MULTIPLE HOLLOW-CONE-LIKE SPRAY FORMATION BY CONTROLLING INTERNAL FLOW OF MULTIPLE HOLE NOZZLES

Yasuhide Tani 1, Masuaki Iwamoto 2, Takashi Suzuki 3 and Yoshiyasu Inoue 4

1 Project Leader, Powertrain Control Systems Business Group, DENSO CORPORATION, yasuhide_tani@denso.co.jp
2 Powertrain Management Systems Eng. Dept., DENSO CORPORATION, masuyuki_iwamoto@denso.co.jp
3 Associate Professor, Dept. of Mechanical Engineering, Toyohashi Univ. of Technology, takashi@mech.tut.ac.jp
4 Graduate Student, Dept. of Mechanical Engineering, Toyohashi Univ. of Technology, tkk8007-9107.phone@ezweb.ne.jp

ABSTRACT This paper describes multiple hollow-cone liquid-sheet injection and atomization using newly developed plate-type multi-hole nozzle for fuel injector of SI engine. Atomization process and spray characteristics of the prototype nozzles were examined experimentally. It was found that hollow-cone shaped liquid sheet was injected from each hole of the new nozzles. Breakup length of liquid film injected from the new nozzle was much shorter than that from conventional nozzle. Mean droplet size of the new nozzle was also much smaller than that of conventional nozzle. The liquid flow in the nozzle was analyzed numerically using commercial CFD code to clarify the mechanism of hollow-cone shaped liquid sheet injection. The result showed that the liquid flew into each nozzle hole with circumvolution. The hollow-cone liquid sheet should be injected from the each nozzle hole owing to the circumvolution.

Keywords: Atomization, Fuel injector, Plate-type nozzle, Photographic observation, Numerical analysis

1. INTRODUCTION

These days, from the viewpoint of protection of the global environment, further reduction in emission and improvement of thermal efficiency is urgently needed in the automotive gasoline engines. Size-reduction of fuel spray droplets in the automotive gasoline engines employing the port fuel injection system is regarded as an effective measure to overcome these tasks (1). A multiple hole plate nozzle has been widely used for the intake fuel injection as it produces fine spray to a certain degree at a relatively low fuel pressure as well as has a simple structure and high productivity (2). The study has been made aiming at further atomization by heating the nozzle, or combining an ultrasonic transducer with the nozzle (3). However, the study shows such disadvantageous points as complicated structure, low reliability level, and low productivity. In view of this, in the previous report (4), we have proposed a nozzle (Fig.1b) that considerably accelerates the atomization by injecting a hollow-cone-like liquid film from its nozzle holes under the control of the upstream flow of the nozzle holes of a multiple hole plate nozzle (Fig.1a).

This report proposes a nozzle of a simpler structure that can similarly inject a hollow-cone-like liquid film (Fig.1c). For the prototype nozzle, we observed the atomization process using flash photography and investigated the atomization characteristics. We also revealed the injection mechanism of hollow-cone-like liquid film through numerical analysis of the internal flow of the nozzle.

2. EXPERIMENTAL OBSERVATION

2.1 Experimental equipment and method

Figure 2 shows the nozzle used for the experiment and Fig. 3 shows the outline of the experimental equipment. The nozzle body simulates the nozzle assembly of a commercial multiple hole plate injector of the same size, with a replaceable nozzle plate at the end. The liquid is supplied from the upper end, passing through the needle valve, and injected from the holes of the nozzle plate. The nozzle plates used are shown in Fig. 2 (II), (III). The (II) is a conventional 4-hole nozzle, which is a 0.2mm-thick stainless steel plate with four nozzle holes each of 0.34mm in diameter. The (III) is a prototype plate of the nozzle we invented, which is a similar nozzle plate with four d=0.34mm nozzle holes on which B=0.1 to 0.2mm-thick flow guide plate having a rectangular window is placed. Liquid is injected from the nozzle holes through the narrow clearance formed by the flow guide. We adapted nine types of prototype nozzles, which differ in the arrangement of nozzle holes and the configuration of flow guides (see table in Fig.2). #1a, #2a and #3a used the flow guide with a 0.1mm-thick rectangular window, and differ only in the nozzle-hole intervals A. These are referred to as series-a hereafter. Similarly, #1b, #2b and #3b using the 0.15mm-thick flow guide are called series-b, and #1c, #2c
and #3c using the 0.2mm-thick flow guide are called series-c. As a test liquid, dry solvent at room temperature was used and injected consistently into the air under a $\Delta p = 0.3$MPa injection pressure.

The breakup process of the injected liquid jets was flash-photographed using transmitted light from a stroboscopic source. For each condition, the length of liquid jet, $L_b$, the spray cone angle, $\alpha_F$, $\alpha_S$, and the angle formed by spray cone axes, $\beta_F$, $\beta_S$, as defined in Fig. 4, were measured.

On the other hand, as shown in Fig. 5, the diameters of the spray droplets were measured using a commercially available droplet-diameter measuring device based on laser diffraction (Tonichi Computer Applications Co., Ltd., LDSA-1500A). Incident light was a parallel beam of an He-Ne ion laser with a diameter $\phi 14$mm, and the measurement was conducted 100mm downstream of the nozzle end. A multiple variance histogram was used for the droplet size distribution function, to calculate Sauter mean diameter, $D_{32}$.

### 2.2 Result and discussion

An example of flash photographed breakup processes of liquid jets injected from the invented nozzle and from the conventional nozzle is shown in Fig. 6. In the conventional nozzle, a turbulent liquid column was injected from each nozzle hole and broke up at about 10mm downstream of the nozzle. (Fig. 6 (b)). On the contrary, in the invented nozzle, a hollow-cone-like liquid film was injected from each nozzle hole and broke up into fine liquid droplets more quickly. (Fig. 6 (a)). This is because the internal flow of the nozzle was controlled, as presented in our previous report (4), by the flow guide plate installed.

Figures 7, 8 and 9 show the values defined in Fig. 4 of liquid jets immediately after injection, measured from photographs. Figure 7 also shows the coefficient of discharge, $C_d$, defined by the expression below. ($Q$ indicates flow rate, and $\rho$ indicates density of liquid.)

$$Q = C_d \cdot \pi \cdot d^2 \cdot \sqrt{\frac{2\Delta p}{\rho}}$$

(1)

Figure 7 indicates that with any prototype plate, the breakup length, $L_b$, of the liquid film is the same as or lower than that of the conventional nozzle. The values of $C_d$ are about the same or even greater than the conventional
Fig. 6 Typical flash photographs of liquid jets

Fig. 7 Breakup length and discharge coefficient.

Fig. 8 Cone angle.

Fig. 9 Angle between cone-axes.

Fig. 10 Example of droplet volume frequencies

Fig. 11 Sauter mean diameter of droplet
nozzle. As will be explained later, it is advantageous for a fuel injector nozzle where $C_\theta$ does not decrease even with improved atomization.

Figure 8 indicates that with any prototype plate, the cone angles $\alpha_F$ and $\alpha_S$ are greater than that of the conventional nozzle, and a hollow-cone-like liquid film can be injected. Also, series-c shows a different tendency from series-a and series-b. This seems to be attributable to the difference in the internal flow pattern of the nozzle, caused by the increase in the thickness of the flow guide plate. Comparison of Fig. 7 and Fig. 8 shows a tendency whereby, when $\alpha$ is larger, $L_3$ becomes shorter and $C_\theta$ declines slightly. This tendency is similar to that of the swirl injector.

Meanwhile, Fig. 9 shows that with any prototype plate, the angles formed by the axes of the hollow-cone-like liquid film injected from each nozzle hole, $\beta_F$ and $\beta_S$, are about 20°, and 0 to 20°, respectively, both far smaller than 36° - the angle formed by the nozzle-hole axes. This indicates that liquid flows inside the nozzle mainly toward the central axis of the nozzle. The reason for such a flow in the opposite direction of the direction predicted from the geometric configuration of the nozzle will be examined by means of numerical analysis in the following chapter.

Next, we examined the diameters of spray droplets. Figure 10 shows an example of the examination results of the distribution in the diameter volume frequencies. Distribution of diameter number frequencies of the spray droplets of #2b nozzle and a conventional type nozzle are shown in the figure. From the figure we can see improved atomization in the invented nozzle compared with the conventional nozzle, as it has higher frequencies of 100μm or smaller liquid droplets and does not generate 200μm or larger droplets. Figure 11 shows the average $D_{32}$ measured at $z=100$mm. The figure shows two sets of results; the case where $D_{32}$ is larger than the conventional type, as in the cases of #1a, #1c and #3a, and the case where $D_{32}$ is smaller than the conventional type. Comparison with Fig. 8 shows that $\alpha_F$ and $\alpha_S$ are small when $D_{32}$ is larger than the conventional type while $\alpha_F$ and $\alpha_S$ are large when $D_{32}$ is lower than the conventional type as in the cases of #2a and #2b. This suggests that the larger $\alpha_F$ and $\alpha_S$ are, the smaller $D_{32}$ becomes. We presume that this is because when the spray cone angle is large, the injected liquid film quickly becomes a thin film, promoting atomization, as is the case with the swirl injector. The reason for the different tendency shown only by series-c is probably that the spray similar to that of the swirl injector could not be formed because the thickness of its flow guide plate was too big.

These results suggest that it is necessary for the invented nozzle to inject liquid films with large cone angles and make them break up immediately in order to obtain fine sprays, after optimizing the flow guide configuration, nozzle-hole arrangement, and axes direction to prevent interference between sprays.

3. NUMERICAL ANALYSIS

3.1 Analysis method

Figure 12 shows the analytical model and computational grid used for the numerical analysis of the internal flow of nozzles. The computational region was from upstream of the needle valve to just after the nozzle exit, and since the nozzle is symmetric with respect to a plane, flow analysis was conducted for 1/4 of the region employing the VOF method using a turbulent model at the same time. Minimum grid interval was 10μm. Entrance and exit were the pressure boundaries, and the injection pressure was 0.3MPa - the same as the experiment. Drysolvent values were used as the liquid property values. Star-CD, a commercial CFD code, was employed for actual analysis.

3.2 Results of analysis

Figure 13 and 14 shows the results of the analysis of the internal flows of the three series-b nozzles. The trajectory of arbitrary supposed particles and their flow velocities are indicated as their streamlines in the Fig. 13. The contour map and velocity vectors of the liquid velocity on the central surface of the narrow clearance flow path formed by the flow guide are provided in the Fig. 14. The maximum flow velocity, $V_{\text{max}}$, within this surface is also shown. Taking Fig. 13 (b) as an example, the flow can be explained as follows; main liquid flows radially into the clearance flow path from below the needle valve, but because of the side walls of the flow path, the liquid in the regions close to the walls flows parallel to the side walls. As a result of this phenomenon, regions close to the side walls have a higher flow velocity than the regions near the symmetric surface. Due to such velocity distribution, the liquid flows round from the outer part of the rectangular flow path into the nozzle holes and flows out in a swirl. We assume this swirling flow enables the invented nozzle to inject a hollow-cone-like liquid film from each nozzle hole.

Comparison of three results provided in Fig. 14 shows that maximum flow velocity value is largest in #1b. Because the nozzle-hole positions of #1b are far from the side walls of the rectangular flow path, the liquid which has been sufficiently accelerated near the side walls flows
directly into the nozzle holes. Also, as the liquid swirls out at a higher velocity than the others, the cone angle of #1b was larger than the others in the experimental observation.

4. CONCLUSION

We have invented a multiple hole nozzle which injects a hollow-cone-like liquid film from each nozzle hole by controlling the upstream flow of the nozzle holes of a plate nozzle. By observing the atomization process and investigating the atomization characteristics of the prototype nozzles, we confirmed that it substantially improves atomization compared with the conventional nozzle. We also revealed the injection mechanism of the hollow-cone-like liquid film through numerical analysis of the internal flows of the nozzles.

5. NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>flow guide width</td>
<td>[mm]</td>
</tr>
<tr>
<td>B</td>
<td>flow guide thickness</td>
<td>[mm]</td>
</tr>
<tr>
<td>Lb</td>
<td>breakup length</td>
<td>[mm]</td>
</tr>
<tr>
<td>d</td>
<td>nozzle hole diameter</td>
<td>[mm]</td>
</tr>
<tr>
<td>Cd</td>
<td>discharge coefficient</td>
<td>[-]</td>
</tr>
</tbody>
</table>
\[ \alpha \] spray angle \[ \text{[deg]} \]
\[ \beta \] cone-axes angle \[ \text{[deg]} \]
\[ \rho \] density of liquid \[ \text{[kg/m}^3] \]
\[ \Delta p \] injection pressure \[ \text{[MPa]} \]
\[ D_{32} \] Sauter mean diameter \[ \text{[\mu m]} \]

6. REFERENCES