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Effects of Needle Response on Spray Characteristics in High Pressure Injector Driven by Piezo Actuator for Common-Rail Injection System

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The common-rail injection systems, as a new diesel injection system for passenger car, have more degrees of freedom in controlling both the injection timing and injection rate with the high pressure. In this study, a piezo-driven injector was applied to a high pressure common-rail type fuel injection system for the control capability of the high pressure injector's needle and firstly examined the piezo-electric characteristics of a piezo-driven injector. Also in order to analyze the effect of injector's needle response driven by different driving method on the injection, we investigated the diesel spray characteristics in a constant volume chamber pressurized by nitrogen gas for two injectors, a solenoid-driven injector and a piezo-driven injector, both equipped with the same injection nozzle with sac type and 5-injection hole. The experimental method for spray visualization was based on back-light photography technique by utilizing a high speed framing camera. The macroscopic spray propagation was geometrically measured and characterized in term of the spray tip penetration, spray cone angle and spray tip speed. For the evaluation of the needle response of the above two injectors, we indirectly estimated the needle's behavior with an accelerometer and injection rate measurement employing Bosch's method was conducted. The experimental results show that the spray tip penetrations of piezo-driven injector were longer, on the whole, than that of the solenoid-driven injector. Besides we found that the piezo-driven injector have a higher injection flow rate by a fast needle response and it was possible to control the injection rate slope in piezo-driven injector by altering the induced current.

Key Words: Piezo Actuator, Injector, Diesel Spray, Common-rail Type Fuel Injection System

Nomenclature

L	: Displacement of piezo stack
I	: Output (induced) current
V	: Output voltage
Cp	: Coefficient of expansion
n	: Each number of piezo stack
A	: Cross-sectional area
P	: Pressure
$(a\rho)$	: Acoustic impedance
ρ	: Density
t	: Time after start of injection
dq/dt	: Injection rate
$(dq/dt)/dt$	: Slope of injection rate

1. Introduction

In the latest direct injection diesel engine, the fuel is distributed to the injector from a high pressure accumulator, called the common-rail

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(European patent, 1993 ; Boehner and Hummel, 1997). Advantages of common-rail injection system, which is fed by a high pressure fuel pump and used instead of conventional rotary pump injection system, is enabling the high pressure injection and have a flexibility in controlling both the injection timing and injection rate. From this point of view, it is very important to control the fuel delivery from common-rail to nozzle inside injector due to the fact that inector needle is controlled by the electro-hydraulic balancing with high fuel pressure (Payri et al., 2004). Namely, the electro-hydraulic injector for the common-rail injection system must be designed to meet the precise high fuel delivery control capability (Bianchi et al., 2000 and 2003).

In the electro-hydraulic injector, the injection nozzle is being opened and closed by movement of a injector's needle which is balanced by pressure at the nozzle seat and at the needle control chamber, at the opposite end of the needle. Currently, most high pressure injector in use has a needle driven by the solenoid coil energy and the driving current is controlled by the peak and hold method. Its main disadvantage in diesel engine application is high power consumption and high power loss through solenoid coil. Because this system requires the permanent current during activation of the solenoid control valve. Moreover, this system have a slow needle response, which is generated by the solenoid control valve, due to the exponential increase of current charged in solenoid coil by induced voltage. Also it has to be separated recharge phase over injector or coil.

In order to overcome this drawback, the several studies have been performed. These related study can be divided into the following two research approaches.

One is related to improve in injection rate by the controllable solenoid injector. Ganser (1998) developed the double-stop solenoid valve and tested on a hydraulic injector test bench. The opening of injector's nozzle needle valve is electri-hydraulically controlled by a double-stop solenoid valve. The results showed that the proposed design allowed a better control of the initial shape of the injection rate. And Tanaka et al. (1998) developed by applying the hydro-mechanical position-feedback mechanism to the needle valve and the tendem arrayed giant-magnetostrictive-actuator to control of the two-port pilot valve driven by solenoid coil.

The other is related to apply the piezo-actuator as prime movers in fuel injector. Piezo-actuator has become an area of increased interest in the past ten years. Usually it used as sensors in such applications as pressure transducers. Recently the needle driving mechanism by means of piezo-electric actuator instead of the conventional solenoid valve have stuided. Renner (1998) have presented promising results controlling the injection timing by piezo-actuator in high pressure fuel injector. The main advantage of injector driven by piezo-electric actuator is to allow a better control of the initial shape of the injection rate (Fettes and Leipertz, 2001 ; Taylor and Washington, 2003).

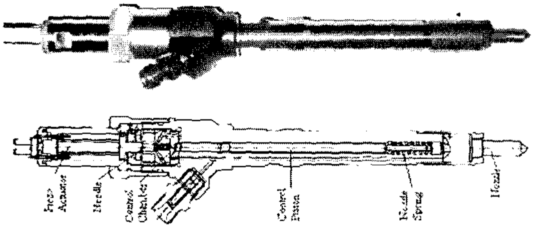
Although there are many investigated research results, most investigations on the above two injectors were carried out separately. Because a one-to-one comparison between the two injector is still difficult and the consistency of experimental apparatuses, particularly the injectior's driver, and test conditions are hard to obtain.

In this study, the effects of the needle response and piezo-electric characteristics in a high pressure injector driven by piezo actuator on the injection rate and diesel spray have been investigated. Ultimately, the comparison results between the solenoid-driven injector and piezo-driven injector in term of the injection rate and spray characteristics obtained in a constant volume chamber pressurized by nitrogen gas were presented including the piezo-electric characterization results of the piezo-driven injector. Of course, the two injectors tested by the same experimental common-rail type fuel injection system and compared with the same test conditions to get consistency in results. It is worthwhile to note in advance that the solenoid-driven injector with a nozzle of mini-sac volume and 5-injection hole, which is currently used in high pressure common rail injection system (Morita, 2003), was taken as a reference system to make a comparative research.

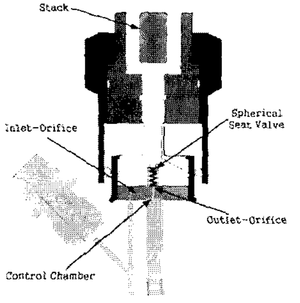
2. Feature of Piezo-driven Injector

In this study, the prototype piezo-driven injector was used to evaluate the potential of new control capability of injector's needle and is shown in Fig. 1(a) with internal structure layout of this injector. The prototype piezo-driven injector is composed of a piezo actuator, a control chamber, a needle and a nozzle part. The same nozzle unit used in the solenoid-driven injector equipped at this piezo-driven injector's body. The fuel flow path in control chamber with two orifices of the piezo-driven injector is shown in Fig. 1(b). This configuration is different to that of the solenoid-driven injector due to the piezo stack's position. The diameter of inlet orifice and outlet orifice and the stack's displacement play an important role in performance of the piezo-driven injector. Optimization of design parameters about this control chamber was already carried out in a preliminary study using AMESim code (Lee et al, 2003).

A main key of this prototype piezo-driven injector is a ceramic-based piezo actuator based on the application of an electric charge. The specifications of the prototype piezo actuator used in this study are given in Table 1.



(a) Internal structure



(b) Control chamber inside injector's body

Fig. 1 Layout of internal structure and control chamber in prototype piezo-driven injector

The piezo actuator with the electric charge control concept makes use of the inverse piezo-electric effect. Fig. 2 shows the theory of the inverse piezo-electric effect for the mechanical output force. The highly precise piezo actuator is controlled by charge-discharge of output pulse current in a piezo stack.

Fig. 3 represent the current and voltage wave for driving of the piezo-driven injector. The controller of a piezo-driven injector is triggered by

Table 1 Specifications of the piezo stack used

Parameter	Unit	Value
Stack size	mm	7×7×32.7
Capacitance	μF	4.1
Driving current	A	7
Driving voltage	V	120
Pre-load	N	1,000

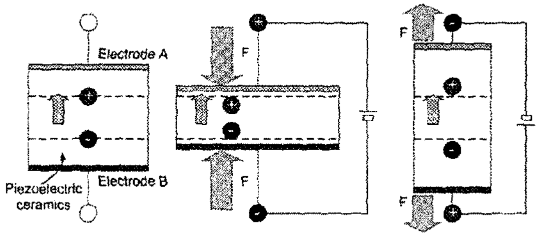


Fig. 2 Theory of the inverse piezo-electric effect

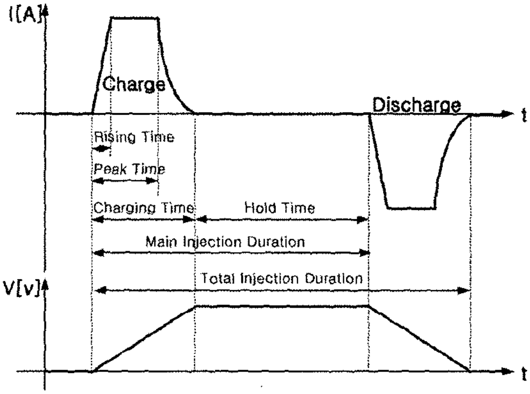


Fig. 3 Driving current wave in piezo-driven injector

square wave TTL signal. And the displacement [L] of piezo stack is determined by the coefficient of expansion [Cp, m/v] and each number [n] of stack and applied voltage [V]. The related equation is given by Eq. (1) as follows.

$$L = Cp \cdot n \cdot V \qquad (1)$$

As shown Eq. (1), the operating characteristics of a piezo-driven injector is influenced by the applied voltage. When the voltage is applied to a piezo-electric stack, its dimension will be changed. As reference, the injection duration in this study means the total injection duration, including the discharging time, if there is not worth mentioning.

3. Experimental Apparatus and Procedure

3.1 Experimental Apparatus

3.1.1 Needle behavior's evaluation

In order to measure the longitudinal vibration frequency of the same direction as the needle shift, the accelerometer (Bruel & Kjare, Type 4371), which is mounted on the flat area in the two injector's outside body with the same nozzle configuration, was applied. It is a very useful to the estimation of the needle's behavior indirectly, which is moved by the electric output force, in the piezo-driven injector. Because the direct measurement of needle's movement without the any modification work inside injector is very difficult.

3.1.2 Fuel injection rate measurement

The injection rate characteristics are closely related to spray characteristics and ultimately have an effect on the combustion process. Previous research has shown that injection shape control can be a very effective means to control exhaust emissions, fuel consumption and combustion noise (Gill and Herzog, 1993; Beidl et al., 1998). In this study, the injection rate measuring instrument based on the Bosch's operating principle was used to measure the transient fuel flow rate in two injectors. Fig. 4 shows the layout of the experimental apparatus. A measuring tube with an inner diameter of 4.57 mm and a length of 10,850 mm was fabricated in the form of coil type with diameter of 250 mm. The piezo-electric type pressure sensor (Kistler, Type 6052B) was installed at the middle of the injector adaptor. A cylindrical accumulator with a volume of 700 cc was installed in front of the back-pressure regulator. This regulator was utilized to keep engine-like pressure condition to be required and can be adjusted up to the pressure range of 3 MPa. The back-pressure within the accumulator was measured by Bourdon tube pressure gauge.

3.1.3 Macroscopic spray visualization

A schematic diagram of experimental apparatus used in this study to measure and observe the sparay behavior generated by two injectors with different needle-driving method was shown in Fig. 5. It consists of a constant volume chamber, common-rail fuel injection system, control unit, fuel pump driven by DC motor, pressure regu-

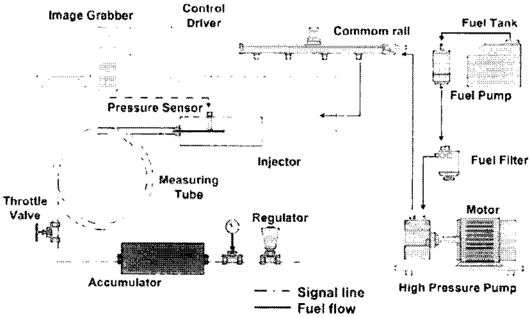


Fig. 4 Experiment setup for measuring injection rate

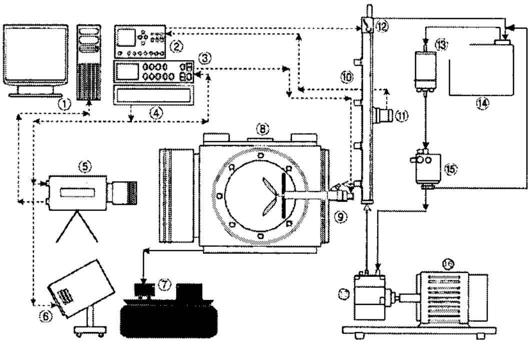


Fig. 5 Schematic arrangement of macroscopic spray visualization

lator and high speed framing camera system.

A high pressure injector that has 5 holes with nozzle hole diameter of 0.168 mm was placed in the center of the constant volume chamber and the fuel in the common-rail is pressurized by a high pressure pump, which driven by a DC motor of 3.7 kW. In the case of diesel fuel, the injector operates the maximum injection pressure up to 135 MPa. The high pressure diesel fuel through the nozzle in injector was injected into the constant volume chamber with three quartz windows. It was filled up by pressurized nitrogen gas at ambient pressure of 0.1, 1.5, 3.0 and 4.5 MPa to investigate the effects of ambient pressure on the spray shapes and the structures of non-evaporating unconfined intermittent spray.

In the visualization setup (Kunkulagunta, 2000), the spray shapes were photographed by a high speed camera system (Phantom v7.0) with the speed operating up to 10,000 frames per second and analyzed by a personal computer with an imaging board and imaging software. Lighting was obtained through the use of a Xenon lamp of 2 kW with air cooling system, which was triggered by a TTL signal.

The injection duration and injection timing were controlled by changing the TTL pulse signal of a delay generator (DG535). This enabled the injection driver and imaging board to receive an external trigger for the acquiring high speed diesel spray with elapsed time. Single shot injection for two injectors was electronically controlled by a common-rail injection controller, respectively.

The electrical specification of a solenoid-driven injector controlled by the peak and hold method is as follows : coil resistance of 0.335 Ω, coil inductance of 196 μH, peak current of 20A, hold current of 11A. Whereas the piezo-driven injector is controlled by charge-discharge of output pulse current induced from a specially fabricated controller (HVP Pulser Unit, Germany ; Refer to On-Line Document made by Follansbee, 2002) for the exclusive use of the piezo-driven injector.

3.2 Test procedure

The investigations on the piezo-electric characteristics and spray characteristics at injection pressure of 40 MPa and 130 MPa was performed by using two injectors with a same mini-sac volume nozzle. Representing a part load of a direct injection diesel engine, several injection durations were selected including the pilot injection duration (Lee et al., 2004). Because the multiple injections are already realized by modern common-rail fuel injection system (Manfred et al., 1994). During the pilot injection, a small fuel quantity at engine operating conditions is injected, thereby shorten the ignition delay of the main injection, ultimately reduce a combustion noise and NOx emission (Flaig et al., 1999). The spray cone angle, spray tip speed and spray tip penetration were measured by using the back diffusion light illumination method based on the macroscopic spray measurement function of a high-speed imaging software (Phantom Co.). The experimental conditions are summarized in Table 2.

Table 2 Experimental conditions

Parameter	Value	Reference
Pump speed (rpm)	800	Correspond to diesel engine speed of 1600
Rail pressure (MPa)	40, 130	Controlled fuel temperature : 30±1℃
Injection duration (μs)	200, 500, 900, 1400	
Driving current (A)	3, 4, 5, 6, 7	Only piezo-injector
Driving voltage (V)	120	Only piezo-injector

4. Results and Discussions

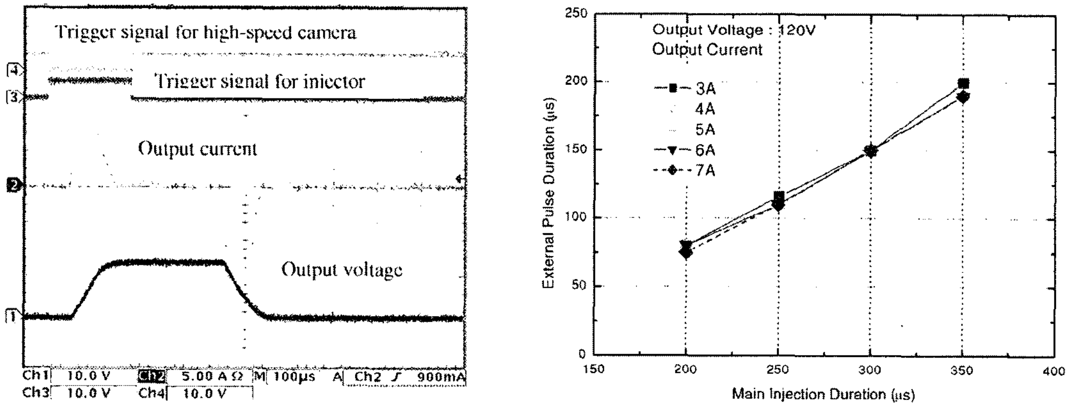
4.1 Piezo-electric characteristics of a piezo-driven injector

In order to examine the operation and capability of a piezo-driven injector, we firstly examined the piezo-electric characteristics of a piezo-driven injector.

Fig. 6 shows the driving characteristics in a piezo-driven injector according to output currents and voltages. Fig. 6(a) shows the output current and voltage wave, which is measured in output current of 7A and voltage of 120V (10 times on the graph), of the prototype piezo-driven injector. The delay time in a piezo-injector's controller to generate the output signal for driving the a piezo-driven injector is constant value of about 50 μs regardless of output current and voltage. And Fig. 6(b) shows the effect of main injection duration according to the different external input pulse duration in a piezo-injector's controller, which is measured in output voltage of 120V. The main injection duration is proportional to external input pulse duration, even if there are a few difference in the case of the output current of 3A. We found that the main injection duration can be closely adjusted by changing the external input pulse duration, which can be a mapping parameter in ECU (engine control unit) of the real vehicle. The more details about this main injection duration described in Fig. 6(c) and (d). Fig. 6(c) shows the effect of the output current on the hold time in the main injection duration. We found that the higher the output current in a piezo-injector's controller, the longer the hold time is. The charging time of a piezo-electric crystal decreases fastly into the steady state of needle with increase of output current and decrease of induced voltage as shown in Fig. 6(d). From this result, we know a piezo-driven injector can provide high flexibility in shaping the injection rate by the optimized control of the output pulse current and voltage. As already mentioned, this study was carried out to assess the effect of spray characteristics through this above results.

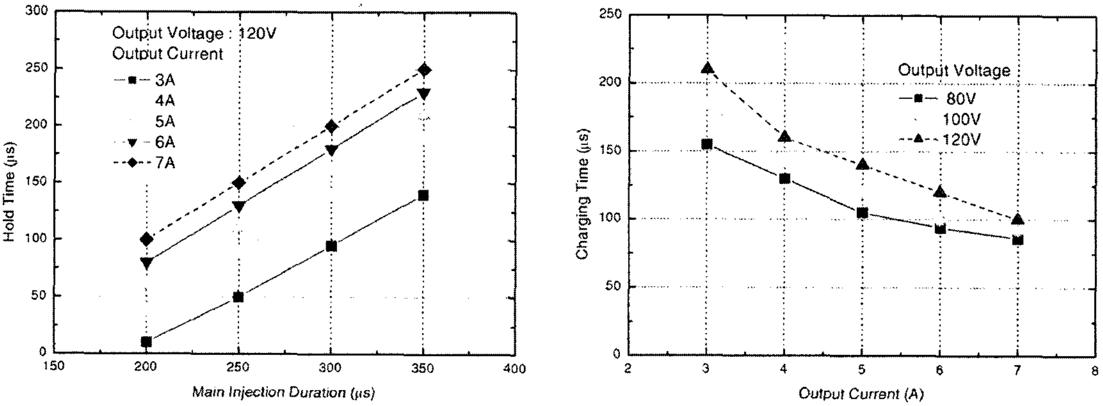
4.2 Needle's behavior characteristics

The needle's behavior of two injectors were indirectly measured by using the accelerometer, that was mounted on the injector's outside body. Fig. 7(a) and (b) show the signal frequency measured to represent the behavior of needle driven



(a) Output current and voltage wave

(b) Effects of the external pulse duration

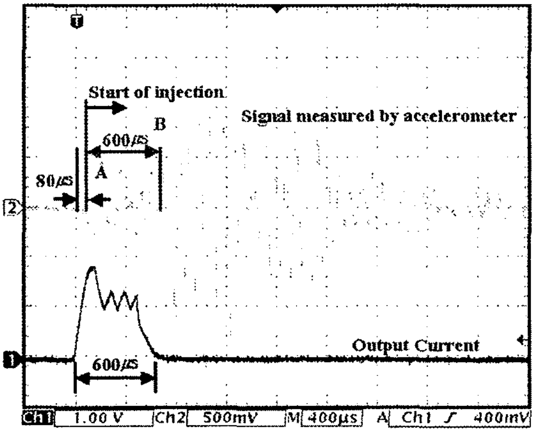


(c) Variation of hold time

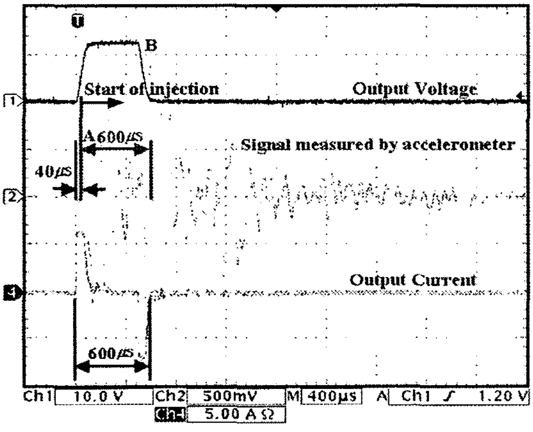
(d) Variation of charging time

Fig. 6 Driving characteristics of piezo-driven injector with the output current of 7A and the output voltage of 120V in a prototype piezo-driven injector and the solenoid-driven injector under the injection pressure of 130 MPa, respectively. The outside shape of two injectors to install the accelerometer differ due to the different inner structure for a needle's driving, even if both injectors have the same nozzle. The relative magnitude's differences of the signal measured by the accelerometer for both injectors were appeared but not regarded as a considerable factor in this study.

As can be seen in Fig. 7, we found the measured vibration signal is in good agreement with the output current and voltage wave in a prototype piezo-driven injector. The amplitude of the peak signal with left indicator (A) on the graph, which can be considered as the highest needle position, is lower compared to that of the other peak signal with right indicator (B), which can be considered as the closed needle position. This is reason that impact force generated between the needle and the nozzle when the needle had been shifted inside the sac region from full lift position to closed position is stronger due to the inertial force of fuel flow under high fuel pressure. From this graph, we can be predicted that a prototype piezo-driven injector have a faster response on the needle valve than the solenoid-driven injector. Namely, the time consumpted in order to reach upto the highest position from closed state for the needle of the prototype piezo-driven injector can be reduced approximately 50% more on basis of SOI (start of injection) than the solenoid-driven injector if this prototype piezo-driven injector have a piezo stack with larger current capacity than 7A.



(a) Solenoid-driven injector



(b) Piezo-driven injector

Fig. 7 Opening and closed timing of needle in two injectors for qualitative analysis

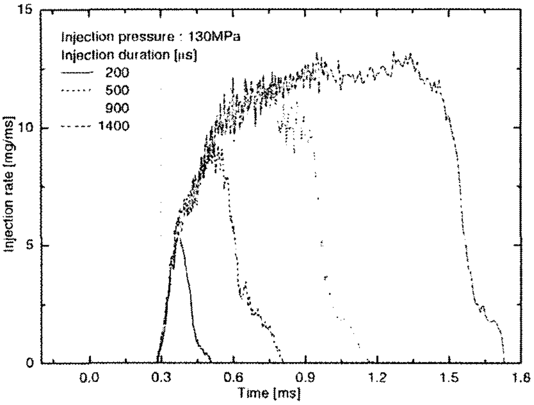
4.3 Fuel injection rate characteristics

In order to compare the injection rate characteristics on two injectors, the pressure value measured in injection rate experiments used then the injection rate was determined by Eq. (2) as follows.

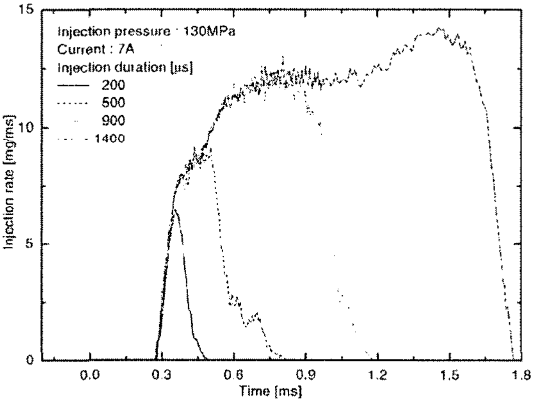
$$dq/dt = A/(a\rho)P \tag{2}$$

where the acoustic impedance, $(a\rho)$, is 0.12 kgfs/cm^3 in case of the diesel fuel. A and P are the cross-sectional area and pressure in tube respectively.

Fig. 8 shows the effects of injection duration on injection rate for two different injectors. As the injection duration increases, the difference of injection rate between two injectors increases. The location of the maximum injection rate that corresponds to the full needle lift of two injectors make a clear difference in the long injection duration, but it similar relatively in the short injection duration. On the whole, in case of the piezo-driven injector, the injection rate is higher than the solenoid-driven injector. Fig. 9 shows the comparison of injection rate between the solenoid-driven injector and the piezo-driven injector with two different currents at injection pressure of 130 MPa and injection duration of 500 μs. In the case of the piezo-driven injector, the injection rate increases rapidly at the initial stage of injection and then decreases fastly along the elapsed time when the injection process is closed, which is steeper than that of the solenoid-driven injector. Also this steep injection rate gradient of the piezo-driven injector vary with the induced currents. It seems that the discrepancy in the injection rate gradient is occurred by the characteristics of different injector's needle response to high pressure injection as already experimentally verified in Fig. 7. From this result, we found the piezo-driven injector can provide a high flexibility in shaping the injection rate by the optimized control of the output pulse current and a relatively fast response on the needle behavior, which is favorable for the spray and combustion enhancement.



(a) Solenoid-driven injector



(b) Piezo-driven injector

Fig. 8 Injection rate profiles of two injectors

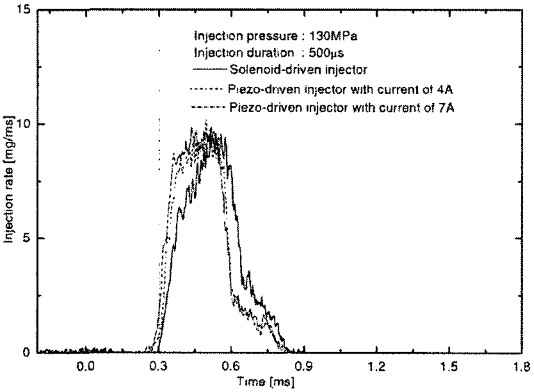


Fig. 9 Comparison of injection rate between solenoid-driven injector and piezo-driven injector with two different currents

4.4 Macroscopic spray characteristics

Fig. 10 shows the effect of ambient pressure on spray cone angle and spray tip penetration with the variation of time after start of injection for piezo-driven injector with the induced (output) current of 7A and injection pressure of 40 MPa. The current of 7A at output voltage of 120V in a piezo-driven injector correspond to fast response condition on injector's needle with a short delay time for an actuation and charging time of 100 μs. In order to measure the spray cone angle in this study, the edge of diesel spray was defined as a line of 80% transmittance of back-light in the raw spray images (Chang and Farrell, 1997).

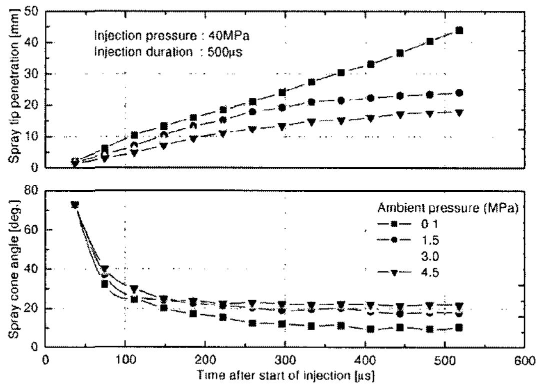


Fig. 10 Effect of ambient pressure on spray cone angle and spray tip penetration

An increase in ambient pressure results in an increase of spray cone angle from the initial stage of spray. In the case of spary tip penetration, the entire spray tip penetration increases linearly with time including at the last stage of injection. Injection pressure is one of the important factors in common-rail fuel injection system. The effect of injection pressure on spray cone angle and spray tip penetration for piezo-driven injector with the induced current of 7A and ambient pressure of 3 MPa is shown in Fig. 11. As shown in this figure, it is founded that the piezo-driven injector have the capability to control with stable injection according to injection pressure. The injection pressure of 40 MPa correspond to that of idle condition in diesel engine. Fig. 12 shows the effect of induced current on spray cone angle and spray tip penetration at injection pressure of 130 MPa and ambient pressure of 3 MPa for piezo-driven injector. The marks indicated in Fig. 12 denotes a 10% range on the current of 4A basis.

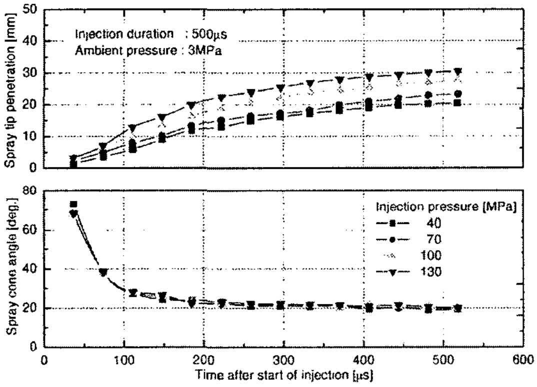


Fig. 11 Effect of injection pressure on spray cone angle and spray tip penetration

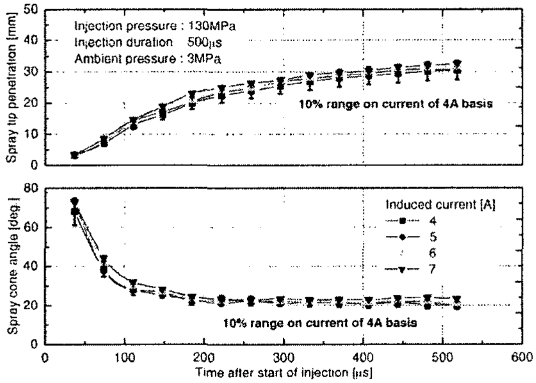


Fig. 12 Effect of induced current on spray cone angle and spray tip penetration

It is shown that the spray tip penetration becomes larger with increasing an induced current to piezo stack in piezo-driven injector. In the case of current of 7A, the spray tip penetration in an intial stage of spray under 200 μs increase more than a 10% range on the current of 4A basis.

A higher induced current causes a more wide spray cone angle in 10% range on the current of 4A basis. From the results of the effect of induced current, it is confirmed that a faster spray development can be adjusted by changing the induced current, which enables control of the injection rate shape.

Although there are reports of injection rate shape control based on the solenoid control technology (Erlach et al., 1995; Coldren and Moncelle, 1997), there are almost no detail reports based on piezo-driven control. Fig. 13 represents the comparison of spray cone angle and spray tip penetration between solenoid-driven injector and piezo-driven injector with different induced current at injection pressure of 130 MPa, ambient pressure of 3 MPa and injection duration of 500 μs. There is an obvious difference in spray characteristics with time after start of injection. The solenoid-driven injector produces a

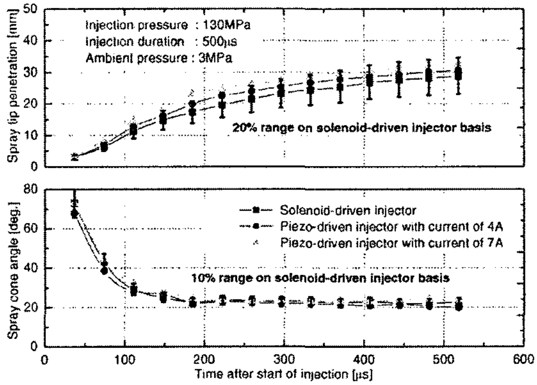
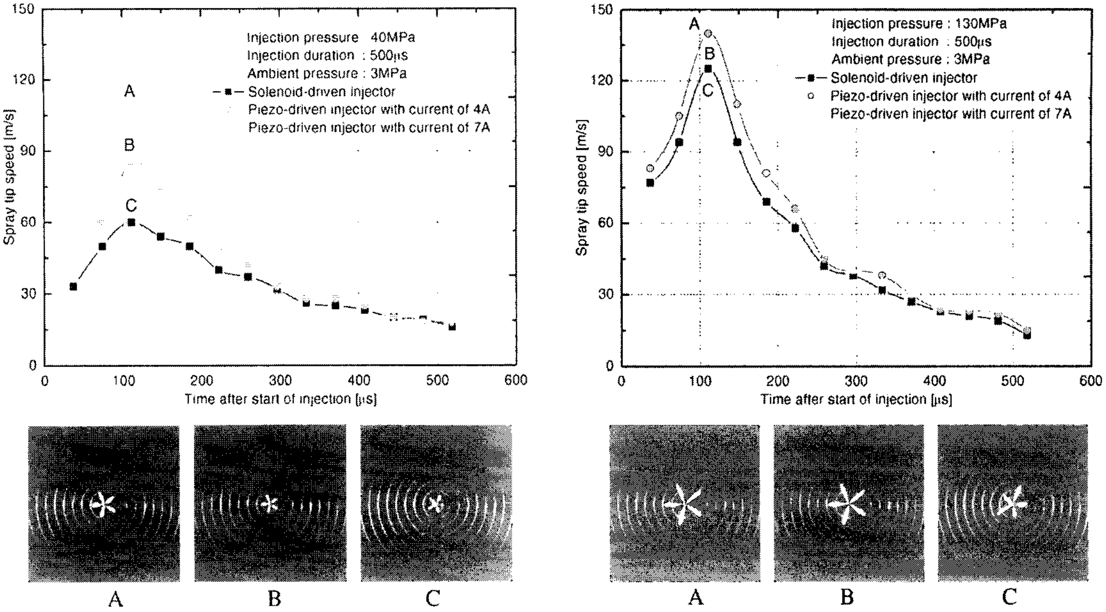


Fig. 13 Comparison between solenoid-driven injector and piezo-driven injector with different currents at injection pressure of 130 MPa and an ambient pressure of 3 MPa



(a) Injection pressure : 40 MPa (b) Injection pressure : 130 MPa

Fig. 14 Comparison of spray tip speed distributions for two injectors at ambient pressure of 3 MPa

relatively lower spray tip penetration and somewhat wide spray cone angle than the piezo-driven injector. In the case of piezo-driven injector with current of 7A, the spray tip penetration in an intial stage of spray under 200 μs increase more than a 20% range on the solenoid-driven injector basis. As mentioned above in two other experiments, this is due to the higher injection flow rate by a fast needle response.

Fig. 14 shows the spray tip speed distributions with the overall shape of spray images between solenoid-driven injector and piezo-driven injector. Spray tip speed increases rapidly with increase of injection pressure. It is found that the piezo-driven injector produces a relatively faster injection velocity due to higher fuel momentum than solenoid-driven injector. This difference of spray tip speed in the low injection pressure is larger than the high injection pressure.

In order to investigate an initial response of the piezo-driven injector (Kohketsu et al., 2000), the comparison of mean spray tip penetration and slope of injection rate during 0.1ms after start of injection at injection duration of 500 μs is shown in Fig. 15. As a result, the mean spray tip penetration and slope of injection rate for 0.1ms interval in piezo-driven injector increased by 28% and 41% than the solenoid-driven injector at in-

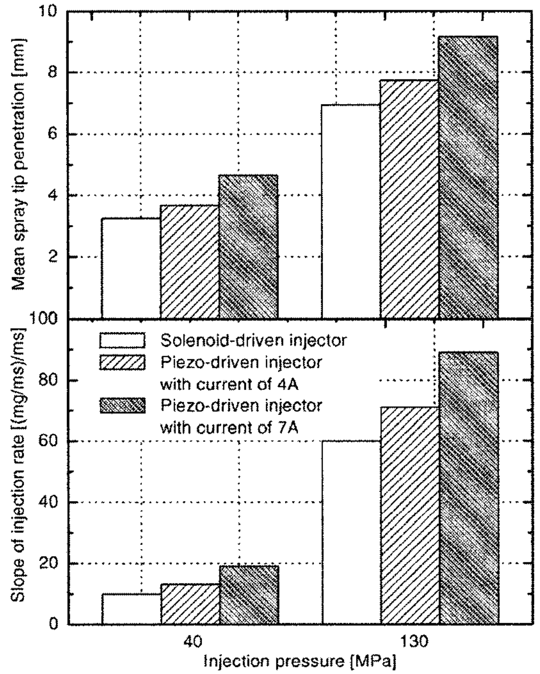


Fig. 15 Comparison of slope of injection rate and mean spray tip penetration for two injectors at ambient pressure of 3 MPa

jection pressure of 130 MPa, respectively. It turned out that it was possible to control the injection rate slope in piezo-driven injector. Therefore, this flexibility of piezo-driven injector made it possible to select the optimum injection rate slope in advance, depending on engine operating characteristics.

5. Conclusions

This paper introduced the piezo-driven injector for new control capability of the high pressure injector's needle in common-rail fuel injection system. And the prototype injector system was designed and fabricated. The several experimental analysis was conducted and compared to clarify the spray characteristics between the piezo-driven injector and solenoid-driven injector, both equipped with the same injection nozzle configuration. The back diffusion light illumination method, with optical system for high speed temporal photography, was applied for the analysis of the spatial variation of the high pressure spray. The main results drawn from this study are summarized as follows :

(1) The charging time in piezo-driven injector depend on the given output current regardless of injection duration. This charging time decreases fast into the steady state of needle with increase of output current. From this result, a higher output current is more desirable for the piezo-driven injector to maintain the higher injection rate.

(2) The piezo-driven injector has short injection delay and a faster spray development and produces higher injection velocity than solenoid-driven injector. It also has a better spray tip penetration due to higher fuel momentum.

(3) The spray characteristics is sensitive to induced current force in piezo-driven injector. A faster spray development by altering the injection rate shape can be adjusted in piezo-driven injector according to induced current. This confirmed the fact that the piezo-driven injector is a high degree of flexibility in injection rate shape control.

(4) Finally, we expect that by the application of a piezo-driven injector, its advantages of a faster fuel intake with stronger spray structures toward the combustion chamber can be a basis for better air-fuel mixing rate.

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