

Study of DME Diesel Engine for Low NO_x and CO₂ Emission and Development of DME Trucks for Commercial Use

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ABSTRACT

Study of DME diesel engines was conducted to improve fuel consumption and emissions of its. Additionally, DME trucks were built for the promotion and the road tests of these trucks were executed on EFV21 project. In this paper, results of diesel engine tests and DME truck driving tests are presented. As for DME diesel engines, the performance of a DME turbocharged diesel engine with LPL-EGR was evaluated and the influence of the compression ratio was also explored. As for DME trucks, a 100,000km road test was conducted on a DME light duty truck. After the road test, the engine was disassembled for investigation. Furthermore, two DME medium duty trucks have been developed and are now the undergoing practical road testing in each area of two transportation companies in Japan.

INTRODUCTION

From the requirement of CO₂ reduction for global warming issue and energy security, the new power sources involved next generation internal combustion engines is required for future automobiles. While Hybrid Electric Vehicles and Electric Vehicles are expected to be used in passenger cars, the internal combustion engine, particularly the diesel engine, will play a significant role in the future for heavy-duty trucks due to its high thermal efficiency and high energy density compared to future batteries. And Di-Methyl Ether (DME) has a high potential as an alternative fuel for diesel engines of the future.

DME generates little amount of soot in its combustion. Therefore an engine fueled by DME does not require after-treatment devices like diesel particulate filters (DPF) which is needed to clean exhaust gasses in using light oil and diesel oil synthesized by the Fisher-Tropsch method. This enables the user to decrease life cycle costs. In addition DME, which has a high cetane number and can thus be used in diesel

engines, produces better thermal efficiency than compressed natural gas (CNG) or liquefied petroleum gas (LPG) used for Otto engines. Moreover, DME can be extensively adapted to diversification of raw materials for production in the future because it can be produced from various sources such as coal, natural gas, biomass and so on. Also, the use of Bio-DME is available, which can decrease emitted CO₂.

Because of these factors, DME is being focused on as an alternative fuel for the diesel engine. At the same time, until now many studies related to diesel engines fueled by DME have been made. In addition to studies for DME spray and the seat abrasion in injectors, studies of the performance of DME engines and road test results of trucks equipped with DME engines were reported [1,2,3,4]. As in this study, DME engines equipped with common rail systems and DME vehicles with this engine have been developed [5].

Previously, DME naturally aspirated engines equipped with common rail systems were developed, and emission results complied with the post new long term (PNLT) regulations of Japan, by using a large amount of EGR and only diesel oxidation catalysts without DPF. In addition, a DME light duty truck installed with this naturally aspirated engine was developed. It obtained the Ministry's certification and was tested within the Environmentally Friendly Vehicles 21 (EFV21) Project of the Ministry of Land, Infrastructure, Transport and Tourism in Japan.

Next, a DME turbocharged engine equipped with a common rail system was developed for further improvement of fuel consumption compared with the DME naturally aspirated engine. Its emission results were also complied with PNLT regulations by using a large amount of EGR and only diesel oxidation catalysts without DPF. In addition, two DME medium duty trucks, installed with the same turbocharged engine, have also been certified by the Ministry. These trucks were tested within the EFV21 project, and are currently being tested in each area of two transportation companies in Japan [6].

In this paper, the DME turbocharged engine's exhaust gas recirculation (EGR) system has been changed from a high-pressure loop EGR (HPL-EGR) to a low-pressure loop EGR (LPL-EGR) for further improvement of exhaust emissions and fuel consumption. The results of the performance evaluated in this engine test are shown, at the same time, the effect of compression ratios with LPL-EGR system is explained. In addition, as for DME truck, results of the road tests and the disassembly analysis of a DME light duty truck are shown, and the statuses of demonstration road test of DME medium duty trucks are explained.

ENGINE TEST

TEST ENGINE

Table 1 shows engine specifications, and Figure 1 shows the engine performance of brake torque and brake power during full load. In this experiment, the engine employed is an ISUZU 4HK1-TCN. The full load performance of the test engine fueled by DME was set at the same as that of the base engine fueled by light oil. Maximum torque was 419Nm at 1600rpm, and maximum power was 114kW at 2600rpm. The engine used for testing was equipped with a common rail injection system modified for DME. The differences between the engine modified for DME and the base engine are mainly the injectors, common rail and the supply pump. Injectors have no static leakage because DME is low viscosity, and its maximum injection pressure is 80MPa. In regards to the injection pressure, Konno et al. reported that the average interior equivalence ratio of spray was nearly identical for a light oil spray with 200MPa injection pressure compared to a DME spray with 60MPa injection pressure [7]. The common rail has a pressure reduction valve, which allows pressure control to be adapted for transient engine operation. The supply pump is a pre-stroke control type and has a rod seal to prevent leakage of DME on its plunger. As for the after-treatment device, only two oxidation catalysts are installed to this DME engine without using DPF because DME forms little soot in its combustion. One 1.9L catalyst is located after the turbine outlet while the other catalyst, 5.1L, is located on the downstream side of the exhaust pipe. The DME fed to the engine contains a lubricant of fatty acid of 100ppm to prevent metal abrasion.

This time, the EGR system has been changed from HPL-EGR to LPL-EGR. Figure 2 shows an outline of the EGR system for both HPL-EGR and LPL-EGR systems. The LPL-EGR system takes EGR gas after the turbine outlet and delivers it to before the compressor inlet while HPL-EGR system takes EGR gas from exhaust manifold and delivers it to the intake manifold. Therefore, the amount of exhaust gas which passes the turbine on LPL-EGR system is greater than that of HPL-EGR system when EGR gas is fed to the engine. In the case of adapting the LPL-EGR system to engines fueled by light oil, corrosion by sulfur content on the compressor vanes and so on, is a serious problem. Also, EGR gas has to be taken after DPF because of pollution by soot, which is gen-

Table.1 Test engine specifications

Engine Name	4HK1-TCN
Engine Type	4Stroke, L4, SOHC
Bore × Stroke	φ 115mm × 125mm
Displacement	5193cc
Compression Ratio	14.5:1, 17.5:1(Base), 20.5:1
Charge Type	VGS Turbocharger with Intercooler
Ignition Type	Compression Ignition
Fuel Injection System	Common Rail
Injection Type	Direct Injection
Injection Pressure	MAX80MPa
Injection Nozzle	7-φ0.35mm
EGR System	LPL-EGR
Exhaust Gas Aftertreatment	Oxidation Cat. 1.9L Oxidation Cat. 5.1L

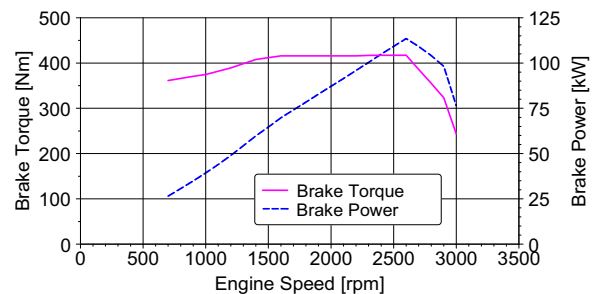


Fig.1 Full load engine performance

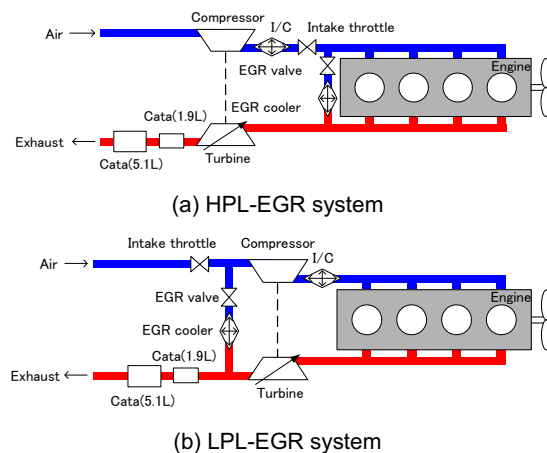


Fig.2 Outline of system

erated during the combustion of light oil. For the LPL-EGR system on the engine fueled by DME, however, corrosion from sulfur or pollution of soot is not a problem. Moreover, DME allows the system to take EGR gas from the turbine outlet and shorten the EGR pipe length without passing the DPF.

RESULTS OF STEADY STATE TESTS

Steady state engine tests were conducted to find performance for DME turbocharged engines with a compression ratio 17.5, and an LPL-EGR system. For the LPL-EGR equipped engine, an intake throttle valve (ITV) was used to reach a sufficient EGR rate, because it could not be sufficiently achieved by using only the EGR valve opening.



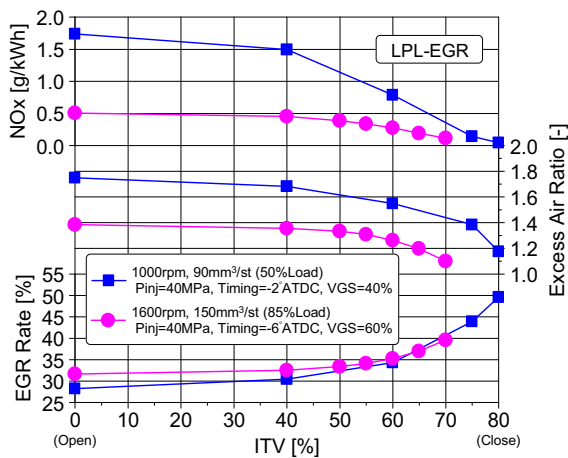


Fig.3 Effect of ITV opening rate with EGR valve fully opened on EGR rate, excess air ratio, and NOx in LPL-EGR system

In the first place, the EGR characteristic when ITV was used with the EGR valve fully opened is shown. In Figure 3, the change of NOx, excess air ratio and the EGR rate corresponding to the ITV opening rate (ITV [%]) are shown for each condition of which engine speed and quantity of fuel injection was 1000rpm - 90mm³/st (Around 50% load) and 1600rpm - 150mm³/st (Around 85% load). Where fuel injection pressure (Pinj [MPa]), fuel injection timing (Timing [° ATDC]) and the variable geometry-turbo system (VGS) nozzle opening rate (VGS [%]) were constant respectively, and the EGR valve was fully opened. The ITV opening rate is closed with an increase of the value of ITV on this figure's horizontal axis.

As Figure 3 indicates, the EGR rate rose with an increase in the ITV opening rate, while the NOx and excess air ratio decreased at the same time. When the ITV opening rate was 0%, the EGR rate was about 28% and the NOx was about 1.7g/kWh at 1000rpm - 90mm³/st and the EGR rate was about 32% and the NOx was about 0.5g/kWh at 1600rpm - 150mm³/st. And with the ITV opening rate increasing, the EGR rate rose to about 50% and the NOx decreased to about 0.2g/kWh at 80% ITV opening rate at 1000rpm - 90mm³/st and the EGR rate rose to about 40% and the NOx decreased to about 0.2g/kWh at 70% ITV opening rate at 1600rpm - 150mm³/st. It can be seen from what has been said above, that using ITV with an EGR valve brings a high EGR rate and is effective in reducing NOx.

In the second place, the characteristics of intake and exhaust on an LPL-EGR system were compared with that of an HPL-EGR system. Figure 4 shows the change of the turbine expansion ratio, turbine efficiency, compressor efficiency and EGR rate with respect to the VGS nozzle opening rate when the condition of engine speed and quantity of fuel injection was 1600rpm - 150mm³/st (Around 85% load). Where the EGR valve was fully opened and the ITV opening rate was constant on the LPL-EGR system. The EGR rate on the LPL-EGR system was controlled by adjusting ITV opening rate because it could not be sufficiently achieved by using only the EGR valve opening as stated above. Also, the EGR valve opening rate

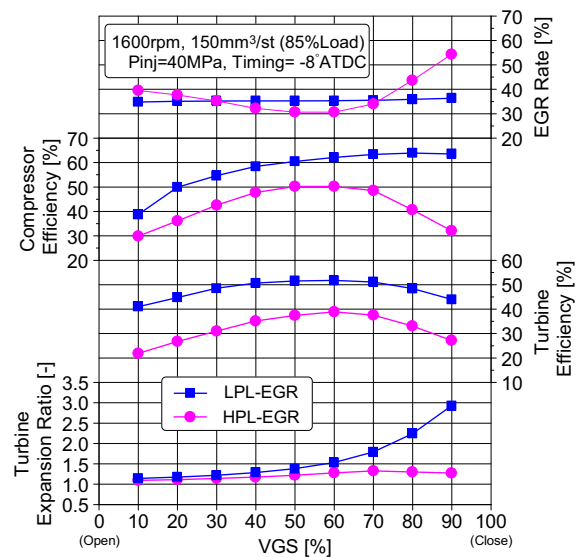


Fig.4 Variations of turbine expansion ratio, turbine efficiency, compressor efficiency and EGR rate with VGS nozzle opening rate

was constant and ITV was fully opened on the HPL-EGR system. Hereat, the VGS nozzle opening rate is closed with an increase of the value of VGS on this figure's horizontal axis; the fuel injection pressure and the fuel injection timing between each EGR system was the same respectively.

In Figure 4, the turbine expansion ratio on the LPL-EGR system was higher than that of the HPL-EGR over the whole range of the VGS nozzle opening rate. The difference between each system increased with an increase in the VGS nozzle opening rate. Also the turbine efficiency and compressor efficiency increased by 10% or more on the LPL-EGR system, compared with HPL-EGR system. As for the EGR rate, that of the LPL-EGR system was constant to changes in the VGS nozzle opening rate although that of the HPL-EGR system varied with changes in the VGS nozzle opening rate because the recirculated exhaust gas is susceptible to turbine gas-flow and efficiency for structure of the HPL-EGR system.

Next, trade-off between NOx and BSFC (Brake Specific Fuel Consumption) was explored on both the LPL-EGR and HPL-EGR systems, with consideration of the characteristics of intake, exhaust and EGR. Figure 5 shows the trade-off of NOx and BSFC, which was obtained by changing the fuel injection timing of each EGR rate in condition of 1600rpm - 150mm³/st on each EGR system, where conditions of the fuel injection pressure and the VGS nozzle opening rate were the same respectively. As for label of axis, the label of left axis describes BSFC for DME and label of right axis describes BSFC converted into the light oil lower heating value.

As Figure 5 indicates, the trade-off of NOx and BSFC on the LPL-EGR system was improved compared with that on the HPL-EGR system. As for these results, refer to Figure 6, which plots the EGR rate, and boost pressure to excess air ratio for the data of Figure 5. This figure indicates that the EGR rate has increased by about 7% and boost pressure rose by about 20kPa