Diesel Spray Characteristics of Common-Rail VCO Nozzle Injector

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Abstract.

Spray characteristics of diesel fuel injection is one of the most important factors in diesel combustion and pollutant emissions especially in HSDI (High Speed Direct Injection) diesel engines where the interval between the onset of combustion and the evaporation of atomized fuel is relatively short. An investigation into various spray characteristics from different holes of VCO(Valve Covered Orifice) nozzles was performed and its results were compared to standard sac nozzle. The global characteristics of spray, including spray angle, spray tip penetration, and spray pattern were measured from the spray images which were frozen by an instantaneous photography with a spark light source and ICCD. These spray images were acquired sequentially from the first injection to fifth injection to investigate injection to injection variation. For better understanding of spray development and their internal structures, a long-distance microscope was used to get magnified spray images at the vicinity of the nozzle hole with a laser sheet illumination. Also backward illuminated images with a spark light source were taken to understand surface structures of dense spray from VCO nozzle of common-rail injection system.

INTRODUCTION

HSDI diesel engines are recently developed for passenger cars owing to their superior fuel economy. In order to improve emission characteristics, VCO nozzle injector equipped with common-rail system in which injection pressure, injection duration, and injection timing are free from engine operating conditions is getting widely used. Reducing the amount of injected fuel during ignition delay period with pilot injection reduces heat release rate in the premixed combustion phase, resulting in a lower noise and NOx emission. VCO nozzle has the advantage in reducing this in that it has orifices that are directly covered by the needle surface, so that it minimizes the room for the remaining fuel in the nozzle between injections as in sac nozzle. Furthermore this avoids the dripping of large droplets at the final stages and eventually decreases HC emission.

It has been reported that two-spring injector combined with a VCO nozzle for conventional cam-driven injection system is effective in reducing HC and NOx emission, though it increases smoke under low-load conditions.[1] Experimental studies have revealed that smoke increase is mainly caused by spray formation irregularity induced by needle tip deviation from the seat center under a condition of low needle lift, which leads high local fuel concentration.[2] Detailed research on spray patterns of VCO nozzle under low needle lift condition has been performed with large-scale transparent nozzles and confirmed that eccentricity of the needle tip and partial hydraulic flip are responsible for different spray patterns, which can be identified into three distinct types.[3] One is of the type normally produced by multi-hole sac nozzle, another type is a hollow cone spray of wide angle, and the other is produced by partial hydraulic flip, which is directed more biased to one side and has a small spray angle because a side of fuel flow boundary inside hole may be remaining detached till the exit.

An enlarged transparent model of a six-hole vertical mini-sac nozzle has been used to allow visualization of the flow at Reynolds and Cavitation numbers matching those of real size injectors operating under normal diesel engine conditions.[4] The results revealed that the flow development in multi-hole vertical nozzles, despite the axisymmetric geometry, may lead to hole-to-hole flow variations as a result of the transient nature of the cavitating structures formed inside the sac volume and holes.

There have been some efforts to analyze the spray produced by each hole of VCO nozzle mounted on an electro-injector with a cap to cover the nozzle in the way that only one hole at a time could inject in the spray chamber.[5-7] The droplet size investigation showed that SMD increases with radial distance from the center of the spray, or the core of the spray contains smaller particles.[6,7]

Recently, spray characteristics of injectors equipped with VCO nozzle, from unit injector or common rail system are investigated with long-distance microscope.[8] The visualization revealed spray asymmetry and instability including spray angle variation, hole-to-hole and injection-to-injection variation.

The objective of this study is to measure global characteristics of sprays from VCO nozzles equipped with common-rail injection system, paying particular attention to the spray patterns at the beginning of the injection, and to get better understanding on spray structure in the vicinity of the hole with microscopic images.

EXPERIMENTAL SETUP

Spray characteristics from VCO nozzles equipped with common-rail system were investigated under atmospheric and pressurized conditions in a spray chamber through various optical observations. The BOSCH common-rail system is composed of CP3 pump, which can rise the fuel pressure up to 1350bar and common-rail, which has internal volume of $18cm^3$ and supply fuel to four injectors. High-pressure chamber was pressurized by filling nitrogen up to 30bar and depressurized down to 6mmHg with vacuum pump. The pressure chamber allows optical accesses through three circular windows of 80mm diameter. Two visualization techniques were used for macroscopic observation. Spray images frozen by spark light source, which had light duration of shorter than 100ns were acquired with CCD camera and taken by a frame grabber. Shadowgraph technique was also applied to all sprays from the nozzle holes with Ar-ion laser and ICCD camera whose gating time was 70ns. Figure 1 shows schematic layout of experimental setup for macroscopic and microscopic visualizations.

Microscopic visualization was performed in two ways. Thin laser sheet was incident through one spray and scattered light was acquired with ICCD camera, which has gating time of 70ns. Long distance microscope was used to get high magnification more than seven times. Back illumination with spark light source was utilized to investigate initially developed spray surface profile. ICCD camera equipped with long distance microscope was also used to freeze the image within 10ns.

Figure 1

The VCO nozzle investigated in this study has five holes of an identical inclination angle and spray cone angle of 152°. This nozzle has double-guided needle and the diameter of each hole is 0.144mm.The sac nozzle compared with this nozzle has five holes of which diameter is 0.146mm and has spray cone angle of 152°. Experimental conditions are summarized in table 1.

Table 1

RESULTS AND DISCUSSIONS

HOLE-TO-HOLE AND INJECTION-TO-INJECTION VARIATION OF SPRAY PATTERNS

It was found that, injection-to-injection variability of spray patterns was negligible in a macroscopic point of view except that the penetration of first injected one or two sprays were shorter than the consecutive sprays. This was observed in both VCO and sac nozzles.

Hole-to-hole variations were only observed in sac nozzle in terms of spray angle. The penetration of spray from each hole of sac nozzle was almost identical and slight difference might be induced from the different momentum exchange rate with ambient gas. When chamber pressure was 6mmHg, spray penetration of each hole was identical though spray angle variation still existed. It was observed in the previous work with rotary pump that hole-to-hole variation of sac nozzle was negligible, while hole-to hole variations in VCO nozzle were observed in terms of spray angle and spray penetration, especially for initial development of spray. [9] Macroscopic images showed that initially developed sprays from VCO nozzle could be identified as three distinct types. Figure 2 shows typical images of spray patterns from a VCO nozzle without common-rail system under low needle lift condition at atmospheric, 15bar and 30bar conditions, respectively.

Figure 2

The VCO nozzle used for the previous study had single-guided needle, while the VCO nozzles used for this study had double-guided needle. When needle lift is small, single-guided needle is apt to be directed to one direction inducing non-uniform pressure and flow field around the periphery of nozzle hole inlets. As mentioned above in introduction this non-uniformity has been found responsible for the hole-to-hole variations at low needle lift conditions.

SPRAY ANGLE AND SPRAY TIP PENETRATION

Figure 3 represents averaged penetrations of sprays from VCO nozzle injected to atmospheric ambient condition with various common-rail pressures. Among many correlation based on experimental data and turbulent gas jet theory, one proposed by Dent [10] was adopted for comparison, which can be summarized by the following equation

$$S=3.07(\Delta P/\rho_g)^{1/4}(d_0 t)^{1/2}(294/T_g)^{1/4} \qquad (1)$$

S : spray tip penetration

ΔP : pressure drop across the nozzle

t : time after the start of injection

ρ_g : gas density

T_g : gas temperature

d_0 : nozzle hole diameter

It is interesting to observe that the penetration increase rate of the spray injected with common-rail pressure 1000bar is lower than other sprays and the predicted value by equation (1). At the early stage of injection, between start of injection (SOI) and about 0.3ms, spray penetration increase rate is increasing with the common-rail pressure. However, after this period penetration increase rate continuously decreases with common-rail pressure. When common-rail pressure was 250bar, the lowest pressure, at about 0.75ms from SOI, spray penetration increase rate reduced to the predicted value by equation (1).Though enough data could not be acquired because of limit of viewing field, after 1.2ms from SOI, spray penetration was saturated to a certain value. It can be summarized that the spray penetration can be divided into three stages according to their increasing rate, and the duration of each stage is related to injection pressure. At the first stage, penetration increase rate is increasing according to the common-rail pressure. At the second stage, penetration increase rate is decreasing with common-rail pressure. At the third stage, spray penetration is saturated to a certain value.

Spray penetration was acquired from the macroscopic Mie scattering images, only liquid phase fuel concentration above a certain threshold affected the data. High injection pressure increases atomization of fuel and mixing with ambient gas and slows down the liquid spray penetration increase rate. This can be a possible mechanism that can explain observed results.

Figure 3

Figure 4 represents the spray penetrations of VCO and sac nozzle. The difference was hardly recognized at the same condition. As gas density is increased, spray penetration is decreased. According to equation (1), spray penetration at higher gas density should decrease to about 44%, which is well coinciding with Fig. 4.

Figure 4

Figure 5 represents averaged spray angle of VCO nozzle at 1ms after SOI as a function of common-rail pressure. It is derived from macroscopic images and it shows that higher injection pressure induce larger spray angle. This result is correspondent to the general trend. [11] However, spray angle measured from microscopic images that were taken near the hole showed contradicting results. The angle of the spray injected at 1200bar was smaller than that injected at 250bar as will be shown in Figs. 8 and 11.

Figure 5

SPRAY STRUCTURES OF VCO NOZZLE

Figure 6 show that VCO spray structures vary with the ambient gas density. Generally, gas density at start of injection is about 15-25kg/m$^{3.}$ When ρ_g was 33.8kg/m^3, a feather like structure with puffy edge appeared. In case chamber pressure was vacuum, conical spray shape maintained during injection period because aerodynamic interaction between spray and ambient gas was negligible. Figure 7 represents the sac spray structures at different gas densities. Like VCO nozzle, the feather like structure appeared at high ambient gas density condition. It is noticeable that breakup takes place inside of the spray at vacuum condition. Because aerodynamic breakup is hard to occur, hydraulic breakup or flash atomization could be a mechanism of this phenomenon. However, considering above images acquired at ambient pressure condition (ρ_g =1.23kg/m^3), velocity rearrangement or turbulence effect inside the spray is not appropriate. Though it is not certain yet, cavitation bubble expansion might be a mechanism of this spray breakup. Fath *et al*. [12] proposed that the cavitation bubbles produced inside the nozzle will enhance the disintegration of liquid jet from sac nozzle.

Figure 8 shows microscopic images of cross section of the 5-O'clock VCO spray in Fig. 6 when injection pressure was 250bar and injection duration was 1.2ms. Figure 9 is microscopic images of the same spray in Fig. 8, which was acquired with back illumination to investigate surface profile. At 3μs from SOI, transparent bubble appears. This bubble seems to be the membrane, which have been attached inside the hole with surface tension. As the liquid column exists from the hole, this membrane deformed to a bubble that is followed by arbitrary shapes at the tip of liquid column. After 30μs from SOI, asymmetric waves developed on the liquid column and about 0.1ms from SOI, a typical spray pattern of atomization regime appears. Because of large relative velocity, unstable ligaments are forming around the spray surface. In the previous study [9], it was observed that droplets are forming from the ligaments. Figure 10 is a microscopic image of early spray development of VCO nozzle equipped with two spring injector of which first spring opening pressure is 220bar. It shows deformed membrane, ligament, and droplets forming from ligament clearly.

Figure 11 is microscopic images of cross section of the 5-O'clock VCO spray in Fig. 6 when injection pressure was 1200bar and injection duration was 0.4ms. Figure 12 is microscopic images of the same spray in Fig. 11, which were acquired with back illumination to investigate surface profile. Unlike the spray of injection pressure 250bar, typical pattern of atomization regime appears without asymmetric waves.

It is observed that about 20μs from SOI, droplets are forming from ligaments.

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

CONCLUSIONS

Spray characteristics of VCO nozzle for common rail injection system were investigated through macroscopic and microscopic images with various optical techniques. The findings from this study are summarized as follows.

1. Injection-to-injection variability of spray was observed for first injected one or two sprays.
2. Hole-to-hole variation of spray from VCO nozzle with double-guided needle was negligible. However, hole-to-hole variation was observed in sac nozzle in terms of spray angle.
3. Spray angle measured from the macroscopic images increase with injection pressure, however the angle measured from the microscopic images decrease.
4. Spray penetration can be divided into three stages according to their increasing rate and the duration of each stage is related to injection pressure. At the first stage, penetration increase rate is increasing according to the common-rail pressure. At the second stage, penetration increase rate is decreasing with common-rail pressure. At the third stage, spray penetration is saturated to a certain value.
5. When ambient gas density was high, a feather like spray structure with puppy edge appeared.
6. When sac spray is injected to vacuum, break up takes place inside of the spray. This might be due to cavitation bubble expansion.
7. For spray of injection pressure 250bar, it takes about 0.1ms from SOI to transfer into atomization regime, however for spray of injection pressure 1200bar, typical pattern of atomization regime appears without asymmetric waves
8. Droplets are formed from the ligaments around the spray surface at the early spray.

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Fig.1 Experimental setup for macroscopic and microscopic visualization

Fig.2 Initial development of spray from VCO nozzle with single-guided needle without common rail (0.1ms after start of injection)

a)ρ_{gas}=1.23kg/m^3 b)ρ_{gas}=16.9kg/m^3 c)ρ_{gas}=33.8kg/m^3

Fig.3 Spray penetration from VCO nozzle under atmospheric ambient condition

Fig.4 Comparisons between spray penetrations from VCO and sac nozzles

Fig.5 Effect of injection pressure on the spray angle from VCO nozzle

Fig.6 Mie scattering and shadow graph images of sprays injected from VCO nozzle, injection pressure 1200bar, 0.25ms after SOI (from top : first row ρ_{gas}=33.8kg/m^3 second row ρ_{gas}=1.23kg/m^3 third row ρ_{gas}=6mmHg)

Fig.7 Mie scattering and shadow graph images of sprays injected from sac nozzle, injection pressure 1200bar, 0.16ms after SOI (from top : first row ρ_{gas}=33.8kg/m^3 second row ρ_{gas}=1.23kg/m^3 third row ρ_{gas}=6mmHg)

Fig.8 Microscopic images of early spray development of VCO nozzle, injection pressure 250bar, ρ_{gas}=1.23kg/m^3 (from left : 3, 5, 10, 15, 20, 25, 30, 40, 50, 100, 150μs after SOI)

Fig.9 Microscopic images of early spray development of VCO nozzle, injection pressure 250bar, ρ_{gas}=1.23kg/m^3 (from left : 4, 10, 15, 20, 25, 30, 40, 50, 120μs after SOI)

Fig.10 Microscopic images of early spray development of VCO nozzle equipped with two spring injector of which first spring opening pressure is 220bar, start of injection

Fig.11 Microscopic images of early spray development of VCO nozzle, injection pressure 1200bar, ρ_{gas}=1.23kg/m^3 (from left : 4, 6, 14, 19, 24μs after SOI)

Fig.12 Microscopic images of early spray development of VCO nozzle, injection pressure 1200bar, ρ_{gas}=1.23kg/m^3 (from left : 5, 10, 15, 20, 25μs after SOI)

Table 1 Summary of experimental conditions

Nozzle	Chamber pressure	Common-rail pressure
VCO 0.176mm, 5hole,152°, double-guided VCO 0.144mm, 5hole,152°, double-guided Sac 0.146mm, 5hole,152°	6mmHg Ambient 30bar(N_2)	250bar 1200bar

Engine speed: 1200 rpm

Solenoid energizing duration: 1.2ms@250bar, 0.41ms@1200bar