

Experimental Study on Mixture Formation and Ignition Processes of Spray Injected by Hole-Type Nozzle for DISI Engine

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ABSTRACT

The purpose of this study is to investigate the spray characteristics and ignition stability of gasoline sprays injected from a hole-type nozzle. Using a single-hole VCO (Valve-Covered-Orifice) nozzle, the spray characteristics were studied with LAS (Laser Absorption Scattering) technique, and then flame propagation and ignition stability were investigated inside a high temperature high pressure constant volume vessel using a high speed video camera. The spatial ignition stability of the spray at different locations was tested by adjusting the position of the electrodes. By adjusting the ignition timings, the stable ignition windows for 3 determined locations where the ignition stability was high at a fixed ignition timing were studied. The flame propagation process was examined using high speed shadowgraph method. Experimental results show that when the ignition points are located on the spray axis, the ignition probability is low. When the distance between the ignition point and the spray axis increases, the ignition probability increases and then decreases. High ignition probability distribution did not coincide with vapor phase equivalence ratio distribution. Too dense liquid phase (droplets) will decrease ignition probability, while proper liquid phase density can improve the ignition stability. When the ignition point is located at downstream of the spray, the high ignition probability range becomes a little wider, while the ignition timing should be retarded. After ignition, the flame propagates mainly to the downstream and expands to the radial direction of the spray.

INTRODUCTION

It has been 15 years since the first launch of the commercial gasoline direct injection (GDI) engine[1,2]. It was believed as one of the most promising technique in internal combustion engines mainly due to the excellent fuel economy[3]. However, challenged by the significantly improved port fuel injection engines and diesel engines, gasoline direct injection engines did not spread worldwide as people expected before[4]. The wall-guided combustion system, which is called the first generation GDI combustion system, has the disadvantages of high HC and SOOT emissions caused by wall wetting[5,6]. The spray-guided

combustion system representing the most promising concept for meeting the future CO₂ targets allows the mass production of stratified direct injection gasoline engines for automotive applications[7]. Obviously, the most critical issue for the application of spray-guided combustion system is its ignition stability, since the time between start of injection and ignition is much shorter than that in a wall-guided combustion system, needless to say the port fuel injection combustion system. The piezo outwardly opening injector and multi-hole injector are suitable for spray-guided combustion system because they have relatively stable spray shape under different ambient pressures, which offers an opportunity to be ignited by the spark plug at proper timing [8-10]. The multi-hole injector, which has been very successful in direct injection diesel engines, has the advantages of flexible spray pattern and low cost. The objective of this paper is to investigate the spray and mixture formation processes as well as the ignition performance of the spray injected from hole-type nozzles.

SPRAY AND MIXTURE FORMATION PROCESSES

LASER ABSORPTION SCATTERING (LAS) TECHNIQUE

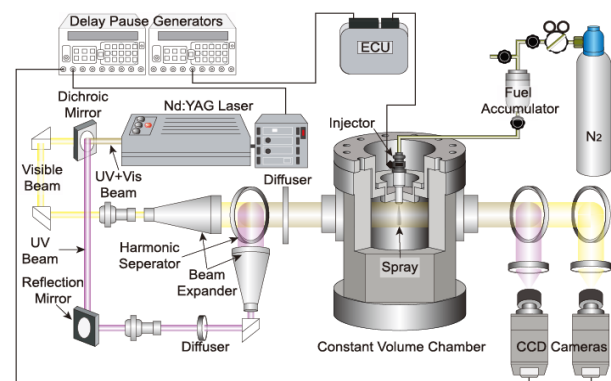


Fig. 1 LAS experimental setup

Figure 1 shows a schematic of the LAS system, fuel injection system, and constant volume vessel. A pulsed

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Nd:YAG laser (Continuum, NY 61-10) was employed to provide two-wavelength beams, one at ultraviolet band of 266 nm and the other at visible band of 532 nm. The two beams were separated by a dichroic mirror and were magnified to a diameter of 100 mm by beam expanders. Then the two beams were combined into a coaxial beam by a dichroic mirror, beamed through the constant volume vessel, transmitted through the spray, and separated again on the other side. In order to minimize the Schlieren-like effect due to the ambient gas density gradient in the LAS images, a diffuser was set between the harmonic separator and the window of the vessel. Finally, the two beams were focused and then were captured by two CCD cameras (Hamamatsu Photonics, C4880). The laser firing, fuel injection and CCD shuttering timings were controlled by delay pulse generators (Stanford Inc., DG 535). The image acquisition and arithmetic processing were carried out using an IPLab (Spectrum Signal Analytics) image analysis system. Detailed description on methodology of LAS technique can be found in some researches [11-13].

In this study, p-Xylene was used as the test fuel because it strongly absorbs the ultraviolet light (266 nm) and is transparent for the visible light (532 nm). At the same time, p-Xylene has similar physical properties of boiling point, viscosity, and evaporation characteristics to those of gasoline. Moreover, the incident light extinction through the fuel vapor in the mixture well obeys Lambert-Beer's law, and it has good temperature independence.

The inlet of the injector was connected to a fuel accumulator, which can be pressurized to a pressure of more than 20 MPa using a high-pressure N₂ cylinder.

During the experimental process, four spray images were taken at each laser shot timing. Then the four images were averaged in order to eliminate the shot-to-shot variation and get relative stable characteristics of the spray.

After some image processing and data arithmetic, the equivalence ratios of vapor phase and liquid phase were calculated with Onion-peeling deconvolution method. During the deconvolution process, the temperature distribution inside the spray was calculated with the consideration of the latent heat absorption due to the evaporation of the droplets inside the spray.

Molar absorption coefficient ε is an important characteristic in the calculation process. For a certain fuel, the molar absorption coefficient is influenced by ambient pressure and temperature. The molar absorption coefficient of p-Xylene was measured using a set of specially designed experimental equipment. Under the ambient pressure of 1 MPa, the molar absorption coefficient of p-Xylene can be expressed as a function of ambient temperature:

$$\varepsilon = 10^{(-0.0002633 \cdot T_a + 2.328)}$$

EXPERIMENTAL CONDITIONS

Experimental conditions are shown in Table 1. The ambient conditions were set to simulate the actual conditions in the cylinder of a DISI engine just before the

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end of compression stroke. In order to avoid combustion of p-Xylene under high ambient temperature, nitrogen gas was used as the ambient gas.

Table 1 Experimental conditions for LAS

Ambient gas	N ₂
Ambient temperature /K	500
Ambient pressure /MPa	1.0
Test fuel	p-Xylene
Nozzle type	Hole type, VCO
Nozzle hole diameter /mm	0.15
L/D	2
Number of holes	1
Injection pressure /MPa	20
Injection duration /ms	1. 1
Injection quantity /mg	1.88
Laser shot timing /ms AEOI	-0.5, 0, 0.5 1.0, 2.0

※ AEOI, After End of Injection

LAS EXPERIMENTAL RESULTS

Liquid and vapor phase equivalence ratio distributions

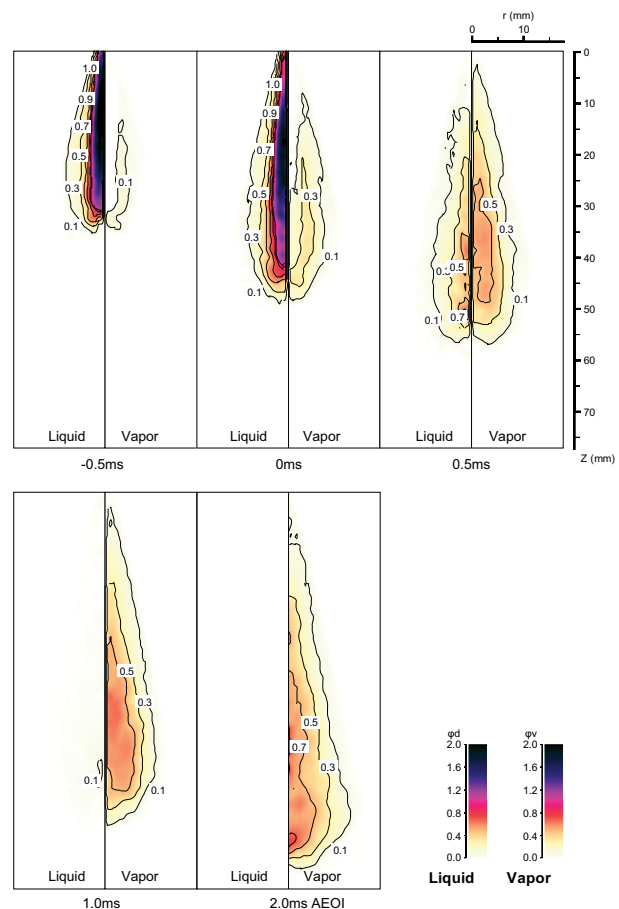


Fig. 2 Liquid and vapor phase equivalence ratio distributions

Figure 2 shows the experimental results of liquid and vapor phase equivalence ratio distributions at different laser shot timings. The contour lines show the value of equivalence

ratio for both liquid and vapor phase fuel. $Z=0$, $r=0$ shows the location of the nozzle hole exit.

At early timings (-0.5 and 0 ms AEOL), the liquid phase equivalence ratio is high especially in the central area of the upstream of the spray. After the end of injection, the liquid phase equivalence ratio decreases dramatically. At about 1.0 ms AEOL, almost all of the liquid phase fuel is vaporized and only in a small area inside the spray the equivalence ratio is higher than 0.1. At the timing of 2.0 ms AEOL, no liquid phase can be detected from the image, which means that all fuel is vaporized.

The vapor phase equivalence ratio increases little by little. At the timing of -0.5 ms AEOL, only a small amount of vapor phase can be detected in the peripheral area of the spray, and almost no vapor phase fuel can be detected near the nozzle hole exit. That is because that at the timing of -0.5 ms AEOL is during the injection process. It needs time to evaporate for the droplets injected from the nozzle hole. With more air entrained into the spray, the vapor phase equivalence ratio increases with the expansion of the spray volume. After the end of injection, the vapor phase equivalence ratio near the nozzle hole exit decreases with the downward movement of the whole spray. At both timings of 0 and 0.5 ms AEOL, the dense vapor phase fuel area is located between 20 mm and 50 mm away from the nozzle tip.

It should be noted that the equivalence ratio value shown in Fig. 2 is smaller than the actual gasoline sprays injected to ambient air. During the experiments, p-Xylene was used as the substitute fuel for gasoline. The molar weight and stoichiometric ratio difference in p-xylene and gasoline should be responsible for the difference in the equivalence ratio. Nevertheless, the relative equivalence ratio distribution should be similar for p-Xylene and gasoline, since they have similar physical characteristics.

Mass of vapor phase fuel

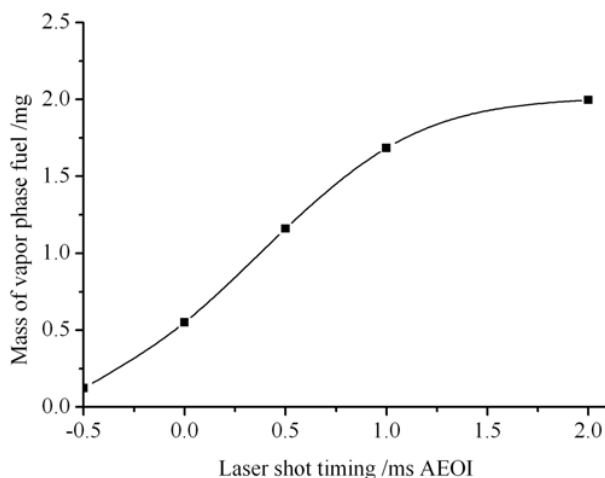


Fig. 3 Mass of vapor phase fuel

Figure 3 shows the mass of vapor phase fuel at different timings. The mass of vapor phase fuel increases slowly before the timing of 0 ms AEOL. Then the curve of mass of

vapor phase fuel shows almost a linear relationship with laser shot timing between 0 and 1.0 ms AEOL. At the timing of 1.0 ms AEOL, more than 80 percent of fuel became vapor phase. At a certain timing between 1.0 and 2.0 ms AEOL, the liquid phase fuel evaporated totally.

Spray tip penetration

The spray tip penetration measured from the raw images is shown in Fig. 4. From the timing of -0.5 ms AEOL to 2.0 ms AEOL, the slope of the spray tip penetration curve, which represents the velocity of the spray tip, keeps decreasing due to its momentum loss. This phenomenon also indicates that from the upstream to the downstream of the spray, the local velocity inside the spray decreases with the increase in the distance from the nozzle tip.

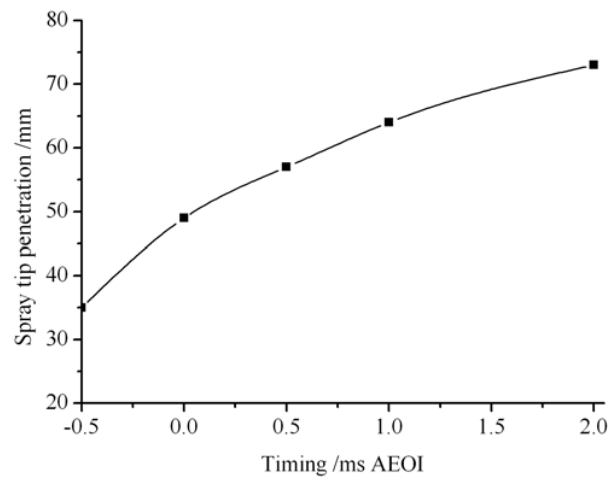


Fig. 4 Spray tip penetration

IGNITION AND FLAME PROPAGATION PROCESSES

In a high pressure high temperature constant volume vessel, ignition experiments were finished in order to test the spatial distribution of the ignition probability and the consequent flame propagation process.

EXPERIMENTAL SETUP AND PROCEDURE

The ignition and flame propagation processes were studied in a constant volume vessel using high speed shadowgraph method. Figure 5 shows the experimental setup. A Xenon lamp was used as the illuminating light source. At first, the light from the Xenon lamp was reflected by a total reflection mirror, and then reflected by a concave mirror. The light became parallel after the concave mirror, and then transmitted the spray and combustion area inside the constant volume chamber. Reflected by another concave mirror and total reflection mirror, the transmitted light was captured by a high speed video camera with proper ND filters before its lens. A pair of electrodes were mounted in one of the side windows. An adjustable electrode gap was located inside the spray area, in order to ignite the spray during the spray process. The discharge of the electrodes

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