Hydraulic Simulation and Experimental Analysis of Needle Response and Controlled Injection Rate Shape Characteristics in a Piezo-driven Diesel Injector

Jinwook Lee, Kyoungdoug Min
Seoul National University, Republic of Korea

Kernyong Kang
Korea Institute of Machinery and Materials, Republic of Korea

Choongsik Bae
Korea Advanced Institute of Science and Technology, Republic of Korea

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ABSTRACT

The More precise control of the multiple-injection is required in common-rail injection system of direct injection diesel engine to meet the low NOx emission and optimal PM filter system. The main parameter for obtaining the multiple-injections is the mechanism controlling the injector needle energizing and movement. In this study, a piezo-driven diesel injector, as a new method driven by piezoelectric energy, has been applied with a purpose to develop the analysis model of the piezo actuator to predict the dynamics characteristics of the hydraulic component (injector) by using the AMESim code and to evaluate the effect of this control capability on spray formation processes. Aimed at simulating the hydraulic behavior of the piezo-driven injector, the circuit model has been developed and verified by comparison with the experimental results. We found that the input voltage exerted on piezo stack is the dominant factor which affects on the initial needle behavior of piezo-driven injector than the hydraulic force generated by the constant injection pressure. And the piezo-driven injector has more degrees of freedom in controlling the injection rate with the high pressure than a solenoid-driven injector. The piezo-electric characteristics of a piezo-driven diesel injector, which was manufactured as prototype version was experimentally examined to confirm the injection driving principle based on the inverse piezo-electric effect and to ensure the operating performance of a prototype piezo-driven injector. The injection duration is proportional to the external input pulse duration for driving the piezo-driven injector. The higher the output current (voltage) applied to piezo-driven injector's controller, the longer the hold time on the injection duration is. The charging time decreases rapidly as the output current increase. And the needle’s response of a piezo-driven injector by using an accelerometer has been investigated together with the evaluation of the injection rate employing Bosch’s method. Results were compared between a conventional solenoid-driven injector and the piezo-driven injector, both equipped with the same micro-sac multi-hole injection nozzle. The experimental results show that the piezo-driven injector has a higher injection flow rate by a fast needle response time and it is possible to control the injection rate slope by altering the induced current. Also these experimental results showed favorable agreement with the predicted simulation results by AMESim environment.

INTRODUCTION

The electro-hydraulic injector for the common-rail injection system must be designed to meet the precise high fuel delivery control capability [1, 2]. In the electrohydraulic 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 injector system requires the permanent current during activation of the solenoid control valve. Moreover, this system has a slow needle response, which is generated by the solenoid control valve, due to the exponential increase of current charged in solenoid coil. Because this injector system requires the permanent current during activation of the solenoid control valve. Moreover, this system has 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 current. Also it has to be separated recharge phase over injector or coil. To overcome those disadvantages, piezo-driven injectors have been also introduced for controlling the needle movement. Although there are some investigated research results [3, 4, 5, 6], 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 injector’s driver, and test conditions are hard to obtain. In this study, we considered the piezo-actuator as a prime mover in fuel injector and analyzed the dynamic characteristics of the hydraulic piezo-driven injector by using the AMESim simulation code. Eventually we investigated the effects of this piezo-driven injector’s control capability on the injection rate and high speed spray formation.

PIEZO DRIVEN MECHANISM IN FUEL 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 Figure 1(a) with internal structure layout of this injector [7]. 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 Figure 1(b). The configuration of driving part of piezo-driven injector 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. A prototype piezo-driven injector was used to investigate the piezoelectric characteristics and the macroscopic spray characteristics between the conventional solenoid-driven injector and piezo-driven injector. The actuation mechanism of this piezo-driven injector is based on the inverse piezoelectric effect with the electric charge and discharging control concept. Figure 2 shows the schematically the driving principle for mechanical force output in a piezo-driven injector. The highly precise piezo actuator is controlled by charge-discharge of output pulse current. The controller of a piezo-driven injector is triggered by the square wave TTL signal. When a voltage is applied to a piezoelectric stack, its dimension will be changed. In case of the unloaded single-layer piezo actuator, the displacement of a piezo stack can be calculated by the following Equation (1).

\[
\Delta L = S \cdot L_0 \approx \pm E \cdot d_{ij} \cdot L_0 \quad (1)
\]

Where, \(\Delta L\) : displacement of a piezo stack  
\(S\) : strain  
\(L_0\) : piezo ceramic length  
\(E\) : electrical strength  
\(d_{ij}\) : piezoelectric coefficient

The piezo stack is assembled with thin, laminar wafers of electroactive ceramic materials electrically connected in parallel. So the displacement of a piezo actuator which behaves as a capacitor in this study, is proportional to electric charge.

![Figure 1](image_url)

(a) Internal structure  
(b) Control chamber inside injector’s body

**Figure 1** Layout of internal structure and control chamber of a prototype piezo-driven injector used

![Figure 2](image_url)

(a) Theory of the inverse piezoelectric effect  
(b) Driving output current and voltage wave

**Figure 2** Operating principle of piezo-driven injector
HYDRAULIC MODELING AND SIMULATION

In this section, a piezo-driven injector has been applied with a purpose to develop the analysis model of the piezo actuator to predict the dynamic characteristics [8, 9] of the hydraulic component by using AMESim code and to evaluate the effect of needle movement on the injection characteristics. The details of the hydraulic behavior have been investigated using a developed actuation model for piezo-driven injector and compared the driving model for the solenoid-driven injector.

HYDRAULIC MODELING

The conventional common rail fuel injection equipment of Diesel engine together with its control system has been modeled by means of AMESim environment as a unified approach to mechatronic modeling. In order to take into account the hydraulic characteristics of a piezo-actuator within the piezo-driven injector, we developed the related analytic model for a piezo-actuator and verified with comparison of the experimental results. And the analysis of dynamic behavior in piezo electro-hydraulic injector was performed in this study. The detailed model simulating the piezo actuation mechanism of the piezo-driven injector is shown in Figure 3 and compared the model corresponding to a standard solenoid coil in solenoid-driven injector. It is numerical code in which each physical component is represented by an appropriate icon and is associated to one or more lumped parameter models.

The suction force and first order time lag for the driving force was endowed in a solenoid-driven injector. Meanwhile, the inverse piezo-electric effect was considered in a piezo-driven injector. By using this analytic model, the piezo-electronically controlled injector modeling was realized to solve the dynamic characteristics of a complex hydraulic circuit, as shown in Figure 4. A simplification of the complete scheme has been obtained by using the mathematical component that allows to collect more sub-models into a single one. Such a component is composed of basic (spring, inertia and ball poppet with conical seat, mass with friction and ideal end stop, linear hydraulic pressure source, flapper nozzle valve, leakage and viscous friction, hydraulic flow rate sensor) and self-developed elements (driving part i.e. solenoid and piezo stack, as shown in Figure 3).

**Figure 3** Scheme of analytic models corresponding to driving mechanical force between solenoid and piezo injector

![Diagram of analytic models](image)

**Figure 4** Scheme of equivalent hydraulic circuit to investigate the high pressure injector behavior

![Diagram of hydraulic circuit](image)
HYDRAULIC SIMULATION

In order to investigate the behavior of the piezo stack only used in piezo-driven injector and the inverse piezoelectric effect for producing the mechanical force output, the driving circuit model was verified by comparison with the experimental results before the hydraulic simulation. Because the 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. The simulations have been performed by considering the one injection of 1ms and by imposing the different common rail pressure of 100Mpa, 150Mpa and 200Mpa between the solenoid and piezo-driven injector.

**Table 1 Specifications of the piezo stack used**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack size</td>
<td>mm</td>
<td>7×7−32.7</td>
</tr>
<tr>
<td>Capacitance</td>
<td>μF</td>
<td>4.1</td>
</tr>
<tr>
<td>Driving current</td>
<td>A</td>
<td>7</td>
</tr>
<tr>
<td>Driving voltage</td>
<td>V</td>
<td>120</td>
</tr>
<tr>
<td>Pre-load</td>
<td>N</td>
<td>1,000</td>
</tr>
</tbody>
</table>

EXPERIMENTAL SET-UP

FUEL INJECTION RATE

The injection rate characteristics [10, 11] 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. In this study, the injection rate measuring instrument based on the Bosch’s operating principle was used to measure the transient fuel flow rate between solenoid and piezo-driven injector. Figure 5 shows the layout of the experimental set-up. A measuring tube with an inner diameter of 4.57mm and a length of 10,850mm was fabricated in the form of coil type with diameter of 250mm. The piezo-electric type pressure sensor was installed at the middle of the injector adaptor. A cylindrical accumulator with a volume of 700cc 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 3MPa. The back pressure within the accumulator was measured by Bourdon tube pressure gauge.

INJECTOR NEEDLE MOVEMENT

In this study, as shown in Figure 6, we considered the two experimental apparatus for the prediction and comparison of needle response time between solenoid and piezo-driven injector. Firstly, in order to measure the longitudinal vibration frequency of the same direction as the needle shift, the accelerometer, which is mounted on the flat area in the two injector’s outside body with the same nozzle configuration, was applied. Secondly the pressure sensor was located on the 2mm position from one injection nozzle hole to measure the time difference of spray detection after the start of input current. These are a very useful approach method to the estimation of the needle’s behavior indirectly, which is moved by the electric output force, in the solenoid and piezo-driven injector. Because the direct measurement of needle’s movement without the any modification work inside injector is very difficult.

**Figure 5 Schematic diagram of the experimental arrangement for measuring the fuel injection rate**

(a) Accelerometer (b) Pressure sensor

**Figure 6 Photograph of the two experimental apparatus to investigate the injector needle response between solenoid and piezo-driven injector with the same micro-sac 5-hole injection nozzle**
A schematic diagram of experimental apparatus used in this study to measure and observe the spray behavior \cite{12, 13, 14} generated by two injectors with different needle-driving method was shown in Figure 7. It consists of a constant volume chamber, common-rail fuel injection system, control unit, fuel pump driven by DC motor, pressure regulator and high speed framing camera system. As shown in Table 2, a high pressure injector that has 5 holes with nozzle hole diameter of 0.168mm 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 3.7kW. 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 to investigate the effects of ambient pressure on the spray shapes and the structures of non-evaporating unconfined intermittent spray. In the visualization setup, the spray shapes were photographed by a high speed camera system 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 2kW with the air cooling system, which was triggered by a TTL signal. The injection duration and injection timing was 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 the common-rail injection controller respectively.

### RESULTS AND DISCUSSION

#### HYDRAULIC CHARACTERISTICS

The fuel properties have been set according to ISO 4113. All the simulations have been performed assuming a constant pressure source connected to the supply line of the electronically controlled injector and an atmospheric pressure as regards the delivery pressure level. In this study, the analytic model for a piezo actuator, including the linear signal force and piezo stack, was developed and verified with experimental result. Also the behavior of all hydraulic volumes has been simulated between solenoid and piezo-driven injector. Figure 8 shows the inverse piezoelectric effect of piezo stack obtained by hydraulic simulation. As can be seen, the piezo stack has a linear behavior and this show the close agreement between the predictions and experimental values. In addition, we found that the input voltage applied on the piezo stack is the dominant factor which affects on the initial needle movement. Also the thickness of ceramic layer must be determined by this input voltage, as shown in Figure 9. This trend is strictly connected with dynamic of opening and closing of both the ball poppet valve and the nozzle flapper in Figure 4.

#### NEEDLE RESPONSE 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 Equation (2) as follows.

$$\frac{dq}{dt} = A / (a \phi) \cdot P$$

(2)

where, the acoustic impedance, \((a \phi)\), is 0.12kgs/cm\(^2\) in case of the diesel fuel. \(A\) and \(P\) are the cross-sectional area and pressure in tube respectively.

Figure 10 shows the effects of injection duration on injection rate for the piezo-driven injectors. As the injection duration increases, the injection rate increases. Also the location of the maximum injection rate that corresponds to the full needle lift of injector increases along the relative long injection duration. Figure 11 shows the comparison of injection rate between the solenoid-driven injector and the piezo-driven injector with two different currents at injection pressure of 130MPa and injection duration of 500 \(\mu s\).
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 varies with the induced currents. On the whole, in case of the piezo-driven injector, the injection rate is higher than the solenoid-driven injector.

**Figure 8** Model validation for piezo actuator

**Figure 9** Simulated hydraulic characteristics results of piezo-driven injector
The needle’s behavior of two injectors was indirectly measured by using the accelerometer that was mounted on the injector’s outside body. Figure 12(a) and (b) show the signal frequency measured to represent the behavior of needle driven 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 130MPa, respectively. The outside shape of two injectors to install the accelerometer differs 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 Figure 12, 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.

Figure 10 Fuel injection rate profiles of piezo-driven injector

Figure 11 Comparison of fuel injection rate between solenoid and piezo-driven injector with two different currents

Figure 12 Opening and closed timing of needle in two injectors for qualitative analysis

Figure 13 Comparison results between calculated and measured injection rate in piezo-driven injector
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 consumed in order to reach up to 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. Also we found that this result has a good agreement with the measuring result of the spray detection time using the piezo sensor in Figure 6(b). Additionally Figure 13 represents the comparison results of the injection rate obtained by the hydraulic simulation and experiment in piezo-driven injector and shows the close agreement.

MACROSCOPIC SPRAY CHARACTERISTICS

Figure 14 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 130MPa, ambient pressure of 3MPa and injection duration of 500 $\mu$s. There is an obvious difference in spray characteristics with time after start of injection. The solenoid-driven injector produces a 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 initial stage of spray under 200 $\mu$s 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. Figure 15 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.

Figure 14 Comparison between solenoid and piezo-driven injector with different currents at injection pressure of 130Mpa and an ambient pressure of 3Mpa

Figure 15 Comparison of spray tip speed distributions for two injectors at ambient pressure of 3MPa
CONCLUSION

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 piezo-driven 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 main results drawn from this study are summarized as follows:

The injection rate result obtained by AMESim simulation was reasonably agreed with the experimental result. The piezo-driven injector has a faster spray development, longer spray tip penetration and produces higher injection velocity than a solenoid-driven injector. Eventually 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.

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.

Finally, we expect that by the application [15, 16] 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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REFERENCES


CONTACT

Jinwook Lee, Ph.D. Senior Researcher in KIMM

Graduated from Seoul National University and Work for Engine Research Center in Korea Institute of Machinery and Materials (KIMM) since 1993.

E-mail: immanuel@kimm.re.kr Phone: +82 42 868 7386