INCLUSIVE DATA ON EVAPORATING FUEL SPRAY INJECTED BY HOLE-TYPE D.I. DIESEL INJECTOR
(Hole geometry, injection rate, liquid/vapor phase concentration distributions, spray/mixture properties)

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ABSTRACT

The spray and mixture characteristics are the primary factors which control the fuel-air mixing formation and subsequent combustion processes in D.I diesel engines. This paper presents the inclusive data on evaporating fuel spray injected by the hole-type D.I. diesel injector. By means of the Laser Absorption Scattering (LAS) technique, we provided the integrated information on the fuel spray, from the nozzle hole geometry, injection rate to the liquid/vapor phase concentration distributions and spray/mixture properties. This work is believed to offer a comprehensive database for validating the CFD simulation code and is helpful to in-depth understand the spray behavior of the hole-type injector. Furthermore, based on the LAS measurements of the temporal variations of the concentration distributions in the fuel spray, effects of the injection parameters, such as the injection pressure and nozzle hole diameter were examined. The results show that increasing the injection pressure can enhance the ambient air entrainment, correspondingly promote the fuel-air mixing and eventually improve the fuel evaporation, whereas the effect of the nozzle hole diameter on the fuel-air mixing and evaporation presents double-faced and turns inconspicuous in the case of higher injection pressure.

Key Words: Fuel Spray, Diesel Engine, Laser Diagnostic, Laser Absorption Scattering Technique, Mixture Property

1. INTRODUCTION

As it is well-known in the diesel engine community, the process of injecting fuel into the combustion chamber is responsible for the quality of the air/fuel mixture that is achieved. The efficiency of combustion relies heavily on the quality of this mixture and greatly influences engine performance as well as pollutant emissions [1, 2]. The ideal situation would be to ensure that all the injected fuel is in contact with the maximum amount of available oxygen, so that promoting evaporation and the burning of the hydrocarbons is as complete as possible, on the other hand the high local fuel concentrations are avoided, thus limiting the maximum temperatures that normally occur locally and which are well known for inducing the formation of nitrogen oxides [3].

It can consequently be stated that the mixture concentration distributions inside a fuel spray is essential in in-depth understanding the spray structure and mixture properties. As the vapor and liquid droplets exist concurrently in the evaporating fuel spray, the quantitative measurement becomes rather complicated. Throughout the open literature numerous studies can be found to clarify the spray characteristics as tip penetration, cone angle and drop size. However, the detailed insights into the mixture characteristics, such as vapor/liquid phases concentration distributions, ambient air entrainment and mass frequency of fuel vapor/droplets, are rarely touched. Fortunately, an ultraviolet-visible laser absorption-scattering (LAS) technique was recently developed to provide quantitatively and simultaneously measurements of the vapor/liquid phases concentration distributions in fuel sprays [4, 5]. As the signal-to-noise ratio is high and not easily affected by oxygen quenching, the LAS technique is regarded as a promising approach and its measuring accuracy has already been confirmed to be considerably reliable for both of diesel and gasoline sprays. On the other hand, the main objective of injection is for the spray to come into contact with as much fresh air as possible. Utilizing a nozzle of small orifices together with high injection pressure facilitates stronger own turbulence inside the fuel spray and smaller droplets which can maximize the contact surface between fuel and air [3], thus enhancing the fuel atomization and evaporation. However, the spray structure and mixture characteristics usually changes...
under various operating conditions, thus an in-depth investigation of it is of necessity.

The aim of this paper is to provide the inclusive data on the evaporating fuel spray injected by the hole-type D.I. diesel injector via the LAS technique. Firstly, the nozzle hole geometry and injection rate were presented, then the concentration distributions of both the vapor and liquid phases in the spray were quantitatively clarified and its variation with time was elucidated. Finally, the spray and mixture properties were studied in detail. Meanwhile, the effects of injection pressure and nozzle hole diameter on the mixture characteristics were investigated.

2. EXPERIMENTAL SETUP AND PROCEDURES

The LAS technique was adopted to analyze the spray/mixture properties. Detailed discussions of the LAS principle can be found in the previous work of the research group [4, 5]. A schematic diagram of the optical arrangement of the LAS imaging system, the fuel injection system and the constant volume vessel is shown in Fig. 1. A pulsed Nd:YAG laser (Continuum NY61-10) was employed to provide two-wavelength beams, one at ultraviolet band 266 nm and the other at visible band 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, and 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 on the LAS image, a diffuser is set between the first dichroic mirror and the window of the vessel. Finally, the two beams were focused and captured by two CCD cameras (Photometrics Star I). The images were transferred to a computer for LAS image analysis. In the injection system, a common rail injection system and single orifice hole-type injectors, which were specially built for the test, were employed. 1,3-dimethylnaphthalene (1,3-DMN), which has physical properties close to diesel fuel and been proven to be suitable to the application of the LAS technique, was selected as the test fuel [5]. A pulse generator (DG 535, Stanford Inc.) was used to synchronize the Nd:YAG laser, the CCD cameras and the injection system.

A brief introduction of the LAS image processing is as follows. First, the images with and without the spray at both wavelengths were taken. Next the extinction images of \( \log(I_0/I_t)_{\lambda} \) at the absorbing wavelength and \( \log(I_0/I_t)_{T} \) at the transparent wavelength were obtained. Then the extinction image at transparent wavelength was removed from the extinction image at the absorbing wavelength to give the optical thickness of the vapor phase. Based on the Lambert-Beer’s law and the onion-peeling model, the concentration distribution of the vapor phase were obtained by evaluating the simulating model of mixture temperature in the spray. Moreover, by summing up the vapor mass over the whole spray, the total mass of vapor in the spray could be calculated and further, the total mass of droplets \( M_f \) was obtained according to the fuel injection rate. Again, applying the onion-peeling model, the concentration of liquid phase was deduced.

3. EXPERIMENTAL CONDITIONS

Experimental conditions are listed in Table 1. The ambient gas is nitrogen, its temperature and pressure were set at 760K and 4.0MPa, which is corresponding to the ambient conditions of an actual diesel engine at the start of the injection. In order to clarify the effects of nozzle specifications and injection pressures on the mixture characteristics, two nozzle hole diameters (0.125, 0.135mm) and three injection pressures (60MPa, 90MPa and 120MPa) were employed in this work. Fuel injection quantity per cycle was fixed at 3.35mg by referring to the injection quantity per orifice per cycle at full load of the production D.I. diesel engine for all test cases. In order to determine the precise injection duration, the needle lift and fuel injection rate curves were preliminarily examined for each experimental condition (shown in the following section). The laser shot timing was selected at 0.3, 0.6, 1.0, 1.5 and 2.0ms after the start of injection (ASOI).
Table 1 Experimental Conditions

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<tr>
<td>Ambient Gas</td>
<td>Nitrogen</td>
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<tr>
<td>Ambient Temperature $T_a$, K</td>
<td>760</td>
</tr>
<tr>
<td>Ambient Pressure $P_a$, MPa</td>
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<tr>
<td>Test Fuel</td>
<td>1,3-Dimethylnaphthalene</td>
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<td>Fuel Injection System</td>
<td>Common Rail Type</td>
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<tr>
<td>Nozzle Hole Diameter $D_0$, mm</td>
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<tr>
<td>Injection Pressure $P_{inj}$, MPa</td>
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<tr>
<td>Injection Duration $t_{inj}$, ms</td>
<td>1.12 0.85 0.72 0.93 0.75 0.59</td>
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<tr>
<td>Injection Quantity $M_f$, mg/cycle</td>
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<tr>
<td>Laser Shot Timing $t_s$, ms ASOI</td>
<td>0.3, 0.6, 1.0, 1.5, 2.0</td>
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4. RESULTS AND DISCUSSION

4.1 Nozzle hole geometry and injection rate

The D.I. diesel injectors with a single-orifice nozzle, which were specially built, were employed. The diameter and length of the orifice keeps the same as those used in the commercial engines, except that the number of orifices was changed from the original six to one. The configuration of the injector and details of the nozzle tip are shown in Fig.2.

Fig.2 Configuration of Injector and Details of Nozzle Tip

A needle lift sensor was mounted to measure the needle lift curve. The fuel injection rate was obtained by a new injection rate measuring system (FJ-7000, Ono Sokki Co., Ltd). The measurement under high back-pressure is possible which is more accurate than that under the atmospheric condition. The results are shown in Fig.3, which give the needle lift curves and the injection rate profile curves according to various injection conditions. In these figures, we could know that the fuel injection rate is significantly affected by the total section area of nozzle hole and injection pressure. As total section area of nozzle hole is larger and injection pressure is higher, initial injection rate increases and injection duration decreases, which indicates the higher injection velocity.

4.2 Vapor/liquid phases equivalence ratio distributions

Figure 4 shows the temporal development of spatial vapor/liquid phases equivalence ratio distributions in the spray as a baseline compared with other injection conditions. The injection pressure is 90MPa and the nozzle hole diameter is 0.125mm. The left hand side of each distribution in Fig.4 shows the liquid phase and the right hand side shows the vapor phase. The results indicate that at 0.3ms and 0.6ms ASOI, which are still within the injection period, the magnitude of equivalence ratio of the liquid phase is much greater than that of the vapor phase in these two cases, that is, the droplets generally dominate the whole spray plume. And the
A liquid-containing core is observed in the region near the spray axis close to the nozzle tip, of which the maximum equivalence ratio exceeds 2.5. In the meanwhile, the vapor exists mainly in the outer region of a certain distance (about 10mm) along the spray axis from the nozzle tip. In other words, rare vapor is generated in the region near the nozzle tip within an axial distance of 10mm where the liquid core exists. On the other hand, after the injection duration, it is easy to find that the liquid phase disappears gradually and the vapor phase obviously grows and distributes more extensively. To put it more precise, at 1.0ms ASOI, the highest equivalence ratio of liquid markedly drops from 2.5 to about 0.8, and the location of the rich liquid phase moves to the direction of the spray tip. Furthermore, by the end of 2.0ms, almost all fuel has been completely vaporized, and no droplets remain. Comparatively, the vapor-gas mixture becomes richer and the area of the rich mixture is bigger as time proceeds. It is interesting to observe that the axial location of rich vapor-gas mixture region does not greatly change for the three timings, almost keeps in the axial distance of 20-30mm. This is maybe attributed to the fact that the vapor phase is affected more easily by the ambient air motion, and the high ambient pressure suppresses the air motion.

The radial and axial distributions of equivalence ratios of liquid and vapor phases at 0.3~2.0ms ASOI are summarized in Fig. 5. Firstly, look at the radial distributions of the equivalence ratio at 40mm downstream from the nozzle tip, which is shown in Fig. 5(a). The difference between the vapor and liquid phases is obvious. The distributions of the vapor phase equivalence ratios show an anticlastic shape except at 0.3ms ASOI when the spray has not reached the measurement distance, that is, the relatively low equivalence ratio around the spray axis, and then the curves turn upwards to reach a peak at about 4.0mm radial distance and fall again in the periphery of the spray. This is maybe caused by the existence of high density liquid phase in the axial region, which suppressed the evaporation. It should be pointed out that the trend of distributions is almost the same for all test timings. Whereas the radial distribution of the liquid phase equivalence ratio shows a gradually falling curve, and the magnitude decreases gradually with the increase in the radial distance and elapsed time, especially between 1.0ms and 1.5ms ASOI. On the other hand, the data of axial distributions of vapor equivalence ratios (Fig. 5b) demonstrates that the curves show two peaks except for the 0.3ms ASOI case, the first peak exists at the axial location of about 25mm, corresponding to that observed in Fig. 4, and the appearance of second peak moves to the spray tip with the spray development. In short, the shape of curves is something like a saddleback. Meanwhile, the liquid phase equivalence ratios decrease with the axial distance for all timings, and a rapid drop can be observed at the timings of 1.0ms and 1.5ms ASOI, indicating the high evaporating rate.

Figure 6 shows the effect of injection pressure on the equivalence ratio distributions of both the liquid and vapor phases in the sprays at 1.0ms ASOI. Compared to those with an injection pressure of 60MPa, the sprays with the injection pressures of 90MPa and 120MPa penetrate farther, and show a lower overall equivalence ratio of the liquid phase. The highest equivalence ratio of liquid phase fuel presents a remarkable decrease with the increase of injection pressure, from the value of 1.2 (in the case of 60MPa) to about 0.5 (in the case of 120MPa). Meanwhile, it can be seen that the equivalence ratio of the vapor phase increases when increasing the injection pressure, and the vapor-ambient gas mixture is much wider.
Fig. 6 Effect of Injection Pressure on Equivalence Ratio Distributions

(D<sub>0</sub>=0.125mm, M<sub>f</sub>=3.35mg, t<sub>s</sub>=1.0ms ASOI, P<sub>a</sub>=4.0MPa, T<sub>a</sub>=760K)

Fig. 7 Equivalence Ratio Distributions for Larger Nozzle Hole Diameter

(D<sub>0</sub>=0.135mm, P<sub>inj</sub>=90MPa, M<sub>f</sub>=3.35mg, t<sub>inj</sub>=0.75ms, P<sub>a</sub>=4.0MPa, T<sub>a</sub>=760K)

Fig. 5 Radial and Axial Distributions of Liquid and Vapor Equivalence Ratios

(P<sub>inj</sub>=90MPa, D<sub>0</sub>=0.125mm, t<sub>inj</sub>=0.85ms, M<sub>f</sub>=3.35mg, P<sub>a</sub>=4.0MPa, T<sub>a</sub>=760K)

Fig. 6 Effect of Injection Pressure on Equivalence Ratio Distributions

(D<sub>0</sub>=0.125mm, M<sub>f</sub>=3.35mg, t<sub>s</sub>=1.0ms ASOL, P<sub>a</sub>=4.0MPa, T<sub>a</sub>=760K)

Fig. 7 Equivalence Ratio Distributions for Larger Nozzle Hole Diameter

(D<sub>0</sub>=0.135mm, P<sub>inj</sub>=90MPa, M<sub>f</sub>=3.35mg, t<sub>inj</sub>=0.75ms, P<sub>a</sub>=4.0MPa, T<sub>a</sub>=760K)
spreading. The evidence reflected from the above results indicates that, as expected, the higher injection pressure can enhance atomization of the fuel spray, and then improve the evaporation.

Figure 7 gives the contours of equivalence ratio distributions for the nozzle of 0.135mm hole diameter under injection pressure of 90MPa. It is found that, during the injection period (0.6ms ASOI), the area and the amount of the rich liquid phase with $\Phi_d > 2.0$ apparently increase and the relatively higher equivalence ratio of vapor phase ($\Phi_v > 0.3$) does not appear compared to those with 0.125mm nozzle hole diameter (shown in Fig.4). In the contrast, it is interesting that after the end of injection (1.0 and 1.5ms ASOI), much higher equivalence ratio of liquid phase (like $\Phi_d > 0.8$ in 1.0ms) can be observed and the region of richer vapor-gas mixture ($\Phi_v > 0.4$) is found to be more concentrated around nozzle tip with smaller nozzle hole diameter. These phenomena are believed to be contributed as follows. As the fixed injection quantity, the injection duration is longer for the 0.125mm nozzle hole diameter case, thus gives less fuel amount by the same laser shot timing within the injection period. Moreover, it is commonly considered that, the smaller nozzle hole diameter usually generates the smaller mean diameter of fuel droplets, which is helpful in fuel-air mixing and promoting the evaporation. On the other hand, after the end of injection, the persisting period form the end of injection to the same laser shot timing is shorter in case of 0.125mm nozzle hole diameter than that of 0.135mm case for the longer injection duration, therefore, the evaporation is relatively insufficient and results in the remaining of high equivalence ratio liquid phase in the spray.

4.3 Spray/mixture properties

Spray properties. Spray tip penetration and cone angle are usually used to describe the spray properties. Figure 8 shows the spray properties versus time after the start of injection under various injection conditions. The liquid phase penetration is believed as an important factor since the liquid phase sprays with higher concentrations have a greater tendency to form a liquid film on the wall surface. The over-penetrating liquid core usually results in wall-wetting in the cylinder and is probably one of the main sources contributing to the high pollutant emissions in engine applications. Thus, the liquid phase penetration is defined as the fastest penetration distance of the liquid phase spray with an equivalence ratio above 1.0 in this study. As shown in Fig. 8 (a), with increasing the injection pressure, the liquid phase penetration increases at 0.3ms ASOI for the higher injection momentum, whereas the lower liquid phase penetration is achieved at 0.6ms ASOI, which is believed as the contribution of the effect of promoting the evaporation.
Moreover, most of the liquid cores have disappeared at 1.0ms ASOI except for the cases of 60MPa. Therefore, increasing injection pressure can reduce the high liquid phase concentration in the fuel spray. Meanwhile, slightly decrease in liquid phase penetration is observed in the case of smaller nozzle hole diameter regardless of the injection pressure.

The vapor phase penetration shown in Fig.8 (b) is defined as the farthest penetration distance of the vapor phase fuel with an equivalence ratio of 0.1. As expected, the vapor phase penetrates farther by higher injection pressure, and shorter under the condition of smaller nozzle hole diameter.

Spray cone angle was also measured and the extracted data from the acquired LAS results are plotted in Fig.8 (c). The results exhibit such close values that it would be difficult to draw a clear conclusion over a possible tendency, so it leads to the conclusion that there is no direct and great influence of injection pressure and nozzle hole diameter over the cone angle in the test range of this study.

Mixture properties. More detailed investigation concerning the effect of injection pressure and nozzle hole diameter on mixture properties is taken, which is illustrated in Fig. 9. The histories of fuel mass, mass of entrained ambient gas into the sprays and the mean equivalence ratio of total fuel (vapor and liquid phases) are taken into account. As shown in the Fig.9 (a), it is not difficult to find that the mass of liquid phase fuel decreases and the mass of vapor phase fuel increases with the increase of injection pressure at all test timings, similarly, the amount of entrained air is greater with higher injection pressure. This is expected, increasing the injection pressure, which generates higher momentum of the spray, usually results in greater tip penetration and smaller mean diameter of droplets, then consequently more air is sucked into the spray to enable an enhance of fuel-air mixing. Therefore, it is reasonable that the lower mean equivalence ratio of total fuel is achieved by the higher injection pressure pray with different nozzle specifications.

Effect of nozzle hole diameter on the mixture properties is illustrated in Fig.9 (b). The similar trend is found as that of equivalence ratio distributions (shown in Fig.4). At the early stage of injection (0.3ms and 0.6ms ASOI), the mass of vapor phase and entrained ambient gas increase, at least keep equivalent, by the smaller nozzle hole diameter 0.125mm, whereas the lower mass of liquid phase and mean equivalence ratio of total fuel are achieved simultaneously. After the end of injection (1.0~2.0ms ASOI), the reverse occurs. These facts just support the explanation given in the previous section, which is believed as a comprehensive result of longer injection duration and smaller mean diameter of the fuel spray. Moreover, Fig.10 gives the ratio of fuel evaporation with two nozzle hole Specifications.

Fig.9 Mixture Properties under Various Injection Conditions.
diameters under various injection pressures. It should be noted that although the double faced effect of nozzle hole diameter is demonstrated, the difference becomes unconspicuous as injection pressure increases, especially in the case of injection pressure of 120MPa. It is considered that in case of optimizing the injection conditions for promoting the fuel evaporation and air entrainment, the method of increasing the injection pressure can be more effective than changing of nozzle hole diameter.

2. The radial distributions of the vapor phase equivalence ratios show an anticlastic shape, whereas those of the liquid phase show a gradually decrease with the increase in the radial distance and the elapsed time. On the other hand, the curves of the axial distributions of vapor equivalence ratios show two peaks in the nozzle-side main body of the spray and around the spray tip, and the liquid phase equivalence ratios along the spray axis decreases with the axial distance at all test timings.

3. Increasing injection pressure makes more ambient air entrained into the spray, correspondingly promotes the fuel-air mixing, decreases the liquid phase penetration, and eventually the lower mean equivalence ratio of total fuel can be achieved.

4. Effect of nozzle hole diameter on the mixture characteristics shows double-faced. During the injection duration, the smaller nozzle hole diameter gives the higher evaporation rate. In contrast, after the end of injection, the evaporation is relatively insufficient due to worse air entrainment, thus the richer liquid phase remains. Moreover, this effect turns unconspicuous in the case of higher injection pressure.

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