Development of Plate-type Fine Atomizing Nozzles for SI Engines with Intake-port Fuel Injection

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Key Words: Atomization, Fuel injector, Plate nozzle, Atomization Enhancement, Internal Flow

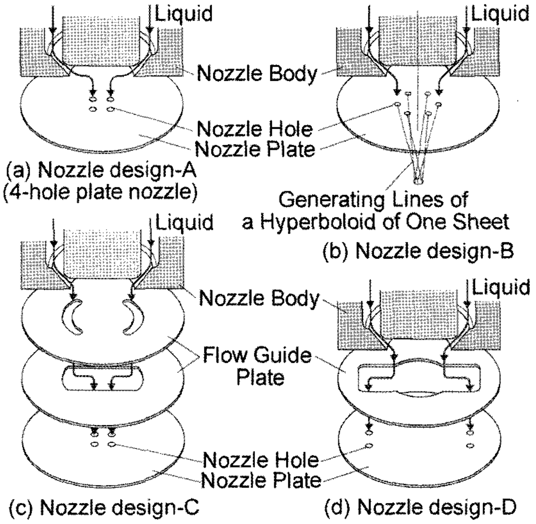
Abstract

This paper presents both experimental and numerical studies regarding nozzles used for the SI engine application, particularly for the intake-port fuel injection type. The atomization mechanism of the multi-hole plate nozzle was investigated experimentally. It was found that the nozzle design added turbulence into the liquid-film jet and the jet disintegrated rapidly. Based on the results, various plate types for the nozzle were developed and tested; six hole nozzle for liquid jet interaction, plate-type nozzle with flat duct channel, and the simpler structured nozzle. The spray characteristics of the prototype nozzles were examined experimentally while the internal flow of the nozzle was investigated computationally. It was shown that turbulent liquid-film was injected and atomization quality was improved by controlling the internal flow condition of the plate-type nozzle.

1. Introduction

From the viewpoint of global environment protection, further reduction of pollutant exhaust emission and improvement of thermal efficiency have been needed in the automotive gasoline engines. As much quoted, size-reduction of fuel spray droplets is one of the effective measures to satisfy the requirements, especially for the port-fuel-injected engines(1, 2). Several attempts have been made to provide fine fuel spray, e.g. nozzle heating, ultrasonic vibration of nozzle, and air assisting(3). Although these strategies were effective, the nozzles based on these strategies had disadvantages such as complicated construction, low productivity, and not so high reliability level. One of the authors developed the multiple-hole plate nozzle(4). The plate nozzle has been widely used for the intake-port fuel injection, since the nozzle is simple in construction and shows reasonably good performance at a relatively low injection pressure. However, further research and development are needed on the fuel injection nozzles to achieve the low emission and high efficiency automotive SI engines.

This paper deals with recent research and development of the port-fuel-injection nozzle by the



(a) Nozzle design-A (4-hole plate nozzle)
(b) Nozzle design-B
(c) Nozzle design-C
(d) Nozzle design-D

Fig. 1 Designs of plate-type nozzle

(2006년 12월 29일 접수 ~2007년 1월 24일 심사완료)

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authors[5-10]. In the first stage, atomization mechanism of the multi-hole plate nozzle (Nozzle design-A; see Fig. 1(a)) was investigated. It was found that the nozzle design added turbulence into the liquid-film jet and the jet disintegrated rapidly. That is, fuel atomization would be further enhanced, if perturbed hollow-cone-like liquid film was injected from the plate-type nozzle. Several attempts were made to enhance atomization of the plate-type nozzle. The first attempt was to form a hollow-cone-like spray by utilizing interaction of liquid jets (Nozzle design-B; see Fig. 1(b)). Six liquid jets were injected from a nozzle plate to form a hyperboloid of one sheet. Although hollow-cone-like fine spray was discharged, the nozzle had a deficiency in spray pattern. The second attempt was to inject hollow-cone-like liquid film from each hole of plate-type nozzle by controlling the internal flow (Nozzle design-C; see Fig. 1(c)). A flat duct channel was installed on the upstream side of 4-hole plate for the purpose of controlling internal flow condition. Although the nozzle showed good atomization performance, the nozzle design had a deficiency; the nozzle for intermittent injection was complicated in construction. Then, the simpler structured nozzle (Nozzle design-D; see Fig. 1(d)) was designed. The nozzle design was successful; hollow-cone-like fine spray was injected from each nozzle hole. Liquid flow in the nozzle was simulated numerically to explain the mechanism of hollow-cone-like spray injection. Finally, it was concluded that turbulent liquid-film was injected and atomization quality was improved by appropriate control of the internal flow condition of the plate-type nozzle.

2. Atomization mechanism of plate nozzle (Nozzle Design-A)

The multiple-hole plate nozzle, developed by one of the authors[4], has been widely used for the intake-port fuel injection of SI engines. The nozzle discharges fine fuel spray at a relatively low injection pressure, although the nozzle is simple in construction. It is obvious that there is an agent of atomization enhancement inside the nozzle, because the plate nozzle discharges much finer spray than the plane orifice nozzle.

In advance of the new nozzle design, the behavior of liquid jet and the spray characteristics were examined in detail with changing the configuration of the 4-hole plate nozzle, and the atomization mechanism of the multiple-hole plate nozzle was discussed.

2.1 Experimental setup

Figure 2 shows a schematic diagram of an experimental setup. Fig. 3 shows the real-scale nozzle assemblies used in the investigation. Each nozzle assembly had transposable 4-hole nozzle plate at the end. The nozzle assembly of Fig. 3(a) was reproduced from a commercial plate nozzle, which was composed of nozzle plate and needle valve. Liquid was supplied from the upper end, passed through the model of needle valve, and injected from the nozzle plate. The nozzle assembly of Fig. 3(b) is the simplified one; the valve seat was removed and the valve head was replaced with flat head needle.

Figure 4 shows the nozzle plate attached to the nozzle bodies. Four nozzle holes were bored by

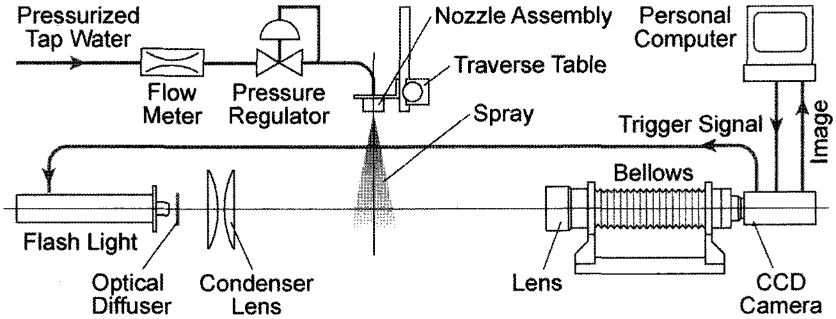


Fig. 2 Schematic diagram of experimental setup

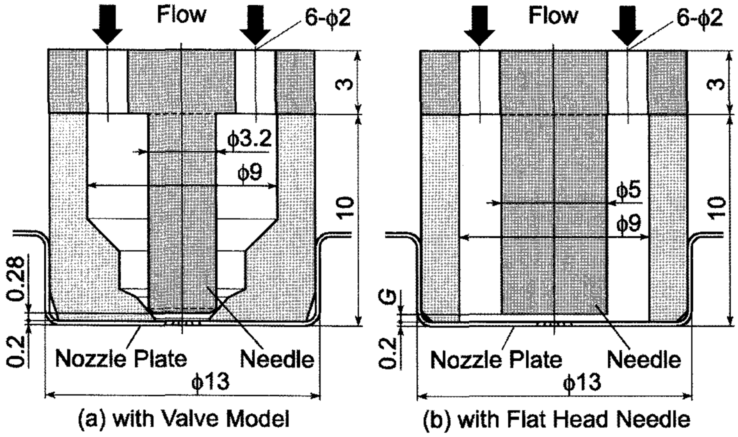


Fig. 3 Real-scale nozzle assemblies

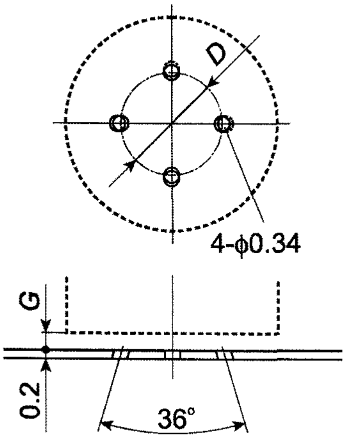


Fig. 4 Test nozzle plate (Nozzle design-A)

electro-discharge machining. Diameter of the holes were 0.34 mm. Axes of the holes were inclined outward. Experimental investigation was performed mainly using the nozzle body of Fig. 3(b). The clearance, *G*, between needle top and nozzle plate ranged from 0.1 to 0.4 mm, and the pitch circle diameter (P.C.D.), *D*, of nozzle holes ranged form 1.2 to 2.4 mm. Experimental investigation was also performed using the nozzle body of Fig. 3(a) with the nozzle plate of 1.2 mm P.C.D.

Behavior of liquid jets was observed by flash photography. Size of spray droplets was measured by the in-flight image analysis(7). In place of liquid fuel, tap water was injected continuously from the nozzle assemblies into atmosphere with the injection pressure of 0.3 MPa, aiming to obtain an insight into the atomization phenomena by the unsophisticated apparatus.

2.2 Experimental results

Figure 5(a) shows the flash photographs of liquid jets injected from the nozzle assembly with model of needle valve (Fig. 3(a)). Surfaces of the liquid jets were strongly perturbed, and the liquid jets dis-

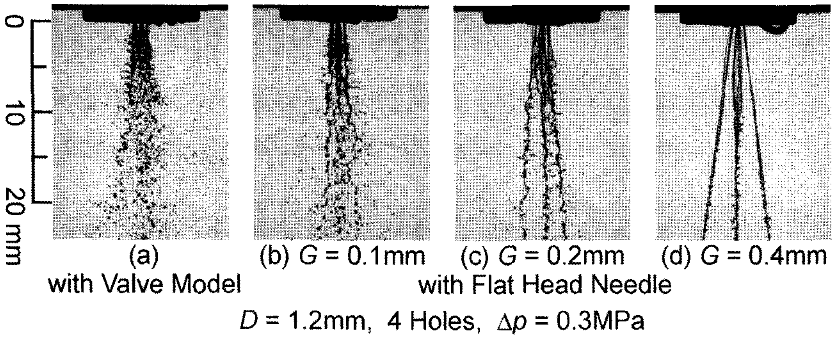
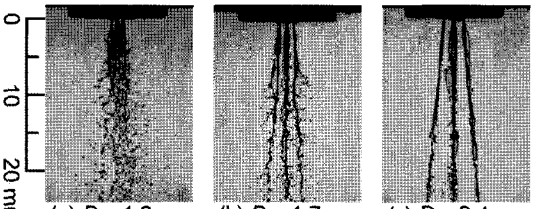


Fig. 5 Flash photographs of liquid jets showing the effects of nozzle-body configuration (Nozzle design-A)



(a) $D = 1.2\text{mm}$ 4 Holes (b) $D = 1.7\text{mm}$ 4 Holes (c) $D = 2.4\text{mm}$ 4 Holes

$G = 0.1\text{mm}$, $\Delta p = 0.3\text{MPa}$, with Flat Head Needle

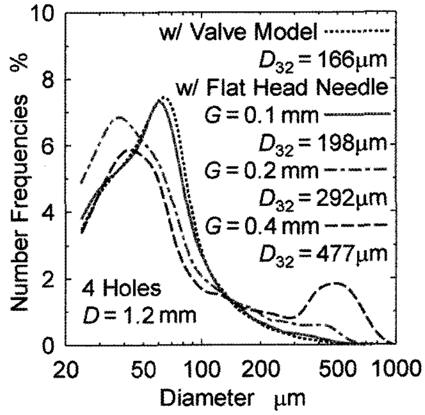
Fig. 6 Flash photographs of liquid jets showing the effects of P.C.D. of nozzle holes (Nozzle design-A)

integrated rapidly into fine droplets. (b) to (d) of Fig. 5 are photographs of liquid jets injected from the nozzle assembly with flat head needle (Fig. 3(b)). The effects of the clearance, *G*, between needle top and nozzle plate are shown in the figure. When the clearance was small, the liquid jets disintegrated rapidly in a similar manner to that shown in Fig. 5(a). However, smooth liquid jets were injected and hardly disintegrated when the clearance was large. Fig. 6 shows photographs of liquid jets injected from the nozzle assembly with flat head needle. The effects of P.C.D., *D*, of nozzle holes are shown in the figure. When the P.C.D. was small, the liquid jets disintegrated rapidly. On the contrary, the surfaces of liquid jets were not perturbed so much and the liquid jets did not breakup rapidly when the P.C.D. was large. As descried above, the liquid jets rapidly disintegrated only in the case of small clearance and small P.C.D.

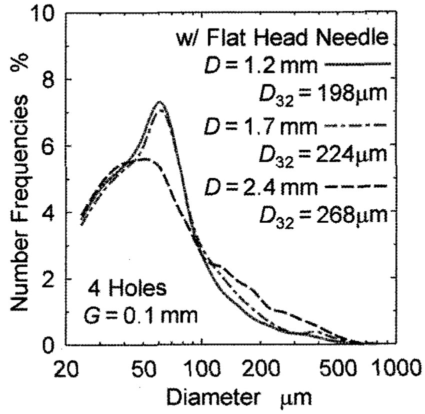
Figure 7 shows the number distributions of droplet size injected from the nozzle assembly with flat head needle. Fig. 7(a) illustrates the effects of the clearance, *G*, and Fig. 7(b) illustrates the effects of the P.C.D., *D*. When the clearance was large, not only small droplets but also huge droplets were formed, as shown in Fig. 7(a). When P.C.D. was large, many large droplets were discharged, as shown in Fig. 7(b). Data of the nozzle assembly with valve model was also shown in Fig. 7(a). Only in case of small clearance and small P.C.D., the nozzle assembly with flat head needle discharged fine spray and the Sauter mean diameter, D_{32}, was comparable to that of the nozzle assembly with valve model.

Detailed observation was made on liquid flow around the exit of nozzle assembly with flat head needle using a long-distance-microscope. The results are shown in Fig. 8. Fig. 8(i) are close-up shots of the liquid jets. Photographs of Fig. 8(ii) were taken from a point on the nozzle hole axis. As shown in Fig. 8(ii), liquid flowed out from inner half of the nozzle hole, and outer half of the nozzle hole was cavity. It was obvious that the separation of liquid flow occurred at only outer side of the nozzle hole. As shown in Fig. 8(i), plane liquid jet was injected from each nozzle hole and the liquid jet was accompanied with thin liquid film, when the clearance was small. The surface of jet was strongly perturbed.

Turbulence intensity of jet flow was measured by injecting air from a scale-up model by 20 times of the commercial nozzle under the condition of similar Reynolds number. It was found that the turbulent

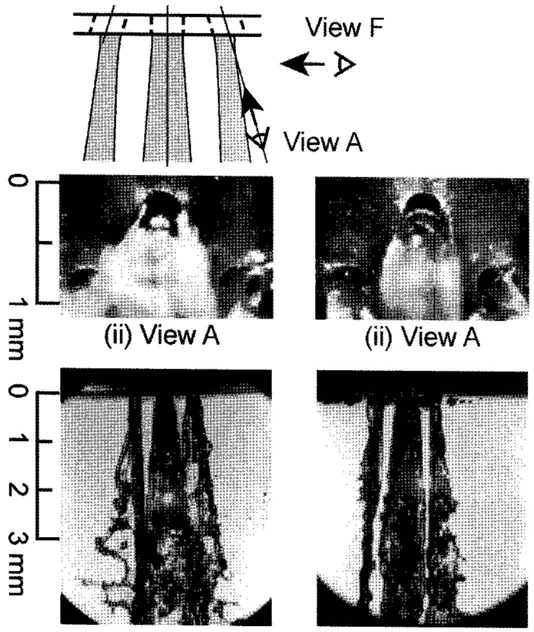


(a) Effects of Clearance



(b) Effects of P.C.D.

Fig. 7 Number distribution of droplet size (Nozzle design-A)



(i) View F (a) *G* = 0.1 mm

(i) View F (b) *G* = 0.2 mm

with Flat Head Needle
D = 1.2mm, 4 Holes, Δp = 0.3MPa

Fig. 8 Liquid flow around nozzle exit (Nozzle design-A)

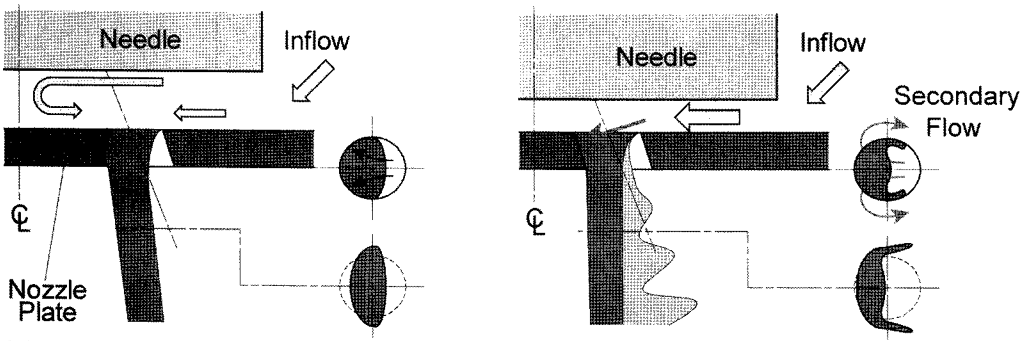
intensity of jet flow was larger than 10%.

Based on these results, the liquid flow mechanism in the nozzle was discussed. When the clearance and the P.C.D. were relatively large, liquid should flow into each nozzle hole almost uniformly, as illustrated in Fig. 9(a). Consequently the smooth jet should be injected in the case of large clearance. However, the centripetal flow between nozzle plate and needle top should be fast and the flow should impinged strongly upon the inner wall of nozzle hole in case of small clearance and small P.C.D. The secondary flow should be introduced by the flow interaction with the inner wall, as illustrated in Fig. 9(b), and the liquid flow became plane liquid jet accompanied with thin liquid film. Furthermore, strong turbulence should be introduced because the liquid flow changed its direction quickly at the nozzle hole inlet. As the results, the strongly perturbed liquid-film should be injected from each nozzle hole when the clearance and the P.C.D. were small. Since the perturbed liquid-film disintegrated rapidly into small droplets, the multi-hole plate nozzle discharged fine fuel spray at a relatively low injection pressure. In other words, perturbed liquid film injection is one of the effective measures to enhance atomization.

3. Hollow-cone-like spray by 6-jet interaction (Nozzle Design-B)

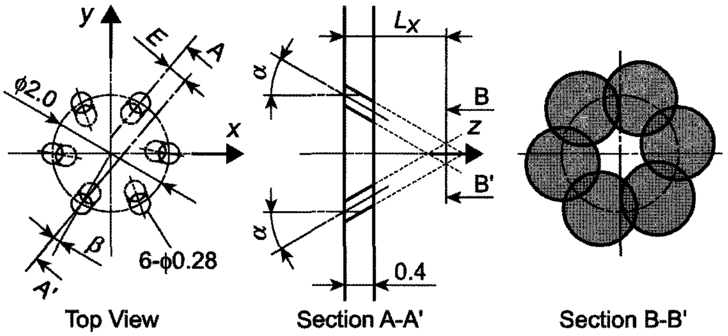
The 6-hole nozzle was designed aiming to form a hollow-cone-like turbulent liquid film. The nozzle injected six liquid jets to form a hyperboloid of one sheet (Nozzle design-B; see Fig. 1(b)). The behavior of liquid jets and the spray characteristics were examined using the prototype nozzle.

Figure 10 shows the nozzle plate used in the study. Six nozzle holes were bored through the nozzle plate so as the hole axes corresponded to the generating-lines of a hyperboloid of one sheet. The diameters of nozzle holes were 0.28 mm. The pitch circle diameter



(a) Large Clearance or Large P.C.D (b) Small Clearance & Small P.C.D

Fig. 9 Models of liquid flow passing through nozzle hole

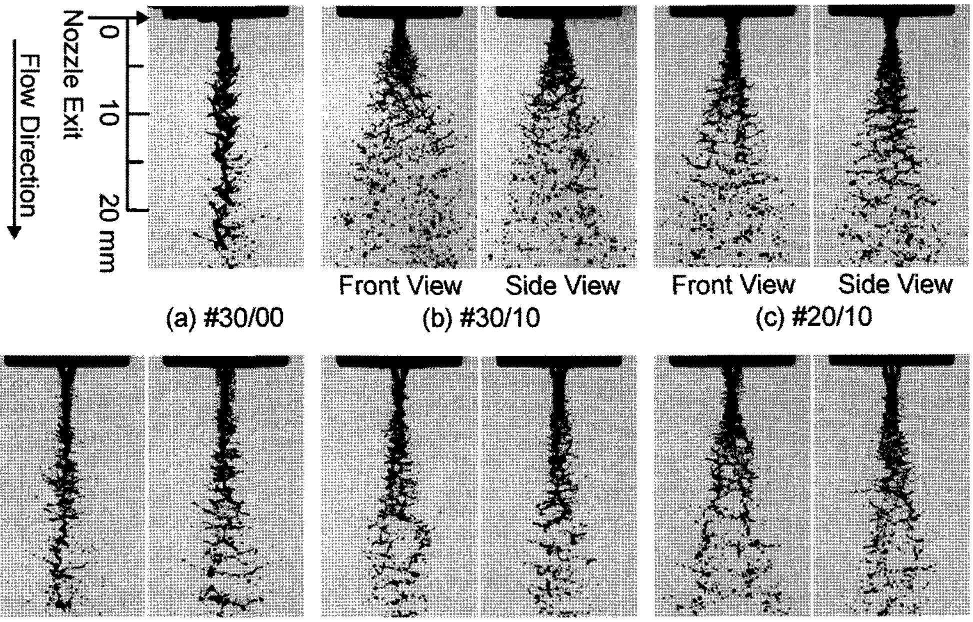


Top View   Section A-A'   Section B-B'

Plate ID	α (°)	β (°)	$\frac{E}{d}$	$\frac{L_x}{d}$
#30/00	30	0	0	6.2
#30/10	30	10	1.24	6.1
#20/10	20	10	1.24	9.7
#15/05	15	5	0.61	13.3
#15/10	15	10	1.24	13.1
#15/15	15	15	1.85	12.9

Configuration of Nozzle Holes

Fig. 10 Test nozzle plate (Nozzle design-B)



Front View   Side View   Front View   Side View

(a) #30/00   (b) #30/10   (c) #20/10

Front View   Side View   Front View   Side View   Front View   Side View

(d) #15/05   (e) #15/10   (f) #15/15

with Flat Head Needle, G=0.1mm, Water, Δp=0.3MPa

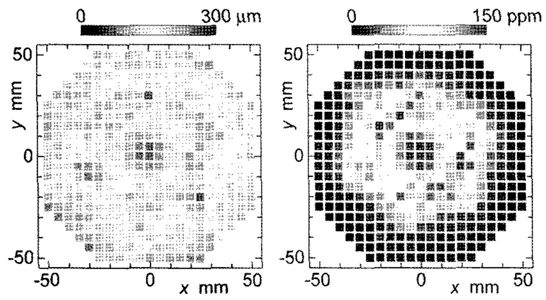
Fig. 11 Flash photographs of liquid jets (Nozzle design-B)

of nozzle holes was 2.0 mm on the upper surface of the nozzle plate. Experimental investigation was performed with changing the leaning angle, α, and the twist angle, β, of nozzle-hole axes. The configuration of test nozzle plates is tabled in Fig. 10. The nozzle plates are numbered after the leaning angle and the twist angle.

The nozzle plate was attached to the nozzle body with flat head needle (Fig. 3(b)). The clearance, G, between needle top and nozzle plate was 0.1 mm. From the nozzle assembly, tap water was injected continuously into atmosphere with the injection pressure of 0.3 MPa. Behavior of liquid jets was observed by flash photography. Size of spray droplets was measured by the in-flight image analysis.

Figure 11 shows typical flash photographs of liquid jets injected from the prototypes. When the twist angle, β, of nozzle-hole axes was zero, the liquid jets collided each other to form a compact jet at just downstream of nozzle exit, as shown in Fig. 11(a). Whereas the six liquid jets focused and interacted each other to form an annular liquid jet at just downstream of nozzle exit when the twist angle was 10°. The annular liquid jet spread like a hollow-cone spray, as shown in Fig. 11(b), (c). The liquid jet broke up into many fine droplets at about 10 mm downstream from nozzle exit. The cone angle of the spray depended upon the leaning angle, α, of nozzle-hole axes. The larger the leaning angle became, the wider the spray spread. Liquid stems that originate from six liquid jets were observed during the breakup process in case of relatively large twist angle. The interaction between six liquid jets might be insufficient in this case.

Figure 12 shows distributions of Sauter mean diameter, D_{32}, and fraction of liquid-phase at 100 mm downstream from the nozzle #30/10. The distribution of liquid fraction showed a halo pattern, as illustrated in Fig. 12(b). The Sauter mean diameter was relatively large where the liquid fraction was high, as shown in Fig. 12(a). These features of spray pattern were similar to those of hollow-cone spray injected from a swirl atomizer.



(a) Sauter Mean Diameter, D_{32} (b) Fraction of Liquid-phase

#30/10 with Flat Head Needle, G=0.1mm, Water, Δp=0.3MPa

Fig. 12 Distributions of Sauter mean diameter and liquid fraction (z=100 mm, Nozzle design-B).

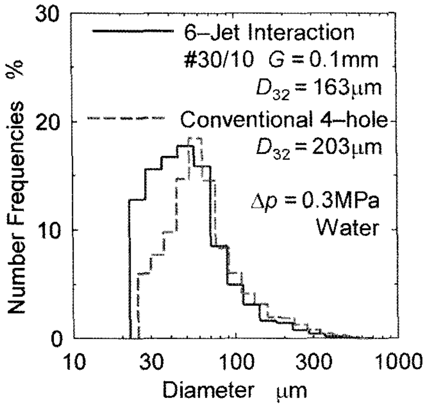


Fig. 13 Number distributions of droplet size. (z=100 mm, Nozzle design-B)

Figure 13 shows the number distributions of droplet size. Data of the 6-hole nozzle #30/10 and data of the conventional 4-hole plate nozzle are shown in the figure. The mean droplet size of the 6-hole nozzle was smaller than that of the conventional 4-hole nozzle.

These results showed that the nozzle of 6-jet interaction produced hollow-cone-like fine spray if the configuration of nozzle holes were appropriate. However the nozzle design appears to be dropped, because the spray pattern does not fit for the bifurcating intake-port, which is widely employed in current automotive SI engines.

4. Plate-type nozzle with flat duct (Nozzle Design-C)

An idea, injecting hollow-cone-like spray from each nozzle hole, was conceived. We preceded nozzle design by trial and error, and a plate-type nozzle was developed (Nozzle design-C; see Fig. 1(c)). A flat duct was installed on the upstream side of 4-hole plate for the purpose of flow control. Behavior of the liquid jets was observed in detail and the spray characteristics were examined using the prototype. The intermittent fuel injection test was also performed.

4.1 Nozzle design and continuous spray test

Figure 14 shows the prototype of newly designed nozzle. The prototype was similar to the nozzle assembly with flat head needle (Fig. 3(b)), except for that two screen plates were located between the 4-hole nozzle plate and the needle top to form a rectangular flat duct. Liquid flowed into the duct from both ends, flowed through the duct and injected from the nozzle holes. Diameter, d, of each nozzle hole was 0.34 mm. P.C.D. of nozzle holes was 1.2 mm. The clearance between the needle top and the nozzle plate was 0.1 mm. Thickness of the screen plates was also 0.1 mm. Experimental investigation was performed within the range of the duct width, W, from 2 to

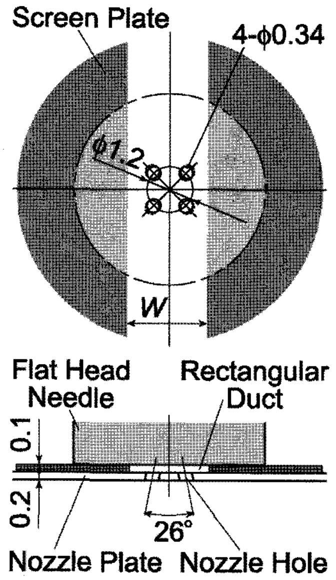


Fig. 14 Structure of prototype (Nozzle design-C)

3 mm. Tap water was injected continuously from the nozzle assembly into atmosphere with the injection pressure of Δp=0.3 MPa. Behavior of the liquid jets was observed by flash photography. The Sauter mean diameter, D_{32}, of spray droplets was measured by the in-flight image analysis. The discharge coefficient, C_d, defined by Eq. (1) was also measured. (Q indicates liquid flow rate and ρ_l indicates liquid density.)

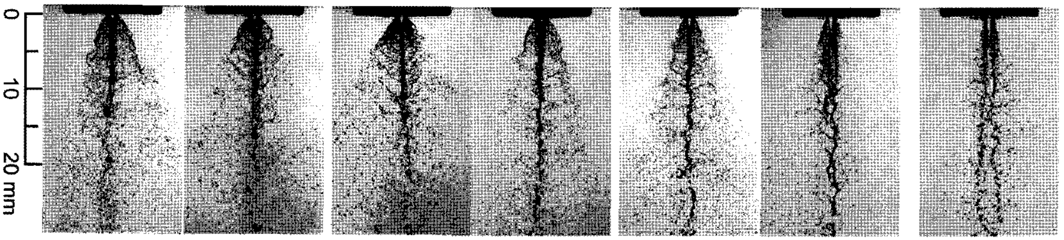
$$Q = C_d 4\frac{\pi d^2}{4}\sqrt{\frac{2\Delta p}{\rho_l}} \qquad (1)$$

Figure 15(a)-(c) show two views of liquid jets injected from the prototypes of the plate-type nozzle with flat duct. The Sauter mean diameter and the discharge coefficient were also listed below each figure. The hollow-cone-like spray was injected from each nozzle hole of the prototype, although the spray cones interacted each other in part. Detailed observation suggested that the liquid flowed out from each nozzle hole with swirling motion. The flat duct should act as a controlling device of liquid flow pattern inside the nozzle. The Sauter mean diameter, as well as the discharge coefficient, depended upon the width of the flat duct. The Sauter mean diameter was smallest at the intermediate duct width. Fig. 15(d) shows the flash photograph of liquid jets injected from conventional 4-hole plate nozzle. Solid sprays were discharged from the conventional nozzle, contrary to the prototype. The Sauter mean diameter of the prototype was much smaller than that of conventional nozzle. However, the discharge coefficient of the prototype was smaller than that of conventional nozzle.

4.2 Intermittent fuel injection test

Based on the continuous spraying test, a prototype nozzle for intermittent injection was fabricated. Fig. 16 shows the construction of the intermittent injection nozzle with flat duct. The injection nozzle without flat duct was also used as a reference. Injecting n-Heptane into atmosphere, the intermittent fuel injection test was performed. The behavior of liquid jet was observed by flash photography. Sauter mean diameter, D_{32}, of spray droplets was measured by the laser diffraction method.

Figure 17 shows flash photographs of fuel spray. The hollow-cone-like fine spray was discharged from each nozzle hole of the nozzle with flat duct. Each



Front View Side View
(a) W = 2.05 mm
C_d = 0.37, D_{32} = 134 μm

Front View Side View
(b) W = 2.65 mm
C_d = 0.43, D_{32} = 115 μm

Front View Side View
(c) W = 3.0 mm
C_d = 0.53, D_{32} = 222 μm

(d) w/o Screen
C_d = 0.55
D_{32} = 224 μm

Fig. 15 Flash photographs of liquid jets (Nozzle design-C, Δp=0.3MPa, Water)

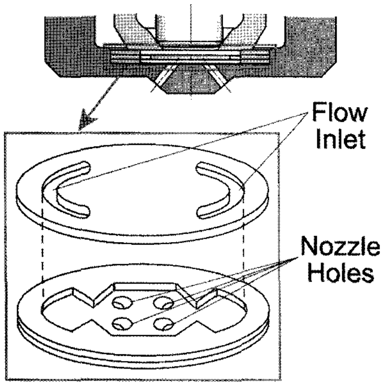


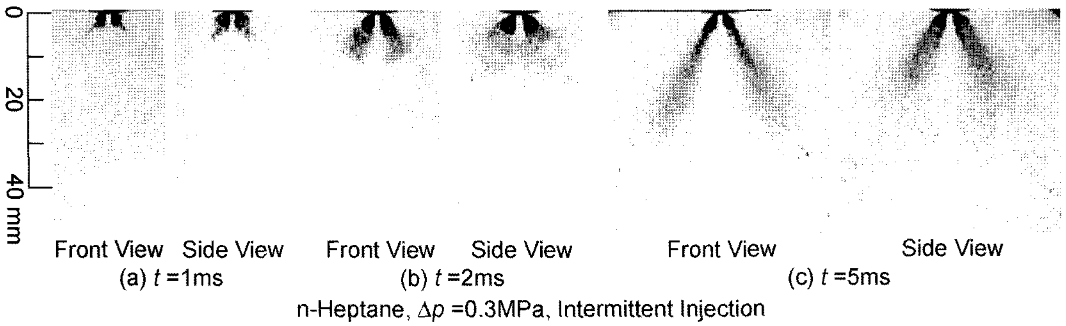
Fig. 16 Construction of intermittent injection nozzle (Nozzle design-C)

liquid jet spread like hollow-cone in the beginning stage of injection, as shown in Fig. 17(a), and kept the hollow-cone shape in the injection duration.

Figure 18 shows the time variations of Sauter mean diameter for various injection pressures. (a) and (b) of Fig. 18 show Sauter mean diameters of the nozzle with flat duct and the nozzle without flat duct, respectively. Comparison between these two charts showed that the nozzle with flat duct discharged much smaller droplets than the nozzle without flat duct. The nozzle without flat duct discharged relatively coarse spray, especially in the beginning stage of injection, as shown in Fig. 18(b). On the contrary, the nozzle with flat duct did not discharge coarse spray in the beginning stage, and the Sauter mean diameters were always small in the injection duration. It was suggested that the performance of the nozzle with flat duct was remarkable in the case of relatively low injection pressures.

5. Simply structured nozzle (Nozzle Design-D)

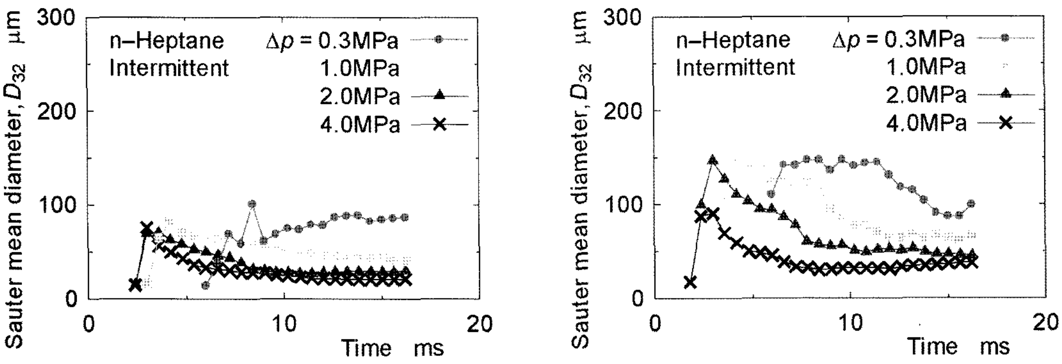
Although the plate-type nozzle with flat duct discharged fine spray, the design had a deficiency in



(a) t =1ms (b) t =2ms (c) t =5ms

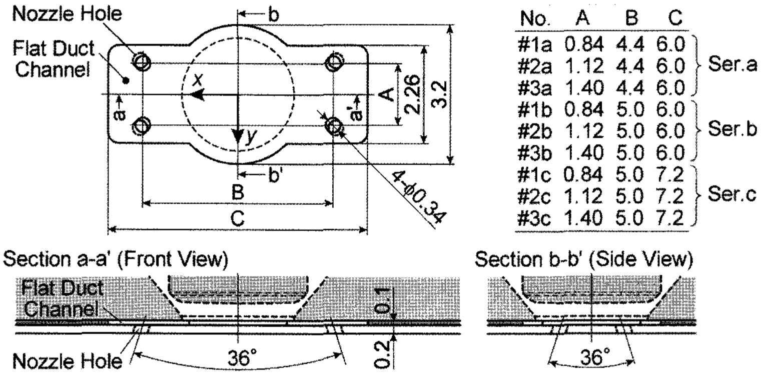
n-Heptane, Δp =0.3MPa, Intermittent Injection

Fig. 17 Flash photographs of intermittent spray (Nozzle design-C, Intermittent injection nozzle with flat duct)



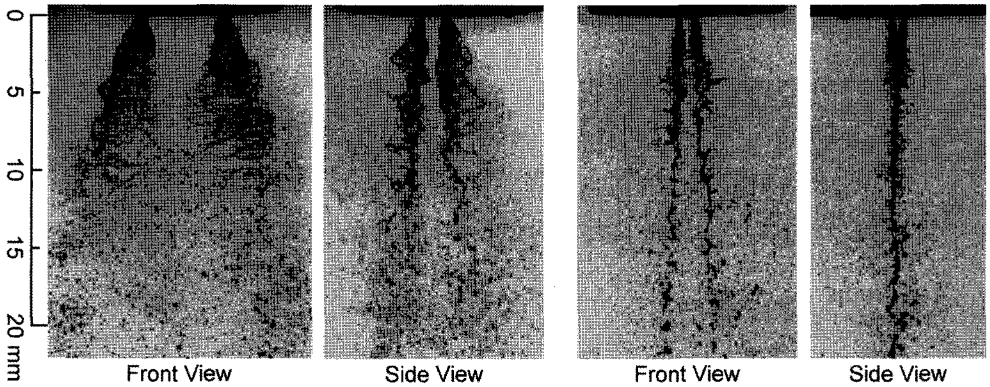
(a) with Flat Duct (b) without Flat Duct

Fig. 18 Time variations of Sauter mean diameter (Nozzle design-C, Intermittent injection nozzle)



No.	A	B	C	
#1a	0.84	4.4	6.0	Ser.a
#2a	1.12	4.4	6.0	
#3a	1.40	4.4	6.0	
#1b	0.84	5.0	6.0	Ser.b
#2b	1.12	5.0	6.0	
#3b	1.40	5.0	6.0	
#1c	0.84	5.0	7.2	Ser.c
#2c	1.12	5.0	7.2	
#3c	1.40	5.0	7.2	

Fig. 19 Configuration of nozzle plate and thin plate with rectangular window (Nozzle design-D)



(a) New Nozzle #3c (b) Conventional Nozzle

Fig. 20 Flash photographs of liquid jets (Nozzle design-D, Δp=0.3 MPa, Water)

the low discharge coefficient. And also the intermittent injection nozzle was complicated in construction. We designed the simpler structured nozzle that enhance atomization by employing a similar strategy (Nozzle design-D; see Fig. 1(d)). Fabricating prototypes of the nozzle, continuous water spray test was performed. Fuel spraying test was also performed. Liquid flow inside the nozzle was simulated numerically to explain the mechanism of multiple hollow-cone-like spray injection.

5.1 Nozzle design and experimental study

Thin plate with a rectangular window was installed between the nozzle plate and the nozzle body of Fig. 3(a) to form two flat ducts on the upstream side of 4-hole plate. Fig. 19 shows configuration of the nozzle plate and the thin plate with rectangular window. Liquid was supplied from the upper end of the nozzle assembly, passed through the model of needle valve and flowed into the flat ducts. The liquid flowed through the ducts and injected from nozzle holes located near the end of flat ducts. Note that, the flat ducts could be fabricated by the machining of nozzle body in actual production process of the fuel injection nozzle. Several prototypes were fabricated. Dimensions of the prototypes are also tabled in Fig. 19.

Continuous spray test was performed first by injecting tap water into atmosphere with injection pressure of 0.3 MPa. Fig. 20(a) shows the flash photograph of the liquid jets injected from the prototype. The flash photograph of the liquid jets injected from the conventional 4-hole plate nozzle was also shown in Fig. 20(b) Perturbed hollow-cone-like liquid-film was injected from each nozzle hole of the prototype. The behavior of liquid jets was almost similar to that of previous nozzle (nozzle design-C), except that the

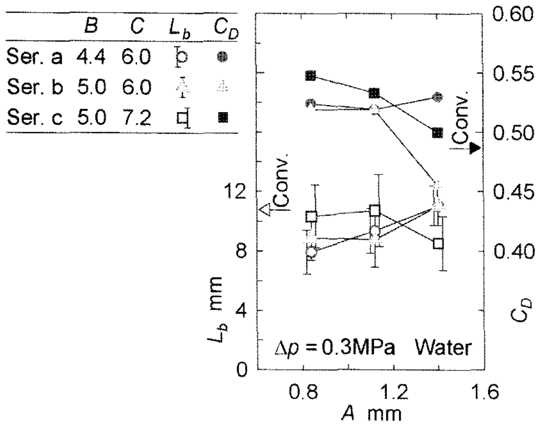


Fig. 21 Breakup length of liquid jet and discharge coefficient (Nozzle design-D)

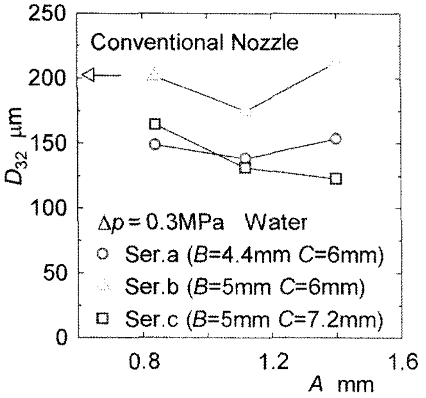


Fig. 22 Sauter mean diameter of spray (Nozzle design-D)

spray cones scarcely interacted each other.

Figure 21 shows the breakup length, L_b, of liquid jet injected from the prototype. The breakup length depended upon the nozzle configuration, and tended to become large with increase of the distance, A, between nozzle holes. The arrow heading to left side of Fig. 21 indicates the breakup length of the conventional plate nozzle. Except for the prototype #3a, the breakup lengths of the prototypes were shorter than that of the conventional nozzle.

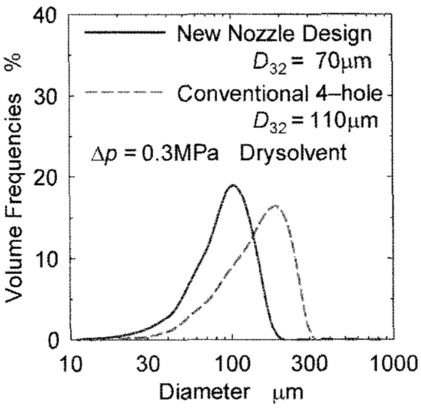


Fig. 2 Volume distributions of droplet size (Nozzle design-D)

Figure 21 also shows discharge coefficient, D_d, of the prototype. The discharge coefficient depended upon the nozzle configuration and tended to become small with increase of the nozzle-hole distance. The arrow heading to right side of Fig. 21 indicates the discharge coefficient of the conventional plate nozzle. Except for the prototype #3b, the discharge coefficients of the prototypes were larger than that of the conventional nozzle.

Sauter mean diameter, D_{32}, of spray droplets injected from the prototypes was measured by the in-flight image analysis. The results are shown in Fig. 22. The Sauter mean diameter depended upon the nozzle configuration and tended to be local minimum at the intermediate nozzle-hole distance. The arrow heading to left side of Fig. 22 indicates Sauter mean diameter of the conventional plate nozzle. Except for the prototype #3b, the Sauter mean diameters of the prototypes were smaller than that of the conventional plate nozzle. In the case of prototype #3c the Sauter mean diameter was smallest within this experimental range. The Sauter mean diameter of prototype #3c was almost half of that of the conventional nozzle.

Then the fuel-spraying test was performed. Drysolvent (gasoline for industrial purpose) was injected into atmosphere with the injection pressure of 0.3 MPa. Fig. 23 shows typical examples of the volume distributions of droplet size measured by the laser diffraction method. The solid curve indicates the volume distribution of droplet size of the prototype nozzle, and broken curve indicates that of the conventional plate nozzle. The prototype nozzle discharged finer spray than the conventional nozzle.

5.2 Numerical simulation

Liquid flow in the newly designed nozzle was simulated numerically to explain the mechanism of multiple hollow-cone-like spray injection. Fig. 24

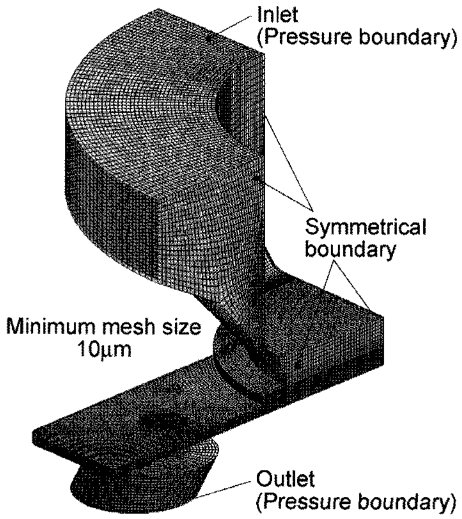
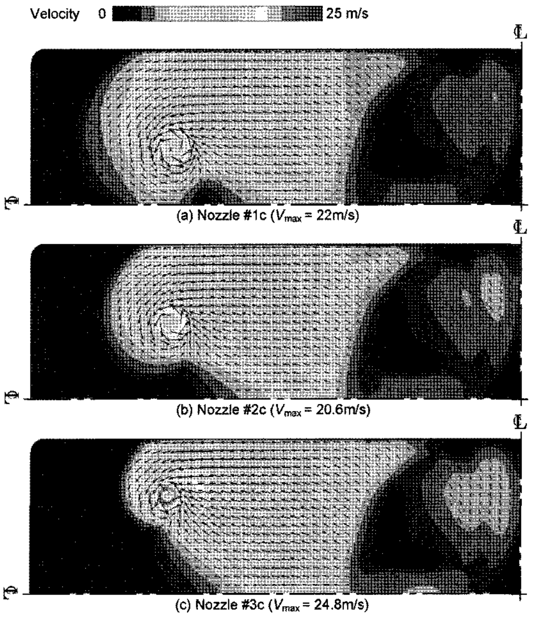


Fig. 24 Numerical model and computational grid

shows numerical model and computational grid employed in the simulation. The computational region was quarter of the nozzle, since the nozzle was symmetrical with respect to the central planes. The minimum grid interval was 10 mm. Boundary condition of constant pressure was applied to the inlet plane (upstream of the needle valve) and the outlet plane (just downstream of the nozzle exit). The pressure difference between inlet and outlet was 0.3 MPa; the same as the injection pressure of the experimental investigation. Thero-physical properties of n-Heptane were used as liquid properties. Flow equations with the volume of fluid (VOF) technique and the k-ε turbulent model were solved numerically using the commercial CFD code, Star-CD.



(a) Nozzle #1c (V_{max} = 22m/s)

(b) Nozzle #2c (V_{max} = 20.6m/s)

(c) Nozzle #3c (V_{max} = 24.8m/s)

Fig. 25 Numerical results (Velocity vectors and contour map of velocity)

Figure 25 shows the representative results of numerical simulation. The contour maps of flow velocity and the velocity vectors on the central plane of the flat ducts are provided in the figure. The maximum flow velocity, V_{max}, on the central plane is also shown below each map. The liquid flow inside the nozzle could be expressed as follows; the liquid passed through the needle valve and extended radially along the upper-side of nozzle plate. The liquid flowed into each flat duct, and the liquid flow near the sidewalls of duct turned its flow direction to the axis of duct. Consequently the velocity profile in the flat duct became a shape of letter "M". Due to the velocity profile, the liquid mainly flowed into each nozzle hole from the outer side of the duct, and strong swirling motion was provided in the upstream of each nozzle hole. The swirling motion should enable the nozzle to inject hollow-cone-like liquid film from each nozzle hole.

Comparison of the three results provided in Fig. 25 showed that the strength of the swirling flow depended upon the distance between the nozzle holes, and the swirling flow was strongest in the case of nozzle #3c. This result agreed with the experimental fact that the Sauter mean diameter of prototype #3c was smallest.

As described above, the simply structured nozzle (the nozzle design-D) has satisfied the requirement of fine fuel atomization, which is essential for the SI engines with port-fuel-injection. The nozzle should also satisfy the requirements of high productivity, high reliability level, and suitable spray pattern for the intake-port fuel injection.

6. Summary

Several attempts had been made to develop the fine atomizing nozzles for SI engines with intake-port fuel injection.

The atomization process of conventional 4-hole plate nozzle was investigated experimentally. It was found that the nozzle design added turbulence into the liquid-film jet and the liquid jet disintegrated rapidly. Based on the results, several nozzles had been developed that could inject perturbed hollow-cone-like liquid film.

6-hole nozzle of jet-interaction was developed first. The nozzle injected six liquid jets to form a hyperboloid of one sheet. The jets interacted each other and extended into a hollow-cone-like spray. The mean droplet size was smaller than that of the conventional nozzle. However the nozzle had a deficiency in spray pattern.

4-hole plate-type nozzle with flat duct was developed secondly aiming to inject hollow-cone-like liquid-film from each nozzle hole. The continuous water spray test and the intermittent fuel injection test were performed. Though the nozzle showed good performance, the intermittent injection nozzle was complicated in construction.

Finally we designed the simpler structured nozzle. The nozzle had two flat ducts for two pairs of nozzle holes. The continuous water spray test revealed that hollow-cone-like spray was discharged from each nozzle hole and the mean droplet diameter was much smaller than that of the conventional nozzle. The internal flow was simulated numerically and the mechanism of the hollow-cone-like spray injection was explained.

It was concluded that perturbed liquid-film was injected and the atomization quality was improved much by appropriate control of the internal flow condition of the plate-type nozzle.

Acknowledgement

Authors would like to express special thanks to Okamoto, A. and Iwamoto, M. of DENSO CORP. who assisted the numerical work, and to Inagaki, H. of Toyota Central R&D Lab. Inc. who assisted the drop size measurements. A number of students assisted with this work, and the authors also give thanks to Inoue, Y., Tokutomi, H., Sawai, T. and Takaoka, H.

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