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COMBUSTION AND EMISSION CHARACTERISTICS OF A TURBOCHARGED DIESEL ENGINE FUELLED WITH DIMETHYL ETHER

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ABSTRACT–This paper is concerned with an experimental study of a turbocharged diesel engine operating on dimethyl ether (DME). The combustion and emission characteristics of DME engine were investigated. The results showed that the maximum torque and power with DME could achieve a greater level compared to diesel operation, particularly at low speeds; the brake specific fuel consumption with DME was lower than the diesel at low and middle engine speeds. The injection delay of DME was longer than that of diesel. However, the maximum cylinder pressure, maximum pressure rise rate and combustion noises of DME engine were lower than those of diesel. The combustion velocity of DME was faster than that of diesel, resulting in a shorter combustion duration of DME. Compared with the diesel engine, NO_X emissions of the DME engine were reduced by 41.6% on ESC data. The DME engine was smoke free at all operating points of the engine.

KEY WORDS : Dimethyl ether, Combustion, Emissions, Smoke

1. INTRODUCTION

Emission legislation for diesel engines across the world has continuously sharpened. The primary target of this legislation has been the reduction of the emissions of nitric oxides (NO_X) and particulate matter (PM) by these engines (Baert *et al.*, 1999). As far as pollutant diesel emissions are concerned, one promising way to reduce harmful emissions is to use alternative fuels (Choi and Oh, 2005; Lu *et al.*, 2005; Ofner *et al.*, 1998). In the past ten years, dimethyl ether (DME) with its high cetane number and superior combustion and emissions characteristics has attracted the attention of scientists worldwide. Since 1995, Denmark Technical Uinversity, Haldor Topsoe A/S, Navistar, AVL, AMOCO has performed an extensive investigation into diesel engines fuelled with DME. Previous work had revealed that the DME engine was high efficiency, ultra-low NOx emissions, smoke free and low noise (Fieisch *et al.*, 1995; Hwang *et al.*, 2003; Morsy *et al.*, 2006; Sorenson *et al.*, 1995; Paul and Herwig, 1995). In China, many universities are devoted to the investigation on the diesel engines fuelled with DME. The application of alternative fuel is more imperative in China (Song *et al.*, 2003). China is rich in coal and lacking of petroleum, while DME can be made from a variety of resources such as coal, natural gas, crude oil, waste and biomass. Since 1997, we had been investigating on the injection spray, combustion, reliability and sealant materials of DME. Based on the background, a turbocharged DME engine was developed, and a DME city bus was developed in 2005, it had been run for more than 2000 km. This paper is concerned with the combustion and emission characteristics of a turbocharged engine fuelled with DME.

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2. MODIFICATION OF DIESEL ENGINE

The chemical structural formula of DME is CH_3-O-CH_3, which is the simplest ether compounds. DME has only C-H and C-O bonds and lacking of C-C bond, while the molecule has oxygen content, it contributes to better spray combustion and soot free. The physical and chemical properties compared with diesel are shown in Table 1.

DME is in a gaseous state at the ambient pressure and temperature, its vapor pressure is 0.51 MPa. And its vapor pressure increases with the rising of temperature. It was increased to more than 1.5 MPa by an electric pump to avoid formation of vapor in fuel supply system. The circulation of fuel reduces the temperature of the injection pump. This has proven to be an effective method. The

Table 1. Physical and chemical properties of DME and diesel.

Properties	DME	Diesel
Chemical formula	CH_3-O-CH_3	$C_nH_{1.8n}$
Molecular weight (g)	46.07	190–220
Boint point °C	–24.9	180–360
Liquid density g/cm^3	0.668	0.84
Reid vapour pressure/MPa	0.51(20°C)	–
Low heat value MJ/kg	28.4	42.5
Cetane number	55–66	40–55
Ignition temperature	235	250
Oxygen content (wt%)	34.8	0
Stoichiometric air-fuel ratio	9.0	14.6

low heat value of DME is only 66.8% of that of diesel; it is necessary to increase the fuel supply to ensure the same engine power. The plunger diameter was enhanced from 12 mm to 13 mm, the injection nozzle was enlarged from 0.24 mm to 0.4 mm together with the inlet diameter of high pressure pipe was increased from 1.8 mm to 2.2 mm to increase the cross-sectional flow of the pipe. The fuel supply system is shown in Figure 1. The accumulator was used to keep the pressure of the pipe. The relief valve was used to regulate the pressure of the system. Since DME has a low viscosity, to ensure reliability and durability of the parts of the fuel system, 2% castor oil was added to DME.

3. EXPERIMENTAL APPARATUS AND PROCEDURE

Experiments were conducted with a six-cylinder, turbo-charged, inter-cooled, four-stroke, direct-injection diesel engine. The specifications of the engines operating on diesel and DME are listed in Table 2.

The cylinder pressures of the diesel and DME engine were tested respectively. Based on the recorded data, the rate of heat release (ROHR), accumulated ROHR, pressure rise rate were obtained. Combustion characteristics of full load at the speeds of 800 rpm, 1400 rpm and 2200 rpm were investigated together with engine emissions. By considering the low emissions of HC and CO of compression ignition engine, the experiment only analyzed the NO_x and smoke emissions. The Concentrations of NO_x were measured by a MEXA-7000 Chemiluminescence Analyzer, and the smoke emissions were tested by a full-automated fqd-102A smoke meter.

The fuel delivery advance angle of the DME engine was altered to three different positions for better analysis of combustion and emission characteristics.

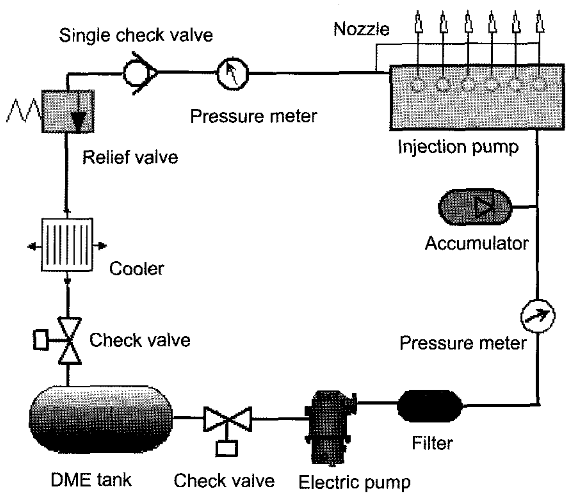


Figure 1. Schematic block of the DME supply system.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1. Performance Characteristics

4.1.1. Comparison of torque and power

Figure 2 shows the comparison of torque and power at

Table 2. Engine specifications.

	Diesel engine	DME engine
Model	D6114ZLQB	D6114ZLQB
Bore×Stroke	114×135 mm×mm	114×135 mm×mm
Displacement	8.27 L	8.27 L
Compression ratio	18:1	18:1
Fuel delivery advance angle	9/(°CA BTDC)	9/(°CA BTDC)
Maximum torque/Speed	1000 N.m/1400 r/min	1030 N.m/1400 r/min
Related power/Speed	184 kW/2200 r/min	190 kW/2200 r/min
Injection pump	P7100	P8500
Plunger diameter	12 mm	13 mm
Nozzle number×Orifice	6×0.24 mm	6×0.40 mm

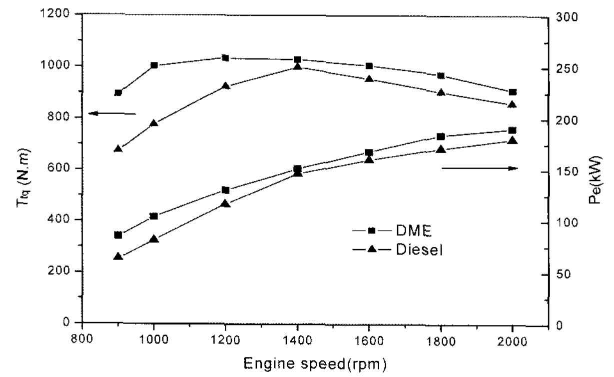


Figure 2. Comparison of torque and power of DME engine and diesel engine at full load.

full load operating at the optimum injection condition. As can be seen in Figure 1, the torque with DME was greater than with diesel at all engine speeds, therefore, the power with DME also increased at any engine speed, particularly at low engine speeds. The output torque with DME at the speed of 1000 rpm was 1003 N.m, which was increased by 29.1% over the diesel engine. It was increased 32.8% at the speed of 900 rpm. There was no smoke limit to DME engine; the output power could be improved by increasing the fuel supply. This is beneficial to the city bus, as it is stopped and started frequently. The larger torque can meet the demand. This seems to be the most important result of this study.

4.1.2. Comparison of brake specific fuel consumption

Figure 3 shows the comparison of Brake specific fuel consumption (BSFC) of DME engine and diesel engine at full load. The BSFC was calculated on diesel consumption. As can be seen from Figure 3, the BSFC was lowest at medium speed. To diesel engine, when the speed was less than 1600 rpm, the BSFC increased with the decrease of engine speed. when the speed was larger than 1600 rpm the BSFC increased with an increase of engine speed. The BSFC of the DME kept the same trend as diesel engine. The lowest BSFC speed was 1400 rpm, which was lower than that of diesel engine. When the engine speed was less than 1500 rpm, the BSFC of DME engine was lower than that of diesel engine. While it was higher than that of diesel engine at high speeds. This can be explained by the following reasons: When the speed increases, the fuel supply increases, the injection duration

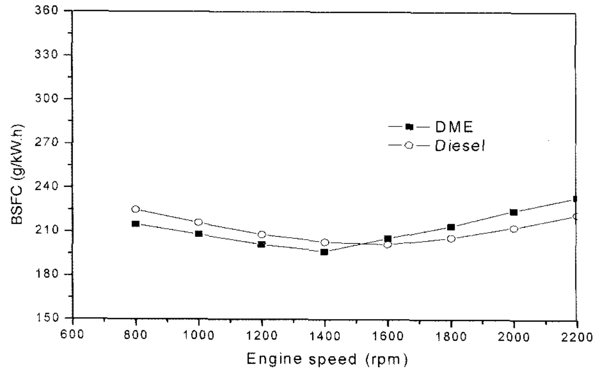
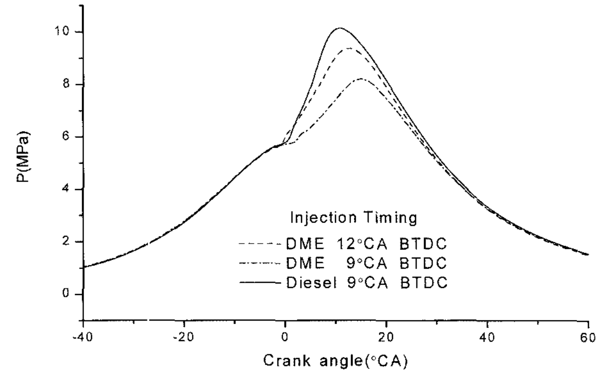
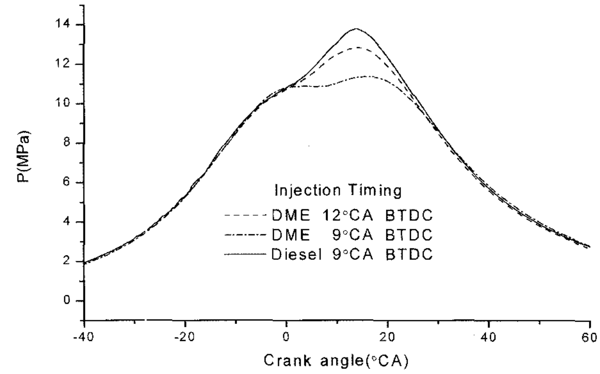


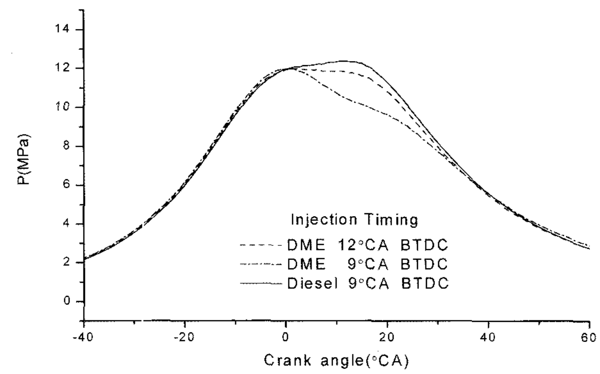
Figure 3. Comparison of BSFC of DME engine and diesel engine at full load.



(a) 800 rpm P_{me}=0.87 MPa



(b) 1400 rpm P_{me}=1.52 MPa



(c) 2200 rpm P_{me}=1.21 MPa

Figure 4. Comparison of cylinder pressure of DME engine and diesel engine.

and combustion was enlarged. Therefore, the BSFC of DME engine was higher than that of diesel engine.

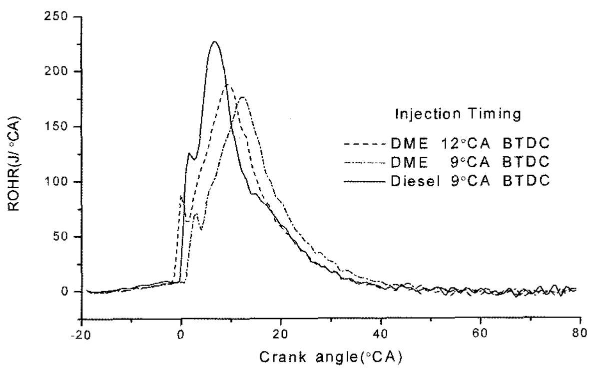
4.2. Combustion Characteristics

4.2.1. Comparison of cylinder pressure

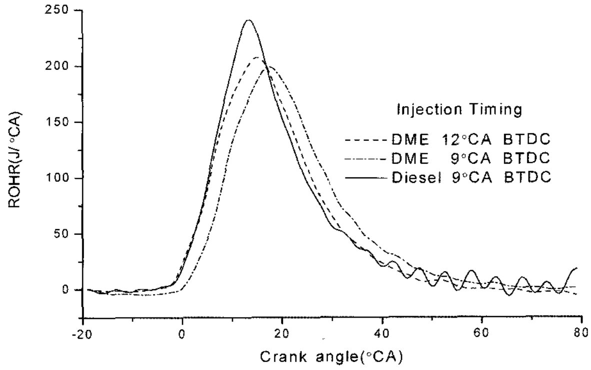
Figure 4 shows the comparison of cylinder pressure of DME engine and diesel engine. As can be seen from Figure 4(a), at the speed of 800 rpm, the maximum pressure of the DME engine was lower than that of diesel engine. And it lagged behind the diesel engine. The maximum pressure of DME engine was 9.3 MPa at the position of 12°CA–14°CA ATDC when the fuel delivery advance angle was 12°CA BTDC. The maximum pressure of DME engine was 8.2 MPa at the position of 14°CA–16°CA ATDC when the fuel delivery advance angle was 9°CA BTDC. The smaller of the fuel delivery advance angle, the lower the peak pressure. The maximum pressure of diesel engine was 10.1 MPa at the position of 10°CA–12°CA ATDC when the fuel delivery advance angle was 9°CA BTDC. The peak pressure of DME was 4°CA later than the diesel at the same fuel delivery advance angle. When the speed was 1400 rpm, both the maximum pressure of DME engine at 12°CA BTDC fuel delivery advance angle and the maximum pressure of diesel engine as the fuel delivery advance angle were at the position of 14°CA–15°CA ATDC. The peak pressure of DME engine was 12.8 MPa while the peak pressure of diesel engine was 13.3 MPa. The maximum pressure of DME engine was 11.5 MPa when the fuel delivery advance angle was 9°CA BTDC, it was 2°CA later than that of diesel at the same fuel delivery advance angle. This can be explained by the following reasons: DME has a higher cetane number, a lower auto-ignition temperature, faster vaporization and better atomization and ignition properties. The ignition delay of DME is shorter than that of diesel, which results the lower cylinder pressure of DME. A previous study revealed that the velocity of sound in DME fuel is 980 m/s, which is lower than that in diesel fuel (1330 m/s), which means that pressure wave propagation will take longer in the DME engine compared with the diesel engine, and consequently the DME engine will have a longer fuel injection delay than the diesel engine (Huang *et al.*, 1999). The longer injection delay of DME results the lagged maximum pressure.

4.2.2. Comparison of ROHR

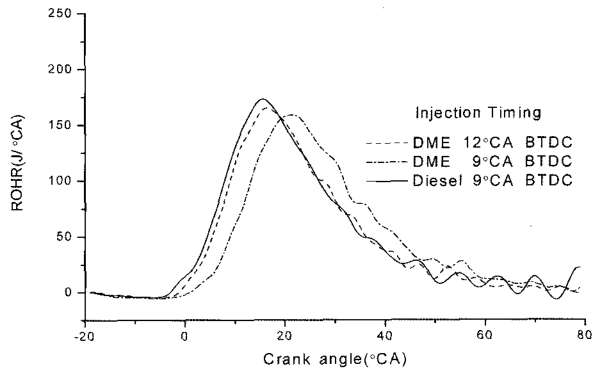
Figure 5 shows the comparison of heat release rate of DME engine and diesel engine. As can be seen in Figure 5, the peak of ROHR of premixed combustion was very low, while the peak of ROHR of diffusion combustion was very high. The peak of ROHR of DME engine was lower than the diesel engine. It can be explained by the following reasons: the temperature and pressure of the inlet air was very high, resulting a shorter ignition delay, less fuel burnt in the ignition delay. The ignition delay of DME was shorter than that of diesel engine, resulting in lower peak of ROHR. The peak of ROHR of DME engine was reduced with the reducing of the fuel delivery advance angle. The less the fuel delivery advance, the shorter the ignition of the combustion, less fuel burnt in the combustion delay, resulting the lower peak of ROHR. When the engine was operating at the speed of 1400 rpm



(a) 800 rpm P_{me}=0.87 MPa

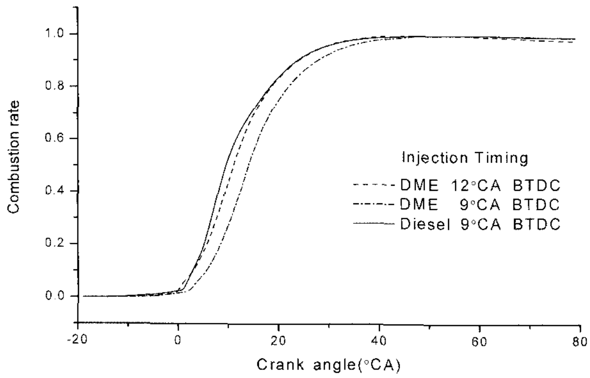


(b) 1400 rpm P_{me}=1.52 MPa

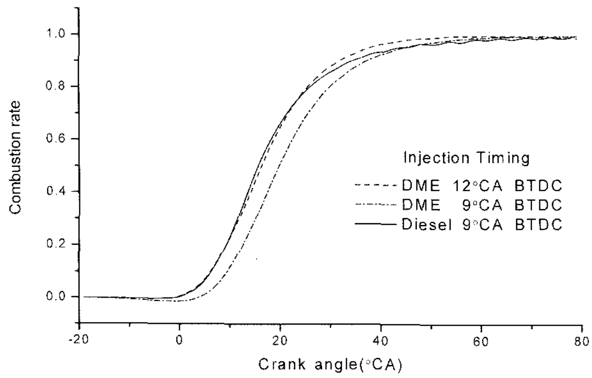


(c) 2200 rpm P_{me}=1.21 MPa

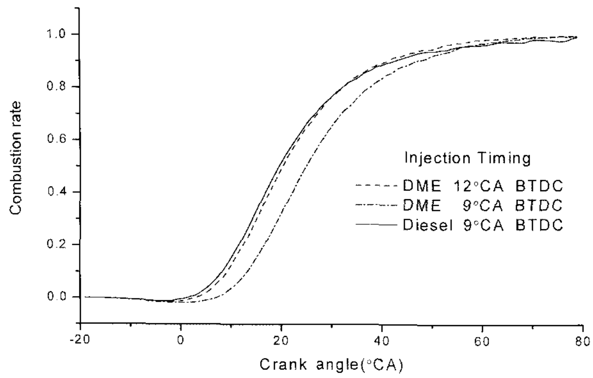
Figure 5. Comparison of ROHR of DME engine and diesel engine.



(a) 800 rpm P_{me}=0.87 MPa

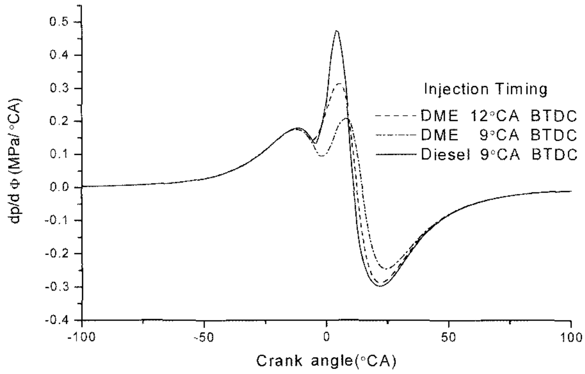


(b) 1400 rpm P_{me}=1.52 MPa

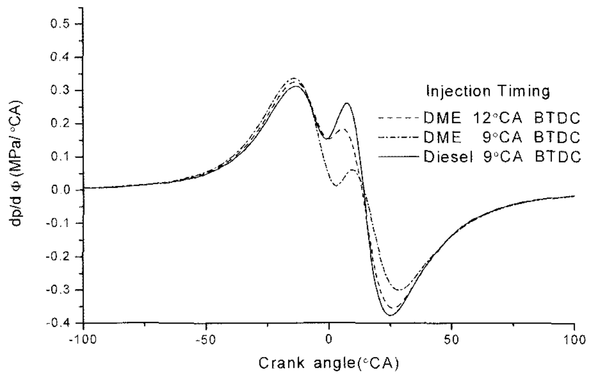


(c) 2200 rpm P_{me}=1.21 MPa

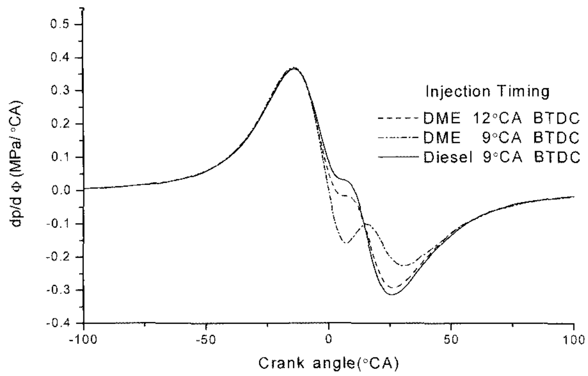
Figure 6. Comparison of accumulated ROHR of DME engine and diesel engine.



(a) 800 rpm P_{me}=0.87 MPa



(b) 1400 rpm P_{me}=1.52MPa



(c) 2200 rpm P_{me}=1.21 MPa

Figure 7. Comparison of pressure rise rates of DME engine and diesel engine.

and 2200 rpm, there wouldn't be the trace of premixed combustion in the curve of ROHR; it turned to be a single peak curve. The peak of ROHR of DME engine was still lower than that of diesel engine.

4.2.3. Comparison of accumulated ROHR

Figure 6 shows the comparison of accumulated heat release of DME engine and diesel engine. As can be seen in Figure6, the start combustion point of the DME with 12°CA BTDC fuel delivery advance angle was later than the diesel at 9°CA BTDC fuel delivery advance angle, the DME engine with 9°CA BTDC fuel delivery advance angle was later. The compression characteristics of DME engine was larger than that of diesel, it resulted larger volume change when compressed. The increasing and reducing of pressure of DME engine was slower than that of diesel, the injection delay of DME was larger than that of diesel. It was known from this figure, the end of DME

Table 3. The noise of DME vehicle.

NO.	Item	Diesel	DME
1	The noise of accelerating outside engine dB(A)	82.9	80.8
2	Noise in bus dB(A)	80.8	76.4

combustion wasn't later than that of diesel though the later injection. Since DME had better spray, the mixture and diffusion of DME was faster than that of diesel. The combustion velocity of DME was faster than that of diesel. The combustion duration of DME engine was shorter than that of diesel engine.

4.2.4. Comparison of pressure rise rates

Figure 7 shows the comparison of the pressure rise rates of the DME engine and diesel engine. As can be seen in Figure 7, the pressure rise rates of the DME engine at 12°CA BTDC fuel delivery advance angle was lower than that of diesel at 9°CA BTDC fuel delivery advance angle. The pressure rise rates of the DME engine at 9°CA BTDC fuel delivery advance angle was still lower. Which resulted the lower combustion noise of the engine. Noise was tested by the standard of GB1496-76, "Measurement method for Vehicle Noise". The test results (Table 3) showed that the noise of accelerating of DME engine was 80.8 dB(A), which was 2.1 dB(A) lower than that of diesel engine. The noise in the bus was 76.4 dB(A), 4.2 dB(A) lower than that of diesel engine. It proved that the DME engine ran softly, the combustion noise of DME engine was lower than that of diesel engine.

4.3. Exhaust Emission Characteristics

4.3.1. Exhaust emissions at full load

4.3.1.1. Comparison of NO_x emissions at full load

Figure 8 shows the comparison of the NO_X emissions of DME and diesel engine at full load. The out power of DME engine and diesel engine kept the same level. It was known from Figure 8, NO_x emissions of the DME engine were lower than the diesel engine throughout the speed range. NO_x reduced up to 50% when the fuel delivery advance angle was 9°CA BTDC. The NO_x emissions of DME engine at 12°CA BTDC delivery advance angle was still lower than that of diesel at 9°CA BTDC. It was greatest at medium and high engine speeds. This can be explained by the following reasons: The ignition delay of DME was shorter than that of diesel, less fuel accumulated in the ignition delay, the maximum temperature of DME engine was lower than that of diesel engine, resulting in less NO_x emissions.

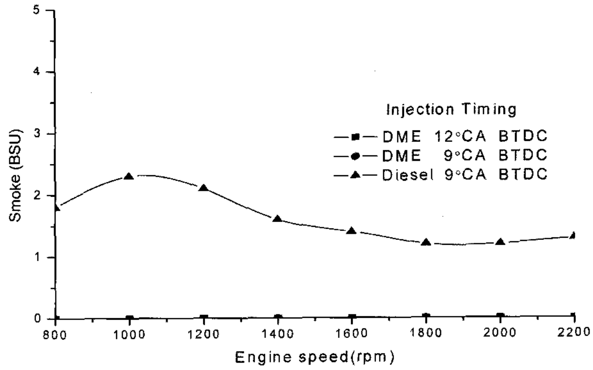


Figure 9. Comparison of Smoke at full load.

4.3.1.2. Comparison of smoke at full load

Figure 9 shows the comparison of smoke throughout the load range of the DME engine and diesel engine. It can be noted from Figure 9, smoke was zero for the DME engine through the speed range. The smoke of diesel was much higher than the DME engine. The inlet air was not sufficient for the turbocharged engine at low engine speeds causing the supercharge ratio to reduce, the smoke increased greatly at low speeds. The O_2 content contained in the DME reached 34.8%, and there was no C-C bond in DME, all were beneficial to complete combustion,

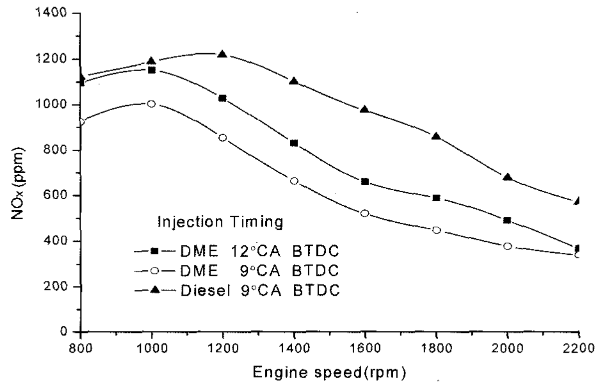


Figure 8. Comparison of NO_X emissions at full load.

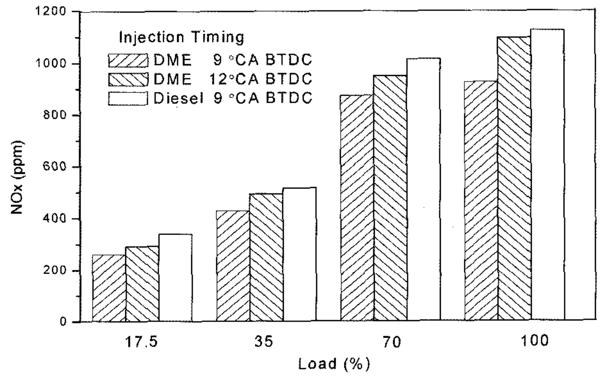


Figure 10. NO_x emissions at 800 rpm.

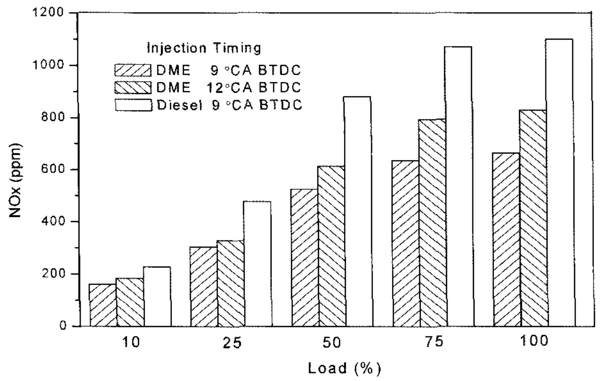


Figure 11. NOx emissions at 1400 rpm.

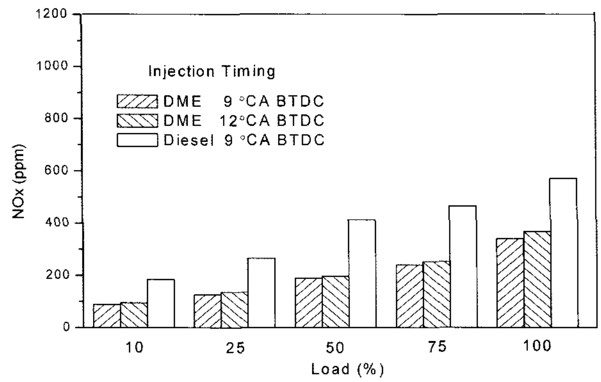


Figure 12. NO_x emissions at 2200 rpm.

therefore smoke of DME engine could reach near zero during the entire load range.

4.3.2. Comparison of NO_X emissions at part loads

Figures (10–12) show the comparison of NO_x emissions of the DME engine and diesel engine at part loads of different engine speeds. It can be seen from these figures: as the load increased, the NO_x emissions of DME and diesel engine kept the same trend, NO_x emissions would increase with the increasing of load. The NO_x emissions of DME engine was lower than the diesel engine. The NO_x emissions of DME engine were 20% lower than the diesel engine at low engine speeds. It was reduced by 50% at high engine speeds. This can be explained by: The maximum temperature increased with the increasing of load, and accordingly the NO_x emissions would increase. The cetane number of DME was higher than that of diesel, the ignition delay of DME was shorter than that of diesel, and the maximum temperature of DME engine was lower than that of diesel engine.

4.3.3. Test results of EU- III

The National Center of Heavy Duty Vehicle Quality

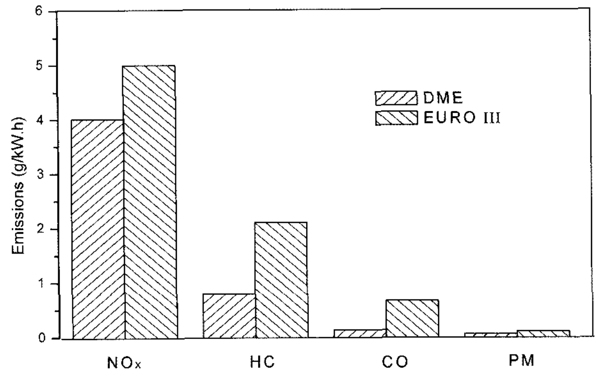


Figure 13. ESC emissions (g/kW.h).

Supervision & Inspection calculated the 13 mode ESC emissions above (Figure 13). The requirements for the proposed Euro III heavy-duty truck emissions appeared to be satisfied with DME. The results showed the NO_x emission of the engine was 4.014 g/kW.h, CO emission was 0.129 g/kW.h, total HC emission was 0.787 g/kW.h, which was a reduction of 19.7%, 80.5%, and 62.5% than the ESC limit allows. The NO_x emission of original diesel was 6.87 g/kW.h. Compared to the ESC data of diesel, the NO_x emission of the DME engine was reduced by 41.6%. The soot emissions of DME engine were zero, the particulates came mainly from the lubricated oil, and particulates were only half of the proposed ESC limit. The speeds of ETC relative to A, B, C were 1400 rpm, 1700 rpm, 2000 rpm. The engine was accelerated from 10% load to 100% suddenly; the maximum soot in the procession was zero.

5. CONCLUSIONS

The results obtained from this study can be summarized as follows:

DME improved the maximum torque and power at full load greater than the diesel engine, particularly at low engine speeds. The fuel consumption at low engine speeds was lower than diesel.

The maximum cylinder pressure, the maximum pressure rise rates and combustion noise of DME engine were all lower than the diesel engine. While the diffusion of DME was faster than that of diesel, the combustion duration with DME was shorter than the diesel.

Compared with the diesel engine, NO_x emissions of DME engine decreased remarkably, this was more obvious at high engine speeds. The DME engine was smoke free throughout all the operating points of the engine. It would be effective to further reduce NO_x emissions of the engine by EGR without resulting in an increase of smoke. The emissions of the DME engine achieved the limits of EU-III.

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