Application of a Computer Model to Various Specifications of Fuel Injection System for DI Diesel Engines*

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A combined experimental and computational investigation was performed in order to evaluate the effects of various design parameters of an in-line injection pump on the nozzle exit characteristics for DI diesel engines. Measurements of the pump chamber pressure and the delivery valve lift were included for validation by using specially designed transducers installed inside the pump. The results confirm that the simulation model is capable of predicting the pump operation for all the different designs investigated pump operating conditions. Following the successful validation of this model, parametric studies were performed which allow for improved fuel injection system design.

Key Words: Fuel Injection, Diesel Engine, Computational Fluid Dynamics, Compressible Flow, Pipe Flow, In-Line Pump, Delivery Valve Lift Sensor, Injection Rate

1. Introduction

The fuel injection system on a DI diesel engine has to perform several functions, such as metering the quantity of fuel injected, accurate timing of the injection, and mixing the fuel with air in the combustion chamber within the available time. Therefore, the system performance has much influence on the engine performance and should be designed and manufactured to conform the engine specifications. Moreover, to reduce operation hours for design, the simulation model, which can expect the fuel injection performance, is necessary. For example, this kind of work has been done by Russel, M.F. et al.⁽¹⁾, Arcoumanis, C. et al.⁽²⁾, and Gavaises, M.⁽³⁾ But the accuracy of the computation results is insufficient on various types of engines because of complicated phenomena. Recently the author reported the computer model⁽⁴⁾, which can predict the inside flow of the in-line pump with hole type nozzles, has been built and has been validated.

The purpose of this paper is to find the usefulness

of the model generally. This can be accomplished by making clear the influences of different specifications of the fuel injection system on the fuel injection performances.

The target fuel injection system is for DI diesel engines. It consists of an in-line pump connected to multi hole injection nozzles. In order to confirm that this computer model is useful for various specifications, the validations have been done for six types of different pumps.

For detail validation, the pump chamber pressure and the delivery valve behavior should be experimented. Because the pump chamber pressure is the first position where the pressure generates in the fuel injection system, and the behavior of the delivery valve near this position has much influence on the fuel injection performance. Under the circumstances, to add to the traditional measuring points, such as line pressure, needle lift, injection quantity, injection rate, and pump chamber pressure, the delivery valve behavior was measured. In order to measure this parameter, a specially designed transducer is installed inside the pump⁽⁵⁾.

After the validation of this model, parametric studies were done to investigate the influence of basic specifications of the pump, such as plunger diameter,

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cam lift, and etc. on the fuel injection performance.

2. Simulation Model

Figure 1 shows a schematic of the examined fuel injection system. This system consists of the pump, the high pressure pipe, and the nozzle, which are shown in the previous paper⁽⁴⁾. As the basic specifies of the target of this study, the plunger diameter of the in-line pump is 10 mm, the internal diameter and the length of the high pressure pipe are 1.6 mm and 510 mm, and the needle valve opening pressure of the nozzle is 17.0 MPa at first stage and 23.2 MPa at second stage. The number of the nozzle hole is 5, and each hole diameter is 0.24 mm. The flow is assumed as one-dimensional because the length of the pipes is much longer than the diameter. This model is based on the mass and momentum conservation equations for the calculation of flow in pipes, behavior of valves, and mean pressure of volumes. As for the pressure propagation, the method of characteristics is used⁽⁶⁾. The input data is the cam profile, slots at each part, and backpressure (fluid or gas). The cavitation in the nozzle, the dynamic discharge coefficients, pressure loss, various flow condition, fuel properties, elastic of the pipes, and leakage are modeled on the previous paper⁽⁴⁾. The model was applied to the method of characteristics. The model consists of 19 basic elements, such as cam, slots, volumes, valves, pipes, backpressure, and nozzle sac. The model can be applied for various types of fuel injection systems

because any combination of these basic elements can be selected by approximating the boundary conditions.

Due to high-pressure injection for recent years, for more accurate prediction, it is necessary to predict leakages of each positions detail. As for this issue, the detail prediction is given by the model, which is shown in the previous paper⁽⁴⁾. As for the residual pressure, it is derived from the experimental data of the standard specification as the initial condition. It has been made sure that it converges within four cycles' calculations. When the line pressure drops under the cavitation pressure (assumed as 1 kPa) in the calculation, the pressure is assumed 1 (kPa) and the void is not considered. Details about the mathematical modeling can be found in the previous paper⁽⁴⁾.

3. Validation of the Model

3.1 Measurement of the fuel injection rate

The injection rate is measured by the Zuich method. In this method, the fuel is injected into the vessel, in which the backpressure remains constant. By using the known volume of the vessel and measured pressure inside, the injection rate is calculated as the following equation.

$$R = \frac{V}{K} \cdot \frac{dP}{dt} \quad (1)$$

Where K (Pa) is bulk modulus of the fuel, V (m³) is the volume of the vessel, P (Pa) is the pressure inside, and R (m³/s) is the injection rate.

Fig. 1 Standard model of fuel injection system

3.2 Development of the delivery valve lift sensor

The delivery valve is near the position where the pressure first generates. Therefore this valve's lift is an important factor for fuel injection performance, and it is important to obtain this data for a detail validation of the model. Different from other types of pumps, this valve in the in-line pump has flow paths in its stopper. That is why the general type of transducer is not useful, and the specially designed transducer has been developed, which is shown in Fig. 1. Instead of the spring holder, which functions the stopper of the delivery valve and flow paths, a specially designed holder made from synthetic resin is replaced. It contains coil, lead wire, and repositioned flow holes. The effective flow area of the holes and the initial spring force of the delivery valve are the same as the original. A sensor probe (diameter 0.7 mm) attached to the delivery valve is inserted into the spring holder. The maximum lift is 5.4 (mm) and the depth of the probe is from 3.0 mm (lift zero) to 8.4 mm (lift maximum). The displacement of the probe, due to the valve lift, is converted to the inductance.

Figure 2 shows the calibration results of this sensor. The correlation coefficient between the valve lift (position of the probe range 3.0–8.4 (mm)) and the output voltage signal of this sensor is 0.99.

At the same time, in order to validate the pump chamber pressure without changing the original pump chamber volume and the original delivery valve holder's elasticity, a specially designed delivery valve holder was installed inside the pump. A pressure transducer was installed in this holder (Fig. 1).

Figure 3 shows the comparison between the computational and experimental results for the pump chamber pressure, the delivery valve lift, the line pressure (at the pump end and the nozzle end points), the needle lift, and the injection rate for Case 6 (Table 1). It is argued that each prediction is very close to the measured values. Similar results were obtained for all the other conditions investigated.

Fig. 2 Calibration of the delivery valve lift sensor

Table 1 Operating conditions

Case	Pump speed (r/min)	Rack position (mm)	Load (%)
1	325	6.16	idle
2	720	11.48	100
3	720	9.99	75
4	720	8.58	50
5	1200	11.48	100
6	1200	9.83	75
7	1200	7.73	50

Fig. 3 Comparison between computational and experimental results (Case 6)

3.3 Validation for other specifications

Since the model was found to predict accurately the pump operation itself, it was used in order to investigate the effects of the various parameters of the pump as listed in Table 2 on the fuel injected quantity. For the specifications from 1 to 4, each one corresponds to the cylinder number of the test piece of the in-line pump for 4 cylinders. Specification 1 is the standard. The plunger diameter and number of grooves for spill port are changed in specifications 2, 3, and 4. Figure 4 shows the schematic of the CPV (Constant Pressure Valve). CPV opens only when the pressure in the high-pressure pipe becomes larger than the pump chamber pressure. This occurs after the termination of injection due to the reflected pressure waves traveling through the fuel injection system. CPV is often used for high-pressure fuel injection systems.

In case CPV is used for validation due to the easily removable screw structure of the delivery valve unit, the delivery valve unit of the No.1 cylinder is changed to CPV. The cam profile is common in each specification. In case the simulation model is applied to specification 5, the elements of Volume (Delivery dead volume), Valve (RFR valve), and Volume (RFR & connection dead volume) in Fig.1 are changed for Volume (CPV), Valve (CPV), and Slot (CPV). The application to the different type of the pump is easy, and this is the strong point of this model.

Table 2 Specifications of the pump designs investigated

Spec.	1	2	3	4	5
Delivery valve	Standard	Standard	Standard	Standard	CPV
Plunger diameter	10.0 mm	10.0 mm	10.5 mm	10.5 mm	10.0 mm
Number of grooves	Single	Double	Single	Double	Single

Fig. 4 Schematic representation of Constant Pressure Valve

Figure 5 shows the influence of the difference of the pump specification on the pump pressure and the fuel injection rate in Case 5. In this case, the pump pressure is higher than in other cases. In comparison with specifications 1 and 3, by increasing the plunger diameter, the pump chamber increases at a faster rate and reaches higher values before the spill port opens. This is reflected in the fuel injection rate. As both the simulation and the experimental data confirm, injection quantity in specification 3 is larger. By comparing the pump chamber pressure for specifications 1 and 2, it can be concluded that when the double grooves type is used, the pressure drops faster after the spill port opens than in the case of the single groove type, due to the larger flow area available. The number of grooves strongly affects the end of injection and the shape of the injection signal, which becomes sharper after its peak value, and thus the injection quantity is significantly reduced. The case of specification 5 was found to have a small effect on the start of injection. This is due to the design of the delivery valve, which has a zero retraction stroke for the CPV design, thus allowing more fuel to flow through the valve seat from the pump chamber to the

Fig. 5 Comparison between computational and experimental results (Case 5)

rest of the fuel injection system.

To investigate the effect of various parameters of the pump on the fuel injection quantity, the corre-

Fig. 6 Comparison between the computational and the experimental results for the fuel injection quantity for all test cases and all different specifications

Fig. 7 Effect of delivery valve shape (cut area) on fuel injection quantity, Start of injection and end of injection (Case 1)

sponding results are given in Fig. 6 for all seven operating conditions and for all five different specifications. In each case two different curves are plotted. First shows the ratio between the measured quantity of specification 1, and second expresses the same ratio obtained using the simulation model. It is clear that the simulation model predicts reasonably well the effects of the various pump design parameters on the fuel injection quantity.

Figure 7 demonstrates the effect of the cut distance of the delivery valve, shown in Fig. 1, on the fuel injection quantity and the injection timing. As can be seen, a larger valve cut distance results in increasing the fuel injection quantity, advancing the start of injection, and extending the injection period. These phenomena were seen in both experiments and calculations. This is due to the larger quantity of fuel delivered from the pump chamber through this cut area. This was the case only for the 325 rpm, low idle condition, because the fuel quantity through the cut area is small and the effect is neglected in other high speed cases.

4. Parametric Study

Following the successful validation of the model, an extensive set of parametric studies examining the effect of various geometric parameters on the nozzle exit characteristics was performed. Figure 8 shows the effect of various parameters in Case 3 on the fuel injection quantity and the start of the injection, respectively. Each parameter is changed from -20% to $+20\%$ on the model. Their effects are also briefly described in Table 3; the values listed represent the mean slope of the curves plotted in Fig. 8.

As for the influence on injection quantity, the plunger diameter affects it most and the spill port diameter is second. The spill port diameter relates to the effective plunger stroke. The influence of the cam slope and the nozzle hole diameter follow. The cam slope data was obtained by changing the cam lift of each cam angle.

As for the influence on the start of injection, the plunger diameter affects it the most. The length of the high pressure pipe, cam slope, and the needle preload of the nozzle follow. Based on these results, the prediction of the fuel injection performances can be done rapidly in case that the specifications are changed. Also, in the adjustment and measurement processes in the production lines, the influences of the needle preload and the effective stroke of the plunger on the fuel injection performances can be estimated quantitatively.

Table 3 Relative variation of various parameters as a function of percentage increase from their normal values (Mean slope of curves at Case 3)

Parameter	Fuel quantity [% / %]	Start of injection [deg. / %]
Cam lift slope	+1.27	-0.019
Plunger diameter	+2.06	-0.032
Spill port diameter	-1.95	-0.008
Hi. pres. pipe length	-0.10	+0.021
Hi. pres. pipe diameter	-0.11	0.000
Nozzle hole diameter	+1.21	+0.003
1st sp. needle preload	-0.20	+0.010

● Cam lift slope	○ Hi. pres. pipe length
▲ Plunger diameter	△ Hi. pres. pipe diameter
■ Spill port diameter	□ Nozzle hole diameter
	× 1st sp. Needle preload

Fig. 8 Effect of various specifications on, (a) Fuel injection quantity, (b) Start of injection (Case 3)

5. Conclusion

The computer model of the fuel injection system for diesel engines, which was built in the previous paper⁽⁴⁾, was applied to an in-line pump with hole type nozzles.

For the validation of the model, measurements of the delivery valve lift, the pump chamber pressure, the line pressure, the needle valve lift, and the fuel injection rate were performed. The delivery valve behav-

ior is great contribution to fuel injection performance and it is measured by using the specially designed transducer installed inside the pump. The calculation results coincided with the experimental results well. Furthermore, on the six different specification pumps, the trend of the fuel injection quantity in both calculations and experiments were validated to well agreement in wide range running conditions.

Following the successful validation of this model, parametric studies were performed in order to examine the effects of the main parameters on the fuel injection quantity and injection rate. In order to improve the performance of the fuel injection system, these results can be used for the prediction on design and on production lines such as adjustment and measurement processes.

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