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A comparison between using biofuel blends and diesel oil in marine diesel engine

Moustafa Tarek Elgendy, Mosaad Mosleh, Nader R. Ammar
Department of Naval Architecture & Marine Engineering, Alexandria University, Egypt

Abstract

The energy shortage and more strict environmental standards make the energy efficiency and environmental protection become the most important issues to be considered by shipping industry and shipbuilding industry. So a good marine diesel engine not only has to keep good dynamic and steady characteristics, but also has to improve fuel economy and minimize the emissions. In order to meet these requirements, it is necessary for the marine diesel engine model to predict its properties in the severe environmental conditions, such as load changing quickly. In the other hand, the model is one of the most important parts of the marine simulator for dynamic simulation and fault diagnosis. In the effort to find an alternative source of energy for diesel engines various solutions have been proposed, one of which is the use of biofuel blends as supplement or substitute for liquid diesel fuel. One of the main purposes is to find ecofriendly sustainable fuel. The efficiency, exhaust gas temperature, nitric oxide, carbon monoxide, unburned hydrocarbons and soot emissions are to be considered. Also, the use of previous mentioned blends as pilot fuel to be used with natural gas as primary fuel in dual fuel engine. Given that the experimental measurements cover a wide range of liquid diesel supplementary ratios without any appearance of knocking phenomena, the belief is strengthened that the findings of the present work can be very valuable if used to apply this technology on existing DI diesel engines.

Keywords: biomass blends, combustion behavior, maximum cylinder pressure and temperature and emissions

Introduction

Biofuel as fuel oil.

A fossil fuel cannot be considered as a renewable or sustainable source of energy because it takes millions of years to form and humans really can’t wait that long. Biofuel, on the other hand, produced from biomass, which can be produced year after year through sustainable farming practices. This means biomass and biofuel are renewable (we can replace used biofuel over a very short period of time).Biodiesel, defined as the mono-methyl esters of vegetable oils or animal fats, is an environmentally attractive alternative to conventional petroleum diesel fuel (petro-diesel). Produced by trans-esterification with a monohydric alcohol, usually methanol, biodiesel has many important technical advantages over petro-diesel, such as inherent lubricity, low toxicity, derivation from a renewable and domestic feedstock, superior flash point and biodegradability, negligible sulfur content, and lower exhaust emissions. Important disadvantages of biodiesel include high feedstock cost, inferior storage and oxidative stability, lower volumetric energy content, inferior low-temperature operability, and in some cases, higher NOx exhaust emissions. Biodiesel is meant to be used in standard diesel engines and is thus distinct from the vegetable and waste oils used to fuel converted diesel engines. Biodiesel can be used alone, or blended with petro diesel in any proportions; The National Biodiesel Board (USA) also has a technical definition of "biodiesel" as a mono-alkyl ester. (Lewis; *et al* 2012) [6]

Blends of biodiesel and conventional hydrocarbon-based diesel are products most commonly distributed for use in the retail diesel fuel marketplace. Much of the world uses a system known as the "B" factor to state the amount of biodiesel in any fuel mix:

- 100% biodiesel is referred to as B100
- 20% biodiesel, 80% petro diesel is labeled B20
- 5% biodiesel, 95% petro diesel is labeled B5
- 3% biodiesel, 45% petro diesel is labeled B4 (Omidvarborna; *et al*, 2014) [4]

Processing of biofuel oil

Biodiesel production starts with pressing the crop, which yields a liquid oil fraction to be converted and a first by-product, oil cake, used as cattle feed. Vegetable oils are extracted from oil seeds by mechanically pressing or extraction with a solvent, like hexane, the latter technology resulting in higher yields.

Vegetable oils can be used directly as diesel engine fuels, but this requires engine modification because some of their properties are less advantageous for this application. Two major problems are their very high viscosity and poor thermal and hydrolytic stability. They also have less favorable ignition qualities.

After filtering the vegetable oil, esterification transform the large branched molecule structure of the oils into smaller, straight chained molecules similar to the standard diesel hydrocarbons. (Demirbas; 2008) [1]

Three basic routes to producing biodiesel from oils can be distinguished

1. Base catalyzed transesterification of the oil.
2. Direct acid catalyzed trans-esterification of the oil,
3. Conversion of the oil to its fatty acids and then to biodiesel.

Most of the biodiesel produced today is done with the base catalyzed reaction for several reasons; it is a low temperature and pressure process, it has a high yield (98%) with minimal side reactions and reaction time, it is a direct conversion to biodiesel with no intermediate compounds.

This process takes place in a simple reactor system at low temperature (range 50-66 ºC) and pressure (around 1.4 bars). The first step in conversion process is the mixing of methanol and the catalyst, which is usually sodium hydroxide (caustic soda) or potassium hydroxide (potash). Excess methanol is added to ensure the total conversion of the triglycerides into esters. The catalyst/methanol mixture is fed into a closed reactor vessel, which prevents the loss of alcohol, and then the vegetable oil is added to the reactor. The reaction mixture is left to settle in the vessel for 1 to 8 hours.

After being separated from the glycerin, the methyl esters are purified. By means of a washing process, residual catalyst and soaps are removed. The purity of the esters produced in this way amounts to about 98%. This can be improved further by distillation. The end product is an amber-yellow colored liquid with a strongly reduced viscosity.

As an indication regarding the proportions in the reaction, 100 units of fat or oil (e.g. rapeseed oil) react with 10 units of a short chain alcohol in the presence of a catalyst (usually sodium or potassium hydroxide) to produce 10 units of glycerin and 100 units of biodiesel.

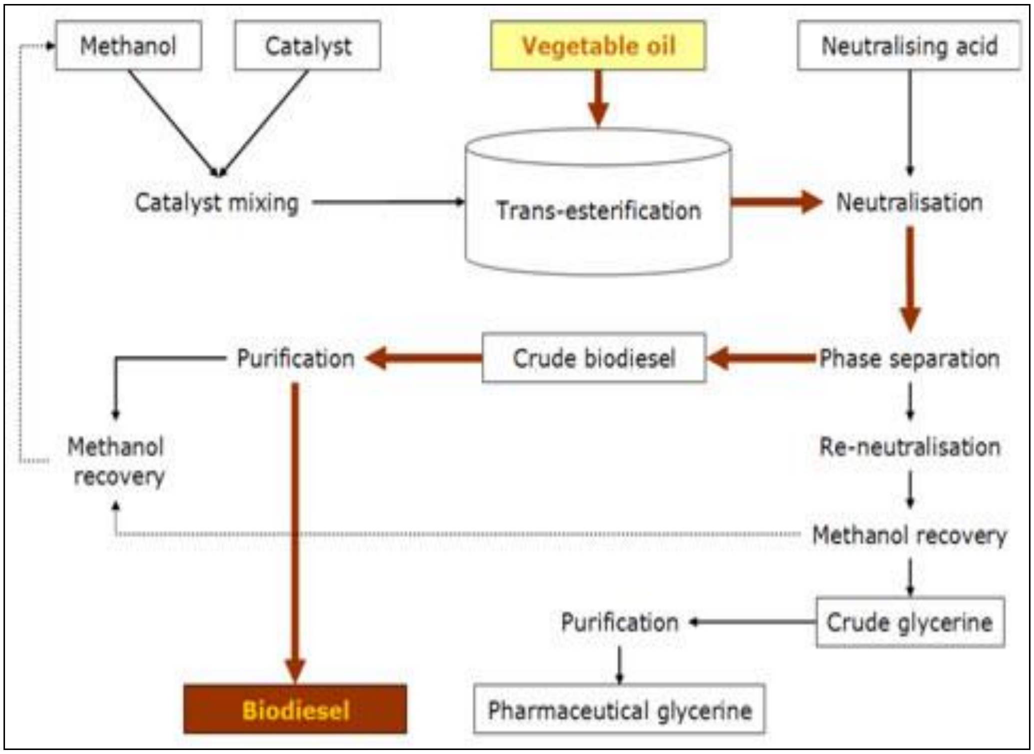

Fig 1: Simplified representation of the biodiesel conversion process from vegetable oil (source: europia.org)

Due to their physical and chemical properties, biodiesel fuels are appropriate for combustion in compression-ignition engines (diesel engines). One important difference is the lower heating value of biodiesel, due to the much higher oxygen content compared to standard diesel. Therefore, a higher volume of biodiesel is required to provide the same global energy output than conventional diesel.

Two other important parameters influence the interaction between biodiesel and the engine: the stability and the viscosity. Viscosity, which is higher for biodiesel than for standard diesel, affects the atomization of the fuel during injection. Below 0°C, problems also occur with the supply of biodiesel from the tank to the engine and the cold start behavior of the engine. These problems can be solved by fuel heating or adding additives, such as flow enhancers. Biodegradability is very favorable from the environment perspective, but it also means that the fuel is less stable; thus, storage of FAME requires special attention.

Biodiesel production began in Austria in 1988 with a 500 t/y plant owned by a farmers' co-operative. Other plants soon followed, and the first industrial-scale biodiesel plant, with a capacity of 10000 ton annually, started up in Austria in 1991. In the following years larger plants were established all over Europe. Examples are Livorno-Italy (up to 80000 ton annually), Rouen-France or Rotterdam-Netherlands (800000 ton annually). The European Union is today the principal region in the world having developed the biodiesel sector. Europe produced 9,187,000 tons of biodiesel fuel in 2012, representing an average annual increase of 57% over the last 5 years. Even though there is currently a production overcapacity in Europe, numerous new units should be created over the next years to meet the requirements of the European directive on biofuels. The leading European biodiesel producer is Germany, with a production of 2,492,000 tons. (Source: European biomass industry association)

Since biodiesel fuels have similar fuel properties compared to diesel, it can be mixed with fossil diesel in any proportion for application in conventional diesel engines. Nevertheless, there is some evidence that FAME attack some plastic materials used for seals, hose, paints and coatings. For this and other reasons, it is generally accepted that mixtures of standard diesel with up to 30% FAME (by volume) can be used in existing diesel engines, but there are concerns about the interaction of higher percentage blends with the components of the fuel injection system. For example, in the case that 100% RME is to be used, a number of relatively minor changes in the engines are required. Engine manufacturers often recommend not applying mixtures in their engines with a proportion of RME higher than, for example, 5%. A reason for this is that the certification level for the engine with regard to NOx emissions can be exceeded when a large proportion RME is used. Moreover, the durability of the engine cannot be guaranteed if the engine is run with any other fuel than the one it is constructed, tested and certified for. Many diesel engine producers are working on an (improved) application of biodiesel. The present diesel market is completely dominated by fossil fuel. Biodiesel is an environment-friendly fuel with clear and substantial advantages over conventional diesel, but even at full production it could only ever meet around 8% of the diesel market. Market niches should therefore be identified where the distinctive benefits of biodiesel will be best appreciated. Alternatively, biodiesel can simply be blended with fossil diesel, as in France. This approach retains many of the overall advantages of biodiesel, without requiring customers to be aware of what they use. (Source: European biomass industry association)

Table 1: Relation between DO, RME and SME

Fuel properties	Diesel	RME	SME
Molecular weight [kg/k mol]	170 - 200	~ 300	~ 310
Density [kg/l] at 15ºC	0.84	0.88	0.87
Oxygen content [wt-%]	0 - 0.6	9 - 11	10 - 11
Lower Calorific Value [MJ/kg] at 15ºC	42.7	37.3	32
Lower Calorific Value [MJ/l] at 15ºC	35.7	32.8	
Cetane number	50	51 - 58	46 – 67
Stoichiometric air/fuel ratio [kg air/kg fuel]	14.5	12.3	12.6
Kinematic viscosity [mm2/s] at 20ºC	4	4.5 - 7.4	-
Flash point [ºC]	77	91 - 179	110 - 174

Source: European biomass industry association

Table 2: Relation between DO, JME

Fuel properties	Diesel	JME
Molecular weight [kg/kmol]	170 - 200	290
Density [kg/l] at 15ºC	0.84	0.866
Oxygen content [wt-%]	0 - 0.6	5
Lower Calorific Value [MJ/kg] at 15ºC	42.7	38.4
Lower Calorific Value [MJ/l] at 15ºC	35.7	47.6
Cetane number	50	55-63.5
Stoichiometric air/fuel ratio [kg air/kg fuel]	14.5	14.4
Kinematic viscosity [mm2/s] at 20ºC	4	31.6
Flash point [ºC]	77	91

Source: European biomass industry association

As a biofuel, biodiesel has high amounts of oxygen. When this fuel is mixed with pure diesel, the existence of extra oxygen will improve the combustion properties of pure diesel as well as the combustion quality of the engine in the power phase. However, extra oxygen is desirable only to a specified amount; when it is increased; some of the thermo-physical properties such as heating value, octane number, density, and viscosity are negatively affected. These factors not only increase fuel consumption, but also worsen the combustion quality. (Fernando, *et al* 2004) [2]

Case Study

This work is based on the experimental studies carried by Mahmoud Abbas at the Arab Academy For Science and Technology and Maritime Transport work shop to study the effect of using Jatropha methyl ester instead of using diesel oil to check the effect on combustion process and the knocking phenomena (if occurs). (M. Abbas*; et al* 2014) [3].

Table 3: Engine Specifications

Maker	Apan Diesel India
Rated Power	7.5 KW
Rated speed (RPM)	1500
No. of cylinder	1
Type of aspiration	Natural aspiration
Cooling medium	Air
Cycles	4-strokes
Bore	110 mm
Stroke	102 mm
Compression ratio	16.5
Cubic capacity	896 cc

Table 4: Gen. Specifications

Maker	Kaijeili Group China ST-7.5
Type	A-C synchronous
Rated Power	7.5 KW
Voltage	220 V
Current	34.1 Ampere
Power factor	1.0
Frequency	50 Hz
Speed (RPM)	1500

The experiment was set up as the engine was coupled to electric dynamometer, where the later was connected in turn to a 6KW resistive lighting loads where the engine was loaded by 4 steps load each of which was 1.5KW. A tank and flow metering system was used to measure the flow of different blend samples.

Table 5: Measurements

Item to be measured	Measurement method
Air mass flow rate	2 orifice and manometer
Fuel mass flow rate	Calibrated burette
RPM	Optical tachometer
Cylinder P max	Indicator gauge

Flue gas as O2, CO, SO2, NO, NO2, H2S, Air Temp, Pressure and soot	Flue gas analyzer IRM 300

Model Validation

First as per experiment the diesel engine was started on diesel till warmed up then went on loads using pure diesel oil, after which engine was operated on Jatropha biodiesel oil at the same loads to study the difference performance parameters. In the present study the results of the experimental work was compared with the results obtained from DIESEL-RK program for validation.

Crank angle curve is very important as using this curve facilitates the prediction of proper timing for injection, injection periods, different combustion periods, and cylinder pressure for any diesel engine. Maker of diesel engines measure these curves and draw them in the manuals to compare the performance at different running conditions with the ideal curve drawn in the manual.

To predict the model, the experimental results were used as boundary condition for the model and the results after running the model so as to compare them with the results already given by the maker in the manual such that if an agreement established between both of them, the model can be used in any test and validation occurs.

The model results at high load (at 6 KW) shows good agreement with the maker curve for the maximum pressure as the maximum pressure for the maker was 80 bar and for model was 86.265 bar which equals only 6.265 bar more than maker curve providing accuracy of 93% for running on D.O. The study shows also that both maker and the model show nearly the same pressure trend until the ignition which means that the compression pressure and the increase in the peak pressure are almost the same.

Pure diesel oil was compared to biofuel blends; Jatropha methyl ester JME B100, rapeseed methyl ester RME B100 and soybean methyl ester SME B100. Also, to study the effect of introducing different concentration of diesel oil with biofuel blend; Soybean methyl ester SME B40 and B20. All the previous blends were studied as major fuel in the model.

Table 6: Validation for diesel oil

Parameter	Model value	Experimental value	Error %
P. maximum	86.265	80	93%
T. maximum	1241.7	1200	96.6%
NOx emission	900	1000	90%

Table 7: Validation for Jatropha methyl ester

Parameter	Model value	Experimental value	Error %
P. maximum	83.353	76	91.17%
T. maximum	1174.5	1280	91.75%
NOx emission	1000	900	90%

At simulation of nitrogen oxides formation it is accepted that the cylinder is divided into two zones: zone of fresh charge and zone of burnt gas. Zone of fresh charge consists of air, fuel and residual gas. Before combustion fresh charge zone is alone. During combustion a volume of burnt gas zone increases. At calculation of combustion there is an assumption that a local air-fuel equivalence ratio at combustion varies linearly from initial value A/F $_{\text{initial}} < 1$ up to 1. Current value of air-fuel equivalence ratio at combustion A/F $_c$ is a function of crank angle and f_z is combustion duration as crank angle,

$$AF_c = AF_{ini} + \frac{1 - AF_{ini}}{\varphi_z}\varphi,$$

Features of a designed procedure are:

Step by step calculation of equilibrium composition of combustion products for eighteen species in the burnt gas zone (Zvonov; 1973) [7].

Kinetic calculation of thermal nitrogen oxides formation with chain Zeldovich mechanism (Zeldovich; 1966) [8]

As for requirements of combustion of propellants in explosion engines defining the formation "thermal" NO is, in tendered model all calculations are yielded on the thermal mechanism. Because in engine a "thermal" NO are main, in simulation model all calculations are carried out with thermal mechanism. The oxidizing of nitrogen will be on the chain mechanism, basic reactions are:

$O_2 <=> 2O;$ (1)
$N_2 + O <=> NO + N;$ (2)
$N + O_2 <=> NO + O.$ (3)

The calculation of NO formation with equation of the chain mechanism is carried out for the zone of combustion, and then the medial NO concentration over whole combustion chamber is determined. Volume concentration of NO in combustion products formed in a current calculation step is defined with equation:

$$\frac{dr_{NO}}{d\varphi} = \frac{p \cdot 2{,}333 \cdot 10^7 \cdot e^{-\frac{38020}{T_{cz}}} \cdot r_{N_2eq} \cdot r_{Oeq} \cdot \left[1 - \left(\frac{r_{NO}}{r_{NOeq}}\right)^2\right]}{RT_{cz} \cdot \left(1 + \frac{2346}{T_{cz}} \cdot e^{\frac{3365}{T_{cz}}} \cdot \frac{r_{NO}}{r_{O_2eq}}\right)} \frac{1}{\omega},$$

Where: p is a cylinder pressure, Pa;
T_{cz} is a temperature in a burnt gas zone, K;
R is a gas constant, J/(mole K);
w is an angular crank velocity, 1/sec;

$r_{NO\ eq}$, $r_{N2\ eq}$, $r_{O\ eq}$, $r_{O2\ eq}$ are equilibrium concentrations of an oxide of nitrogen, molecular nitrogen, atomic and molecular oxygen, accordingly.

The equilibrium concentrations of 18 species are calculated on every time step. List of species includes: O, O_2, O_3, H, H_2, OH, H_2O, C, CO, CO_2, CH_4, N, N_2, NO, NO_2, NH_3, HNO_3, HCN. Overall system of equations includes: 14 equilibrium equations, 3 equations of material balance, and Dalton equation.

NO concentration in a cylinder: $r_{NO\,c} = r_{NO}\, r_{bc}$, and r_{bc} is a fraction of burnt gas in a cylinder.

NO concentration in a "dry" burnt gas of a cylinder: $r_{NO\,dry} = r_{NO} / (1 - r_{H2O})$,

where: r_{H2O} is a volume fraction of water vapor in a combustion chamber.

Specific NO emission, g/kWh:

$$e_{NO} = \frac{30\, r_{NO}\, M_{bg}}{L_c\, \eta_M} 3600000,$$

Where: M_{bg} is a mass of burnt gas in a cylinder at the end of combustion, k mole;

L_c is working cycle work, kJ,

η_M is a mechanical efficiency of engine.

Comparison between D.O and Biodiesel Fuels Using P-Curves:

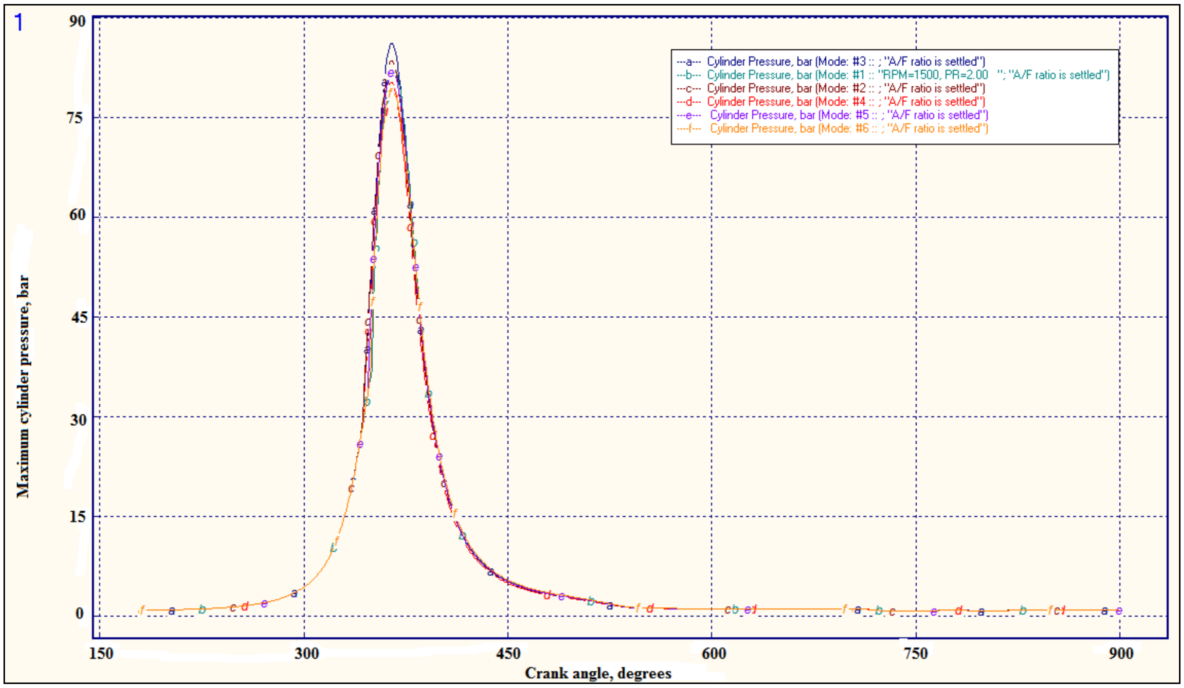

Fig 2: Shows the Pressure versus Crank angle curve.

Fig. 1 shows comparison between Pressures versus crank angles for D.O and Biodiesel blends after running the theoretical analysis of the model. The model curve shows that the maximum pressures are as per the following table

Table 8: represents the P-max for different blends.

Blend	D.O	JME	RME	SME B100	SME B40	SME B20
P max. bar	86.265	83.353	86.161	80.328	82.03	79.157

The deviation between the different blends is not exceeding 6bar which shows a good agreement between them also it indicates that the knocking phenomena will not be anticipated at using biodiesel blends of different concentration of diesel oil in the blend.

The slight variation between D.O and biodiesel blends is related to difference of Cetane number, higher viscosity and volatility of blends which provide them poor atomization compared to D.O.

The highest value found to be for rapeseed methyl ester with 86.161bar followed by Jatropha methyl ester with 83.353bar then soybean methyl ester found to be 80.328bar. Also, it is found that the concentration of diesel oil within the blend has an influence on the pressure arising from combustion inside the cylinder which is obvious in the table 7-1 as 100% soybean methyl ester has 80.328bar while increasing concentration of diesel to 40% increases pressure to 82.03bar in case of SME B40 while the best found for diesel 20% as SME B20 79.157bar.

The model results at high load (at 6 KW) shows good agreement with the maker curve for the maximum pressure as the maximum pressure for the maker was 80 bar and for model was 86.265 bar which equals only 6.265 bar more than maker curve providing accuracy of 93% for running on D.O. The study shows also that both maker and the model show nearly the same pressure trend until the ignition which means that the compression pressure and the increase in the peak pressure are almost the same.

It is noted that with varying the orifice diameter of the injector; the variation is higher in case of biomass blend compared to diesel oil. Smaller nozzle diameter corresponds to greater cylinder pressure, greater rate of pressure increase and larger amount of premixed burning of both fuels.

Also, while trying the model on different timing; it was noted that there is great effect on maximum combustion pressure which was greater in case of biomass blends compared to diesel oil.

Comparison between D.O and Biodiesel Fuels Using T-Curves

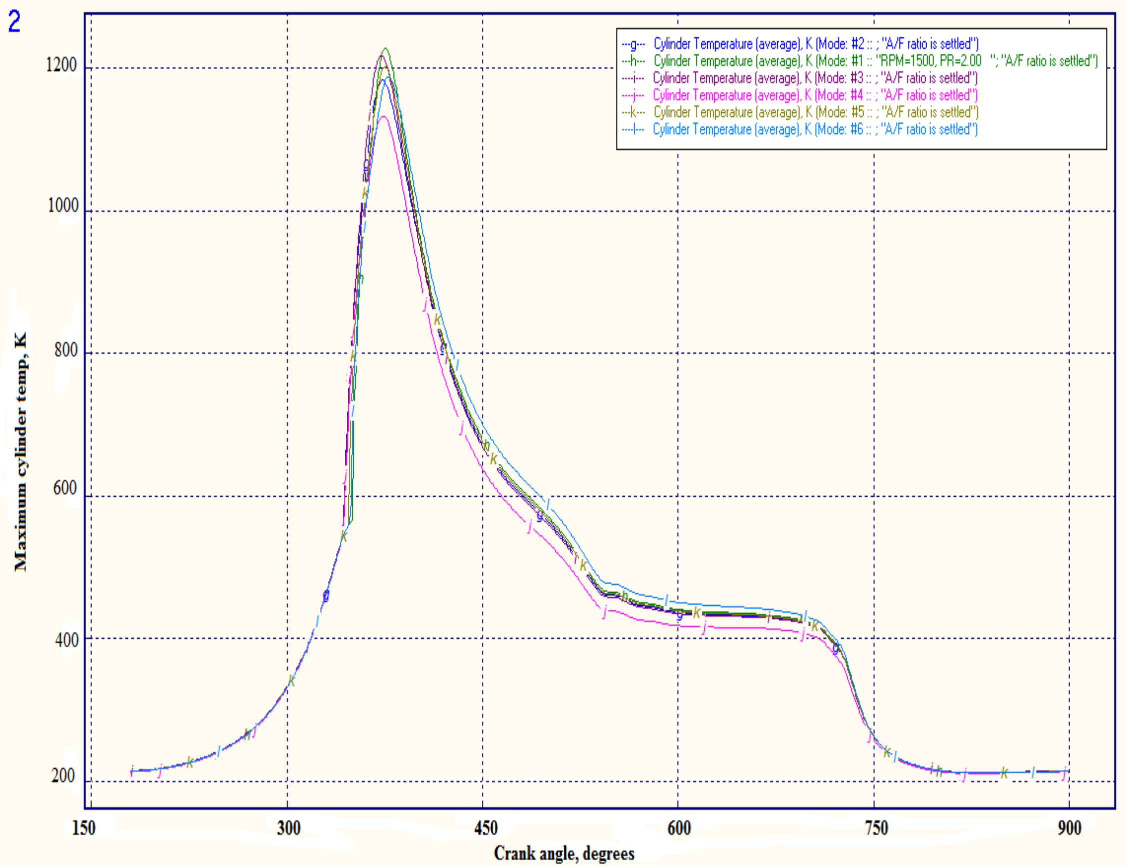

Fig 3: Shows the Temperature versus Crank angle curve.

It is very difficult to compare between the model results and the experimental result simply because measuring the maximum cylinder temperature in the model was not possible. Fig.2 comparison between diesel oil and different biodiesel blends of different concentrations to study the difference in maximum temperature in the different cases and the results were as per the following table:

Table 9: Represents the T-max for different blends.

Blend	D.O	JME	RME	SME b100	SME B40	SME B20
T max. K	1241.7	1174.5	1226.7	1099.2	1203.1	1181.9

From the previous table it is obvious that the difference across different temperature was very small not exceeding 100k so therefore there is a good agreement between diesel and biodiesel blends. Also the trend of the temperature increase was in the same boundaries. Pure diesel found to have the highest maximum temperature of 1241 K followed by rapeseed methyl ester 1226 K then Jatropha methyl ester 1174 K.

The effect of concentration of diesel in the concentration on the maximum temperature of the blend is obvious as pure soybean methyl ester SME B100 has maximum temperature of 1099K while increasing diesel content by 20% increases maximum temperature to 1181 and further increase to 40% lead to increase of temperature to 1203K.

Science biofuel blends have higher ignition delay more than diesel oil which indicates shorter ignition delay in biofuel blends and better premix combustion phase for such blends compared to diesel oil.

It was noted that while varying the nozzle diameter of injector there was greater effect on maximum combustion pressure in case of biomass blends compared to diesel oil that’s arising from the characteristic of biomass in atomization which is worse compared to diesel oil. The smaller the nozzle the greater amount of premixed burning.

Comparison between D.O and Biodiesel Fuels Using Nox-Curves

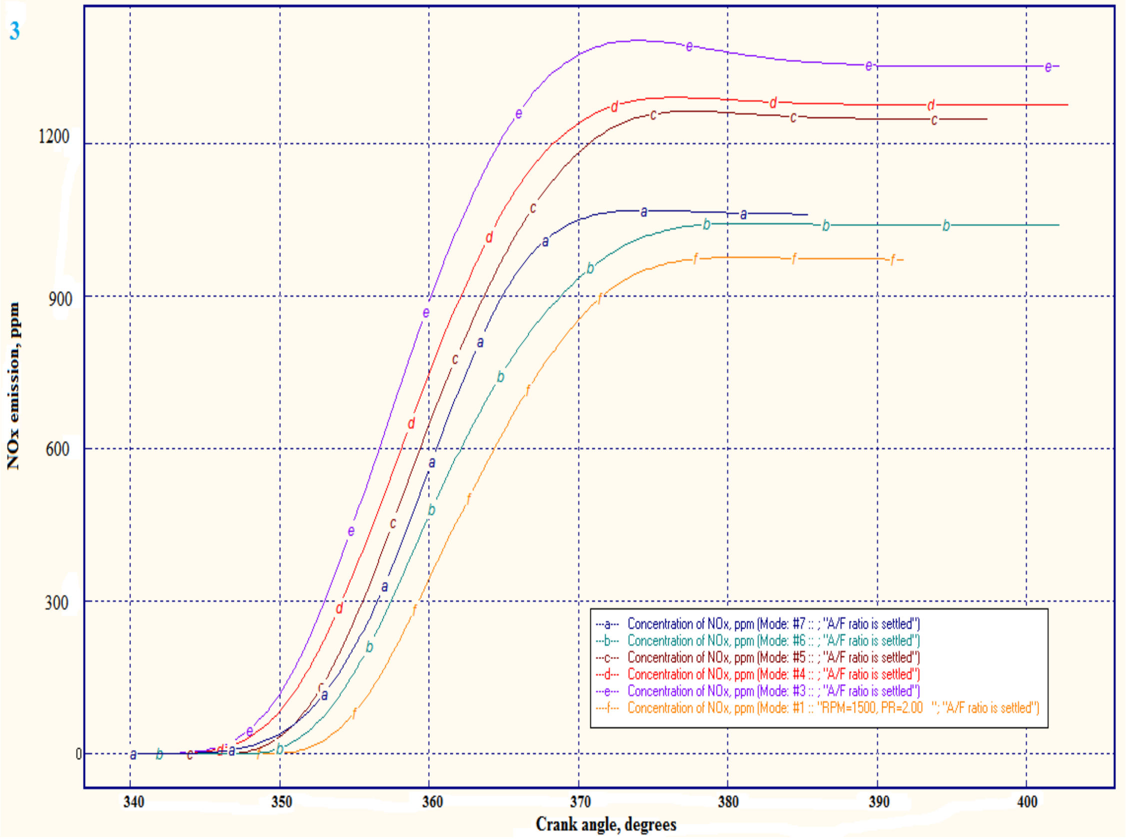

Fig 4: Relation between NOx versus crank angle for different blends

Fig.3 shows the model results for different blends with compared to diesel oil one. Since the experimental results obtained showed that NOx emissions for diesel oil was about 940 ppm and that for JME was about 1000 ppm. The results of the model using different blends were as the following table

Table 10: represents the P-max for different blends.

Blend	D.O	JME	RME	SME b100	SME B40	SME B20
NOx ppm	1063	1180	1417	1494	1449	1155

Therefore, there is a good agreement between the difference between the result obtained experimentally and the result obtained by running the model. Also biodiesel blends show to be in accordance with IMO regulations regarding to NOx emissions globally. The results are not encouraging regarding environmental view but it shows that biodiesel blends can be used as alternative fuel within the limits of IMO regarding to MARPOL 73/78 convention and it amendments. Also, it is obvious that higher oxygen concentration in biodiesel blends causes increase in the produced NOx.

Biodiesel and its blends in general are known to produce lower carbon monoxide, soot, hydrocarbon emissions, and higher NO_x emissions compared with regular diesel. Because of the lower heating value of biodiesel, more biodiesel should be burned to produce the equivalent energy of ULSD (ultra-low sulphur diesel). Also, due to the presence of high oxygen content in biodiesel fuels, generally biodiesel fuels emit more NO_x than regular diesel for the same heat generation. The reduction of NO_x emissions is one of the most important technical challenges facing biodiesel, especially in light of the increasingly stringent exhaust emission regulations. NO_x formation during biodiesel combustion is associated with a number of factors such as the property of biodiesel and combustion conditions. Combustion temperature influences thermal NO_x emissions. Therefore, low-temperature may help thermal NO_x reduce during combustion, leading to low-temperature combustion or LTC technology. (Omidvarborna; *et al*. 2015) [5]

Conclusions

This theoretical study disclose the effect of combustion on using diesel oil compared to different biofuel blends of different concentrations as Jatropha methyl ester (JME), rapeseed methyl ester (RME) and soybean methyl ester (SME) and with different concentrations as SME100, SME40 and SME20 on the combustion behavior in terms of cylinder maximum pressure, cylinder maximum temperature and nitric oxide emissions produced. It was conducted the absence of knocking phenomena across the results of all cases and all operational mode even at high load which is the study case 6KW. Also, the emission found to be in accordance with MARPOL regulation ANNEX VI regarding prevention of air pollution.

It is clear that with higher Cetane number presents in biofuel blends as JME and RME participates in shorter ignition delay which is presented in delay increase of pressure and temperature of biodiesel blends compared to diesel oil where the angle of maximum cylinder pressure shifted by about 8 degrees compared to diesel oil.

Since the presence of high oxygen content in biodiesel fuels, generally biodiesel fuels emit more NO_x than regular diesel for the same heat generation. The reduction of NO_x emissions is one of the most important technical challenges facing biodiesel, especially in light of the increasingly stringent exhaust emission regulations. NO_x formation during biodiesel combustion is associated with a number of factors such as the property of biodiesel and combustion conditions.

Injection timing found to have great influence on the performance of the engine and emissions of both fuel blends the diesel oil as well as biomass blends; where increasing the injection timing led to decreasing emissions with the decrease of the maximum cylinder pressure.

Decreasing the diameter of the nozzle of the injector led to increasing the maximum pressure of the cylinder, increasing the rate of increasing the pressure within the cylinder, higher emissions generated and increasing the amount of premixed burning.

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