

# PERFORMANCE AND EMISSION EVALUATION OF A DIESEL ENGINE WITH SME AND MARINE FUEL BLENDS

## ОЦЕНКА ЭКСПЛУАТАЦИОННЫХ КАЧЕСТВ И ПОЛЛЮЦИИ ДВИГАТЕЛЯ ДИЗЕЛЯ С SME И ГОРЮЧЕЙ СМЕСИ

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### Abstract

This paper presents the results of investigations carried out in studying the fuel properties of soybean methyl ester (SME) and its blend with marine diesel fuel from 5%, 20% and 50% blends by volume and in running a diesel engine with these fuels. The series of tests are conducted using each of the above fuel blends, with engine working at 1200, 1600, 2000 and 2400 rpm at full load. Engine tests have been carried out with the aim of obtaining comparative measures of the brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), mechanical efficiency (ME), exhaust gas temperature, and emissions of CO, NO<sub>x</sub>, smoke opacity and CO<sub>2</sub> to evaluate and compute the behavior of the diesel engine running on the above-mentioned fuels. BSFC of the four different kinds of fuels decreased slightly with the increase the proportion of fuel blends. The addition of biodiesel in MF fuel improved the emissions of PM.

**KEYWORDS:** MARINE FUEL, SOYBEAN OIL METHYL ESTER, BIO DIESEL.

### Nomenclature

BSFC	brake specific fuel-consumption (g/kWh)
BTE	brake thermal efficiency (%)
LHV	lower heating value (kJ kg <sup>-1</sup> )
ME	mechanical efficiency (%)
MF	marine fuel (DMX)
$\dot{m}_f$	fuel mass flow rate (kg s <sup>-1</sup> )
n	engine speed (rpm)
$P_e$	effective power (kW)
Pi	indicating power (kW)
SME	soybean oil methyl ester
$T_{exh}$	exhaust gas temperature (°C)
k	smoke (m <sup>-1</sup> )

### 1. Introduction

Recent years, biodiesel have received significant attention both as a possible renewable alternative fuel and as an additive to the existing petroleum-based fuels. Biodiesel exhibits several merits when compared to that of the existing petroleum fuels. Many researchers have shown that particulate matter, unburned hydrocarbons, carbon monoxide, and sulfur levels are significantly less in the exhaust gas while using biodiesel as fuel. However, an increase in the levels of oxides of nitrogen is reported with biodiesel [1]. In addition, since biodiesel does not contain carcinogens such as polyaromatic hydrocarbons and nitrous poly-aromatic hydrocarbons, it produces pollutants that are less detrimental to human health [2].

Petroleum fuel emissions have harmful effects on the nature. For example, uncontrolled CO<sub>2</sub> increase causes greenhouse gases to exceed which subsequently results in temperature increase in the nature. The other major harmful emissions are CO, NO<sub>x</sub> and UHC (unburned hydrocarbon). In addition, our energy reserves are decreasing proportionally to increasing energy demand [3]. So, in the last couple of decades alternative fuels have gained a great importance [4] and a lot of researches have been made on this topic in this sense. Natural gas, hydrogen, vegetable oil, alcohol and biogas are some of the most important alternative fuels. The usage of bio-fuels and alcohols (ethanol, methanol) in the diesel fuels as a blend has been intensively researched in the last couple of decades.

The performance and exhaust emissions of diesel engines using various biodiesels have been studied by many investigators [1-10]. Marine engines account for about 30% of nonroad engines, but as they tend to be concentrated in coastal areas (ports, recreational areas, lakes, rivers, etc.), the local levels of pollutants may become too concentrated. Recreational sailboats powered by auxiliary diesel engines have proven to be a reliable

and high profile market for Biodiesel. In 1997, CytoCulture surveyed 100 recreational boaters in the San Francisco Bay area and found that 97 % of the vessels using biodiesel from 1993 to 1997 were sailboats. Most of the boats were in the 30 to 50 foot range, and most had smaller diesel engines (12-50 HP) that consumed relatively little fuel [11].

Rakopoulos et.al were conducted to evaluate the use of sunflower and cottonseed oil methyl esters (biodiesels) of Greek origin as supplements in the diesel fuel at blend ratios of 10/90 and 20/80, in a fully instrumented, six-cylinder, turbocharged and after-cooled, direct injection (DI), Mercedes-Benz, mini-bus diesel engine. Fuel consumption, exhaust smokiness and exhaust regulated gas emissions such as nitrogen oxides, carbon monoxide and total unburned hydrocarbons were measured. They showed that all the tested bio-diesel blends could be used safely and advantageously in the present bus diesel engine, at least in these small blending ratios, with the cottonseed bio-diesel showing emissions-wise a small superiority over its sunflower bio-diesel counterpart concerning soot and CO emissions [12].

The marine diesel emissions of greatest concern are released from large commercial and military ships because they represent the largest source of marine emissions. In this paper, detailed experimental results are given on the performance and exhaust missions, fuel consumption measurements, exhaust gas temperatures of direct injection diesel engine fuelled with soybean methyl ester (SME), marine fuel (MF) and their fuel blends. In this study, all the experiments were performed without any modification on the engine.

When B100 fuel was used in engine instead of diesel fuel, it results in better engine performance at high altitudes [13]. Ghobadian et al [14] used biodiesel, which was produced from waste vegetable cooking oil of a restaurant. They found that power and performance with fuel blends were similar to net diesel fuel. Brake specific fuel consumption (BSFC) was also similar to net diesel fuel. Brake thermal efficiency for biodiesel was slightly increased in B20; HC, CO and CO<sub>2</sub> emissions were decreased with biodiesel while NO<sub>x</sub> emission were slightly increased [15]. Devan and Mahalakshmi [16] also demonstrated that CO, HC and smoke emissions decrease while NO<sub>x</sub> slightly increases with the bio-fuel blends. They also showed that lower heating value of the blends were similar to diesel fuel. Mustafa Canakcı and et al [17] found that maximum torque obtained with the WPOME (waste palm oil methyl ester) and COME (canola oil methyl ester) bio-fuels was lower than that of PBDF (petroleum based diesel fuel), brake specific fuel consumption was higher than that of PBDF and peak cylinder gas pressure obtained with COME was similar to PBDF. They also showed that lower smoke, HC, CO<sub>2</sub> and CO emissions were obtained with bio-fuels than diesel fuel.

According to [19] sensible performance and emission results obtained in short-term operation with the vegetable oils while some problems such as filter clogging, carbon deposits and compression ring grooves occurred in long-term duration. In the same research, it was found that brake thermal efficiency was %1.61 lower, minimum BSFC was 0.05 kg/kwh higher and BSEC was 867.11 kj/kwh higher with net deccan hemp vegetable oil than that of diesel fuel. In another experimental study [18] it was found that the engine power output and the fuel consumption of the engine obtained with vegetable oil and its blends were so close to the results obtained with pure diesel. It was also found that NO<sub>x</sub>, CO and HC emissions were lower with vegetable oil and its blends than that of pure diesel. According to [19] engine power and brake mean effective pressure (BMEP) decreased slightly and brake specific fuel consumption (BSFC) increased slightly with the increasing ratio of jojoba oil in the fuel blend. Vegetable oils have high viscosity compared to diesel fuel that may cause some problems. According to [20] heating or diluting with other fuels could reduce viscosity of oils and with the increasing temperature viscosity of vegetable oil blends get close to that of diesel fuel. It was found that rubber seed-oil diesel could be alternatively used instead of diesel fuel when it is preheated or diluted [21]. According to [22] diesel fuels and marine fuels are also shown with extensive emission analysis that the addition of biodiesel fuels to the standard diesel fuel enhances the emission characteristics of diesel engines.

## 2. Experimental set up

A four stroke, direct injection, naturally aspirated four-cylinder four-stroke diesel engine is employed for the present study. The schematic layout of the experimental apparatus is shown in Fig. 1. The engine has a maximum power output of 40 kW, a compression ratio of 16.8:1, a cylinder bore of 100 mm, a stroke of 100 mm, and a displacement of 3.14 liters. The engine was coupled to a Schenk hydraulic dynamometer, and the engine speed was measured with a tacho-generator connected to the dynamometer.

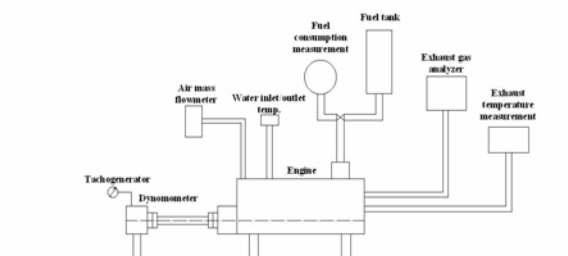


Fig. 1 The schematic layout of the experimental setup.

The load and speed of the engine were controlled by adjusting the dynamometer resistance and injection rate of the fuel pump. The fuel consumption of the engine was determined by measuring the fuel level decrease in a measurement container in a given period of time. The volumetric flow rate of the intake air was measured using a rotary type flow meter. A surge tank located between the air flow meter and intake manifold was used for damping out the pulsations produced by the engine, thus obtaining a steady airflow. The exhaust gas temperature was measured using a thermocouple connected to the exhaust pipe just downstream of the exhaust manifold. The cooling water temperatures at the inlet and outlet of the engine block were measured using "Pt 100" thermocouples. The exhaust emissions, namely CO, CO<sub>2</sub> and NO<sub>x</sub>, were measured using Horiba gas analyzer. Further details of the instrumentation are summarized in Table 1.

Table 1 The specifications of Horiba MEXA 574-GE emission analyzer.

Emission	NO <sub>x</sub> (ppm)	CO (ppm)	CO <sub>2</sub> (%)
Operating range	0-5000	0-10	0-20
Accuracy	0.050	0.01	0.02
Precision	±1 %	±0.05%	±0.1 %

First, the engine was tested with the pure fuels of MF and SME. Then, 5%, 20% and 50% blends of SME with MF were also tested. Physical characteristics of the tested fuels are given in Table 2. All tests were performed under steady-state conditions. The BSFC, BTE, ME, exhaust gas temperature, and exhaust emissions such as CO, CO<sub>2</sub> and NO<sub>x</sub> have been investigated.

Table 2 Physical characteristics of test fuels.

Fuel Property	Method	MF	SME
Density (kg/m <sup>3</sup> , 15 °C)	ASTM D1298	830	881
Viscosity (cSt, 40 °C)	ASTM D 445	3.7	4.173
Lower Heating Value (kJ/kg)	ASTM D 4809	44308	37388
Cetane Index	ASTM D 976	45	-
Cetane Number	ASTM D 613	-	50
Sulfur (wt. %)	ASTM D 4294	0.29	-
Flash Point (°C)	ASTM D 93	75	105
Cloud Point (°C)	ASTM D 97	-6	-
	ASTM D 2500	-	-3
Particulate Matter (mg/L)	ASTM D 5452	3	-

In the tests, the engine speed was changed between 1200 and 2400 rpm with intervals of 200 rpm, while the engine was operated at full load. Before each fuel test, the fuel tank of 16 liters capacity and fuel lines were drained, and the engine was operated at least 15 minutes to stabilize on the new fuel. At each speed, the engine was operated 5 minutes to achieve steady-state conditions, and the data were collected at sixth minute. Each test was repeated 3 times and the results of the 3 repetitions were averaged. In each test, coolant and exhaust temperatures, fuel consumption, airflow rate, and exhaust emissions were recorded systematically. The fuel delivery angle of the fuel injection system was kept constant at 14° BTDC.

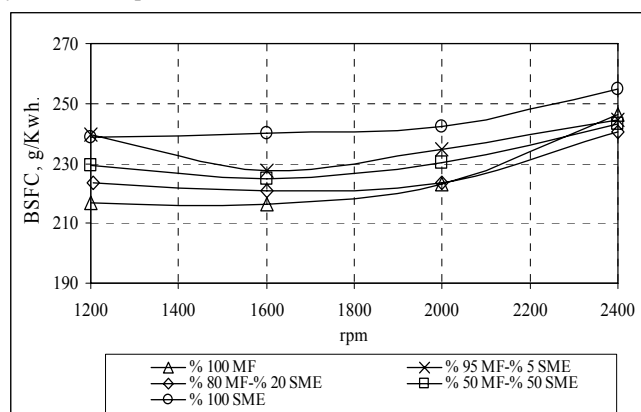


Fig. 2 The brake specific fuel consumption of the test engine vs. engine speed at full load

### 3. Results of discussion

The *BSFC* of the test engine as a function of engine speed at full load is shown in Fig. 2. The *BSFC* is the fuel consumption rate ( $\dot{m}_f$ ) per unit effective power ( $P_e$ ), i.e.

$$BSFC = \frac{3600 \dot{m}_f}{P_e} \quad (1)$$

It is generally accepted that fuel consumption is proportional to volumetric energy density of the fuel based upon the lower and net heating value [2]. In this experiment, the SME's lower heating value (LHV) is lower than the MF (LHV<sub>SME</sub>= 37388 kJ/kg and LHV<sub>MARINE FUEL</sub>= 44308 kJ/kg), it yields higher *BSFC* values. Consequently, fuel economy is lower on biodiesel as stated by Graboski *et al.* It is observed that MF appears to have a lower *BSFC* value than other blends. The *BTE* of the test engine as a function of engine speed at full load is shown in Fig. 3. The *BTE* indicates the energetic performance of the engine and defined as the ratio of the power output to the fuel energy input, i.e.

$$BTE = \frac{P_e}{\dot{m}_f LHV} \quad (2)$$

where *LHV* is the lower heating value of the fuel. It is observed that pure SME yields maximum *BTE*, which is followed by the other blends in diminishing order. The brake thermal efficiency is defined as the actual brake power per cycle divided by the amount of chemical energy as indicating by the fuel's LHV [6]. It is noticed that the use of oxygen-rich biodiesel promote a better combustion, thus improving the thermal efficiency compared to the other blends.

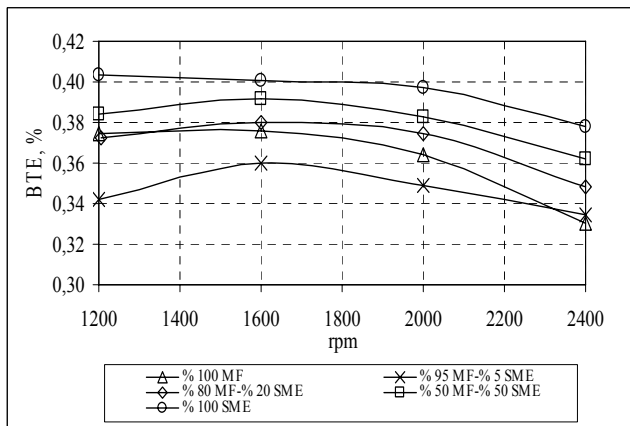


Fig. 3 The brake thermal efficiency of the test engine vs. engine speed at full load

The mechanical efficiency (*ME*) of the engine as a function of engine speed at full load is shown in Fig. 4. The *ME* is defined, as the ratio of the power output to the fuel energy input, i.e. the power that is formed in the combustion chamber is effective power. This power is bigger than the power that is taken through the out-power, because there are many losses through the engine during generating the power.

$$ME = \frac{P_e}{P_i} \quad (3)$$

It is seen that pure MF yields maximum *ME* values while SME results in minimum *ME*. Because, the energy density of SME (LHV<sub>SME</sub>=37388 kJ/kg) is lower than the MF (LHV<sub>MF</sub>=44308 kJ/kg). The exhaust gas temperature of the engine as a function of engine speed at full load is shown in Fig. 5. Exhaust temperatures are affected by ignition delay. Biodiesel that has a slightly lower cetane rating results in longer ignition delay and slower burning

rate [8]. Higher ignition delay results in a delayed combustion and higher exhausts gas temperatures. The gas temperature also presented variations when the injection system was inspected due to improve performance of diesel engine [4].

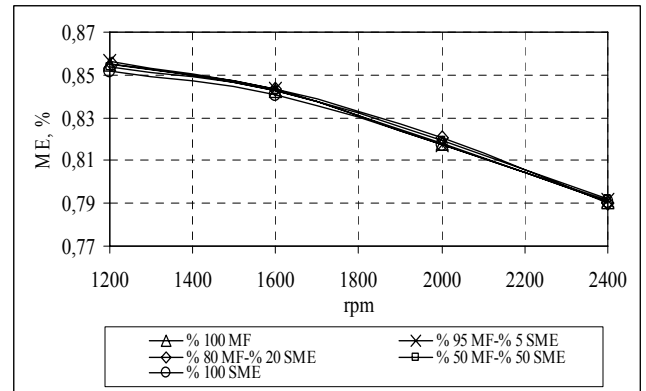


Fig. 4 The mechanical efficiency of the test engine vs. engine speed at full load.

The emission characteristics of biodiesel are of special interest regarding compliance with environmental standards. The NO<sub>x</sub> emissions of the engine as a function of engine speed at full load are shown in Fig. 6. In diesel engine the formation of mixing fuel is heterogeneous, because of this reason; the region next to stoichiometric ratio, formation of NO<sub>x</sub> was reached maximum level. Resulting from the oxidation of atmospheric nitrogen at the high temperatures inside the combustion chamber of the engine, the NO<sub>x</sub> emissions depend on the speed and load as well as the

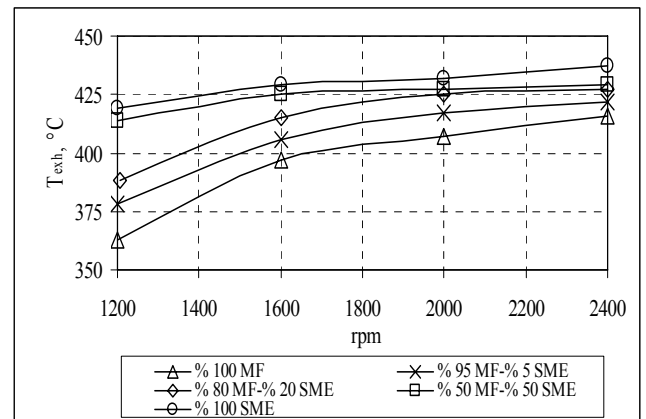


Fig.5. The exhaust gas temperatures of the test engine vs. engine speed at full load

fuel type. It is observed that SME yields higher NO<sub>x</sub> emission compared with other fuel blends. This can be attributed to the higher oxygen content in the SME. Because the oxygen-rich biodiesel promotes a better combustion, the formation of NO<sub>x</sub> emissions increases with the use of biodiesel and its blends. The mechanism of NO<sub>x</sub> formation from atmospheric nitrogen has been studied extensively and it is accepted that it is highly dependent upon temperature, due to the high activation energy needed for the reactions involved. Hence the most significant factor that causes NO<sub>x</sub> formation is high combustion temperatures.

Data from the soybean diesel study of Graboski *et al.* have been reanalyzed to gain a greater understanding of the increase in NO<sub>x</sub> emissions. The NO<sub>x</sub> emissions are clearly dependent upon speed and load. Analysis of the test results shows that the maximum NO<sub>x</sub> emissions increase proportionally with the mass percent of oxygen in the SME [2,5]. On the other hand, fuel density is

known to effect emissions of NO<sub>x</sub> from diesel engine. The NO<sub>x</sub> emissions increase because the fuel injectors inject a constant volume or larger mass for the more dense fuel, a given speed and load [2]. In order to get a full scale view of the total NO<sub>x</sub> behavior, the maximum NO<sub>x</sub> values were showed as a function of mass percent of fuel oxygen and engine speed as shown Fig. 6.

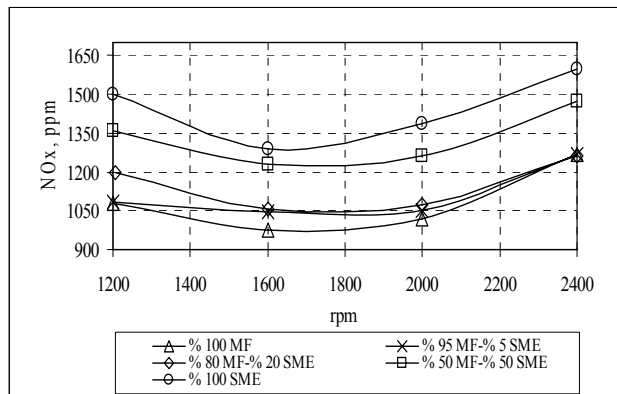


Fig.6 NO<sub>x</sub> emissions of the test engine vs. engine speed at full load.

At full load, the oxygen content of the blends and pure bio fuels seems to play an important role in reducing CO emissions at full load. The most accepted explanation for this behavior is that the oxygen content of the different bio fuels helps to complete the oxidation of carbonaceous species during combustion. Biodiesel contains about 10-11% oxygen by weight; this helps for the complete combustion. The use of biodiesel shows in the reduction of CO emission level [10]. The CO emission of engine at full load is shown in Fig. 7. The CO emission level decreased with increasing SME percentage in MF.

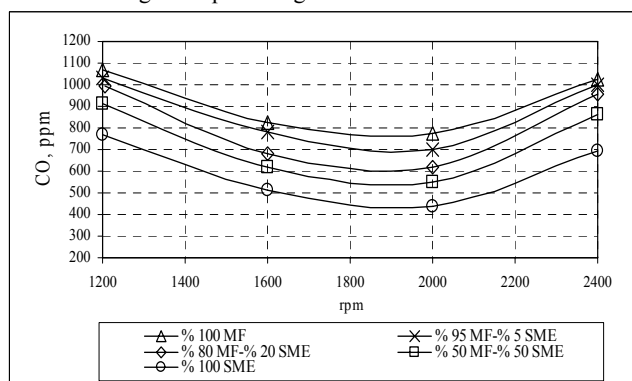


Fig.7 CO emissions of the test engine vs. engine speed at full load.

The CO<sub>2</sub> emission of the engine as a function of engine speed at full load is shown in Fig. 8. The amount of CO<sub>2</sub> in exhaust emission is an indication of the complete combustion of fuel. Because, SME fuel results in higher exhaust temperatures as shown in Fig. 5 it causes a more complete combustion, thus yielding slightly higher CO<sub>2</sub> emissions compared with other fuel blends. In most reported studies; fuel consumption is calculated from the CO<sub>2</sub> emissions and an analysis of the fuel carbon content. A more accurate approach is due to combine CO<sub>2</sub> emission measurements with a gravimetric measurement of fuel consumption [2].

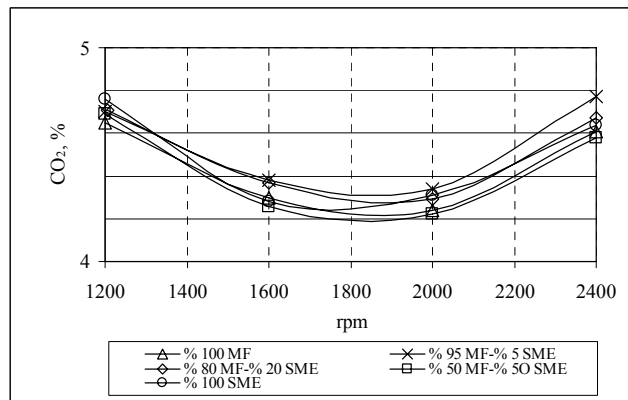


Fig.8 CO<sub>2</sub> emissions of the test engine vs. engine speed at full load.

The use of biodiesel significantly reduced smoke opacity. Biodiesel had the greatest effect on smoke in the lugging mode where B10 reduced smoke by 28.6% and B20 reduced smoke by 50% [2]. In this study, biodiesel addition reduced particulate emission in all stage as seen in Fig. 9. The maximum smoke opacity was indicated 100 % MF at 1200 rpm. The reason of this trend is the amount of sulfur concentration into MF. It is observed that pure SME yields minimum smoke opacity, which is followed by the other blends in diminishing order.

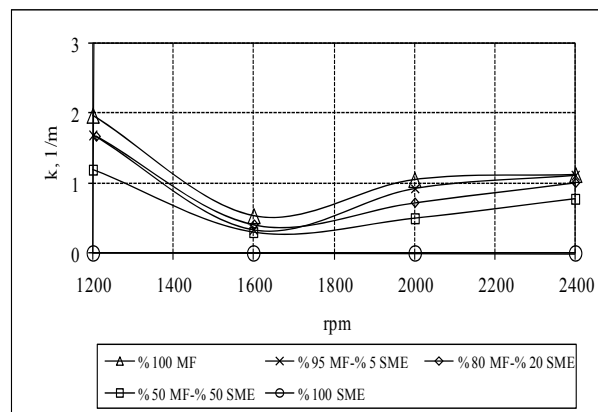


Fig.9. Smoke opacity of the test engine vs. engine speed at full load.

#### 4. Conclusions

In this paper, SME/MF blends under constant engine torque at full load and varied engine speeds have been tested in a four-stroke four cylinders diesel engine. The experimental results are described as follows:

- i. The substitution of MF with biodiesel (SME) led to a combination of positive and negative outcomes.
- ii. The addition of biodiesel in MF fuel improves the emissions of PM, which comprise a serious disadvantage of the diesel engine, especially in polluted areas such as port and beach.
- iii. CO emissions were dropped ( $CO_{\text{MARINE FUEL}}=630$  ppm;  $CO_{\text{SME}}=530$ ppm at 1600 rpm at full load. There was 16 % drop) when running on SME and its blends.
- iv. The main reason of increasing fuel consumption is that SME' lower heating value (37388 kj/kg) is smaller than marine fuel's lower heating value (44308 kj/kg). Any way a lower fuel consumption rate is required for a fuel with a higher heating value. The marine fuel has the highest heating value among four fuel blends. All blends under same load, the lower calorific value of the fuels that contain biodiesel, this behavior was expected.
- v. BSFC of the four different kinds of fuels decreased slightly with the increase the proportion of fuel blends. % 100 MF appeared to have a lower bsfc value than the

other fuel blends (dropped 7 %). This was primarily due to MF's lower fuel consumption rate and SME's LHV under same conditions.

- vi. The SME was found to have the highest exhaust temperature due to its oxygen content 11.2 % higher than marine fuel' one.
- vii. The maximum NO<sub>x</sub> emission was indicated % 100 SME blend and 2400 rpm. However, the NO<sub>x</sub> emissions were lower, respectively, using marine blends (especially % 50 marine fuel - % 50 SME)

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