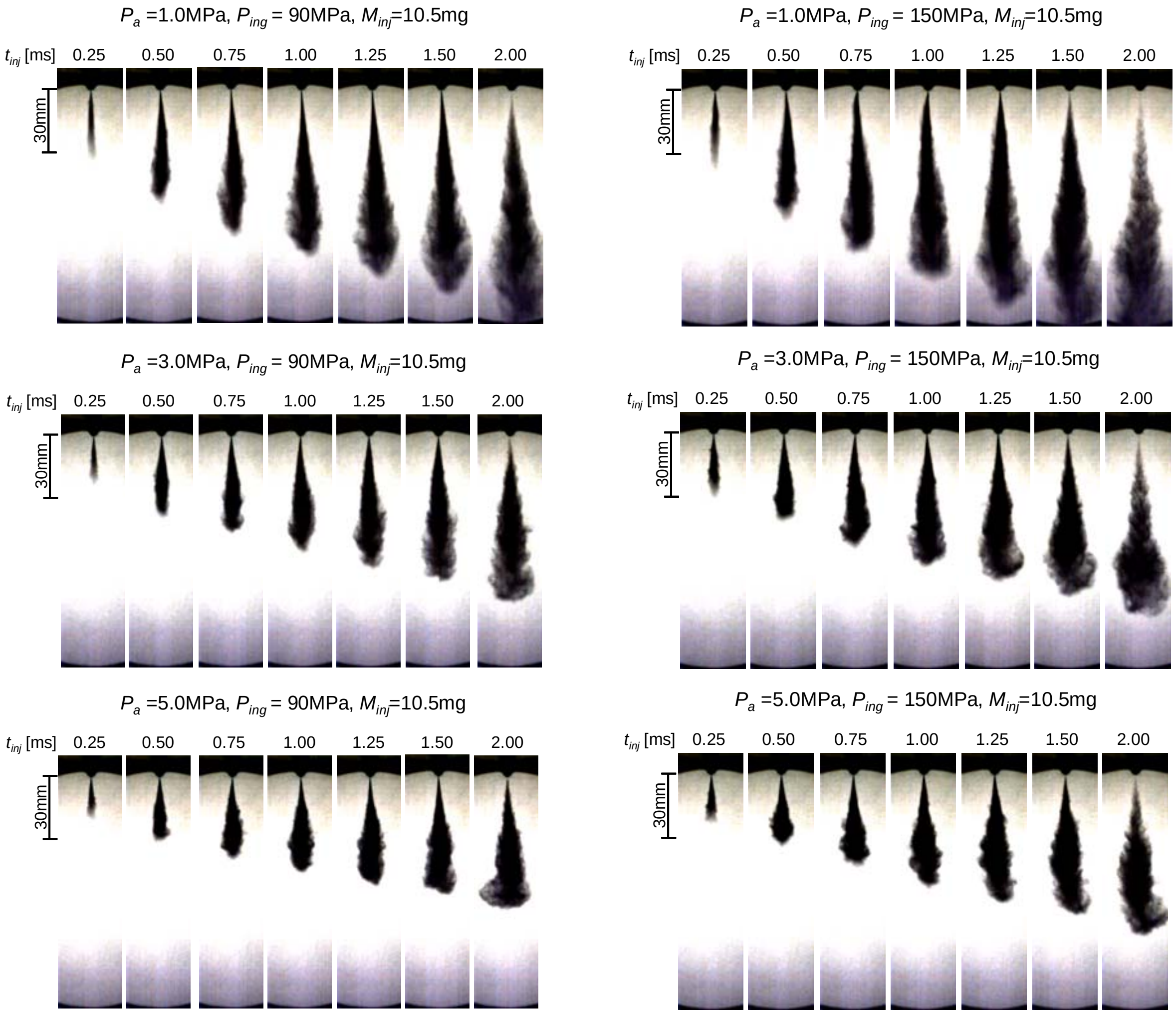

Figure 2. Behavior of free spray

Table 2. Sauter mean diameter

	P_{inj} = 90MPa			P_{inj} = 150MPa		
P_a [MPa]	1.0	3.0	5.0	1.0	3.0	5.0
D_{SMD} [μm]	8.3	13.91	17.70	7.73	12.96	16.49

$$D_{SMD}/d_0 = MAX[D_{SMD}^{LS}/d_0,\ D_{SMD}^{HS}/d]. \qquad (1)$$
$$D_{SMD}^{LS}/d_0 = 4.12Re^{0.12}We^{-0.75}(\mu_l/\mu_a)^{0.54}(\rho_l/\rho_a)^{0.18}.$$
$$D_{SMD}^{HS}/d_0 = 0.38Re^{0.25}We^{-0.32}(\mu_l/\mu_a)^{0.37}(\rho_l/\rho_a)^{-0.47}.$$

Figure 3 shows distribution of excess air ratio in P_{inj} = 90MPa and 150MPa at t_{inj} = 1.0ms. In each injection pressure, as ambient pressure became high, the zone of homogeneous excess air ratio spread from middle part of spray to spray tip. It was considered that the ambient gas was entrained into the spray, and momentum of disintegrated spray particles decreased at high ambient pressure. In other words, the momentum of disintegrated spray particles was transferred to the entrained gas and the particles lost their momentum. Moreover, since ambient gas density was increased with an increase of ambient pressures, this momentum transfer became obvious with an increase of the ambient gas density. Therefore, mass of entrained gas was large and the area of homogeneous excess air ratio increased with an increase of ambient pressure.

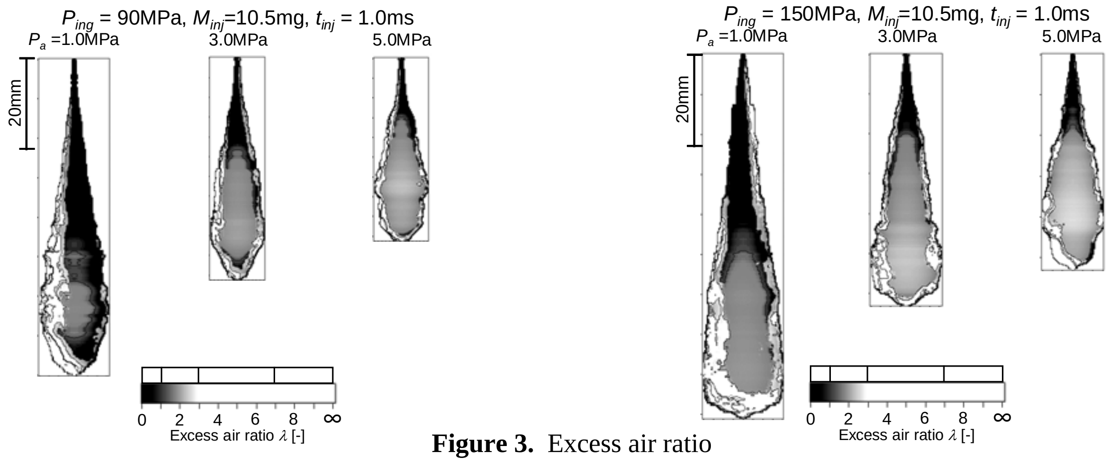

Figure 3. Excess air ratio

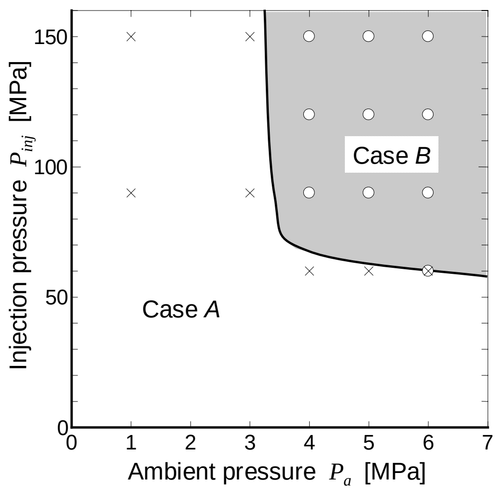

Figure 4. Effect of ambient and injection pressures

In the view point of spray shape, the side periphery of free spray where excess air ratio was high ($\lambda \cong 7$) was straight at P_a = 1.0MPa and 3.0MPa. On the contrary, the side periphery at P_a = 5.0MPa suddenly expanded at the middle part of spray area of low excess air ratio ($\lambda \cong 2$), that appeared on the center axis of the spray. It was considered that air entrainment suddenly increased at this position.

As mentioned above, the spray shape was divided into two cases. Case A corresponds to the spray shape which side periphery is straight. Case B represents the spray shape which side periphery suddenly expands. Classification of spray configuration is shown in Fig.4. In this figure, the horizontal axis is ambient pressure, and the vertical axis is injection pressure. The gray zone corresponded to the area where Case B shapes were observed. The border existed between 3.0MPa and 4.0MPa in ambient pressure. The border for injection pressure existed between P_{inj} = 60MPa and 90MPa at P_a = 4.0MPa and 5.0MPa. In the condition of P_a = 6.0MPa, the border existed on P_{inj} = 60MPa. In this condition, it was very difficult to judge whether spray shape was Case A or Case B.

In order to observe the internal structure of free spray, tomographic images of spray were taken using a laser light sheet of Nd:YAG laser. Figure 5 shows the tomographic images. The laser light sheet was irradiated from the left side. In the case of P_a = 1.0MPa, the spray developed into slender shape. On the contrary, when the ambient pressure was 3.0MPa and the injection pressure was 90MPa, a wavy motion was observed after t_{inj} = 0.50ms. As the injection pressure increased to 150MPa, the wavy motion appeared conspicuously. When the ambient pressure was 5.0MPa, the waving spray was observed from earlier stage of spray in each injection pressure (P_{inj} = 90MPa and 150MPa). From laser tomographs obtained in this study, the wavy spray motion was clearly found in high ambient pressure and high injection pressure conditions. It seems that the wavy motion affected the development of free spray and was associated with the effect of ambient pressure on spray behavior.

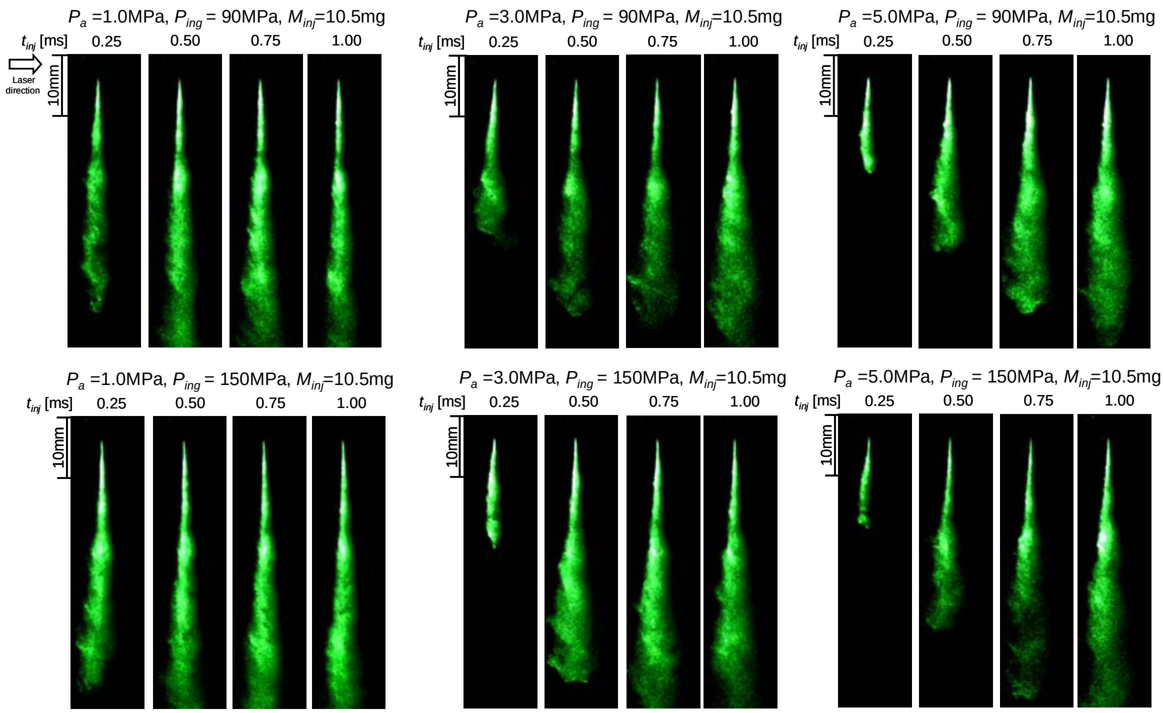

Figure 5. Laser sheet tomographies of free spray

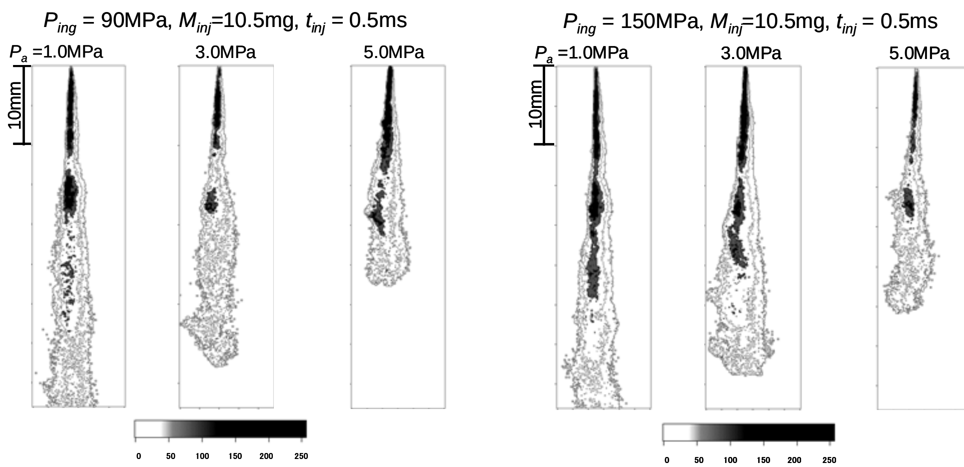

Figure 6. Distribution of spray density

In order to analyze the internal structure of free spray, distributions of spray density were estimated. In the tomographic image of spray, whiteness (brightness) of image corresponds to a spray area; that is, white area of spray image indicates the area that spray density is high, and black area indicates that no spray is there. Thus the tomographic images were taken in a personal computer as digital images and whiteness of pixel was divided into 256 levels. The level of 256 means that spray density is the highest, and the level of 0 means there was no spray. The results are shown in Fig. 6. When the ambient pressure was 1.0MPa, high density zone distributed linearly. Also, in the condition of P_a =3.0MPa, high density zone distributed linearly at P_{inj} =90MPa. However, as the injection pressure was 150MPa, small waving of high density zone was found. When the ambient pressure increased 5.0MPa, the wavy distribution was clearly found. As for the formation mechanism of wavy motion, we speculated that the earlier injected part of spray stagnated when the spray developed to some extent, and then the later injected part of spray developed with avoiding the stagnated spray, or the earlier injected part of spray blocked the later injected part of spray, therefore, the later part bent like backling.

Conclusions

The behavior and structure of diesel free spray in high ambient pressure condition was investigated experimentally, and the following results were obtained.

(1) In the high ambient pressure condition, the momentum of free spray decreased and the mass of entrained gas was enlarged. Therefore, lean homogeneous excess air ratio area was formed widely.

(2) The configuration of free spray, where spray density was high, suddenly expanded at the middle spray part corresponding to the end of high density area since the entrainment of surrounding gas increased suddenly in this part.

(3) The wavy motion of high density spray zone was clearly found in the high ambient pressure condition. It seems that the wavy motion affected the development of free spray and was associated with the effect of ambient pressure on spray behavior.

(4) As for the formation mechanism of wavy motion, we speculated that the earlier injected part of spray stagnated when the spray developed to some extent, and then the later injected part of spray developed with avoiding the stagnated spray, or the earlier injected part of spray blocked the later injected part of spray, therefore, the later part bent like backling.

Nomenclature

d_0 Nozzle hole diameter
D_{SMD} Sauter mean diameter
D_{SMD}^{HS} Sauter mean diameter of high speed jet
D_{SMD}^{LS} Sauter mean diameter of low speed jet
Re Reynolds number
We Weber number
μ_l Fuel viscosity
μ_a Air viscosity
ρ_a Ambient density
ρ_l Fuel density

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