

Improvement of Atomization and Flow Characteristics of Atomization Enhancement Nozzle for Direct Injection Diesel Engine

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Abstract

The purpose of this study is to improve atomization characteristics of a injection nozzle for a direct injection Diesel engine. It is necessary to obtain spray that suitable for combustion of fuel, that is, large spray angle, short liquid core length and small droplet diameter. In the previous study, the single hole atomization enhancement nozzle, which excellent spray characteristics are obtained at relatively low injection pressure, was developed. In this study, it was investigated about atomization of spray of the multi-hole atomization enhancement nozzle, and aimed to improve atomization characteristics and to obtain excellent spray characteristics. Effects of dimensions of the atomization enhancement nozzle, such as inlet shapes of nozzle hole, hole length and hole diameter, on atomization characteristics were investigated. As a result, it was cleared that in case of the multi-hole atomization enhancement nozzle with hole number of $N=4$, breakup length becomes short and spray angle becomes large about two times compared with the actual single hole nozzle. Atomization characteristics of intermittent injection were improved considerably at high-ambient pressure condition by using the multi-hole atomization enhancement nozzle with hole number of $N=4$, which was dressed with round inlet cutting at the inlet of the nozzle hole.

Keywords: Atomization, Atomization Characteristics, Spray Angle, Diesel Nozzle, Atomization Enhancement

Introduction

It leads to improve combustion efficiency, exhaust gas characteristics and progress of fuel consumption rate by improvement of atomization condition of fuel spray. It is a matter of great urgency to reduce carbon dioxide caused by global warming. The final objects of this study are improvement of combustion characteristics of a direct injection Diesel engine, reduction of soot emission and progress of fuel consumption rate by improvement of spray characteristics. In the previous studies, it was cleared that cavitation phenomenon in the nozzle hole is considerably affected to atomization of spray [1]-[10]. Moreover, it was developed the atomization enhancement nozzle [11], which excellent spray characteristics with large spread angle of spray, short breakup length for small type direct injection Diesel engine and small droplet diameters, are obtained at relatively low injection pressure.

The purposes of this study are design of the atomization enhancement nozzle that high-dispersion and high-efficiency spray are obtained for engine combustion and improvement of spray and flow characteristics of the direct injection Diesel nozzle. The effects of the atomization enhancement nozzle on atomization of intermittent spray at atmospheric and high-ambient pressure conditions and application to the actual Diesel injector were investigated [12]-[15].

The hole nozzle for the direct injection Diesel engine is dressed with round inlet cutting at the inlet of the nozzle hole in order to become large of discharge coefficient, that is, improve flow characteristics. At previous results, it was cleared that although spray tip penetration of the atomization enhancement nozzle is short, spread of spray becomes large considerably compared with a previous single hole nozzle for the direct injection Diesel injector at the intermittent spray under high-ambient pressure condition, and it was indicated possibility of application to the actual Diesel injector [13].

However, it is known that when round inlet cutting was dressed, high-injection pressure of fuel is necessary to obtain excellent spray characteristics. Recently, although injection pressure tend to increase, for instance, high-injection pressure of 300 MPa (3000 bar) and small hole diameter of 0.01 mm order, it is demanded from automobile makers that excellent spray characteristics is obtained at relatively low injection pressure and the same hole diameter as a general type Diesel injection nozzle.

In this study, we work on design and development of injection nozzle for the direct injection Diesel engine that the same excellent spray characteristics as ones at real Diesel engine condition high-injection pressure of 200 MPa are obtained at relatively low injection pressure and it is able to achieve improvement of flow characteristics at relatively low injection pressure.

In this paper, the atomization enhancement nozzle, which was dressed with round inlet cutting, was developed in order to improve both spray characteristics and flow characteristics. Moreover, this developed injection nozzle is installed at injector for a direct injection Diesel engine.

As a result, it was clarified that in case of the atomization enhancement nozzle with round inlet cutting, breakup length becomes short about 20 p.c. and spray angle becomes large about two times, compared with the single hole nozzle for the actual Diesel engine. Atomization characteristics were improved considerably by using the atomization enhancement nozzle with round inlet cutting.

Experimental Apparatus and Method

Experimental apparatus is shown in Fig.1. Figure 1 (a) shows apparatus for steady state injection and (b) shows one for intermittent injection. As shown in Fig.1 (a), experimental apparatus for steady state injection consists of a high-pressure pump worked by an air compressor, a spark light source for taking photographs of spray. Water at room temperature pressurized by the high-pressure pump was continuously injected under atmospheric pressure condition. Maximum injection pressure is 10 MPa, and experimental data is discussed at spray region that even though the injection pressure is increased, breakup length and spray angle are almost constant. It was verified that the injection pressure, which corresponds to spray region, is guessed about over 5 MPa. Disintegration behavior of spray was photographed by scattered light, using a stroboscope.

Breakup length of a liquid core, which is defined as distance from the nozzle exit to breakup point of the liquid core, was measured by electrical resistance method [1] in which a screen detector was used. Breakup length is defined as the liquid core length, which was injected from one nozzle hole. In case of the multi-hole nozzle, it is necessary to measure the liquid core length of sprays injected from each nozzle holes. Sprays injected from each nozzle holes are generated one spray. Therefore, breakup length was measured by previous measurement method and definition. Spray angle was defined as spray boundary, and it was measured by images of photographed sprays.

As shown in Fig.1 (b), experimental apparatus for intermittent injection consists of super high-pressure pump, microcomputer for control of injection time, injection duration and irradiation time of stroboscope, digital camera, stroboscope and pressure vessel. Light oil for fuel was intermittently injected under room temperature of $T_a=300$ K and high-ambient pressure condition of $P_a=1.6$ MPa at the differential pressure of injection of $P_i=100$ MPa. Spray was photographed at the arbitrary time after start of injection from $t=0.1$ ms to $t=3.0$ ms. The injection duration of fuel was $T_{inj}=0.9$ ms for the hole diameter of $D_i=0.15$ mm.

Schematic of test nozzles are shown in Fig. 2. Figure 2 (a) shows the injector for the direct injection Diesel engine, (b) shows the single hole nozzle for the actual Diesel engine, (c) and (d) show the multi-hole atomization enhancement nozzle invented in this study. Figure 2 (c) is sharp inlet shape nozzle (called Nozzle-S) and (d) is the nozzle which was dressed with round inlet cutting at the inlet of the nozzle hole (called Nozzle R_d). Here, the multi-hole atomization enhancement nozzle (Nozzle-S) was used to consider the effect of existence of round inlet curvature (Nozzle-S and Nozzle- R_d) on atomization characteristics. Total sectional area of nozzle holes of the single hole nozzle (b) and the multi-hole atomization enhancement nozzle (c), (d) are almost same values. Structure of the atomization enhancement nozzle invented in the previous study is that the bypass, which is connected between the upstream chamber correspond to the sac chamber of an actual Diesel injector, and the gap which is installed at middle of the nozzle hole. Role of the bypass is that increasing the pressure in the gap in order to occur collapse of cavitation bubbles and strong disturbance and giving swirling flow from the bypass in

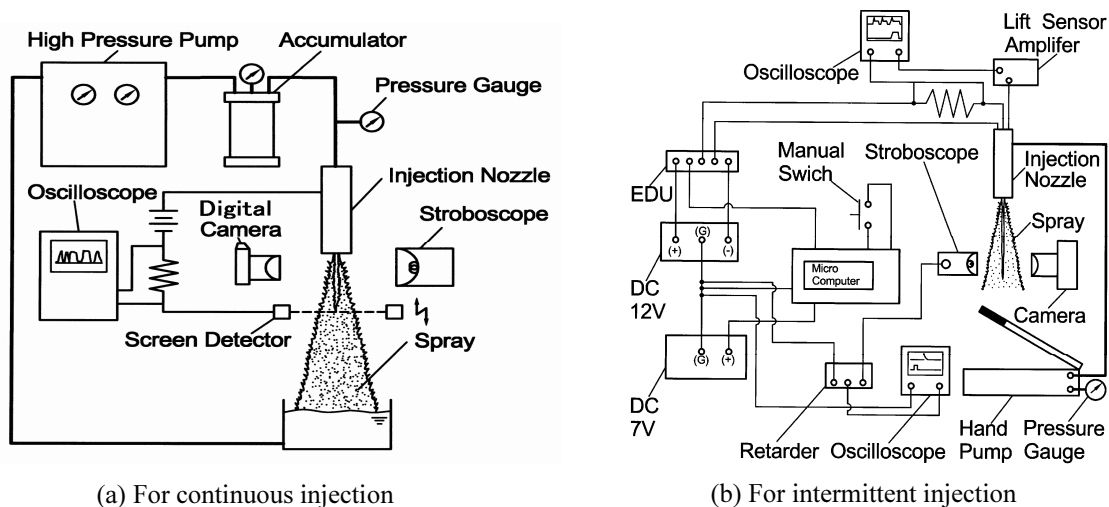


Figure 1 Experimental apparatus

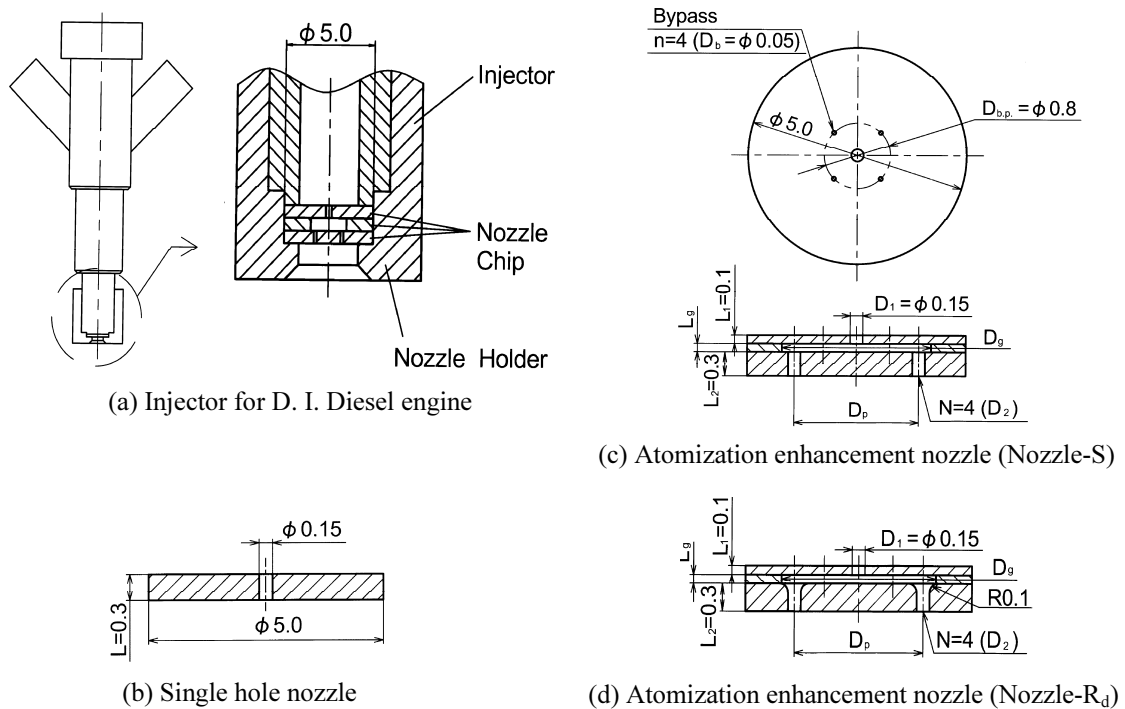


Figure 2 Test nozzles

order to occur collapse of cavitation bubbles and strong disturbance and giving swirling flow from the bypass in the gap. It is expected that the issuing spray expands significantly radial direction of spray by this swirling flow.

Results and Discussion

Effect of Inlet Shapes of Nozzle Hole Downstream from Gap on Atomization Characteristics of Steady State Injection

The effect of inlet shapes of nozzle hole on atomization of spray is shown in Fig.3. Moreover, the effects of inlet shapes of nozzle hole on breakup length and spray angle are shown in Figs.4 and 5, respectively. As shown in Fig.3, spread of spray of Nozzle-R_d becomes larger than Nozzle-S.

As shown in Fig.4, breakup length of Nozzle-R_d becomes short compared with Nozzle-S at all differential pressure of injections. At microscopic view, although differences between breakup length of Nozzle-S and Nozzle-R_d is only a few mm length of 1, 2 mm, breakup length of Nozzle-S and Nozzle-R_d are short of 4 mm and 5 mm, breakup length of Nozzle-R_d becomes short about 20 p.c. compared with one of Nozzle-S and hole diameters are small of 0.15 mm. From these results, when the nozzle, which was dressed with round inlet cutting at the inlet of the nozzle hole, is used, it is effective method to short breakup length.

As shown in Fig.5, spray angle of Nozzle-R_d becomes large compared with one of Nozzle-S at all differential pressure of injection. When spray angle was compared at the maximum differential pressure of injection of 10 MPa, spray angle of Nozzle-R_d becomes large about 1.5 times as one of Nozzle-S.

From these results, when the nozzle, which was dressed with round inlet cutting at the inlet of the nozzle hole, is used, it is effective method to obtain high-dispersion spray, short breakup length and large spray angle. Moreover, the mutual relationships, that is, when breakup length is short and spray angle is large, are obtained.

It is expected that although excellent atomization characteristics is obtained at low-injection pressure, volumetric flow rate at low-injection pressure is a little compared with high-injection pressure conditions. The effect of inlet shapes of nozzle hole on volumetric flow rate is shown in Fig.6. As shown in Fig.6, volumetric flow rate of Nozzle-R_d, is obtained about 60 p. c. larger than one of Nozzle-S at all differential pressure of injection. For instance, in case of Nozzle-R_d, volumetric flow rate of Nozzle-S at maximum differential pressure of injection of P_f=10 MPa is obtained at small injection pressure of about 30 p. c., and flow characteristics is improved significantly.

In general, when the nozzle, which was dressed with round inlet cutting at the inlet of nozzle hole, is used, although volumetric flow rate is improved, atomization characteristics are getting worse with an increase in volumetric flow rate. However, from these results, it can be seen that the nozzle invented in this study which have atomization enhancement mechanism (bypass and gap) and round inlet cutting at the inlet of the nozzle hole, both atomization characteristics and flow characteristics are improved significantly.

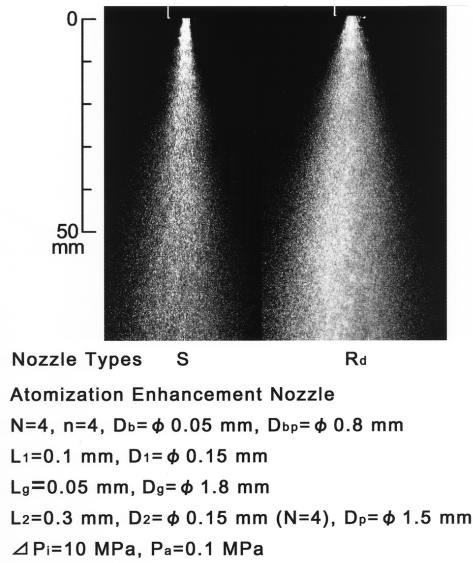


Figure 3 Effect of inlet shapes of nozzle hole on atomization of spray

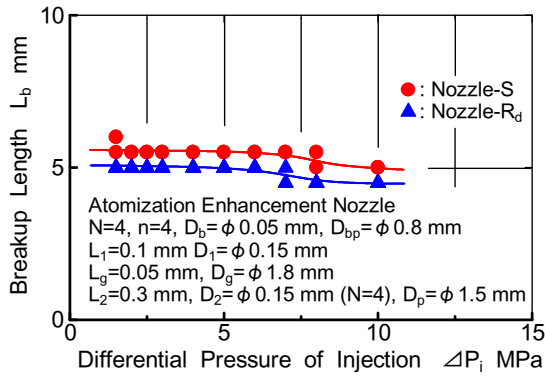


Figure 4 Effect of inlet shapes of nozzle hole on breakup length

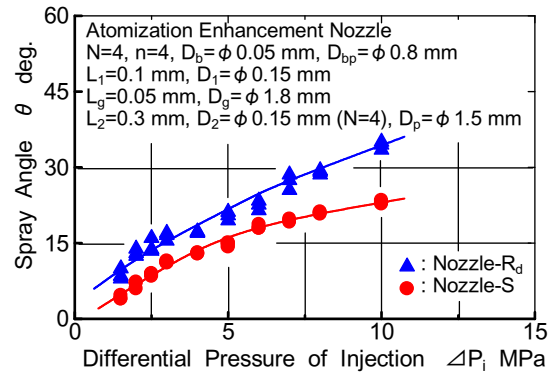


Figure 5 Effect of inlet shapes of nozzle hole on spray angle

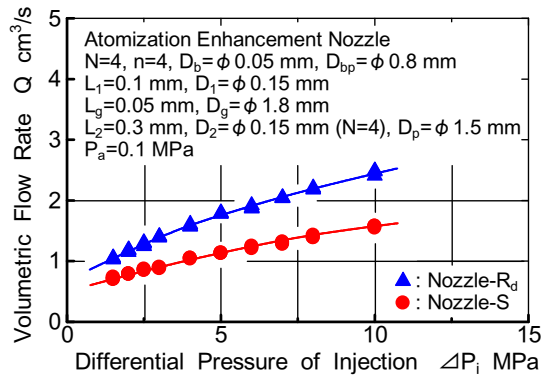


Figure 6 Effect of inlet shapes of nozzle hole on volumetric flow rate

Effect of Gap Length of Nozzle Hole on Atomization Characteristics of Steady State Injection

The effect of gap length of nozzle hole on atomization of spray is shown in Fig. 7. Moreover, the effects of gap length of nozzle hole on breakup length and spray angle are shown in Figs.8 and 9, respectively. Gap lengths L_g were changed 0.05, 0.1 and 0.3 mm.

As shown in Fig.7, when gap length L_g is shortest of $L_g=0.05$ mm, spread of spray becomes largest, and with an increase in gap length decrease in spread of spray. Moreover, as shown in Figs.8 and 9, breakup length of $L_g=0.05$ mm becomes shortest and one of $L_g=0.3$ mm becomes longest at all differential pressure of injection. At the maximum differential pressure of injection of $P_i=10$ MPa, breakup length of $L_g=0.05$ mm becomes short about 40 p. c., compared with one of $L_g=0.3$ mm. Furthermore, spray angle of $L_g=0.05$ mm becomes largest and spray angle becomes large about two times as large as one of $L_g=0.3$ mm at larger than $P_i=7$ MPa. The mutual relationships between breakup length and spray angle, are obtained.

In general, it has the following tendency that atomization of spray becomes worse with an increase in volumetric flow rate and excellent spray characteristics is obtained with a decrease in volumetric flow rate at same differential pressure of injection. In case of $L_g=0.05$ mm, it is guessed that volumetric flow rate becomes small due to narrow space in gap. That is, liquid flow, which is flowed into nozzle hole upstream from gap D_1 and bypass, becomes small due to remain in gap. Hence, it was studied that effect of gap length of nozzle hole on volumetric flow rate, changing gap length. The effect of gap length of nozzle hole on volumetric flow rate is shown in Fig.10. As shown in Fig.10, volumetric flow rate are almost same values independent of gap length at arbitrarily differential pressure of injection. Therefore, in spite of almost same volumetric flow rate, spread of spray and spray angle becomes large about two times compared with the longer gap length of nozzle hole, and it is considered that disturbance of liquid flow in gap is affected considerably to atomization of spray by gap length of nozzle hole.

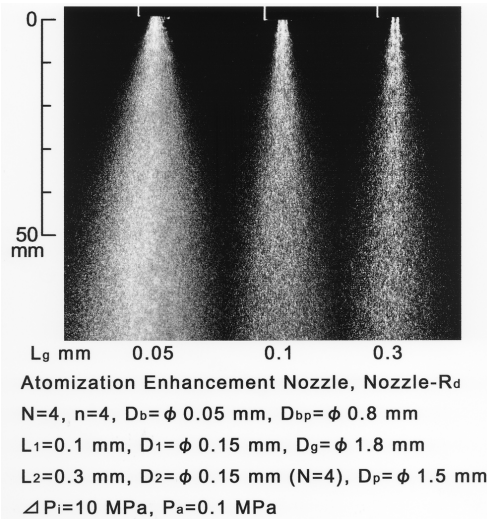


Figure 7 Effect of gap length of nozzle hole on atomization of spray

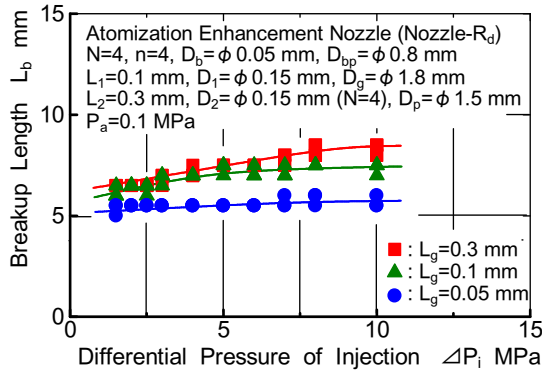


Figure 8 Effect of gap length of nozzle hole on breakup length

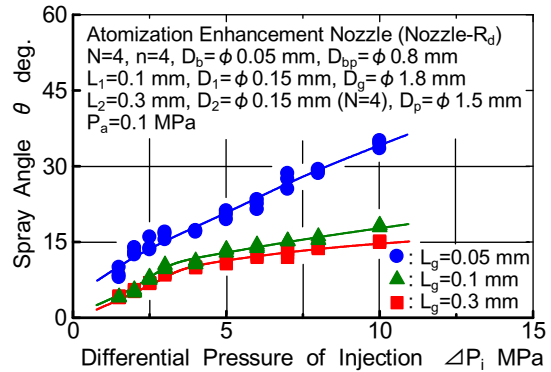


Figure 9 Effect of gap length of nozzle hole on spray angle

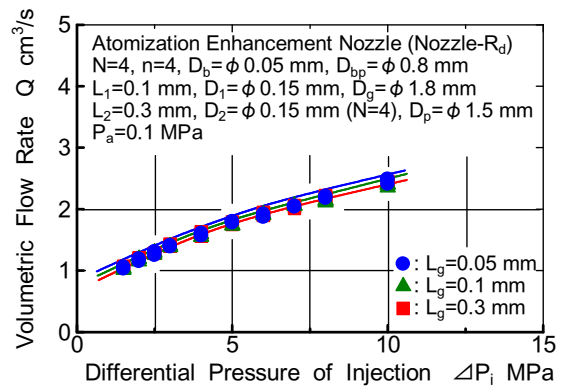


Figure 10 Effect of gap length of nozzle hole on volumetric flow rate

Effect of Hole Diameter Downstream from Gap on Atomization Characteristics of Steady State Injection

The effect of hole diameter downstream from gap D₂ on spray angle at maximum differential pressure of injection of P_i=10 MPa is shown in Fig.11. As shown in Fig.11, spray angle of D₂=0.15 mm (Hole number of N=4) (A₁ < A₂) is large about more than two times, compared with one of D₂=0.08 mm (Hole number of N=4) (A₁ = A₂). The reason is considered that since disturbance due to occurrence of cavitation in the nozzle hole upstream from gap and swirling flow by the liquid flow incoming from bypass, in case hole diameter downstream from gap is large, inlet loss at nozzle hole downstream from gap is small. Moreover, it is considered that since momentum toward radial direction of spray is increased by disturbance of liquid flow and swirling flow, spray angle becomes large considerably.

Comparison between Single Hole Nozzle for Actual Diesel Engine and Multi-hole Atomization Enhancement Nozzle Invented in This Study

In the previous study, it was cleared that spread of spray of Nozzle-R_d is considerably larger than one of Nozzle-S and when the hole diameters downstream from gap D₂ is larger than the hole diameter upstream from gap D₁, breakup length becomes short, spray angle becomes large and atomization characteristics is improved. From these backgrounds and results, the test nozzle was used Nozzle-R_d and D₁ < D₂ (A₁ < A₂); (D₁: Hole number of N=1, D₂: Hole numbers of N=4).

Atomization and development processes of intermittent sprays of the single hole nozzle for actual Diesel engine and the multi-hole atomization enhancement nozzle are shown in Fig.12. Figure 12 (a) is the single hole nozzle and (b) is the multi-hole atomization enhancement nozzle. As shown in Fig.12, when spread of sprays are compared at arbitrary times after start of injection, spread of sprays of the multi-hole atomization enhancement nozzle are larger than one of the single hole nozzle, droplets of spray is dispersed widely toward radial direction of spray. In case of the single hole nozzle, when time after start of injection exceeds about t=0.9 ms,

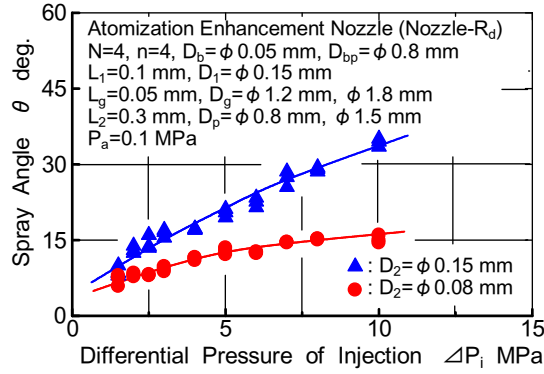


Figure 11 Effect of hole diameter downstream from gap on spray angle

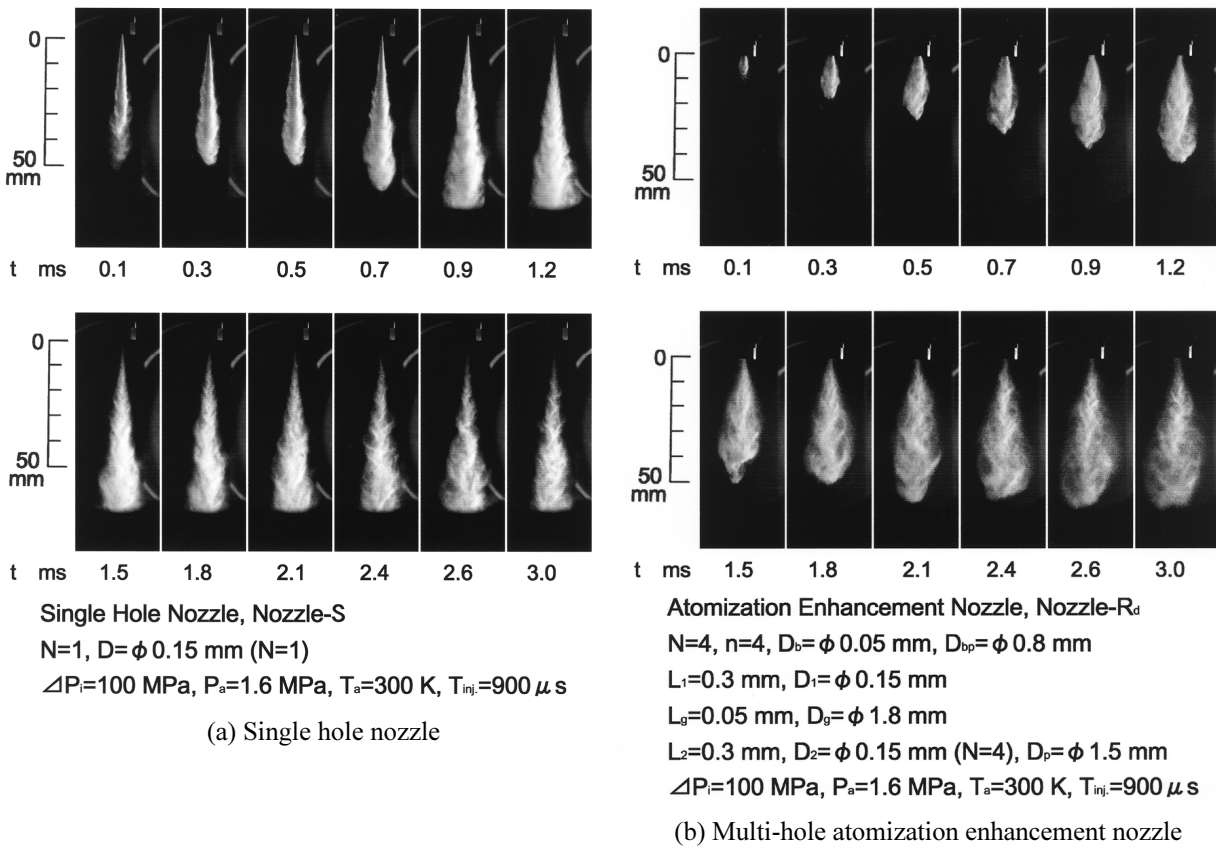


Figure 12 Atomization of intermittent spray of single hole nozzle for actual Diesel engine and multi-hole atomization enhancement nozzle (Nozzle-R_d) as a function of time after start of injection

spray tip of the single hole nozzle is hidden from the observation window, that is, spray tip goes through the observation window. To the centrally, spray tip of the multi-hole atomization enhancement nozzle is observed in the observation window. From these results, spray length of the single hole nozzle is longer than one of the multi-hole atomization enhancement nozzle, it can be seen that spray tip penetration becomes large.

As a consequence of these results, it can be seen that the multi-hole atomization enhancement nozzle, which atomization characteristics was improved considerably at steady state injection, is used, spread of spray becomes large considerably, high-dispersion spray is obtained and atomization of spray is improved considerably at high-ambient pressure condition.

Moreover, it is well known that atomization characteristics of the nozzle, which was dressed with round inlet cutting at the inlet of the nozzle hole, becomes worse considerably. However, when the nozzle, which has atomization enhancement mechanism (bypass and gap) and round inlet cutting at the inlet of the nozzle hole, was used, both atomization characteristics and flow characteristics are improved significantly.

Summary and Conclusions

- (1) In case round inlet cutting was dressed at the inlet of the nozzle hole (Nozzle R_d), spread of spray becomes large compared with sharp inlet shape nozzle (Nozzle-S).
- (2) When the shorter gap length of nozzle hole ($L_g=0.05$ mm) was used, it is effective atomization enhancement of spray. Moreover, spray angle of the shorter gap length ($L_g=0.05$ mm) becomes large about two times compared with one of the longer gap length ($L_g=0.3$ mm).
- (3) When the hole diameters downstream from gap D_2 are larger than the hole diameter upstream from the gap D_1 [Nozzle- R_d , $D_1 < D_2$ ($A_1 < A_2$)], breakup length becomes short and spray angle becomes large and atomization characteristics is improved. Moreover, spray angle becomes large about more than two times compared with the nozzle which total sectional areas of nozzle holes are same [Nozzle- R_d , $D_1 = D_2$ ($A_1 = A_2$)].
- (4) Spray length, that is, spray tip penetration of the single hole nozzle of the actual Diesel engine is stronger than one of the multi-hole atomization enhancement nozzle. Moreover, spread of intermittent spray of the multi-hole atomization enhancement nozzle is larger than one of the single hole nozzle and high-dispersion spray was obtained.

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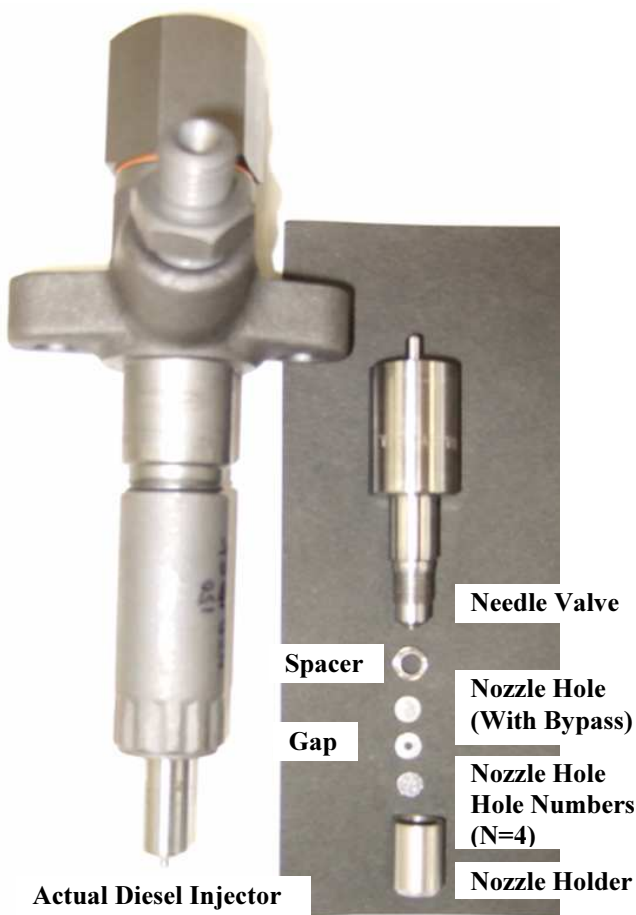
References

- [1] **Hiroyasu, H., Arai, M. and Shimizu, M.**, Break-up Length of a Liquid Jet and Internal Flow in a Nozzle, *Proc. 5th International Conference on Liquid Atomization and Spray Systems*, (1991), pp.275-282.
- [2] **Soteriou, C., Andrews, R. and Smith, M.**, Direct Injection Diesel Sprays and the Effect of Cavitation and Hydraulic Flip on Atomization, *SAE Technical Paper*, No. 950080, (1995), pp. 27-52.
- [3] **Chaves, H, Knapp, M., Kubitzek, A., Obermeier, F. and Schneider, T.**, Experimental Study of Cavitation in the Nozzle Hole of Diesel Injectors Using Transparent Nozzles, *SAE Technical Paper*, No. 950290, (1995), pp. 645-657.
- [4] **Badock, C., Wirth, R., Kampmann, S. and Tropea, C.**, Fundamental Study of the Influence of Cavitation on the Internal Flow and Atomization of Diesel Sprays, *Proc. 13th Institute for Liquid Atomization and Spray Systems-Europe*, (1997), pp. 53-59.
- [5] **Schmidt, D. P., Rultand, C. J. and Corradini, M. L.**, A Numerical Study of Cavitating Flows Through Various Nozzle Shapes, *SAE Paper*, No. 971597, 1997.
- [6] **Tamaki, N., Nishida, K., Shimizu, M. and Hiroyasu, H.**, Effects of Cavitation and Internal Flow on Atomization of a Liquid Jet, *Atomization and Sprays*, Vol. 8, No. 2, pp. 179-197, 1998.
- [7] **Badock, C., Wirth, R., Fath, A. and Leipertz, A.**, Investigation of Cavitation in Real Size Diesel Injection Nozzles, *International Journal of Heat and Fluid Flow*, Vol. 20, pp. 538-544, 1999.
- [8] **Henry, M. E. and Collicott, H.**, Visualization of Internal Flow in a Cavitating Slot Orifice, *Atomization and Sprays*, Vol. 10, No. 6, pp.545-563, 2000.
- [9] **Arcoumanis, C. and Gavaises, M.**, Cavitation in Diesel Injectors: Modeling and Experiment, *Proc. 14th Institute for Liquid Atomization and Spray Systems-Europe*, pp. 248-255, 1998.
- [10] **Yule, A. J. Dalli, A. M. and Yeong, K. B.**, Transient Cavitation and Separation in a Scaled-up Model of a VCO Orifice, *Proc. 14th Institute for Liquid Atomization and Spray Systems-Europe*, pp. 230-235, 1998.
- [11] **Tamaki, N., Shimizu, M. and Hiroyasu, H.**, Enhancement of the Atomization of a Liquid Jet by Cavitation in a Nozzle Hole, *Atomization and Sprays*, Vol. 11, No.2, (2001), pp. 125-137.
- [12] **Tamaki, N., Nishida, Y. and Hosokawa, T.**, Practical Study on High-Dispersion and High-Penetration Diesel Injection Nozzle: 1st Report, Effects of Geometric Shape of High-Dispersion Atomization Enhancement Nozzle on Atomization of Intermittent Spray, *Proc. 21st Institute for Liquid Atomization and Spray Systems-Europe*, CD-R, 6 pages, 2007.
- [13] **Tamaki, N., Morimoto, K., Chiba, M.**, Practical Study on High-Dispersion and High-Penetration Diesel Injection Nozzle (Second Report: Atomization of Intermittent Spray of High-Dispersion Atomization Enhancement Nozzle at High-Ambient Pressure), *Proc. 22nd Institute for Liquid Atomization and Spray Systems-Europe*, CD-R, 7 pages, 2008.
- [14] **Tamaki, N.**, Effects of Cavitation in a Nozzle Hole on Atomization of Spray and Development of High-Efficiency Atomization Enhancement Nozzle, *Proc. 11th Internal Conference on Liquid Atomization and Spray Systems ICLASS 2009*, CD-R, 6 pages, 2009.
- [15] **Tamaki, N., Kato, A., Kato, K. and Imano, K.**, Improvement of Atomization Characteristics of Spray by Multi-Hole Nozzle for Pressure Atomized Type Injector, *Proc. 23rd Institute for Liquid Atomization and Spray Systems-Europe*, CD-R, 7 pages, 2010.

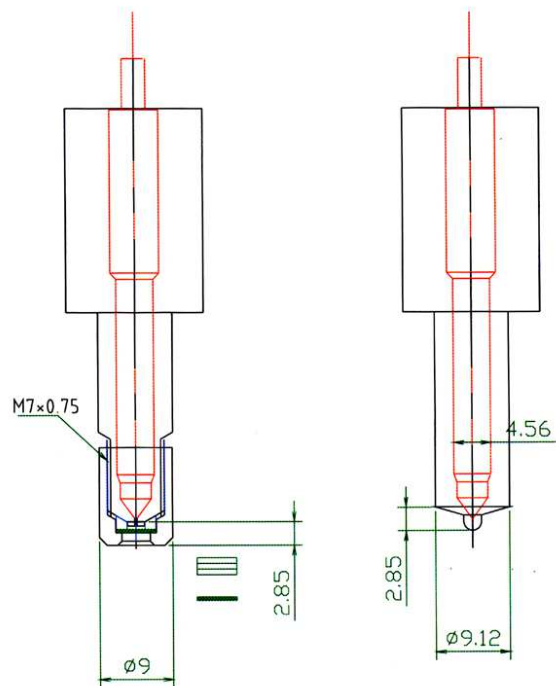
Future Works

The hole nozzle for an actual Diesel engine is usually used multi-hole nozzle, for instance, hole numbers of 4 and 6. It is apprehensive that since the multi-hole atomization enhancement nozzle invented in this study is consists of three plates, that is, separated one nozzle hole and bypass, gap and another separated four nozzle holes, application way for Diesel engine injector might be difficult. However, in case mechanics of this multi-hole atomization enhancement nozzle is composed at the actual Diesel nozzle, for instance, the bypass is connected to the gap at arbitrary location of the actual Diesel injector, pressure in the gap increases with an increase in the injection pressure, disturbance due to collapse of cavitation bubbles and swirling flow from the bypass occur in the gap and atomization of the issuing spray is enhanced. Therefore, even though hole number of this multi-hole atomization enhancement nozzle invented in this study is single hole separated by 4 holes, it is guessed that spray spreads considerably radial direction compared with the actual multi-hole nozzle.

It is possible that the multi-hole atomization enhancement nozzle with atomization enhancement mechanism, that is, the bypass and the gap, fits together the actual Diesel injector. Aspect and schematic of the actual Diesel injector, which the nozzle tip of the actual Diesel injector was processed to install the invented atomization enhancement nozzle, is shown in appendix Figs.1 and 2, respectively. It is planned that the multi-hole atomization enhancement nozzle, which performs atomization enhancement mechanism, is installed at the actual Diesel injector and Diesel engine, and investigates about combustion and exhaust characteristics in order to improve engine performance, fuel consumption rate and thermal efficiency, and leads to reduce carbon dioxide.



Appendix Figure 1 Aspect of the actual Diesel injector installed atomization enhancement nozzle



Appendix Figure 2 Schematic of the actual Diesel injector installed atomization enhancement nozzle