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A STATISTICAL ANALYSIS OF A FUEL INJECTION RATE WAVEFORM BY THE BOSCH METHOD ACCORDING TO A PIEZOELECTRIC INJECTOR DRIVING PATTERN

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ABSTRACT

To drive a diesel piezo injector, the charge and discharge of the current supplied to the piezo stack in the injector are controlled as a pair. The charge and discharge currents expand and contract the piezo stack, respectively. The expansion of the piezo stack causes an increase in the hydraulic pressure that presses the top of the injector needle, which results in the fuel injection. In contrast, the contraction of the piezo stack stops the fuel injection. The charge and discharge currents are controlled by a peak and hold method. The hold current is controlled by PWM (pulse width modulation) control of the driving power supplied to the injector. The duty ratios of the PWM signal used for the hold current control are 10%, 30%, and 100%. The injector driving voltage was 140V. A variety of charge and discharge current waveforms were generated by combining the duty ratio control of the PWM waveform with the driving power source. To measure the time-resolved injected mass under various current waveform conditions, the Bosch method was used in this study. An uncertainty analysis was performed on the Bosch injection rate waveform when it was measured 40 times for each fuel injection condition.

Keywords: piezo injector, fuel injection rate, Bosch method, charge and discharge current, pulse width modulation.

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INTRODUCTION

Despite the excellent fuel efficiency of diesel engines, the hazardous exhaust gas problem remains to be solved [1-4]. Particularly, PM2.5 (particulate matter 2.5 microns in diameter) particles have recently been found to be composed of the direct emission gas of diesel engines with a secondary product of NOx [5]. A key part of the diesel engine's performance is the fuel injection system. Before the introduction of the common rail fuel injection system, which is electronically controlled, a mechanical fuel injection system was used. The mechanical fuel injection system drives the fuel pump with the engine shaft to pressurize the fuel. Given that the fuel injection pressure in the mechanical pump varies during the fuel injection process, the spray characteristic is not uniform during the fuel injection, and it is difficult to control the fuel injectionquantity and timing precisely [6, 7]. To solve the problems of noise, vibration, and the harmful emissions of diesel engines which use a mechanical pump, an electronically controlled common rail system was introduced [8].

The factors that have the greatest influence on diesel engine performance are the fuel injection pressure and the fuel injection timing. It is well known that diesel engines perform well when the fuel injection pressure is high and there are no restrictions on the fuel injection timing. The higher the fuel injection pressure is, the finer the atomization of the spray becomes. Fine atomization improves the air-fuel mix. The fuel injection timing to achieve the optimum engine performance differs depending on the engine operating conditions (e.g., the engine load, and engine speed). Therefore, the fuel injection system should have no restrictions on the fuel injection timing control. The differences between a mechanical fuel injection system and a common rail system are the magnitude of the fuel injection pressure and the injection timing control method used.

A mechanical injection pump controls the start and end of the fuel injection according to the magnitude of the fuel supply pipe pressure, as fed by a plunger. The state of the spray is not uniform because the pressure of the fuel line changes during the fuel injection period. In addition, when the injection pressure is not high enough, atomization of the spray is not sufficient. The injection timing of the mechanical fuel injection pump is controlled by a spring mass system called a timer, and the injection timing can be controlled in a straight line shape with a constant gradient by the engine speed. On the other hand, the common rail system maintains a constant injection pressure (rail pressure) during the fuel injection period, which can be as high as 2000 bar. This is five times the average injection pressure of the mechanical fuel injection system. There is no restriction on the fuel injection timing when using a common rail system. These advances have greatly improved diesel engine performance capabilities [9].

The electronically controlled injectors used in common rail systems include the solenoid type and the piezo type. Solenoid-type common rail injectors are reliable and cost-effective. The solenoid-type injector has an advantage in that it can be fabricated in a more compact form than the piezo type. On the other hand, piezo injectors offer lower power consumption, and a faster fuel injection response [10] (100 to 150 μs) than the solenoid type, and the flexibility of multiple injections is excellent. Although solenoid-type injectors are now most commonly applied to diesel engines, piezo-type injectors are still attracting attention [9, 11].

The solenoid-type injector has a built-in solenoid that controls the opening and closing of the high-pressure hydraulic passage in the injector. The start and stop processes of the fuel injection are achieved by controlling the current supplied to the injector solenoid. The current waveform supplied to the solenoid-type injector is the peak and hold type [12]. On the other hand, the piezo-type injector incorporates a piezo stack as a means of opening and closing a high-pressure hydraulic passage in the injector. Fuel injection by a piezo injector is accomplished by charging the current to the piezo stack and then discharging it. That is, when driving voltage is supplied to the injector, the piezo stack expands, the high-pressure hydraulic passage opens, and the fuel flows, and when the electric current charged in the piezo element is discharged, the hydraulic passage is blocked and the fuel injection is then stopped [13, 14]. Thus, the current pattern supplied to the injector has a considerable influence on the fuel injection quantity and timing.

Zhao *et al*. [15] studied the dynamic response characteristics of a solenoid-type injector according to the hold current supplied to the injector using a computer simulation. Andadi *et al.* [16, 17] studied a theoretical model of the effects of the current and temperature on the operation of the solenoid. Zhao *et al.* [18] studied the relationship between the injector driving voltage and the solenoid opening response time and solenoid power loss. Lee and Lee [19] statistically studied the effects of the injector driving current pattern on the fuel injection rate waveform of a solenoid injector.

There are two methods of fuel injection control of a piezo injector: the direct method and the indirect method [20]. The first generation of piezo injectors uses an indirect servo-hydraulic actuation mechanism, and the second generation of piezo injectors uses a direct method in which the piezo stack actuator directly controls the needle movement. Plamondon and Seers [21] developed a dynamic multiple-injection model of a first-generation piezo injector. Payri *et al*. [22] and Marcian *et al.* [23] studied the fuel injection rate characteristics according to partial needle lift changes by controlling the charge amount using a direct control piezo injector.

Meanwhile, there have been too few studies of the injector fuel injection characteristics and the fuel injection rate waveform according to the charge and discharge current patterns in piezo injectors. In this study, the fuel injection rate waveform was repeatedly measured by the Bosch method [24] when various charge and discharge currents were supplied to a first-generation piezo injector. In addition, an uncertainty analysis of the measured injection rate waveforms at opening, stationary, and closing time intervals was performed.

EXPERIMENTAL PART

Figure-1 shows the internal structure of the piezo injector. The piezo injector consists of a piezo element stack, a connecting plunger, a valve plunger spring, a switching valve, a valve control chamber, and a nozzle needle. The fuel line machined inside the injector consists of a high-pressure fuel line from the common rail and a low-pressure fuel return line that collects the leaking fuel from the moving parts of the injector. The hydraulic pressure in the valve control chamber acting on the top surface of the nozzle needle determines the start and stop processes of the fuel injection. The hydraulic pressure acting on the top surface of the nozzle needle is established by opening and closing the switching valve. The switching valve is opened or closed by the expansion or contraction of the piezo stack. When the piezo stack is expanded by supplying driving current to the injector, the connecting plunger and valve control plunger push the switching valve and the pressure acting on the top surface of the nozzle needle then decreases as the fuel in the valve control chamber flows out. Thus, the fuel is injected due to the lift of the nozzle needle. The fuel injection stops when discharging the charge current in the piezo stack. When the charged current is discharged from the piezo element stack, the piezo element stack returns to its original size, which increases the pressure in the valve control chamber with the lifting of the switching valve. The increase of the pressure in the valve control chamber stops the fuel injection.

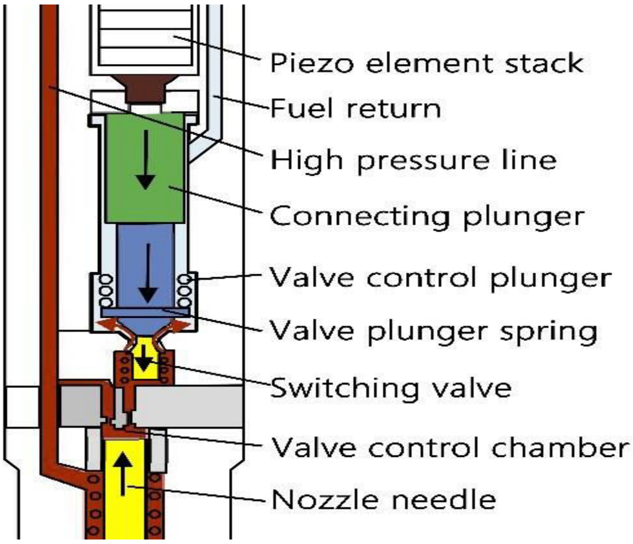

Figure-1. The inner structure of a typical piezo-injector [13].

Figure-2 shows a schematic diagram of a piezo-injector driving circuit. The piezo stack has capacitance characteristics. Charging the current to the piezo stack expands it, and it returns to its original size when the charged current is discharged. Therefore, the piezo-injector driving circuit should be able to charge and discharge the current in the piezo stack. As shown in Figure-2, this process consists of three steps: charge, maintain the charge, and discharge. When charging the piezo stack, MOSFET 1 is turned on and MOSFET 2 is turned off, as shown in Figure-2a. A driving voltage of 140 V is supplied to the injector to expand the piezo stack. In the maintenance step, both MOSFET 1 and MOSFET 2 are turned off. During this period, the driving voltage is

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maintained at 140V, and fuel injection is also maintained. Fuel injection is stopped by discharging the charge current from the piezo stack. When discharging, MOSFET 1 and MOSFET 2 are turned off and on, respectively, as shown in Figure-2c. The control signals inputto the GATE terminals of MOSFET 1 and MOSFET 2 were generated from the CCP1 and CCP2 pins of the Microchip PIC17917 microcontroller. The piezo injector driving voltage, the control signal voltage from the CCP1 and CCP2 pins, and the injector drive current were measured using a four-channel oscilloscope. Research on piezo injectordrivers has been performed by Lee and Lee [13].

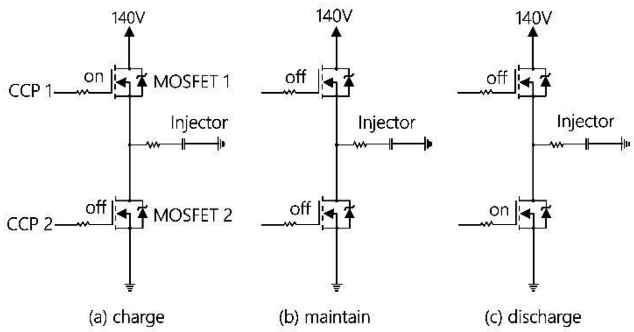

Figure-2. MOSFET1 and MOSFET2 on/off state in the piezo-injector driving circuit according to the (a) charge (b) maintain (c) discharge states [13]

Figure-3 shows the experimental setup used to measure the time-resolved fuel injection rate of the piezo injector. The measurement system consists of a low-pressure fuel pump, a high-pressure fuel pump, a common rail, a piezo injector, a heat exchanger, an oscilloscope, and the BOSCH system [25]. Fuel supply to the high-pressure fuel pump is accomplished by a low-pressure pump in the fuel tank. The high-pressure fuel pump was driven by a 7.5 kW three-phase AC motor. The rotation speed of the AC motor was adjusted using an inverter. The high-temperature return fuel from the common rail and piezo injector raises the fuel tank temperature. Thus, a heat exchanger was used to keep the temperature of the feed fuel constant. A J-type thermocouple was installed in the fuel tank to monitor the temperature of the fuel tank. During the experiment, the fuel temperature in the fuel tank was maintained at a constant 27 ℃ by a flow of cooling water in the heat exchanger. The common rail pressure was set by changing the duty ratio of the power supplied to the rail pressure control valve. The duty ratio control signal is generated from the CCP pin of the microcontroller. The target rail pressure was set by inputting the potentiometer voltage to the microcontroller PIC16F917 analog input pin, which resulted in the setting of the duty ratio of the CCP pin output signal correspondingto the potentiometer voltage.

The Bosch method [25] was used to measure the time-resolved injection rate during the fuel injection. The Bosch method calculates the time-resolved fuel injection rate based on the pressure wave signal caused by injecting the fuel into a brass tube filled with the fuel, which eliminates the influence of reflected waves generated during the fuel injection. The brass tube is sufficiently long so that the influence of the reflected waves can be excluded. The steps of the time-resolved injection rate as a measurement procedure by the Bosch method can be summarized as follows. First, the AC motor rotation speed was set using the inverter. Next, the potentiometer knob was adjusted to set the common rail pressure to the target pressure. After the constant rail pressure is reached, the piezo injector is driven to repeat the fuel injection at a constant interval. At this time, the fuel injection pressure wave signal, injector driving voltage, CCP1 and CCP2 signals, and the injector driving current were recorded using the oscilloscope. The fuel injection was repeated 2000 times and the injected fuel was collected into a mess cylinder. The weight of the collected fuel was measured

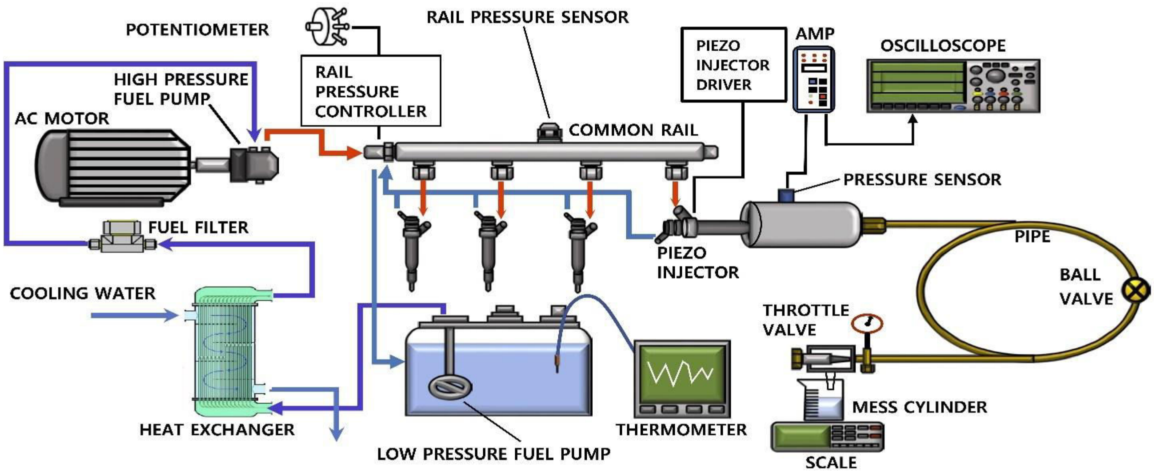

Figure-3. Experimental setup for measuring the fuel injection pressure wave with the BOSCH method.

using a scale, and the injected fuel mass per injection was calculated by dividing the measured weight by the repeated numbers of fuel injections (2000 in this study).

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RESULTS AND DISCUSSIONS

Figures 4-6 show the measurement results of the injector drive voltage, injector driving current, and charge and discharge control signal according to the three control signals. The time intervals of the charge, maintain, and discharge signals are 300μs, 1000μs, 400μs, respectively Here, the time interval of the maintain coincides with the fuel injection period, from the start of the charge control signal to the start of the discharge control signal, which is a total of 1000 μs. The injector driving voltage used in this study is close to 140V, and the maximum driving current

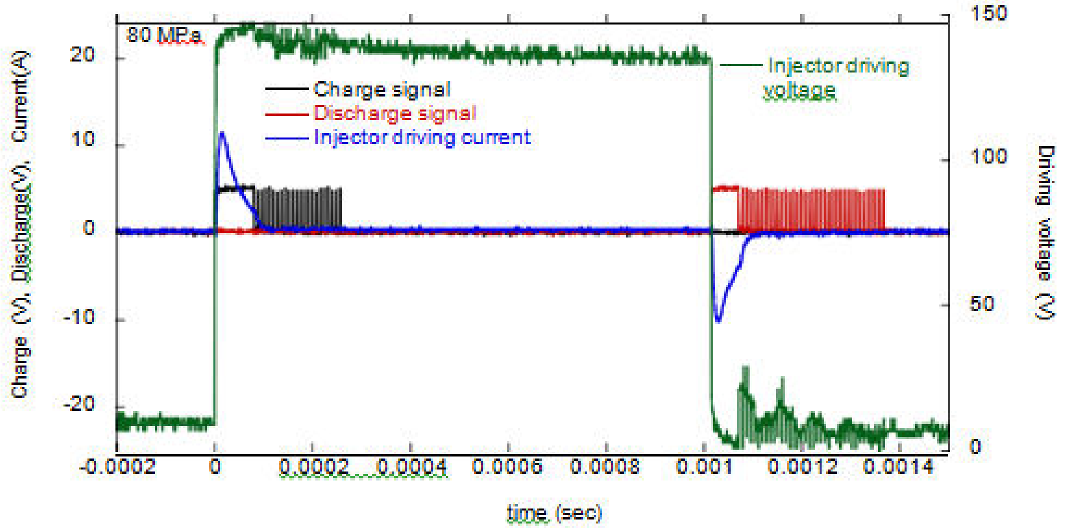

Figure-4. Measurement results of the charge and discharge control signals, injector driving current and injectordriving voltage using a four-channel digital oscilloscope (10% duty ratio in the hold part).

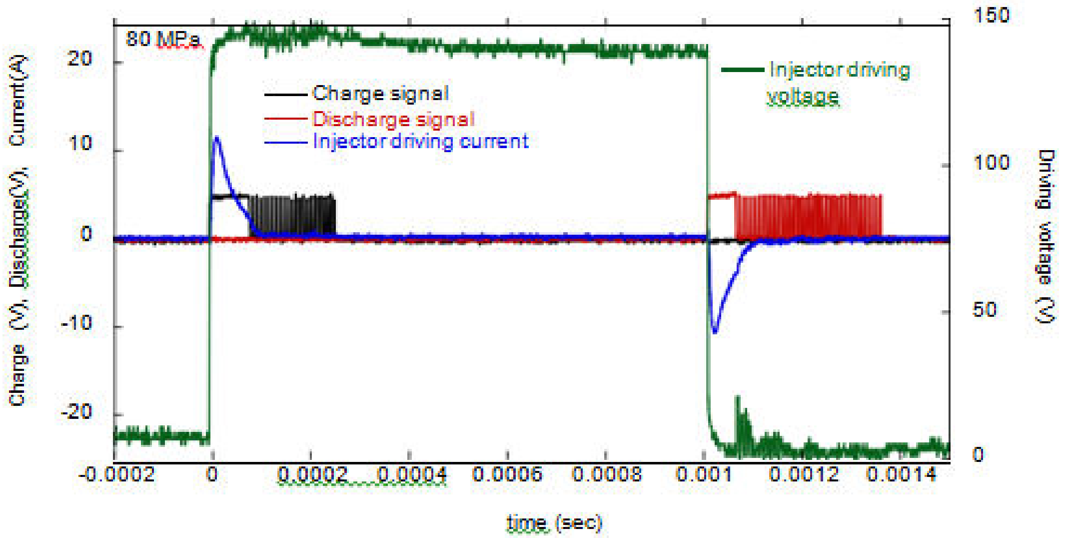

Figure-5. Measurement results of the charge and discharge control signals, injector driving current and injectordriving voltage using a four-channel digital oscilloscope (30 % duty ratio in the hold part).

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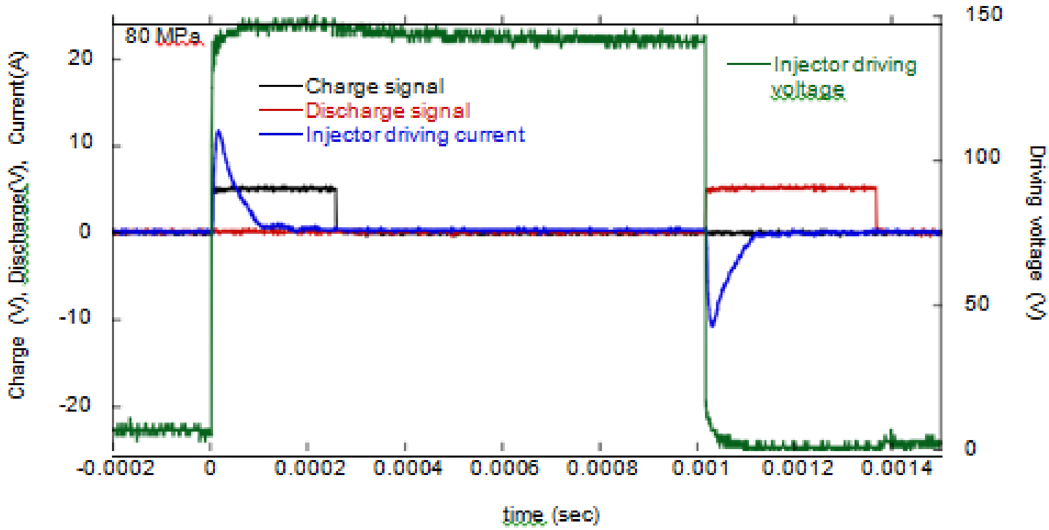

Figure-6. Measurement results of the charge and discharge control signals, injector driving current and injectordriving voltage using a four-channel digital oscilloscope (100% duty ratio in the hold part).

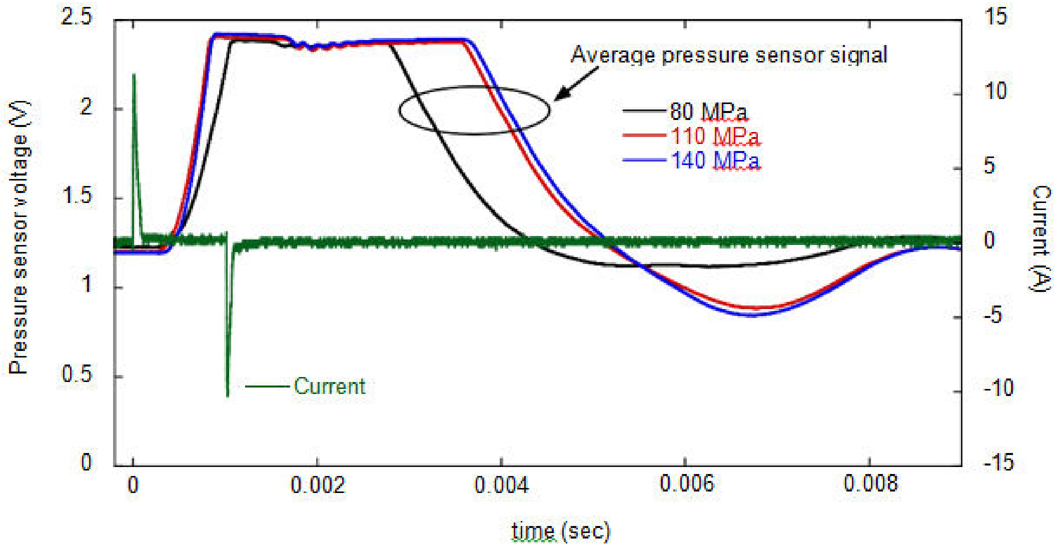

Figure-7. Average pressure sensor signals which measure the pressure wave caused by the fuel injection with the BOSCH method and the injector driving current at rail pressures of 80, 110, and 140 MPa.

Corresponding to the driving voltage is approximately 10A. The voltage of the charge and discharge control signal is about 5V.

The control signals used to drive the piezo injector are the output from the CCP1 and CCP2 pins of a Microchip PIC 16F917 microcontroller. The control signals for the charge and discharge shown in Figures 4-6 are output from the CCP1 and CCP2 pins, respectively. The commonrail pressure is 80 MPa. The charge and discharge control signal is a combination of the PWM waveforms and the duty ratio. There are three types of charge and discharge control signal combinations used in this study. The charge and discharge control signal has what is termed a peak and hold shape. The duty ratio of the peak part signal is set to 100%, and the duty ratio of the hold part is set to 10% or 30%. The charge and discharge control signal shown in Figure- 4 consists of waveforms with a duty ratio of 100% in the peak part and a duty ratio of 10% in the hold part. The charge and discharge control signal shown in Fig. 5 consists of waveforms with a duty ratio of 100% in the peak part and a duty ratio of 30% in the hold part. The charge and discharge control signal shown in Figure-6 consists of waveforms with a 100% duty ratio in both the peak and holdparts.

Figure-7 shows the average value of the pressure wave signal measured with the Bosch method (PWSBM) when fuel is injected at the three injection pressures of 80, 110, and 140 MPa. The injector driving current is also

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shown in Figure-7. The charge and discharge control signals used in Figure-6 were used here as well. The PWSBM values for each fuel injection pressure were measured repeatedly 40 times for a statistical analysis. The fuel injection period is 1000 μs. The charge and discharge control signals and theinjector driving voltage are identical under all rail pressure conditions. Therefore, the driving current was also the same in all of the repeated experiments. The driving current in Figure-7 rises sharply in unison with the charge control peak signal. The rising timing of the PWSBM signal, which means the start of the fuel injection, is a certain time later than the driving current rising timing. The slope of the rising curve of the PWSBM shows a larger value at 110 and 140 MPa as compared to that at 80 MPa. The slope of the rising PWSBM curve was nearly identical at both 110 MPa and 140 MPa. The larger slope of the PWSBM curve at the higher rail pressure is due to the faster movement of the nozzle needle at higher rail pressures. As the nozzle needle moves faster, the opening speed of the nozzle hole is faster, resulting in a larger slope of the PWSBM during the charge time interval. The slopes of the PWSBM curves in the discharge time interval show similar values in the discharge interval at all common rail pressures. The similar slopes of the PWSBM curves in the discharge time interval are related to the nozzle needle returning process, which stops the fuel injection. The nozzle needle returns due to the spring restoring force and does not depend on the common rail pressure. The PWSBM in the maintaining time interval shows a nearly identical value.

Figures 8-10 shows the PWSBM deviation % from the average value at each measurement time step of thePWSBM when driving the piezo injector with the three charge and discharge control signals shown in Figures 4-6. The PWSBM measurements are repeated 40 times in each experimental condition. To process the PWSBM deviation % at each time step statistically, a normal distribution was used as the error distribution function. The PWSBM deviation % was obtained at a 95 % confidence level. In Figure-8, the PWSBM deviation % at the common rail pressure of 80 MPa is nearly 0.2% in the charge and discharge time interval and close to 0% in the maintenance time interval. In the maintenance time interval, the PWSBM deviation % was very low because the nozzle needle was in a fully lifted state and showed a constant fuel injection rate. On the other hand, in the charge and discharge time interval, the PWSBM deviation % shows a larger value of 0.2 % because the nozzle needle lifts vary during the charge and discharge time interval. It can be seen that there is almost no difference in the PWSBM deviation % according to the three charge and discharge control signals shown in Figures 4-6.

Figure-9 shows the PWSBM deviation % at the rail pressure of 110 MPa. In the maintain time interval, the PWSBM deviation % is close to 0, similar to that at the rail pressure of 80 MPa. In charge and discharge time intervals, there is a difference in the PWSBM deviation % accordingto the three charge and discharge control signals shown in Figures 4-6. The PWSBM deviation % in the charge and discharge time interval is in the range of 0.4 ~ 0.8%. The PWSBM deviation % in the charge and discharge time interval showed the smallest value under the P&H DR 30% condition (peak & hold duty ratio = 30%). The PWSBM

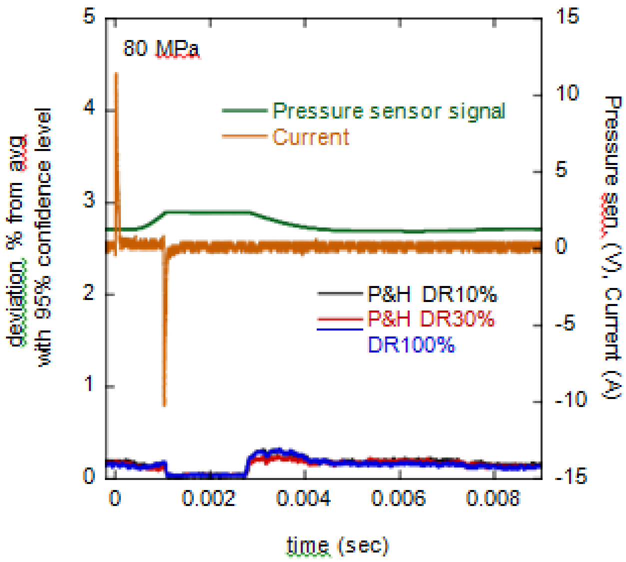

Figure-8. Deviation % from the average of the PWSBM according to the charge and discharge control signals at a rail pressure of 80 MPa.

deviation % increases under the DR 100% condition (peak only) and the P&H DR 10% condition (peak & hold duty ratio = 10%) in order. These results indicate that as the rail pressure increases, the piezo injector PWSBM deviation % increases and is also affected by the charge and discharge control pattern arising from the peak and hold combination. Figure-10 shows the PWSBM deviation % at the rail pressure of 140 MPa. The PWSBM deviation % increased to 2% in the charge and discharge time interval. Moreover, the PWSBM deviation % according to the three charge and discharge control signals shown in Figures 4-6 shows results similar to those at the rail pressure of 110 MPa. In addition, the fuel injection failed under the charge and discharge P&H DR 10% control condition. These results indicate that as the rail pressure increases, the injector drive current must be increased further to inject fuel stably.

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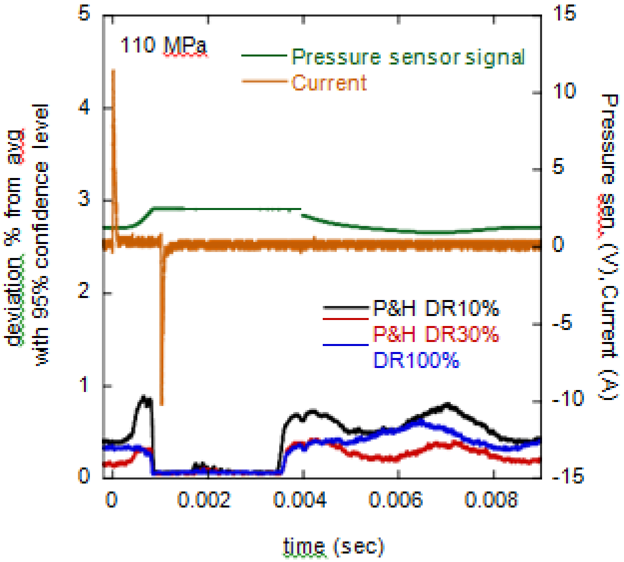

Figure-9. Deviation % from the average of the PWSBM according to the charge and discharge control signals at a rail pressure of 110 MPa.

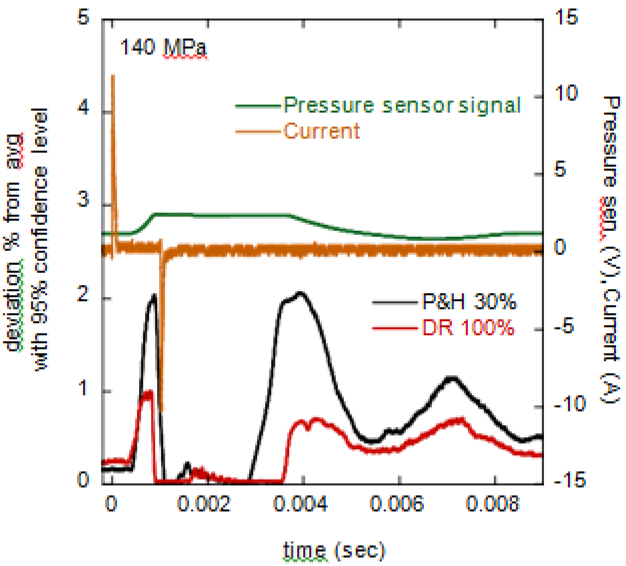

Figure-10. Deviation % from the average of the PWSBM according to the charge and discharge control signals at a rail pressure of 140 MPa.

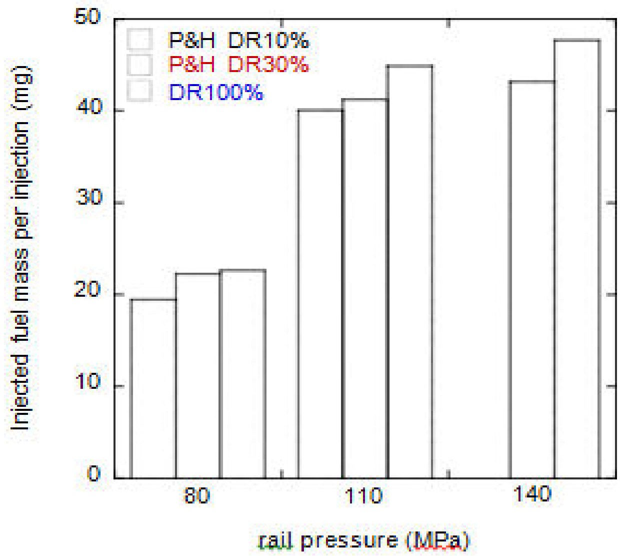

Figure-11. Injected fuel mass per injection according to various fuel injection conditions

Figure-11 shows the injected fuel mass per injection according to the common rail pressure under which the three charge and discharge control signals shown in Figures 4-6 are used in the experiment. Under each experimental condition, the injection of fuel was repeated 2000 times and the injected fuel was collected in a mess cylinder. The collected fuel mass was measured using a scale. The injected fuel mass per injection in Figure-11 was calculated by averaging the measured mass outcomes. It can be seen that the injected fuel mass per injection for a common rail pressure depends on the piezo injector driving condition. The injected fuel mass per injection at all of the common rail pressures tested here is largest with the charge and discharge control signal of DR 100 %, followed by P&H DR30% and finally P&H DR10%. Additionally, Figure-11 shows that an increase in the common rail pressure requires a higher injector driving current and the charge and discharge control signal of DR 100 %, as shown in Figure-6.

CONCLUSIONS

When driving a piezo injector, whether the fuel is injected or not depends on both the charge and discharge control patterns, which consist of the peak and hold waveform and the rail pressure. Fluctuation of the injected fuel quantity is considerable with a low duty ratio of the hold interval in the peak and hold waveform.

At a common rail pressure of 80 MPa, there was almost no difference in the PWSBM deviation % according to the charge and discharge control signal for a piezo injector. At the rail pressure of 80 MPa, the PWSBM deviation % at the 95% confidence level was 0.2% in the charge and discharge time interval and nearly 0% in the maintenance time interval. On the other hand, when the rail pressure is high (110 MPa, 140 MPa), there is a clear difference in the PWSBM deviation % according to the charge and discharge control signal for the piezo injector.

To inject fuel in a piezo injector stably, an increase in the common rail pressure requires a higher injector driving current, which means that the charge and discharge control signal with a duty ratio of 100 % is preferable.

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