Research and development of hydrogen direct-injection internal combustion engine system

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Abstract: - The research and development of hydrogen-internal combustion engine (ICE) system for heavy-duty trucks, with the goal of allowing carbon dioxide (CO_2)-free operation in transportation department, has been carried out. The high-pressure hydrogen gas direct-injector was adapted to the single-cylinder ICE. The high-pressure direct-injection combustion system shows that high thermal efficiency, high specific output and low NOx emission were confirmed. From these results, it is concluded that the possibility of the application from those results to a multi-cylinder hydrogen-ICE is high. The NOx storage reduction (NSR) catalyst system was applied as the after-treatment device of the exhaust NOx emission from hydrogen-ICE and it was confirmed that very low effect to fuel consumption and high reduction effect of NOx emission were feasible experimentally.

Key-Words: - Hydrogen, Internal combustion engine, Heavy-duty truck, Carbon dioxide-free, NOx emission reduction, High-pressure hydrogen injector, Direct injection, NOx storage reduction catalyst

1 Introduction

Many of transportation of the freight in Japan depend on the use of diesel trucks. In Japan, a large reduction in the amount of particulate matter (PM) and nitrogen oxide (NOx) emitted from diesel trucks has been demanded, just as in recent years better emission control of carbon dioxide (CO_2) came to be demanded as an important part of global warming prevention. The use of hydrogen as the main component on the feed side raises the problem of how to create a CO_2-free process at the time of hydrogen production, but it is possible to have CO_2-free operation of the vehicle by using hydrogen as a fuel.

Encouraged by this, the fuel-cell vehicle (FCV), which uses hydrogen as a fuel, is being developed energetically in many countries, but presently there is still much technical effort remaining for mass production. Besides, the development is limited to passenger car and shuttle bus. Conversely, the hydrogen-ICE vehicle can easily be produced with its existing engine, and it is said that the hydrogen-ICE vehicle can easily realize the same specific output as existing diesel-engine vehicles, while its low exhaust gas levels may be next to those for electric vehicles (EV).

Based on this background, a development project for a hydrogen-ICE system for trucks is being pushed forward as one part of the Next-generation Environmentally Friendly Vehicles Development and Commercialization Project (EFV21) of the Ministry of Land, Infrastructure and Transport (MLIT) in Japan. This project has the goal of producing a high-performance hydrogen-ICE system showing equal specific output and fuel consumption as a mass-produced diesel engine for trucks, and an ultra-low NOx characteristic of less than 1/4 of the New Long-term Emission Regulatory Requirements

in Japan. The core development technologies for this project are a hydrogen gas high-pressure direct-injector, a NOx reduction catalyst system, and a combustion control system.
In this report, the development status and some problems encountered are reported.

2 Target and Strategy of Development

In this project, which aims at an application to the medium duty truck with a Gross-vehicle-weight (GVW) of 8 tons, a plan to remodel the base engine into a hydrogen-ICE was made. The base engine is a mass production 7.7 L 6-cylinder turbocharged diesel engine (HINO J08-TI) in the natural aspirated (NA) state.

The specifications of the target hydrogen-ICE were shown in Table 1. The main remodeling points from the base engine are reduction of the compression-ratio by the addition of a mechanism to the piston and the addition of the sparkplug.
The performance targets of this project using this engine with a NOx reduction catalyst system are shown in Table 2. The main aims are the equal output of power and fuel consumption as the base engine and a lower NOx value than the 0.5 g/kWh specified by the Japanese New Long-term Emission Regulatory Requirements for the transient driving mode (JE05).
In addition, a strategy to approach the target performance started with the performance of the multi-port-injection (MPI) hydrogen-ICE, as shown in Fig.1. Because this starting point uses the condition that the output power largely falls from the base engine, recovery of the output power by direct-injection (DI) was planned. The problem of NOx increasing at the same time was solved by the optimization of the Exhaust-Gas-Recirculation (EGR), fuel injection timing, spark ignition timing and the NOx-Storage-Reduction (NSR) catalyst system.

3 Development and Assessment of Core Technologies

The progress of this project is influenced by the progress of the core development technologies that were stated above. The detail of each core development technology and its progress until the end of the latest budget year, the provided results and a general assessment are shown below.

Table 1 Specifications of Target Hydrogen-ICE

Item	Specification
Base Engine	Hino J08-TI
Engine Type	4 Cycle Inline 6 Cylinders
Cooling System	Water Cooled
No. of Valves	4 valves
Engine Displacement	7.684 L
Bore × Stroke	112 mm × 130 mm
Compression Ratio	13 : 1
Fuel	Direct-inj. High-press. Hydrogen
Injector	Hole Type: Multi Holes
	Max. Inj. Press.: 20MPa
EGR System	Water Cooled EGR
Ignition System	Spark Ignition
Aspiration	NA

Table 2 Performance Targets of Project

Item	Target Performance
Output Power	147 kW @3,000rpm, NA
	(IMEP: 0.85 MPa)
Fuel Economy	The Same Level of NA DE
Emission	NOx: Less than 0.5 g/kWh by JE05 Drive Mode
	(less than 1/4 of the New Long-term Regulation)
	PM: Near Zero Level
	CO_2/CO/HC: Near Zero Level

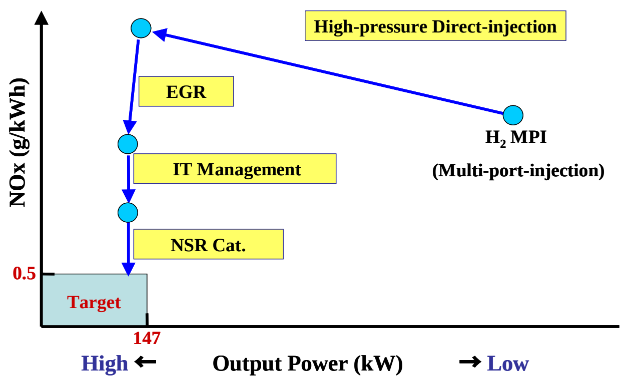
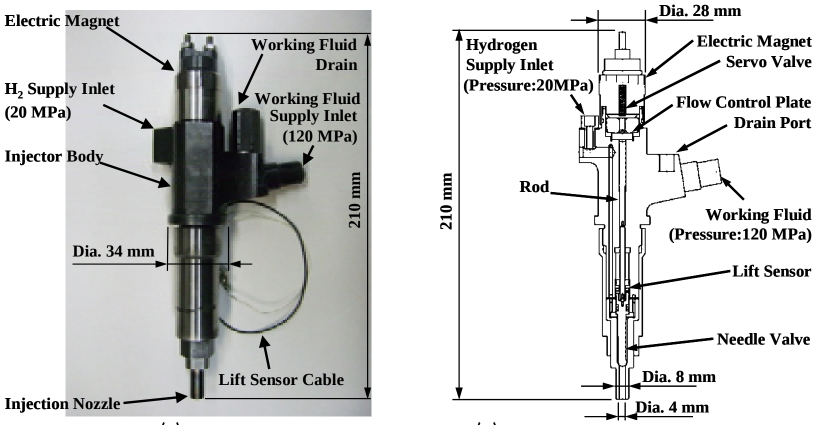


Fig. 1 Strategy to Approach NOx and Output Power Target

3.1 Injector of Direct-injection of High-pressure Hydrogen Gas

The hydrogen gas high-pressure direct-injector developed in this project is shown in Fig.2. Its greatest feature is the ability to inject hydrogen of 0.4 liters at standard temperature and pressure (STP) with a crank angle of 30 degrees and an engine speed of 3,000 rpm. A common-rail hydraulic pressure to drive the needle in this injector was used. With this, independent



(a) Photo (b) Cross-sectional Drawing

Fig. 2 Common-rail Type Hydrogen Gas High-pressure Direct-injector

Table 3 Specifications of Single-cylinder Hydrogen-ICE

Item	Specification
Base Engine	FD1
Engine Type	4 Cycle Single Cylinder
Cooling System	Water Cooled
No. of Valves	2 valves
Engine Displacement	1.054 L
Bore × Stroke	108 mm × 115 mm
Compression Ratio	13 : 1
Fuel	Direct-inj. High-press. Hydrogen
Injector	Hole Type: 9 Holes (Dia. 1.3 mm)
	Max. Inj. Press.: 20 MPa
EGR System	Water Cooled EGR
Ignition System	Spark Ignition
Aspiration	NA

control of hydrogen supplied at a maximum of 20 MPa is possible . This injector is the inward opening needle type and has a multi-hole nozzle in the nose and geometry such that it can be equipped to the base engine. The control of the injection-timing and period is performed by the spill amount and timing of a working fluid supplied to this injector from the common-rail system, enabling the multi-injection to have a high-speed response.

The investigated results that applied this injector to the single-cylinder hydrogen-ICE are reported. The specifications of the single-cylinder hydrogen-ICE are shown in Table 3, and the combustion-chamber configuration is shown in Fig. 3. This specification and configuration are different from the target hydrogen-ICE. The combustion-chamber of the single-cylinder hydrogen-ICE was concave, but

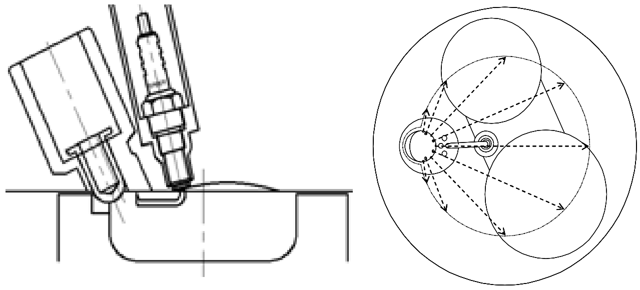


Fig. 3 Combustion Chamber Configuration of Single-cylinder Hydrogen-ICE

designed so that the injector was posted to the edge of the combustion chamber in order to spout out in the shape of a fan from nine holes to dispense hydrogen equally throughout the combustion chamber. In addition, the center electrode of the sparkplug was extended so that firing was performed in the neighborhood of the hole on the injector.

The injection-pressure, injection-timing and ignition-timing were changed for every combination of engine speed and Indicated Mean Effective Pressure (IMEP). The thermal efficiency, NOx, excess air ratio and exhaust gas temperature at the measured points of the combination of engine speed and the IMEP are shown in Fig. 4.

In addition, the relationships between the thermal efficiency and NOx in the three combinations of injection-timing and ignition-timing are shown in Fig. 5.

The following effects were noted:

(1) The IMEP equivalent to 147 kW in the multi-cylinder hydrogen-ICE was confirmed in the single-cylinder hydrogen-ICE.

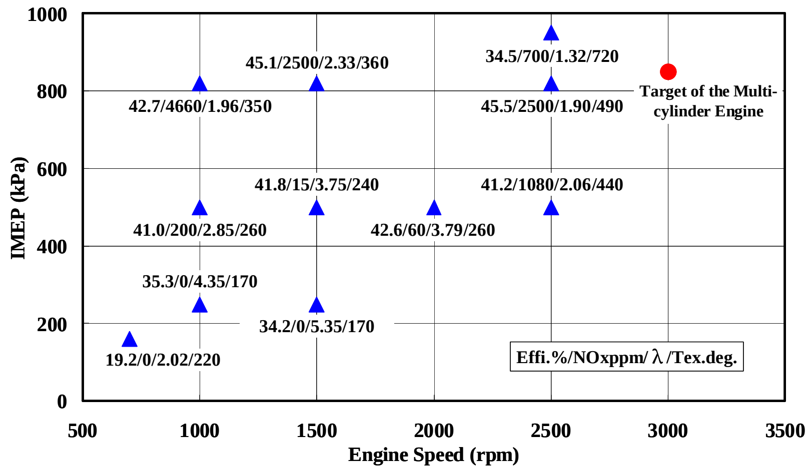


Fig. 4 Characteristic in Single-cylinder Hydrogen-ICE

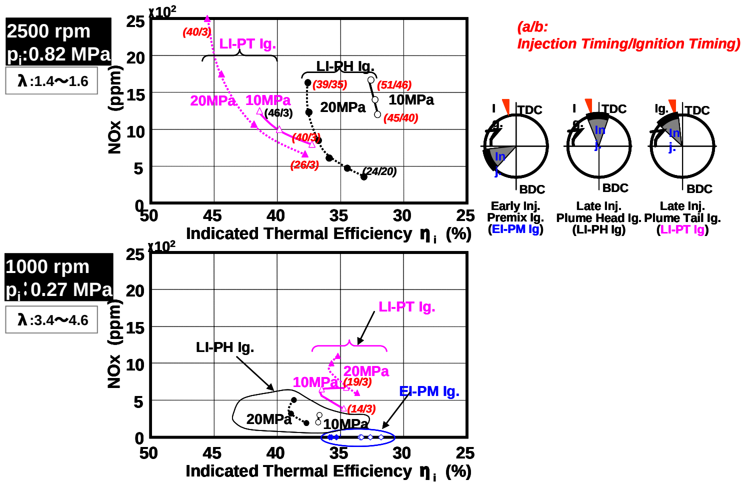


Fig. 5 Relationship of Thermal-efficiency and NOx in Combination of Injection-timing and Ignition

(2) An early injection is good under the low-speed and low-load conditions, so that some thermal efficiency is maintained, and NOx is held at approximately zero.

(3) In spite of increasing the quantity of NOx emissions under the high-speed and high-load conditions, it was possible to relatively restrain the quantity of NOx emissions while maintaining high thermal efficiency by using the EGR and late injection together.

In addition, on the occasion of application to the DI multi-cylinder hydrogen-ICE, we recognized that it was necessary to plan stability (variation restraint) improvement. The trial manufacturing development for this effort is under way now.

3.2 NOx Reduction Catalyst System

The specifications of the NOx reduction catalyst system, which consists of a NSR catalyst and an oxidation catalyst, are shown in Table 4. Eight liters of the Pt/Rh-based NSR catalyst of were arranged on the upstream side, and four liters of the Pt-based oxidation catalyst were arranged on the downstream side. The NSR catalyst was chosen because of its

Table 4 Specifications of NSR Catalyst & Oxidation Catalyst

Item	NSR Catalyst	Oxidation Catalyst
Content	8 L	4 L
Radius	Dia. 9 inches	Dia. 9 inches
Cell Thickness	4 mil	4 mil
Cell Density	600 cells/inch^2	600 cells/inch^2
Composition	Pt/Rh	Pt

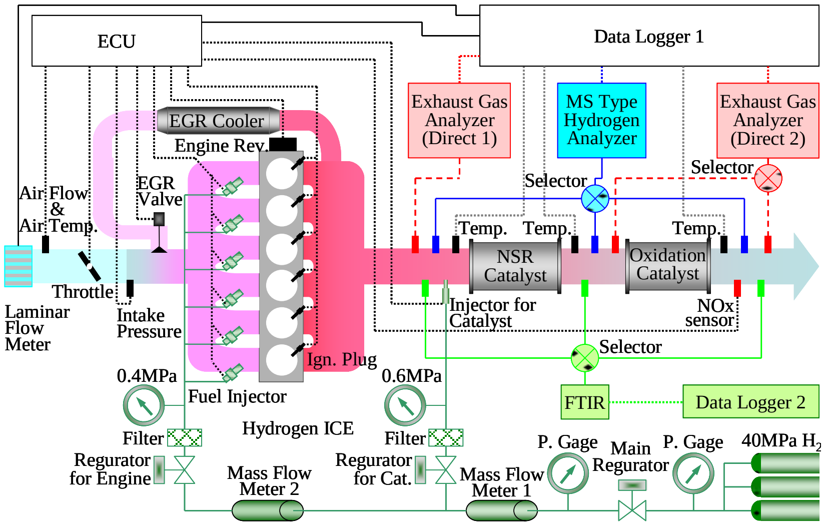


Fig. 6 Experimental Apparatus Diagram

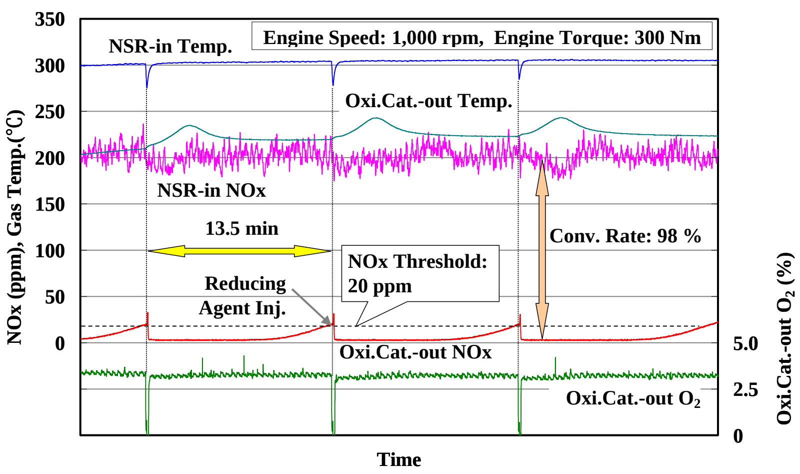


Fig. 7 Typical Characteristic of NOx Reduction

superior performance in diesel-oil and dimethyl-ether (DME). The oxidation catalyst was added for the purpose of purifying the unburned hydrogen from the hydrogen-ICE and the hydrogen that was not used, although it was supplied as a reducing agent.

Before the production of the DI multi-cylinder hydrogen-ICE, a MPI multi-cylinder hydrogen-ICE was remodeled from the base engine. The function of the NOx reduction catalyst system was investigated in this experimental system, as seen in Fig. 6. In this investigation, the engine was operated at a constant speed, and the measurements were done in a state such that the exhaust gas temperatures in the upstream and downstream regions of the NSR catalyst were stable. When the value at the NOx sensor, which was installed downstream of the oxidation catalyst, reached the threshold, a reducing agent was supplied automatically from the electromagnetic type injector that was set upstream of the NSR catalyst. Because of the limit on maximum injection quantity for the reducing agent, the investigation was carried out under the conditions that the remaining oxygen concentration was low and the NOx concentration upstream of the NSR catalyst was high. The engine speeds were 1,000 rpm and 1,750 rpm; engine torque was 300 Nm; and the excess-air-ratio (λ) was about 1.2.

A typical example of the NOx conversion situation at an engine speed of 1,000 rpm, with an injected quantity of 36.5 liters (STP) of the reducing agent, is shown in Fig. 7. The horizontal axis indicates the time, the left vertical axis shows the NOx concentration and the exhaust gas temperature upstream of the NSR catalyst and the exhaust gas

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Table 5 H_2 Consumption and NOx Conversion Rate

Engine Speed	1,000 rpm	1,750 rpm
Engine Torque	300 Nm	300 Nm
Gas Temperature (NSR-in)	300 deg.	400 deg.
Gas Temperature (Oxi.Cat.-out)	220 deg.	380 deg.
H_2 Consumption Rate of Engine	500 L(STP)/min	856 L(STP)/min
Injection Interval of Reducing Agent	13.5 min	24.0 min
Quantity of H_2 Consumption of Engine	6,750 L(STP)	20,500 L(STP)
Quantity of Injection of Reducing Agen	36.5 L(STP)	50 L(STP)
Reducing Agent / Engine	0.5 %	0.2 %
NOx Concentration (NSR-in)	200 ppm	160 ppm
NOx Conversion Rate	98 %	98 %

STP: Standard Temperature and Pressure

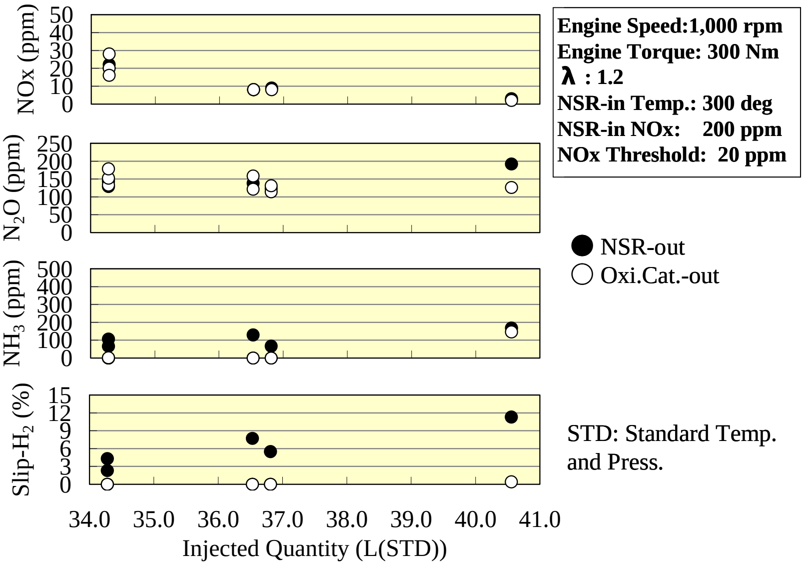

Fig. 8 Emission Characteristic of Substances

temperature downstream of the oxidation catalyst and the right vertical axis displays the remaining oxygen concentration downstream of the oxidation catalyst . In this condition, the NOx conversion rate was 98%. The NOx conversion rate is defined in the following equation: (1 - the NOx concentration downstream of the oxidation catalyst / The NOx concentration upstream of the NSR catalyst) * 100. Because the injection interval of the reducing agent was 13.5 minutes, the quantity of hydrogen consumed by the hydrogen-ICE during this period was 6,750 liters (STP). Thus, the ratio for the NOx reduction (= reducing agent injection quantity / engine consumption * 100) was 0.5 %. This is less than a general diesel engine system. Thus, the superiority of the hydrogen as the reducing agent was confirmed.

A comparison between the hydrogen consumption and the NOx conversion rate in representative conditions (engine speeds: 1,000 rpm, 1,750 rpm) is shown in Table 5. The hydrogen consumption was 0.5 % at an engine speed of 1,000 rpm, but it was 0.2 % at 1,750 rpm because the NOx concentration upstream of the NSR catalyst was low. The NOx conversion rate was 98 % with both conditions.

All experimental data on NOx, nitrous oxide (N_2O), ammonia (NH_3) and slipped-hydrogen in the downstream of the NSR catalyst and the oxidation catalyst when the injected quantity of reducing agent was changed from 34.3 liters (STP) to 40.6 liters (STP) at an engine speed of 1,000 rpm are shown in Fig. 8. The measured value of NOx downstream of the oxidation catalyst was the stable state value after the temporary peak; the other substance's value was the peak. We noticed that the NOx conversion performance was such that there was much remaining reducing agent. As for N_2O, the correlation with the

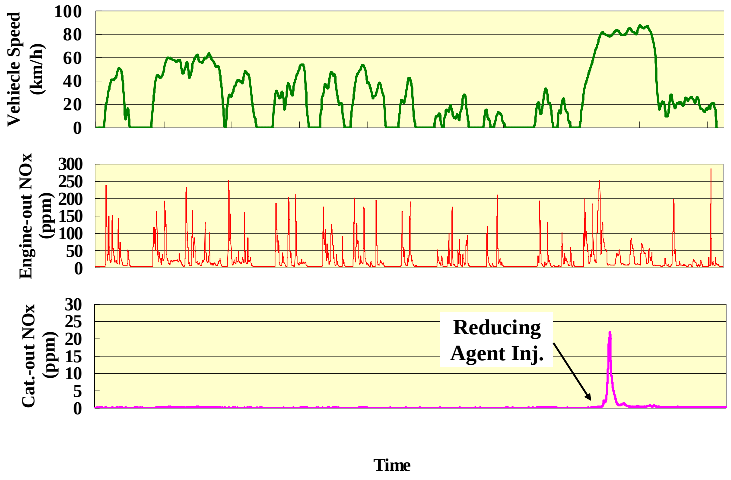

Fig. 9 Results of JE05 Driving Mode Experiment

injected quantity of reducing agent was not confirmed. When the injected quantity of the reducing agent was almost equal to or less than 37 liters (STP), the concentration of NH_3 became zero downstream of the oxidation catalyst. From this, NH_3 was decreased by the oxidation catalyst. The purification of the slipped hydrogen with the oxidation catalyst in all conditions was confirmed. This did not depend on the injected quantity.

From these, the following effects were noted.

(1) The NOx conversion rate was 98 %, and the hydrogen consumed as the reducing agent was 0.2 - 0.5 % of the consumption of the engine.

(2) When there was too much reducing agent feed, NH_3 and slipped hydrogen were detected.

These were reduced by an oxidation catalyst in a restrictive condition.

(3) N_2O occurred just after the supply of the reducing agent.

The research and development of the future hydrogen-ICE aims at the specific output at the same level as the current gasoline and diesel engines, and it should be accelerated more. Because it is thought that the NOx emissions increase with an increase in the output, it is thought that a dependence of the post-treatment will be raised.

3.3 Engine Control System

The engine control system in this project consists of part of the multi-cylinder hydrogen-ICE and part of the NOx reduction catalyst system. Before the production of the DI multi-cylinder hydrogen-ICE, the combination characteristics of the combustion control system was examined by using the MPI multi-cylinder hydrogen-ICE and the NOx reduction catalyst system. The investigations of the NOx reduction catalyst system were similar. This confirmation was performed by using an apparatus, as seen in Fig. 6, for a transient driving test mode (JE05).

These results are shown in Fig. 9. It was confirmed that following a vehicle-speed command involves an injection action of the reducing agent.

From these, the following effects were noted.

(1) A transient driving test mode (JE05) was carried out, and it was confirmed that combustion control of the multi-cylinder hydrogen-ICE was functioning.

(2) The control of the NOx reduction catalyst system was also confirmed in the transient driving test mode (JE05).

After the completion of the DI multi-cylinder hydrogen-ICE system, further tests will be conducted.

4 Conclusion

The research and development for the hydrogen-ICE engine system for heavy-duty trucks, with the goal of allowing CO_2-free operation of transportation of the freight in Japan, has been carried out.

The results from these research and development are as follows.

(1) Injector of high-pressure hydrogen gas direct-injection was applied to the single-cylinder hydrogen-ICE. The hydrogen direct-injection engine system by use of this injector showed high thermal efficiency, high specific output and low NOx emission. From these, it was concluded that feasibility in the multi-cylinder hydrogen-ICE was high.

(2) The NOx-Storage-Reducing (NSR) catalyst system was adapted to the hydrogen-ICE, and it was confirmed that the rich-spike with low fuel consumption loss and low NOx emission were feasible experimentally.
(3) From experiments on the transient operation, the feasibility of the hydrogen internal combustion engine control system was partially demonstrated.

On the other hand, for successful completion of the development project, it is clear that the stability of the injector of high-pressure hydrogen gas direct-injection is an important subject. Trial manufacturing development for this is currently underway.

Acknowledgement

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