# DEVELOPMENT OF DME (DIMETHYL ETHER) FUELED DIESEL ENGINES FOR LIGHT-DUTY TRUCKS MEETING 2009 JAPAN EMISSION REGULATION

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***Abstract***

*DME fuel has been attracting attention as an alternative fuel for diesel engine. DME has a high cetane number and compression ignition capability. This enables a high thermal efficiency comparable to diesel engines. Moreover, DME creates no smoke or sulfur oxide. However, even when using DME, NOx still remain problems under stringent exhaust emission regulations. For severe NOx regulation and develop of alternative fuel for diesel engines, the diesel engines (Isuzu Motors Limited: 4HG1T) fueled with DME for light-duty trucks using a jerk type in-line DME injection system which meet the JAPAN 2009 emissions regulation was developed. Adopting the lower exhaust emission technology, such as a large volume EGR system with air-throttled and inter-cooled turbo-charging, National Traffic Safety and Environment Laboratory and Bosch Corporation has demonstrated the low-emission engines which achieve to reduce NOx emission level by about 50% (0.37 g/kWh) of the 2009 emissions regulation (<0.7 g/kWh) without a NOx reduction catalyst system.*

***Keywords:*** *light duty tracks, diesel engines, alternative fuels, DME, emission regulations*

## 1. Introduction

The introduction of new, cleaner fuels for diesel automobiles is being studied for the following objectives: as a means of taking drastic measures against the pollution of air with suspended particulate matter (SPM) and nitrogen dioxide ($NO_2$) in urban areas, as a countermeasure against global warming, and for diversifying automobile fuels. Among them, dimethyl ether (DME) features good compression ignitability without emitting black smoke during combustion. Thus, when DME is used in heavy-duty diesel vehicles, the particulate matter (PM) and nitric oxide (NOx) emissions can be reduced to almost zero, while engine and vehicle performance levels remain equivalent to those of conventional diesel [1].

Meanwhile, light-duty diesel trucks are commanding a significant presence in cities, where they are used primarily for deliveries. Because the operation of these trucks affects residential areas, the introduction of next-generation, low-emission, light-duty trucks is desired. Their PM and NOx emissions should be practically zero, while their utility factors such as engine performance, drivable range, and load capacity should remain the same as those of existing light-duty diesel trucks.

In the present study, we developed a DME engine for light-duty truck application, aimed at ultra-low level exhaust gas emissions without using after-treatment devices such as a diesel particulate filter (DPF) or NOx reduction catalyst. This paper gives an outline of the injection, intake, and exhaust systems of the developed DME engine. In addition, it describes the results of an exhaust gas emissions test that was conducted, targeting PM emissions of almost zero and NOx emissions below the levels of the 2009 Japan Emission Regulation.

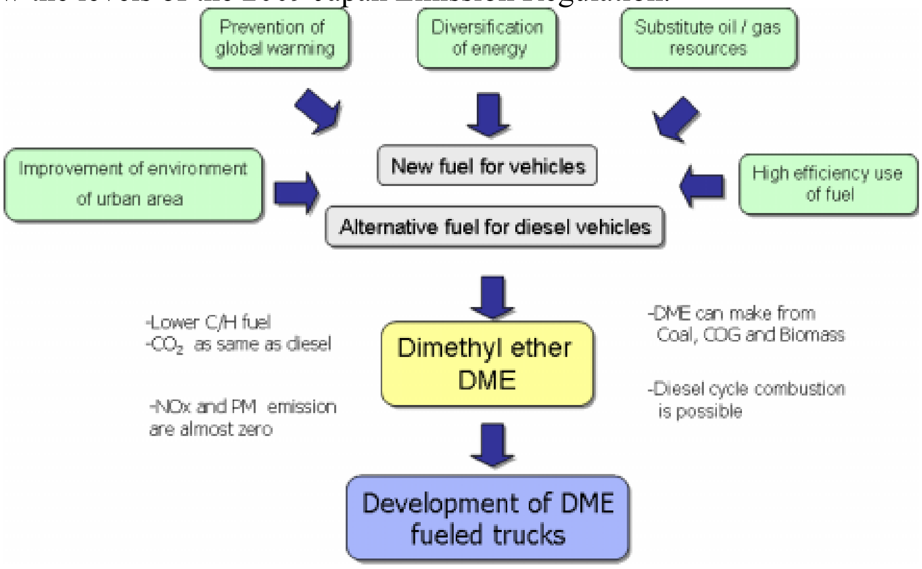


*Fig. 1 Background of Development*

## 2. Development Targets and Purpose

The present development has been carried out as part of the Next-Generation, Low-Emission Vehicle Development - Practical Implementation Project (EFV21) by the Ministry of Land, Infrastructure, and Transport [2]. The development engine is a DME engine for a 2-ton capacity light-duty truck, with the following development objectives:

Exhaust emissions*: *measurement by the JE-05 exhaust emissions test mode
NOx: 0.5 g/kWh (approx. 2/3 of 2009 mean value standards)
CO: 2.22 g/kWh (2009 mean value standards)
NMHC: 0.17 g/kWh (2009 mean value standards)
PM: 0.0 g/kWh (near zero)
Fuel economy and engine output: same as base diesel engine

The DME engine was developed based on the concept as follows. It uses an inline jerk-type fuel injection pump, which has been optimized for small DME engine application, in order to produce the proper power output. Furthermore, it puts the high efficiency of diesel combustion to its best use in achieving fuel economy. The use of the storage reduction type NOx reduction catalyst has been proven to be highly effective in significantly reducing NOx in DME engines [1]. However, because the exhaust temperature of a small engine is low, it does not perform well in terms of the catalytic activity. Another issue is the lack of space for installing a catalyst along the exhaust system. By putting the foremost feature of the DME engine, which emits zero black smoke emissions, to its best use, we aimed to meet the target NOx level through the use of a large-volume exhaust gas recirculation (EGR) system.

## 3. DME Engine Development

### 3.1 Engine and Emission Control System

*Table 1. Specifications of the DME engine*

| | Base diesel engine | DME engine |
|---|---|---|
| Model | ISUZU 4HG1T | ← |
| Cylinder | Inline 4 | ← |
| Bore * Stroke | 115mm * 110mm | ← |
| Total displacement | 4570cc | ← |
| Compression ratio | 19.0 | ← |
| Maximum power | 89kW / 3200rpm | ← Target |
| Maximum torque | 325Nm / 1800rpm | ← Target |
| Injection system | Inline jerk (PE-S4AD105) | ← Modify for DME |
| Aspiration | Turbo charge | T/C with intercooler |

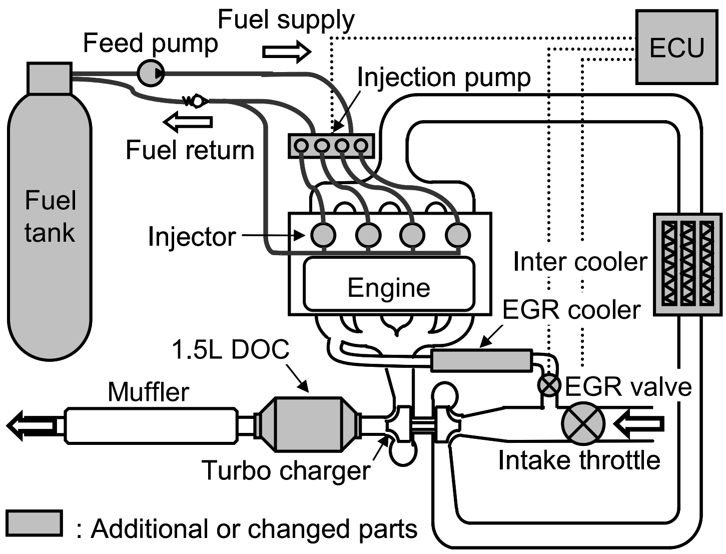


*Fig. 2 Outline of DME Engine and Exhaust System*

Table 1 shows the main specifications of the DME engine. Fig. 2 shows the outline of the DME engine and the exhaust system. The engine is to be installed on a 2-ton, light-duty truck intended for urban deliveries. The DME injection system is installed on the base engine, which is a 4.6-liter displacement, inline 4-cylinder, and turbocharged engine. To carry out a large-volume EGR as a NOx reduction measure, the EGR gas that has been branched off from the exhaust manifold has been recirculated into the intake side of the turbocharger compressor. During a certain operating range of EGR, including idling and low-speed, low-load conditions, the intake-air is throttled to ensure a high EGR rate. Furthermore, to enhance the NOx reduction effect by suppressing the temperature rise of the EGR gas and charged intake air, a high-performance EGR cooler and an intercooler have been provided. As a countermeasure against the emission of unburned fuel that results from the high-volume EGR, a compact, 1.5-liter oxidation catalyst has been equipped near the exit side turbocharger.

### 3.2 DME Injection System

DME has some 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.

*Table 2 Properties of DME*

| | 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 | $N/m^2$ | $6.37\times 10^8$ | $1.49\times 10^9$ |
| Lower Calorific Value | MJ/kg | 28.8 | 42.7 |
| Vapor pressure (@293K) | kPa | 530 | - |
| Auto ignition temperature | K | 508 | 523 |

*Table 3 Comparison of Injection System specifications*

| | | Base Injection System (PE-S4AD105) | DME Injection System (PE-S4AD105) |
|---|---|---|---|
| Plunger | Diameter | 10.5mm | ← |
| | Lead | 25 Lead | 30 Lead |
| Cam | Lift | 11mm | ← |
| | Profile | PEA-U-10 | PEA-U-104 |
| Timer | Advance Angle | 4° (Np:1100～1535rpm) | 6.7° (Np:500～1500rpm) |
| Nozzle | Type | DLLA-P | ← |
| | Number | 5 | ← |
| | Orifice Dia. | 0 24mm | 0.38mm |
| | $P_o$ | 18.5MPa, 21.5MPa (2 spr.) | 11.8MPa (1 spr.) |

The injection system [3], which is optimized for DME application, is based on the jerk-type fuel injection pump, which is believed to easily ensure the basic operation reliability even with the use of a low lubricity fuel, such as DME. Table 3 compares the main specifications of the base diesel injection system and the DME injection system. Fig. 3 shows the configuration of the DME injection system. The DME fuel system consists of the following changes:

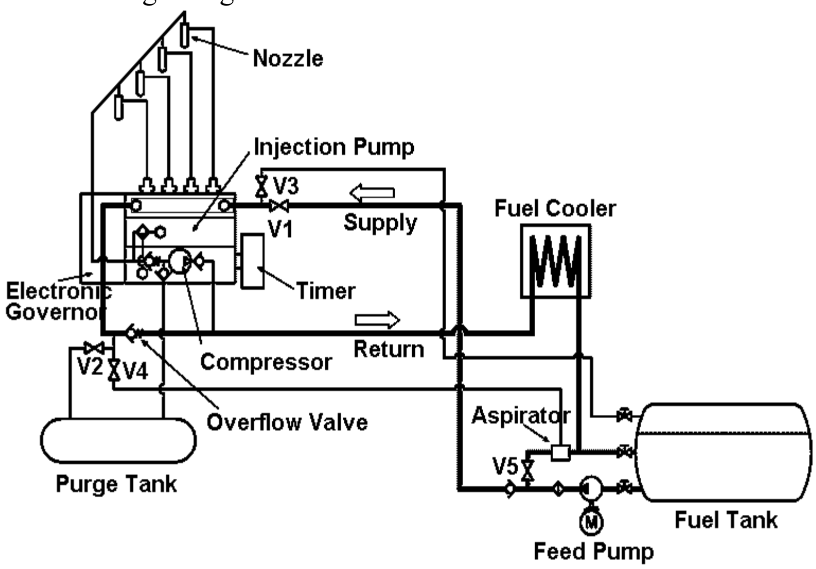


*Fig. 3 Configuration of Jerk Type DME Injection System*

1) Larger injection volume: Because the injection volume of DME must be double that of diesel fuel, an injection pump with the largest plunger diameter in the series and cam lift is used. To produce a large, effective stroke, the angle of the plunger lead has been extended upright and the injection pump cam profile is used that can produce a large pumping stroke. To suppress the increase in the injection duration associated with the large injection volume, the injection orifice area of the injection nozzle has been increased. At the same time, the shape and area of the seat has been revised, in order to optimize a needle-tip shape that eliminates seat restriction.
2) Larger advance timer: The volumetric elasticity of DME is approximately one-third that of diesel fuel, creating a greater delay in injection timing than diesel fuel. For this reason, this system has adopted a larger advance timer.
3) Low-pressure supply system: To ensure the stable injection of DME, which is a liquefied gas fuel, it is necessary to use a feed pump to pressurize the fuel higher than the saturated vapor pressure, and deliver it to the injection pump in the liquefied state (the delivery flow rate is 4L/min and the delivery pressure is the in-tank vapor pressure + 0.5 MPa).
4) Preventing leakage into the combustion chamber: The gas sealing performance of the diesel injection nozzle is not perfect. Therefore, after the engine is stopped, this system purges the fuel remaining in the fuel delivery pipes, high-pressure injection pipes, and injection nozzles through the use of the following combination: suction by an aspirator, introduction of fuel vapor from the tank, and operation of a valve.
5) Suppressing plunger leakage: The fuel injection pump is an oil-filled type that prevents DME from entering the engine crankcase. The pressure increase in the cam chamber must be prevented by the gasification of the DME, which has leaked from the plunger into the cam chamber. To do so, a compressor, which is driven by the injection pump camshaft, gasifies the leaked DME by reducing its pressure, and converts it back into the liquefied state and returns it to the fuel tank.
6) Ensuring lubricity: To prevent the plunger seizure due to the low lubricity of DME, 800 ppm of LZ539ST, a lubricity improver, has been added to the DME fuel (99.99% purity).

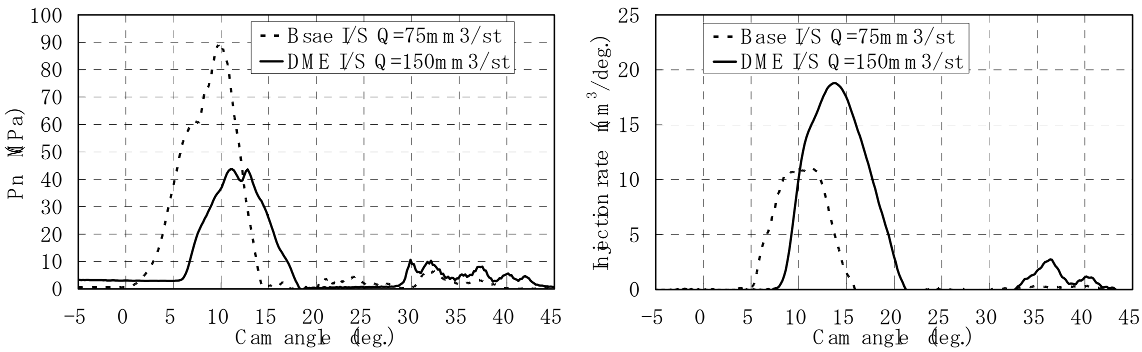


*Fig. 4 Comparison of Injection Characteristics*

Fig. 4 shows a comparison of the injection pressure (pipe pressure at the nozzle) and injection rate measurements obtained from these injection systems. The injection pump speed was set to 1500 rpm, and the injection volume was set to 75 $mm^3$/st for the diesel fuel and 150 mm3/st for the DME, in accordance with their heat values. As with the diesel fuel system, the DME system was able to attain a stable injection waveform that is reproducible.

## 4. Engine Performance Test

### 4.1 Output

Fig. 5 shows the output characteristics of the DME engine and the base diesel engine. The torque curve for the test engines was set to be within the maximum torque and the exhaust temperature limit of the base diesel engine. As a result, the DME engine has produced a power output that exceeds the base diesel engine. In particular, because the DME engine is not subject to a torque limitation associated with the emission of black smoke, its torque can be increased in the low-speed range, creating a practically flat torque curve between 1,000 and 3,000 rpm. Fig. 5 shows the output characteristics of the DME engine and the base diesel engine. The torque curve for the test engines was set to be within the maximum torque and the exhaust temperature limit of the base diesel engine. As a result, the DME engine has produced a power output that exceeds the base diesel engine. In particular, because the DME engine is not subject to a torque limitation associated with the emission of black smoke, its torque can be increased in the low-speed range, creating a practically flat torque curve between 1,000 and 3,000 rpm.

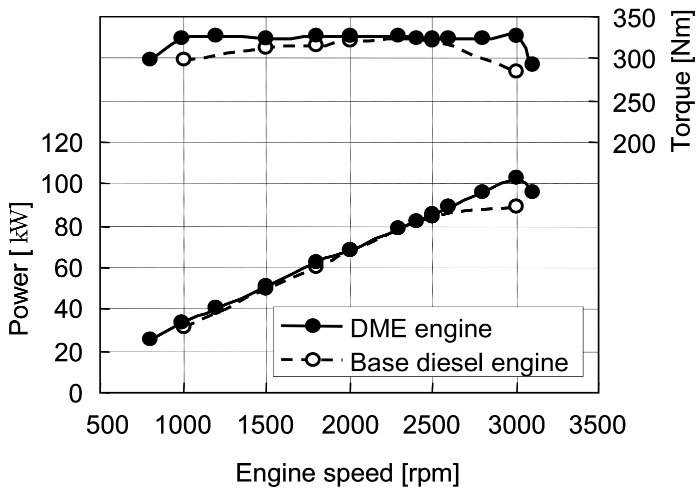


*Fig. 5 Engine Output Curve*

**4.2 Optimizing EGR**

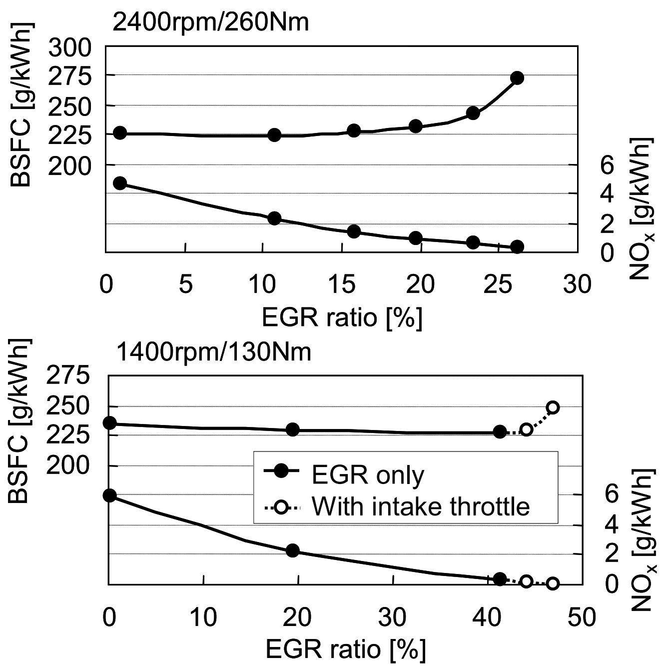


*Fig. 6 Effect of EGR on BSFC and NOx*

Fig. 6 shows the results of an examination of the relationship between the exhaust gas recirculation (EGR) rate, brake specific fuel consumption (BSFC), and NOx emission during a high-speed, high-load operation (2,400 rpm at 260 Nm). At EGR rates of up to 20%, NOx emissions can be reduced without adversely affecting the BSFC rate. Similarly, the figure shows the results obtained during a low-speed, low-load operation (1,400 rpm at 130 Nm). In this operating range, the changes in the BSFC rate are minimal even when the EGR valve is opened fully. Therefore, through the concurrent use of the air-throttle valve, the EGR rate was increased to approximately 45%.

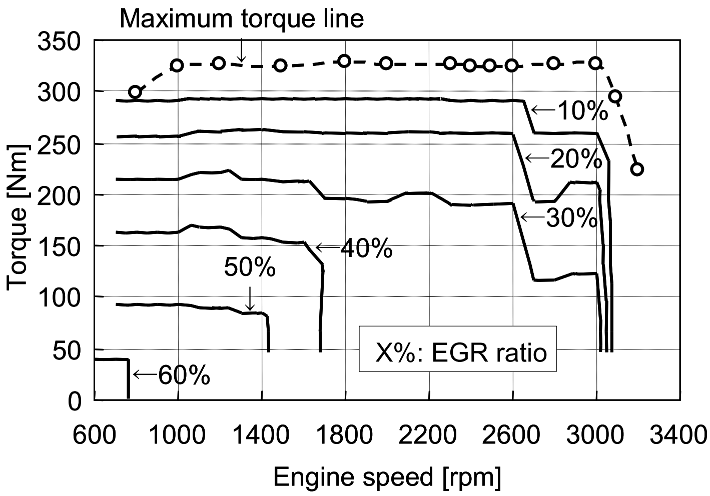


*Fig. 7 EGR Ratio Map*

Based on these findings, Fig. 7 shows the results in which the EGR rates were set on a BSFC-priority basis, in all operating ranges of the engine. The EGR rate in which the air-throttle was used concurrently was limited to an operating range of below 1,600 rpm and below 130 Nm. The EGR rate set here was a large-volume EGR exceeding 40%. Moreover, the EGR rate at idle was set to 70%.

### 4.3 Exhaust Emission Test

Fig. 8 shows the NOx emission behavior observed during a JE-05 exhaust emission test mode. Due to the effect of the EGR, the NOx emission concentration is suppressed to about 100 ppm or less even during acceleration, or a high-speed, or high-load operating condition.

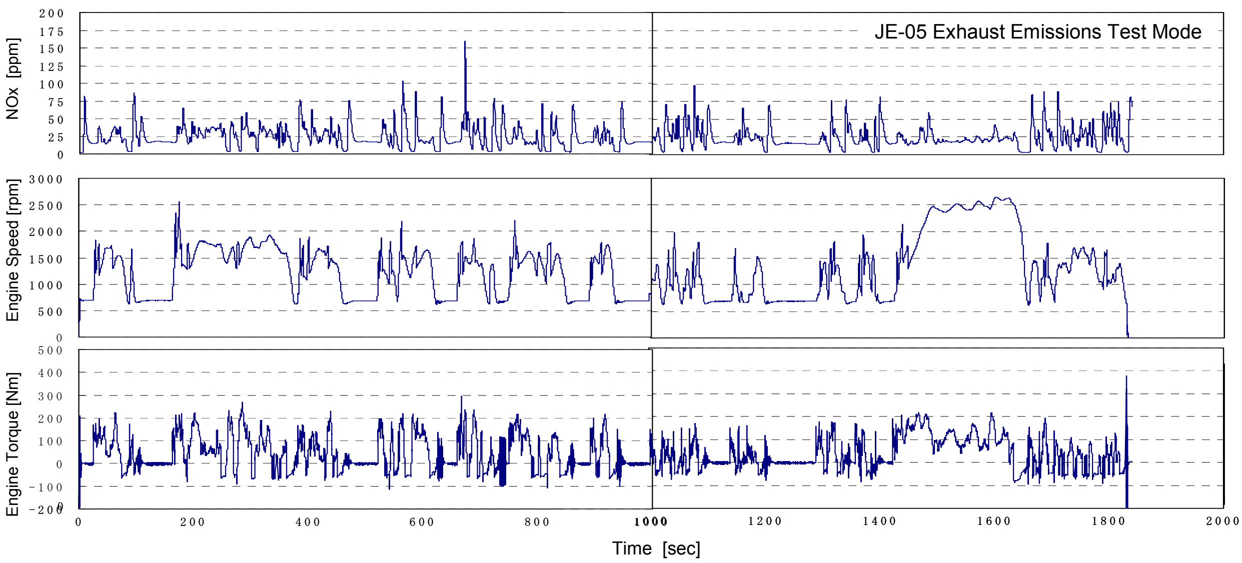


*Fig. 8 NOx Emission Behavior during JE-05 Emission Test Mode*

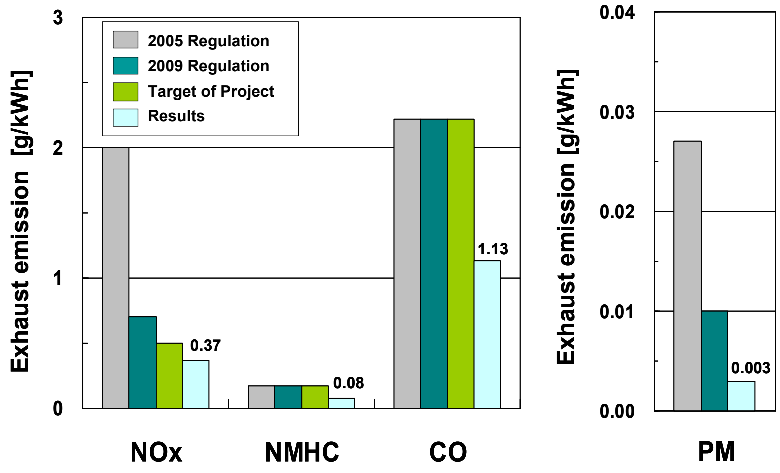


*Fig. 9 Emission Test Results (JE-05 Emission Test Mode)*

Fig. 9 shows the results of a JE-05 exhaust emission test conducted on a DME engine that uses a large-volume EGR system and a compact oxidation catalyst. The NOx emission level was approximately one-half the value prescribed by the 2009 Japan Emission Regulation, thus attaining our development target. Even non-methane hydrocarbons (NMHC) and carbon monoxide (CO) emissions, which had been feared to increase due to the use of the large-volume EGR, were actually lower than the 2009 Japan Emission Regulation levels. The PM emission is nearly zero, easily meeting the 2009 Japan Emission Regulation requirements.

### 4.4 Comparison to Commercial Diesel Engine

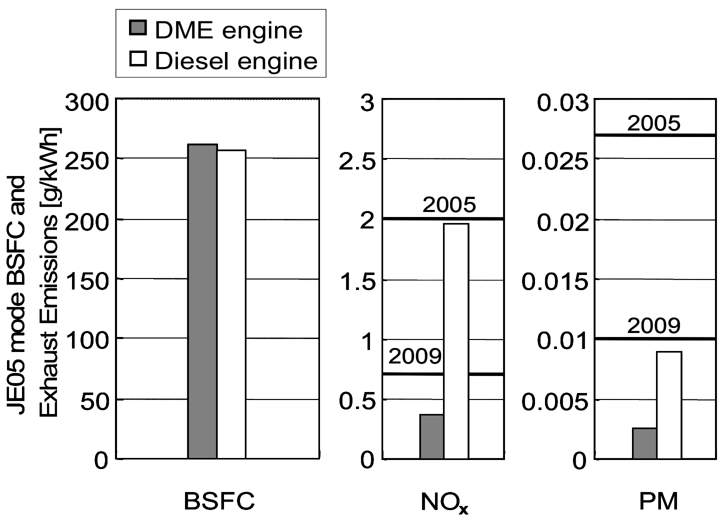


*Fig. 10 Comparison of BSFC, NOx and PM (JE-05 Mode)*

Fig. 10 shows the results of a comparison of BSFC, exhaust emission, and PM obtained through a JE-05 exhaust emission test mode operation of the DME engine and a commercial, light-duty truck diesel engine (set to 4.1-liter displacement, compliance with the new short-term regulation, DPF + NOx storage reduction catalyst system, ultra-low PM emission level, 2-ton load capacity). The diesel engine was tested with a low-sulfur diesel fuel (10 ppm). Although a rich spike was provided to the NOx catalyst at this time, no regeneration of sulfur or PM from the DPF was carried out. The DME engine has produced practically the same BSFC as the commercial diesel engine, and low levels of NOx at 80%, and PM at 70%.

## 5. Conclusions

A DME engine for light-duty trucks that uses an inline jerk-type DME fuel injection syaytem aimed at complying with the 2009 Japan Emission Regulation has been developed. Performance and exhaust emission tests (JE-05 emission test mode) conducted on this engine have produced the following conclusions:

1) In spite of using only a large-volume EGR, without the use of a DPF or NOx reduction catalyst, the engine has achieved a NOx level that is approximately one-half the 2009 Japan Emission Regulation level, thus attaining the development target.

2) The use of the small oxidation catalyst enabled the engine to achieve NMHC and CO emissions that are below the 2009 Japan Emission Regulation levels. The amount of PM emission is nearly zero, easily meeting the 2009 Japan Emission Regulation requirements.

3) The output of the DME engine was greater than the base diesel engine. Compared to a low exhaust emission type commercial diesel engine, the DME engine has produced practically the same BSFC (JE-05 emission test mode), and low levels of NOx at 80%, and PM at 70%.

In the future, we need to evaluate and examine the developed DME engine in terms of functions, practicability, reliability, and durability by assemble it on a vehicle, test-driving it on public roads under varying atmosphere environments.

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