ABSTRACT  An experimental and numerical study was conducted on the spray and mixture properties of the hole-type injectors for D.I. gasoline engines. The Laser Absorption Scattering (LAS) technique was adopted to simultaneously measure the spatial distributions of the liquid and vapor phase concentrations in the fuel spray injected into a high-pressure and high-temperature constant volume vessel. Effect of diameter and length-to-diameter ratio of the nozzle hole L/D on the spray and mixture properties were examined. The smaller hole diameter and L/D produce the shorter tip penetration, the wider vapor phase dispersion of the spray, and the larger mass of vapor phase fuel around the stoichiometric equivalence ratio in the entire spray. The numerical analysis of a nozzle internal flow was executed to this experiment result.

Keywords: Fuel Spray, Internal Combustion Engine, Gasoline Engine, Mixture Formation, Laser Diagnostics

1. INTRODUCTION
The combustion systems used in the Direct Injection Spark Ignition (DISI) engines are based on the wall guided concept so far, which carries the combustible mixture to the spark plug location by the spray/wall interaction [1]. In order to reduce the inherent smoke emission from the wall guided DISI engines and to further improve their thermal efficiencies, attempts are being made to change the combustion system to the spray-guided concept in order to avoid the wall wetting of the fuel spray and the resultant rich mixture preparation. In the spray-guided combustion system, hole type injectors are used due to their consistent spray angle characteristics against changing ambient pressure, which the swirl type injector used for the wall-guided combustion system does not have [2]. It is a critical issue to clarify the mixture properties as well as the spray properties of the hole type injectors in developing the spray-guided combustion systems for the DISI engines. One of the authors have developed the LAS (Laser Absorption Scattering) technique, which is the simultaneous and quantitative measuring method of the liquid and vapor phase concentration distributions in the diesel-like fuel spray [3,4,5]. Recently two of the authors have applied the LAS technique to the analysis of the gasoline-like fuel spray [6,7]. In this study, the application of the LAS technique was made of the gasoline-like fuel spray injected by the hole type injector for the DISI engines. Effects of the hole geometry, such as hole diameter and length-to-diameter ratio of the nozzle hole (L/D ratio), on the spray and mixture properties were clarified. The experimental results were compared with the calculated results by Computational Fluid Dynamics (CFD).

2. EXPERIMENTAL APPARATUS AND PROCEDURES

2.1 High-Pressure and High-Temperature Constant Volume Vessel and LAS System
Schematics of the high-pressure and high-temperature constant volume vessel, the fuel injection system and the LAS system are shown in Fig. 1 and experimental conditions are shown in Table 1. The ambient gas is nitrogen, its pressure and temperature was set at 1.0MPa and 500K, respectively. This condition imitated the compression stroke of the DI gasoline engine. Four kinds of injectors where the diameter and L/D ratio were different were used. Injection pressure was set at 20MPa, and quantity at 3.47mg. As shown in Fig. 1 the spray was injected into the high-pressure and high-temperature constant volume vessel. The spray was irradiated by two-wavelength beams, one at ultraviolet band 266 nm and the other at visible band 532 nm. The light extinction images that were attenuated in the spray was separated the ultraviolet and the visible beam again and captured by two CCD cameras. The images were transferred to a computer for the LAS image analysis.

Fig. 1 Experimental Apparatus
Fig. 2 Extinction of Incident Light through Evaporating Spray at Wavelengths $\lambda_A$ and $\lambda_T$

2.2 Principle of Laser Absorption Scattering (LAS) Technique [6,7]

As shown in Fig. 2, a two-wavelength ($\lambda_A$; absorption wavelength, $\lambda_T$: transparent wavelength) incident light of intensity $I_0$ transmits through a mixture of both vapor phase and liquid phase droplets, and is attenuated into a transmitted light of intensity $I_t$.

The extinction of absorption wavelength light $\log(I_0/I_t)_{abs}$ is attributed to the liquid phase scattering and absorption $\log(I_0/I_t)L_{Lscat}+L_{Labs}$ as well as the vapor phase absorption $\log(I_0/I_t)L_{Vabs}$ and its extinction rate is defined by Eq. (1). The extinction of transparent wavelength light $\log(I_0/I_t)_{Lscat}$ is attributed to only the liquid phase scattering $\log(I_0/I_t)L_{Lscat}$ and its extinction rate is defined by Eq. (2).

$$\log\left(\frac{I_0}{I_t}\right)_{abs} = \log\left(\frac{I_0}{I_t}\right)_{Lscat} + \log\left(\frac{I_0}{I_t}\right)_{Labs} + \log\left(\frac{I_0}{I_t}\right)_{Vabs} \tag{1}$$

$$\log\left(\frac{I_0}{I_t}\right)_{Lscat} = \log\left(\frac{I_0}{I_t}\right)_{Lscat} \tag{2}$$

Because it is confirmed that the liquid phase absorption $\log(I_0/I_t)_{Labs}$ that is the 2nd member at the right side of Eq. (1) can be disregarded [5,6], and the liquid phase scattering $\log(I_0/I_t)L_{Lscat}$ of both wavelength is almost identical [5,6], the extinction rates by the vapor absorption and the liquid scattering can be derived as Eqs. (3) and (4), respectively. Based on Eq. (3), extinction by the vapor phase $\log(I_0/I_t)L_{Labs}$ is gained by subtracting the extinction of transparent wavelength $\log(I_0/I_t)_{Lscat}$ from the extinction of absorption wavelength $\log(I_0/I_t)_{abs}$.

$$\log\left(\frac{I_0}{I_t}\right)_{Labs} = \log\left(\frac{I_0}{I_t}\right)_{abs} - \log\left(\frac{I_0}{I_t}\right)_{Lscat} \tag{3}$$

$$\log\left(\frac{I_0}{I_t}\right)_{abs} = \log\left(\frac{I_0}{I_t}\right)_{Lscat} \tag{4}$$

In this study, the fourth harmonic output (wavelength 266nm) of an Nd:YAG laser was adopted as the absorption wavelength $\lambda_A$, and the second harmonic output (wavelength 532 nm) as the transparent wavelength $\lambda_T$, since the test fuel (p-xylene) strongly absorbs the ultraviolet light (266 nm) and is transparent at the visible light (532 nm) [6]. Based on Lambert-Beer’s law and the onion-peeling model, the concentration distributions of the vapor phase fuel were obtained. By summing up the vapor mass over the whole spray, the total mass of vapor in the spray was obtained. By subtracting the total mass of vapor from the mass of fuel injected, the total mass of droplets in the spray was obtained. By adopting the onion-peeling model and Bouguer-Lambert-Beer’s law, the concentration distributions of the liquid phase fuel were obtained.

3. RESULTS AND DISCUSSION

3.1 Equivalence Ratio Distributions of Liquid and Vapor Phases

Figure 4 shows the equivalence ratio distributions of the liquid and vapor phases in the fuel spray. The left hand side of each distribution in Fig. 4 shows the liquid phase and the right hand side shows the vapor phase. The images were taken at 2.0ms after the start of injection when the fuel injection was finished for all cases. Since the injection quantity was adjusted to 3.47mg for various hole diameter and L/D ratio injectors, the injection duration is different according to the injector. The duration from the end of injection (EOI) to the imaging timing for the small hole diameter D=0.135mm is 0.142ms (Fig. 4(a), L/D=1) and 0.189ms (Fig. 4(b), L/D=1), and for the large hole diameter D=0.155mm, 0.582ms (Fig. 4(c), L/D=1) and 0.5ms (Fig. 4(d), L/D=1). Thus, as is seen in Figs. 4(a) and (b), the region with the relatively high liquid phase equivalence ratio appears in the vicinity of the injector for D=0.135mm, while the liquid phase equivalence ratio is not so high for D=0.155mm in Figs. 4(c) and (d).

The spray tip penetration could be defined by the penetration of the vapor phase whose equivalence ratio is $\Phi_v=0.1$. The spray tip penetration of the injectors with the small hole diameter D=0.135mm is shorter than that with the large hole diameter D=0.155mm regardless of the hole L/D ratio. The spray tip penetration of the nozzle with small L/D ratio is shorter than that with large L/D ratio within the same hole diameter.

### Table 1 Experimental Conditions

<table>
<thead>
<tr>
<th>Ambient Condition</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature: $T_a [K]$</td>
<td>500</td>
</tr>
<tr>
<td>Pressure: $P_a [MPa]$</td>
<td>1</td>
</tr>
</tbody>
</table>

### Injection Condition

<table>
<thead>
<tr>
<th>Fuel</th>
<th>P-xylene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector</td>
<td>Hole Type</td>
</tr>
<tr>
<td>Number of Holes</td>
<td>1</td>
</tr>
<tr>
<td>Hole Diameter [mm]</td>
<td>0.135 0.155</td>
</tr>
<tr>
<td>L/D</td>
<td>1.0 2.0 1.0 2.0</td>
</tr>
<tr>
<td>Injection Duration [ms]</td>
<td>1.858 1.811 1.418 1.5</td>
</tr>
<tr>
<td>Injection Pressure [MPa]</td>
<td>20</td>
</tr>
<tr>
<td>Injection Quantity [mg]</td>
<td>3.47</td>
</tr>
</tbody>
</table>
region, which are a little different from the liquid phase distribution. When the liquid fuel in the spray evaporates, the vapor is dropped from the liquid phase flow into the ambient gas and then it is distributed behind the liquid phase. The vapor phase around the spray tip is caught up by the succeeding vapor phase flow, then the high vapor phase equivalence ratio appears around the spray tip.

3.2 Axial Distributions of Vapor Phase Equivalence Ratio

Effect of hole diameter. Figures 5 and 6 show the effect of the hole diameter on the axial distributions of vapor/liquid phase equivalence ratios. As shown in Figs. 5(a) and 6(a), the region with the relatively high vapor phase equivalence ratio appears in the vicinity of the spray tip for $D=0.135\text{mm}$ regardless of the hole L/D ratio. Moreover, the axial distribution of the vapor phase equivalence ratio for $D=0.135\text{mm}$ shows the flat shape along the spray axis. This tendency that is the effect of hole diameter is similar for the condition at 2.5ms after the start of injection, though the result is not shown in the paper. The evaporation of the fuel at 2.5ms has ended almost because enough time passes from the EOI. Therefore, it seems that the effect of the hole diameter on the mixture properties of 2.0ms and 2.5ms doesn't depend on differing the injection duration according to the hole diameter. Figures 5(b) and 6(b) show the axial distribution of the liquid phase equivalence ratio. There is a region with the high liquid phase equivalence ratio in the vicinity of the injector for $D=0.135\text{mm}$ regardless of the hole L/D ratio, since the duration from the EOI is shorter for $D=0.135\text{mm}$ than $D=0.155\text{mm}$.

Effect of L/D. Figures 7 and 8 show the effect of the hole L/D ratio on the axial distributions of vapor/liquid phase equivalence ratios. As shown in Figs. 7(a) and 8(a), the region with the high vapor phase equivalence ratio appears in the whole spray for $L/D=1$ regardless of the hole diameter. This tendency is more remarkable for $D=0.155\text{mm}$ shown in Fig. 8(a). Figures 7(b) and 8(b) show the axial distribution of the liquid phase equivalence ratio.

![Fig. 4 Effect of Hole Geometry on Liquid and Vapor Phase Equivalence Ratio Distributions](image)

![Fig. 5 Effect of Hole Diameter on Axial Distributions of Vapor/Liquid Equivalence Ratios for L/D = 1, t=2.0ms](image)
3.3 Radial Distribution of Vapor Phase Equivalence Ratio

Figure 9 shows the radial distributions of the vapor phase equivalence ratio at Z=35mm downstream from the injector tip. The axial distance of Z=35mm is about the spark plug location in the spray guided combustion system arrangement. In the case of L/D=1, there is a high distribution of the vapor phase equivalence ratio in the range of 5 to 10mm from the spray axis.

There is a region with the high liquid phase equivalence ratio in the whole spray for L/D=1 regardless of the hole diameter. In the case of L/D=1, the liquid phase equivalence ratio is low, then the vapor phase equivalence ratio is high in the whole spray.

Fig. 6 Effect of Hole Diameter on Axial Distributions of Vapor/Liquid Equivalence Ratios for L/D = 2, t=2.0ms

Fig. 7 Effect of L/D on Axial Distributions of Vapor/Liquid Equivalence Ratios for D=0.135mm, t=2.0ms

Fig. 8 Effect of L/D on Axial Distributions of Vapor/Liquid Equivalence Ratios for D=0.155mm, t=2.0ms

Fig. 9 Radial Distributions of Vapor Equivalence Ratio at Z=35mm, t=2.0ms
3.4 Temporal Variations of Vapor Phase Equivalence Ratio at Spark Plug Location

Figure 10 shows temporal variations of the vapor phase equivalence ratio at the spark plug location, that is, the axial distance of \( Z = 35 \) mm and the radial distance of \( R = 5.0 \) mm from the spray axis. The arrow at the left bottom in Fig. 10 indicates the injection duration given to each injector. When the injector condition is \( D = 0.135 \) mm and \( L/D = 1 \), the high vapor phase equivalence ratio is kept from 1.5 ms to 2.5 ms after the start of injection.

![Fig. 10 Temporal Variations of Vapor Equivalence Ratio Distributions at Radius R=5.0mm for Axial Distance Z=35mm, t=2.0ms](image)

3.5 Temporal Variations of Mass of Vapor and Liquid

Figures 11 and 12 show temporal variations of mass of vapor and liquid phases in the whole spray for \( L/D = 1 \) and 2, respectively. Each figure includes two temporal variations for hole diameters of \( D = 0.135 \) mm and \( D = 0.155 \) mm. The mass of total fuel increases as time passes by the EOI. The mass of a total fuel reaches the injection quantity (3.47 mg) at EOI. The mass of fuel is divided into the liquid phase, the rich vapor phase (1.3 < \( \phi_v \) < 1.3), vapor phase around the stoichiometric equivalence ratio (0.7 < \( \phi_v \) < 1.3), and the lean vapor phase (\( \phi_v < 0.7 \)).

Effect of hole diameter. As shown in Figs. 11(a) and (b), the mass of fuel of the lean mixture (\( \phi_v < 0.7 \)) for \( D = 0.135 \) mm is less than that for \( D = 0.155 \) mm from 2.0 ms to 2.5 ms after the start of injection. The mass of vapor phase fuel around the stoichiometric equivalence ratio (0.7 < \( \phi_v < 1.3 \)) for \( D = 0.135 \) mm is more than that for \( D = 0.155 \) mm from 2.0 ms to 2.5 ms after the start of injection. Figures 12(a) and (b) show that these tendencies are similar for the condition of \( L/D = 2 \).

Effect of \( L/D \). As shown in Figs. 11(a) and 12(a), the mass of fuel of the lean mixture (\( \phi_v < 0.7 \)) for \( L/D = 1 \) is less than that for \( L/D = 2 \) from 2.0 ms to 2.5 ms after the start of injection. The mass of vapor phase fuel around the stoichiometric equivalence ratio (0.7 < \( \phi_v < 1.3 \)) for \( L/D = 2 \) is more than that for \( L/D = 1 \) from 2.0 ms to 2.5 ms after the start of injection. Figures 11(b) and 12(b) show that these tendencies are similar for the condition of \( D = 0.155 \) mm.

3.6 Mass Frequency of Vapor Phase Equivalence Ratio

Effect of hole diameter. Figure 13 shows the effect of the hole diameter on the mass frequency of the vapor phase equivalence ratio over the entire spray at 2.0 ms after the start of injection.

![Fig. 13 Mass Frequency of Vapor Phase Equivalence Ratio](image)

![Fig. 11 Temporal Variations of Mass of Vapor and Liquid in Spray for L/D=1](image)

![Fig. 12 Temporal Variations of Mass of Vapor and Liquid in Spray for L/D=2](image)
The mass of vapor phase fuel around the stoichiometric equivalence ratio $\phi_v=1.0$ for the hole diameter $D=0.135\text{mm}$ is more than that for $D=0.155\text{mm}$. This tendency is similar for the condition of $L/D=2$, though the result is not shown in this paper. Therefore, the mass of vapor phase fuel around the stoichiometric equivalence ratio $\phi_v=1.0$ for $D=0.135\text{mm}$ is more than that for $D=0.155\text{mm}$ regardless of $L/D$ ratio. This tendency that is the effect of hole diameter is similar for the condition at 2.5ms after the start of injection, though the result is not shown in the paper. Therefore, it seems that the effect of the hole diameter on the mixture properties of 2.0ms and 2.5ms doesn't depend on differing the injection duration.

Effect of $L/D$. Figure 14 shows the effect of $L/D$ ratio on the mass frequency of the vapor phase equivalence ratio over the entire spray at 2.0ms after the start of injection. The mass of fuel vapor phase around the stoichiometric equivalence ratio $\phi_v=1.0$ for $L/D=1$ is more than that for $L/D=2$. This tendency is similar for the condition of $D=0.155\text{mm}$, though the result is not shown in the paper. Therefore, the mass of vapor phase around the stoichiometric equivalence ratio $\phi_v=1.0$ for $L/D=1$ is more than that for $L/D=2$ regardless of the hole diameter.

![Fig. 15 Computational model for CFD](image)

![Fig. 16 Computed Velocity Vector Distributions at the Section C](image)

3.7 Internal Flow of Nozzle Hole

As were described in the previous sections, the smaller hole diameter and the smaller $L/D$ ratio decrease the spray tip penetration and liquid phase penetration, increase the vapor phase equivalence ratio at the spark plug location, and increase the mass of vapor phase fuel around the stoichiometric equivalence ratio. In this section, discussion is made on the correlation of the internal flow of the nozzle hole in the CFD calculations with these spray and mixture characteristics[8]. The behavior of the internal flow is considered as follows [9].
Calculations were carried out with STAR-CD, a commercial CFD application. The computational three-dimensional model employed in the simulation of nozzle internal flow is shown in Fig. 15. The total number of cells used for this model was about 610,000 and the minimum cell size is 0.7e-3 mm. As the numerical approach, the fuel and air flow of nozzle internal was first analyzed by using a two-phase flow analysis method employing a volume of fluid (VOF) model and the standard high Reynolds number k-epsilon turbulence model\[10\][11]. The VOF method was used to calculate the two-phase gas-liquid flow, consisting of fuel and air[12]. Octane was used as fuel. The inlet and the outlet of the model were applied a pressure boundary condition as shown in Fig. 15. Corresponding to the experiments, the pressure of 20MPa was given as the inlet boundary condition and the pressure of 1MPa was given as the outlet boundary condition.

As the initial conditions, the pressure 1MPa of the fluid regions are specified. Figures 16(a) and (b) show the velocity vectors in the nozzle region of cross section C. Figures 17 and 18 show the spray axial velocity distributions, radial velocity distributions and turbulence energy distributions from near nozzle wall to center of nozzle of cross section B.

**Effect of hole diameter.** Figure 17(a) shows the spray axial velocity distributions when L/D=1, and the nozzle hole diameter is different. For both of the hole diameters D=0.135mm and D=0.155mm, the similar distributions were observed. This tendency is similar at section A. Figure 17(b) shows the radial velocity distributions when L/D=1, and the nozzle hole diameter is different. The radial velocity for D=0.155mm is faster than that for D=0.135mm at center of nozzle and it is more same at near nozzle wall.

![Fig. 17 Effect of Hole Diameter on Spatial Variation of (a) Axial Velocity (b) Radial Velocity (c) Turbulence Kinetic Energy, from Nozzle Wall to Center of Nozzle of Cross Section B](image)

![Fig. 18 Effect of L/D on Spatial Variation of (a) Axial Velocity (b) Radial Velocity (c) Turbulence Kinetic Energy, from Nozzle Wall to Center of Nozzle of Cross Section B](image)
The radial velocity is an order that is considerably less than the axial velocity. Figure 17(c) shows the turbulent kinetic energy distributions when L/D=1, and the nozzle hole diameter is different. The turbulent kinetic energy for D=0.135mm more than that for D=0.155mm from near nozzle wall to center of nozzle. In the case of D=0.155mm, the turbulence is attenuated near the exit of the nozzle hole. Therefore the nozzle hole diameter of D=0.135mm results in wider dispersion, larger spray angle, shorter penetration, and enhances the fuel atomization and evaporation.

Effect of L/D. Figure 18(a) shows the spray axial velocity distributions when the nozzle hole diameter D=0.135mm, and L/D is different. Figure 18(b) shows the radial velocity distributions when the nozzle hole diameter D=0.135mm, and L/D is different. The radial velocity for L/D=1 is faster than that for L/D=2 at center of nozzle. Figure 18(b) shows the radial velocity distributions when the nozzle hole diameter D=0.135mm, and L/D is different. The radial velocity distributions for D=0.135mm is more than that for D=0.155mm from near nozzle wall to center of nozzle. Figure 18(c) shows the turbulent kinetic energy distributions when the nozzle hole diameter D=0.135mm, and L/D is different. The turbulent kinetic energy distributions for D=0.135mm is more than that for D=0.155mm from near nozzle wall to center of nozzle. Therefore the nozzle hole of L/D=2 results in narrower dispersion, smaller spray angle, larger penetration, and poor fuel atomization and evaporation. The above discussion is corresponding to the experiment results shown in Figs 4, 9 and 10. However, more analyses of the internal flow of the nozzle hole and its effect on the spray behaviors are required.

4. CONCLUSIONS

By using the laser absorption and scattering (LAS) technique, the mixture formation processes in the DISI engine sprays were investigated under different nozzle hole diameters and L/D ratios. The following conclusions were obtained:

1. The spray tip penetration of the nozzles with the small hole diameter is shorter than that with the large hole diameter regardless of the hole L/D ratio. The spray tip penetration of the nozzles with the small L/D ratio is shorter than that with the large L/D ratio regardless of the hole diameter. The change of the liquid phase penetration for the hole diameter and L/D ratio is similar to the spray tip penetration, that is, shorter liquid phase penetration for small hole diameter and small L/D ratio.

2. The axial distribution of the vapor phase equivalence ratio for the small hole diameter is flatter than that for the large hole diameter regardless of the hole L/D ratio. The axial distribution of the vapor phase equivalence ratio for the small L/D ratio is higher than that for the large L/D ratio regardless of the hole diameter.

3. In the case of the small hole diameter and the small L/D ratio, there is a high distribution of the vapor phase equivalence ratio in the spray boundary around the axial distance of the spark plug location.

4. The mass of fuel of the lean mixture (φ<0.7) for the small hole diameter is less than that for the large hole diameter regardless of the hole L/D ratio. The mass of fuel of the lean mixture for the small L/D ratio is less than that for the large L/D ratio regardless of the hole diameter. The mass of vapor phase fuel around the stoichiometric equivalence ratio (0.7<φ<1.3) for the small hole diameter is more than that for the large hole diameter. The mass of vapor phase fuel around the stoichiometric equivalence ratio for the small L/D ratio is more than that for the large L/D ratio regardless of the hole diameter.

5. REFERENCES


