DEVELOPMENT OF A DME (DIMETHYL ETHER) FUELED HEAVY-DUTY ENGINE WITH LEAN NOX TRAP

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Abstract

In recent years, attention has focused on smokeless, sulfur-free dimethyl ethyl (DME) as a clean fuel for heavy-duty diesel vehicles. As a part of its Next-Generation Environmentally Friendly Vehicles Project (EFV21), the Ministry of Land, Infrastructure and Transport has developed a heavy-duty truck in the 20-ton class that uses DME as its fuel. A lean NOx trap system (NSR Type: NOx Storage Reduction) has also been developed to achieve the EFV21 NOx target of 0.5 g/kWh, which is only one-fourth of the new long-term regulation value promulgated in 2005 Japan. The optimization of the NSR system's rich spike control, catalyst capacity, etc., has reduced NOx to 0.11 g/kWh, a level that is close to zero.

Keywords: Alternative Fuel, Emission, After-treatment, NOx storage reduction, DME, Heavy-Duty Truck, NOx, PM.

1. Introduction

There is strong demand for a solution to the problem of air pollution (NOx and SPM) in urban areas and a reduction in the amount of carbon dioxide emitted by motor vehicles. Further efforts to reduce the environmental problems caused by motor vehicles will require that Environmentally Friendly vehicles (EFVs) with zero or near-zero emissions be more widely used. In May, 2001, the Ministry of Land, Infrastructure and Transport established the General Strategy Council for the Development and Dissemination of Environmentally Friendly Vehicles to decide on a comprehensive strategy for the development, introduction, and promotion of EFVs. In December of that year, the Next-Generation Environmentally Friendly Vehicles Working Group, which was created within the General Strategy Council, assembled a report on the rapid development and commercialization of the next generation of environmentally friendly heavy-duty vehicles. The report declared that in the heavy-duty vehicle field, it is necessary to develop the next generation of EFVs by 2010 or early by enabling existing heavy-duty vehicles to use alternative fuels, so that they emit 0.2 g/kWh or less of NOx, one-tenth of the new long-term regulation value of 2005, and near-zero PM,. In April, 2002, the Ministry of Land, Infrastructure and Transport launched the Next-Generation Environmentally Friendly Vehicles Project (EFV21 project) and decided to develop four candidate vehicles and one engine for the next-generation EFVs, which is expected to be commercialize, within three years, by March of 2005, as shown in list. A heavy-duty truck that uses DME fuel would be expected to have nearly the same fuel consumption as an existing diesel truck, and it does not emit smoke, so it was chosen as a candidate for the EFV21 project.

Table 1. Specifications of the DME engine

Base engine	NISSAN DIESEL., FE6T
Type	4-cycle, water-cooled
Cylinder	in-line, 6 cylinders
Valve type	OHV, 2valves
Bore/Stroke [mm]	108/126
Displacement [cc]	6,925
Compression ratio	17.5
Swirl ratio	1.9
Aspiration	Turbocharged with intercooler
Combustion type	Compression ignition
Max.Power [kW/rpm]	199/2700
Max. Torque [Nm/rpm]	750/1100
Emission reduction	EGR, Oxidation catalyst, NSR(*)

*NSR: NOx storage reduction catalyst system

Table 2. Properties of DME [2]

	Unit	DME	Diesel fuel
Liquid Density	kg/m^3	667	831
Cetane Number		>55	40-55
Stoich.A/F ratio	kg/kg	9	14.6
Boilling point	K	248	453-643
C ratio	wt%	52.5	86
H ratio	wt%	13	14
O ratio	wt%	34.8	0
Modulus of elasticity	N/m^2	6.37×10^8	1.49×10^9
Lower Calorific Value	MJ/kg	28.8	42.7
Vapor pressure (@293K)	kPa	530	-
Auto ignition temperature	K	508	523

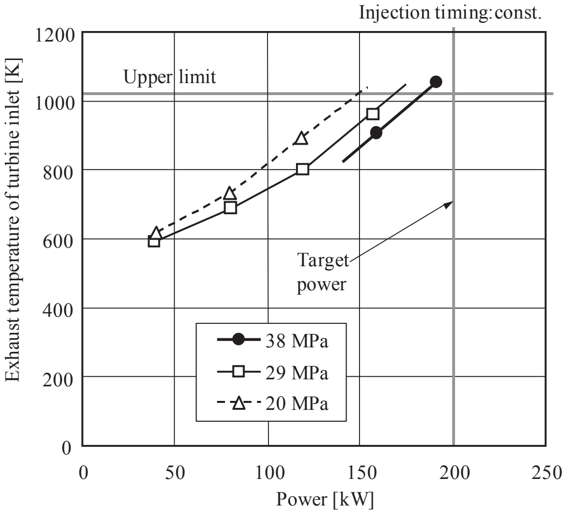

Fig. 1. Effect of fuel injection pressure in the low-speed and high-load operating area

Basic data of EFV21 project

- Time period: 3 years, from April 2002 through March 2005.
- Subjects: Completion of prototype vehicles by March 2005, and evaluation of the vehicles' performance.
- Prototype vehicles and engine: DME fueled truck, Ultra-Clean CNG fueled truck, Series H/B diesel bus, Parallel H/B diesel truck, Ultra-Clean diesel engine.
- Development budget: Support from Ministry of Land, Infrastructure and Transport (MLIT), Total budget included all vehicles for 3 years Approximately 5 billion yen (approximately 42 million dollars.

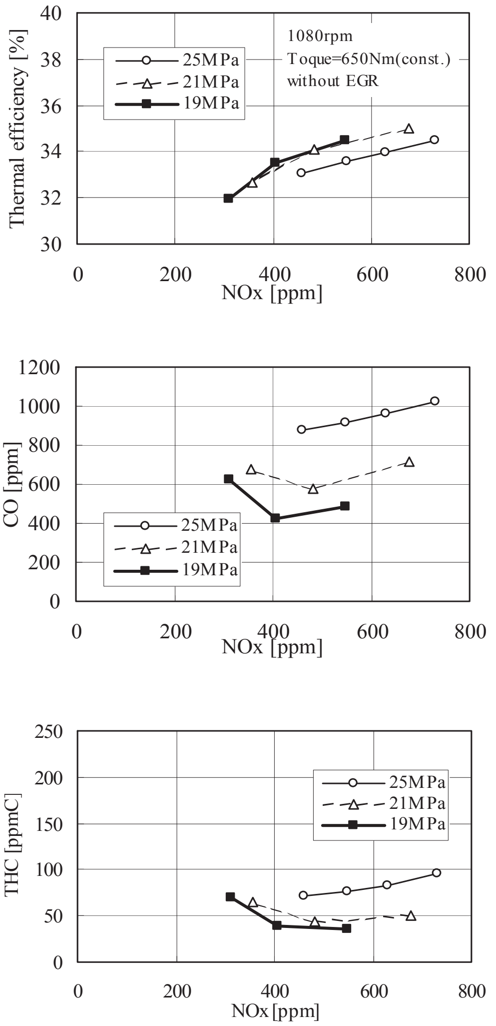

Fig. 2. Effect of fuel injection pressure at high engine speed (2700rpm)

2. Development Targets for Heavy-duty DME Truck

The target heavy-duty DME truck has a long cruising distance and is used for inter-city transport. It is a 20 ton GVW size with a load capacity of 10 tons.

Specific development target values are shown in the following list.

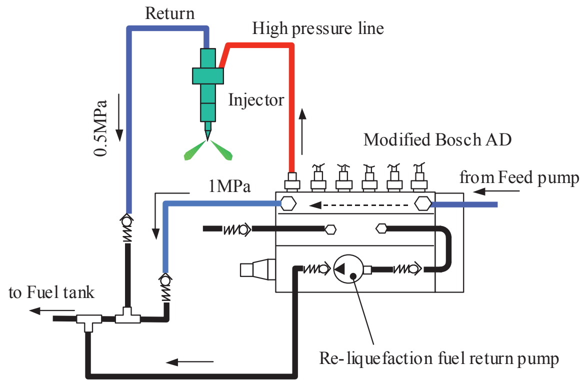

Fig. 3. Fuel injection system for DME engine

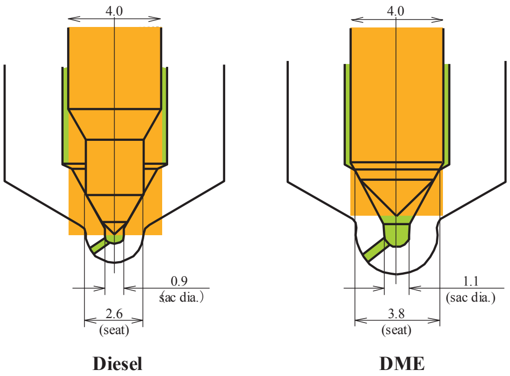

Fig. 4. Comparison of the nozzle shape

- Exhaust emissions (JE-05 mode):
  NOx = 0.5g/kWh or less,
  PM = 0.0g/kWh (negligible),
  CO = 2.22g/kWh or less,
  NMHC = 0.17g/kWh or less.
- Fuel consumption: Equivalent to base diesel engine.
- Power output: Equivalent to base diesel engine.
- Cruising distance and load capacity: Equivalent to base diesel powered truck.

3. DME Engine Development

The main specifications of the DME engine are shown at table 1. A turbocharged, intercooled diesel engine with 6.9L displacement was used as a baseline in order to ensure adequate power and performance for application to a heavy-duty truck.

3.1 Fuel Injection System Development

DME has some fairly unique characteristics compared to diesel fuel. The physical properties of DME are shown in Table 2. Most importantly, the liquid density of DME is about 80% of diesel fuel, and the specific energy content is about 70% of diesel fuel. Therefore, one must inject about twice the fuel volume compared to diesel fuel, in order to ensure the same power output as the diesel engine. In addition, the compressibility of DME is significantly higher (even in the liquid state), and it also has lower viscosity and lower lubricity. Therefore, it is not possible to use a conventional unmodified diesel fuel system for DME [1].

The effect of fuel injection timing and injection pressure on performance and emissions was investigated for each operating range using a common rail injection system. Results are shown in Figs. 1 and 2. It may be concluded from these results that the optimum fuel injection pressure in the low-speed high-load operating range may be about 19MPa, from the viewpoint of minimizing emissions and fuel consumption. Referring to Fig. 2, it was found that the target power level could not be achieved at under approximately 39MPa fuel injection pressure.

The previously obtained fuel injection parameters were recorded and an inline fuel injection pump with conventional spring-loaded needle injector was applied to the DME engine. This system (Jerk pump type system) has a comparatively simple structure, but it has very high actuation reliability. An improved version of the Bosch PE-6AD type was developed here, with a higher fuel supply capacity, so as to raise the injection quantity to about twice the normal diesel amount.

The main differences in this pump and the base diesel one are shown below;

1) Larger diameter plunger,

2) Pumping stroke increase,
3) Special treatment of the plunger surface,
4) Cam profile change,
5) Electronic control of the governor.

A schematic diagram of injection system is shown in Fig. 3.

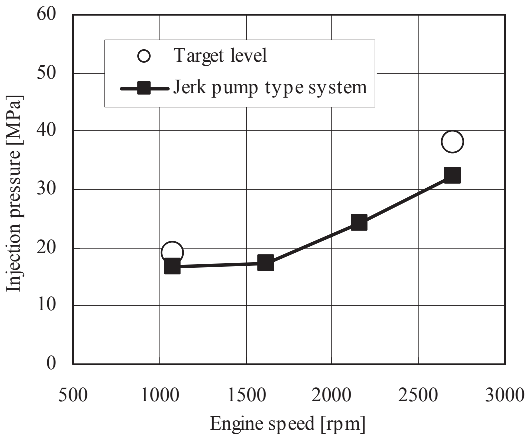

Fig. 5. Maximum fuel injection pressure at full load operation

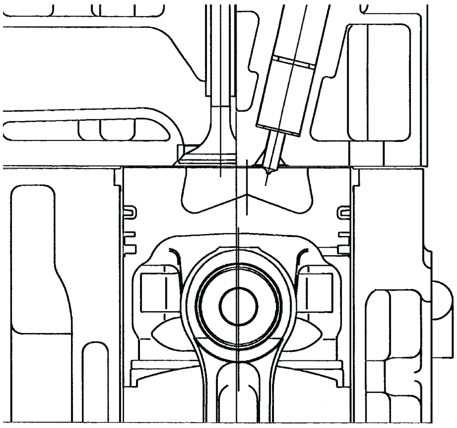

Fig. 6. DME Engine combustion system

Appropriate mechanical fuel injection timing advance was used to ensure optimum timing at each engine speed. The DME fuel system also utilized a re-liquefaction pump for returning any DME leakage into the cam case of the pump back to the tank. In addition, the injection pump has its own lubricating oil, so that the DME would not become mixed with the engine oil. The total nozzle hole area was increased to twice that of a typical diesel injector. This necessitated a change in the nozzle seat area and the shape of the resulting needle and sac region are shown in Fig. 4. System performance is shown in Fig. 5, up to the maximum injection pressure at full load operation with this injection system.

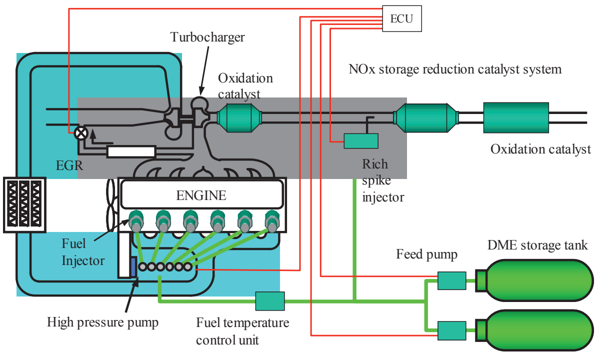

Fig. 7. DME engine system with EGR

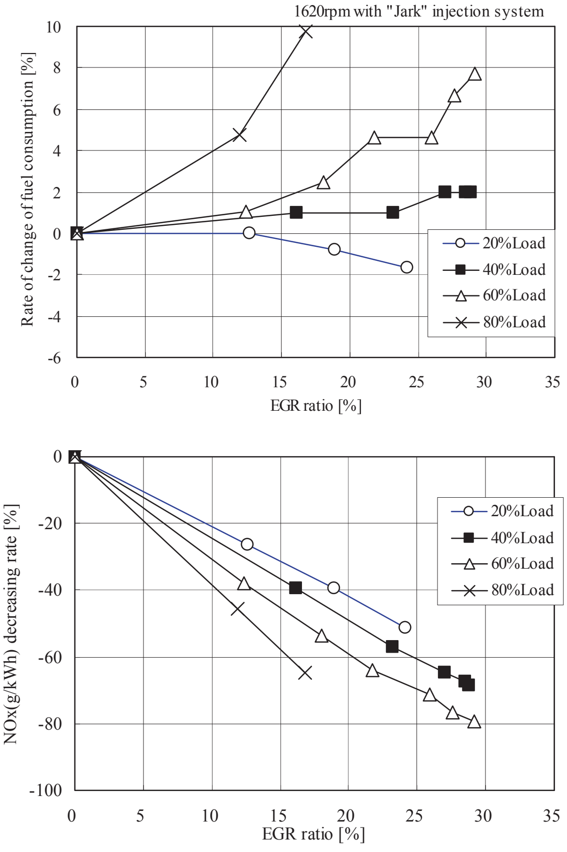

Fig. 8. Effect of EGR ratio on BSFC and NOx at 1620rpm

3.2 Combustion system

The combustion chamber configuration chosen here was a toroidal design with a 58mm diameter, and the compression ratio was 17.5 (same as base engine). The combustion system configuration is shown in Fig. 6.

3.3. EGR

The DME engine does not emit black smoke in the exhaust gas. Therefore, drastic NOx reduction by EGR is possible, in addition to optimization of the fuel injection timing. [3] As such, a significant NOx reduction was attempted using EGR. The exhaust gas was extracted from upstream of the turbine in the exhaust manifold, and supplied upstream of the compressor. A schematic of the EGR system is shown in Fig. 7.

The effect of varying the EGR ratio on performance and emissions is shown in Fig. 8. These results show that at this mid-load operating point, there was no deterioration in fuel consumption, even though NOx is halved at some of the EGR ratios used here.

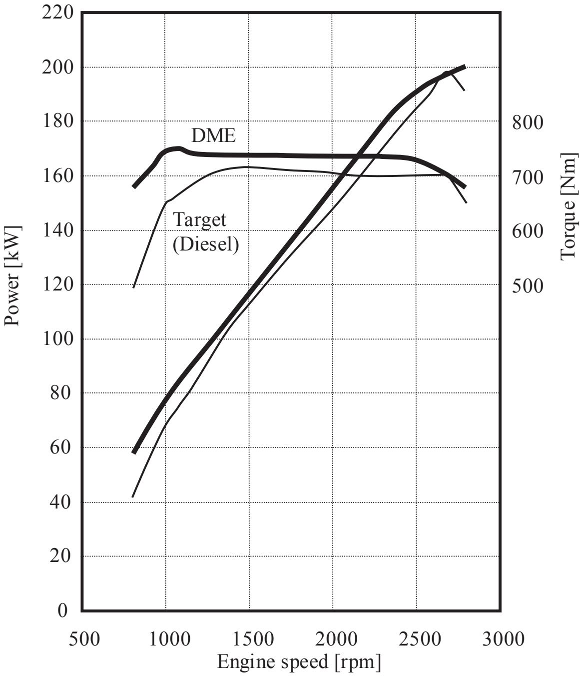

Fig. 9. Full load performance of DME engine

3.5 Power performance

The full-load performance of the DME engine is shown in Fig. 9. Note that the maximum torque and power of the DME engine could equal or surpass those of the base diesel engine, because the DME engine does not emit black smoke. We will note here that the maximum output was equivalent to the diesel engine while not exceeding the exhaust temperature limit.

4. Catalyst system development

4.1 Oxidation catalyst

It was noticed that THC emissions were higher with the improved jerk-pump type injector system. This was considered to result from the shape of the nozzle tip for the DME engine, which was required by the higher injection rate target. Thus, THC clean up was attempted using an oxidation catalyst at the turbocharger turbine outlet. The catalyst capacity was 1.5L, and a platinum-based catalyst was selected because it has shown the highest clean up performance for DME. Using the exhaust gas of a DME engine, the CO and NMHC conversion ratios for this catalyst are shown in Fig. 10.

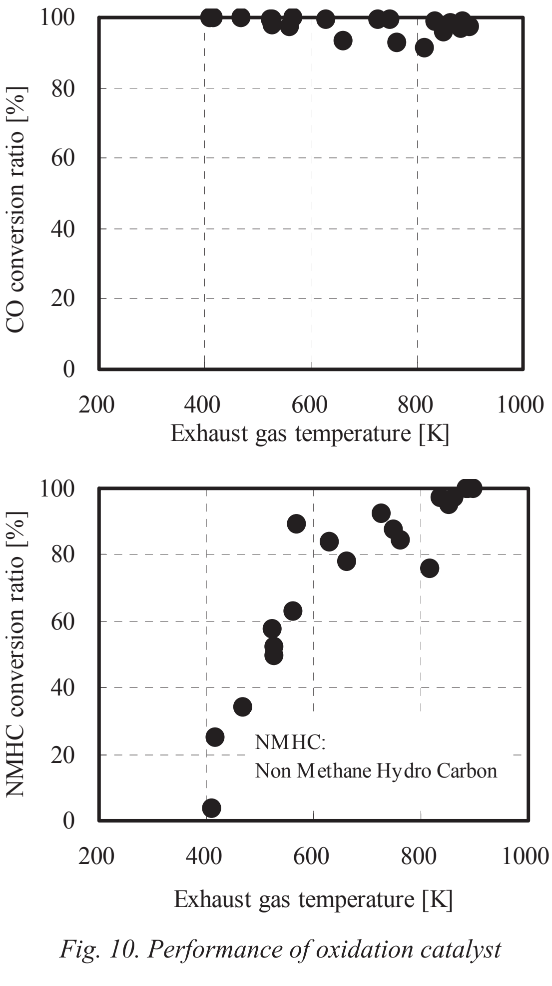

Fig. 10. Performance of oxidation catalyst

4.2 NOx storage reduction catalyst

To achieve the NOx target, an NSR system that uses DME as a reducing agent was developed for the heavy-duty DME engine. Preliminary tests to select the NSR catalyst were carried out using a single-cylinder DME engine with a displacement of 1 liter. Several types of NSR catalysts were tested, and, as seen in Figure 11, the final choice was a platinum/rhodium catalyst that provides good NOx conversion rate over a comparatively wide temperature range. Also, because PM and SOx do not accumulate in the catalyst for a DME engine, a NSR catalyst with a cell density higher than that of the NSR catalyst for a diesel engine is used.

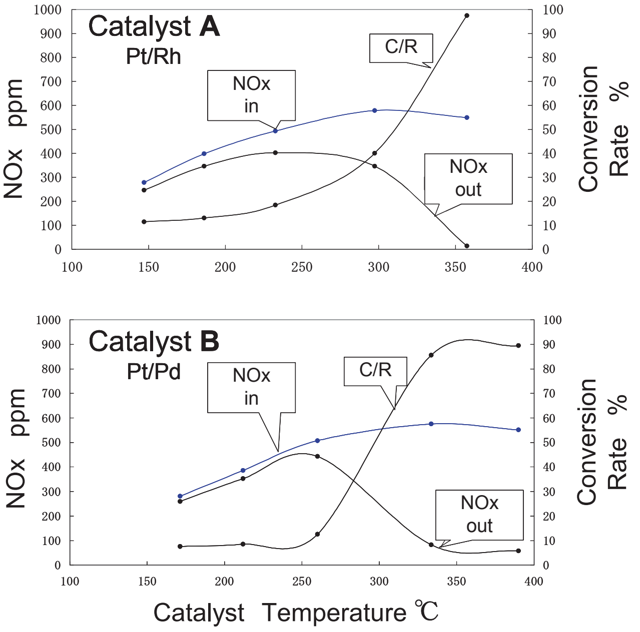

Figure 11. Characteristics of NSR catalyst

Figure 12 shows an overview of the NSR test apparatus that was used for engine bench test. The injector that is used for the rich spike is installed in the exhaust pipe using an adapter, just upstream from the NSR catalyst. Downstream from the NSR catalyst, a 5.1-liter platinum/palladium oxidation catalyst is installed to prevent the hydrocarbon slip that accompanies the rich spike. The signals from the NOx concentration sensors and temperature sensors upstream and downstream from the NSR catalyst are used along with the engine speed and the acceleration stroke signals as the input signals for controlling the rich spike. The timing, interval, and number of cycles for the rich spike were determined by means of a rich spike control algorithm that was created based on the results of rich spike optimization testing.

Tests were conducted to optimize the rich spike, the control of exhaust gas temperature, and the catalyst capacity in the NSR system. The test conditions are shown in Table 3. In the sequence from Control 1 to Control 4, the control of the timing, injected quantity, and injection interval for the rich spike has been made more precise. In Control 5, heat insulation for the exhaust pipe and intake air throttling during idling have been added as ways of raising the exhaust gas temperature. In Control 6, the capacity of the NSR catalyst has been increased from 8 liters to 13 liters. Figure 14 shows the relationship between NOx and brake specific fuel consumption (BSFC) in the JE-05 test, as well as the relationship between non-methane hydrocarbons (NMHC) and carbon monoxide. NOx is decreases in half by EGR and further reduced by the NSR catalyst. However, when the NSR catalyst is used, there is a trade-off between NOx reduction and fuel consumption. In the end, the NOx target was achieved by throttling the intake air during idling, and increasing the capacity of the NSR catalyst. The same measures also made it possible to achieve the NMHC target.

5. Exhaust emissions and fuel consumption performance

The results of the JE-05 emissions test for the NSR system that was developed are shown in Figure 13. The NOx results of 0.11 g/kWh indicate that the project target was achieved by a comfortable margin. The carbon monoxide and NMHC targets were also achieved. The level of PM has been reduced almost to zero (0.01 g/kWh), less than one-twentieth of the new long-term regulation value. When equipped with the NSR system, the DME engine for heavy-duty trucks conforms to the Japanese regulations for 2009, which as of May, 2005, gives it lowest emissions levels in the world for a heavy-duty truck engine, as shown in Figure 14. Figure 15 shows emission regulation for H/D diesel engines.

Figure 16 shows the diesel converted fuel consumption that was calculated on the basis of the CO_2 emissions in the D-13 emissions test mode. With DME fueling the overall fuel consumption was very similar to the base diesel engine level, even when DME was used as a reducing agent [4] [5].

6. CO_2 Emissions

Figure 17 shows a comparison of the DME engine's CO_2 emissions in the D-13 emissions test mode with those of a diesel engine with the same displacement. The DME engine's CO_2 emissions are somewhat lower than those of the diesel engine, even when the NSR system is used.

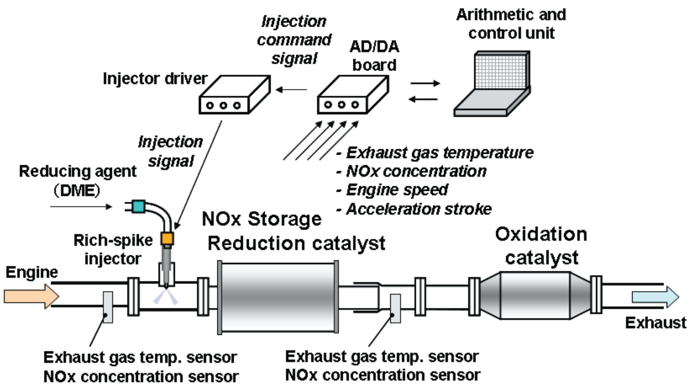

Fig. 13. NSR system for engine bench test

Table 3. Test conditions of NSR system

Base	Base engine condition
EGR	Exghaust Gas Recirculation control
Rich spike control	
Control 1	R/S injection is applied in regular interval and quantity
2	Optimization in the R/S injection interval
3	Optimization in the R/S injection quantity
4	Precision of R/S interval and quantity
5	Installation of intake throttle and thermal insulation in exhaust system
6	Optimization of catalyst volume (8L NSR catalyst + 5L NSR catalyst)

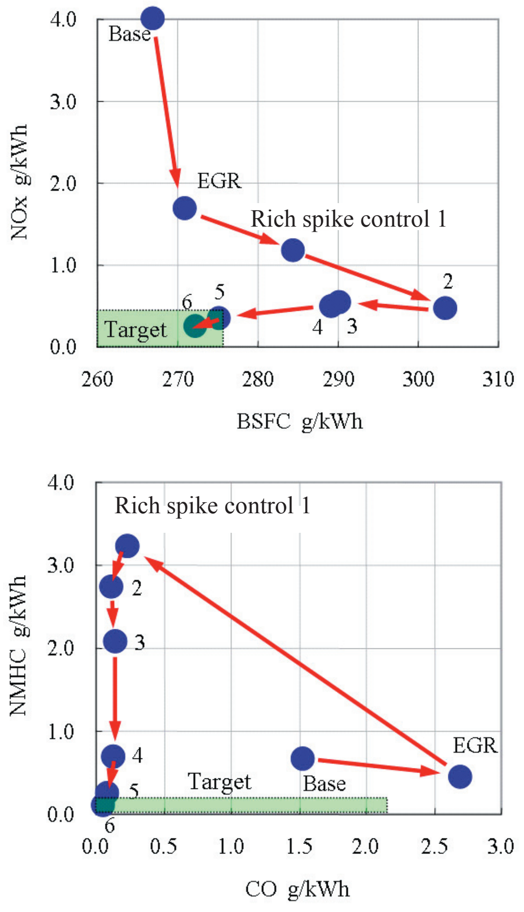

Fig. 13. Relationship between BSFC, NOx, NMHC and CO emissions in the JE-05 test

7. Conclusions

This project expanded the boundaries of alternative clean fuel application to real-world transportation. From the work done here, we can make the following conclusions:

1) The power and performance of the DME engine developed here exceeded those of an equivalent diesel engine.

2) Application of EGR and a NOx reduction catalyst allowed NOx levels to reach ultra-low levels. Specifically, typical values were 1/4 of the 2005 (Japan) long-term regulation limit.

3) The power and performance of the DME truck was equivalent to a diesel truck.

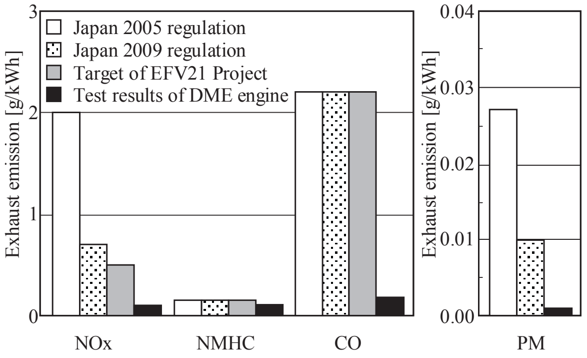

Fig. 14. Emission test Results (JE-05 test)

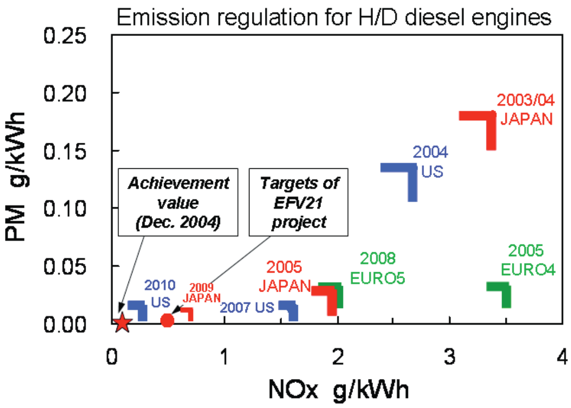

Fig. 15. Achievement level of emissions

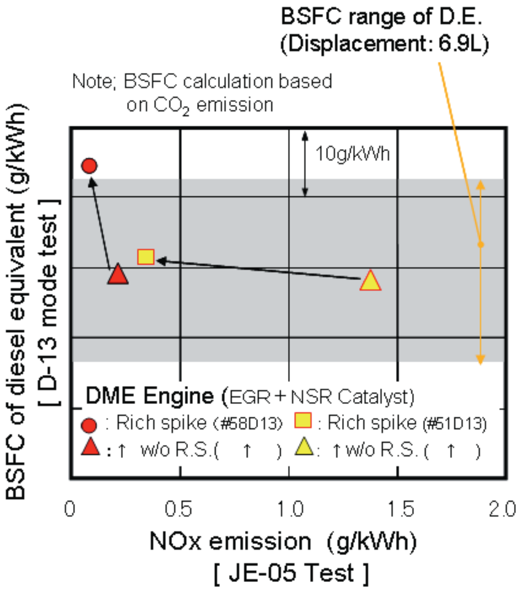

Fig. 16. Fuel consumption comparison with diesel engine (D-13 mode test)

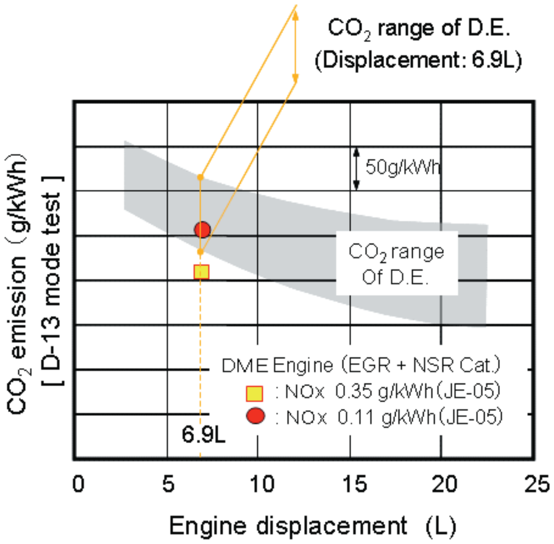

Fig. 17. CO_2 emission (D-13 mode test)

4) Future work should include investigation of user-friendliness, reliability and durability of the DME truck in various environments and conditions by extensive field testing.

8. Acknowledgements

The development reported here was carried out as a part of the Ministry of Land, Infrastructure and Transport's Next-Generation Environmentally Friendly Vehicles Project (EFV21), with collaboration among industry, government, and academia. The developers want to take this opportunity to express their sincere gratitude for the generous cooperation they received in the course of the project.

9. References

[1] D. Ushiyama, T. Noda, S. Nozaki and H. Oikawa, “An Investigation of DME Injection Characteristics using Jerk type In-line Injection System”, JSAE paper 20035068 (2003).

[2] “Journal of Society of Automotive Engineers of Japan”, vol.52, No.7, July, 1998.
[3] Y. Sato, A. Noda, T. Sakamoto and Y. Goto, “Performance and Emission Characteristics of a DI Diesel Engine Operated on Dimethyl Ether Applying EGR with Supercharging ”, SAE Paper 2000-01-1809.
[4] Seang-Wock Lee, et al., “The Development of NOx Storage Reduction System for Heavy-Duty Dimethyl Ether Engine”, SAE 2005-01-1088.
[5] Y. Sato, et al., “Research and Development of Heavy-Duty Truck fueled with DME – Development and Performance of a DME engine-“, JSAE 2005 5298 (2005).