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EFFECTS OF NOZZLE OPENING PRESSURE AND FUEL INJECTION TIMING ON ENGINE PERFORMANCE AND EXHAUST EMISSIONS OF A DIESEL ENGINE FUELLED WITH MARINE FUELS

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ABSTRACT

The study aims to investigate the effects of operational parameters such as nozzle opening pressure and fuel injection timing on exhaust emissions of a single cylinder diesel engine fuelled with distilled marine fuels. Tests were performed on a single cylinder, 13 kW, natural aspirated, direct injection and air cooled diesel engine at 1600 RPM constant engine speed. The tests were conducted for three different nozzle opening pressures (20, 22 and 24 MPa) and 3 different nozzle opening pressures (25° bTDC, 20° bTDC and 15° bTDC). The experiments were repeated at least three times to increase the reliability of the results. The results of the study show that increasing nozzle opening pressure increases the BTE and NO_x *emissions whereas decreases* CO *emissions, specific fuel consumption and exhaust gas temperature. Advancing fuel injection timing reduces the* CO *emissions but increases* NO_x *emissions. The paper provides detailed test results, explanations and discussion.*

Keywords: *Diesel engines, nozzle opening pressure, injection timing, exhaust emissions, marine fuels.*

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DENİZ YAKITLARI KULLANILAN BİR DİZEL MOTORDA ENJEKTÖR AÇILMA BASINCI VE YAKIT PÜSKÜRTME ZAMANLAMASININ MOTOR PERFORMANSI VE EGZOZ SALIMLARI ÜZERİNDEKİ ETKİLERİ

ÖZET

*Bu çalışma yakıt olarak deniz yakıtları kullanılan bir dizel motorda enjektör açılma basıncı ve yakıt püskürtme zamanlamasının motor performansı ve egzoz salımları üzerindeki etkilerini gözlemlemeyi amaçlamaktadır. Çalışma kapsamında yapılan ölçümler 13 kW güce sahip, tek silindirli, doğal emişli, direkt püskürtmeli ve hava soğutmalı bir dizel motorda 1600 RPM sabit motor devrinde yapılmıştır. Deneyler üç farklı enjektör açılma basıncı (20, 22 ve 24 MPa) ve üç farklı püskürtme zamanlaması (*ÜÖN öncesi *25°,* ÜÖN öncesi *20° ve* ÜÖN öncesi *15°) değerlerinin kullanılmasıyla yapılmıştır. Tüm ölçümler sonuçların güvenilirliğini arttırmak üzere en az üç defa tekrar edilmiştir. Çalışmanın sonuçları, enjektör açılma basıncındaki artışın fren termal verimi ve azot oksit salımlarını arttırdığını ancak karbonmonoksit salımları, egzoz gaz sıcaklığı ve özgül yakıt sarfiyatını arttırdığı görülmüştür. Yakıt püskürtme zamanlamasının erkene alınmasının ise karbonmonoksit salımlarının düşmesini sağladığı ancak azot oksit salımlarının artışına sebep olduğu görülmüştür. Çalışma deneylerle ilgili detaylı sonuçları, açıklamaları ve konu ile ilgili tartışma kısımlarını içermektedir.*

Anahtar Kelimeler: *Dizel motorlar, enjektör açılma basıncı, yakıt püskürtme zamanlaması, egzoz salımları, deniz yakıtları.*

1. INTRODUCTION

Growing global economy, industrialization, population growth, urbanization and improved need for energy access results a rapid increase in global energy demand. Studies on estimation of the future of energy market (Shell, 2008:12; US EIA, 2016:7; World Energy Council, 2016:19) argue that energy production from fossil fuels will still be dominant on global energy market in the next 50 years. As energy generators from fossil fuels, diesel engines are the most reasonable option for energy production due to their high thermal efficiency. One of the main reason behind the air pollution and global warming is the energy production from fossil fuels. Requirements of decreasing exhaust emission released by diesel engines have become a crucial concern for the global energy market.

Maritime transport activity plays a critical role in the global economy by dominating the international trading (Lam and Lai, 2015; Lai et al. 2011). The importance of maritime transport will continue with the foreseen growth in world trade. Considering more than four fifths of world trade is carried by seaway transport (UNCTAD, 2019:4), maritime transport is very important to connect the geographies and sustaining the economic growth all around the world. Marine transportation accounts for less than 3% of total global greenhouse gas (GHG) emissions (Mersin, Bayırhan and Gazioğlu, 2019:1; Crist, 2009; Cristea, Hummels, Puzzello and Avetisyan, 2013:163; ICS, 2014:3). International Energy Agency (IEA) key world energy statistics (IEA, 2019:39) reported that maritime transportation industry has a 6.8% share on global fossil fuel consumption. These statistics signify the effect of maritime transportation to greenhouse gas inventory of the marine environment. Due to approximately 70% of marine transportation based emissions occur in the area less than 400 km from the land (Endresen et al., 2003), it could be said ship emissions are one the major reason of air pollution in coastal areas. Considering that greenhouse gas emissions from international shipping are a type of 'conditional' marine pollution (Shi, 2016), it could be argued that decreasing the amount of exhaust emissions from maritime transportation industry play a critical role for the sustainability of the marine environment.

International Maritime Organization – IMO, a specialized agency of the United Nations, sets the global standards for the safety, security and environmental performance of maritime industry. International Convention for the Prevention of Pollution from Ships (MARPOL) was adopted at IMO to prevent or minimize the negative outputs of the industry. Despite, continuous improvements made through amendments to MARPOL regulations and the considerable effort of IMO there are still a number of unregulated factors which effect the emission quantities of ships. One of the most important unregulated factor about emission control of ships is continuous inspection of operational parameters such as nozzle opening pressure (NOP), fuel injection timing (FIT), kinematic viscosity of fuel.

A considerable amount of literature has been published on the effects of operational parameters of diesel engines on exhaust emissions. Extant researchers have described the role of these parameters on diesel engine performance and exhaust emissions. Some studies about the effects of NOP and FIT on motor performance and exhaust emission were illustrated in Table 1.

Depending on the literature review, it is evident that NOP and FIT have a significant influence on performance and exhaust emissions of diesel engines. However, suggesting general hypothesis on the effect of NOP or FIT on the engine performance and emissions is not possible. The studies in the literature also stated that many other parameters might affect the experimental results. BTE increases by increasing NOP due to smaller fuel droplets in diameter, better atomization, better mixing and enhanced combustion inconsistent with the findings of studies. However, some studies (Deep et al., 2016; Agarwal et al., 2013) showed that increasing NOP lead to a decrease in BTE. The studies explained the underlying reasons of the divergence that the fuel droplets that decrease in diameter due to higher NOP and therefore decrease in their momentum may not be able to reach areas near the cylinder head and piston head in the combustion chamber. Agarwal et al. (2013) explained the divergence that smaller droplet size and better mixing in cylinder reduce the ignition delay significantly which led to knocking in engine and fluctuations in-cylinder pressure and temperature. The other explanation for the underlying reason of reducing of BTE with increasing FIT was the improper timings of peak values of combustion characteristics (Deep et al., 2016). SFC, which is the ratio of fuel consumption to the net thrust has a negative correlation with BTE which is the ratio of energy in the brake power to the fuel energy (Deep et al., 2016; Agarwal et al., 2013; Raheman et al., 2008). Some studies (Agarwal et al.,2014; Anbarasu and Karthikeyan, 2017; Liu, Yao and Yao, 2015) stated that increasing NOP resulted in a decreasing in BTE. According to the studies, the main reason of the finding is that better atomization and enhanced combustion through higher NOPs increases penetration length and spray cone angle which increases heat release rate and BTE thus decreases SFC. Agarwal (2013) explained that higher exhaust gas temperatures might be the result of lower NOP. Because larger droplet size which was resulted by lower NOP during the injection may promote heterogeneous combustion which causes the BTE to decrease. Thus, the energy which is released by exhaust gas increases under these circumstances. If NOP is too high, ignition delay becomes shorter, and the possibility of homogeneous mixing and BTE decrease. It may lead to the smoke formation in the exhaust outlet (Çelikten, 2003; Anbarasu and Karthikeyan, 2017) and higher temperature in the exhaust gas. It can be observed that both CO and HC follow the same trend because these are the results of incomplete combustion. The formation rate of CO and HC in the exhaust gas decreases by increasing NOP due to better atomization,

Table 1: Literature Review

Author(s)	Year	Aim of the study	Findings
Kumar et al.	2017	To investigate the effect of 200 bar, 220 bar and 240 bar NOPs on the performance and emission characteristics on a single cylinder diesel engine fuelled with 20% and 30% blends of mahua methyl ester with diesel	The brake thermal efficiency (BTE) and nitrogen oxides (NOx) emissions increase whereas carbon monoxide (CO) and hydrocarbon (HC) emissions decrease by increasing NOP
Mohan et al.	2014	To investigate the performance and emission characteristics of a diesel engine fuelled with 20% blend of mahua methyl ester with diesel fuel for 225, 250 and 275 bar NOPs and varying FITs from 19° bTDC to 27° to optimize the use of mahua methyl ester in accordance with ISO 8178 standard.	BTE increases, specific fuel consumption (SFC), smoke level, NOx and CO emissions decrease by increasing NOP. Besides, NOx and CO emissions decrease by advancing FIT. What is interesting about the study is that it showed whether implementing fuel injection strategies could meet the existing emission norms. Thus, the study has reported that 20% blend of mahua methyl ester could be used by increasing NOP to 275 bar or by retarding FIT to 21° bTDC to meet the requirements of Central Pollution Control Board of India.
Anbarasu and Karthikeyan	2017	To investigate the performance and emission characteristics of a single cylinder diesel engine fuelled with blends of canola emulsion biodiesel and diesel fuel at 200, 220 and 240 bar NOPs and constant FIT.	BTE, maximum cylinder pressure and NOx emissions increase while SFC decreases by increasing NOP.
Liu et al.	2015	To investigate the effect of NOP on the performance and exhaust emissions of a 6-cylinder common-rail diesel engine fuelled with diesel and methanol.	Increasing NOP results in a decrease of combustion duration, CO and smoke emissions while the increase of NOx and CO2 emissions. Besides, the study made a comparison between only diesel mode (D mode) and diesel methanol dual fuel mode (DMDF) of the test engine. According to the findings of the study NOX emissions increase and smoke emissions decreases as NOP increases in DMDF mode. Compared to D mode, the study found that there is an obvious increase in CO and HC emissions but a reduction in CO2 emissions.

Table 1: Literature Review (Continued)

Labecki and Ganippa	2012	To investigate the combustion and emission characteristics of the rapeseed oil (RSO) and blends for changing different NOPs from 800 to 1200 bar and different FITs vary from 9° bTDC to TDC.	Once the nozzle opening pressure was increased the ignition delay reduced for all test fuels. A shorter ignition delay for high nozzle opening pressure also advanced enhanced combustion and increased the cylinder pressure and heat release rate. By increasing NOP, the exhaust smoke level, HC and CO emissions decreased while the NOx emissions increased. Retarding FIT caused late combustion.
Puhan et al.	2009	To investigate the effects of changing NOP from 220 bar to 200 and 240 bar on performance, emission and combustion characteristics of high linolenic linseed oil methyl ester indirect injection diesel engine.	BTE and HC emissions increase and the smoke level decrease especially at high loads. Besides, SFC, NOx emissions and peak cylinder pressure increase while CO emissions and cumulative heat release decrease by an increase or decrease in NOP from the set point of 220 bar.
Çelikten	2003	To investigate the effects of changing NOP between 100 and 250 bar on performance and emissions of a 4-cylinder, turbocharged diesel engine with indirect injection.	The performance of the engine was affected by NOP and the maximum performance has been obtained at 150 bar.
Içingür and Altıparmak	2003	To investigate the effects of changing NOP between 100 and 250 bar and different fuel cetane numbers on the performance and emission characteristics of a 4-cylinder diesel engine.	smoke level decreased by increasing NOP. Besides, NOx and SO2 emissions decreased, smoke level increased by increasing cetane number due to shorter ignition delay period.
Deep et al.	2016	To investigate the influence of changing FIT between 21° and 25° bTDC and changing NOP between 200 and 300 bar on working parameters of a single cylinder diesel engine fuelled with a blend of castor biodiesel.	maximum cylinder pressure, heat release rate, pressure rise rate, CO and HC emissions increase by advancing IT. BTE and NOx emissions decrease, SFC increase in case of an increase or decrease in FIT. Besides maximum cylinder pressure, heat release rate, ignition delay period and NOx emissions decrease CO and HC emissions and smoke opacity increase by increasing IP.
How et al.	2018	To investigate the influence of changing FIT between 12° bTDC and 2° aTDC and split injection strategies on performance of an engine.	BTE, NOx emissions and peak pressure increase and SFC and peak mean gas temperature decrease by advancing FIT.

Source: Compiled by author

better mixing and enhanced combustion (Mohan et al. 2014; Anbarasu and Karthikeyan, 2017, Liu, Yao and Yao, 2015). However, the findings of some studies (Puhan et al., 2008; Deep et al., 2016; Agarwal et al., 2013) do not support the results of studies mentioned above. The studies found that increasing NOP may result in higher CO and HC emissions due to very long penetration distance which causes wall impingement. The reason for the difference between the results may stem from the different increasing ratios of NOP in the studies. It can be deduced from the literature review; it is obvious that increasing NOP provides better mixing and enhanced combustion unless the fuel droplets hit the cylinder surface and piston head. Cylinder pressure at the start of injection may also affect the penetration distance. CO_2 is formed due to sufficient oxidation of CO. The decrease of CO and HC emissions provides an increase in CO_2 emissions (Labecki and Ganippa, 2012). However, it may well be argued that there would be a slight increase in CO_2 emissions resulted by a decrease in CO emissions by comparing the ratios of the components in the exhaust gas. Increasing NOP results (2013) expressed that poor combustion characteristics including knocking of the engine may cause low thermal efficiency, and high fuel consumption as well as higher CO_2 formation in the exhaust gas. Besides, the increasing fuel consumption for same power output increases CO_2 emissions (Sayin et al. 2009). The formation rate of NO_x in the exhaust gas is highly dependent on in-cylinder temperature and pressure. Increasing NOP causes shorter ignition delay by better mixing. Short ignition delay leads to more heat release in the premixed stage of combustion which causes a sharp pressure rise in the cylinder.

The studies on the effects of FIT to engine performance and exhaust emissions showed that BTE increases while SFC decreases by advancing FIT due to more time for combustion. Furthermore, the retarding FIT may lead to late combustion. Thus the pressure rise may occur on expanding stroke (Mohan et al, 2014). However, some studies suggested that incorrect matching of TDC and peak pressure development may occur by excessive advancing FIT (Raheman and Ghadge, 2008 and Janardhan et al., 2014). One can infer that the timing of peak values is an important parameter for BTE (Deep et al. 2017). The pressure rise timing near to the TDC provides higher BTE and lower SFC. EGT decreases with complete combustion. By advancing FIT, a larger part of the injected fuel is burnt in the flame prorogation stage of combustion which results in lower EGT (Rostami et al., 2014; Raheman and Ghadge, 2008). Another reason for decreasing BTE by advancing FIT may be stemmed from that earlier combustion due to advanced FIT provides enough time for hot gases to cool down. Advancing FIT improves air-fuel mixing quality due to the availability of more time for mixing and oxidation. Thus, CO and HC emissions decrease.

However, if FIT is advanced excessively, it may result in wall impingement. Hence, it will increase CO and HC levels in the exhaust gas. When FIT advanced, the ignition delay increases which enables longer time for mixing and increases the amount of the fuel burnt just after the ignition. Therefore, combustion pressure can reach higher pressure levels, and it provides an increase in NO_x emissions.

The need to reduce exhaust emissions is a major concern for all sectors in which energy is produced from fossil fuels. Despite the significant share of maritime transportation in the global fuel consumption which was mentioned by the IEA statistics (2019), there is no published study in the literature to observe the effects of fuel injection parameters on performance and exhaust emissions of a diesel engine fuelled with marine fuels.

Present study aims to investigate the effects of NOP and FIT on the performance parameters and exhaust emissions of a single cylinder diesel engine fuelled with diesel fuel in accordance with EN590 standards and marine diesel fuels in accordance with ISO 8217 standards.

2. Experimental Setup and Procedure

2.1. Experimental Setup

The experiments were conducted on a single cylinder, 4-stroke, air cooling, natural aspirated diesel engine fuelled with highway diesel oil (EN590) in accordance with EU standards, DMA marine diesel oil (DMA) in accordance with ISO 8217 standard and %5 blend of RME 180 heavy fuel oil in accordance with ISO 8217 standard and DMA (DMA95). Table 2 provides the properties of the test engine and Figure 1 illustrates the experimental setup.

Krohne Optimass 3300c mass flow meter was used to measure mass flow, temperature and density of the fuel. SFC was calculated by using measured mass flow rate by dividing to instant motor power. Test engine was started with commercial diesel oil at the cold start of the engine due to the higher kinematic viscosity of some test fuels. Then the fuel was changed over to the test fuel. The density of fuel was measured to ensure whether the fuel at the inlet of the test engine changed over to the test fuel.

Table 2: Properties of the Test Engine

Items	Specifications
Make-model	Antor 4LD820
Fuel Injection	Direct
Cylinder Number	Single cylinder
Displacement	817 cm^3
Compression Ratio	17:1
Bore x Stroke	102 x 100 mm
Cooling System	Air Cooled
Rated Speed (RPM)	3000
Maximum Power (ISO 1585)	13 kW
Maximum Torque	48 Nm at 1600 RPM
Nozzle opening pressure (Default)	200 bar
Fuel Injection Timing (Default)	22° bTDC

Source: Compiled by authors

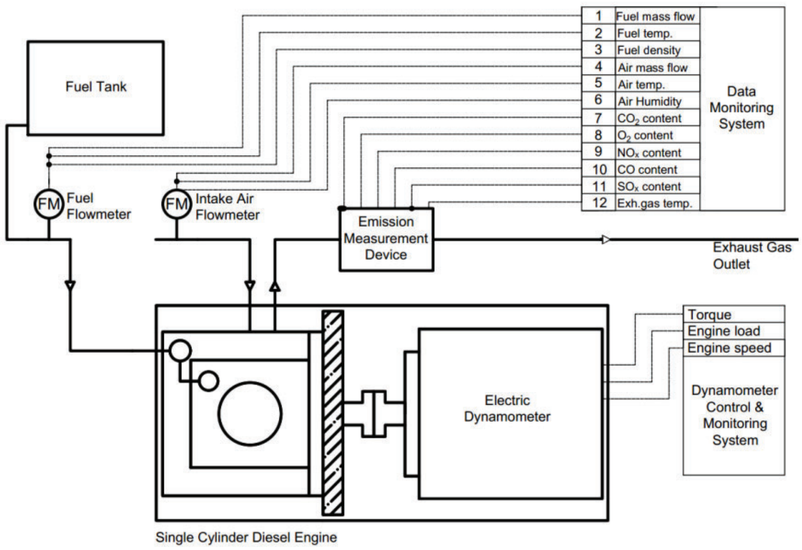

Figure 1: Experimental Setup
Source: Generated by authors

Krohne Optiswirl 4200 vortex flowmeter was used to measure the mass flow, temperature and humidity of intake air. Intake air temperature and humidity were used for correction of actual NO_x emission ratio in the exhaust gas. Emission correction factor was calculated by using the following equation which is stated in MARPOL 73/78 NO_x Technical Code.

$$k=\frac{1}{1-0.0182(H_a-10.71)+0.0045(T_a-298)} \quad (1)$$

Where, k is the correction factor for NO_x, H_a is the humidity and T_a is the temperature of intake air. Testo 350 Maritime portable exhaust gas analyzer which was approved by MARPOL Annex VI was used to measure the exhaust emissions. The exhaust gas analyzer measured exhaust gas temperature, NO_x, CO, O_2, CO_2 and SO_2 emissions. Shaft torque was calculated by using the torsional moment of the motor shaft. Esit STSC 50 load cell was used to measure torsional moment. Table 3 shows the measurement ranges and accuracies of all measured parameters.

Table 3: Measurement ranges and accuracies of test parameters

Measured parameters	**Range**	**Accuracy**
Torsional moment	0-50 kg	±0.05 kg
Exhaust gas temperature	-40-1000°C	±5°C
CO emission	0-3000 ppm	±%1
CO_2 emission	0-40% (volumetric)	±%2
NO_x emission	0-3000 ppm	±%2
SO_2 emission	0-3000 ppm	±%1
O_2 emission	0-25% (volumetric)	±%2
Fuel mass flow	0-22.5 kg/h	±%0.1
Fuel density	400-3000 kg/m3	±2 kg/m3
Fuel temperature	-40-150°C	±1°C
Intake air humidity	0-100%	±%0.1
Intake air temperature	-10-50°C	±1°C

Source: Compiled by authors from equipment datasheet.

Measurements were carried out by using EN 590 highway diesel oil, DMA marine diesel oil and DMA95 which is 5% blend of RME 180 heavy fuel oil and DMA as test fuels. Table 4 provides some properties of test fuels. Analysis of the test fuels were performed at Tüpraş Izmir Refinery Laboratories in compliance with given test methods. The test fuels differ in kinematic viscosity, density and sulfur content significantly. Therefore, the effects of kinematic viscosity, density and sulfur content on motor performance and exhaust emissions could be observed by experimental results.

Table 4: Properties of test fuels

Property	Unit	Test method	EN590	DMA	DMA95
Cetane Number		EN 15195 EN ISO5165	62.4	-	-
Cetane Index		EN ISO 4264	57.2	57	56.2
Density (15°C)	kg/m^3	EN ISO 3675 EN ISO 12185	827.1	829.3	836.3
Sulphur content	mg/kg	EN ISO 20846 EN ISO 20884	9.9	-	-
Sulphur content	%	ISO 8754	-	0.097	0.28
Flash Point	°C	EN ISO 2719	60	60	60
Carbon Residue	%	EN ISO 10370	<0.1	<0.1	<0.1
Ash content	%	EN ISO 6245	0.0016	0.0024	0.0040
Water content	mg/kg	EN ISO12937	<0.1	<0.1	<0.1
Lubricity	micron	EN ISO 12156	436	430	409
Kinematic viscosity	mm^2/sec	EN ISO 3104	2.785	5.499	14.410
Carbon content	%		86.2	86.2	86.2
Hydrogen content	%		13.6	13.55	13.42

Source: Compiled by authors from test results

2.2. Experimental Procedure

In the experiments, the effects of fuel injection timing (FIT) and nozzle opening pressure (NOP) on engine performance and exhaust emissions on single cylinder diesel engine fuelled with EN590 diesel fuel, DMA marine diesel fuel and DMA95 5% of RME180 heavy fuel oil and DMA were investigated. All the measurement equipment in the test setup were calibrated according to the instruction books before starting the experiments. It is ensured that all parameters except the variables changed for tests are fixed during the experiments. During the tests, all the measurements were taken 3 minutes after the exhaust gas temperature would rise or down to a constant level. Each measurement was repeated three times at different times, and the test result value was accepted as the average of the three values. The difference between the average of the three measurements and the end measurement values was found to be less than the measured value of 3%.

For the first experiment, the engine was able to reach a maximum speed of the test engine -3000 RPM- when the nozzle opening pressure and timing were set to the factory outlet values, 200 bar and 20° bTDC. Then, the engine was loaded at various loads. As a result, the engine speed changed from 3000 RPM to 1200 RPM gradually. The instantaneous motor momentum is measured at each speed drop of 100 RPM. As a result of these measurements, it was determined that the highest motor torque was measured at 1600 RPM for each test fuel. When the maximum torque values obtained at 1600 RPM, the lowest torque value at 1600 RPM was measured as 39.23 Nm for DMA95 fuel. For this reason, this value was used as the highest torque value to be able to compare in equal conditions during the use of each fuel type on the tests. Measurements were taken at motor torques of 39,23, 29,42, 19,61 and 9,81 Nm and at 1600 RPM for each fuel. Figure 2 shows the torque values for each motor speed and each test fuel.

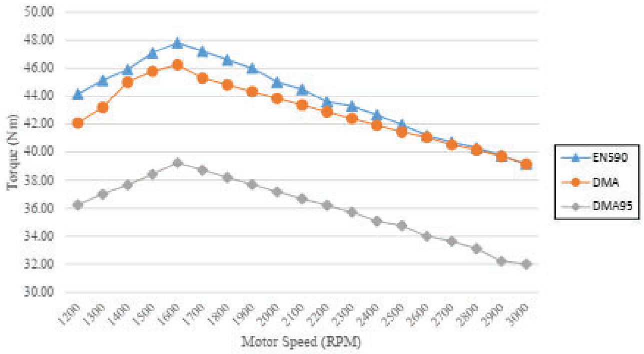

Figure 2: The torque measurements for each motor speed and each test fuel

Source: Generated by authors

Nozzle opening pressure (NOP) was changed by adding or removing shims under the spring of fuel valve. 20 bar nozzle opening pressure change could be achieved by adding or removing 0.15 mm shim. Nozzle opening pressure was tested on a hydraulic test device before and after each experiment. Experiments were performed at 180, 200 and 220 bars nozzle opening pressures at constant engine speed with different test fuels and injection timings. Fuel injection timing (FIT) was changed by adding or removing different thickness metal gaskets under the fuel pump body. 5 change in FIT could be achieved by adding or removing 0.85 mm gaskets. Fuel injection timing was tested manually according to the instruction book of the test engine. The flywheel of the test engine was signed to read the crank angle. Fuel injection valve and fuel outlet pipe of the fuel pump were dismantled, and engine shaft was turned by hand. Then the crank angle was read at the time of fuel spill from the fuel pump. Experiments were performed at 25° bTDC, 20° bTDC and 15° bTDC injection timings at constant engine speed for different test fuels and nozzle opening pressures.

3. RESULTS AND DISCUSSION

3.1. Brake Thermal Efficiency

Figure 3 shows the effects of nozzle opening pressure on brake thermal efficiency (BTE) of the test motor for each fuel. It was found that BTE increased as a result of an increase of NOP due to improved atomization and better combustion, especially at higher motor loads. These results are consistent with the studies indicating the relationship between BTE and NOP.

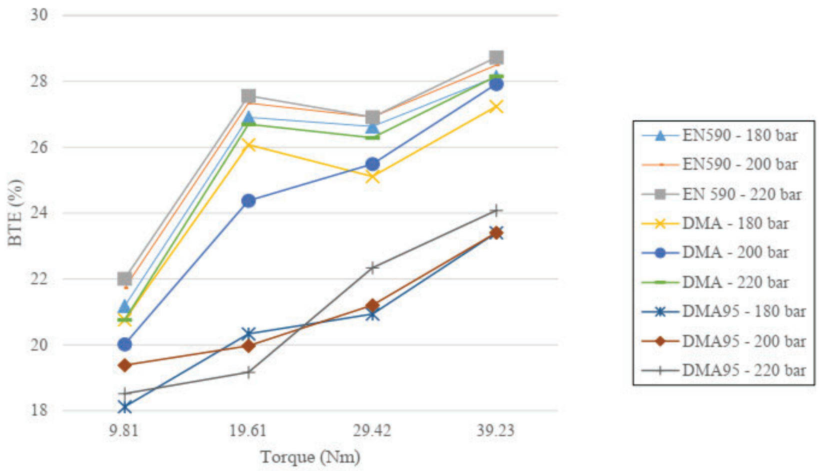

Figure 3: The effects of NOP on BTE
Source: Generated by authors

Interestingly, it is observed in the experiments that in the use of high kinematic viscosity fuels at low engine loads, the change in NOP causes the irregular change in BTE. The reason behind this results may stem from the design criteria of the fuel valve of the test engine. It is not designed for the usage of high viscosity fuels. Another reason may be that high viscosity fuels lead to large fuel droplets on injection and increasing diameters cause the increase of momentum of the fuel droplets. It may result in deposit formation on the cylinder liner surface and decrease BTE. The maximum BTEs of EN590, DMA and DMA95 fuels are 28.73%, 28.15% and 24.08% respectively. Obviously, there is a significant negative correlation between fuel kinematic viscosity and BTE.

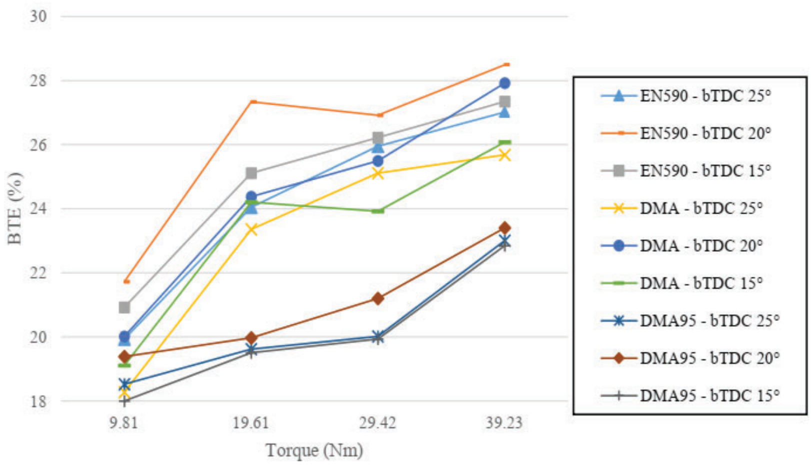

Figure 4: The effects of FIT on BTE
Source: Generated by authors

Figure 4 compares BTEs of the test engine fuelled with test fuels for different injection timings at different motor loads. It is apparent from this chart that advancing FIT from original injection timing of 20° bTDC decreases BTE for all fuels. Retarding FIT leads to a decrease in BTE for EN590, DMA and DMA95 fuels, 4.21%, 7.05% and 4.88% respectively at 39.23 Nm motor torque. A possible explanation for this might be that retarding injection timing may lead to reducing effective pressure due to late combustion and lower pressure rise. Despite a slight increase, BTE did not change significantly by advancing FIT from 20° bTDC to 25° bTDC. This finding is contrary to previous studies which have suggested that advancing FIT causes to increase in BTE. However, the experimental results may have been affected by some other variables such as changing ratio of FIT, compression ratio, fuel injection strategy, intake air characteristics and other operational parameters of the test engine.

3.2. Exhaust Gas Temperature

Figure 5 depicts the effects of NOP on exhaust gas temperature (EGT) of the test engine fuelled with EN590, DMA and DMA95 fuels under different engine loads. In the figure, there is a clear trend of decreasing EGT by increasing of NOP for all test fuels. A possible explanation is that increase in NOP decreases the ignition delay period during the combustion. The change reduces the time required for complete combustion. The energy released per gram fuel increase, more combustion heat can be converted into mechanical energy. Therefore, the exhaust gas energy is expected to decrease.

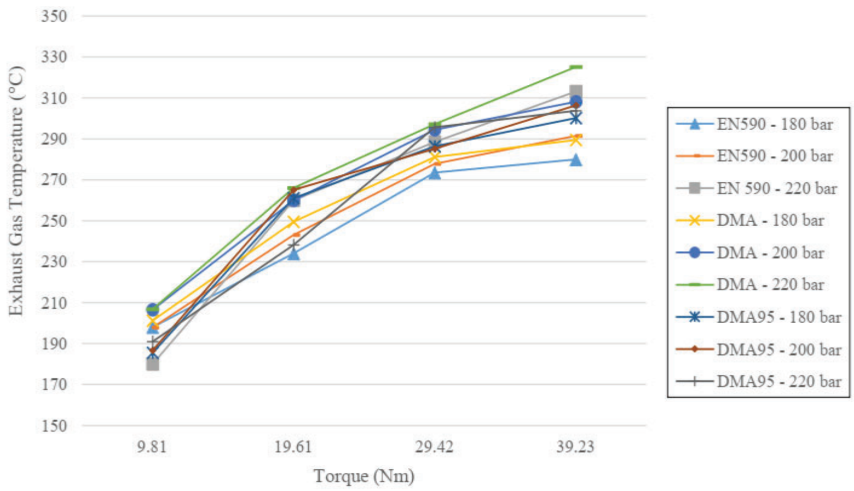

Figure 5: The effects of NOP on Exhaust Gas Temperature
Source: Generated by authors

Figure 6 presents the effects of FIT on EGT of the test engine fuelled by the test fuels under different loads. It is clear that EGT decreases by advancing FIT 5 from original injection timing of 20° bTDC and vice versa. It may be due to the fact that advancing the start of ignition may provide a longer time for combustion which enables more efficient combustion.

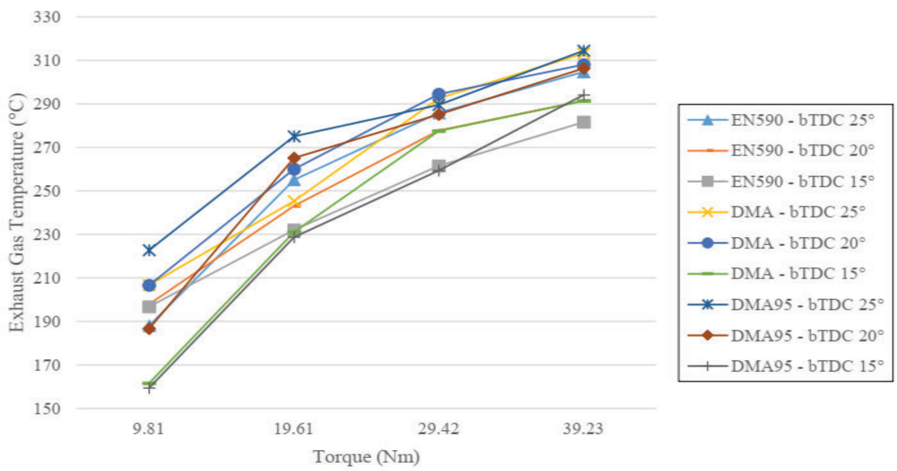

Figure 6: The effects of FIT on Exhaust Temperature
Source: Generated by authors

The changing trends of EGT which was shown in Figure 5 and Figure 6, and BTE which was shown in Figure 3 and Figure 4 suggests that a strong negative correlation may exist between EGT and BTE. The reasons for the correlation may be that efficient burning of the fuel in the diesel engine provides better combustion and it may decrease waste heat removed from the cylinder by exhaust gas.

3.3. Oxides of Nitrogen

Figure 7 illustrates the results obtained from the experimental analysis of the effects of NOP on the NO_x emissions. There is a clear trend of increasing NO_x emissions by increasing NOP. The pressure and temperature rise in the combustion chamber is expected to be sharper due to improved penetration and better fuel-air mixing quality by higher NOP. A positive correlation was found between NOP and NO_x formation in the present study. The result reflects with Zeldovich Mechanism (Zeldovich, 1946) which stated that high combustion temperatures result in high NO_x formation. However, increasing NOP caused to lower NO_x emissions at low loads. Fuel droplets, which is reduced in diameter and thus reduced in their momentum may not reach the cylinder wall in the combustion chamber since the fuel is supplied in smaller quantities due to low load. Therefore, the air around the piston head and near the cylinder wall surface may not mix with the fuel. It reduces combustion efficiency and adversely affects the overall fuel-air mixture quality especially in the use of DMA and DMA95 fuels with low kinematic viscosity. For this reason, an increase in the nozzle opening pressure may lead to a reduction in NO_x emissions at low loads.

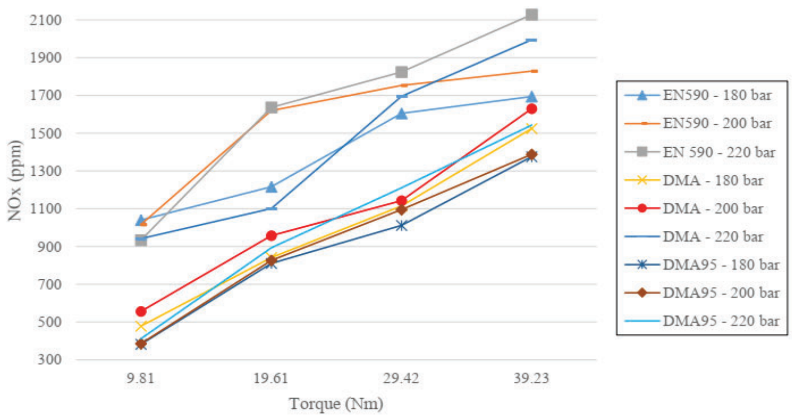

Figure 7: The Effects of NOP on NO_x emissions
Source: Generated by authors

Figure 8 illustrates the effect of FIT on the NO_x emissions. It can be seen that advancing FIT increases NO_x formation rates. The possible explanation for that is because advancing FIT results in higher combustion temperatures because of more fuel can be injected on ignition delay period and it causes a sharp pressure rise in flame propagation stage of combustion.

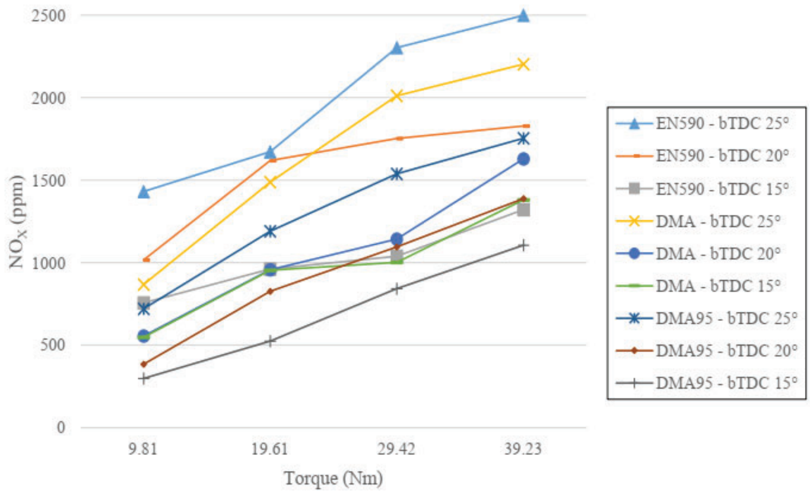

Figure 8: The Effects of FIT on NO_x emissions
Source: Generated by authors

The results which are shown in Figure 7 and Figure 8 indicate that use of higher kinematic viscosity test fuels causes to lower NO_x formation. A possible explanation for this is that increasing kinematic viscosity of the test fuels may cause larger fuel droplets during the injection. Therefore, it may decrease air-fuel mixing quality, combustion temperatures.

3.4. Carbon Monoxide

Figure 9 shows the effect of NOP on the CO emissions on the test engine fuelled with test fuels under different loads. CO emissions decreased with increasing NOP. A possible explanation for this might be that fuel-air mixing quality increases by increasing NOP. It provides more suitable conditions for the oxidation of carbon atoms in the combustion chamber. Considering the fact that CO is formed by incomplete combustion of the fuel, better mixing quality results in complete oxidation of carbon atoms. Thus, fuel-air mixing quality leads to increase of CO_2 emissions during a decrease of CO emissions. What is interesting about the data in this figure is that CO emission rates for 9.81 Nm motor torque is higher than the rates for 19.61 Nm motor torque despite the emission rates has a positive correlation between the motor torque. The underlying reason might be that less fuel is supplied to the cylinder at low loads, resulting in unburnt air masses especially around the cylinder wall and the piston head in the cylinder.

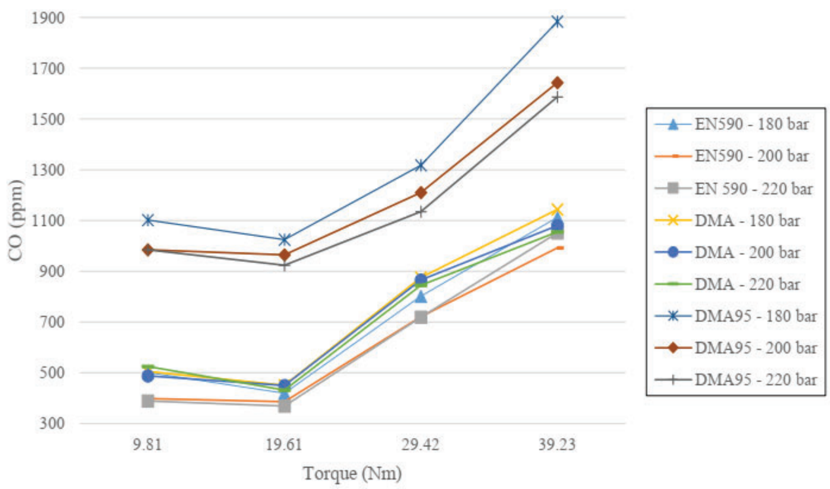

Figure 9: The Effects of NOP on CO Emissions
Source: Generated by authors

Figure 10 shows the effect of FIT on CO emissions on the test engine. CO emissions decreased with the advancing FIT and vice versa. Advancing FIT provides a longer period for fuel-air mixing. Better fuel-air mixing may lead to decrease in CO emissions.

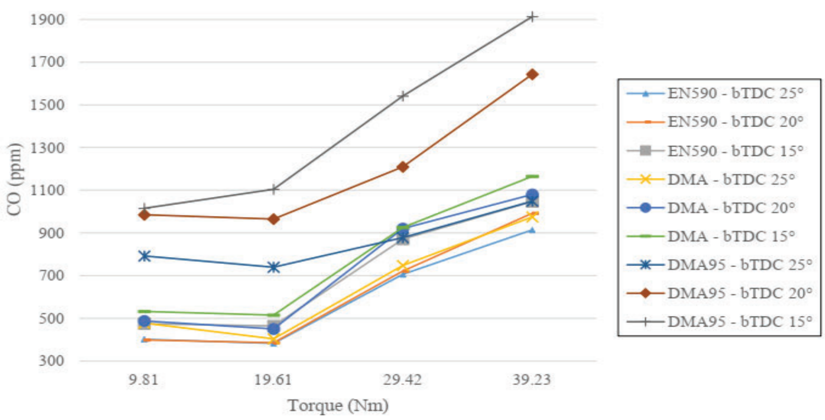

Figure 10: The Effects of FIT on CO Emissions
Source: Generated by authors

Figure 9 and Figure 10 illustrate the effects of fuel types on CO emissions. A positive correlation was found between CO emissions and kinematic viscosity of the test fuels. The reason for the finding may be the fact that use of higher kinematic viscosity fuels may results in longer diameter fuel droplets during the injection. It may cause poor fuel-air mixing quality and higher CO emissions.

3.5. Carbon Dioxide

Figure 11 and Figure 12 show the effect of NOP and FIT respectively on CO_2 emissions on the test engine fuelled with each test fuel. Because of CO_2 emissions are formed by oxidation of the carbon atoms in the fuel, there may be a positive correlation between CO_2 emission rates and the fuel consumption. Increasing of fuel consumption lead to CO_2 emissions to increase.

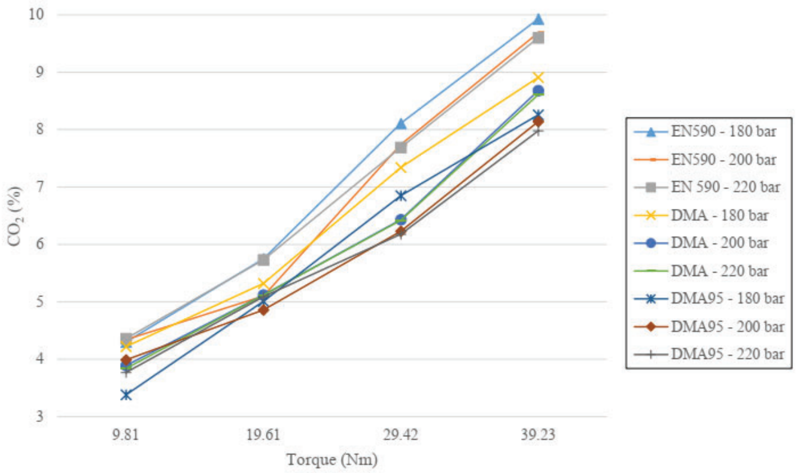

Figure 11: The Effects of NOP on CO_2 Emissions
Source: Generated by authors

According to the figures, the usage of high kinematic viscosity fuels causes a decrease in CO_2 emissions. Considering CO emissions are formed by insufficient oxidation of carbon atoms in the fuel, it can be assumed that incomplete combustion might be one of the main reason for decreasing of CO_2 emissions. However, since the percentage of CO_2 is more than the percentage of CO in the exhaust gas, CO formation and incomplete combustion has a little effect on CO_2 emissions.

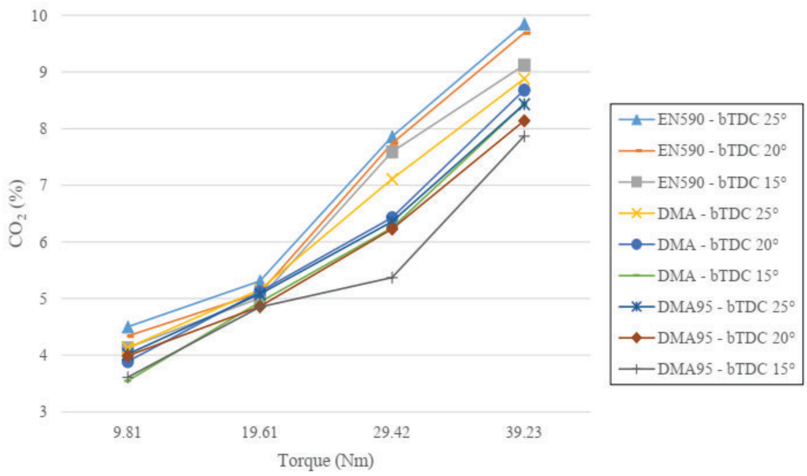

Figure 12: The Effects of FIT on CO_2 Emissions
Source: Generated by authors

3.6. Sulphur Dioxide

Figure 13 and Figure 14 indicates the effects of NOP and FIT respectively on SO_2 emissions on the test engine fuelled with DMA and DMA95 fuels. SO_2 emissions of the test engine fuelled with EN590 fuel could not be measured since the Sulphur content of the fuel is very low.

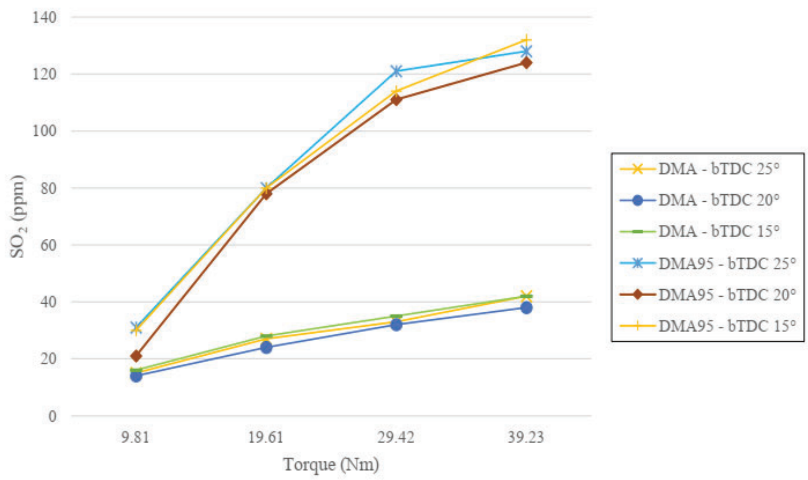

Figure 13: The Effects of NOP on SO_2 Emissions
Source: Generated by authors

The results of the experiments show that formation of SO_2 in the exhaust gas is directly related to the Sulphur content of the fuel and fuel consumption. Because some 98% of the sulphur contained in the fuel can be oxidized in combustion process (Kozak and Merkisz, 2005), the sulphur content of the fuel and fuel consumption may be the major parameters affecting the SO_2 content in the exhaust gas. Besides, no significant correlation was found between other fuel physical parameters and SO_2 emissions.

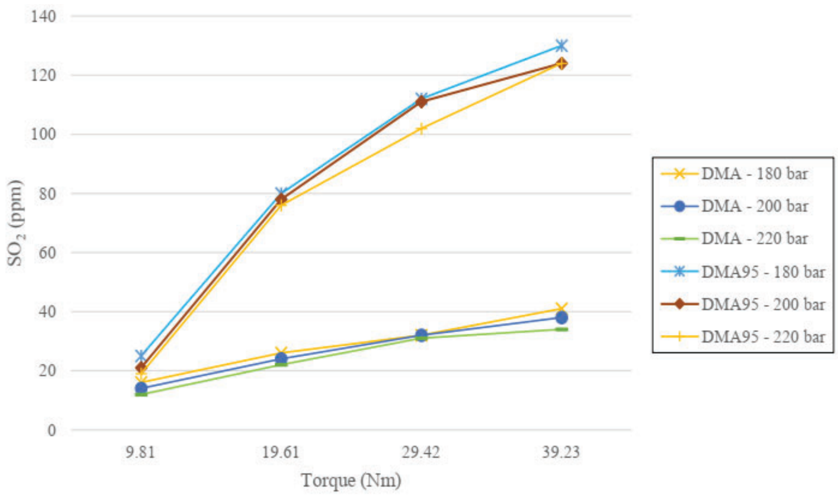

Figure 14: The Effects of FIT on SO_2 Emissions
Source: Generated by authors

4. CONCLUSIONS

The experiments were conducted on a constant speed (1600 RPM) diesel engine with 180, 200 and 220 bar NOPs and at 25° bTDC, 20° bTDC and 15° bTDC FITs under 4 different motor loads and with using three different fuels EN590 diesel oil, DMA marine diesel oil and 5% blend of RME 180 and DMA fuel. Results showed that increasing NOP improves atomization and enhances better combustion. This situation increases BTE and decreases SFC. Increasing NOP leads to shorter ignition delay which reduces the time required to complete combustion. More completed combustion provides lower CO emissions. Interestingly, increasing NOP causes to higher CO emissions and lower BTE for low loads. The reason behind this, droplets which is reduced in diameter and thus reduced in their momentum due to higher NOP may not reach the cylinder wall in the combustion chamber since the fuel is supplied in smaller quantities due to low load. Changing in NO_x emissions by NOP is mainly related to combustion temperature and pressure in the cylinder. Therefore, NO_x emissions increased by increasing NOP due to better mixing and higher temperature and pressure during combustion.

According to the experimental results, when FIT was advanced, no significant increase in BTE was recorded as the previous literature highlighted. However, the experimental results may have been affected by some variables such as changing ratio of FIT, compression ratio, fuel injection strategy, intake air characteristics and other operational parameters of the test engine. Advancing FIT and the start of ignition may provide a longer time for combustion. Thus, longer combustion period may result in lower EGT and CO emissions. Advancing FIT leads to higher combustion temperatures and pressure because of more fuel can be injected on ignition delay period which causes a sharp pressure rise in flame propagation stage of combustion which causes an increase in NO_x.

Density and kinematic viscosity of the fuel are crucial parameters for combustion. Higher viscosity fuels used in the study resulted in lower thermal efficiency. The underlying reason for the decrease of BTE may be stem from that the injection of high viscosity fuels results in longer diameter droplets and it decreases fuel-air mixing quality. Decreasing mixing quality requires a longer time to complete combustion. Incomplete combustion causes higher CO emissions and SFC and lower BTE. Furthermore, increasing NOP with high viscosity fuels may lead to large fuel droplets on injection, and increasing diameters may cause to increase the momentum of the fuel droplets.

This study is the preliminary one to investigate the effects of NOP and FIT on a diesel engine fuelled with marine diesel fuels. However, the results of the study are limited to include measurements on HC emissions based on the insufficient experimental setup. More comprehensive investigations can be performed by measuring the cylinder pressure and ignition delay. Notwithstanding these limitations, the study indicates the effects of NOP and FIT on a diesel engine fuelled with marine diesel fuels based on the experiments. For further studies, researchers may analyze the effects of intake air parameters on performance and exhaust emissions of a diesel engine fuelled with marine diesel fuels. A further study could assess the effectiveness of changing NOP and FIT at different loads to meet the MARPOL Annex VI emission limits requirements for the maritime industry.

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