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Performance and Combustion Process of a Dual Fuel Diesel Engine Operating with CNG-Palm Oil Biodiesel

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ABSTRACT

Efforts to build and develop a low emission transportation system have been carried out, one of which is by applying biodiesel and natural gas to dual-fuel diesel engine. Biodiesel is an oxygenated, low-sulfur, and high flash point alternative diesel fuel. In the dual-fuel mode, CNG was used as a substitute fuel and palm biodiesel as a combustion pilot which was injected directly into the combustion chamber at 13 °CA BTDC. CNG injection timing was 110 °CA ATDC and the CNG injection duration was gradually increased. Performance and combustion process in single-fuel mode and dual-fuel mode were compared. The engine was kept at a constant speed of 2000 rpm at all load conditions. The results show that the dual-fuel mode at low and medium loads produces in-cylinder pressure and heat release rate lower than single-fuel mode, but at high load, it produces in-cylinder pressure and heat release rate 5.14% greater. CO and HC emissions produced by the dual-fuel mode higher than the single-fuel mode at all loads. Conversely, dual-fuel mode produces 95.58% lower smoke emissions than single-fuel mode at all loads.

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1. INTRODUCTION

The reduced production of fossil energy, as well as global commitment to reduce greenhouse gas emissions, encourage the Government to increase the role of new and renewable energy continuously [1]. In the transportation sector, such as railroads, policies have been issued to substitute fossil fuels with biodiesel and natural gas. Indonesian Railroad (KAI) is currently conducting a trial of converting fossil fuel into natural gas using the Diesel Dual Fuel (DDF) system locomotive [2]. The use of natural gas in trains has several benefits, such as fuel cost efficiency, maintenance cost efficiency, and potential green energy [3].

Biodiesel is a renewable fuel whose properties are very similar to diesel fuel depending on the raw material, so it does not require major engine modifications to be able to use this fuel [4]. In addition, natural gas is more environmental friendly because it produces fewer emissions compared to fossil fuels. The characteristic of a dual-fuel diesel engine is multiple use fuel in the operating process [5].

Several studies on dual-fuel diesel engines have been carried out using various parameters such as variation of the timing [6] and duration of CNG injection [7], optimization of pilot injection timing [8][9][10], and enhance air mass flow rate to the intake manifold [11]. Basically, the timing and duration of CNG injection can affect the combustion process, this is related to the quantity of CNG fuel that enters the combustion chamber during the intake stroke. A dual-fuel diesel engine that operated at constant speed requires a different amount of fuel for each change in engine load so that a constant CNG injection duration will result in a decrease in the percentage of CNG substitution as load increases.

Research conducted by Yang, et al [12] on dual fuel diesel engines fueled by diesel fuel-CNG. From this study, it was found that variations in the injection timing and mass flow rate of CNG at each load could affect the combustion process and emission formation. In a dual-fuel diesel engine, pilot fuel parameters have an important role in the combustion process, this caused the combustion in a dual-fuel diesel engine is more spread out and closer to cylinder wall [13][14][15]. Ryu [16] used a dual-fuel diesel engine fueled by CNG-vegetable oil biodiesel. The results of this study indicate that CO and HC emissions relatively high at low load conditions due to low combustion temperature of CNG. Smoke emission decreased with increasing engine loads.

In this study, dual-fuel diesel engine uses natural gas in the form of Compressed Natural Gas (CNG) which used as a substitute fuel and palm oil biodiesel as a combustion pilot which injected directly into the combustion chamber. The objective of this study was to compare the performance and combustion process of dual-fuel diesel engine fueled by CNG-palm oil biodiesel with conventional diesel engine. The investigation focuses on engine performance characteristics such as in-cylinder pressure, rate of heat release, specific fuel consumption, thermal efficiency, air fuel ratio, and exhaust emission at low, medium, and high load conditions.

2. RESEARCH METHOD

To examine the performance and combustion process of a dual-fuel diesel engine, a single-cylinder diesel engine was modified by adding an electronic control unit (ECU) to manage the CNG injection system. The schematic diagram of the experimental setup and apparatus are shown in Fig. 1.

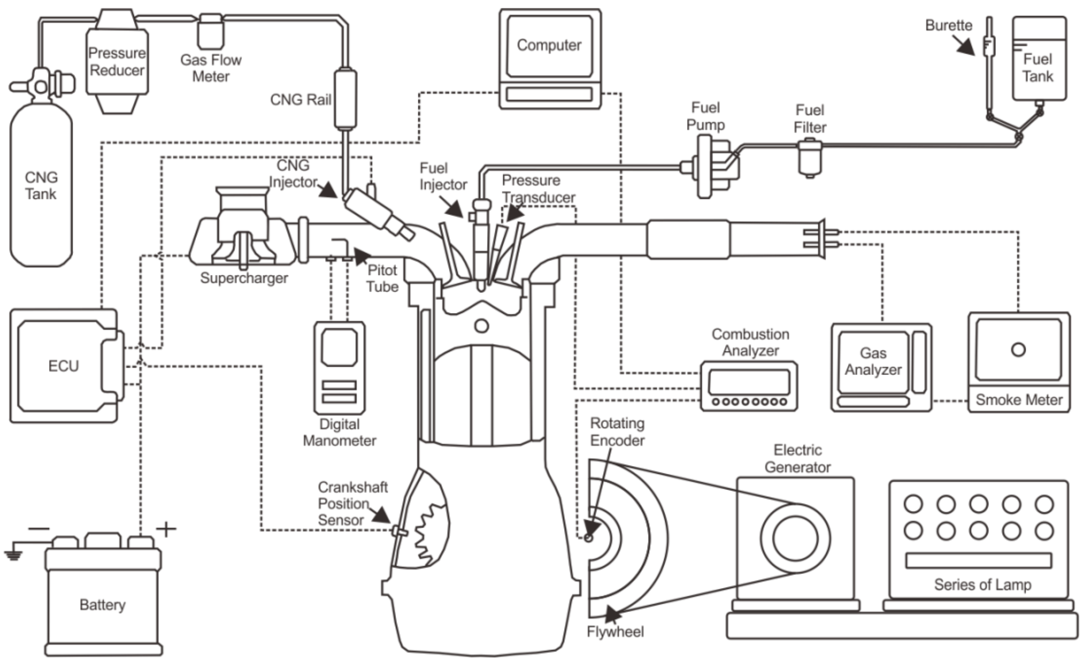

Figure 1. The Schematic Diagram of Experimental Setup and Instrumentation

2.1 Test Engine and Instrument System

The test engine used a single-cylinder, four-stroke, water-cooled diesel engine, with a fuel direct injection system. the detailed specification of the test engine are shown in Table 1. The original engine was modified to suit dual-fuel combustion CNG–palm oil diesel. The original diesel injector mechanically actuated by a Bosch pump remained in use. The supercharger was installed at the end of intake manifold to increase air mass flow rate entering the combustion chamber. Engine was connected to an electric generator with series of lights that used for load variations.

Table 1 - Specification of The Test Engine

Description	Specification	
Type	1 Cylinder, 4 Cycle, Water Cooled Diesel Engine	
Combustion Chamber	Direct Injection	
Bore x Stroke (mm)	82 x 78	
Cylinder Capacity (L)	0.411	
Maximum Output (kW/rpm)	5.97/2400	
Rating Output (kW/rpm)	5.22/2200	
Maximum Torque (kg-m/rpm)	2.6/1900	
Compression Ratio	18:1	
Standard Fuel Injection Timing	13° CA BTDC	
Standard Fuel Injection Pressure	20 MPa	
Valve Timing	Open	Close
Intake	30° CA BTDC	50° CA ABDC
Exhaust	55° CA BBDC	35° CA ATDC

The pressure difference of inlet air mass flow rate was measured with a pitot tube combined with a digital manometer. CNG mass flow rate measurement used gas flow digital meter that continuously record CNG mass flow rate value. To calculate mass flow rate of biodiesel, it could be measured from the consumption time of palm oil biodiesel in the burette. Pressure transducer mounted in the cylinder head was used to measure in-cylinder pressure and heat release rate. Data was measured for 30 consecutive engine cycles with 1 °CA resolution using TMR combustion analysis system. Exhaust emissions were measured by using gas analyzer combined with smoke opacity meter.

2.2 Fuel Characteristics and Fuel Supply System

This study used Biosolar (B30 diesel fuel) which made from 30% palm oil and 70% diesel. Biodiesel (B100) used in this study was produced from 100% palm oil. CNG used in this study was supplied by PGAS Solution Indonesia. The specification of diesel fuel, biodiesel, and CNG are shown in Table 2.

Table 2 – Specification of Fuel

Properties	Diesel Fuel	Palm Oil Biodiesel	CNG
Density @15°C (kg/m3)	815 – 860	875	0.72
Kinematic Viscosity @40°C (mm^2/sec)	2.0 – 4.5	4.5	-
Sulfur content (mg/kg)	3500	2.46	-
Carbon content (%)	86.5	74.3	-
Oxygen content (%)	1.85	12.7	-
Hydrogen content (%)	13.5	13	-
Auto-ignition (ºC)	52	140	700
Cetane number (min)	48	58	-
Octane number (min)	-	-	130
Stoichiometric air-fuel ratio	14.5	13.82	17.24
Lower heating value (MJ/kg)	42.7	37	45.8

In this study, diesel fuel and palm oil biodiesel were used in the single-fuel mode which injected directly into the combustion chamber using a mechanical injection pump with standard injection timing and pressure. CNG was injected into the intake manifold by a gas injector controlled by the ECU. The injector, start of CNG injection, and CNG injection duration were controlled by a driven system and software provided by VemsTune.

The CNG injection parameters are based on previous studies[17], namely for the initial injection timing of 110 °CA ATDC for all load conditions, and for the injection duration of 70 °CA at low load, 90 °CA at medium load, and 110 °CA at high load.

2.3 Experimental Procedure

This experiment was carried out at 20% (1kW), 50% (2.5kW), and 80% (4kW) engine loads. At each engine load, the experiment was kept constant speed of 2000 rpm. The test carried out on the engine divided into two stages. In the first stage, the test was performed with single-fuel mode using Bisolar or palm oil biodiesel at standard injection timing of 13 °CA BTDC. And the second stage, the test was carried out with dual-fuel mode fueled by CNG-palm oil biodiesel.

3. RESULTS AND DISCUSSION

To analyze performance and combustion characteristics of a dual-fuel diesel engine fueled by CNG-palm oil biodiesel, a number of data can be used in the form of in-cylinder pressure, heat release rate, specific fuel consumption, thermal efficiency, air fuel ratio and exhaust emissions.

3.1 In-cylinder Pressure and Heat Release Rate with Variation of Loads

In-cylinder pressure and heat release rate are important parameters used to analyze combustion performance in the internal combustion engine. Fig. 2 shows a graph of in-cylinder pressure and heat release rate in single-fuel and dual-fuel modes at low load with standard pilot injection timing of 13 °CA BTDC. From the figure, it is found that peak of in-cylinder pressure and peak of heat release rate from the single-fuel mode higher than the dual-fuel mode.

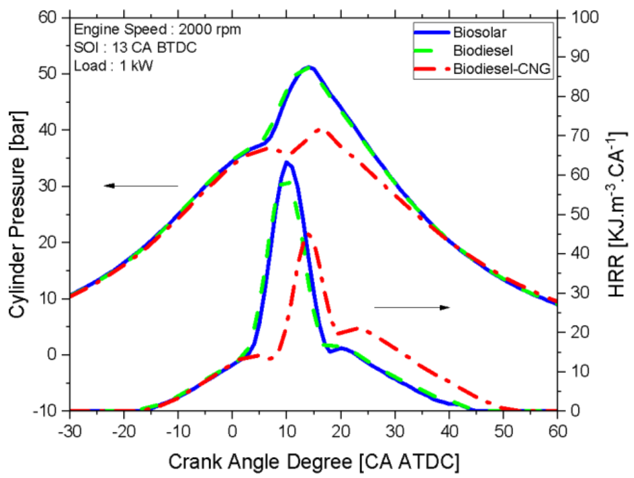

Figure 2. Graph of In-cylinder Pressure and Heat Release Rate for Single and Dual Fuel Modes at Low Load

In addition, the graph shows in-cylinder pressure curve and heat release rate in dual-fuel mode below single-fuel mode curve before piston reaches top dead center. This caused by charge of CNG in the intake stroke resulting in a decrease of temperature and reduced concentration of air mass flow rate in the combustion chamber. So that pilot fuel requires little time to mix with air which in turn slowdown pilot-premixed combustion process. However, after reaching top dead center, in-cylinder pressure and heat release rate in dual-fuel mode tend to be above single-fuel mode. This shows that low temperature of combustion chamber at low load results in a slowdown of diffusion combustion process from dual-fuel mode.

At low load, diesel engine only needs a small amount of fuel to carry out the combustion process. So it can be seen that in dual fuel mode, there is a slight decrease in-cylinder pressure due to ignition delay of CNG. Heat energy generated in the premixed combustion pilot phase is absorbed to trigger the combustion of CNG which has autoignition temperature of 700 °C. At this load condition, the dual-fuel diesel engine only produces peak in-cylinder pressure of 40.13 bar and peak heat release rate of 45.16 $kJ.m^{-3}.CA^{-1}$. For the single-fuel mode, diesel fuel and biodiesel produce peak in-cylinder pressures of 51.25 bar and 51.16 bar respectively, while peak heat release rates are 63.35 kJ. $m^{-3}.CA^{-1}$ and 59.61 kJ. $m^{-3}.CA^{-1}$.

As at low load, Fig. 3 shows graph of in-cylinder pressure in single-fuel and dual-fuel modes with pilot injection timing of 13 °CA BTDC at medium load. From the figure, it can be seen that peak in-cylinder pressure in dual-fuel mode lower than single-fuel mode. However, there is slight increase in pressure peak compared to dual-fuel mode at low load. This is caused amount of fuel that enters the combustion chamber greater, resulting an increase in heat release rate from combustion process.

From Fig. 3, it can be seen that in-cylinder pressure and heat release rate in the single-fuel mode with biodiesel shift to the left approaching top dead center. This caused the oxygen content of biodiesel higher than diesel fuel, thus accelerating the premixed combustion phase. However, peak in-cylinder pressure and heat release rate in single-fuel mode of diesel fuel higher than biodiesel. This influenced by the lower heating value of diesel fuel, resulting in greater heat energy during the combustion process.

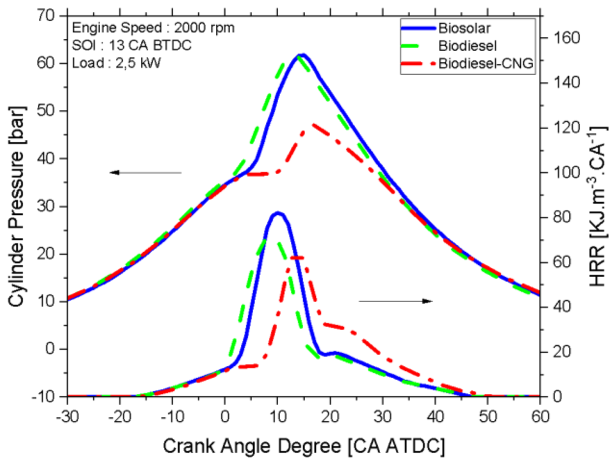

Figure 3. Graph of In-cylinder Pressure and Heat Release Rate for Single and Dual Fuel Modes at Medium Load

Meanwhile, in-cylinder pressure and heat release rate in dual-fuel mode shift to the right and increase rapidly in the premixed combustion pilot phase. But after reaching the peak point, in-cylinder pressure and heat release rate slowly decreases. This caused by decrease in the temperature of combustion chamber and decrease in air mass flow rate due to charge of CNG in the intake stroke resulting delay in the combustion process. At medium load, dual-fuel diesel engine produces peak in-cylinder pressure of 47.03 bar and peak heat release rate of 65.18 $kJ.m^{-3}.CA^{-1}$. For the single-fuel mode, diesel and biodiesel fuels produce peak in-cylinder pressures of 61.73 bar and 61.63 bar respectively, while peak heat release rates are 82.26 $kJ.m^{-3}.CA^{-1}$ and 72.02 $kJ.m^{-3}. CA^{-1}$.

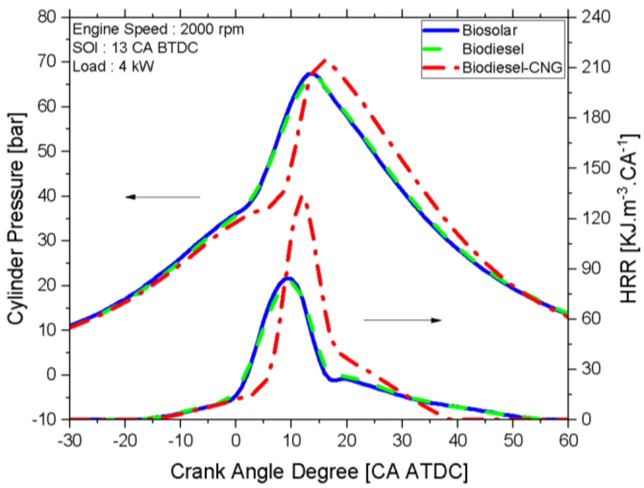

Figure 4. Graph of In-cylinder Pressure and Heat Release Rate for Single and Dual Fuel Modes at High Load

However, peak in-cylinder pressure and heat release rate of the dual-fuel mode is higher than single-fuel mode at high load as shown in Fig. 4. This caused the temperature of combustion chamber has increased at high load, thereby accelerating the burning process of CNG. Lower heating value of CNG greater than diesel fuel or biodiesel results an increase in heat release rate during the combustion process. In single-fuel mode with diesel fuel or biodiesel, heat release rate increases rapidly during the premixed combustion phase to peak of 9 and 10 °CA ATDC, then decreases slowly in the diffusion combustion phase and ends at 55 °CA ATDC.

Whereas in dual-fuel mode, the peak point of heat release rate occurs at 12 °CA ATDC and the diffusion combustion phase ends at 38 °CA ATDC. These conditions indicate that the combustion process in dual-fuel mode ends faster by around 17 °CA at high load. This influenced by high temperature of combustion chamber which approaches autoignition temperature of CNG, thus accelerating process of CNG burning. At high load, dual-fuel diesel engine produces peak in-cylinder pressure of 70.51 bar and peak heat release rate of 133.90 $kJ.m^{-3}.CA^{-1}$. For the single-fuel mode, diesel fuel and biodiesel produce peak in-cylinder pressures of 67.40 bar and 66.72 bar respectively, while peak heat release rates are 84.49 $kJ.m^{-3}.CA^{-1}$ and 82.01 $kJ.m^{-3}.CA^{-1}$.

Overall, ignition delay in dual-fuel mode with standard pilot injection timing is 1-2 °CA longer than single-fuel mode. But as load increases, ignition delay and combustion duration tend to be shorter. This is caused delay from CNG due to the high autoignition temperature resulting in decrease of combustion chamber temperature. Basically, ignition delay and combustion duration in dual-fuel diesel engines must be adjusted to the peak in-cylinder pressure, so that it remains in the range of 10 – 15 °CA ATDC. An ignition delay that is long will have negative impact on the engine, such as appearance of knocking effect, so it is necessary to optimize the ideal pilot injection timing to get maximum performance but still pays attention to the effects caused by the duration of ignition delay.

3.2 Specific Fuel Consumption

Fig. 5 shows the specific fuel consumption graph based on the increase in engine load for single and dual-fuel modes. From the Fig. 5, it can be seen that as the load increases, the value of specific fuel consumption tends to decrease. The lowest specific fuel consumption at high load is produced by single-fuel mode with diesel fuel, which is 229.98 gr/kWh, while the single-fuel mode with biodiesel produces specific fuel consumption which is 15.1% greater than single-fuel mode with biodiesel. This influenced by the lower heating value of diesel fuel which is higher than biodiesel. The dual-fuel mode with CNG-palm oil biodiesel fuel at high load produces specific fuel consumption value that is 4.3% higher than the single-fuel mode with biodiesel. This is caused the charge of CNG in the intake process can reduce air mass flow rate entering the combustion chamber, so that the combustion process occurs in conditions of fuel-rich mixture.

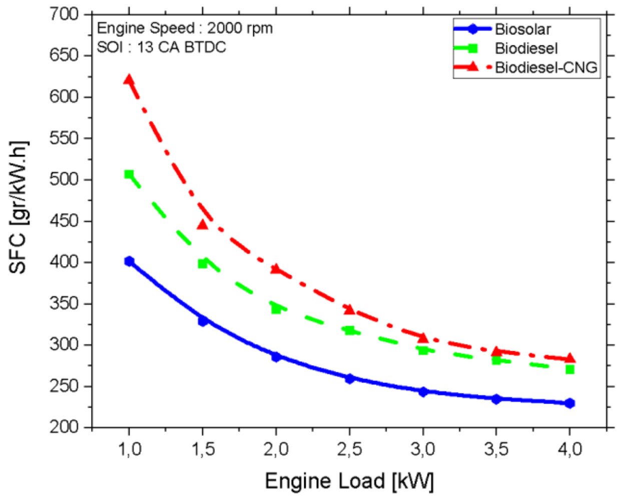

Figure 5. Graph of Specific Fuel Consumption Mode Single and Dual Fuel

From Fig. 5 it can be seen that the value of specific fuel consumption for all tests decreased with increasing engine load. Based on specific fuel consumption graph above, it can be shown that at all loads, the specific fuel consumption value of dual-fuel mode greater than single-fuel mode. However, in dual fuel-mode, CNG mass flow rate is adjusted at several loads, so that it can affect the value of specific fuel consumption. So that there is an increase of the pilot fuel consumption time in the same volume.

3.3 Thermal Efficiency

The following is thermal efficiency graph for single-fuel and dual-fuel modes. In Fig. 6, it can be seen that the thermal efficiency of the single-fuel mode fueled by diesel fuel higher than the single-fuel mode using palm oil biodiesel in all operating conditions. This caused by palm oil biodiesel has higher cetane number than diesel fuel, so the ignition delay in palm oil biodiesel is shorter and results higher specific fuel consumption value. Thermal efficiency of the single-fuel mode with diesel fuel at high loads is 36.66%, while the thermal efficiency in the single-fuel mode with palm oil biodiesel and the dual-fuel mode with CNG-palm oil biodiesel fuel is lower namely 35.92% and 29.04% respectively. Low thermal efficiency in the dual-fuel mode is caused by charge of gas fuel into combustion chamber, thereby reducing the volume of air during the intake process.

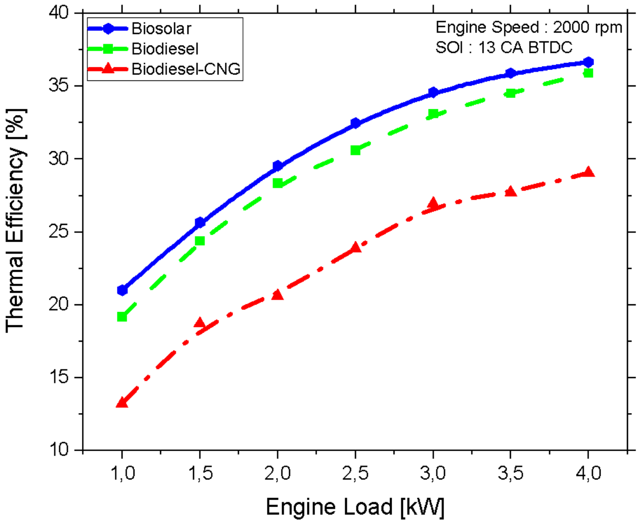

Figure 6. Graph of Thermal Efficiency Mode Single and Dual Fuel

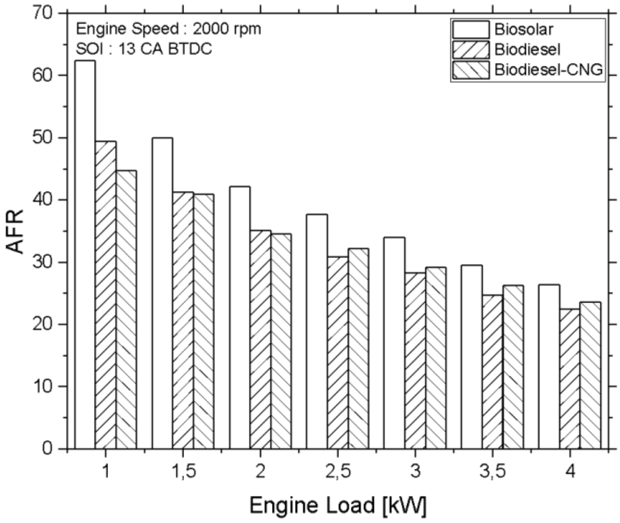

Figure 7. Graph of Air Fuel Ratio Mode Single and Dual Fuel

3.4 Air Fuel Ratio (AFR)

The ratio between air and fuel or commonly referred to as AFR can be used as reference for analyzing combustion performance of internal combustion engines. AFR data can indicate combustion occurs with enough fuel and vice versa. For single-fuel diesel engines with diesel fuel, AFR values range from 18 to 70 [18]. In this study, dual-fuel diesel engines operate with AFR value of around 23 to 45.

In Fig. 7, it can be seen that AFR value in single-fuel mode with diesel fuel at low load is 62.36 where this value indicates that single-fuel mode operates with little diesel fuel. However, it is different from the single-fuel mode with biodiesel and dual-fuel mode with biodiesel-CNG which has lower AFR value of 49.40, and dual-fuel mode around 43 to 45. With increasing of load, AFR value has decreased significantly. This is due to increased mass flow rate of fuel entering the combustion chamber. At medium to high loads with standard pilot injection timing, the dual-fuel mode produces higher AFR value than the single-fuel mode with biodiesel. This influenced by the use of a supercharger in dual-fuel mode so that air mass flow rate entering the combustion chamber in dual-fuel mode is 9.47% higher than single-fuel mode.

3.5 Carbon Monoxide (CO)

In general, carbon monoxide (CO) emissions is result of incomplete combustion process. Fig. 8 shows a graph of CO emissions from single and dual-fuel modes in all engine operating conditions. From the graph, it can be seen that the CO emission of dual-fuel mode for low and medium loads is higher than single-fuel mode. This generated by charge of CNG in the intake process causes lower temperature of combustion chamber, thereby inhibiting pilot fuel from reaching autoignition temperature in premixed combustion pilot phase. However, CO emissions decrease as load on the engine increases. This is due to increase in heat release rate at high load so that the temperature of the combustion chamber rises.

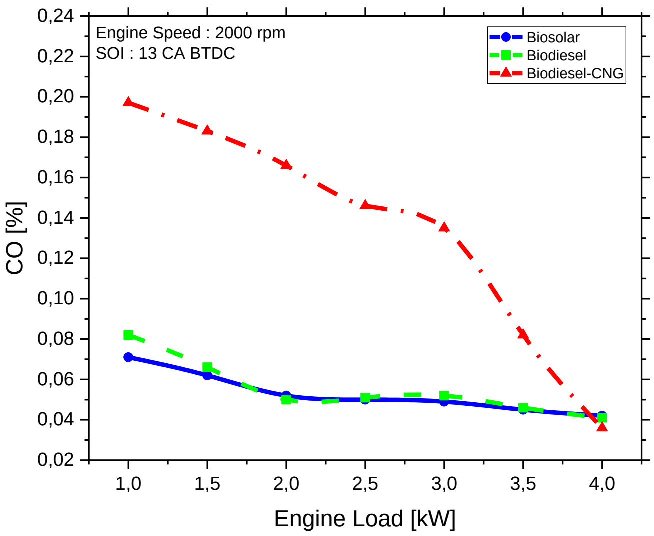

Figure 8. CO Emissions in Single and Dual Fuel Modes

3.6 Hydrocarbon (HC)

In Fig. 9 it can be seen that dual-fuel mode for all engine operating conditions produces HC emissions higher than single-fuel mode. The process of forming hydrocarbon (HC) emissions in dual-fuel diesel engine is influenced by rich fuel mixture. This caused by the charge of CNG in the intake manifold which reduce air volume so that combustion process occurs with less air.

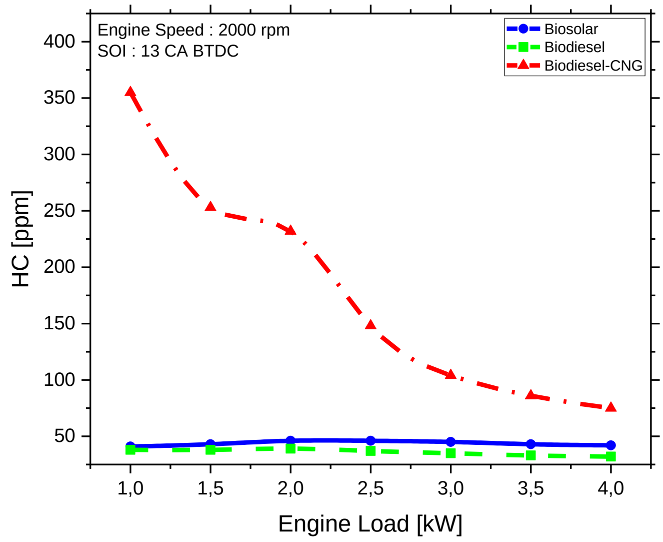

Figure 9. HC Emissions in Single and Dual Fuel Modes

In addition, at low loads, the rate of combustion of CNG is slower. Some of the gas and air mixtures will be wasted due to low oxygen concentration, valve overlap, and cooling on the combustion chamber walls [19][20].

3.7 Smoke Emission

In diesel engines, smoke emissions form in the unburned fuel in the rich zone, where fuel vapors mix with the hot combustion gases. Furthermore, the smoke emission will be oxidized in the flame region when mixed with unburned air. Combustion in dual-fuel mode has significant effect on reducing smoke emissions. Fig. 10 shows smoke emissions from single and dual-fuel modes with varying loads. In the figure, it can be seen that smoke emissions rise with increasing engine load. However, the dual-fuel mode produces lower smoke emissions than single-fuel mode. This caused by CNG combustion process occurs very quickly after premixed combustion phase and the methane content in CNG does not produce particulates in combustion process.

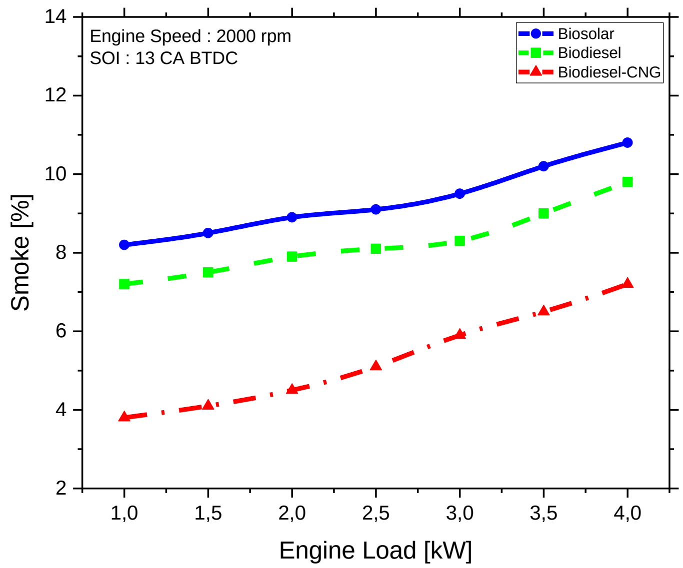

Figure 10. Smoke Emissions in Single and Dual Fuel Modes

4. CONCLUSION

The results of the analysis carried out in this study indicate that the use of CNG-palm oil biodiesel has significant effect on the combustion process of dual-fuel diesel engines in all engine operating conditions. Overall, the dual-fuel mode at low and medium loads results in lower in-cylinder pressure and heat release rates compared to dual-fuel mode at high loads. Ignition delay in dual-fuel mode is 1-2 °CA longer than in single-fuel mode. At high load, dual-fuel mode produces higher in-cylinder pressure and heat release rate compared to single-fuel mode. High specific fuel consumption and low thermal efficiency in dual-fuel mode are caused by the charge of CNG fuel during the intake process. CNG combustion process occurs in dual-fuel mode very quickly after the premixed combustion phase, so it can reduce smoke emissions which are usually produced by conventional diesel engines.

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