A Study on Solenoid Injector Characteristics in a Common Rail Diesel Engine

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***Abstract*—Past efforts in the development of diesel engines were focused on engine performance and functions. Today, implementation of environmental protection policies by the governments has set new directions for engine development. The fuel efficiency of the CI engine is improved to minimize exhaust gas, and post-processing in exhaust gas systems performance enhanced to reduce the emission of toxic contaminants. A common rail direct injection (CRDI) diesel system injects high-pressure fuel directly into the combustion chamber via Common-rail injector. Through this process, complete combustion is achieved in the combustion chamber. The common-rail injector is a critical in terms of combustion emission. This study examined the characteristics of CRDI injector parts and carried out comparative tests on injectors under normal and abnormal conditions. The tests include a compressive pressure test, idle speed comparison test, and injector correction test. Uniform output between cylinders was observed for the normal injector, whereas cylinders with defective injectors showed (-) non-uniformity. Injector correction involved increasing the amount of injected fuel to compensate for the insufficient force between cylinders. Based on the injector current wave, this method of injector correction was found to increase the energizing time by about 0.2 ms in the idle section. The injector fuel return flow test demonstrated an increase in return flow from defective injectors, which can be traced to internal oil fuel leaks or the higher amount of injected fuel.**

***Index Terms*—CRDI (common rail direct injection), ECU (engine control unit), Common rail injector, Cylinder power balance, Injector fuel return flow, Injector fuel correction**

I. Introduction

In the past, the development of diesel engines was focused on technical aspects, especially engine performance and their functions. Significant efforts were exerted on developing quiet engines with improved output and stability to meet the demands of consumers. Today, with the implementation of environmental protection policies, engine development is directed more at fulfilling the environmental regulations of respective governments. Engine manufacturers are actively responding to such rules, such as reducing exhaust gas by improving fuel efficiency and enhancing the performance of post-processing systems to curb the emission of toxic contaminants in exhaust gas [1]-[3]. To reduce the emission of gas, additionally the report studies combustion characteristics [4], [5] on unmodified diesel engine using blended fuel and biofuel [6], [7].

Diesel engines have many uses, including automobiles, construction equipment, marine, defense, and emergency power. To prevent diesel engines from becoming the leading cause of atmospheric pollution, it is essential to achieve complete combustion by directly injecting a proper amount of fuel using a common-rail injector under high pressure into a combustion chamber [8]. Maintaining the ideal ratio of air to fuel is a fundamental solution to reducing toxic gases, and toxic substances remaining after combustion have been treated in pre/post-processing exhaust systems to comply with enforced environmental regulations. Therefore, a common-rail injector has a significant effect on exhaust gas emission of its operating condition and its aging.

One factor to consider when using diesel engines is worn out as they age. Errors in fuel amount control caused by aging can significantly impact combustion [9]. Therefore, having an accurate understanding of the characteristics of the parts of a fuel system can be enabled good use and maintenance of diesel engines, thereby contributing to the prevention of environmental pollution.

The common-rail injector examined in this study is a critical component of the common-rail diesel engine. It is a device that injects fuel amount, calculated by the ECU, under high pressure into the combustion chamber. Understanding its characteristics will allow a more effective response to functional issues that may arise while using common-rail diesel engines.

The purpose of this study was to enhance the understanding control method between injectors and ECU, responsible for precision control in the fuel system of a common-rail direct injection diesel engine, and to perform comparative tests with data obtained from the regular injector and abnormal injector has stuck failure caused by scuffing damaged on needle valve that made low injection amount improperly.

II. Characteristics of Injector Control

A common-rail injector with solenoid type receives control signals from the ECU, opens the injector needle valve, and injects high pressure fuel regulated by electric fuel control actuator into a combustion chamber. This injection progress is started by control ball valve switching in injector, which is controlled by ECU. The

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control ball valve be regulated opening up the return flow path in injector, and it made imbalance of the fuel pressure around needle valve in injector. The needle valve at this moment moves in the direction of the control chamber, which has relatively lower pressure and opens its needle valve. That is to say it occur at the same time fuel return to the fuel tank and fuel injection into the combustion chamber [10]-[12].

The current supplied by the ECU pulls the control ball valve at an intensity of around 19A during the pilot and main injection, and the holding current after that is controlled at around 10 A to keep an opening position.

The ECU also can control the amount of high-pressure fuel injected into each cylinder and individually corrects fuel amounts in cylinders in the event of a lack of power cylinder balance. The trigger time of cylinders with weaker power cylinder balance is increased during the main injection to increase fuel amount, increasing cylinder power. Depending on this correction, each injector in cylinders produce a different return flows amount.

A significant feature of fuel injection by a common-rail system is the ability to perform multiple injections, including the primary and pilot injections [13], [14]. The pilot injection raises the pressure and temperature in cylinders by injecting pilot quantities of around 1 to 4 mg to induce standard ignition of the main injection. This prevents the pressure from rapidly rising during the main injection and shortens the ignition delay. The maximum injection angle of the pilot injection is 90 °BTDC [15].

III. Test Devices and Methodology

A. Test Devices

1) Test engine

The engine used in this study was designed to act as a simulator, thus facilitating the various tests on injector characteristics. Table I and Fig. 1 are shown in the specifications and measuring apparatus on the test engine. The engine was equipped with all devices of actual engines to recreate realistic conditions. An exhaust pipeline and muffler were installed for the engine to experience the same changes in back pressure as actual vehicles. A rubber mountain bracket was used to absorb vibrations from the engine itself. The engine was also comprised of devices for cooling, fuel supply, electronic functions, and lubrication.

TABLE I. Key Specification on Test Engine

Parameter	Specification
Fuel Type	Diesel
No. of Cylinders	4
Bore x Stroke	83 x 92mm
Displacement	1991 cc
Fuel injection	Common-Rail Direct Injection
Compression ratio	17.7:1
Max. fuel injection pressure	1350 bar
Max. Power	115PS/4000rpm
Max. Torque	26kgf.m/2000rpm
Intake system	Turbo Charger Intercooler (TCI)
No. of Injector hole	6
Injection Characteristic	Pilot (1) + Main (1) Injection
Injector type	Solenoid
ECU Controller	BOSCH EMS
Emission Level	EURO3
Before Treatment device	EGR (With water cooling type)
After treatment device	N/A

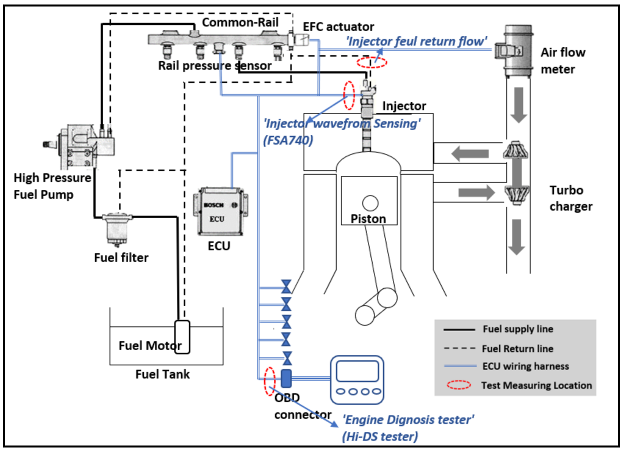


Figure 1. Schematic diagram of measuring apparatus.

2) Data acquisition devices

a) FSA 740: This engine tune-up module supports data acquisition from various sensors, virtual actuator function, oscilloscope, current pick-up, and exhaust gas analysis. The module runs on Windows, and MS Office can be utilized for data analysis.

b) Hi-DS tester: This widely used automotive diagnostic tester has an embedded screen and display injector correction values, ranging from 0 to 4 mm^3, provided by Engine Control Unit to adjust into the uniform cylinder power balance.

c) Injector return flow test kit: fuel flow mesurement kit for injector fuel reture. Consis of 4 pices of measuring beaker and transparent silicon hoses.

B. Methodology

1) Test of common-rail injector characteristics

The common-rail injector was tested using an engine diagnosis tester for idle speed and power balance test. To assess the corrective function of the injector, the injector trigger current was measured using FSA740 has a 1000A current pickup line, and observed for changes. The effects of injector characteristics on return flow were also examined.

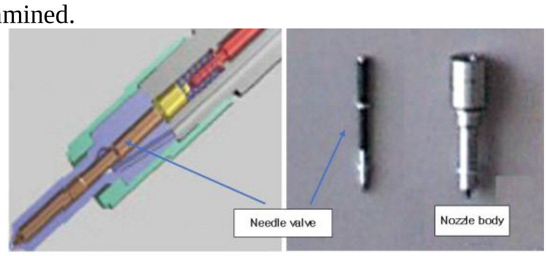


Figure 2. Needle valve and nozzle body in common-rail injector.

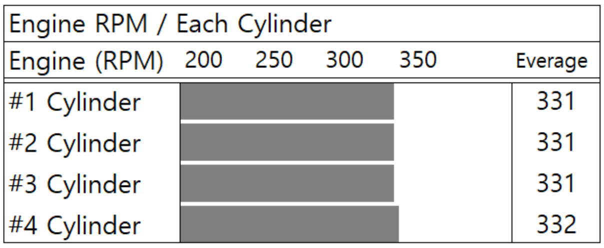
2) *Conditions of measurement*

a) Engine warmed up to around 85 ℃.
b) Comparison tests with abnormal injector in #1 cylinder (needle valve showing uneven wear – defective product which is location in injector as from Fig. 2).
c) Test of fuel type: Pure Diesel (100%), Standard.

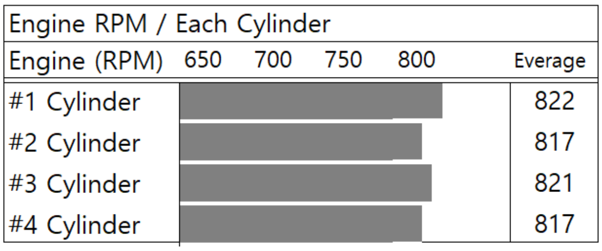
IV. Test Results and Analysis

A. *Status Test of Normal Common-Rail Injector*

Fig. 3(A) shows the load of the engine rotation of each cylinder, which is displayed. The test was measured under engine cranking mode using a Hi-DS Engine Diagnosis Tester connected with an OBD terminal socket in the engine wiring harness. As can be seen from the measurements, the ECU retrieves the RPM deviation of each cylinder from changes in angular acceleration of the crank position sensor. Each cylinder had an average close to or equal to 331 RPM, indicating a normal deviation across cylinders.



(A) Cranking Speed Comparison



(B) Idle Speed Comparison

Figure 3. Test of cylinder power balance without correction under normal injectors.

Fig. 3(B) showed the dynamic balance across cylinders when the cylinders were all subject to the same injection time while idling mode. Since the ECU does not correct injections during this test mode, the measurements show the actual dynamic balance deviation of each cylinder from 817 RPM to 822 RPM. There was a slight positive deviation for cylinders #1 and #3 and a slight negative deviation for #2 and #4. These deviations resulted from the different states of cylinders in the combustion chamber.

To accurately determine the corrective capacity of the ECU, Injector Correction Tests were performed under the same engine conditions. Fig. 4 presents the ECU corrected values and adjusted power balance measurements of each cylinder. The results showed that injector correction compensated for the small (+/-) power balance errors found in the Idle Speed Comparison Test, and uniform cylinder power balance was achieved.

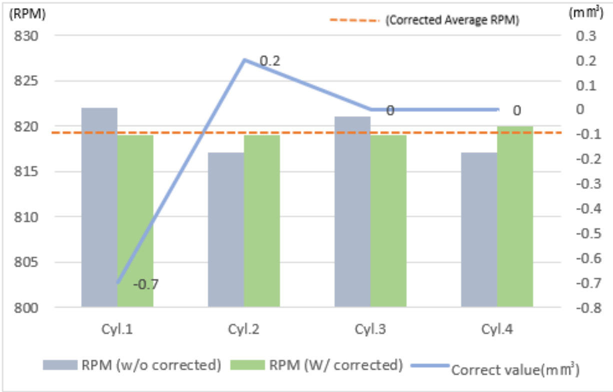


Figure 4. Test of cylinder power balance with correction under normal injectors.

B. *Status Test of Abnormal Injector*

To compare the performance of an engine equipped with a normal injector against an abnormal injector that has needle scuffing damaged, idle speed comparison tests were carried out in cylinder #1. As shown in the results in Fig. 5, cylinder #1 had a lower average than other cylinders. The uneven wear or scuffing failure in the needle valve interfered with regular injector operation. Caused of this, the amount of fuel injected into the combustion chamber seems to be insufficient due to interference of the needle valve operating. Therefore the deviation of power balance across cylinders could be adapted to compensate by the ECU via injector correction.

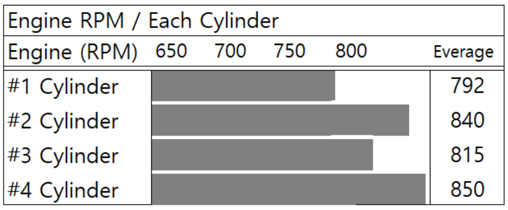


Figure 5. Test of Idle speed under abnormal in #1 cylinder.

However, from the test of injector correction shown in Fig. 6, the ECU corrected the (-) non-uniformity of cylinder #1 by up to 4.0 but failed to achieve uniform power balance across cylinders. This test showed that ECU control is not possible if defects surpass the maximum correctable amount, and that the (-) non-uniformity of one cylinder affects the power balance of other cylinders.

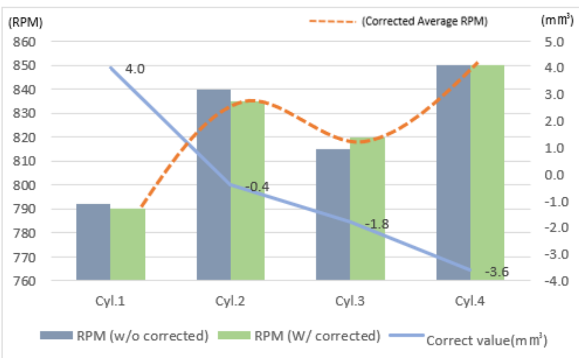
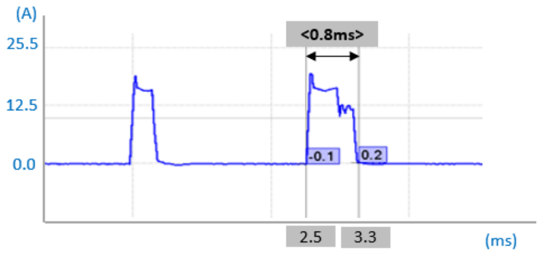


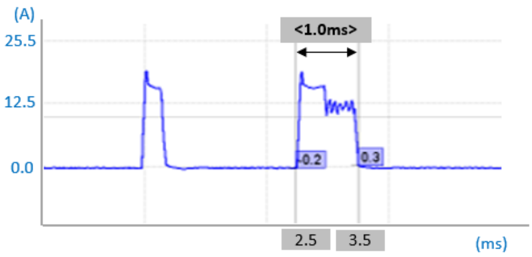
Figure 6. Test of injector correction for defective in number 1 cylinder.

C. Test of Injector Current Pickup

The injector operation currently has two types of waveforms, the pilot injection and the main injection. They operated by 19A of current is passed to complete one cycle with two revolutions of the crankshaft. The purpose of the pilot injection is to inject a small amount of fuel to prevent the rapid increase in pressure caused by delayed ignition during the main injection, which is a weakness of diesel combustion. The amount injected in the pilot injection is around 10% of the main injection, and this creates conditions suitable for normal combustion [16], [17].



(A) Without injector correction at normal condition



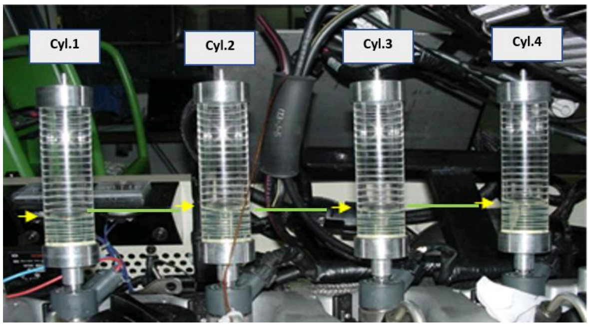
(B) With injector correction at abnormal condition

Figure 7. Test of Injector trigger current wave.

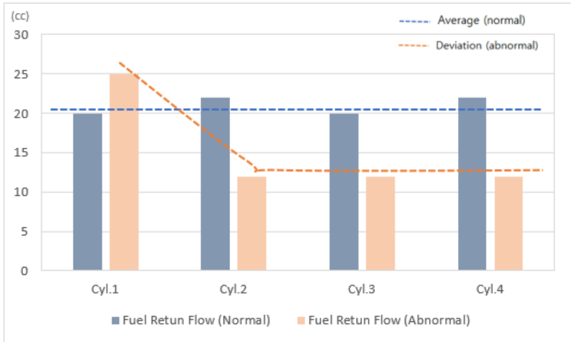
Fig. 7 (A) and (B) injector current waves show injection duration time to compare between normal and abnormal injector tested same engine condition, detected by current pickup sensor in FSA740 tester. The standard injection duration time without correction was measured at 0.8ms under engine idling speed. After replacing the standard injector with an abnormal, the injected duration was measured at 1.0ms. Which is 0.2ms longer than a standard injector. This means that the ECU is performing fuel correction for a longer time by 0.2ms because the abnormal injector has scuffing damage on the needle valve and has a risk of disrupting the needle open when injector operation.

D. Test of Injector Returned Fuel Flow

The common rail injector produces a returned flow simultaneously with the injection. When operating the injector, the magnetic valve bypasses a certain amount of fuel through the return line, once the needle valve moves to the area with lower pressure for fuel injection. The return flow of the injector is the sum of the bypassed fuel through the ball valve control and the amount returned through the injector lubrication line. If the injector is experiencing abnormal wear, the amount of returned flow increases due to internal leakage in the injector.



(A) Injector Return flow Beaker Tester Kit



(B) Amount of injector return flow

Figure 8. Test of Injector returned flow

Fig. 8(A) shows how to be installed and tested the Return Flow Measuring Kit in injectors. After removing fuel return hoses at each injectors, the returned flow kit was installed as shows Fig. 7(A). Fig. 7(B) is the measured result of the return flow between a standard injector and an abnormal injector installed on cylinder #1. This test was proceeding for 3 minutes under engine idling speed. In the case of the standard injector installed, the return flow was uniform across the four cylinders. However, the abnormal injector installed, which contained the needle valve scuffing, had a 5cc greater amount of return flow than the normal injector test; on the other hand, the return flow of the rest of the injectors was 8~10cc lower than the standard injector test. The increased amount of the return flow is result of the ECU (+) injection correction to recover (-) deviation of cylinder power balance.

V. Conclusions

Based on the above analysis, the following conclusions were derived.

There is no function of ECU injector correction in the 'Cranking Speed Comparison Test' and 'Idle Speed Comparison Test' in the Common Rail diesel system.

There is a function of ECU injector correction in the 'Cylinder Power Balance Test', which was adjusted at 819~820 rpm by ECU correction of demand value -4.0 to +4.0.

Deviation of injector fuel returned flow from each cylinder can be diagnosed as injector condition indirectly. In the 'Injector Return Flow Test' with the installed standard injector in the engine, which was measured 20~22cc from all cylinders, but an abnormal injector installed was measured 12~25cc. It was caused by significant deviation due to ECU injector correction, which led to an increase in fuel injection and fuel return flow to compensate for the (-) non-uniformity low power cylinder.

ECU injector correction can be detected by injector current wave. The energizing duration of the current wave can be changed by ECU injector correction demand. The installed standard injector was 0.8ms for energizing duration, but the abnormal injector was 1.0ms, more increased.

Conflict of Interest

The authors declare no conflict of interest

Author Contributions

Keunsang Lee conducted the research & wrote the paper; HaengMuk Cho analyzed the data. all authors had approved the final version.

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