

Characterization of Diesel Common Rail Spray Behavior for Single- and Double-hole Nozzles

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ABSTRACT

Double-hole nozzle and multiple injections have the potential for better fuel atomization and mixing in DI engine. In order to evaluate the behavior of the spray for the double-hole nozzles against traditional single-hole ones, high-speed spray visualization was carried out using a streak film camera and a copper vapor laser, and in combination with a long-distance camera when taking microscopic movies. The spray penetration and the cone angle were measured based on the images and compared for variable injection pressures, and for single and split injections, under ambient and elevated chamber pressure conditions. The results showed that the spray of the double-hole nozzle has comparable penetration but smaller cone angle when viewed from the nozzle end, compared to the single-hole nozzle with the same total hole discharge cross-sectional area. For microscopic view, it was observed that the interaction between the dual sprays is very dynamic. The fuel injection starts earlier and ends later from the lower hole, which also has smaller cone angle oscillations, possibly due to the hydro-erosion characteristic of the nozzle. The microscopic spray angle was observed to converge to a steady-state cone angle, which depends on the injection pressure, but it is smaller than the macroscopic spray angle. By multiple-injection testing, it was revealed that the pilot injection enhances the penetration of the main injection.

INTRODUCTION

Spray characteristics have strong influence on combustion and emission in DI engines. It is well known that better atomization and evaporation are achievable if fuel is injected through a smaller nozzle hole. Many researchers have reported that the Sauter Mean Diameter (SMD) of liquid droplets in the spray decreases for a smaller orifice, while penetration is sacrificed [e.g., 1,2]. Siebers has found that the length of liquid phase penetration in the spray is linearly dependent on the orifice diameter [3]. Advantages of smaller nozzle holes

have been reported for other aspects. Low particulate matter (PM) and carbon monoxide (CO) in emission are attributed to smaller SMD, which enhances evaporation and mixing, and thus shorter ignition delay and possibly better fuel economy [4]. However, the lower penetration of smaller orifice could also create higher equivalence ratio or concentration gradient locally, and could be a concern for high-load performance, especially if not compensated by high injection pressure and optimized injection timing.

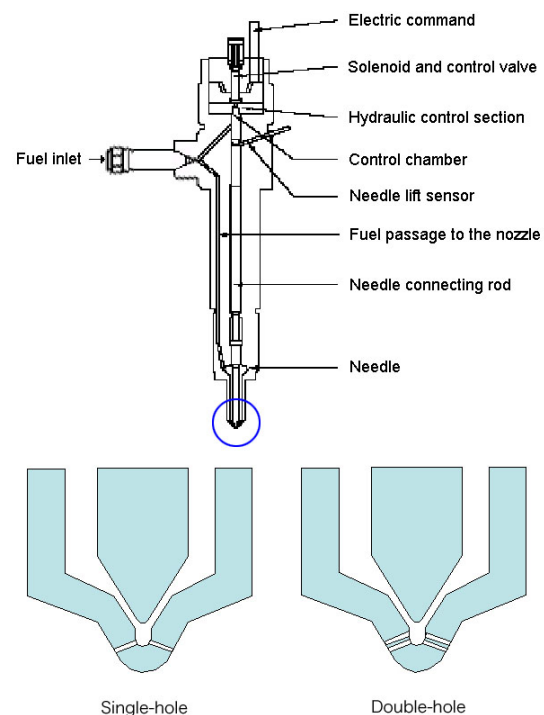


Figure1. Diesel injector and hole layout for a sac-type single-hole and double-hole nozzle

Therefore group-hole nozzle concept was introduced in order to achieve both better atomization and comparable penetration. Double-hole nozzle (DHN) is a type of group-hole nozzle, consists of two micro orifices very

close to each other, which are aligned on the nozzle axis plane, as shown in Fig.1. Given the same hole-diameter, one would expect a faster spray penetration for a double-hole nozzle, as compared to a single orifice, because it has two sources of momentum close together [5]. However, the spatial and temporal distribution of the fuel spray can be affected by the interaction of the two sprays via the air entrainment and droplet collision processes, depending on the spacing and the diverging or converging angle between the two holes [6].

Early results on the atomization and mixing of double-hole diesel spray used research nozzles that have holes at the very tip of nozzle along the injector axis. For example, Prof. Nishida and his research group reported that the spray injected from a double-hole nozzle has similar equivalence ratio distributions for the liquid phase comparing with a single-hole nozzle with the same total discharge cross-sectional area [6-11]. Their work suggests that double-hole sprays could have better atomization and air entrainment and thus improved vaporization and mixing. However, interaction of two jets could have negative effects for air entrainment and evaporation in the overlapped regions of the sprays. The measured averaged droplet size, as represented by SMD, increases due to droplet collisions at the overlap part of two sprays, especially for converging double-hole nozzle. Spray penetration is slightly slower for the double-hole nozzles, compared to the single-hole ones with the same total cross sectional area, but is faster if compared to the single plume injected from only one of the micro holes. Recently, Pawlowski et al. [14] performed spray visualization and measured the velocity of drop for the clustered spray similar to the DHN concept, although all sprays diverged. They found that spray from all investigated divergent DHN penetrates significantly slower than those of a comparable conventional nozzle. Numerical simulations [12, 13] using KIVA CFD code also agree with these experimental results. The measured or computed drop sizes are not as conclusive, varying from a few microns to the 40's [9, 13, 14], reflecting the difficulty associated with measuring dense diesel spray and the difference in the techniques used. However, it is agreed that drop size decreases with orifice diameter.

Split injection has been used extensive for better air-fuel mixing and reducing combustion noise and soot [15]. It is reported that the mass of entrained ambient gas increases remarkably for split injection, and it is possible to form lean and homogeneous mixture with split injection [7].

There are also a few engine experiments demonstrating the benefits of group-hole nozzles, due to better fuel-air mixing. They all showed improvement in the performance and emissions in the light and medium loads [5, 16, 17] for smaller diameter nozzles with grouped or conventional non-grouped geometry. The convergent type double-hole nozzle was mostly encouraging, especially at high loads. Higher engine power was also achievable using the double hole

nozzles, although with possible higher soot emissions [17]. However, more optimization and implementation of split injection strategy are needed to further explore the potentials of group-hole nozzle for advanced diesel engines.

The purpose of this study was to characterize and compare the spray injected from single- and double-hole nozzles with the conventional multi-hole sac nozzle geometry. Visualization of sprays by the streak camera illuminated and framed by high-speed laser was performed. The measured spray penetration and cone angle were compared to evaluate the effects of double-hole on spray formation. Also, the effect of multiple injections was evaluated.

TEST NOZZLES

Seven diesel injectors were tested in the experiment and driven by a laboratory solenoid driver. The specifications for the nozzles are listed on Table1, in witch DH and SH indicate double-hole and single-hole respectively. Total cross sectional area of orifices for single- and double-hole nozzles can be considered as the same.

Table1. Nozzle specifications

Injector	Number of Holes	Hole diameter [mm]	Hole Angle [deg]	Flow rate [cc/min]
DH5A	5x2	0.113	133	700
DH5B	5x2	0.113	133	700
SH5A	5x1	0.16	133	650
SH5B	5x1	0.16	133	650
DH6	6x2	0.14	133	900
SH6A	6x1	0.20	133	900
SH6B	6x1	0.20	133	900

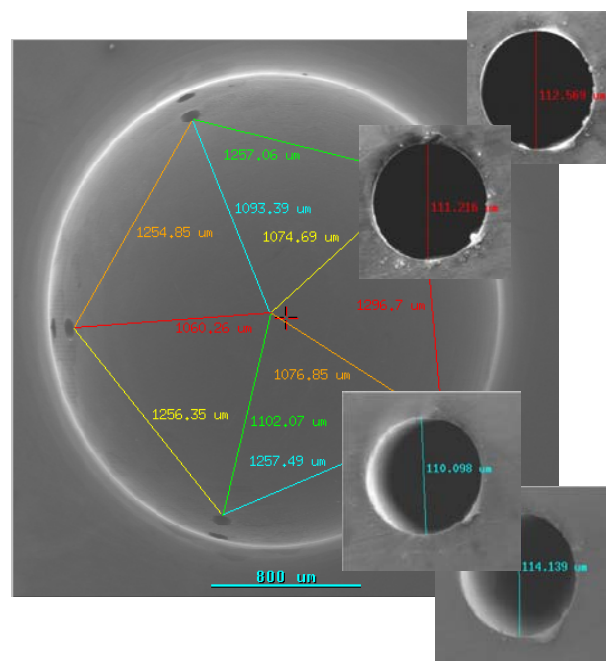


Figure 2 Microscopic image for the 5x2 double-hole nozzle tip.

Fig. 2 shows the microscopic image of a 5x2 nozzle, which was imaged from the tip. The measurements of the hole spacing and nozzle hole size demonstrated good symmetry and machining accuracy. To illustrate the internal flow structure inside the double-hole nozzle structure, computational fluid dynamics simulation of the flow were carried out under steady state full-lift condition [18]. For simplicity, the nozzle geometry without hydro-erosion was used. The cross section vector plots in Fig. 3 shows more flow separation, larger change of the flow direction, and more down-wash at the lower hole, in the entrance area. The computed discharge coefficients under steady-state condition were very similar for both holes: 0.73 at 1000 Bar and 0.75 at 2000 Bar, although the lower hole has just slightly lower value). Fig. 4 also shows slightly more cavitations at the lower hole.

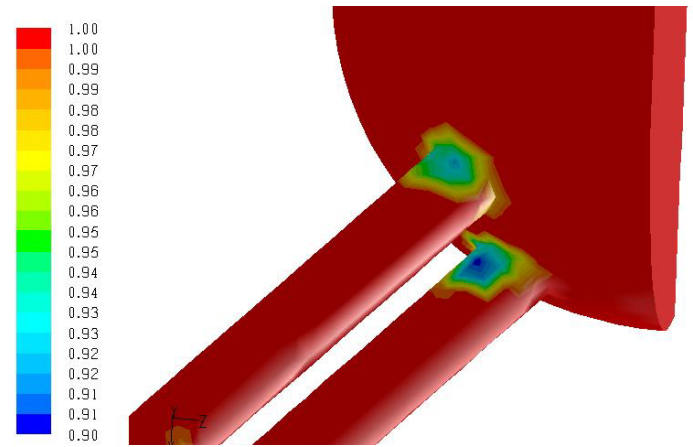
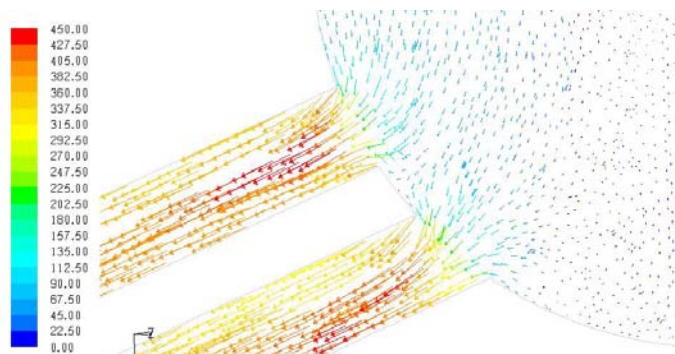
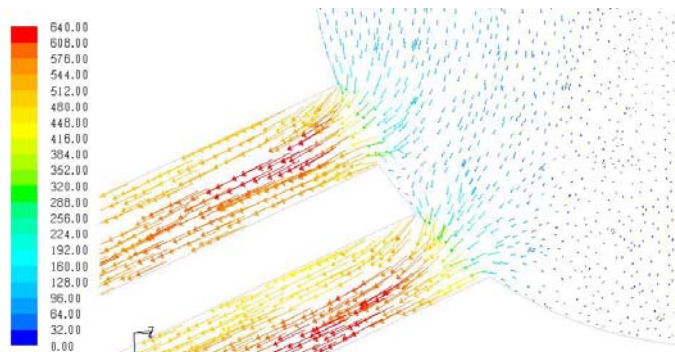


Figure 4 The liquid fraction inside the nozzle surface, $P_{inj}=2000\text{bar}$



(a) $P_{inj}=1000\text{bar}$



(b) $P_{inj}=2000\text{bar}$

Figure 3 The flow structure inside the Nozzle.

EXPERIMENTAL SETUP

Experimental apparatus and test condition are described in Fig. 5 and Table 2. Common-rail system delivered regular diesel to the injector, and the fuel was injected into a pressurized chamber. For the results reported here, the chamber pressure was set at 25bar by compressed nitrogen. Injection pressure of 500, 1000, 1500, 1800, and 2000bar were tested in the experiment. A high-speed drum streak camera, utilizing 35mm photographic film, was used to image the spray. Its mechanical shutter opens for only one revolution during image exposure timing. The illumination and shutter is controlled by a Copper-vapor laser (Oxford CU15), resulting into a framing speed of 10,000 Hertz or higher. The start of injection, and the injection duration were set by a delay/pulse generator, which was synchronized with the camera and laser by a PC.

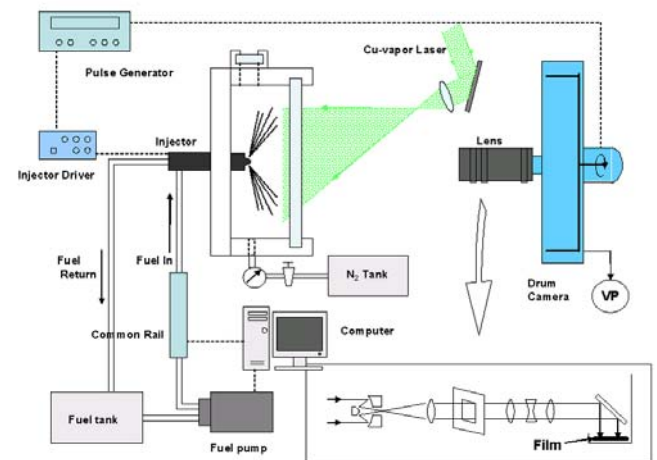


Figure 5. Experimental apparatus

Table2. Test conditions

	Pressurized	Un-pressurized
Ambient Gas	Nitrogen	Air
Ambient Pressure	25 Bar	1 bar
Ambient Temperature	Room temperature	
Test Fuel	Regular Diesel	
Fuel Density	840 kg/m ³	
Injection Pressure	500, 1000, 1500, 1800, 2000	

The spray observed in the experiment could be treated as non-evaporative. Since the temperature in the chamber was low, most of spray components were liquid droplets. Both macroscopic and microscopic imaging methods were carried out for visualization. For the macroscopic, images were taken along the nozzle axis, to visualize all fuel plumes spread radially from the nozzle tip up to 55 mm in order to examine the penetration, cone angle, and overall structure of the sprays. Microscopic imaging utilized a long-distance microscope, which focused on the nozzle exit. More details for experimental setup can be found in the reference [19, 20].

Similar to the convention used in reference [10], the image taken perpendicularly with the injector axis to show both sprays is called “vertical”. On the other hand, it is called a “parallel” image if the camera is set to view from the end of the injector, with the images of the two sprays superimposed on each other.

RESULTS AND DISCUSSION

VISUALIZATION

The macroscopic images of the sprays for the double-hole nozzle are shown in Fig. 6. The start of Injection (SOI) was defined as a point where the spray tip is detected for the first time in the sequence of frames. The sprays were injected by DH5A, the injection pressure and the ambient pressure were 1500bar and 25atm respectively. The injection duration was set to 3ms. It clearly shows how the spray develops with time. It should be noted that the sprays have good symmetry, and the spray-to-spray variation is small. Since the images were taken from the parallel (end view) direction, only five sprays are visible.

Different lighting directions of the high-speed pulse laser were employed in order to visualize the double-hole spray structure microscopically. For example, Figure 7 compares the image taken using the light sheet and the

back-lighting techniques. The light-sheet image on the left shows good 3-D stereography but more difficulties to quantify due to very narrow focal depth. The right image was taken with laser back-lighting and could capture the details of the spray more. Therefore, only the results using backlighting technique are presented in this paper.

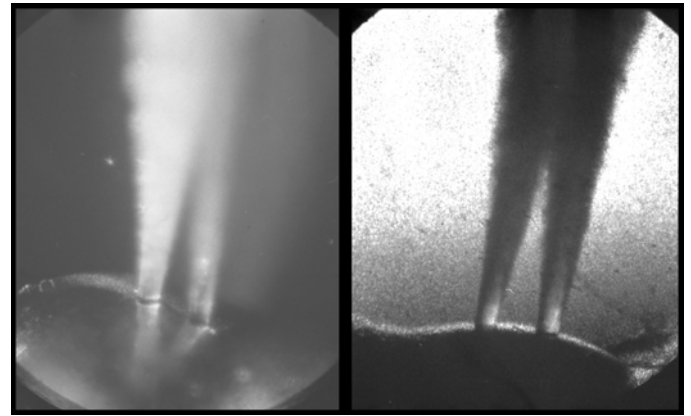


Figure 7. Microscopic images of sprays from double-hole nozzle using light-sheet (left) and back-lighting (right) techniques

Examples of sequential microscopic images are arrayed in Fig. 8. This is the case with injector DH5B with split injection. The nozzle tip was located on the left and outside the boundary of the frames. The injection pressure and the ambient pressure were 2000bar and 25atm respectively. The duration of the pilot injection was 0.6ms, and after 0.2ms of dwell interval, the 2ms of main injection followed. The image clearly shows the transient burst effect at the beginning of injection followed by narrower steady-state spray, similar to reference [19]. The spray angle increases again just before the needle valve is closed, and low-velocity liquid column spray tails are observed after that. This poorly atomized liquid fuel dumped after needle close has been known to contribute to unburned hydrocarbon and PM emissions. In addition, it is observed that the spray closer to the nozzle tip, which was injected from the lower hole, starts injection earlier, and ends later than the upstream spray from the upper hole. The transient dynamics and the hydro-erosion process may create a more favorable discharge condition for the lower hole, but this remains to be investigated further.

MEASUREMENT

In order to determine the spray shape quantitatively, the spray tip penetration and cone angle were measured and plotted with time elapsed from SOI. In addition, spray tip velocity was also calculated using the sequential images in the movies.