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The Effect of Water Emulsified Fuel on a Motorway-Bus Diesel Engine

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In this study, the combustion characteristics and durability of a diesel engine using emulsified fuel was investigated. Water was used in oil type emulsified fuel. In order to understand the effect of emulsified fuel in a wide range of engine running conditions, D-13 mode was selected as a test condition, and a durability test was included to understand the long-term effect of water. Combustion pressure in a cylinder, exhaust emissions, specific fuel consumption, sound level and maximum torque were measured. NOx and PM were simultaneously reduced and the specific fuel consumption was increased and decreased at low and high loads, respectively. There was no trouble and any damage on the parts of the cylinder during a 500 hour durability test.

Key Words : Emulsified Fuel, Micro-Explosion, D-13 Mode Test, NOx, Particulate Matter

1. Introduction

The regulations for NOx emissions and particulate matters (PM) from diesel engines have become severer, which recently drives the development of further technologies. Using water in oil emulsified fuel is a possible way to reduce NOx and PM simultaneously. Many studies have reported about the micro-explosion effect of water in oil emulsified fuel. Micro-explosion was firstly observed by Ivanov and Nefedov (1965), and it was often used to explain the effect of the emulsified fuel on engine performance. They also reported a longer ignition delay by water evaporation. For the cylinder corrosion problem by water impinging on a wall, Jeong (1999) insisted that water in oil was quickly evaporated by micro-explosion into extremely tiny droplets ; this would make the water drops not reach directly to the combustion chamber wall, so there would be no corrosion on the cylinder surface. Tsukahara and Yoshimoto (1992) showed a remarkable reduction of NOx concentration and smoke without increasing the specific fuel consumption, and the maximum combustion pressure decreased by 11% when engines operate with emulsified fuel at low compression ratios. Engine performance of a stable emulsified fuel for internal combustion engines (A-55) was reported by Gunnerman and Russell (1997). The results showed the reduction of NOx and particulate emissions from diesel engines. NOx concentration, smoke density, and BSFC were simultaneously reduced with water in oil in a diesel engine (Ishida et al., 1990).

Previous studies for emulsified fuels mainly have focused just on characteristics of the fuels and tested in an experimental engine, which could hardly explain the combustion characteristics and durability under the actual diesel engine combustion conditions. The present study uses a highway-

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bus engine using water in oil emulsified fuel to understand a simultaneous reduction of BSFC, NOx, and smoke density for an actual engine, and also to understand durability with a D-13 mode including a wide range of running conditions.

2. Experimental Aparatus and Method

2.1 Experimental engine setup

2.1.1 Test engine and setup

Figure 1 is the schematic of the experimental setup. It is divided into three parts. The first one is an engine driving part with a dynamometer, which can control the engine speed within ±20 rpm regardless of engine loads. Another is a cylinder pressure measuring part and the other is an exhaust gas measuring part. A four stroke direct-injection diesel engine with six cylinders and a turbo charger is used in this experiment. This engine is currently used as highway buses or urban buses. The major specifications of the test engine are given in Table 1. During the 500-hour test, the engine is operated at the same condition without any hardware changes.

Table 1 Engine specifications

Item	Specifications
Engine type	TCI Diesel Engine
Displacement [cc]	11149
Bore Stroke [mm]	130× 140
No. of cylinder	6
Compression ratio	16.4
Clearance volume [cc]	120.7
Injection timing [BTDC]	12°

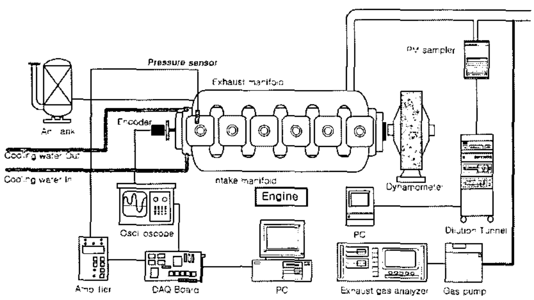


Fig. 1 Experimental apparatus setup

2.1.2 D-13 test mode

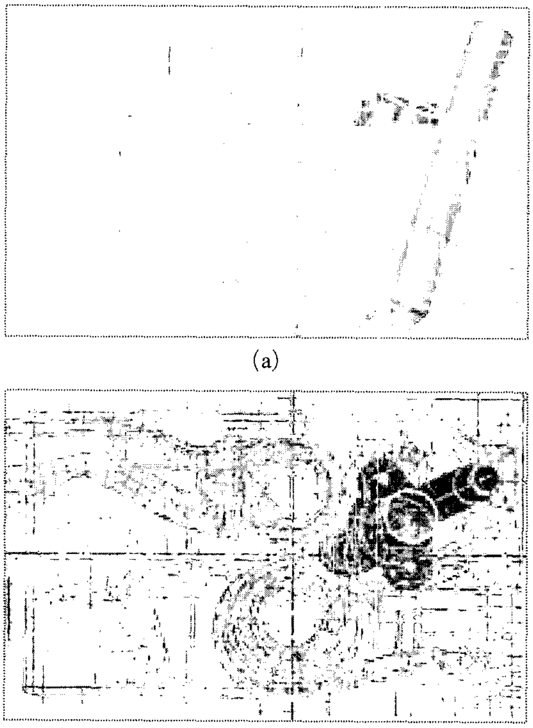
A D-13 mode has 13 different conditions for 78 minutes. The first, the seventh and the thirteenth steps are idle states. The other steps are 10, 25, 50, 75 and 100% of full power at 1200 and 2000 rpm. Durability test is carried out average 8 hours per day and the total durability-test duration is 500 hours.

2.1.3 Cylinder pressure measurement

The pressure measuring system is composed of a pressure transducer, an amplifier and a data acquisition system. The piezo-electric pressure transducer is installed on the cylinder head as shown in Fig. 2.

2.1.4 Exhaust gas measurement

CO, HC, and NOx are measured with the exhaust gas analyzer (HORIBA, MEXA 8120D) and the particulate matter samples are collect-



(a) (b)

Fig. 2 Installation of the pressure sensor

Table 2 Properties of test fuels

Item \ Fuel	Diesel	Emulsion (water 15%)
Density (kg/m^3)	0.8369	0.8619
Kinetic viscosity (m^2/s)	2.9×10^{-6}	5.32×10^{-6}
Ratio of dynamic viscosity	1	1.83

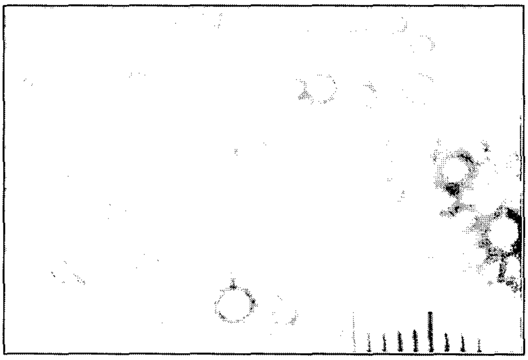


Fig. 3 Photograph of emulsified fuel

ed by a micro dilution tunnel (Sierra, BG-2) through the PM sampler. The samples are measured with an electric balance, which is located in the room having almost constant condition during the measuring. Smoke is measured three times by a Boche smoke meter.

2.1.5 Sound level measurement

Sound levels are measured at several locations simultaneously with B&K 2230 sound level testers.

2.2 Test fuels

Water in oil type emulsified fuel is prepared with a high-speed electric mixer, and the water contents in the emusified fuel are 13%, 15%, and 17%. Table 2 shows the properties of the fuels which are used in the test. The analysis focuses on the 15% water content emulsified fuel producing the best effect on the engine performance. It is confirmed the water droplets in the fuel are in the size less than 10 μm and are uniformly distributed as shown in Fig. 3. The value of the water addition rate designates the volume percent

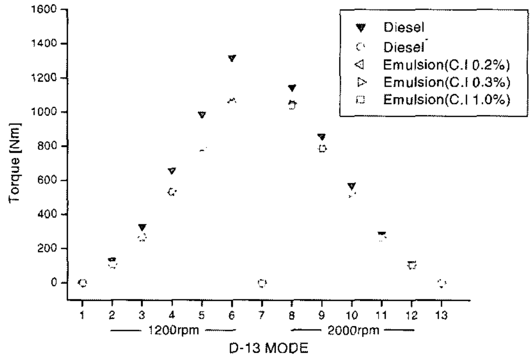


Fig. 4 Comparison of torques for various fuels

of water for the total amount of emulsified fuel including water.

Due to the water addition, cetane number is decreased. Therefore, cetane improver is added as much as 0.2, 0.5 and 1.0% of the emulsified fuel. If there is no mention on the cetane content, the cetane improver of 0.2% is included in the test fuel.

2.3 Torque reformation

Figure 4 shows the reformed torques of diesel, which are compared with those of diesel and water emulsified fuel having different contents of cetane improver. Maximum torque is decreased up to 20% in 1200 rpm, while decreased only 9% in 2000 rpm. At the low loads, however the torques are not much affected by the water and cetane improver contents. Diesel* denotes a reformed test mode which has the same thirteen torque values as those of the emulsified fuel. The reformed diesel mode is used in this study, and "Diesel" means the reformed diesel mode hereafter.

3. Results and Discussion

3.1 Engine performance before durability test

3.1.1 Cylinder pressure

Cylinder pressure of the emulsified fuel is compared with that of diesel in Fig. 5. The pressure is similar to that of diesel by near TDC and slightly lower around TDC and then becomes much lower after TDC. The pressure rapidly increases to the peak pressure, which is higher than that of diesel. Figures 6 and 7 show the cylinder pressures at 1200 and 2000 rpm in the case of 15% water content emulsified fuel. The cylinder pressures are the mean values of the samples received during 400 engine cycles. The pressure increases up to TDC and then decreases with the piston moving down. After deep down, the pressure steeply increases with combustion. The behaviors of the cylinder pressure are similar to one another. However, the pressure decreases much deeper in the low load and low engine speed case. These observations indicate that the self-ignition of water-emulsified fuel is sensitively affected by the engine running condition. If the gas condition in the cylinder is in the enough energy to absorb a water-cooling effect, the cylinder pressure smoothly increases as shown in the case of 890 Nm and 2000 rpm. If not, the pressure significantly decreases after TDC with the long delay of self-ignition as shown in the case of 270 Nm and 1200 rpm.

Figure 8 is the pressure variation during the exhaust process. In the emulsified fuel case, it is expected that the emulsified fuel has much higher exhaust gas pressure than that diesel of due to the exhaust gas increased as much as the amount of the emulsified water vapor. However, it shows the cylinder pressures of emulsified

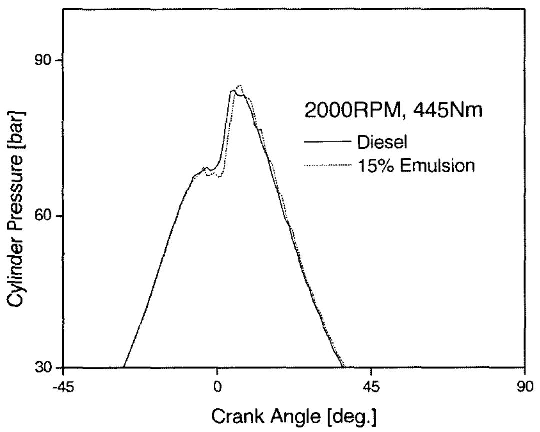


Fig. 5 Cylinder pressure comparison with emulsion fuel

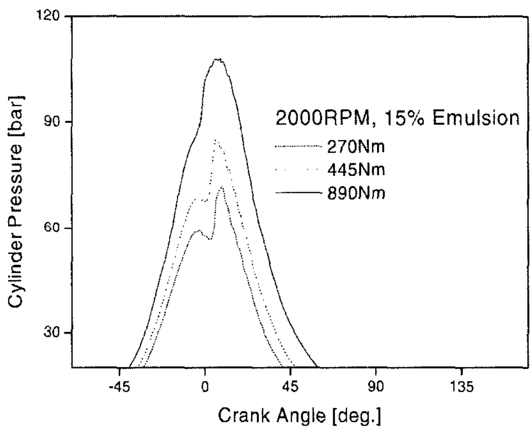


Fig. 7 Cylinder pressure at 2000 rpm

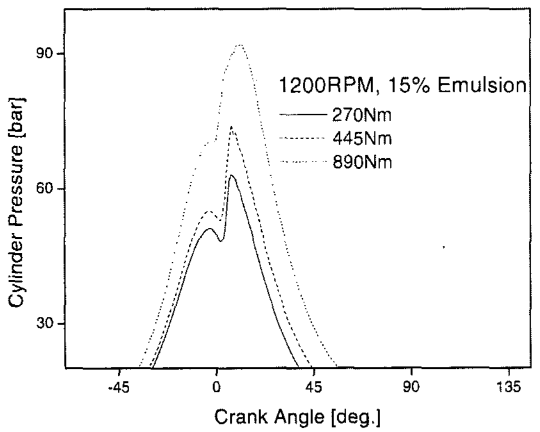


Fig. 6 Cylinder pressure at 1200 rpm

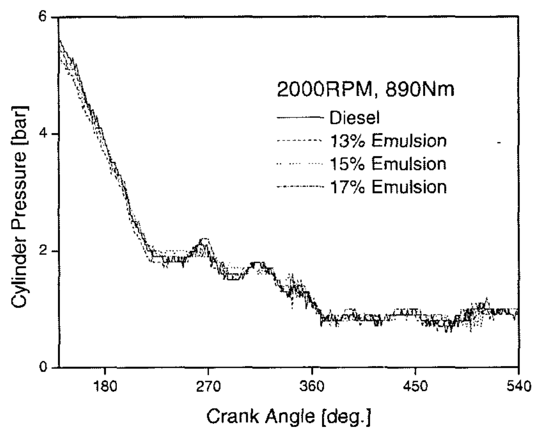


Fig. 8 Cylinder pressure variation during exhaust process

fuels are not much different from those of diesel, which means that the water addition effect on exhaust gas pressure is negligible.

3.1.2 Specific fuel consumption

Figures 9 and 10 are the comparison of specific fuel consumptions in the case of diesel and emulsified fuel with cetane improver of 0.2, 0.5 and 1.0%. The consuming mass of the diesel oil without water is considered for calculating specific fuel consumption. It is well known the emulsified fuel has two opposite effects on combustion, which are micro-explosion effect and heat loss increasing effect by water vaporization. Those are complementary to each other. For that reason, it is predicted that the increase or decrease of BSFC depends on the engine running

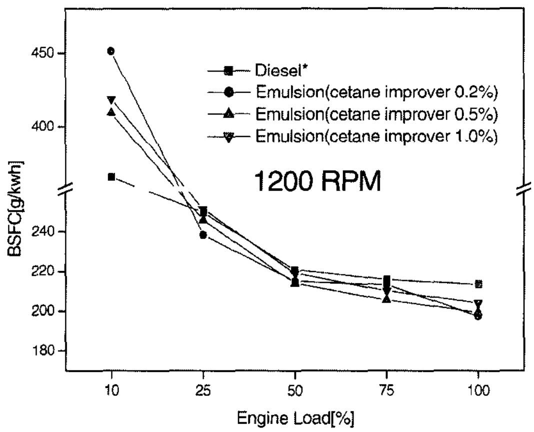


Fig. 9 Comparison of BSFC at 1200 rpm

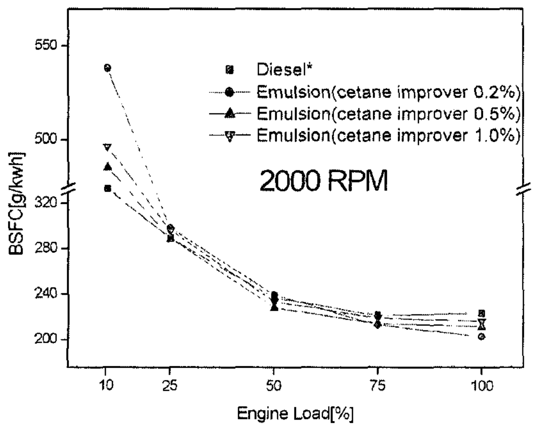


Fig. 10 Comparison of BSFC at 2000 rpm

condition. In the case of 1200 rpm, Fig. 9 shows the high specific fuel consumption at the low load. At 10% load, BSFC is the lowest in the diesel case, which is 23% lower than the consumption in the case of emulsified fuel with 0.2% cetane improver. The specific fuel consumption is improved with increasing amount of cetane improver. Over 25% load, emulsified fuel has less BSFC than diesel fuel ; in this case the cetane improver does not affect the BSFC any more. This trend is shown much clearly in the high load cases of 50, 75 and 100%.

Figure 10 shows that BSFC variation at 2000 rpm is similar to that at 1200 rpm. At 10% load, specific fuel consumption is the lowest in the diesel case. The smaller content of cetane improver has the higher fuel consumption in the condition. At 25 and 50% loads, the specific fuel consumptions are similar to one another but still the diesel case shows the lowest BSFC. In this medium region, specific fuel consumption has a good effect with cetane improver increase. In the case of 75% load, the specific fuel consumption of the emulsified fuel is better than that of the diesel fuel. The less cetane improver gives a better effect on the fuel consumption. Those effects become rather clear at the full load.

The results may be caused by mutual actions of the cylinder cooling effect by the evaporation of water and the flame propagation effect by the micro-explosion. In the case of the low engine speed and low load, the temperature will be low in the chamber during the main combustion period because of the cooling loss and air leakage increase during compression process. Water emulsified fuel takes the additional decrease of temperature in the combustion chamber by evaporation of water. Then the micro-explosion effect will be reduced because it hardly occurs at low temperature. Thus, the specific fuel consumption becomes worse rapidly with emulsified fuel. This problem can be solved by adding the cetane improver helping the self-ignition or by increasing the engine load and speed. In the high engine speed, the temperature in cylinder increases enough to ignite the emulsified fuel because the high speed recovers the temperature reduction by water addition. Thus, the thermal efficiency is improved by the active combustion with micro-explosion.

3.2 Engine performance after durability test

3.2.1 Parts examination

Figure 11 shows the photographs of the under part of cylinder head and piston crown after a 500 hours durability test. When the head was dismantled, the erosion by water was possibly expected because a white region was found differently from a black surface in general diesel engines after the durability test. It distributes around the inlet valve and its component is white fine dust when examined with the naked eyes. It may be not formed by the reaction with cylinder head material but by the surfactant combustion.

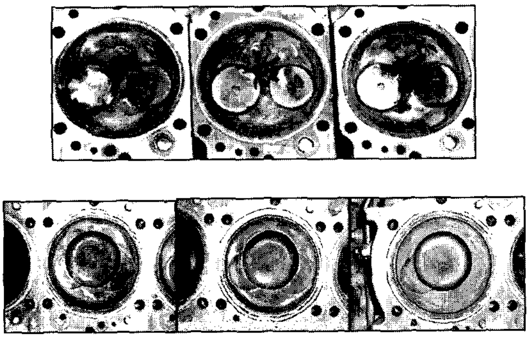


Fig. 11 Engine head and chamber after durability test

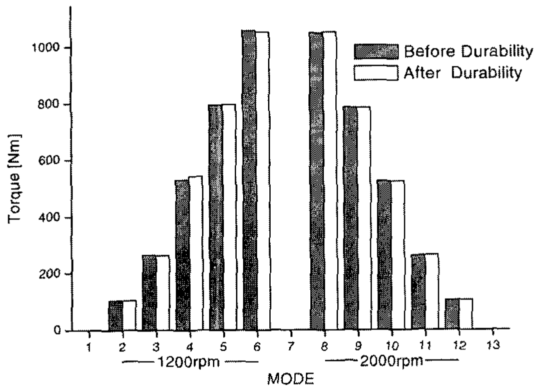
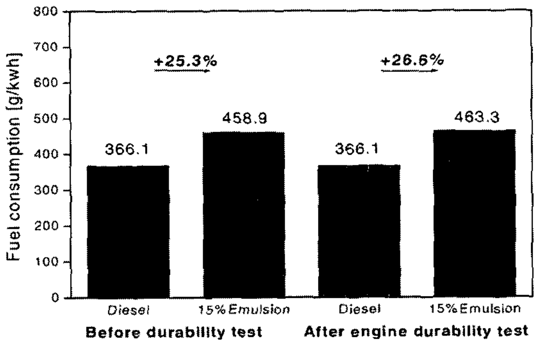


Fig. 12 Comparison of torque before/after durability test

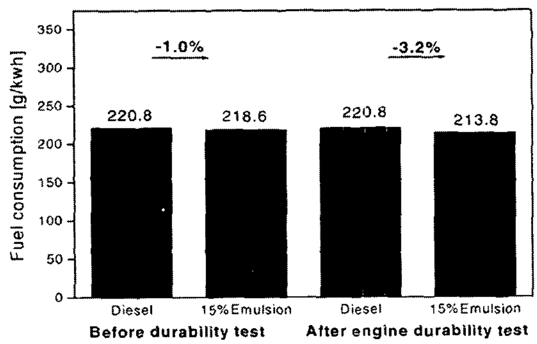
The engine parts of an injection system and an intake and exhaust system have no damage and trouble during the 500-hour durability test.

3.2.2 Torque

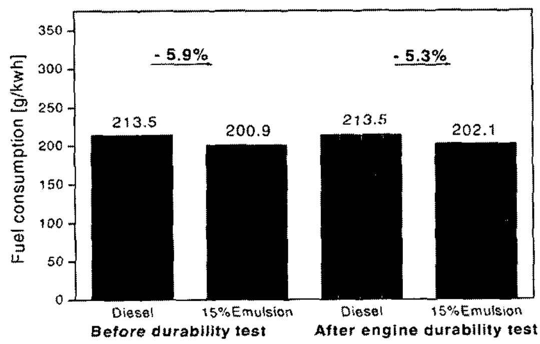
Figure 12 shows the variation of torques before and after the durability test. Torques after the durability test are slightly higher or lower than those before the durability test. The torque differences are less than 5% over all loads.



(a) 10% load



(b) 50% load

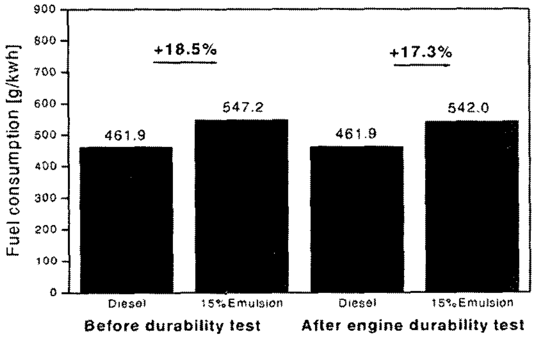


(c) 100% load

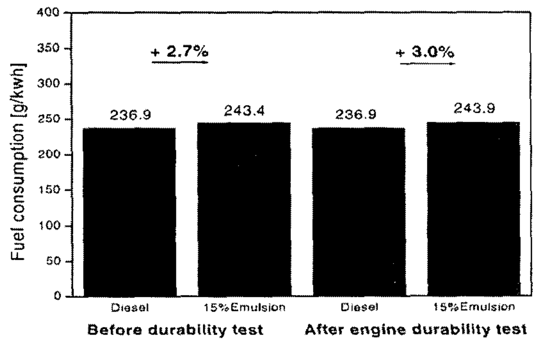
Fig. 13 Fuel consumption comparison at 1200 rpm (Before and after durability test)

3.2.3 Specific fuel consumption

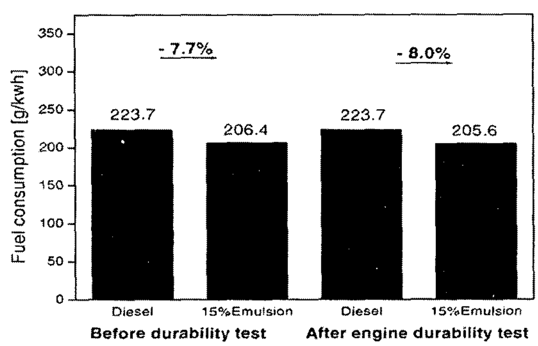
Figures 13 and 14 show the comparison of the specific fuel consumptions before and after the durability test with load variation. The fuel consumptions after the durability test are the same values as those before the test in the diesel case, while the consumptions are slightly increased or decreased with engine load and speed variation.



(a) 10% load

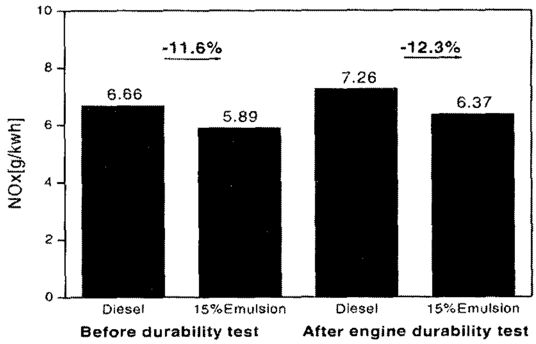


(b) 50% load

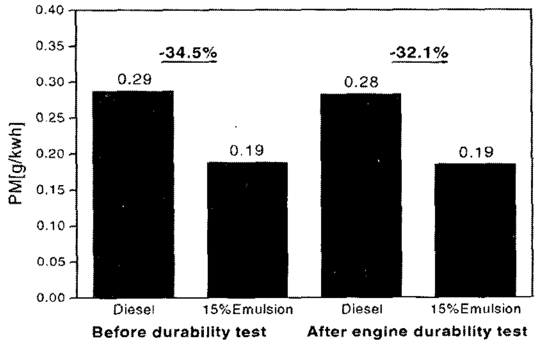


(c) 100% load

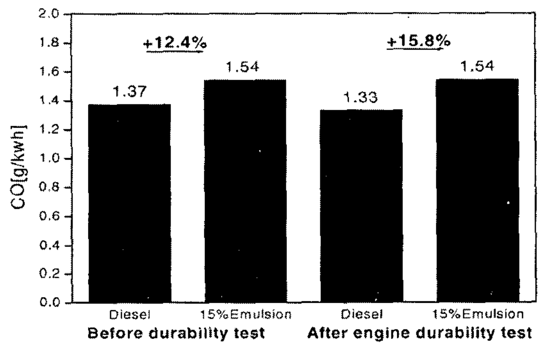
Fig. 14 Fuel consumption comparison at 2000 rpm (Before and after durability test)



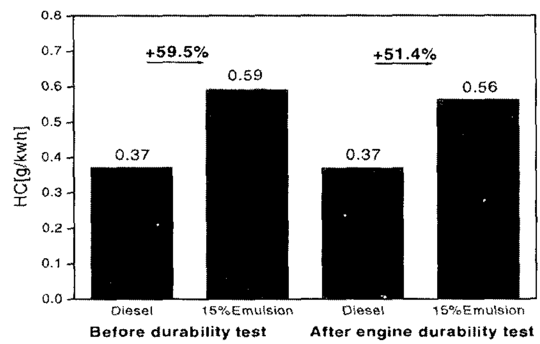
(a) NOx



(b) PM



(c) CO



(d) HC

Fig. 15 Comparison of exhaust gases before and after D-13 mode durability test

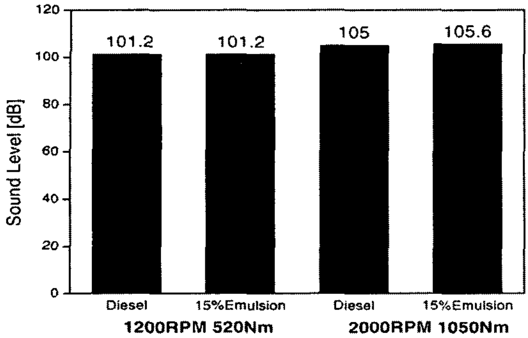


Fig. 16 Sound levels

3.2.4 Exhaust gas

Figure 15 shows exhaust gas variation after the durability test compared to before the durability test. The exhaust gas is measured by D-13 test mode, which has 13 steps over all engine load and speed range. NOx and PM are reduced up to 11.6 and 34.5% simultaneously before the durability test. The reductions are similarly 12.3 and 32.1% after the durability test. On the contrary, CO and HC are increased to 12.4 and 59.5% before the durability test and 15.8 and 51.4% after the test. This indicates the exhaust emissions are not much affected by the durability test.

3.3 Sound level

Figure 16 shows the mean values of the sound levels measured at the several points around the engine. At the medium load of 520 Nm and 1200 rpm the noisy level is just the same value as that in the diesel case. At the full load of 1050 Nm, the noise is slightly louder as much as 0.6 dB, which is only 0.5% of the noisy level. The noise increase by water-emulsified fuel is not considerable at all.

4. Conclusions

In order to better understand the combustion characteristics and the durability of a motorway bus diesel engine using water emulsified fuel, the engine was tested by D-13 test mode for 500 hours. Cylinder pressure was measured in a combustion chamber and exhaust emissions of NOx, PM, HC and CO were also measured. The results show that emulsified fuel is clearly different from pure diesel fuel for the combustion characteristics. Those are summarized as fallows ;

(1) In general, the engine test results agree with the previous studies for emulsified fuel. The maximum cylinder pressure increases and ignition delay period becomes longer.

(2) The specific fuel consumption increases at a low load region, similar at a medium load region and decreases at a full load region.

(3) Maximum torque decreases as much as water contents. NOx and PM are reduced about 12 and 33% respectively in the D-13 mode test.

(4) There is no trouble and any damage on the parts of the cylinder during a 500 hour durability test.

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