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THE NO_x REDUCTION PERFORMANCES OF A MARINE DIESEL ENGINE USING STEAM INDUCTION METHOD FOR BLENDED PALM OIL METHYL ESTER FUEL

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Abstract

Biodiesel fuel such as palm oil methyl esters is an alternative fuel for use in marine diesel engines. In terms of NO_x emission reduction, most biodiesel fuels are unable to produce better results because they consist of a higher cetane number, high oxygen content and produce high peak combustion temperature compared to fossil fuels. The main goal of this study is to investigate NO_x emission reduction using the saturated steam induction method on Cummins NTA 855M marine diesel engine air intake systems fuelled by blended palm oil methyl ester. The experiment used different loads 5%,25%, 50%, 75% and 100% and speeds 800-1600 rpm of the engine to analyse the NO_x emissions. The study discovered that steam induction into the air intake system offers promising potential to reducing NO_x when using palm oil methyl ester as a fuel. This phenomenon occurs, when the oxygen has been replaced by steam, which promotes ignition delay and a decrease in combustion temperature. The technique produces a reduction of NO_x up to 19.75%. This promising result complements the NO_x reduction issue for this fuel.

Keywords: Emission, Humidity, Marine diesel engine, NO_x, Steam.

1. Introduction

The fast-growing global shipping industry consumes a huge amount of fossil fuels that generate excessive emissions daily. Palm oil biodiesel is becoming an alternative source of fuel in use today which also potentially produces cancer-causing emissions such as nitrogen oxides (NO_x) [1].

NO_x contributes to one of the polluting elements in the environment and it can react in the atmosphere to form a photochemical smog [2]. The impacts from long term exposure to smog mainly cause inflammation in respiratory organs such as lungs and alveolus. NO_x also contributes to the formation of fine particles (PM) and ground-level ozone, both of which are associated with adverse health effects [3].

During the combustion process in a marine engine, nitrogen remains inactive. However, a small part of the nitrogen will be oxidized to form NO_x within 20° of the crank rotation after the combustion process [4]. Combustion temperature and oxygen concentrations are two main factors that result in nitrogen being oxidized, this is known as thermal NO_x. Most biodiesel fuel consists of higher oxygen concentrations in their chemical chain [5].

The main purpose of this study is to investigate the contribution of steam induction to the combustion chamber in term of reducing NO_x emission for marine diesel engine. The current review also shows a significant impact of steam in term of NO_x reduction up to 34% and low carbon monoxide [6].

2. Emission Reduction Strategies Review

An emission control strategy is available and has been installed in modern marine diesel engines. This is known as selective catalytic reduction (SCR). Installing the SCR system in a marine diesel engine is an effective strategy to make sure the system works efficiently. It is necessary to maintain an exhaust gas temperature exceeding 200°C to ensure the ammonia will react with the exhaust gas and reduce the NO_x emissions [7, 8].

Exhaust Gas Recirculation (EGR) is another technique that can be used [9, 10]. It can recirculate the exhaust gas into the combustion chamber which is able to reduce the concentration of oxygen in the combustion chamber [11].

This system, however, will generate more particulate matter (PM) [12]. The water addition technique is one of the most useful methods and many researchers have conducted deep studies on this method.

There are various water addition techniques including direct water injection (DWI) [13, 14], Fuel emulsion(FE) [15, 16], humid air motor (HAM), and water mist into scavenging air [17].

2.1. Steam addition techniques

Adding steam into the marine diesel engine combustion process is one of the techniques to lower the NO_x value in the exhaust gas. During the implementation of this technique, water vapour (steam) is used to avoid having any water droplets in the combustion chamber which may create impinging into the cylinder wall. Humid scavenge air is characterised by a significantly higher specific heat capacity than normal dry air.

This experiment will use steam to displace excessive oxygen and it will be absorbing the heat from the combustion chamber due to the presence of small water particles and it promotes humid scavenge air. Through this experiment, the researchers can compare the effect of steam between pure diesel oil and blended biodiesel B10 (10% palm oil-based), B20 (20% palm oil-based), and B30 (30% palm oil-based).

Specific heat capacity can be increased by using humid scavenge air when adding steam to mix with dry air inside the scavenge manifold. Higher specific heat capacity will be lowering the peak combustion temperature. Compared to the water injection method, the scavenge air needs to be heated to 110°C to ensure greater water absorption power [18].

2.2. Scavenge air humidifying techniques

Another way of introducing water into the combustion zone is by humidifying the scavenging air. Steam must be injected or induced into the scavenge system. Steam carries small water particles into the combustion chamber without giving a negative effect on the turbocharger performance. Water addition that uses the scavenge humidifying process is one of the methods to reduce peak combustion temperature which contributes 90% of NO_x formation [19]. Scavenge humidification also has the ability to reduce NO_x similar to Fuel Water Emulsification (FWE). A medium-speed engine equipped with the prototype Humid Air Motor (HAM) system showed a NO_x reduction from 13.5g/kWh to 3.5g/kWh. There was no significant increase in carbon monoxide, deterioration of smoke and Hydrocarbon emissions [20].

3. Description of the Experiment

3.1. Experimental setup and procedures

The experiment setup consists of a Cummins NTA 855M 6-cylinder turbocharged Marine diesel engine, as shown in Fig. 1.

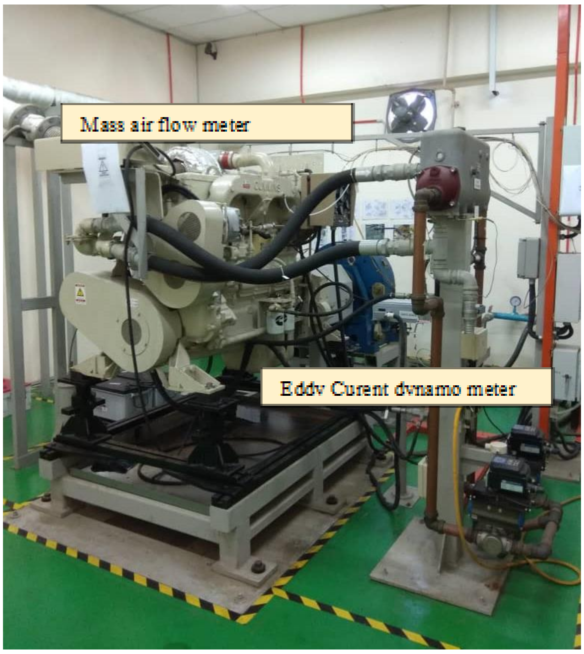

Fig. 1. Cummins NTA 855M 6-cylinder turbocharged marine diesel engine.

This engine has been chosen because it is not equipped with an exhaust gas recirculation system (EGR) so that it can be used to measure the correct amount of emission reduction without any assistance from the different techniques. This engine is using a common rail fuel system, is water-cooled, and has a power rating of 200 kW. The engine is loaded with an eddy current dynamometer brand REO-dEC and is attached to a strain gauge type load cell for measuring the applied load on torque together with the power of the engine. This is linked with a data acquisition system along with a computer. Eddy current dynamometer will provide a different load to the engine with small rotational inertia and fast dynamic response. Engine specifications are given below in Table 1.

Table 1. Cummins NTA 855M engine specifications.

Engine Model	NTA 8558M
Rated Engine Power	200 kW
Rated Engine Speed	1800 rpm
Engine Torque	1068 Nm
Engine Displacement	14010 cc
Engine Bore	139 mm
Engine Stroke	152 mm
Brake Mean Effective Pressure (BMEP)	958 kPa
Fuel Consumption	52.0 litre/hour
Cooling system	Water-cooled
Air Intake System	Single-stage turbocharger
Exhaust Gas System	Direct flow
Fuel system	Common Rail
Fuel injector pressure	1600 bar
Fuel injector angle	152°

Figure 2 shows a schematic diagram for the steam addition technique. Steam is generated by a steam generator with a flow rate of 2 *l*/hr and a temperature of 110°C. The presence of water droplets can do significant damage to the turbocharger blades and will cause pitting. A fine steam trap mesh demister is fitted at the air filter to prevent the presence of any water droplets before they reach the turbocharger compression side. Only dry steam will pass into the scavenge manifold.

By using a pitot principle, total and static pressure components of airflow are measured. The transmitter will measure the volumetric flow of air when the pressure sensing port senses the impact pressure of the approaching air stream. The Mass Air Flow (MAF) sensor will be linking to the data of the acquisition system.

3.2. Fuel blend preparation

Due to both fuel has different viscosity and chemical properties; pure diesel oil was added to palm oil methyl ester at a low mixing rate for 20 minutes before consumed. This also to avoid bubble formation and reach an equilibrium state before consumed [12, 22]. The mixture has been set into 10%, 20% and 30% of palm oil methyl ester together with pure diesel. These fuel samples were named B10, B20 and B30. The properties of blended fuels are as per Table 2.

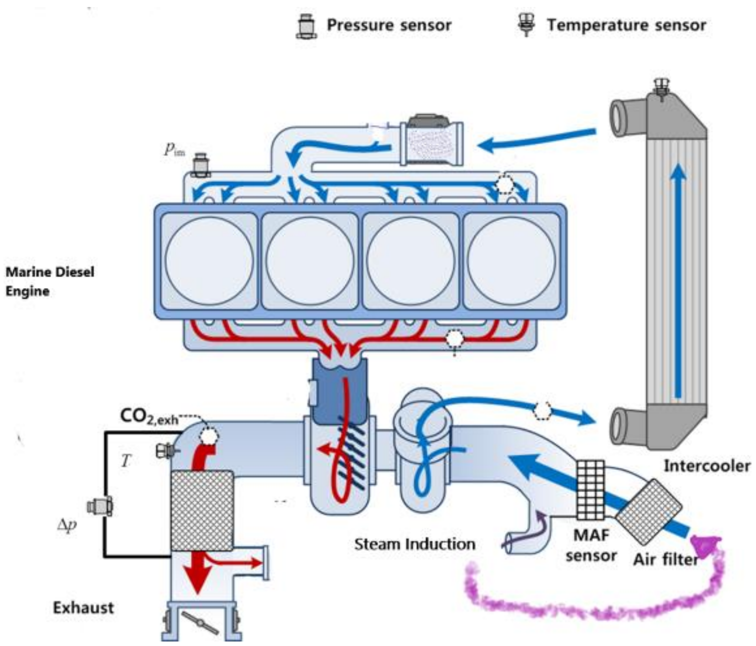

Fig. 2. Schematic diagram for steam addition technique.

Table 2. Properties of (biodiesel) methyl esters with blended fuels.

Fuel	Density @15°C g/ml	Kinematic Viscosity @ 40°C mm²/s	Flash Point °C
Pure Diesel	0.827	2.28	64
B10	0.833	2.49	69
B20	0.835	2.82	71.5
B30	0.841	2.85	82
B100 (Base)	0.875	4.4	172

3.3. Emission sampling

During this experiment, all data are taken after reaching steady-state conditions when exhaust manifold temperature reaches a constant value. All data measurement is repeated at least five times for each test point and the average values are used to minimize systematic error. Engine speed is varied to 800, 1000, 1200, 1400, and 1600 rpm. The speed varies to test emissions quality at different air intake volumes. This experiment varies the engine load at 5, 25, 50, 75 and 100% load by adjusting the dynamometer setting as per Table 3.

Table 3. Engine load percentage.

Engine load	Engine speed (rpm)				
	800 rpm	**1000 rpm**	**1200 rpm**	**1400 rpm**	**1600 rpm**
5%	3 kW	4 kW	5 kW	7 kW	9 kW
25%	15 kW	21 kW	27 kW	37 kW	46 kW
50%	30 kW	42 kW	55 kW	75 kW	92 kW
75%	45 kW	64 kW	82 kW	112 kW	138 kW
100%	60 kW	85 kW	110 kW	150 kW	185 kW

Combustion product samples such as NO_x were taken by using the KANE Auto 4 gas analyser. To ensure the data accuracy, the analyser was sent to the authorized party for service, maintenance and calibration every alternate year and provided with a certificate. Table 4 shows the specification of the gas analyser.

Table 4. Gas analyser specifications.

Parameters	Sensors and Resolutions
Carbon Monoxide	Infrared 0.01%
Oxygen	Fuel cell 0.01%
Hydrocarbon	Infrared 1ppm
Carbon dioxide	Infrared 0.1%
NO_x	Electrochemical 1ppm

4. Results and Discussion

By referring to Fig. 3, B0 fuel shows the highest reduction NO_x up to 21.05% when implementing the use of steam addition technique. A higher percentage of blended biodiesel will result in less reduction of NO_x. From the graph above, B30 blended fuel showed the lowest reduction percentage of NO_x which is 7.28% at 1600 rpm. The variable speed and types of fuel will influence the percentage of NO_x reduction.

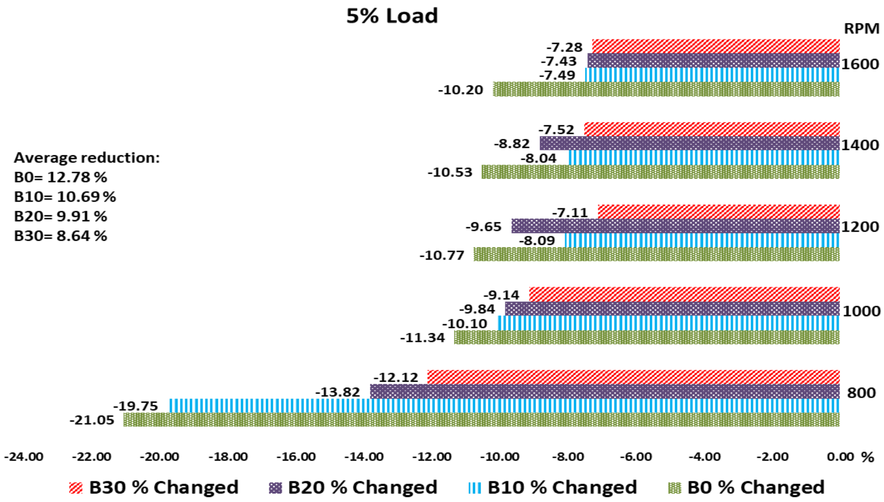

Fig. 3. Percentage of NO_x reduction at 5% of engine load with steam addition at variable speeds using B0, B10, B20 and B30 fuel.

Figure 4 shows that when the engine load was increased to 25%, the highest reduction of NO_x was 19.05% at 800 rpm. On the contrary, the lowest NO_x reduction was 5.02% at 1600 rpm. From the data, it can be concluded that the higher speed has a lesser reduction of NO_x due to the heat generated from the combustion system. The percentage of NO_x reduction in the engine load will be influenced by variable speeds and types of fuel.

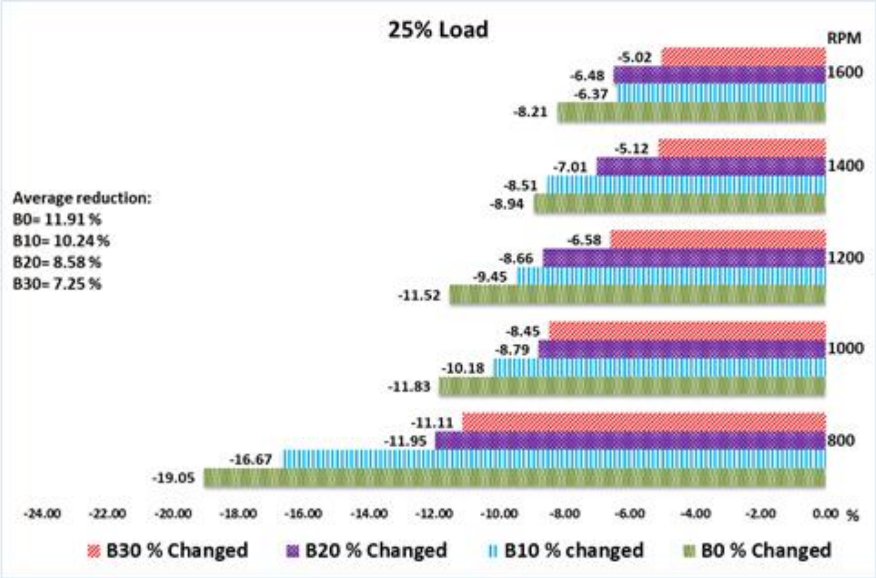

Fig. 4. Percentage of NO_x reduction at 25% of engine load using steam addition with variable speeds and types of fuel.

Figure 5 shows that when the engine at 50% load, the NO_x value will also increase compared to other experiments. The highest NO_x reduction value was 14.81% at 800 rpm. From the data above, the lowest reduction of NO_x was 6.12% at 1600 rpm. The data has been obtained by using the same technique.

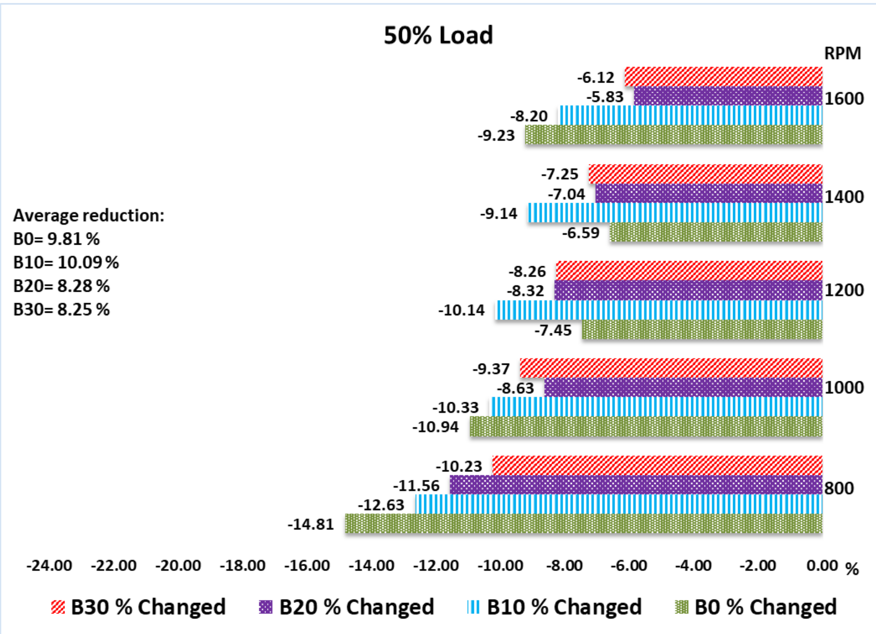

Fig. 5. Percentage of NO_x reduction at 50% of engine load using steam addition with variable speeds and types of fuel.

When engine load was increased up to 75%, B30 blended fuel shows the lowest reduction of NO_x value. It was 5.75% at 1600 rpm. The Highest NO_x reduction is at 800 rpm which was 14.09%. All of the information can be seen in Fig. 6.

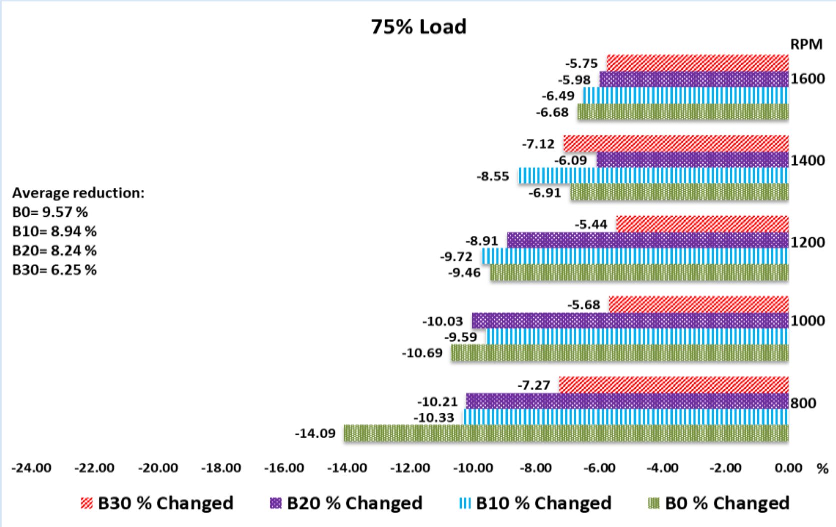

Fig. 6. Percentage of NO_x reduction at 75% of engine load using steam addition with variable speeds and types of fuel.

When the engine load was increased to 100%, most of NO_x value elevates proportionally due to the percentage of load and speed. The highest reduction of NO_x value was at 800 rpm, 11.20% and the lowest reduction was 3.91% at 1600 rpm as shown in Fig. 7. The variable speeds and types of fuel reduce the NO_x during the combustion process.

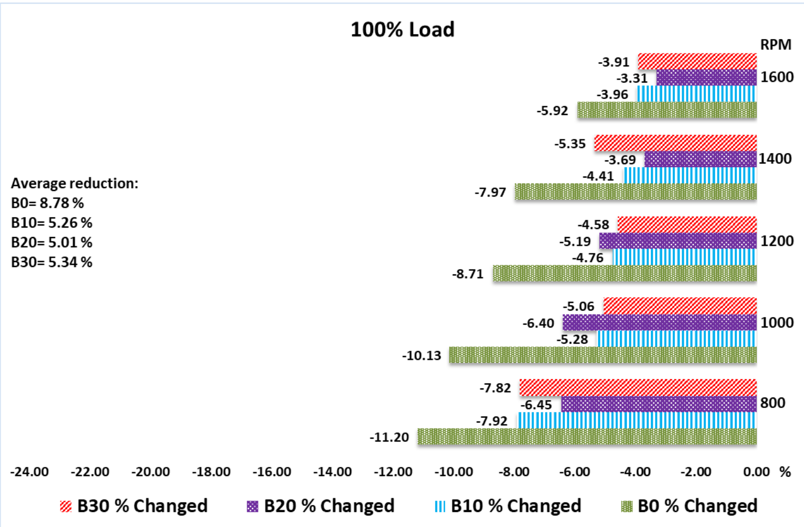

Fig. 7. Percentage of NO_x reduction at 100% of engine load using steam addition with variable speeds and types of fuel.

Figure 8 shows the effect of steam addition into the combustion space when using B0 as a fuel. The reduction of engine exhaust gas temperature was recorded at different speeds and loads. Maximum temperature reduction is at the 25 % engine load and 800 rpm. The minimum reduction percentage is 4.2 % at 1600 rpm and 100% of engine load. This temperature reduction also proves the steam addition will reduce the combustion temperature.

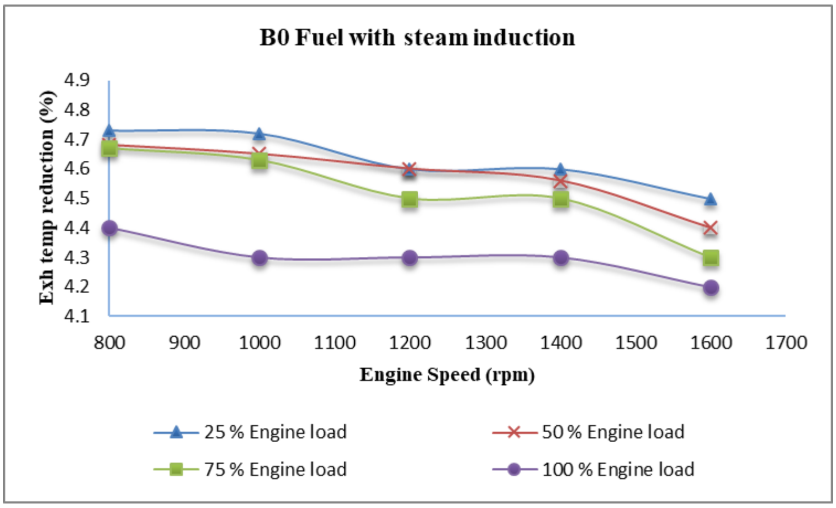

Fig. 8. Exhaust gas temperature reduction percentage using B0 fuel with steam induction.

When changing over to the blended fuel B10, the exhaust gas temperature also significantly reduced as shown in Fig. 9. The effect of steam also positively contributes to the exhaust gas temperature reduction. This will contribute to the NO_x reduction.

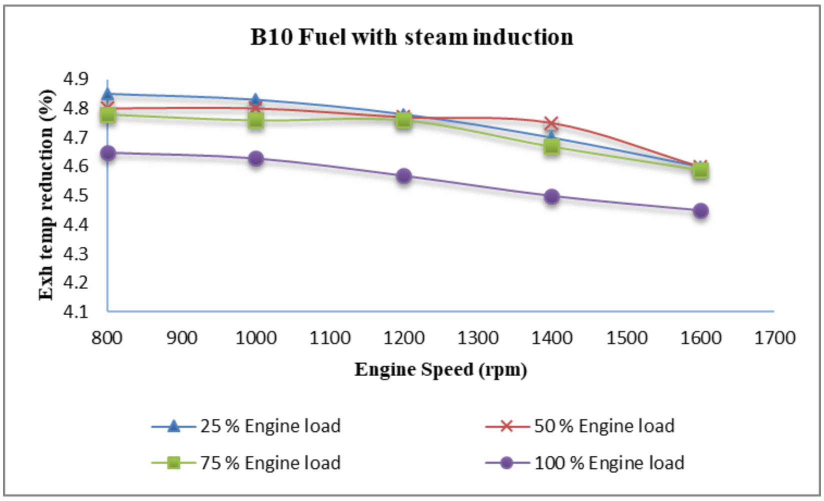

Fig. 9. Exhaust gas temperature reduction percentage using B10 fuel with steam induction.

During this experiment, the main purpose of added steam into the combustion chamber is to reduce the NO_x emission by lower the combustion temperature. Fig. 10 shows the percentage of Exhaust gas temperature reduction when using B20 as a fuel with aid of steam addition.

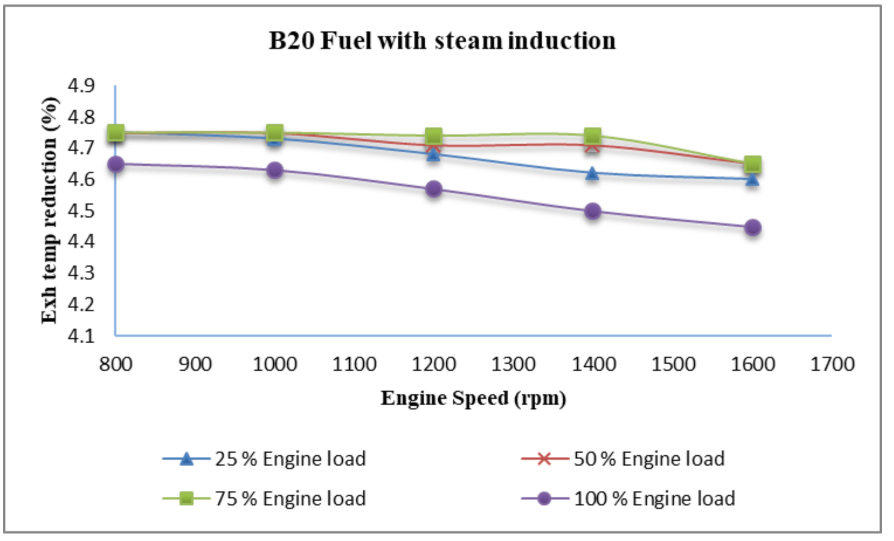

Fig. 10. Exhaust gas temperature reduction percentage using B20 fuel with steam induction.

Figure 11 is the result of the exhaust gas temperature reduction when steam was added into the combustion chamber via air intake while using B30 as a fuel. The maximum reduction is at 800 rpm and 25 % of engine load. The minimum reduction of Exhaust temperature is at 1600 rpm and 100% load.

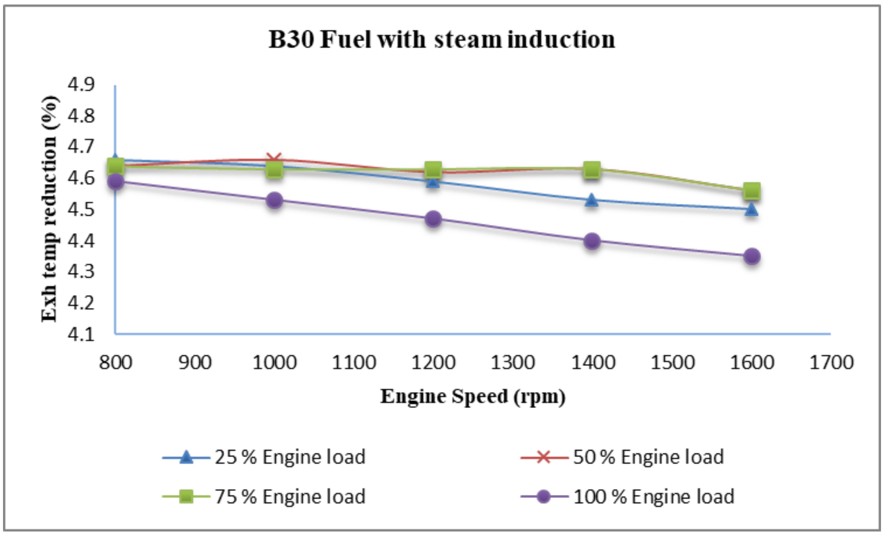

Fig. 11. Exhaust gas temperature reduction percentage using B30 fuel with steam induction.

Figure 12 provides a comparison of the mean temperature in the cylinder before and after the introduction of steam to the combustion chamber via the air intake system. Excessive oxygen is one of the major contributors to the generation of NO_x emissions during the combustion process due to the high combustion temperature that oxidizes oxygen and reacts with nitrogen to produce NO_x emissions. When a certain quantity of oxygen is replaced by steam during the combustion process, the temperature of the combustion becomes lower. Ignition delay will also become longer during this process. This paper found that the steam induction strategy will support the engine powered by biodiesel methyl ester fuel in terms of reducing NO_x emission issues.

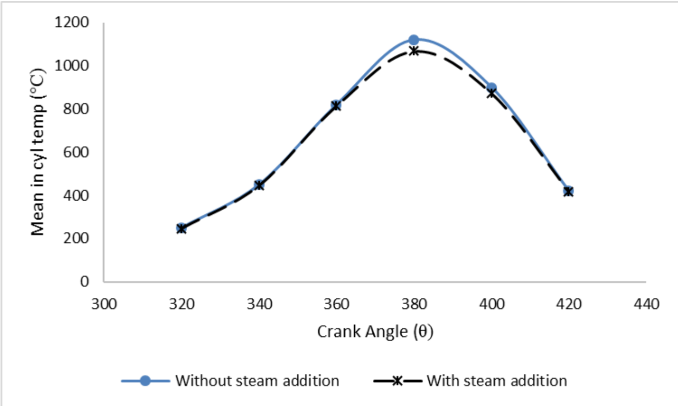

Fig. 12. Mean In-cylinder temperature 1000 rpm at 75% load using B30 fuel.

The significant effect of steam induction in this experiment can be noticed by referring to the cylinder gas pressure. The pressure inside the cylinder is measured at 1000 rpm with 75% engine load when using B30 as fuel. The maximum pressure for B30 fuel without steam induction is 51.73 bar, while the maximum pressure for the same fuel, load and speed with steam induction is 50.69 bar as shown in Fig. 13. 2.01% pressure reduction occurs when steam induction is applied. The presence of steam in the combustion chamber will decrease the oxygen concentration and absorb the heat from the flame. This phenomenon will slightly delay the ignition period.

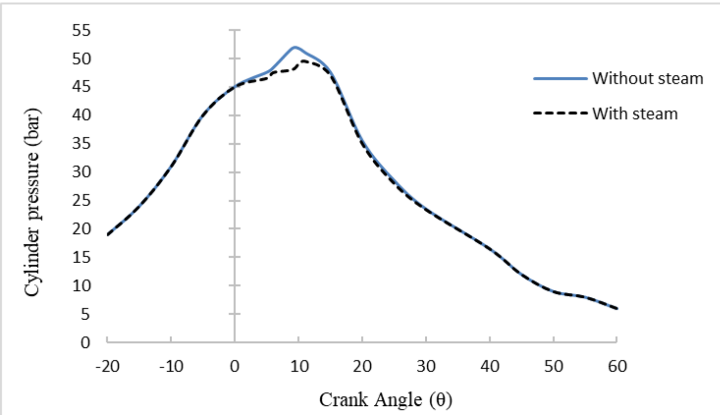

Fig. 13. Comparison of cylinder pressure at 1000 rpm and 75% engine load using B30 fuel.

By referring to the first thermodynamic law, the heat release rate analysis is the most common method to determine the amount of heat required for the combustion period in the engine cylinders as per Eq. (1).

$$\frac{dQ_{net}}{d\theta} = \frac{\gamma}{\gamma-1} p \frac{dV}{d\theta} + \frac{1}{\gamma-1} V \frac{dp}{d\theta} \quad (1)$$

The Q symbol is representing the amount of heat release, γ is the specific heat ratio, θ is the crank angle, V is the cylinder volume and p is the pressure inside the cylinder. The volume of the cylinder is calculated using geometry in this model. The effect of steam induction on the heat release rate to the blended palm oil methyl ester B30 at 1000 rpm is shown in Fig. 14.

Figure 14 shows the fuel-air mixture ignites rapidly when the ignition starts. During the expansion stroke, the diffusion combustion stage occurs due to the burning rate is ruled by the velocity of mixed air-fuel. The presence of steam in the combustion stage will absorb the heat from the combustion chamber. The maximum heat release rate is at 10.33 J/CAD for the B30 fuel without steam induction. For the same fuel, the heat release rate is decreased to 10.02 J/CAD when applying a steam induction system. The adding of steam in this system will reduce the heat release. The reason for the reduction is due to the presence of fine water droplet in the steam that will absorb the heat [23].

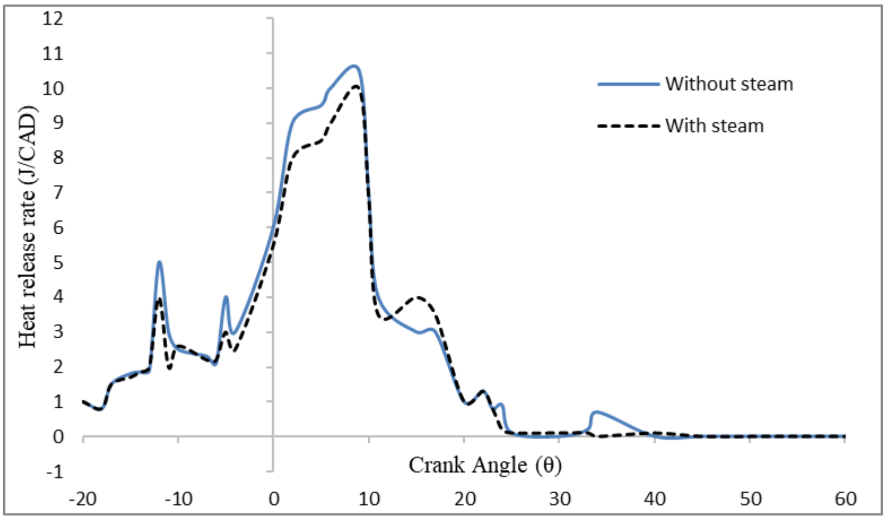

Fig. 14. Heat release versus crank angle for B30 fuel at 1000 rpm.

Effect of steam induction to the NO_x reduction on blended Palm oil methyl ester fuel and discussion.

All data shown in Figs. 3 to 7 are the results comparing based line petroleum diesel B0 and blended biodiesel B10, B20, and B30 at engine speeds ranging from 800 rpm to 1600 rpm. The engine was tested at different loads from 5% up to 100%. Saturated steam was added to the air intake system to measure the reduction of NO_x.

This experiment found that saturated steam played an important role in reducing the NO_x. At the same time, it can remove excessive oxygen, especially during the combustion process by reducing the peak combustion temperature. The common factors for NO_x formation in the cylinder depend on cylinder temperature, type of fuel and oxygen concentration. The previous researcher also has been conducted to investigate the NO_x reduction using air intake humidifying [18].

The results show that induced saturated steam significantly reduces the percentage of NO_x emissions from exhaust gas for diesel fuel (B0, B10, B20, and B30), engine speed ranging from (800 rpm-1600 rpm), engine load 5% contributed to NO_x reduction (12.78%, 10.69%, 9.91%, 8.64%), engine load 25% contributed to NO_x reduction (11.91%, 10.24%, 8.58%, 7.25%), an engine load of 50% contributed to NO_x reduction (9.81.78%, 10.09%, 8.28%, 8.25%),engine load 75% contributed NO_x reduction (9.57%, 8.94%, 8.24%, 6.25%), and an engine load of 100% contributed to NO_x reduction (8.78%, 5.26%, 5.01%, 5.34%) on average, respectively.

The maximum and minimum NO_x reduction for B0, B10, B20, and B30 occurs at 800 rpm, 5% engine load, where the reduction is (21.05%, 19.75%, 13.82%, 12.125%) and at 1600 rpm, 100% engine load, where the reduction is (5.92%, 3.96%, 3.31%, 3.91%), respectively. This result agreed to some other researcher finding [24].

5. Conclusions

The study employed induced steam into a non- EGR marine diesel engine through a scavenges inlet system. The main purpose was to investigate the effects of steam on the reduction of NO_x by using B0, B10, B20 and B30 blended fuel. Compared to B0 fuel, biodiesel blended fuel will have a more unsaturation chain that will produce higher peak combustion temperature and higher cetane number which enhance the “NO_x effect” and lead to the production of more NO_x emissions.

Overall, the higher NO_x reduction occurs at lower engine speed and engine load while less reduction occurs at higher engine speed and engine load. This phenomenon is due to the high combustion chamber temperature for higher engine load and engine speed which produces more NO_x emission. The implication of steam induction slightly reduces the combustion pressure and engine performance.

The application of steam induction is to complement the gap of NO_x issues for biodiesel fuel especially blended palm oil methyl ester. The experiment found that the presence of steam in the combustion space will reduce the peak combustion temperature up to 2.01%, promoting ignition delay and helping reduce the generating of NO_x emissions up to 19.75%. It is still an area to explore and improve where the techniques and methods can be modified to make sure less NO_x is contained in emissions. Direct steam injection into the cylinder head is one of the potential methods to explore, this method will reduce the loss of steam during the scavenging process.

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