

Small Injection Amount Fuel Spray Characteristics Injected by Hole-Type Nozzle for D.I. Diesel Engine

Keiya Nishida, Kuichun LI, and Takeru Matsuo
University of Hiroshima

Daisuke Shimo and Wu Zhang
Mazda Motor Corp

ABSTRACT

Spray characteristics under very small injection amount injected by the hole-type nozzle for a D.I. Diesel engine were investigated using the spray test rig consisting a high-pressure and high-temperature constant volume vessel with optical accesses and a common rail injection system. The Laser Absorption Scattering (LAS) technique was used to visualize the liquid and vapor phase distributions in the evaporating spray. In the very small injection amount condition of the evaporating and free (no wall impingement) spray, the both spray tip penetration and spray angle are larger than those of the non-evaporating free spray. This tendency contradicts the previous observation of the diesel spray with large injection amount and the quasi steady state momentum theory. In the case of the spray impinging on a 2-dimensional piston cavity wall, the spray tip penetration of the evaporating spray is larger than that of the non-evaporating spray. Discussion was made on the mechanisms behind these spray behaviors.

CITATION: Nishida, K., LI, K., Matsuo, T., Shimo, D. et al., "Small Injection Amount Fuel Spray Characteristics Injected by Hole-Type Nozzle for D.I. Diesel Engine," *SAE Int. J. Engines* 8(1):2015, doi:10.4271/2014-32-0124.

INTRODUCTION

Homogeneous charge compression ignition (HCCI) is thought as the ideal combustion mode which can not only improve combustion completeness but also reduce emissions [1]. It is one of the most popular research subjects which has been widely concentrated on by engine researchers. HCCI is difficult to realize in diesel engine especially in traditional type which adopts high compression ratio to achieve high power output. Thus, decreasing compression ratio is thought as one way to realize HCCI combustion mode in a diesel engine [2]. However, the combustions under cold start process and idle mode are unstable in a low compression ratio diesel engine. As a solving method, the multi-pilot injection strategy is always employed [3] under the cold start and idle modes. Under multi-pilot injection condition, the pilot injection mass is always selected as tiny to restrain the uncontrollability of ignition timing. Up to present, there is little investigation focused on tiny mass injection, therefore, the spray behaviors of tiny mass injection is worthwhile to be concentrated on.

What's more, spray/wall interaction occurs in small-bore high speed diesel engines and has strong influences on mixture formation, combustion and emission processes inside the combustion chamber. The influence of impingement on mixture formation is complicated. Impingement is thought as an effective method to improve the mixture formation not only

because the spray/wall impingement gives rise to secondary fuel atomization but also because the spray spreading along the wall enhances the air entrained [4]. Meanwhile, the fuel film is formed after impingement and it takes longer time for it to complete evaporation even the air entrainment is enhanced. In this case, the effects of spray wall interaction on the mixture formation have become the subject of plenty of research works during the past decades [4, 5, 6]. For simplicity, the flat wall was always selected to form impinging spray. However, the structure of impinging wall is complicated in a real engine and the spray often impinges on the piston crown and then forms impinging spray, the mixture formation and combustion process are different from that of flat wall impinging spray. Thus it is worthwhile to investigate the spray behaviors by using two-dimensional piston cavity and forming an engine like impinging spray.

For the above reasons, the aim of this study is to provide information on spray characteristics under tiny mass injection condition. To make a comparison, the normal mass (2.97 mg) and middle mass (0.89 mg) injections were also carried out. After that, spray characteristics under two-dimensional piston cavity impinging condition were investigated.

To describe the spray structure in detail, laser absorption and scattering technique (LAS) was adopted.

EXPERIMENTAL METHODS

This paper will not describe the principle of LAS technique in detail because it has been systematically described in our previous papers [7, 8, 9]. Here, the method of LAS is only simply illustrated as follow which is thought as helpful for readers understand this paper:

Two kinds of laser beams are applied in LAS method, 512 nm (visible, λ_T) and 266 nm (ultraviolet, λ_A). These two incident laser beams pass through the spray which is shown in Fig. 1. The intensities are decreased due to the attenuated effect. In the ultraviolet (UV) image, the intensity attenuation is because of liquid scattering, liquid absorption and vapor absorption, the effect of liquid absorption is negligible; in the visible (Vis) image, the extinction is only resulted from droplets scattering.

Therefore, the line-of-sight vapor phase optical thickness can be achieved by subtracting the visible side optical thickness from the UV side optical thickness. And the concentration of vapor will be calculated by applying Bouguere-Lambert-Beer theory; the droplet concentration will be calculated by adopting the relationship between the Sauter Mean Diameter (SMD) D32 and the optical thickness of visible side. The image processing process is shown in Fig. 2. The optical thickness is averaged from four individual images.

By applying LAS technique, the vapor phase concentration and liquid phase concentration can be quantitatively calculated [7]. However, this investigation is concentrated on the spray structure, as a result, the calculation process is not shown here.

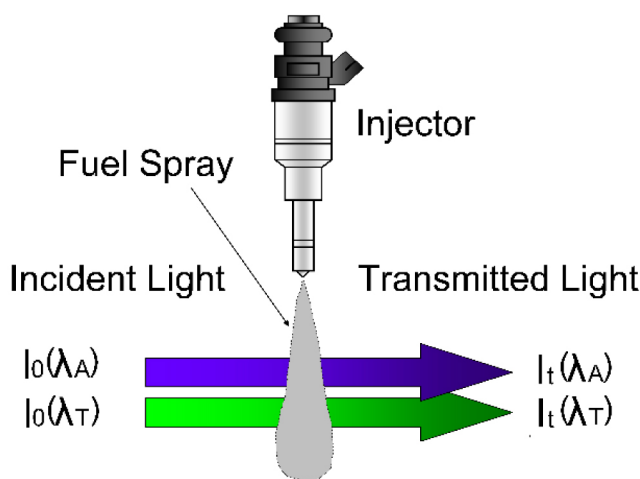


Figure 1. Principle of LAS technique

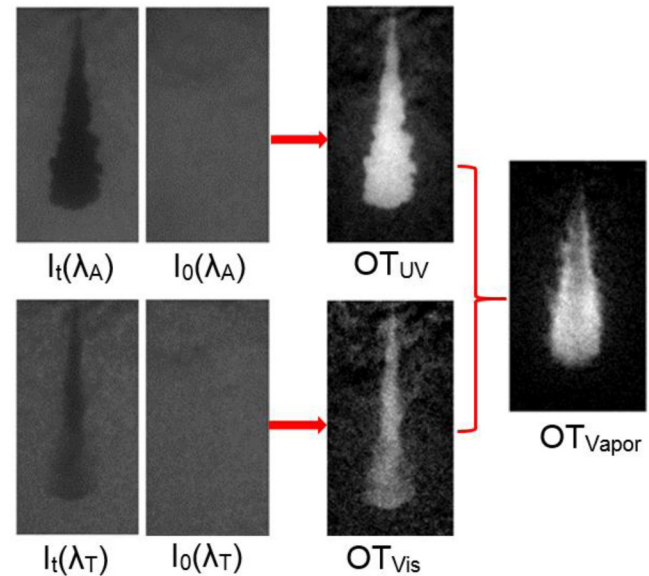


Figure 2. Image processing process of LAS technique

EXPERIMENTAL APPARATUS AND CONDITIONS

The LAS experiment was performed in a high-pressure, high-temperature constant volume combustion vessel, the optical agreement of LAS equipment and injection system are shown in Fig. 3. Transparent quartz windows were employed to make the inside observable and optically accessible. An electric heater was installed at the bottom of the chamber and an air cylinder was applied to produce an engine-like thermodynamic environment. Two thermocouples were employed in order to observe the temperature at different locations inside the combustion chamber. The temperature of the preheater was 700 °C, and the gas could be heated to about 480 °C after flowing through it. After filling the chamber with gas, fuel was injected when the ambient condition was steadily achieved; the difference value of the temperatures detected by the two thermocouples was between ± 5 °C, so it can be considered that the ambient gas was homogeneous when the injection occurred.

A pulsed YAG laser (Continuum NY61-10) was used to form the Vis (second harmonic, 512 nm) and UV (fourth harmonic, 266 nm) lights. The two beams were separated by a dichroic mirror, then the UV and Vis beam were expended respectively. Before pass through the chamber, the two beams were made coaxial again. After being attenuated by the spray, the beams were separated again and were recorded by two CCD cameras (C4880, Hamamatsu Photonics).

A common rail injection system was used to suck the fuel from fuel reservoir and then generate the fuel injection pressure up to 180 MPa. The injector was controlled by the injector ECU. Injection timing, injected mass and image taken timing were controlled by a delay pulse generator (Stanford Inc., DG535).

The injection pulse was defined by the sampling method. The injector used in this study was a single-hole type one and the nozzle diameter is 0.133 mm.

The fuel was 1, 3-dimethylnaphthalene (1, 3-DMN) $[C_{10}H_6(CH_3)_2]$ in this investigation because the properties of it is similar with that of diesel fuel. What's more, the 1, 3-DMN is suitable for LAS experiment because it strongly absorbs UV light and almost does not absorb visible light which are the essential requirement of LAS technique [7].

A two dimensional (2-D) piston cavity was employed to form impinging spray. The impinging distance between the nozzle tip and the impinging point is 30 mm. The specifications of this 2-D cavity are shown in Fig. 4.

The experimental conditions are shown in Tab. 1. Three kinds of ambient conditions were set as: $P_a = 1.4$ MPa, $T_a = 300$ K; $P_a = 2.5$ MPa, $T_a = 530$ K; and $P_a = 3.6$ MPa, $T_a = 760$ K to represent non-evaporating, mid-evaporating and evaporating condition respectively. The evaporating condition was decided as the same condition with the real engine under cold start mode at near TDC timing. To compare spray behaviors directly, the ambient gas densities were kept the same. To avoid reaction, nitrogen was selected as the ambient gas. A piezo actuator type with a diameter of 0.133 mm injector, and three kinds of injection amount were selected as 0.27, 0.89 and 2.97 mg to represent pilot injection, main injection of light load, and main injection of middle load respectively.

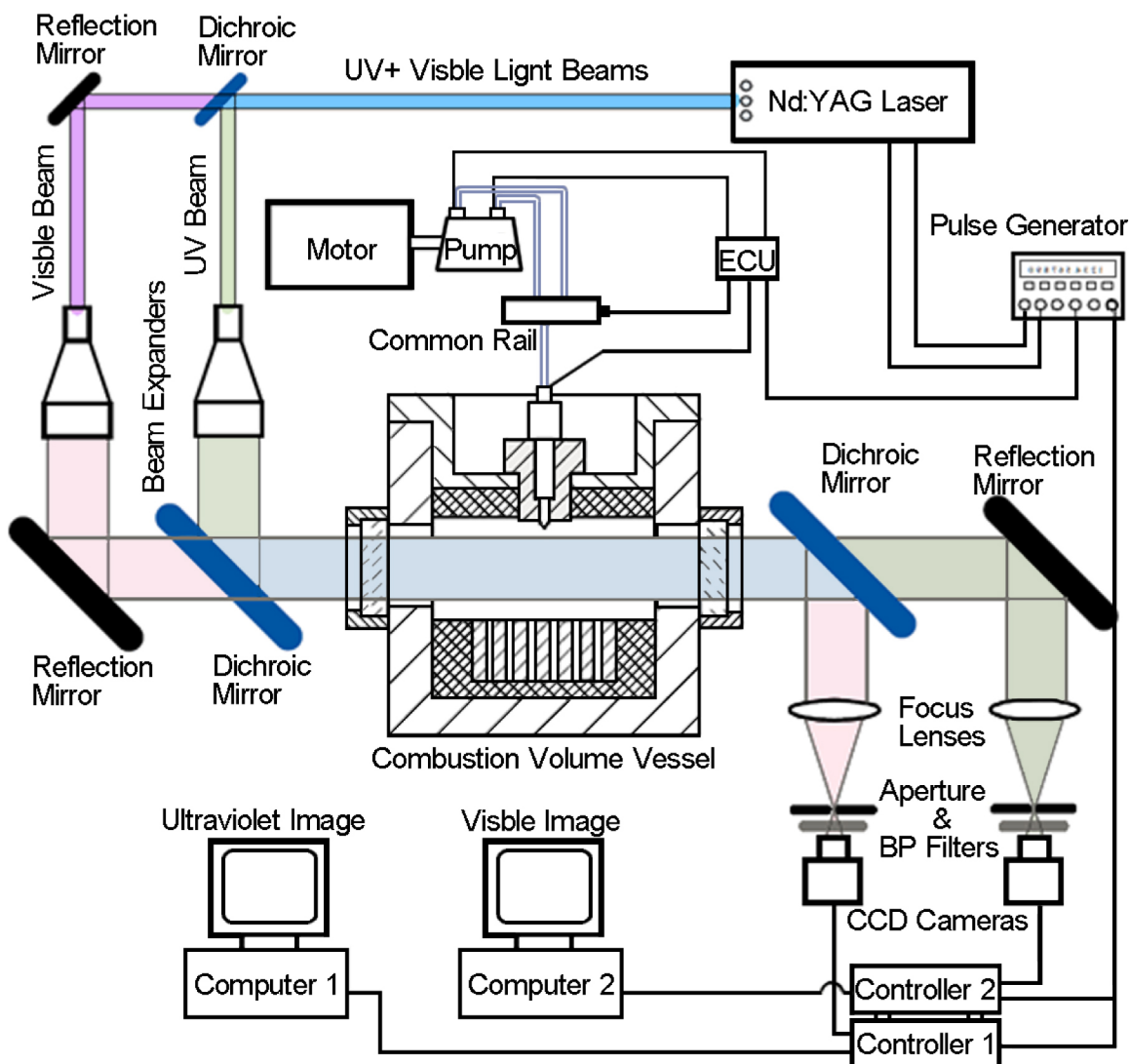


Figure 3. Experimental settings of synchronous experiments of OH* chemiluminescence and two color method

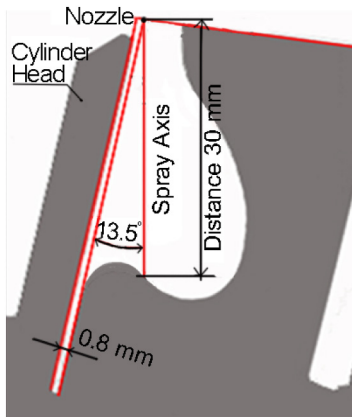


Figure 4. Specification of 2-D piston cavity.

Table 1. Experimental conditions.

Ambient gas	Nitrogen		
Ambient temperature: T_a [K]	300	530	760
Ambient pressure: P_a [MPa]	1.4	2.5	3.6
Ambient density: ρ_a [kg/m ³]	16		
Test fuel	Dimethylnaphthalene $C_{10}H_6(CH_3)_2$		
Injection quantity: Q_f [mg] (Assumption of engine operation)	2.97 (Main injection of middle load) 0.89 (Main injection of light load) 0.27 (Pilot injection)		
Injector type	Piezo actuator type		
Common rail pressure: P_{inj} [MPa]	100		
Nozzle hole diameter: d_0 [mm]	$\phi 0.133$		
Nozzle hole number	1		

RESULTS AND DISCUSSIONS

Mass Flow Rate

The mass injection rate measurement based on Zeuch method [10] was performed to confirm the fuel delivery and injection rate shape by applying injection rate meter (Onosokki Co. Ltd, FJ-7000). The mass flow rate results for all the test conditions are shown in Fig. 5.

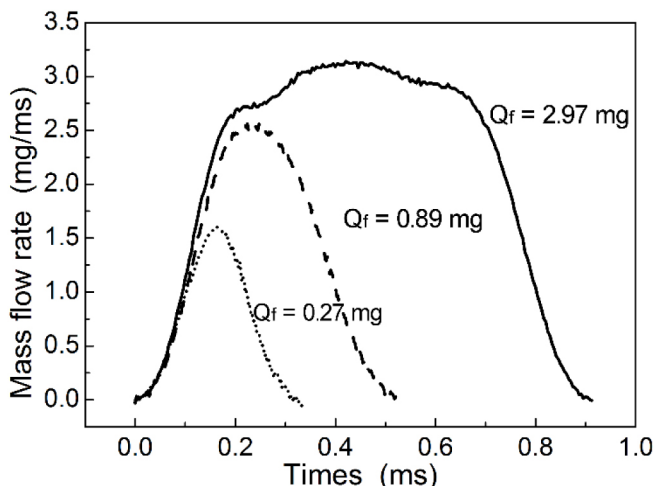


Figure 5. Mass flow rate for all the test conditions.

It shows that the large mass (2.97 mg) injection rate can reach the stable and quasi constant value between 0.2 to 0.7 ms ASOI. However, the injection rates of the other two injection masses cannot reach the quasi steady condition. The mass flow rate of 0.89 mg injected condition comes to 2.5 mg/ms at around 0.2 ms ASOI, which is close to the stable mass flow rate under 2.97 mg injected mass condition. The maximum flow rate of tiny mass injection is around 1.5 mg/ms which is near the half of the stable value of flow rate of 2.97 mg injected mass.

Structure of Spray

Before the discussion of this part, the definitions of the penetration and spray angle should be described. Definitions of penetrations and spray angle of free spray are shown in the left part of Fig. 6. The penetration definition of 2-D piston cavity impinging spray which will be discussed in the next section is also shown in Fig. 6 (right part).

As Fig. 6 shows, the free spray tip penetration is defined as the distance between the nozzle tip to the farthest axial location of the spray boundary. And the spray angle is measured based on the radial distance at the axial location of $\frac{1}{2}$ spray tip penetration. The spray tip penetration of 2-D piston cavity is defined as the combination of axial distance and the arc length of the cavity wall. The spray boundary which is very important when measuring the penetration and angle is defined as the 20% of the maximum intensity.

Figure 7, Fig. 8 and Fig. 9 respectively shows the spray images of 0.27, 0.89 and 2.97 mg in optical thickness at the visible and UV wavelength under different conditions. The spray images under non-evaporating condition in each figure show the thickness of UV wavelength only, this is because there is no vapor phase under non-evaporating condition and the optical thicknesses of UV and visible wavelengths are equal to each other. The bright region in non-evaporating means liquid phase only. Each spray image of mid-evaporating and evaporating conditions is composed of optical thicknesses of visible and UV wavelengths at the left half and right half of the image respectively. As discussed above, the optical thickness of visible wavelength is contributed by droplet attenuation and the optical thickness of UV wavelength is contributed by vapor and droplet attenuations.

As Fig. 7 shown, under non-evaporating condition, spray tip penetration of tiny mass injection does not change a lot from 0.3 to 1.5 ms ASOI. However, when ambient temperature and pressure increase to evaporative conditions (2.5 MPa, 530 K and 3.6 MPa, 760 K), the spray tip penetration and spray angle seem to change a lot with time elapsing. The optical thickness of visible wavelength is always lower than that of UV length, by which the conclusion of liquid phase penetration is nearly the same with that of vapor phase is deduced. It should also note that near the nozzle tip, there is a region with UV optical thickness but without visible thickness, which confirms that the more air entrained into the spray after EOI at the spray tail