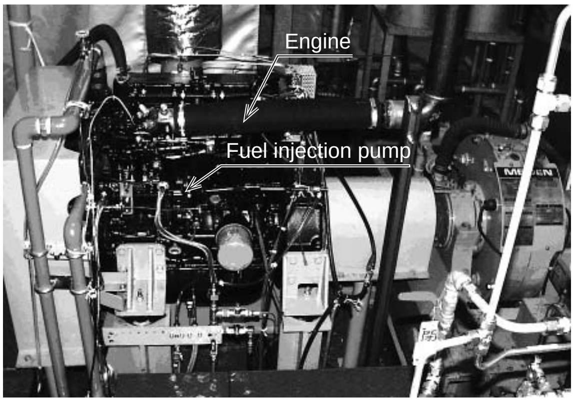

Clean Combustion Technology in Diesel Engines Operated with Dimethyl ether

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Combustion testing has been carried out for an engine using dimethyl ether (DME) which is of interest to the world as a next generation clean fuel. The testing was carried out using so-called retrofitted equipment. The modifications made to the engine to cope with the combustion properties of DME consisted only of enlarging and pressuring the fuel injection system and the addition of an exhaust gas recirculation (EGR) system to take advantage of the cleanliness of DME. As a result, it could be confirmed that a diesel engine using DME as a fuel can operate without emitting smoke over the entire operating range and further, can reduce NOx emissions remarkably through extensive EGR. This also ensures that the diesel engine using DME has very excellent, environmentally friendly, and highly efficient performance characteristics that completely satisfy the requirements of the Tier3 exhaust gas restrictions issued by the Environmental Protection Agency (EPA) in the United States of America.

1. Introduction

A diesel engine is a prime mover that can be applied in a wide variety of uses that support our lives because of its originally high efficiency, easy operability, and high levels of safety.

However, due to its emission of relatively large amount of air pollutants such as NOx and particulate matter (hereafter abbreviated as PM), diesel engines have come to be a focus of attention with regard to the issues of CO_2 and air pollution. In short, society is now demanding that diesel engines operate with clean exhaust while continuing to maintain high levels of efficiency.

On the other hand, there has recently been growing interest in dimethyl ether (hereafter abbreviated as DME), which has been used as a spraying agent, as a fuel. Hence, its introduction is being seriously considered as one candidate of new energy resources in the movement away from petroleum. In addition, it is thought that DME could possibly be used as a clean fuel for diesel engines because of its excellent properties.

In this study, the potential of DME as a fuel ensuring high efficiency and low pollution in diesel engines has been investigated by determining the output, fuel consumption, and exhaust gas properties of a diesel engine using DME as a fuel.

2. Characteristics of DME used as a diesel fuel

First of all, the characteristics of DME used as a diesel fuel, which are supposed from the basic properties of DME itself, were systematically studied before performing the diesel engine tests actually using DME(1).

Table 1 shows the main properties of DME, compared with those of gas oil. DME, which is created through the synthesis of synthesis gas produced mainly from natural gas, is an oxygenated fuel as indicated by its chemical

Table 1 Properties of DME

	DME	Gas oil	Characteristics as diesel fuel
Molecular structure	Oxygenated	Hydrocarbon	Smokeless
Density (kg/m^3 at 20°C)	668	840	
Lower calorific value (kJ/kg)	28 763	42 789	Low output
Liquid viscosity (kg/msec)	0.15	2 – 3	Low lubricity
Boiling point (°C)	–25	180 – 360	Easy vapor-lock
Modulus elasticity (N/m^2)	6.37×10^8	1.49×10^9	Low injecting pressure
Cetane number	More than 55	Less than 60	Means of ignition-support are not necessary. Combustion noise is reduced.
Theoretical air fuel ratio (kg/kg)	8.96	14.7	

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formula $(CH_3)O_2$. Therefore, DME can be expected to burn as a fuel that does not generate black smoke. Methanol is another type of oxygenated fuel that has been of interest as a clean fuel for diesel engines. Like methanol, DME is also supposed to be a fuel that is very effective in reducing the emission of particulate matter from engines. The characteristic of DME that is most notable different from methanol is its property of self-ignition, which is equivalent to gas oil and heavy oil or higher than them. Therefore, it is thought that an ignition-supporting device that is usually needed for methanol is not necessary for DME. This is an advantage of DME using for diesel engines.

On the other hand, DME has a low boiling point, low calorific value, and low viscosity. In order to cope with these disadvantages of DME as a fuel, it is assumed that some modifications, such as increased pressurization and enlargement, will need to be made to the fuel injection system mainly and a lubricity-improving agent will be necessary to be added[2][3].

3. Combustion test of DME diesel engine

In order to grasp the basic combustion characteristics of diesel engines using DME as a fuel and the possibility of the diesel engines being used as next generation high efficiency clean prime movers, a combustion test was carried out using a small-sized high-speed direct injection diesel engine.

3.1 Test equipment and test conditions

Table 2 shows the main specifications of the diesel engine used for the test. The engine is a four cylinder, direct injection type, named S4S diesel engine manufactured by MHI, which was originally equipped with a turbocharger. The turbocharger was removed so that it could be converted to a normal aspiration specification, in order to make it possible to determine the basic combustion properties of DME. The dimensions of the cylinder are a bore diameter of 94 mm, a stroke of 120 mm, and an overall stroke volume of 3 300 cc. In this test, the specifications as an original gas oil diesel engine were kept, except the static fuel injection timing which was advanced by 6° in crank angle in order to make the actual fuel injection timing equivalent to that for gas oil. In other words, this test was carried out with so-called retrofitted equipment so that no conversion was carried out to make the engine itself suitable for DME.

The fuel-supplying system was designed as shown in **Fig. 1**, to cope with the properties of DME. DME was supplied to the engine from a DME bomb container, in a pressurized state of 0.8 MPa using nitrogen. The DME was then supplied to the fuel injection pump in a pressurized state of 1.6 MPa with a booster pump. In order to improve the lubricity of DME, HITEC 4140 produced by the Ethyl Japan Co. was added to the DME with a concentration of 1 000 ppm.

3.2 Results of combustion test

The basic diesel combustion properties of DME were studied using the test equipment described above. Fig. 2 shows a comparison of the injecting and heat-generating properties of DME and gas oil during engine operation with an engine speed of 1 800 rpm and an output of 40 kW, using fuel injection valves of ϕ0.28 mm × 4^N. Since DME has a lower modulus elasticity than gas oil, the injection pressure of DME is lower than that

Table 2 Specifications of test engine

Type of engine	S4S-DI (N/A)
Bore × Stroke (mm)	ϕ90 × 120
Overall stroke volume (litter)	3.3
Compression ratio	17
Type of fuel injection pump	ND-A
Diameter of plunger (mm)	ϕ9
Fuel injection nozzle	ϕ3.8 × 4^N ϕ2.8 × 4^N
Static fuel injection timing (BTDC)	12° (Gas oil) 18° (DME)

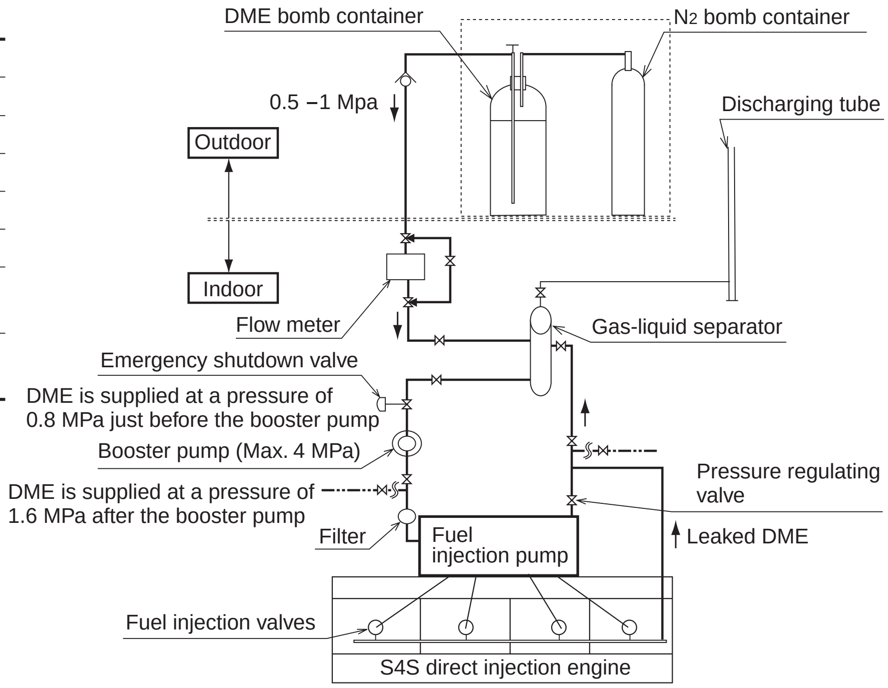

Fig. 1 DME supply line
DME is fed to the engine from a bomb container that is pressurized with nitrogen, and further pressurized by a booster pump in order to supply it to the fuel injection pump.

of gas oil [Fig. 2 (b)]. Since the same quantity of heat is injected using the fuel injection valve with the same nozzle area, the fuel injection duration for DME becomes 50 % longer than that for gas oil [Fig. 2 (a)], taking into consideration the ratios of the calorific values and densities of both type of fuel. However, from the viewpoint of the heat release rate, DME is ignited earlier and the amount of DME initially combusted is smaller than gas oil, and combustion duration is rather smaller than gas oil [Fig. 2 (d)]. A possible reason why the initial combustion quantity of DME has lower than that of gas oil is thought to be because the ignition delay of DME is short and the thermal input is low. This is due to the influence of the easy ignition properties of DME. Accordingly, it can be seen that this combustion property is advantageous in reducing high noise levels, which is one of the disadvantages of diesel engines. Although DME has an fuel injection duration that is as much as 1.5 times longer than that of gas oil, the heat-generating period is not so extended. This seems to be because DME is an oxygenated fuel and the theoretical quantity of air is small.

Fig. 3 shows a comparison of both relationships between the fuel injection duration and combustion duration between the two types of fuels. Based on this figure, the heat-generating period of DME is as short as about 80% of that of gas oil during the same fuel injection duration. This indicates that the combustion velocity of DME is so fast as to be advantageous in maintaining and improving the thermal efficiency of an engine.

Fig. 4 shows a comparison of the levels of fuel con-

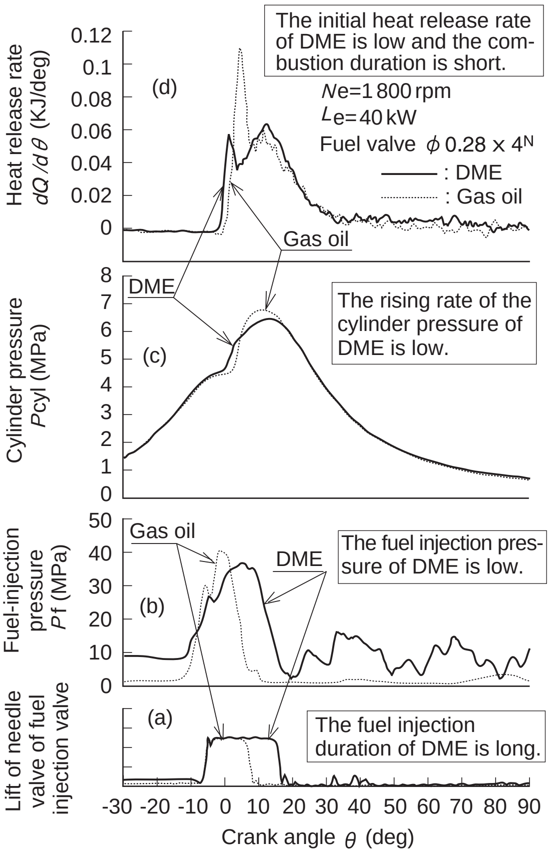

Fig. 2 Basic combustion properties of DME diesel engine
DME is ignited early and its initial heat release is low, while the combustion duration is not so extended.

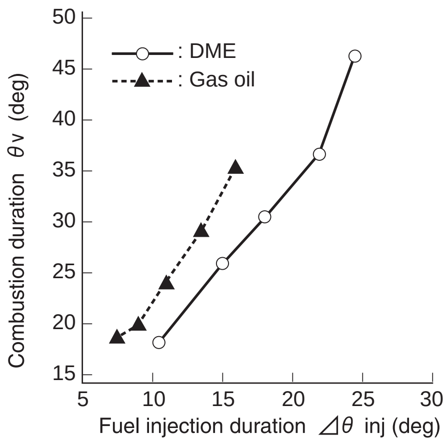

Fig. 3 Relationship between the fuel injecting duration and combustion duration of a DME diesel engine
DME fuel has a high combustion velocity, so that it has an advantage in terms of improving thermal efficiency.

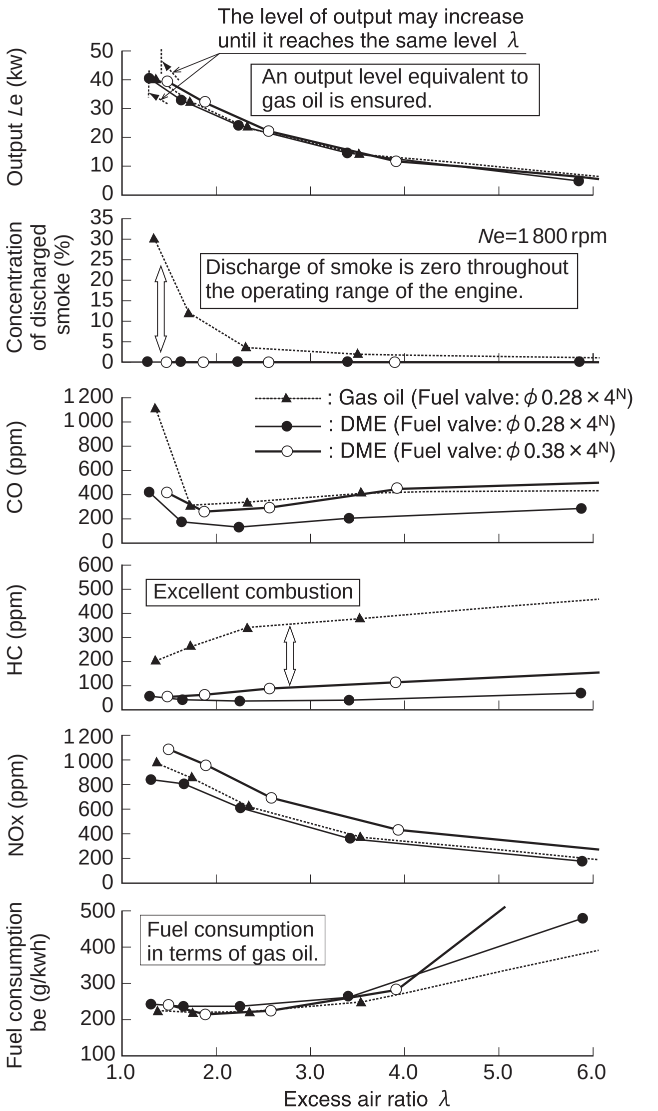

Fig. 4 Performance and exhaust gas levels of a DME diesel engine
A DME diesel engine does not discharge smoke at all anywhere in its operating range. Since the level of CO and HC emissions is also small, DME fuel has extremely excellent combustion properties.

sumption, output, and the composition of the exhaust gases of the test engine for both types of fuels under the following conditions. Gas oil is used with the fuel injection valves that are ϕ0.28 X 4[N], as indicated by the ▲ marks, while DME is used with fuel injection valves that are ϕ0.28 X 4[N] and ϕ0.38 X 4[N], as indicated by the ● and ○ marks, respectively, with the engine load changed at a rotational speed of 1 800 rpm. The *X* axis indicate excess air ratio, which correspond nearly directly to engine load.

From the figure, it can be seen that the level of fuel consumption of the DME diesel engine is equivalent to that of the gas oil diesel engine and that of the output is higher than that of the gas oil diesel engine if the fuel injection nozzle diameter is enlarged. The most important issue with respect to the properties of exhaust gas is that the DME diesel engine discharges no black smoke at all, even under a high load. In addition, the emission of unburned components such as CO and HC is small. Accordingly, DME can be said to have excellent combustion properties, that is, it is an extraordinarily suitable fuel for diesel combustion. On the other hand, the level of NOx emissions from DME is equivalent to or slightly higher than that from gas oil. However, it may be possible to reduce the emission of NOx from DME fuel because DME burns without any smoke. Although EGR is not applicable to a gas oil diesel engine due to the resulting increase in smoke emissions, a large amount of EGR can be applied to a DME diesel engine, even at a high load range.

As a result, with respect to the combustion properties of DME in a diesel engine, it was confirmed that no black smoke is discharged at all and both high combustion velocity and high combustion efficiency can be achieved. Accordingly, it can be clearly said that DME shows great potential as a fuel for high efficiency and low pollution diesel engines.

Thus, an application test of EGR was carried out in order to investigate the possibility of reducing exhaust gas levels further. **Fig. 5** shows the changes of combustion property, thermal efficiency, and exhaust gas components when the amount of EGR is changed at an operation point with an engine speed of 1 800 rpm and an engine load of 40 kW, nearly 100% load. The combustion velocity decreases slightly and the thermal efficiency also decreases slightly with an increase in EGR rate, while at the same time, it is possible to reduce NOx emission levels without discharging black smoke. Specifically, it can be seen that the discharge of NOx can be reduced to about half at an EGR rate of about 12%, for instance. It is difficult to apply EGR at a rate of 10% or more in a typical gas oil diesel engine at such a high load. However, an extremely large amount of NOx reduction can be expected when DME is used as a fuel. It may also be possible to improve the reduction of combustion velocity occurring during the application of EGR, if the fuel system is optimized, for instance, the shape of the combustion chamber and/or the swirl design is optimized and high pressure injection are adopted.

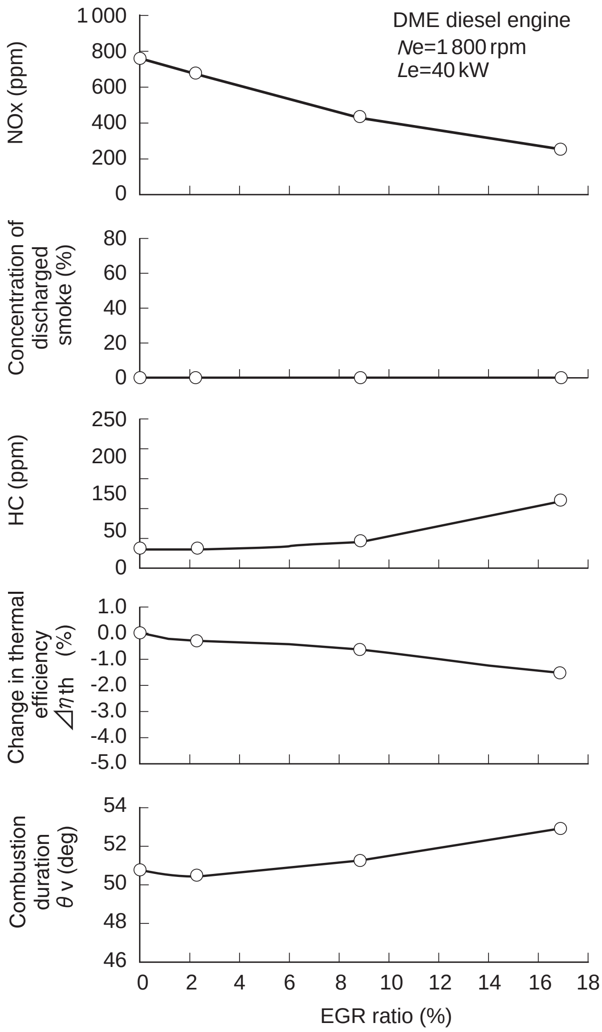

Fig. 5 Changes in exhaust gas and performance levels using EGR
A DME diesel engine remains smokeless even if EGR is added. Furthermore, a large amount of NOx reduction is possible through the application of a large amount of EGR.

From these results, the exhaust gas performance of a DME diesel engine was evaluated using the off-road engine eight-mode evaluation method, with which emission of this test engine is evaluated. At eight different operation points, the optimum EGR for each point was studied and determined, and the amount of PM (used as exhaust gas values) in the exhaust gas was obtained for each optimum EGR. The results are shown in **Fig. 6**. In this figure, the ▲ marks indicate the amounts of PM in the exhaust gas discharged from a gas oil diesel engine. These are at levels that satisfy the levels for Tier2 restrictions set forth by the EPA in the United States. On the other hand, when the fuel used was changed to DME, black smoke was not discharged and levels of HC were reduced, so that the amount of PM was reduced to become closer to the level indicated in the Tier3 restrictions. This is shown by a ● mark in the figure. Furthermore, when EGR was properly added as described above, the values for PM came to a position indicated by a ○ mark, which is at a level that completely satisfies the levels set forth in the Tier3 restrictions.

As shown above, if DME, which is expected to become a next generation fuel, is applied to a diesel engine, even the levels set forth in the third restrictions of the EPA can be satisfied without the need for any advanced fuel injection device or any additional advanced exhaust gas treatment unit, which are currently required for environmental prevention in the diesel engine using gas oil. Moreover, levels of performance, such as engine output and fuel consumption, that are equivalent to or higher than those of a gas oil diesel engine can be kept, even if the equipment is only retrofitted. In other words, it has become clear that DME shows great promise as an excellent fuel for achieving the high efficiency and clean combustion of diesel engines. At present, MHI is accelerating its efforts with the aim of realizing the practical use of DME diesel engines at an early date.

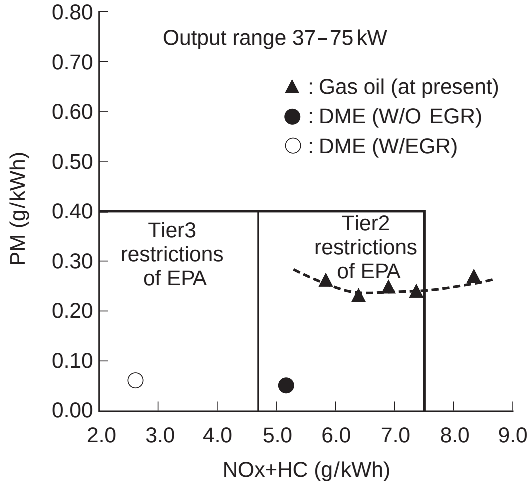

Fig. 6 Eight-mode exhaust gas value of DME diesel engine
The exhaust gas levels of a DME diesel engine was found to be so clean that it can perfectly satisfy the requirements of the Tier3 restrictions set by EPA in the United States.

4. Conclusion

The combustion and performance of diesel engines using DME as a fuel were investigated through combustion tests using a small-sized high-speed direct injection diesel engine. As a result, the following results were obtained.

(1) DME can be said to be a fuel that is suitable for high efficiency low pollution diesel engines. However, various measures need to be adopted to ensure satisfactory levels of performance, including the pressurization and enlargement of the fuel injection system and measures to improve lubricity of DME.

(2) Based on the results of the combustion test provided with the modifications mentioned above, it was possible to confirm that DME diesel engines can ensure levels of output and thermal efficiency that are equivalent to those of gas oil diesel engines. Further, DME fuel was found to have excellent combustion properties that did not result in the discharge of any smoke over the entire operating range of the engine. Moreover, significant reductions in NOx levels become possible through optimization of the fuel system and application of a large amount of EGR. This fact demonstrates that there is great potential for the realization of highly efficient, low pollution diesel engines that meet the requirements of the Tier3 restrictions set by the EPA.

(3) At present, MHI is moving ahead with efforts aimed at realizing the practical use of DME diesel engines at an early date.

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