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Original Research Article

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IMPROVING PRODUCTIVITY AND REDUCING EMISSIONS OF SOLAR-BIOGAS DUAL-FUEL DIESEL ENGINES

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Abstract. *Global energy needs continue to increase, which have been met by fossil fuels, resulting in significant environmental damage. Alternative energy such as biogas is an effective solution to reduce the use of fossil fuels because it has a high auto-ignition temperature (±650°C), making it suitable for use in engines with high compression ratios. This research aims to evaluate the effect of using biogas in dual-fuel diesel engines on performance and exhaust emissions. Experiments were carried out on diesel engines with single and dual-fuel, using variations in biogas flow rates of 3, 4, and 5 l/minute. The research results show that the use of biogas in dual-fuel engines produces higher torque and brake power values compared to single fuel at flow rates of 3 and 4 l/min. In addition, single-fuel diesel engine exhaust emissions show the highest values for CO (0.29%) and CO_2 (5.67%), while dual-fuel engines produce CO (0.27%) and CO_2 (5.51%). These findings show that biogas as a dual-fuel can improve engine performance while reducing harmful emissions, making it a sustainable energy alternative.*

Keywords: Biogas, dual-fuel, diesel, performance, exhaust emissions.

1. Introduction

The world's energy needs continue to increase along with human population growth and sustainable industrial needs. It is estimated that energy demand will increase by 30% until 2040, with most of this need still being met by fossil fuels [1] . Using of fossil fuels as the main energy source has caused significant environmental damage, including air pollution and climate change [2], [3]. Exhaust gas emissions from burning fossil fuels, such as gasoline, diesel, and LPG in internal combustion engines (ICE), contribute greatly to acid rain, global warming, and increased greenhouse gas concentrations [4], [5]. Diesel engines produce large amounts of particulate matter (PM) and nitrogen oxides (NOx) emissions [6]. The most widely used energy source in the machinery and transportation industry is the use of diesel fuel for diesel engines [7], [8].

To reduce environmental impacts, many countries have adopted policies and regulations that encourage using renewable energy [9]. In Indonesia, for example, the government has developed various initiatives to increase the use of renewable energy as part of its commitment to global climate agreements. One promising alternative energy source is biogas [10]. Biogas is produced from agricultural waste, industrial waste, livestock waste, and household waste through anaerobic fermentation which produces methane gas (CH_4) 50-70%, Carbon Dioxide (CO_2) 25-50%, Hydrogen (H_2) 1-5%, and Nitrogen (N_2) 0.3-3% [11]. The potential for biogas as a renewable fuel is very large, because it can reduce dependence on fossil fuels and greenhouse gas emissions.

The use of biogas in diesel engines as a dual-fuel has shown significant potential. Previous research shows that biogas-diesel mixtures can reduce diesel use by up to 63% and even replace up to 90% of diesel consumption [12]. Biogas, with its high auto-ignition temperature (±650°C), is suitable for use in engines with high compression ratios [13]. However, the use of biogas in diesel engines still faces several obstacles, such as decreased thermal efficiency and increased exhaust emissions of carbon monoxide (CO) and hydrocarbons (HC) [14]. On the other hand, the use of biogas can provide economic benefits, including reduced operational costs and increased energy sustainability. Biogas can be mixed homogeneously with air, allowing better ignition thanks to its wide flame range [15]. The biogas used should contain more than 50% CH_4 and be free from hydrogen sulfide, water and siloxane to ensure quality and efficiency [16]. The latest innovations in biogas processing technology and the development of dual-fuel engines continue to be developed to overcome these obstacles [17].

Various researchers have studied dual-fuel diesel engines by examining parameters such as timing variation [18], [19], optimization of pilot injection timing [20], and variation of air flow rate into the combustion chamber. The timing and duration of biogas injection fundamentally affect the combustion process, as it is related to the volume of biogas fuel entering the combustion chamber during the intake stroke. In dual-fuel diesel engines, a variable fuel supply is required according to changes in engine load, so a constant biogas supply can reduce the percentage of biogas substitution as the load increases [21].

Research by Liu et al. (2020) [22] on a dual-fuel diesel engine fuelled by diesel-CNG found that the mass flow rate of CNG affects the combustion process and emissions produced. In the context of a dual-fuel diesel engine, the fuel supply parameter is very important for the combustion process, which makes the combustion more spread and closer to the cylinder wall. This study aims to evaluate the combustion reaction, engine performance, fuel consumption, and exhaust emission characteristics of a dual-fuel diesel engine fuelled by diesel-biogas. The results of this study are expected to provide information related to the use of biogas as an alternative fuel for diesel engines and efforts to reduce environmental damage.

2. Materials and research method

To study the performance and combustion process of a dual-fuel diesel engine, modifications were made to a single-cylinder diesel engine by adjusting the fuel input to regulate the flow of biogas fuel into the combustion chamber. The test scheme of a dual-fuel system diesel engine is shown in Figure 1.

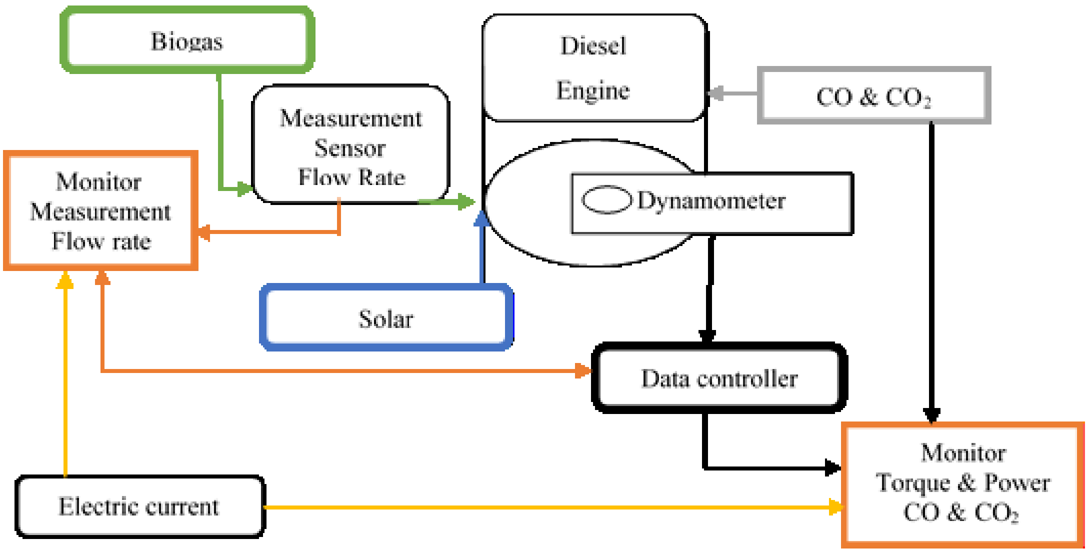

Fig.1. Test Scheme.

2.1. Fuel Characteristics and Fuel Supply Systems

This research uses diesel fuel supplied from PT Pertamina Indonesia. Biogas is produced anaerobically by using cow dung as raw material in a fixed dome type biogas digester with a capacity of 2 m³ which is accommodated in a biogas storage balloon. Diesel and biogas fuel specifications are shown in Table 1.

Table 1. Fuel properties [23]

Properties	**Diesel**	**Biogas**
Lower heating value (MJ/kg)	42	20.958*
Density (kg/m^3)	840	1.12*
Auto ignition temperature (°C)	280	650
Stoichiometric air-fuel ratio	14.60	17
Cetane number	49	-
Octane number	-	130
Laminar burning velocity (m/s)	0.5	0.2

The study used diesel and biogas fuels, diesel fuel was injected directly into the combustion chamber using a mechanical injection pump, and biogas fuel was injected into the intake manifold using a gas injector whose gas volume was controlled by a flow meter with variations of 3 lpm (B3), 4 lpm (B4), and 5 lpm (B5). The biogas flow rate was kept constant at each variation of flow rate and combustion load at each engine speed.

2.2. Test Machines and Test Procedures

The test used a diesel engine with a single cylinder capacity, four strokes, and direct injection fuel system. Detailed specifications of the test engine are shown in Table 2. The test engine was modified to accommodate a dual-fuel system of diesel solar - biogas. Diesel fuel is injected mechanically and biogas is injected using a pump into the intake manifold to the combustion chamber.

Table 2. Diesel engine specifications

Parameter	**Mark**
Machine capacity	0.296 L
Number of cylinders step	Single cylinder four steps
Liner diameter	78mm
Stride length	62mm
Combustion system	direct injection
Power factor	1.0
Count output	5.5 kW

The diesel engine is connected to a dynamometer to measure torque and brake power. The CO_2 and CO sensors are connected to the data controller and the results are displayed on the monitor screen. Diesel fuel is prepared in a measuring cup to measure fuel consumption. Biogas is prepared in a biogas storage balloon with the addition of a flow meter to measure the flow rate injected into the intake manifold towards the combustion chamber. Before evaluating engine performance and emission results, the engine is turned on until it reaches the highest working temperature and engine speed, experiments are carried out at the maximum throttle position with additional braking load until the specified engine speed is reached (2700, 2600, 2500, 2400, 2300, 2200, 2100, and 2000 rpm). All test equipment is set up and recalibrated to ensure the data obtained is valid and accountable. Instrument calibration refers to adjusting an instrument to ensure that the measurement results are in accordance with established standards. This process improves data accuracy and minimizes measurement errors that may occur due to drift or environmental changes since the last calibration was performed [24].

3. Results and Discussion

This section discusses the performance of diesel engines, namely fuel combustion reactions, engine torque, engine power, and specific fuel consumption, as well as exhaust emissions with single fuel and dual-fuel. The exhaust gas emissions analyzed are CO and CO_2 emissions.

3.1 Combustion Reaction

Burning fuel in a diesel engine in this study involves a reaction between hydrocarbons (in diesel and biogas) with oxygen from the air, producing the main products in the form of carbon dioxide (CO_2) and water (H_2O), as well as by-products such as carbon monoxide (CO), nitrogen oxides (NOx), and unburned hydrocarbons (HC). Biogas, with its main content being methane (Ch_4), mixes easily with air, producing a more homogeneous fuel-air mixture than diesel. This can increase fuel combustion efficiency, the methane in biogas helps create a fast initial combustion, thereby increasing the combustion chamber temperature.

Initial reaction of methane combustion:

$$CH_4+2O_2 \rightarrow CO_2+2H_2O \quad (1)$$

The combustion reaction increases the temperature to help evaporation so that the octadecane in diesel burns more quickly. Combustion reaction of octadecane in diesel:

$$2C_{16}H_{34}+49O_2 \rightarrow 32CO_2+34H_2O \quad (2)$$

This more efficient combustion increases pressure in the cylinder, which translates into higher torque. The biogas-diesel mixture produces more uniform and intense combustion, increasing the mechanical energy produced per engine cycle [18]. Thus, increasing the flow of biogas in the fuel mixture directly contributes to increasing engine torque and power, resulting in more optimal engine performance.

3.2 Brake Torque

Engine performance in brake torque shows an increase in brake torque on diesel-biogas fuel compared to single diesel fuel. Increasing the biogas flow rate contributed to an increase in brake torque, with a flow rate of 5 lpm (B5) showing the most significant increase. The test results are presented in Figure 2. On single diesel fuel, brake torque increases with increasing load and decreasing engine speed. At an engine speed of 2700 rpm, the brake torque is initially around 4 Nm, and increases to around 18 Nm at an engine speed of 2000 rpm. At the B3 biogas flow rate, the brake torque produced is higher than single fuel at engine speeds above 2500 rpm, but slightly lower at engine speeds below 2400 rpm.

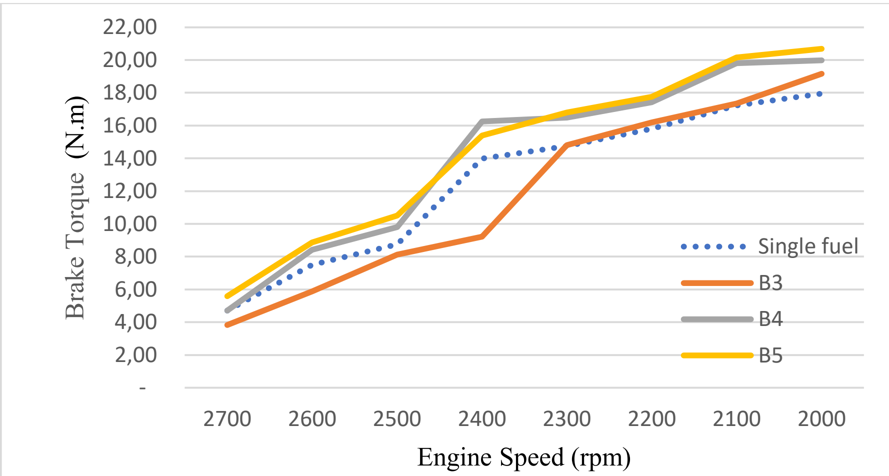

Fig. 2. Brake torque graph at each engine speed.

This indicates that at lower biogas flow rates, combustion may not be optimal at high loads. At the B4 biogas flow rate, the resulting brake torque is consistently higher than single fuel throughout the engine speed range. Brake torque increases from around 8 Nm at 2700 rpm to around 19 Nm at 2000 rpm. At biogas flow rate B5, the brake torque produced is the highest compared to all other variations. Brake torque increases from around 10 Nm at 2700 rpm to around 22 Nm at 2000 rpm. This shows that higher biogas flow rates significantly improve combustion efficiency and engine performance [14]. This phenomenon can be explained by the fact that biogas, which has a high methane component, allows more efficient combustion and increased energy output. However, it is important to note that the optimal biogas flow rate must be adapted to the machine characteristics and operating conditions to achieve the best performance. The use of dual-fuels not only increases brake torque but also shows potential to increase engine thermal efficiency, which could contribute to reduced fossil fuel consumption and greenhouse gas emissions [25].

3.3 Brake Power

The brake power test results show that the use of biogas can increase brake power compared to diesel fuel, which is presented in Figure 3. Brake power increases with increasing braking load and decreasing engine speed. The best biogas flow rate is B5 biogas flow rate, with the highest brake power produced compared to all other variations.

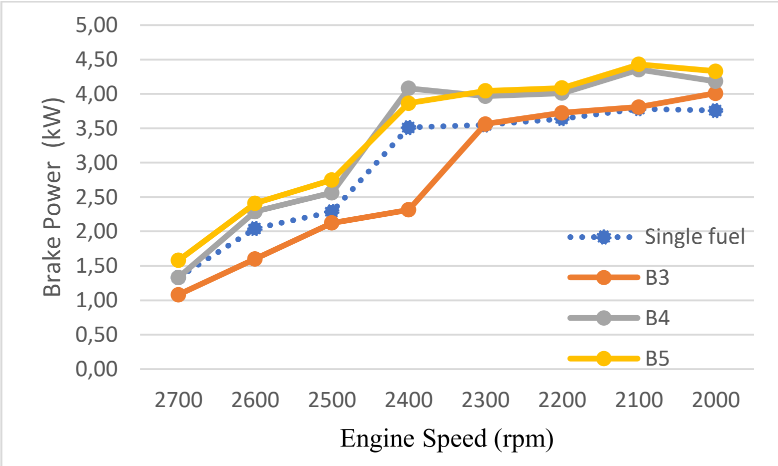

Fig. 3. Graph of brake power at each engine speed

Braking power increases from around 2.2 kW at 2700 rpm to around 4.4 kW at 2000 rpm. The addition of biogas to the combustion chamber produces a more homogeneous biogas-air mixture, increases the formation of ignition kernels, and improves the combustion of the diesel fuel premix [1]. This can improve the thermal efficiency and power output of the diesel engine.3.4 Brake Specific Fuel Consumption (BSFC).

The BSFC test results show that the dual-fuel system can reduce BSFC compared to single diesel fuel. A decrease in BSFC indicates an increase in combustion efficiency, as less fuel is used to produce the same power. The BSFC test results are presented in Figure 4. BSFC tends to be higher at higher engine speeds and decreases as the engine speed decreases on single fuel.

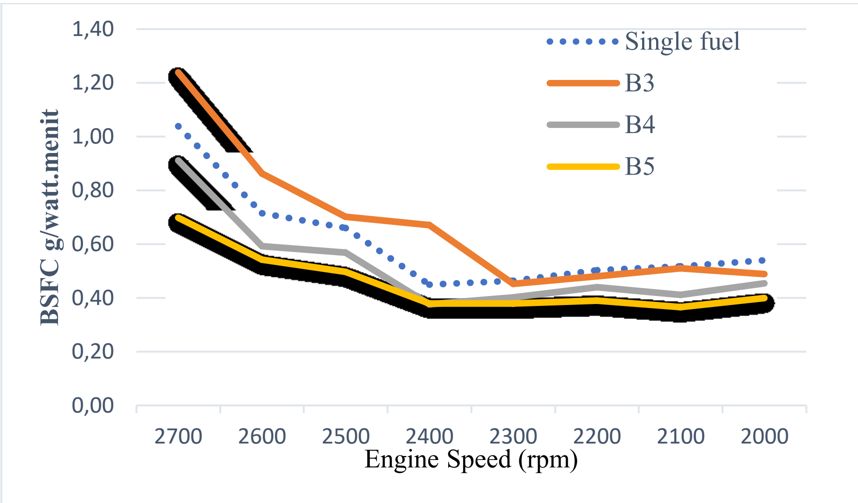

Fig. 4. BSFC graph at each engine revolution.

On dual-fuel, BSFC results at high engine speed (2700-2600 rpm) are higher than with single fuel, but decrease more significantly at lower engine speed. Higher biogas flow rates (B4 and B5) resulted in lower BSFC compared to lower flow rates (B3). This shows that at higher biogas flow rates, combustion is more effective and fuel efficiency increases [23], [26].

3.5 Exhaust gas emissions

The test results show that the concentration of carbon monoxide (CO) is higher in the combustion reaction, this can result in a low combustion temperature resulting in incomplete combustion. With the addition of biogas, the combustion temperature increases because methane can help the combustion reaction run faster [27]. The CO concentration produced in this study is presented in Figure 5. The use of a diesel-biogas mixture in a diesel engine has been proven to reduce carbon monoxide (CO) emissions compared to the use of single diesel. Biogas, especially methane (CH_4), mixes more easily with air, producing a more homogeneous mixture and increasing combustion efficiency. Methane burns faster, increasing the temperature of the combustion chamber, which facilitates more complete combustion of diesel fuel and reduces CO formation [28]. Test results show that biogas flow rates of 4 Lpm and 5 Lpm significantly reduce CO emissions. This research is in line with previous studies, such as Mohsin et al. 2014 [29] and Yoon and lee. 2011 [23], who also found that blending biogas in diesel engines increased combustion efficiency and reduced CO emissions.

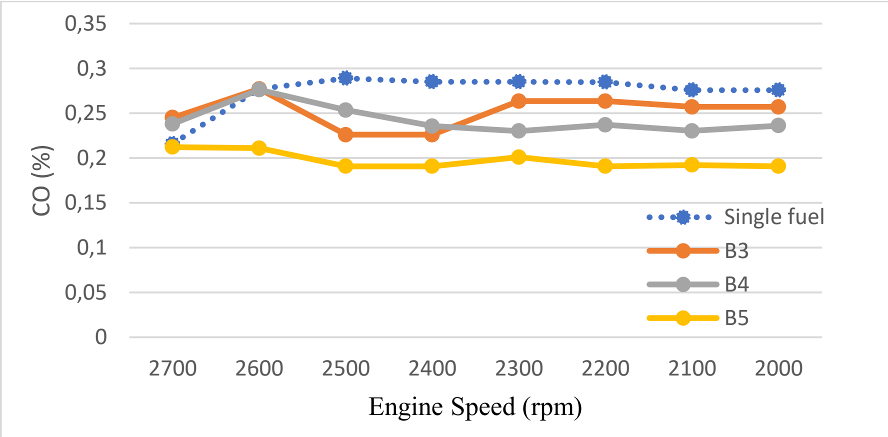

Fig. 5. Graph of CO concentration at each engine speed

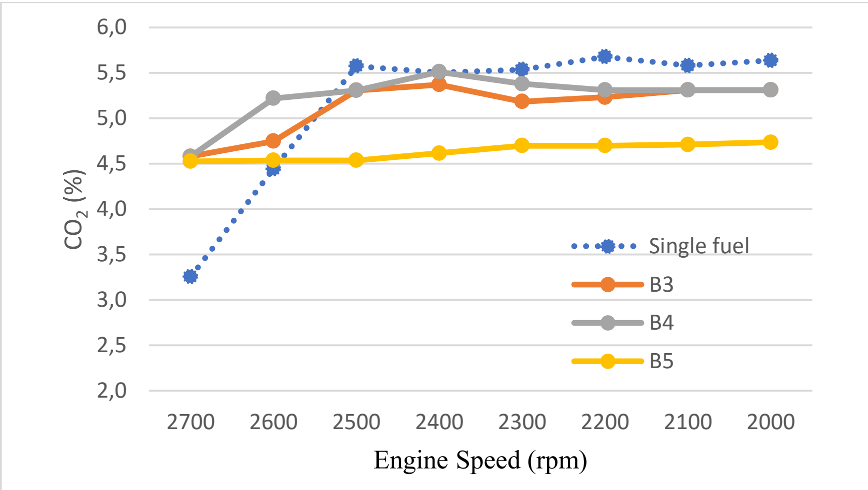

Fig. 6. Graph of CO_2 concentration at each engine speed

CO_2 is the most important gas that causes the greenhouse effect, which is generally produced from burning fossil fuels for transportation [30]. The results of CO_2 emissions can be seen in Figure 6, CO_2 emissions increase as the load increases, the temperature inside the cylinder increases. CO_2 increases when using a single fuel engine as the engine load increases [28]. The difference in CO_2 content when using single fuel and dual-fuel diesel-biogas. In the picture, it can be seen that CO_2 for single fuel reaches 5.67%, while for dual-fuel it is around 5.51%. The results are due to more complete combustion and reduced fuel consumption.

This study offers a novelty compared to previous studies examining biogas use in a dual-fuel diesel system. Several previous studies, such as those conducted by Ambarita (2017) [8] and Barik & Murugan (2014) [6], showed that biogas can reduce CO emissions and improve engine efficiency. However, this study tested variations in biogas flow at three levels (3, 4, and 5 lpm), which has not been widely done before, providing new insights into the effect of biogas flow on engine performance and exhaust emissions. In addition, this study measured the reduction in CO_2 emissions in more detail, with results showing a decrease in CO_2 from 5.67% in single diesel to 5.51% in dual-fuel. These findings indicate that biogas reduces CO emissions and CO2 and improves engine performance, especially at higher biogas flows, which has not been widely discussed in previous literature.

Based on the research results, the best proportion for biogas mixture in a dual-fuel diesel system is at a biogas flow of 5 pm. This flow significantly improves engine torque and braking power compared to 3 and 4 lpm flows. In addition, using biogas with a flow of 5 lpm results in better CO and CO_2 emissions reduction. Although higher biogas flow improves performance and emission reduction, it is essential to consider operational cost and efficiency. Therefore, a biogas flow of 5 lpm is the optimal proportion to balance engine performance and emissions.

4. Conclusion

The use of biogas as an additional fuel increases the homogeneity of the fuel-air mixture, resulting in more efficient and complete combustion. The results show an increase in engine torque and power, as well as a decrease in specific fuel consumption (BSFC). Carbon monoxide (CO) and carbon dioxide (CO_2) emissions are significantly reduced with the use of biogas mixtures. This research shows that biogas-biodiesel blends in diesel engines reduce emissions due to higher combustion efficiency. Overall, diesel-biogas blends offer an environmentally friendly and efficient solution for diesel engines.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRediT author statement

Ridhuan, K.: Conceptualization, Writing - Original Draft; **Mafruddin**: Data Curation, **Irawan, D**.: Conceptualization Writing - Original Draft, Methodology; **Handono, S.D.:** Writing - Review & Editing.
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