M8-004 PERFORMANCE AND EXHAUST EMISSION TESTS FROM A DIRECT INJECTION DIESEL ENGINE FUELED WITH DIMETHYL ETHER (DME)

Iman Kartolaksono Reksowardojo,
Chandra Irawan, Anthonio Marioza, Wiranto Arismunandar

Faculty of Mechanical Engineering and Aerospace Technology
Institut Teknologi Bandung,
Jl. Ganesa 10, Bandumg 40132
Phone+62-22-2534118, FAX:+62-22-2534212, Email:iman@lmbsp.ms.itb.ac.id

ABSTRACT

Dimethyl Ether (DME) has good characteristic for use as fuel in diesel engines. It can be produced from various resources such as natural gas, coke, coal, and biomass. DME can reduce dependence on fossil oil as the basic material to produce diesel fuel. Diesel engines need some minor modifications before substituting DME as fuel, due to some physical differences from diesel fuel. The main modifications involve pressurizing the fuel tank, replacing fuel lines with stainless steel tubing, cooling the fuel injector pump, and setting the optimal injection pressure for the fuel injector. Both DME and diesel fuel were tested in a utility diesel engine at 1350 rpm and 1800 rpm at various loads. It was found that DME delivered only 67% at 1350 rpm and 51% at 1800 rpm of the maximum power obtained from diesel fuel. The fuel efficiency of diesel fuel was higher than that of DME; only about 54% and 65% of the mass of DME delivered the same BMEP (Power) at 1350 rpm and 1800 rpm respectively. DME had better ignition characteristics and the combustion process resulted in cleaner exhaust emission. Compared to diesel fuel UHC emission decreased by 15.35% and 18%, and NOx emission decreased by 60% and 42.4%, at 1350 rpm and 1800 rpm respectively. Also DME did not produce soot at high load.

I. Introduction

Economic growth in Indonesia is accelerating and as a consequence the demand for liquid fuel especially gasoline for light vehicles and diesel fuel for heavier vehicles and industries is rapidly increasing. The increasing demand for crude oil has forced Indonesia to maximize domestic crude oil production and import crude oil from abroad. As crude oil is not a renewable resource, complementary and substitute fuels must be introduced to increasingly replace crude oil as the main source of fuel for motor vehicles, industrial engines and power generators, etc.

Indonesia has many natural resources that can be used as alternative fuel to complement and reduce dependency on crude oil. Other fossil fuel resources such as natural gas and coal are currently used extensively to reduce oil consumption; for example, CNG for taxis and public buses in Jakarta, coal and natural gas for electric generators. Biofuels such as biodiesel and bioethanol have also been introduced for transportation and domestic consumption and are mixed with regular fuels.

Air pollution has become an important problem in Indonesia. Globally the main contributor is from motor-vehicle engine exhaust gases. The main pollutants from internal combustion engine exhaust gas are CO, CO_2, NO_x, SO_x and soot. To reduce CO and soot particulates, improvements in the process of combustion are needed. Reduction of SO_x emissions requires fuel with lowered Sulphur content. Reduction of CO_2 requires increased engine efficiency so that less fuel is burned to produce same power output. Reducing NO_x emission requires lowering combustion temperatures by reducing the proportion of premix combustion. To reduce air pollution the use of environmental friendly fuels has been investigated by various researchers, for example: biodiesel for diesel engines; and CNG for gasoline engines.

A fuel with suitable properties for use in diesel engines is DME (Dimethyl Ether / CH_3-O-CH_3). DME is used as a propellant for paint and cosmetics. The combustion characteristics of DME are better because it contains more Oxygen and less Carbon. It can be produced from diverse range of raw materials including natural gas, coal, and biomass. DME can be considered a suitable complementary fuel for mixture with diesel. DME used in this experiment was synthesized from natural gas, one of the more environmental friendly fuels.

Unlike biodiesel fuel DME can not be used directly in unmodified diesel engines. Minor modifications to the engine's fuel system are required because DME is a gas at atmospheric pressure and temperature. Consequently DME must be pressurized to retain it in liquid form prior to entry in the high pressure fuel pump. The optimum injection pressure for specific supply pressure of DME also has to be determined. All optimizations made were based on experiment.

II. DME and Diesel Fuel Comparison

Dimethyl Ether with chemical formula CH_3-O-CH_3 is a derivative from alcohol, and is a compound with 2 clusters of Carbon and 1 cluster of Oxygen. DME can be synthesized from synthetic gas (H2 and CO) derived by reforming raw material that contains Carbon such as natural gas, coal and biomass by either of of two methods. DME can be produced using a direct conversion process, or using a conventional process by reaction from ethanol [5]. This differs from diesel fuel which is derived by cracking and refining crude oil.

Although DME is in gas form at atmospheric pressure and temperature, it can be liquefied by pressurizing it to 5.1 bars @ 20^{o}C. It can be handled just like LPG. Low liquefaction pressure at room temperature makes it easier to store DME in liquid form by comparison with CNG which must be pressurized at 200 bars @ 20^{0}C. The differences in the properties of DME and diesel fuel affect the characteristics for use as fuel in diesel engines. Comparison of the properties of DME with several other fuels are presented in table 2.1:

Table 2.1 Properties of several fuels [2],[6]

Parameter	Methanol	DME	Diesel Oil	Gasoline
% Oxygen mass	50	34.8	0	0

Boiling Point (^oC)	65.8	-24.8	180-370	35-232
F/A Stoichiometric	0.156	0.111	0.0685	0.0677
LHV (MJ/kg)	19.5	28.4	42.5	44.1
Viscocity cp@20 ^oC	0.56	0.12	1.6-6.88	-
Density (g/ml)	0.79	0.73	0.84	0.74
Flash Point (^oC)	450	235	250	360-380
Latent Heat of Evaporation (KJ/Kg)	-	410	250	-
Cetane Number	5	>>55	40-55	-
Octane Number	111	-	-	88-94

The major differences between diesel fuel and DME from table 2.1 are in the mass of bonded Oxygen - DME 34.8%, diesel fuel 0.0%. The boiling point of DME at atmospheric pressure is much lower than room temperature so it vaporizes if placed in open containers. The LHV of DME is lower than diesel fuel as it contains less Carbon and Hydrogen. DME also has low viscosity by comparison with diesel fuel. The other important difference is that DME has a Cetane number higher than diesel fuel so its potential value as a diesel fuel is quite high.

DME has several advantages to be used for diesel fuel, such as [2], [6]:

- Lower flash point and higher Cetane number compared to diesel fuel, suiting the requirements for diesel engines.
- There is no Sulphur in DME's chemical structure so no SOx emission are produced.
- NOx emission in the exhaust gas are reduced because the combustion temperature is lower than for diesel fuel.
- At high load, DME doesn't produce soot because it mixes and reacts readily with Oxygen in the combustion chamber.

DME also has several disadvantages [2], [6]:

- The low viscosity of DME negatively affects the high pressure pump since wear increases due to lack of lubrication.
- DME vapor can be trapped in the high pressure line between injection pump and injector, delaying injector opening. Local cooling is needed to prevent this.
- The lower density of DME results in shorter fuel penetration when injected into the combustion chamber.
- LHV of DME is only about 65% of diesel fuel. Hence the power generated by an engine fueled from the same volume of fuel is lower.
- Most elastomeric materials are dissolved by DME

The lubrication problem was overcome, based on previous experiments, by blending DME with 1-2% of Castor Oil inside the fuel tank [2],[6].

III. Engine Testing Apparatus

A YANMAR NF-19S, light duty diesel engine with specification listed below was used for testing DME:

Type : One cylinder, 4 stroke.
Bore x Stroke : 110 x 106 mm
Cylinder volume : 1007 cc
Number of valves : 2
Compression Ratio : 18.5: 1
Piston Shape : Toroidal
Fuel System : Direct Injection
Rated Power / rpm : 16 PS / 2200 rpm
Max. Power / rpm : 19 PS / 2400 rpm
Cooling fluid : Water
Starting System : Manual and Electric
Electrical System : Alternator 12 V, 6 A
Lube Oil Capacity : 3.6 ltr
Empty Weight : 192 kg

A schematic of the test equipment is shown in figure 3.1.

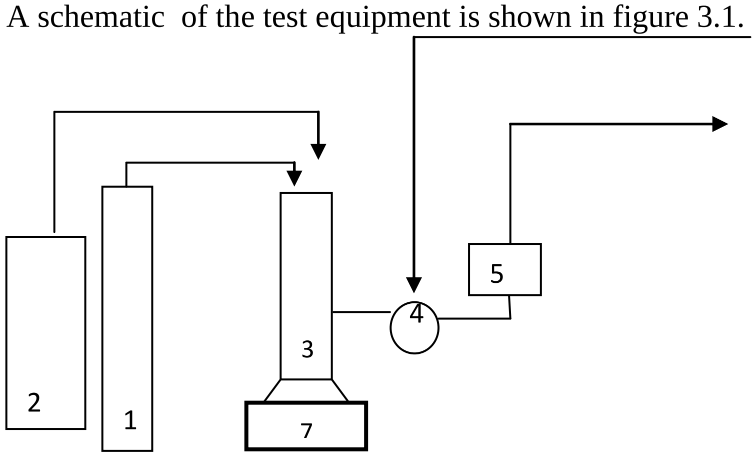
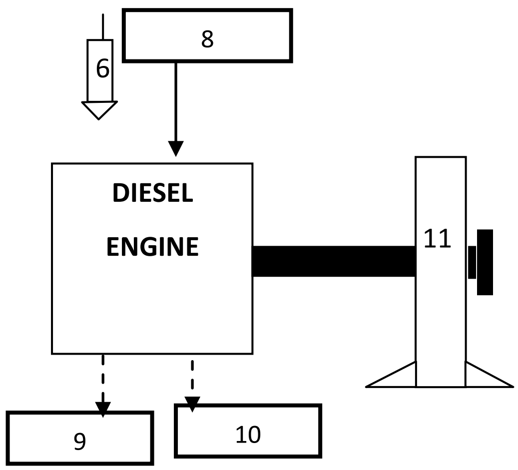


Fig 3.1 Test Equipment

1:Nitrogen tank, 2:DME storage tank, 3:Transfer tank, 4:Pressure regulator, 5:Injection pump, 6:Injector nozzle, 7:Electronic balance, 8:Air flowmeter, 9:Exhaust gas analyzer, 10:Combustion chamber pressure measurement, 11: Dynamometer



To compensate for the higher pressure (min 5.1 barg) applied to the DME and prevent fuel leaks, minor modification of the engine fuel system involved changing all rubber fuel line with stainless steel tubing and replacing the fuel tank with a double ended stainless steel test cylinder. The test cylinder which acted as a transfer tank kept the DME pressurized, provided a place to mix DME and Castor oil, and enabled the measurement of fuel consumption by means of an electronic weight scale. Lubricant (Castor oil) was first injected into the transfer tank; then DME at low pressure from the storage tank. The transfer tank was then pressurized using nitrogen. The pressure at inlet of the injection pump was kept relatively constant, by a pressure regulator.

The transfer tank was maintained at a pressure of 15 bars to ensure that DME reached the injection pump in liquid form. To reduce the temperature of injection pump from engine heat and eliminate consequent vaporization of DME, the injection pump was cooled by water spray. Different injection pressures had been tested to find optimum trade-off between power and efficiency. It was found that 60-70 bar was the optimum injection pressure for DME compared to 220 bars for normal diesel fuel use. Tests were run at constant speed and maximum torque.

Engine performance was measured by dynamometer on the test bench. Exhaust gas was measured by gas analyzer. A pressure transducer mounted in the cylinder head was used to obtain data for analysis of combustion characteristics in the combustion chamber

IV. Test Result

On completion of performance and exhaust emission tests on test bench, the data obtained was processed and comparisons of the performance and exhaust emissions for DME and Indonesian regular diesel fuel (solar) were carried out.

4.1 Effect of DME Injection Pressure

Effect of DME's injection pressure is shown at fig 4.1 and 4.2. Increasing injection pressure results in a decrease in overall performance. When the injection pressure was too low fuel dispersion from the tip of the nozzle lead to ignition delay and raised the levels of unburned hydrocarbon (UHC) in the exhaust gas.

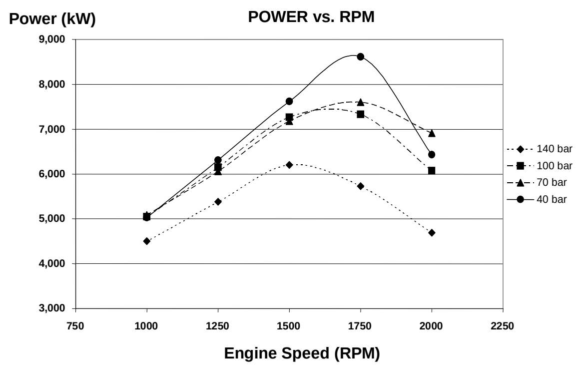


Fig 4.1 Effect of injection pressure on Power

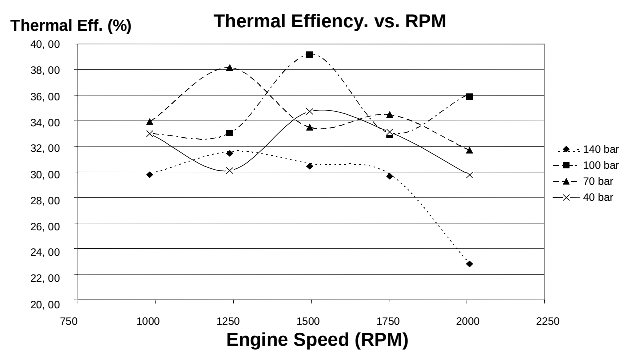


Fig 4.2 Effect of injection pressure on Efficiency

4.2 Performance Analysis on Diesel Engine

In considering the shaft power produced by the engine fueled with DME and regular diesel fuel. figure 4.3 shows that the engine fueled with diesel fuel produced a higher power output than when fueled by DME. At intermediate speed (1350rpm) DME produced 8.38HP, about 65% of the shaft power produced by diesel fuel (12.427 HP). At rated speed (1800rpm) DME produced 8.584 HP, about 51% to the shaft power produced by diesel fuel (16,648HP). This was due to the fact that DME's LHV is only about 65% of that of diesel fuel. At the same fuel flow rate DME delivers lower power output than diesel fuel.

Figure 4.4 and 4.5 show that the *bsfc* (brake specific fuel consumption) of DME was always higher than diesel fuel at both engine speeds. At every load level more DME is consumed to meet the load applied to the engine i.e. more DME is required to produce the same power by comparison with diesel fuel because DME has a lower LHV than diesel fuel.

Figure 4.6 shows that the thermal efficiency of the engine fueled with DME and diesel fuel at rated speed (1800rpm) was almost the same. But at intermediate speed (1350rpm) as shown in figure 4.7, the thermal efficiency of engine fueled with DME was lower than for diesel fuel. This probably resulted from insufficient kinetic energy to spread DME throughout the cylinder at low speed so combustion was less complete.

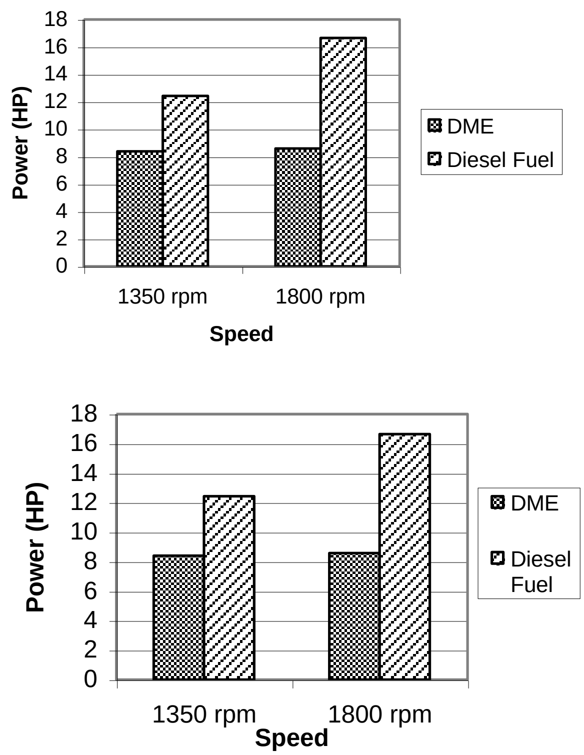


Figure 4.3 Power Vs Speed

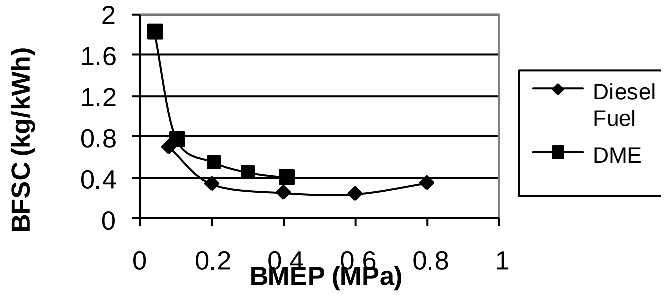


Fig 4.4 BSFC vs BMEP on 1800 rpm

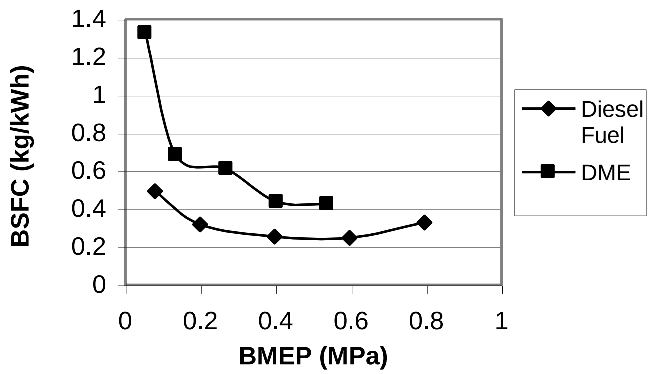


Fig 4.5 BSFC vs BMEP at 1350 rpm

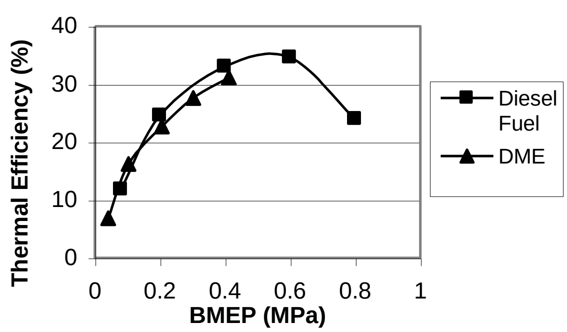


Fig 4.6 Thermal Eff. vs. BMEP at 1800 rpm

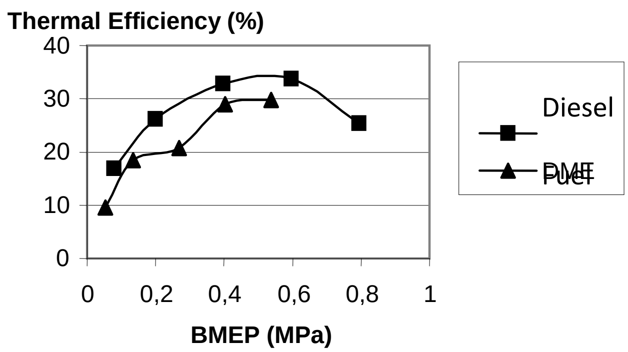


Fig 4.7 Thermal Eff. vs. BMEP at 1350 rpm

4.2 Cylinder Pressure Analysis

Cylinder pressures for each crankshaft angle were displayed by INDY619 software run on a Personal Computer connected to the Indy Module. Cylinder pressures were recorded at rated speed (1800rpm) and maximum load for DME (33Nm). Cylinder pressures for diesel fuel at the same speed and load were also recorded for comparison. The data presented in the charts lie within the compression and expansion regions. The Zero (0) degree point in chart 4.15 and 4.16 is the TDC position of the crankshaft.

Figure 4.15 shows the cylinder pressure vs. crank angle position for DME and diesel fuel. Diesel fuel had a longer ignition delay period as a result of it's lower quality as represented by it's lower cetane number. After the ignition delay period there is rapid combustion increasing the cylinder pressure producing a knocking sound. This phenomenon is termed 'diesel knock'. This phenomenon did not occur with DME due to its higher cetane number, DME results in short ignition delay and stratified burn within the cylinder. Knocking phenomenon for an extended time can lead to engine damage.

Figure 4.16 shows the heat release vs. crank angle in the cylinder. This figure is derived from automatic calculation by the INDY619 software based on pressure vs. crank angle data. The graph shows that the heat release process of DME occurred in stratified condition which also explains the occurrence of the stratified pressure rise in the cylinder. This favourable condition reflects the higher cetane number of DME . By contrast, diesel fuel has a longer ignition delay period so that at the end of delay period the diesel fuel burns, and heat release occurs instantly resulting in a sudden (unstratified) rise in pressure.

4.3 Exhaust Emission Analysis

The exhaust gas analyzer measures the level of emissions of gases contained in the exhaust gas of the test engine, such as Carbon monoxide (CO), Nitrogen Oxide (NOx), Unburned Hydrocarbon (UHC), and Soot level. On completion of tests for both diesel fuel and DME at the same engine speed, emission data were analyzed and compared.

For carbon monoxide emission from diesel fuel (solar) and DME Fig 4.7 and 4.8 show that diesel fuel and DME produce almost the same amount of CO at same speed and same load except that at maximum load, diesel fuel produced a very high level of CO as the soot limit was exceeded. At this point the mixture became too rich and there was be not enough oxygen and mixing time to achieve complete combustion.

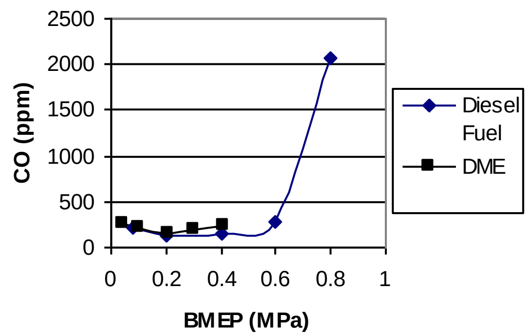


Fig 4.7 CO Emission Comparison at 1800 rpm

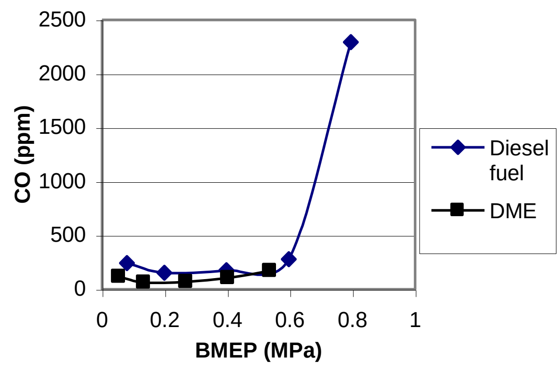


Fig 4.8 CO Emission Comparison at 1350 rpm

Fig 4.9 and 4.10 show the UHC comparison between diesel fuel and DME. At both speeds, UHC emission of DME was always lower than Diesel Fuel. As DME has a higher cetane number it is easier to ignite than diesel. DME also produces smaller droplets when injected so it reacts with Oxygen from air and burns more readily. Also, DME itself contains Oxygen atoms so at high temperature, it may ignite without Oxygen from the air (pyrolysis).

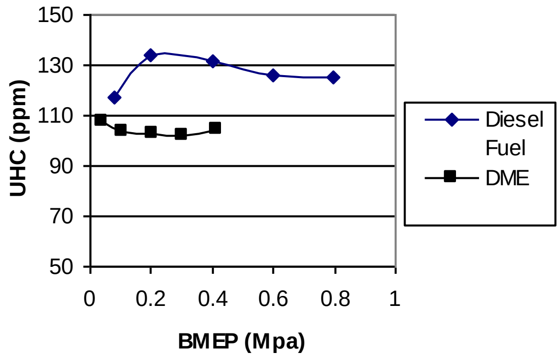


Fig 4.9 UHC Emission Comparison at 1800 rpm

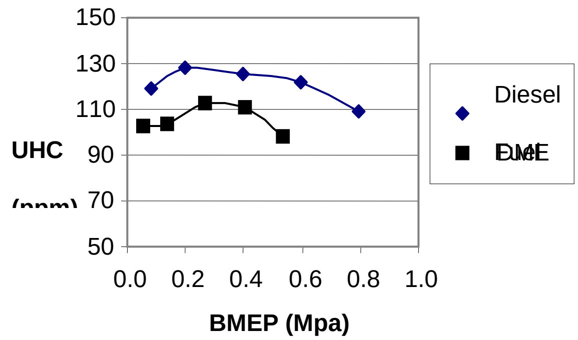


Fig 4.10 UHC Emission comparison at 1350 rpm

Considering NOx emission between DME and Diesel Fuel Fig 4.11 and 4.12. show that the NOx emission from DME was very low compared to diesel fuel. Since DME has higher cetane number ignition delay is reduced preventing rapid combustion at the first stage of the combustion. Prevention of rapid combustion avoids high pressures and temperatures in the combustion chamber (eliminates knocking) and also decreases NOx emission.

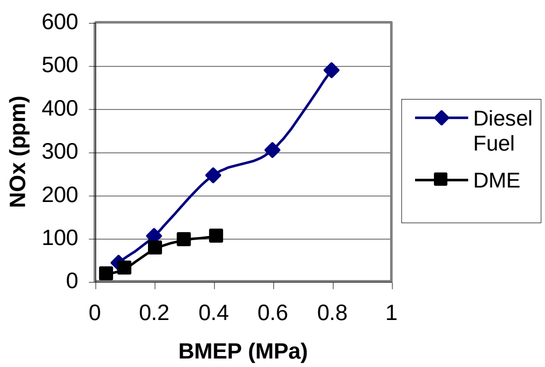


Fig 4.11 NOx Emission Comparison at 1800 rpm

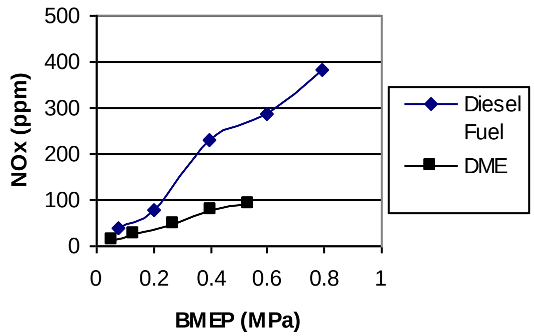


Fig 4.12 NOx Emission comparison at 1350 rpm

Diesel engines usually produce soot at high load due to incomplete combustion of fuel in the combustion chamber. The amount of fuel injected into the combustion chamber is too great, so not all the fuel meets with Oxygen and does not get burned completely. Some of the fuel not burn completely produces CO, and some is simply roasted producing black particulates which constitute black smoke (soot). Soot levels were measured with the Bosch Standard Unit which is scaled from 1-10.

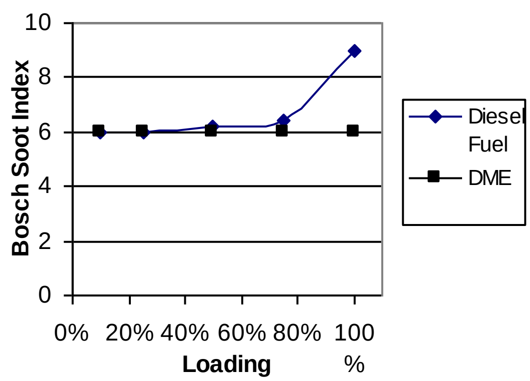


Fig 4.13 Soot Index Comparison at 1800 rpm

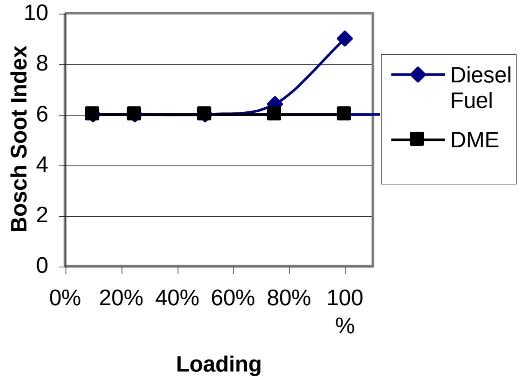


Fig 4.14 Soot Index Comparison at 1350 rpm

Fig 4.13 and 4.14 show that Diesel Fuel soot levels increased with increase in load. At full load the soot level of Diesel Fuel reached level 9 (thick black smoke) consisting of particulates and unburned hydrocarbon whereas DME at full load remained at level 6 (hardly discernable). This is because DME has no soot limit due to additional oxygen supply from within its molecule

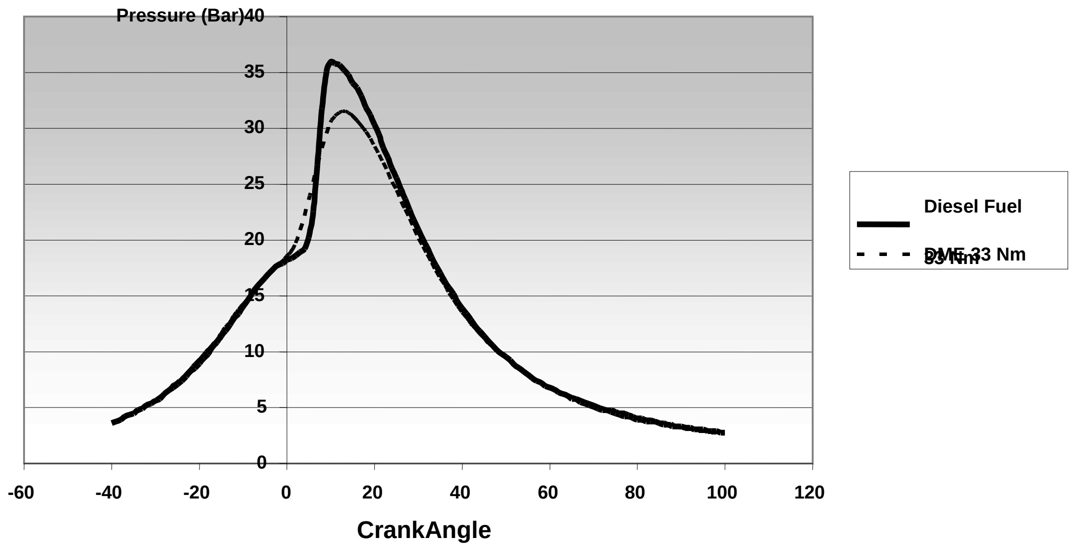


Fig 4.15 Combustion Pressure vs. Crank-angle at 1800 rpm BMEP 410 kPa

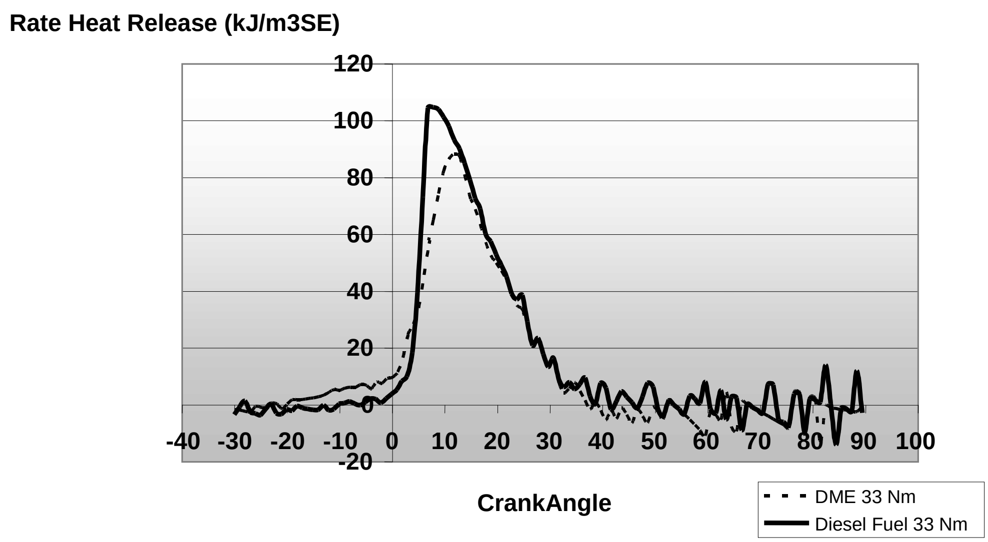


Fig 4.16 Rate of Heat Release vs. Crank angle at 1800 rpm BMEP 410 kPa

V.Conclusions

From this experiment the following conclusions were drawn:

1. DME can be use as a fuel for Yanmar NF-19 Diesel Engines with minor modifications, as follows:
    - Use of a pressurized tank (at 15Barg) to maintain DME in liquid form.
    - Change all fuel lines of rubber with steel tubing.
    - Decrease the injection pressure to 70 Barg
    - Cooling of the high pressure injection pump to avoid DME vaporization.
2. Castor oil improves performance of DME. by increasing viscosity and providing for lubrication of injection pump and injector.
3. Diesel Fuel performs better than DME. At 1800 rpm, maximum output power of DME is about 51% of diesel fuel maximum output power, while at 1350 rpm, DME produces 67% from Diesel Fuel maximum power output.
4. Diesel fuel has a higher fuel efficiency (in fuel mass comparation). At 1800 rpm, diesel fuel used about 65% of DME mass to produce same BMEP, and at 1350 rpm, Diesel fuel used about 54% of DME mass to produce same BMEP.
5. DME has better ignition characteristic in combustion process due to its higher cetane number. DME has shorter ignition delay and better rate of heat release. This will lead to cleaner exhaust emission.
6. DME decreases UHC emission 5.35% at 1350 18% at 1800 rpm by comparison with diesel fuel.
7. There is no significant change in CO emission concentration between DME and diesel fuel.
8. Using DME, NOx emission decrease by 60% at 1350 rpm, and 42.4% at 1800 rpm compared to diesel fuel.
9. Diesel engine did not produce soot at maximum load when fueled with DME.

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VI. ACKNOWLEDGMENT

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