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Development of a Common-rail Type High Pressure Hydrogen Injector with a Large Injection Rate and an Ability of Multiple Stage Injection

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1 Introduction

It is definitely true that the fossil fuel depletion problem and the global environmental problem should be solved immediately. Vehicles used on the earth are required to use fuel produced renewably and have a power system to be of low pollution, high efficiency and high output power as well as compactness and lightness in weight. Though various types of vehicle are being studied in the world for those purposes, they have merits and demerits.

To overcome the problems in the transportation sector, vehicles powered by hydrogen fuelled internal combustion engines with direct injection system (hereafter written as DI-ICE) can be expected to be put into practice soon because the technologies are being used to this day. The engine and fuel supply systems now under development are shown in Fig. 1. In order to accomplish low emission, high thermal efficiency and high output power in the engine system, development of common-rail type high pressure injector with a large injection rate and ability of multiple stage injection is indispensable [1].

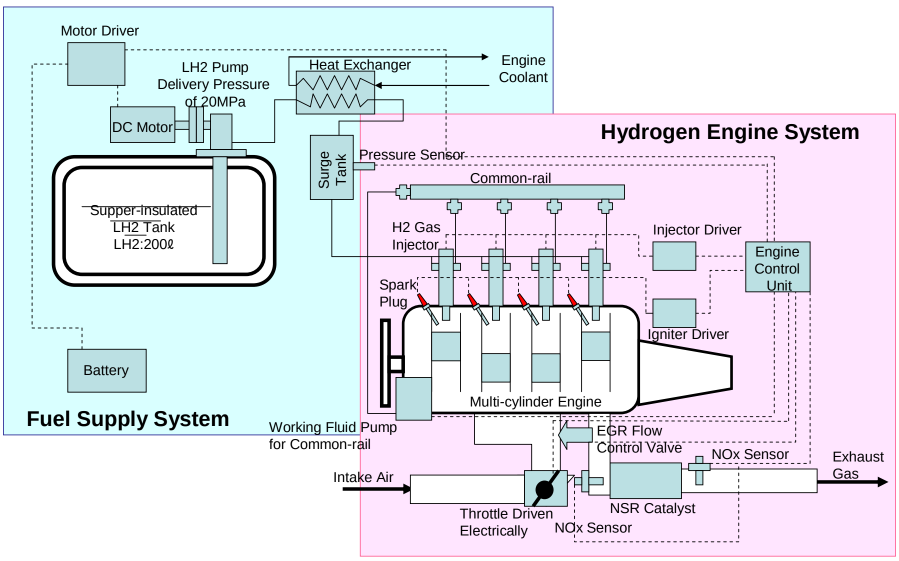


Figure 1: Hydrogen engine and fuel supply system.

There are several characteristics of hydrogen that makes this development difficult, such as small molecular size, low viscosity, low energy density, the gaseous state and some task work in precise machining processes.

This paper describes the features and key technologies of the injector obtained in the development, aiming for larger injection rate and less hydrogen gas leakage at the seating surface between the needle and the nozzle. Furthermore, the result is shown when a 4-cylinder 16-valve water cooled hydrogen fuelled direct injection engine with the developed four injectors installed was run according to the transient emission testing mode so called JE05 on an emission evaluation engine test bench.

2 Injector Developed, Injection Rate Measuring Device and Engine

The development of the injectors was carried out for the hydrogen fuelled truck engines. The injector developed and the device to measure the injection rate and the engine used were as follows.

2.1 Common-rail type injector

Basic requirements of injectors are high injection pressure, large injection rate, quick response, compact, controllability and durability for the DI-ICE mentioned above. To accomplish the requirements, studies were made on various injectors available on the market to find out the driving methods and materials in the design study. In the end, a compact common-rail type injector capable of electronic control was adopted. As the common-rail type injector system consists of a inner-cam type extremely high pressure pump, a common-rail where working fluid is kept at a constant high pressure and fed to the injectors and the injectors with electronic controlled solenoid valves capable of the very swift movement, it was conceivable that, as the matter of course, the common-rail type injectors were able to inject hydrogen gas at high pressure and make multiple stage injection with high response thanks to the very high operating pressure of working fluid.

As shown in Fig. 2 (a), the needle valve is close when the working fluid control valve is closed by the spring while the solenoid coil is deactivated. As shown in Fig. 2 (b), the needle valve is open when the working fluid control valve is opened by activating the solenoid coil. Namely, the activation and deactivation of the solenoid coil enables the needle valve to open and close respectively. It means that the activation and deactivating timings determine the opening and the closing timings, as well as the injection duration time. As a result, the injector can expectedly inject hydrogen gas at high pressure into the combustion chamber electronically. The solenoid coil, the spring and the working fluid control valve disassembled from a diesel fuel common-rail type injector on the market were used. As shown in Fig. 2, hydrogen gas is only fed to the needle valve at the high injection pressure while the working fluid control valve opens and closes in the same manner as a diesel fuel common-rail type injector does.

Table 1 shows the specifications of the injector developed and the hydrogen fuelled direct injection engine used for the JE05 mode emission evaluation. As the engine was the same with the diesel fuelled engine, a special effort was made for the installation of the additional feeding hydrogen pipe to the injector.

Table 1: Specifications of injector and engine.

Injector	Type	Hydraulic with Solenoid Valve
	Injector pressure	10～20MPa
	Working Oil	Diesel Fuel, 60MPa～
	Max Injection Quantity (at 3000rpm,30℃A)	400ml(N)/inj.
Engine	Engine Type	4-Cylinder
	Bore and Stroke	112×120 (mm)
	Displacement	1182cc/cyl
	Compression Ratio	13
	Valve Train	4-Valve SOHC

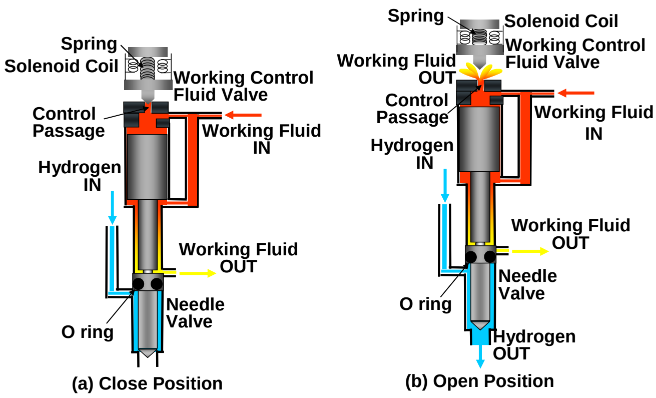


Figure 2: Injector behavior.

The maximum injection rate of the injector was determined by calculating from the condition of the stroke volume of 1.3 liters per cylinder, the volumetric efficiency of 80 % and the stoichiometric mixture strength. The minimum injection rate was determined by the hydrogen gas quantity capable of the engine idling. The allowable amount of hydrogen leakage through the seating surface between the needle and the nozzle was determined experimentally with a view to eliminating the abnormal combustion occurrence.

2.2 Injection rate measuring device and engine

A device was prepared to investigate the characteristics of the common-rail type hydrogen injector such as the injection rate, the functional behavior and the leakage from the seating surface into the combustion chamber. All the parts to make the device were employed from those used in the diesel fuel common-rail system except for the electric motor driving the inner-cam type extremely high pressure pump. Hydrogen gas at the injection pressure was supplied from high pressure cylinders. The pressures and temperatures of the hydrogen and the working fluid were recorded with a data logger. The following data were measured with an oscilloscope; the electronic command signal, the activating electric current generated in the injector electronic driver and the lift of the needle of the injector from the lift sensor embedded in the injector.

To know whether the injectors work functionally as expected in an engine operating condition, the four injectors were installed on the engine as described in Table 1.

3 Injector Performance and Endurance Life Improvements

3.1 Injector performance

To obtain high output power and high thermal efficiency by using hydrogen fuelled DI-ICE, it is necessary to have the injector make injection near at the top dead center in as short a period as possible. In order to obtain high injection rate, two measures were adopted. One was to enlarge the original diameter of 0.22 mm of the control passage which the working fluid control valve opened and closed. The other was to increase the angle of the tapper portion of the needle valve resulting in obtaining larger flow area. The enlargement in the diameter and the increase in the angle successfully enabled the injector to attain the injection rate of 400 ml(N)/1.67 msec. equivalent of 30 degrees crank-angle at 3000 rpm as shown in the specifications of the injector in Table 1. It was also found in the experiment that the injection rate would not be increased without fail when the diameter became more than 0.29 mm. It was conceivable that the maximum lift of the working fluid control valve was smaller than 0.073 mm. For purposes of combustion control in DI-ICE, the multiple stage injection is of great promise.

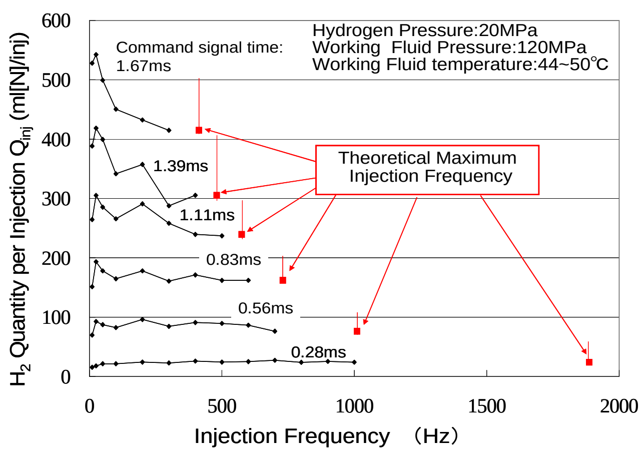
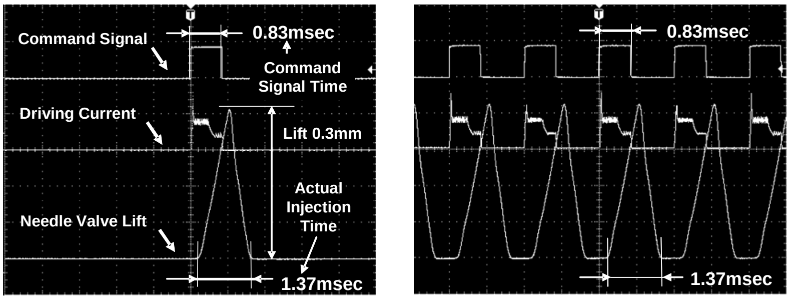


Figure 3: Effect of injection frequency on hydrogen quantity per injection.

As known well, common-rail type injectors are good at the multiple stage injection. It is very important to know to what extent of injection frequency the injector can perform correctly. Figure 3 shows the results of hydrogen quantity per injection Qinj. ml(N)/inj. by varying the command signal time such as 0.28, 0.56, 0.83, 1.11, 1.39, 1.67 msec. In most cases, the measurement was given up because the flow rate was beyond the capacity of the measuring device so that all most measurement stopped on the way to the theoretical maximum injection frequency. Figure 4 shows the command signal, the driving current and needle valve lift at the actual injection time of 1.37 msec. in cases of 10 Hz injection frequency (a) and 500 Hz (b). It is found in the figure that the needle valve lifts make no difference between injection frequency of 10 Hz and 500 Hz. It is quite evident in Fig. 3 and 4 that the developed injector can make multiple stage injection at very high frequency.



(a) Injection Frequency : 10Hz (b) Injection Frequency : 500Hz

Figure 4: Needle valve lift behavior in comparison between injection frequency 10 Hz and 500 Hz.

3.2 Endurance life improvements

When the developed injector is used for experiments and practical use, the consideration to the endurance life is inevitable. As explained in Chapter 2, the common-rail pressure works on the seating surface of the needle valve, namely, the increase of the common-rail pressure makes the seating surface pressure go up resulting in improving the sealing ability. On the other hand, the increase in the common-rail pressure results in smaller injection rate. As it is found that the relationship between the sealing ability and the injection rate is a trade-off manner, the appropriate common-rail pressure was determined experimentally.

It is said that, in case of high pressure hydrogen gas injectors, metal-to-metal contact sealing is subject to leakage of hydrogen gas at high pressure and that the leakage won't stop. To stop the leakage, a little lubricant on the sealing surface largely helps to stop the leakage of hydrogen gas at high pressure. However, the lubricant may generate pollutants such as hydrocarbon, mono-carbon oxide and carbon dioxide resulting in losing the attraction of hydrogen fuelled engines and moreover it may influence combustion of hydrogen-air mixture. As a result, this fails to have this kind DI-ICE called a true hydrogen fuelled DI-ICE. Therefore, the metal-to-metal contact sealing was intentionally employed for the injector sealing while focusing on the seating surface pressure, the precise machining and the surface treatment.

To look for long endurance life, improvements in the following subjects were carried out, expecting 100 hour endurance life.

1. Precise machining of needle valve and surface treatment

Circularity and flatness of the seating surfaces of the needle and the nozzle were improved by much more precise machining. In addition, circularity and cylindricity of the sliding portion of needle valve stem and coaxiality of the seating portion of the needle valve and the nozzle were also improved. As a result, no leakage through the seating surface was found definitely after 3-hour breaking in operation. The width of the seating surface of the nozzle was found to be uniform. As a result, the sealing for hydrogen gas at high pressure reached a practical level. Figure 5 shows the photographs of the seating surfaces of the nozzles; (a) leakage case and (b) no leakage case.

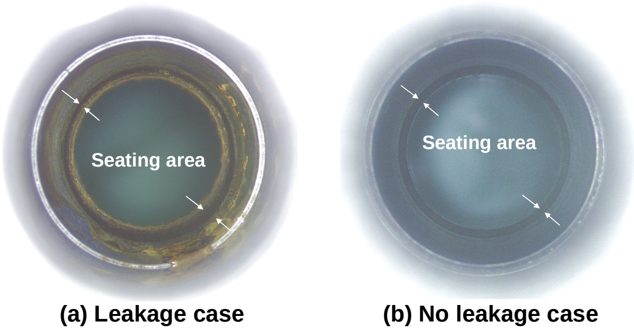


Figure 5: Photographs of the seating surfaces of the nozzles.

A surface treatment was carried out on the surface of the tapered portion of the needle valve to keep the original contour. The surface treatment carried out was a diamond-like carbon (hereafter written as DLC) coating. The DLC used was an amorphous carbon containing hydrogen with which a sliding friction test showed good results [Ref. 2]. Figure 6 shows the photographs of the seating surfaces of the needle valves; (a) No coating, (b) DLC coating.

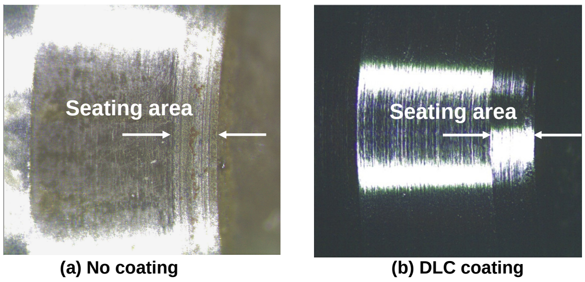


Figure 6: Photographs of the seating surfaces of the needle valves.

2. Precise machining of needle valve stem and surface treatment

For the increase in sealing ability at the seating surface of the needle valve and the nozzle, the clearance at the portion of the needle valve stem was decreased and furthermore circularity and cylindricity of the sliding portion of needle valve stem were improved. In addition, it was necessary to decrease the sliding friction at the portion of the needle valve stem for a stable needle valve lift. To decrease the sliding friction, the surface treatment with the DLC coating mentioned above was made. In Fig. 7, there appears a SEM photograph of the needle valve with DLC coated on, taken after the experimental engine operation. The needle valve stem used in the experimental engine operation was originally damaged and, after that, coated with DLC to investigate whether the DLC coating could stand the actual engine operation or not. As the result of SEM observation, there was no coating damage such as separation. It was found in the experiment that the coating had enough adhesion and endurance. It was also found that the coating could allow the tolerance in the clearance at the portion of the needle valve stem to be loose.

It has been clarified that the DLC coating worked well for experiments and practical use even in the circumstance of hydrogen gas. For further improvement, more study on the surface roughness of the needle valve stem and good coating structure is necessary.

Figure 7: SEM photograph of the needle valve with DLC coated on.

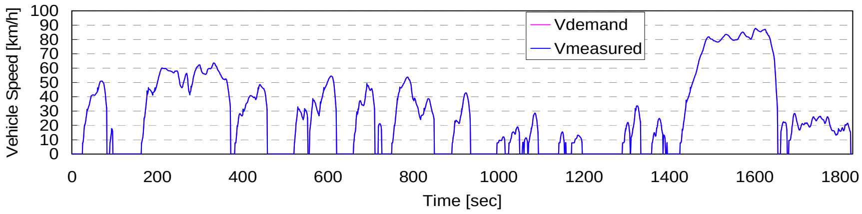


Figure 8: Comparison between vehicle speeds V measured and demanded.

3. Sealing between hydrogen gas and working fluid

High pressure hydrogen gas was applied to the portion of the needle valve and the nozzle in this injector. Injection of the hydrogen gas was made by up and down movement of the needle valve. For the sealing between hydrogen gas and working fluid, a rubber O ring with a nylon backup ring was employed. The surface of the rubber O ring was usually torn off. In this experiment, the sliding surface roughness and the sliding clearance were adjusted smaller than those of the design standards. However, though there was no improvement in the tearing-off of the O ring as usual, the sealing worked well. For the future, structural design change may be necessary to overcome the tearing-off.

4. Engine operation in the emission evaluation transient mode JE05

The JE05 mode operation was actually carried out by using the four developed injectors mounted on the engine described in Table 1. The JE05 mode is a transient operation simulating a real driving. The mode has been used for the emission test of the new long-term regulation since 2007 settled by the Ministry of Land, Infrastructure, and Transport (MLIT) of Japan Figure 8 shows the comparison of the vehicle speeds V measured and demanded. The measured one followed well the demanded one. It means that all the injectors synchronized well with the JE05 mode owing to the high response and the high injection rate of the injectors. In the engine operation, the working fluid was pumped up by an electric motor driving the inner-cam type extremely high pressure pump independent of the engine.

4 Conclusions

The followings are found in the development of the common-rail type hydrogen injectors by using the diesel fuel common-rail system on the market.

Compact common-rail type hydrogen injectors were successfully developed. Hydrogen fuelled engines with high engine performance have been realized by using the injectors developed. It is found that the injectors are good for hydrogen DI-ICE.

The injectors could bring about high injection rate and multiple stage injection.

DLC coating made a large contribution to the endurance life. And the injectors are expected to have the endurance life more than 100 hours.

Machining improvements in circularity, flatness and coaxiality made it possible to use the metal-to-metal sealing even when hydrogen gas was used at high pressure.

By using the injectors developed, a transient operation could be successfully done with a multi-cylinder engine according to JE05 mode. It was found that all the injectors synchronized well with the JE05 mode owing to the high response and the high injection rate of the injectors.

It is largely expected that the common-rail type injectors developed surely bring about further advancement in hydrogen fuelled DI-ICE.

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