

Comparative Analysis of the Effect Dual Spark Ignition and Single Spark Ignition on Performance and Exhaust Emissions in Bioethanol-Fueled Engines

Avita Ayu Permanasari^{1,2*}, Ahmad Faizal Wahidin¹, Hasan Ismail¹, Erwin Komara¹,
Poppy Puspitasari^{1,2}, Gina A. Lorenzo³

¹Department of Mechanical and Industrial Engineering, State University of Malang, Jl. Semarang No. 5,
Malang, 65145, Indonesia

²Centre of Advanced Materials for Renewable Energy (CAMRY), State University of Malang, Jl. Semarang
No 5, Malang 65145, Indonesia.

³College of Engineering, Nueva Ecija University of Science and Technology, Cabanatuan, Philippines
*Corresponding author: avita.ayu.ft@um.ac.id

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ABSTRACT

Bioethanol is an alternative fuel that has a high octane value of around 100 to 110, making it difficult to be applied to spark ignition engines directly. So, it is necessary to make adjustments, including increasing combustion efficiency and thermal efficiency of the combustion chamber by increasing the compression ratio and adjusting the ignition system, both in single spark ignition (SSI) and dual spark ignition (DSI) types. The study aims to determine the effect of SSI and DSI applications on engine performance, specific fuel consumption (SFC), and exhaust emissions using 96% and 99% levels of bioethanol fuel. The results showed that, in general, there was an increase in power, torque, and thermal efficiency as well as a decrease in emissions and better SFC in the DSI engine compared to the SSI engine with 99% bioethanol fuel. The highest power was obtained at 6.89 HP or 5.6% higher than the SSI engine, and peak torque was obtained by 14.95 N.m at 6500 rpm on the DSI engine using 99% bioethanol. Meanwhile, the minimum SFC reduction was obtained at 13.87% lower than that of DSI. The highest thermal efficiency of the DSI engine occurs at 7000 rpm, which is 38.19% when using 96% bioethanol. NOx emission increased when using 99% bioethanol on the DSI engine by 15.58% compared to the SSI engine. CO emissions decreased by 72.51% in the DSI engine with 96% bioethanol fuel. At the same time, CO₂ experienced the highest decrease of 76.92% at 5500 rpm on 99% bioethanol DSI engine.

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Keywords: Bioethanol, dual ignition, emissions, performance, spark plug

I. Introduction

Motorised vehicles are a popular means of mass transport in Indonesia. This is indicated by the increasing quantity of vehicles owned by the community. This rapid growth of vehicles has increased the need and consumption of fuel as the main energy source for vehicles. Meanwhile, fossil fuel reserves have decreased to an alarming level, and it is estimated that the demand for oil energy will increase by 2050. This shows an increase in the rate of development that occurs at 4.7% every year [1]. It is, therefore, imperative to find a replacement fuel source to keep up with the growing demand for fuel.

Transportation is also one of the contributors to CO₂ emissions, which is 20% of worldwide emissions [2]. Efforts to reduce the increase in greenhouse effects from fossil fuel vehicle emissions are by using alternative renewable fuels. Alternative fuels that can be



used are using bioethanol fuel as a substitute fuel or a mixture of fossil fuels. Using bioethanol fuel can significantly reduce the greenhouse gas effect to reduce global warming and climate change [3].

Bioethanol is one of the renewable fuels that continues to be improved in the production process because it is considered an ideal fuel for spark ignition (SI) engines. This fuel is made from plants through a fermentation process using microorganisms. Bioethanol-producing raw materials are divided into 3 groups: starch, sugary juice, lignocellulose, or fiber material. In Indonesia, raw materials for making bioethanol are very easy to find, so it is possible that bioethanol will become a renewable fuel that continues to be developed [4].

The oxygen value content of bioethanol is 30%, so it can be categorized as high-octane gasoline [5]. This oxygen content can affect the emissions and combustion efficiency of bioethanol. The volumetric efficiency of the use of bioethanol fuel increased by 15%-25% compared to pure gasoline when tested on bioethanol mixed with pure gasoline fuel [6]. In addition, the viscosity and density of renewable alternative fuels are different from fossil fuels, thus affecting the octane value [7]. The high octane value of bioethanol fuel requires engine adjustment to fuel characteristics to produce a perfect energy conversion process and low exhaust emissions. Adjustments can be made by modifying the compression ratio and increasing combustion efficiency through ignition timing or by increasing the combustion temperature in the combustion chamber. A common modification is to change the compression ratio, but this change needs to pay attention to the construction of the engine used [8]. While the compression ratio used in the test engine is 15:1, this compression ratio is ideal when used in spark ignition engines with high-octane fuel [9]. A higher compression ratio will result in a high pressure of the fuel and air mixture in the combustion chamber so that the combustion process is more perfect. Increased combustion efficiency can be achieved by adjusting the variation of spark duration or expanding the range of sparks in the combustion chamber. The use of dual spark ignition is intended to improve combustion efficiency by utilizing two sparks from spark plugs to produce more even and more perfect combustion due to a shorter combustion duration [10].

The dual spark ignition is a dual ignition system that produces more excellent combustion in the combustion chamber. The dual spark ignition system uses sparks from two spark plugs to produce combustion with a shorter duration. The cumulative heat release of dual spark plug ignition is much higher than that of single spark plug ignition and can effectively shorten the duration of main combustion [11]. This dual ignition system can be applied to an electronic ignition system by adding ignition coils and spark plugs. Dual coil systems have higher energy density and longer discharge duration than single coil ignitions, allowing them to operate with leaner fuel-air mixtures and reduced emissions [12].

The results of research on dual spark ignition systems compared to single spark ignition fossil fuel engines show a lower engine volumetric efficiency value of 1.2% in the use of dual spark ignition [13]. This decrease in volumetric efficiency can be caused by shorter combustion in dual spark ignition. On the other hand, Prashant et al. [14] conducted experimental research on the performance of dual spark ignition engines fueled by ethanol-gasoline blends. The results showed an increase in thermal efficiency and a decrease in exhaust emissions were achieved. This can be influenced by the maximum pressure and temperature in the combustion chamber from using dual spark ignition, which is higher so that the exhaust gas produced is lower than that produced by using single spark ignition. The higher maximum effective pressure in the cylinder chamber and faster combustion resulting from dual spark ignition indicate that this system allows for more efficient combustion [15].

Other studies have also shown that dual spark ignition can reduce hydrocarbon (HC) and carbon monoxide (CO) emissions. Using dual spark ignition and ignition timing variations can reduce CO and HC emissions by 56.62% and 16.20%. This is because using dual spark ignition and ignition timing can increase the optimization of combustion in the combustion chamber [10]. Combustion optimization occurs because sparks are more evenly distributed so that the fuel and air mixture in the combustion chamber burns perfectly so that emission levels are reduced.

The high oxygen content and octane value in bioethanol require adjustments to the engine in its application. The results of the literature study that has been presented show that the use of dual spark ignition is suitable for improving combustion efficiency because the spark generated from both spark plugs can optimize combustion. However, no one has proven the effect of dual spark ignition when using pure bioethanol fuel, which has a high octane value on engine performance and exhaust emissions. Therefore, this study aims to determine the comparison of the use of dual spark ignition (DSI) and single spark ignition (SSI) on engine performance and exhaust emissions in 110 cc spark ignition engines fueled by 96% and 99% bioethanol, with the hope that the addition of dual spark ignition can affect engine performance, specific fuel consumption, and lower exhaust emissions in environmentally friendly fuel engines.

II. Materials and Methods

The testing phase begins with the preparation of the research object. The fuel used as the object of research is 96% bioethanol and 99% bioethanol produced by PT Smart Lab Indonesia. Variations in fuel levels were used because both are bioethanol levels commonly used in Indonesia. Before using the fuel, testing was done to determine the fuel properties when employed in the spark ignition engine's combustion process. Fuel testing was done to obtain the material properties of the fuel. The material properties of bioethanol fuel are described in Table 1.

Table 1. Fuel properties

Specifications	Bioetanol 96%	Bioetanol 99%
Chemical formula	C ₂ H ₅ OH	C ₂ H ₅ OH
Assy (alcoholmeter)	95.1 – 96.9	min 99.7
Density (kg/m ³)	824.423	805.867
Kinematic viscosity (mm ² /s)	1.33	0.95
Lower heating value (MJ/kg)	17.031	27.118
Flash Point (°C)	17	13
Auto-ignition temperature (°C)	363	455
Octane Number	110	110
Vapor pressure (hPa)	59 at 20 °C	57.26 at 19.6 °C
Vapor density	1.6	1.6
Upper explosion limit (V)	27.7 %	2.5 %
Lower explosion limit (V)	3.1 %	13.5 %

Engine performance testing was carried out using a special fuel tank and burette to calculate the rate of fuel consumption and an On-Wheel Dynamometer for MBRTech to determine the power and torque generated by the engine. Meanwhile, exhaust gas emission testing was carried out using an Exhaust Gas Analyzer. The testing flow using the DSI engine

is shown in Figure 1, while Figure 2 is a test on the SSI engine. The engine used in the research was a 110 cc spark ignition engine designed as a research object and adjusted its specifications for bioethanol combustion, as shown in Figure 3. The engine crankshaft output was connected to the wheels using an automatic transmission with a centrifugal clutch and a single ratio chain. The engine speed variation changes from 3500 to 7000 rpm at each test stage. The engine specifications used are shown in Table 2.

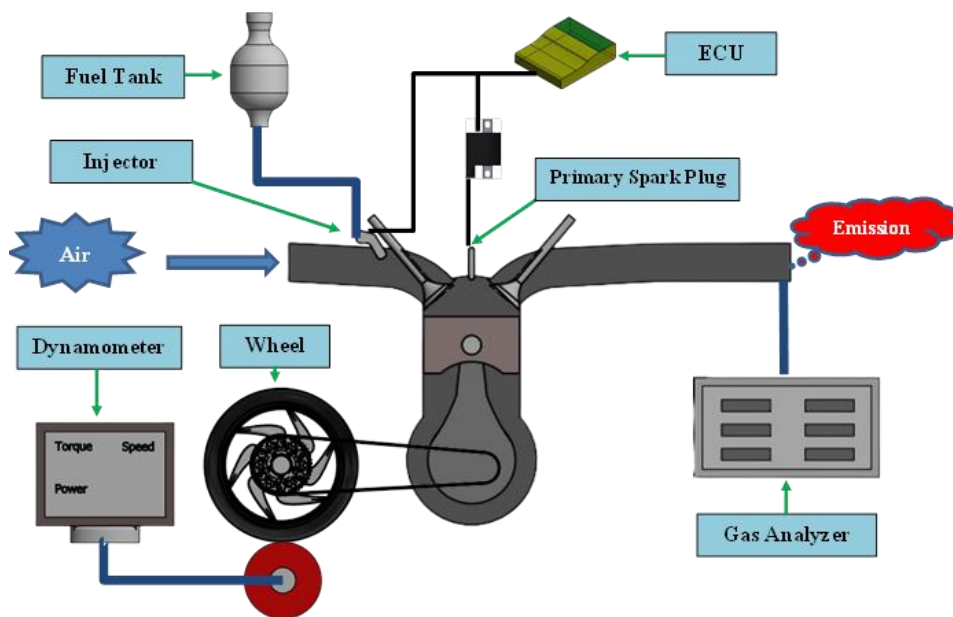


Fig 1. Schematic diagram of SSI engine experimental setup

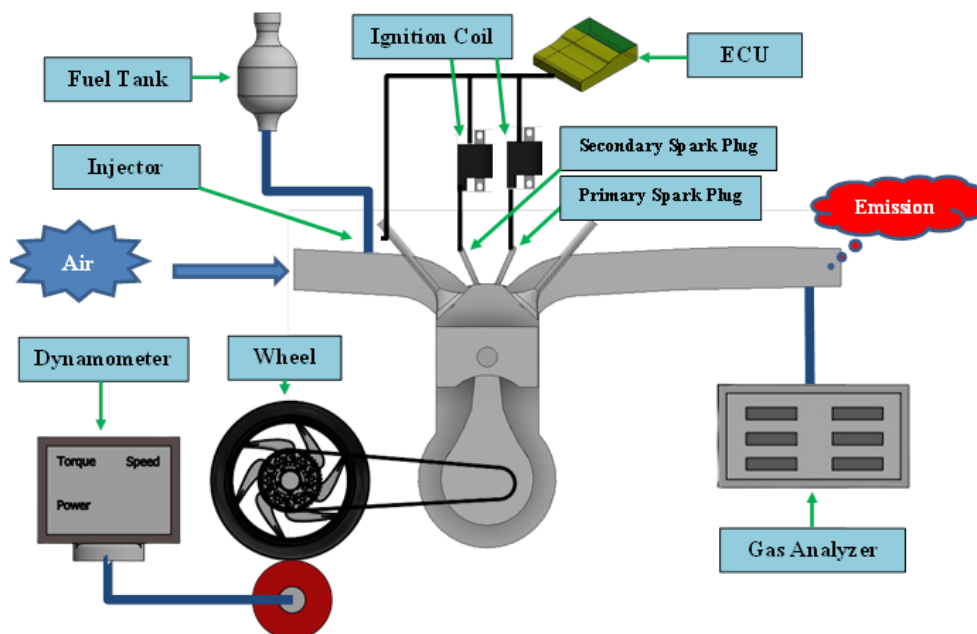


Fig 2. Schematic diagram of DSI engine experimental setup

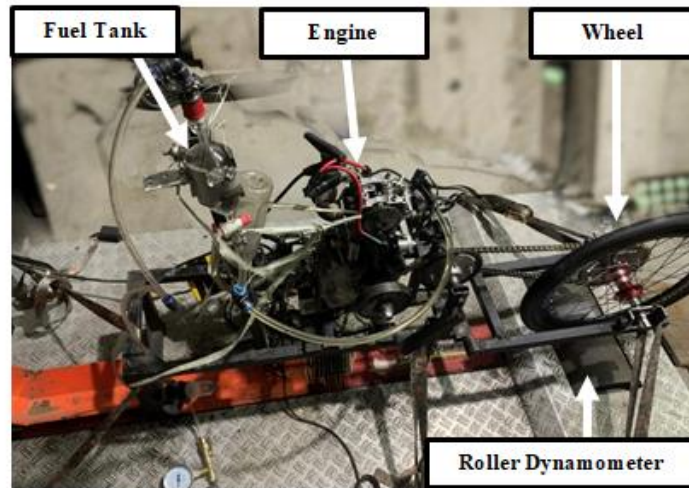


Fig 3. Testing process on experimental machine

Table 2. Engine test specifications

Specifications	
Engine type	4 Stroke
Valve type	SOHC
Engine capacity	108.2 cc
Bore	50.0 mm
Stroke	55.1 mm
Compression ratio	15:1
Ignition	Electronic ignition system
Transmission system	Centrifugal clutch and single ratio (14.6:1)
Fuel system	Fuel Injection

Modifications were made to the cylinder head by adding a threaded hole for the installation of the secondary spark plug, as shown in Figure 4. The use of DSI requires two spark plugs and two ignition coils. The current from the ECU is split into two towards the ignition coil for the primary spark plug and the ignition coil for the secondary spark plug. The installation of the spark plugs is done opposite in the combustion chamber [16].

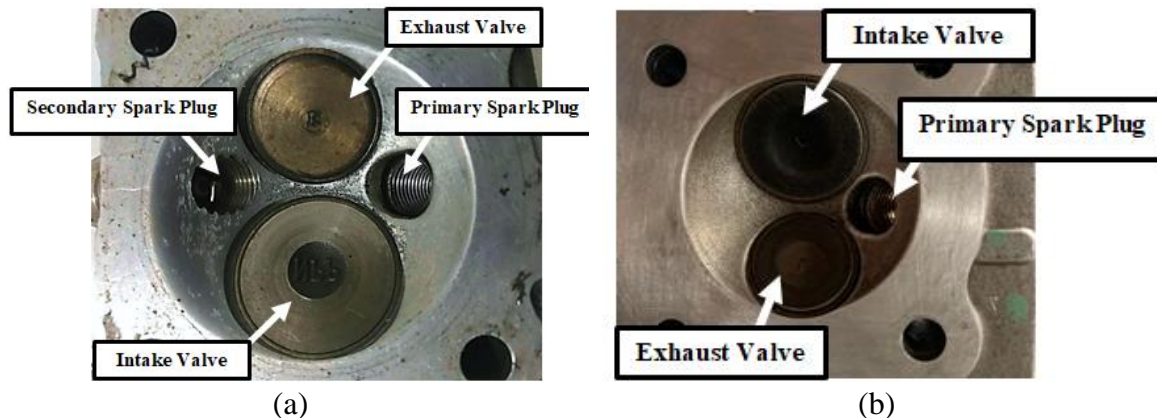


Fig 4. (a) DSI engine cylinder head; (b) SSI engine cylinder head

The data from the test are engine performance and exhaust emissions. Engine performance used in testing engine performance is the power and torque generated from the *Dynamometer*, while the exhaust emission data used is HC, CO, CO₂, and NO_x data [17]. Data on specific fuel consumption (SFC) results are obtained from the ratio of consumption used per hour to produce each kW of engine power as Equation 1 [18]. Thermal efficiency (η_t) can be calculated using Equation 2 by comparing the power generated to the amount of fuel for a certain period of time [18]. The data generated in the form of numbers from testing engine performance, specific fuel consumption, thermal efficiency and exhaust emissions on each independent variable are presented in the form of tables and graphs to facilitate the analysis process and describe the test results.

$$\text{SFC} = \frac{fc}{P_e} \dots\dots\dots (1)$$

$$\eta_t = \frac{P_e}{fc \times \text{LHV}} \times 100\% \dots\dots\dots (2)$$

Where,

SFC = Specific fuel consumption (kg/kWh)

fc = Fuel consumption (kg/h)

P_e = Engine power (kW)

η_t = Thermal efficiency (%)

LHV = Lower heating value (MJ/kg)

III. Results and Discussions

1. Engine Performance

Figure 5 shows the relationship between engine power performance and engine rotation speed variations on SSI and DSI engines fueled by 96% and 99% bioethanol. At 96% bioethanol fuel level, DSI produces the highest power of 6.08 HP at the highest rotation of 7000 rpm compared to the engine using SSI. On 99% bioethanol fuel, the power is 6.89 HP at 7000 rpm engine speed from the use of DSI compared to SSI. The power produced by 99% bioethanol is higher than the 96% content due to the *lower heating* value of 99% bioethanol, which is greater than that of 96% bioethanol, which is 27,118 MJ/kg so that 96% bioethanol to produce the same power as 99% bioethanol requires the supply of a mixture of air and fuel more [19]. However, the use of DSI compared to the SSI engine on 96% bioethanol fuel shows an increase in average power of 13.23%, while the use of DSI on 99% bioethanol fuel average power increased by 5.6% when compared to using SSI. The increase in power from the use of DSI is influenced by the large cylinder pressure and faster heat release rate from bioethanol combustion compared to other fuels [20]. The high octane value of bioethanol requires a large cylinder pressure to produce more complete combustion so that the power produced also increases. In addition, the large mass content of hydrogen in bioethanol has the potential to increase the attractive force with oxygen so that it has the potential to produce H₂O molecules, which can be a coolant in the engine [21]. The addition of DSI to the engine is intended to increase the temperature in the combustion chamber so that the efficient working temperature in the chamber can be achieved and the fuel-air mixture can be converted optimally.

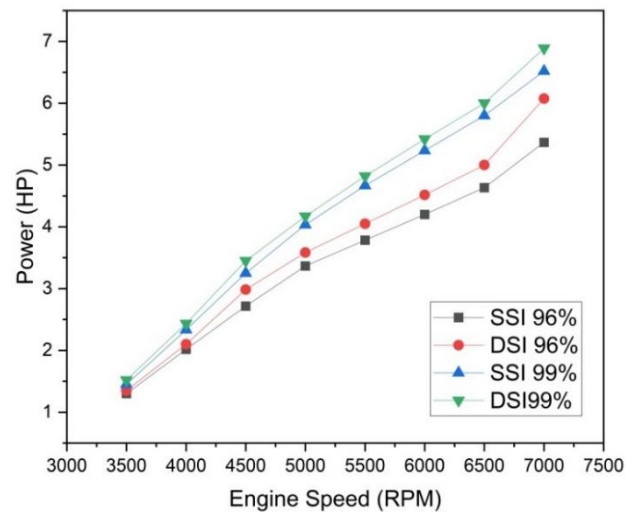


Fig 5. Power results at various engine speed variations using DSI and SSI fueled with 96% and 99% bioethanol.

The relationship between torque and engine speed variations from using DSI compared to using SSI on 96% and 99% bioethanol fuel engines is shown in Figure 6. Peak torque from SSI occurs at 6500 rpm engine speed of 14.28 N.m with 96% fuel and 14.59 N.m on 99% fuel. While using DSI, the peak torque reached 14.30 N.m when using 96% fuel and 14.95 N.m on 99% fuel at 6500 rpm engine speed. There is an increase in torque from the use of DSI compared to SSI, with an average increase of 1.42% on 96% bioethanol fuel, and when using 99% bioethanol, average torque increased by 1.24%. The torque produced by the engine increases in the use of DSI due to the characteristics of bioethanol fuel, which has a slower combustion speed caused by a higher latent heat value of vaporization and a lower speed of flame propagation on bioethanol. So that the addition of spark plugs in the same combustion chamber can result in a shorter and more complete combustion process [22]. This more complete combustion can increase combustion efficiency and make more bioethanol molecules react completely with oxygen. Improved combustion efficiency and fuel energy utilization can ultimately increase the torque produced by the engine [23].

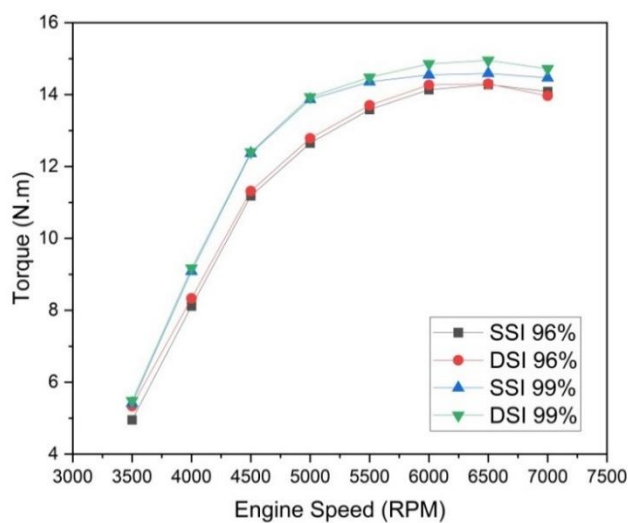


Fig 6. Torque results at various engine speed variations using DSI and SSI fueled by 96% and 99% bioethanol.

2. Specific Fuel Consumption

Specific fuel consumption (SFC) is the ratio between the fuel used and the power output produced by the engine. The relationship of SFC generated from combustion with engine speed from the use of DSI and SSI 96% and 99% bioethanol fuel is shown in Figure 7. SSI on 96% bioethanol fuel produces a minimum SFC of 0.185 kg/kWh at 7000 rpm. At the same speed, the minimum SFC occurs at 0.146 kg/kWh when using 99% bioethanol. In comparison, using DSI produces a lower minimum SFC of 0.16 kg/kWh at 96% bioethanol content when entering the engine speed of 7000 rpm and 0.135 kg/kWh when using 99% fuel content at the same engine speed. This shows a decrease in the average SFC by 13.87% at a 96% level from the use of DSI in the combustion chamber and a decrease in the average SFC by 6.54% in the use of 99% bioethanol. The use of DSI increases the combustion efficiency, accelerates the combustion rate, and increases the peak combustion pressure [24]. This increases power output from the combustion process in the cylinder chamber. In addition, there is a difference in SFC between 96% and 99% bioethanol fuel due to differences in fuel density. Density has an impact on initial injection, injection pressure, and combustion-related fuel injection characteristics in the combustion chamber [25].

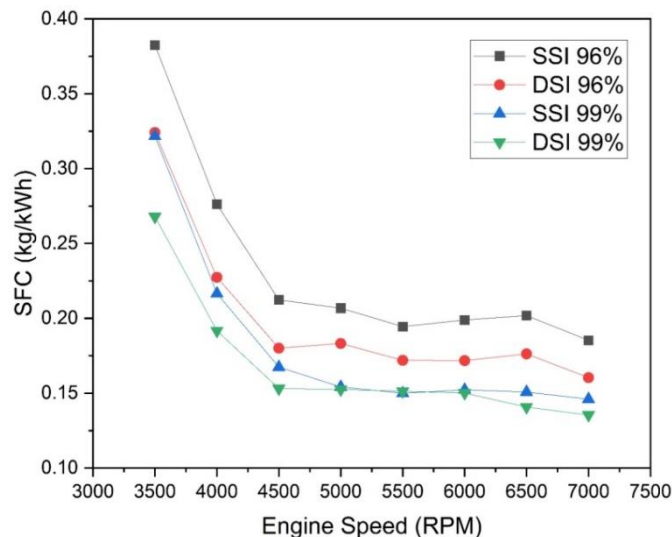


Fig 7. SFC results at various engine speed variations using DSI and SSI fueled by 96% and 99% bioethanol.

3. Thermal Efficiency

Different combustion characteristics and volumetric efficiency will result in different thermal efficiencies. Efficiency is also affected by the type of fuel and air mixture flow into the combustion chamber [26]. The highest thermal efficiency of DSI installation occurs at 7000 rpm engine speed of 36.61% with 96% bioethanol content and 27.24% at 99% fuel content variation. In the use of SSI, the highest thermal efficiency produced is 31.68% at 96% fuel content, and when using bioethanol fuel, 99% thermal efficiency occurs at 25.25%. This shows an increase in average thermal efficiency of 13.87% on 96% bioethanol and 6.54% when the engine uses 99% bioethanol. This increase is due to the combustion duration of the DSI being shorter than that of SSI. With a short duration, the thermal efficiency value produced is higher using the DSI engine than the SSI engine. According to research results from Altin et al. [27], the total combustion duration between dual spark plugs and single spark plugs when tested on bioethanol-fueled engines shows that the combustion duration of single spark plugs is greater. This shorter and more even combustion from the use of DSI

allows the hydroxyl radicals produced from bioethanol to play a more effective role in accelerating the combustion chain reaction. This improves the combustion efficiency and utilization of energy contained in bioethanol fuel. In addition, the high latent heat of vaporization of water from ethanol combustion products can increase the thermal efficiency of the engine [27]. This occurs because the water vapor formed can help the cooling process in the engine, thus reducing heat loss due to radiation and convection. This can prove that hydroxyl groups play a role in creating fuels with high thermal efficiency and low fuel consumption [28].

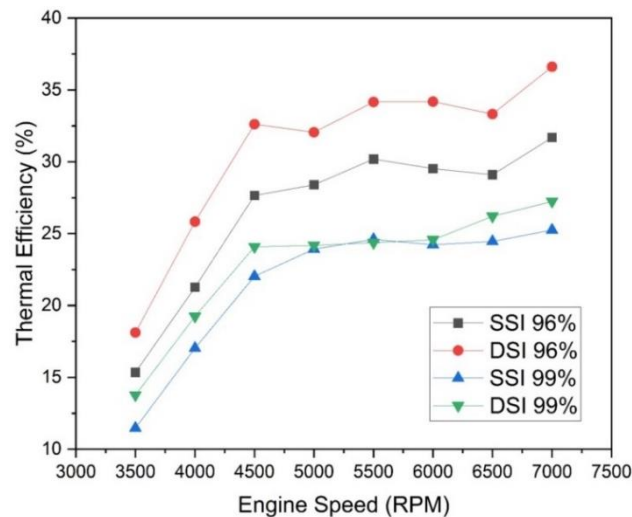


Fig 8. Thermal efficiency results at various engine speed variations using DSI and SSI fueled by 96% and 99% bioethanol.

4. Exhaust Emissions

a. Nitrogen oxides (NO_x)

Three primary factors contribute to NO_x generation in engines: fuel NO_x (which is minimal in engines powered by biogas, ethanol, or CNG due to extremely low nitrogen levels), fast NO_x (which is less significant in SI engines), and thermal NO_x (which is the most significant factor and is determined by temperature and residence time) [29]. Figure 9 shows the relationship between NO_x emissions and engine speed variation in SSI and DSI engines fueled with 96% and 99% bioethanol. The highest NO_x emission occurs with 96% bioethanol fuel using DSI at 0.574 ppm at 3500 rpm engine speed and 0.742 ppm when using 99% bioethanol fuel with the same engine speed compared to the SSI engine. Comparison of the use of DSI with SSI on NO_x emissions has increased. The increase in average NO_x emissions of bioethanol with 96% content in DSI engine compared to SSI occurred by 15.58% and 5.13% at 99% bioethanol. This emission increase occurs because the combustion of bioethanol fuel from the DSI engine is shorter, so the combustion is more perfect [22]. The increase in NO_x emissions is also influenced by the temperature that occurs in the combustion chamber and oxygen in bioethanol; DSI plays a role in increasing the temperature in the combustion chamber, making combustion in the combustion chamber more streamlined [30]. With leaner combustion, the fuel and air mixture will produce lower emissions. In addition, bioethanol has a molecular structure that contains hydroxyl groups (-OH) and does not have carbon-carbon double bonds as in gasoline. This causes bioethanol combustion to tend to produce higher combustion temperatures than gasoline. [23]. With dual spark ignition, faster and more even combustion can further increase the combustion

temperature. The higher combustion temperature causes more nitrogen (N_2) in the air to dissociate and react with oxygen (O_2) to form NO_x . [29].

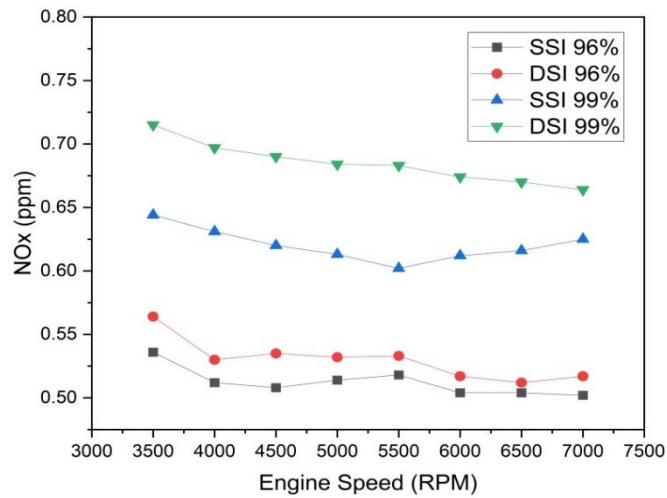


Fig 9. NO_x emissions at various engine speed variations using DSI and SSI fueled with 96% and 99% bioethanol.

b. Hydrocarbons (HC)

HC emissions mostly come from unburned fuel. Figure 10 shows the relationship between HC emissions produced and variations in engine rotation speed on SSI and DSI engines fueled by 96% and 99% bioethanol. At 96% level, the maximum decrease is 31.29%, while at 99% DSI level, the maximum decrease is 59.60%. The high oxygen content of bioethanol promotes increased oxidation of unburned hydrocarbon fuels [31]. So that the use of DSI will avoid combustion failures that occur as a result of the use of bioethanol fuel. In addition, the low calorific value of bioethanol causes a reduction in in-cylinder temperature, which inhibits the formation of a homogeneous mixture so that the combustion process with SSI engines is less than optimal [32]. Reduced HC emissions occur due to an increase in temperature in the cylinder chamber, and fuel can burn evenly when using DSI; this can reduce unburned fuel [33].

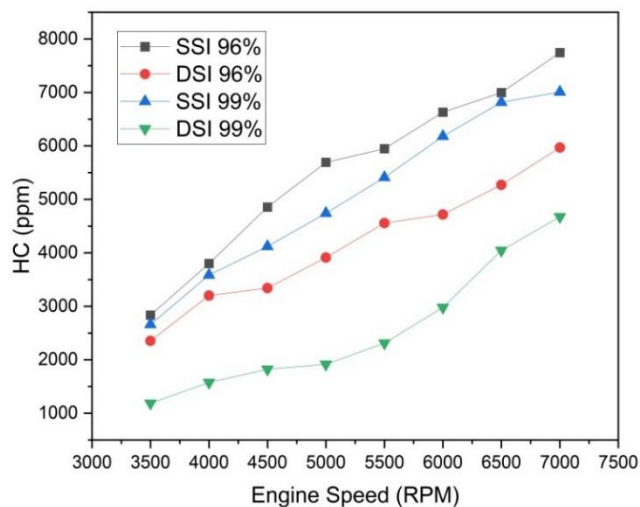


Fig 10. HC emissions at various engine speed variations using DSI and SSI fueled with 96% and 99% bioethanol.

c. Carbon monoxide (CO)

Figure 11 shows the relationship between CO emissions and variations in engine rotation speed on SSI and DSI engines fueled by 96% and 99% bioethanol. Carbon monoxide emissions decreased when the engine used a DSI engine compared to the SSI engine. This is because bioethanol fuel has a lot of oxygen when burned at the appropriate combustion chamber temperature with high flame speed, and increased combustion will produce good atomization to reduce carbon monoxide gas emissions [34]. Compared to using SSI, carbon monoxide emissions decreased on average when using DSI with 96% bioethanol fuel, which is 72.51%, and at 99% bioethanol content, the average reduction in CO emissions that occurs is 58.69%. The presence of oxygen in bioethanol molecules and better oxidative conditions during combustion help reduce CO formation. Meanwhile, dual spark ignition serves to increase turbulence and mixing, thus improving combustion efficiency and reducing CO formation caused by poor mixture. This decrease was also experienced by Ji et al. [35]. CO decreased by 57.6% when using dual spark plugs, caused by the spread of heat from spark plugs that are shorter and more evenly distributed. So that the fuel and air mixture can burn thoroughly in the combustion chamber.

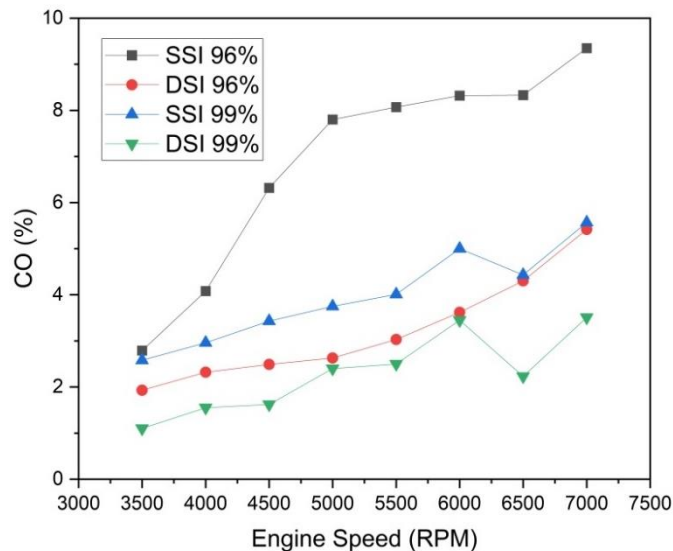


Fig 11. CO emissions at various engine speed variations using DSI and SSI fueled with 96% and 99% bioethanol.

d. Carbon dioxide (CO₂)

Figure 12 shows the relationship between CO₂ gas produced and variations in engine rotation speed on SSI and DSI engines fueled by 96% and 99% bioethanol. CO₂ is an exhaust emission that is very influential on the greenhouse gas effect. CO₂ emissions increase with increasing engine speed because the increase in engine speed results in better mixing of fuel and air particles to accelerate the formation of CO₂ [36]. However, the use of DSI reduces CO₂ emission levels in each fuel. The highest decrease in CO₂ from 96% using DSI was 56.75% at 6500 rpm, while in 99% fuel, the highest decrease occurred at 5500 rpm at 76.92%. Similar to CO emissions, the low CO emissions are due to the higher oxygen content of bioethanol and lower carbon to hydrogen ratio. [37]. The decrease is also due to the use of dual spark ignition, which can improve the homogeneity of combustion in the cylinder by creating two starting points of combustion [35]. More homogeneous and complete combustion can increase the thermal efficiency of the engine, thereby reducing

bioethanol fuel consumption. With lower bioethanol fuel consumption, CO₂ emissions per unit of energy produced will also decrease.

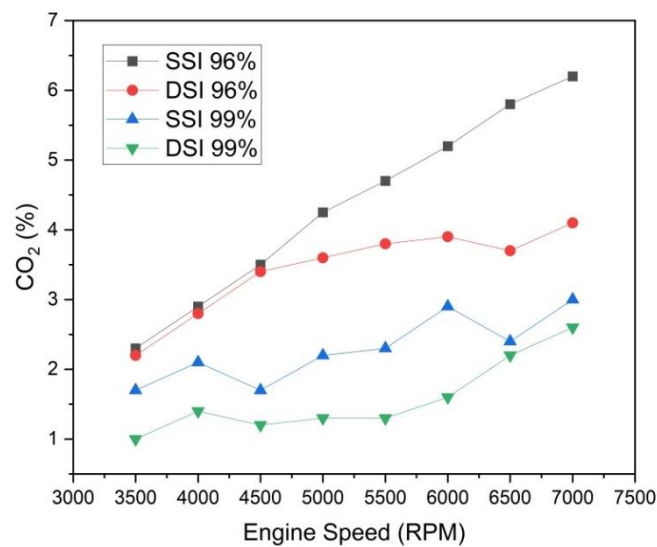


Fig 12. CO₂ Emissions at various engine speed variations using DSI and SSI fueled with 96% and 99% bioethanol.

IV. Conclusions

Experimental research has been conducted by comparing the DSI and SSI engine fueled by bioethanol with 96% and 99% levels. The results show that the use of DSI has an impact in accordance with the initial assumptions, which can improve engine performance and reduce SFC and exhaust emissions. The best results from the use of DSI are shown when using 99% fuel, which produces the highest power of 6.89 HP, peak torque of 14.95 N.m at 6500 rpm engine speed and reduces exhaust emissions and SFC levels from the use of DSI. While on DSI fueled by 96% bioethanol, the highest power generated is 6.08 HP at 7000 rpm and the peak torque that occurs is 14.30 N.m at 6500 rpm. The use of DSI ignition system can optimize combustion in the combustion chamber. However, there are differences in the results of the influence produced on each parameter of engine performance and bioethanol levels that occur due to differences in bioethanol content and properties of the fuel. The nature of bioethanol, which has a high oxygen content, greatly affects the combustion efficiency and oxidation process of bioethanol in the combustion chamber. The level of combustion efficiency that occurs from DSI and SSI engines affects the results of engine performance and exhaust gases.

This study only focuses on the comparison between engines using DSI and SSI with 99% and 96% bioethanol fuel. To further optimize the use of spark ignition engines fueled by bioethanol with high or pure levels, further research is needed by looking at engine performance and emission results if the ignition duration variation is changed or by adjusting the mixture of air and fuel entering the combustion chamber.

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