Automotive Experiences
Vol. 6 No. 1 (2023) pp. 245-258
p-ISSN: 2615-6202 e-ISSN: 2615-6636

Research Paper

# Performance and Emission Characteristics Using Dual Injection System of Gasoline and Ethanol

**Bambang Sulistyo**[1], **Herminarto Sofyan**[1], **Thomas Sukardi**[2], **Agus Widyianto**[3]

[1]Department of Automotive Engineering Education, Faculty of Engineering, Universitas Negeri Yogyakarta, Yogyakarta, Indonesia
[2]Department of Mechanical Engineering Education, Faculty of Engineering, Universitas Negeri Yogyakarta, Yogyakarta, Indonesia
[3]Department of Mechanical and Automotive Engineering, Faculty of Vocational, Universitas Negeri Yogyakarta, Yogyakarta, Indonesia

bambang_sulistyo@uny.ac.id

https://doi.org/10.31603/ae.8070

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Published by Automotive Laboratory of Universitas Muhammadiyah Magelang collaboration with Association of Indonesian Vocational Educators (AIVE)

***Article Info***
*Submitted:*
28/10/2022
*Revised:*
03/04/2023
*Accepted:*
11/04/2023
*Online first:*
20/05/2023

## Abstract

This study successfully investigated the engine performance and emission characteristics of a dual injection system that uses both gasoline and ethanol fuels. The study utilized a microcontroller-based control system (PGM-FI) to substitute ethanol fuel injection for gasoline injection. Ethanol fuel was injected at the inlet with three different pressures: 1.0 bar, 1.2 bar, and 1.4 bar, while gasoline injector pressure was fixed at 2 bar. Results showed that substituting ethanol injection with a pressure of 1 bar resulted in a slight decrease in torque and power, but it was the best compared to the other pressures tested. The study found that the use of ethanol injection resulted in improved fuel economy at an ethanol injector pressure of 1 bar with a reduction in SFC of 8.89%. Exhaust emissions were also reduced, with a maximum reduction in CO emissions of 42.54% occurring at a pressure of 1 bar. Similarly, the lowest HC content in exhaust gas was observed at a pressure of 1 bar, which was reduced by 44.48%. However, the results highlighted that ethanol injection pressure could significantly reduce fuel consumption for case A-04 and increase the air-fuel ratio.

**Keywords:** Dual injection system; Electronic fuel injection; Emission; Ethanol; Fuel consumption

## 1. Introduction

Energy can be obtained from various sources, both renewable and non-renewable [1], [2]. Fossil fuels have contributed to fueling the automotive sector for a long time and perhaps for decades to come [3]. However, as the number of motorized vehicles increases, fuel consumption also increases, which means that the availability of this fuel decreases [4]. For example, the search found no new resources. In this case, oil reserves are expected to run out in the next 10-15 years, so a new source of energy for vehicles must be sought. Biofuels such as ethanol, may be supplied domestically from corn, sugarcane and other agricultural biomass products [5]–[7]. The physical and thermal properties of ethanol are similar to those of gasoline, making it suitable for spark ignition engines, as a mono fuel or blended with gasoline [8]–[10]. Ethanol has been used in recent years because of its low greenhouse effect, high octane number, low harmful emissions into the atmosphere, and its ability to mix with gasoline [11], [12].

Efforts to balance the availability of fuel and increase in motorized vehicles can be done by providing fuel-efficient vehicles. Engine improvements can be achieved by improving the combustion process [13]. The combustion process can be improved by using a four-stroke engine, optimizing the combustion chamber, using an electronic ignition system, and using an electronic fuel injection system. This technology can reduce fuel consumption and extend service life [14]. In addition, fuel cut off technology has also been developed to cut off fuel flow or temporarily stop injection under certain conditions [15]–[17].

Another factor of concern with large numbers of vehicles and high levels of fuel consumption is the generation of pollutant effects from the combustion of vehicle fuel. Pollution due to exhaust gas emissions from burning fossil fuels impacts human health and the environment [18]. Exhaust gas emissions from the combustion of motor vehicles in the form of carbon dioxide ($CO_2$), carbon monoxide (CO), nitrogen oxides (NOx), unburned hydrocarbons, and metallic elements such as lead (Pb) are a serious concern because of the impact on the performance of these gases which can reduce levels of health and safety of human life [19]–[22]. Therefore, modifications to old technology are also made to improve the effect of technology on the environment [23].

In Indonesia, approximately 70% of air pollution is caused by motor vehicle emissions. Motor vehicles emit hazardous substances that can cause negative impacts on human health and the environment, such as lead/lead (Pb), suspended particulate matter (SPM), nitrogen oxides (NOx), hydrocarbons (HC), carbon monoxide (CO), and photochemical oxides (Ox). Motor vehicles contribute almost 100% of lead, 13-44% of suspended particulate matter (SPM) or dust particles, 71-89% of hydrocarbons, 34-73% of NOx, and almost all of carbon monoxide (CO) [24]. An uncontrolled increase will result in a global greenhouse effect that will affect the earth's temperature.

Gasoline-ethanol engines are becoming increasingly popular as a way to reduce greenhouse gas emissions and improve fuel efficiency [11]. Ethanol has a higher octane number than gasoline, so it can be used in engines with higher compression ratios [25]. Therefore, engines powered by gasoline-ethanol blends can achieve higher performance levels than gasoline engines. Another benefit, ethanol is a renewable fuel. Unlike gasoline which is produced from crude oil, ethanol can be produced from various renewable sources such as corn, sugar cane, and even agricultural waste [26].

Many researchers have tried to combine ethanol and fuel in different mixture ratios and pressures to test engine performance and emission characteristics. Li Y *et al.* [27] added several additives such as methanol, ethanol, and butanol into the fuel and then tested its emission characteristics and performance. Adding ethanol and methanol can reduce emissions from NOx and unburned hydrocarbons (UHC). In another study, the addition of ethanol was shown to reduce exhaust emissions such as carbon monoxide (CO), carbon dioxide (CO2), and nitrogen oxides (NOx), but increased gas emissions of hydrocarbons [13]. Manikandan *et al.* [28] reported that the addition of 10% to 30% ethanol can increase torque, power, and fuel economy which is more economical. In terms of exhaust emissions such as HC, $CO_2$, NOx, and CO, ethanol has better performance than gasoline [29]. Several studies have shown promising results by adding ethanol in reducing exhaust emissions (HC, $CO_2$, NOx, and CO) [11], [21], [22] and increasing engine performance (power, thermal efficiency, and specific fuel consumption) [28], [30], [31].

Demirbase *et al.* [32] studied the effect of adding oxygen-containing compounds such as MTBE, methanol, and ethanol to gasoline and concluded that oxygen-containing compounds are cleaner fuels with less post-combustion contamination. Kheiralla *et al.* [33] studied the effect of an ethyl alcohol-petrol mixture on the fuel properties of a variable engine speed. The results concluded that the density and kinematic viscosity of the mixture increased continuously and linearly with increasing ethanol content. Experiments on cars 4-cylinder 4-stroke vehicles using 4 to 20 vol. % ethyl alcohol were carried out by Barakat *et al.* [34]. The graph of fuel consumption (kg/hour) and ethyl alcohol concentration (vol%) obtained at various engine speeds and ethyl alcohol concentration are linear. The fuel consumption rate was higher in the isolate-rich mixture than in the reformed oil-rich mixture.

**Table 1** presents the results of a literature review of several studies conducted on engine performance using different types of fuel. The literature provides results on performance and emissions for different engine types, number of cylinders, displacement, cooling system, power, and torque. Gasoline is supplemented with several other fuel types such as ethanol, methanol, butanol, propanol, and pentanol. Results from several studies show increases and decreases in performance and emissions.

However, there are also some challenges associated with using ethanol in gasoline-ethanol-fueled engines. One of the main challenges is that ethanol is hygroscopic, which means that it absorbs water from the air [8], [35]. This can lead to corrosion in the fuel system and engine, which can cause performance and reliability issues. To address this, gasoline-ethanol-fueled engines are typically designed with special materials and coatings to protect against corrosion.

The literature study concludes that many studies have been carried out on spark ignition engines fueled by ethanol mixtures derived from various feedstocks for various analyses, emissions, and combustion. However, very few studies have been done by varying the injection pressure. This work aims to analyze the effect on combustion, performance, and characteristics of electronic fuel injection (EFI) engines with various ethanol and fuel mixture pressures. The single-cylinder and 4-stroke engines is used in this study, and the injection pressure varied from 1 bar to 3 bar. Furthermore, performance characteristics and exhaust emissions are examined based on these variations.

**Table 1.** Literature review on engine performance when using different types of fuel

| Refs. | Engine data | | | | | Test condition | | Main results | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of cyl. | Cylinder capacity (cc) | Cooling system | Power (kW) | Torque (N.m) | N (rpm) | Fuel | η | SFC | $E_{CO}$ | $E_{HC}$ | $E_{CO2}$ |
| [6] | 1 | 156.6 | A | 13.3 | 1.3 | 2000 to 4000 | Methanol, ethanol and butanol | – | – | ↑ | ↓ | ↑ |
| [20] | 1 | – | W | 105.2 | – | – | Ethanol and gasoline | – | – | ↓ | ↑ | – |
| [36] | 1 | 172 | A | 4.4 | – | 1500 to 2500 | Ethanol and gasoline | ↑ | – | ↓ | ↓ | ↓ |
| [10] | 1 | 143 | – | 2.2 | – | – | Gasoline, ethanol, methanol, propanol, butanol and pentanol | – | – | ↓ | ↑ | ↓ |
| [27] | 1 | 575 | – | – | – | 1200 | Gasoline, ethanol, methanol and butanol | – | ↑ | ↑ | ↓ | – |
| [34] | 4 | 1400 | W | 58.2 | 10.5 | 1200 to 2000 | Ethanol and gasoline | – | ↑ | – | – | – |
| [31] | 1 | – | – | – | – | 2600 to 3450 | Gasoline, ethanol and methanol | – | – | ↓ | ↓ | ↑ |
| [14] | 1 | 249 | A | – | – | 3500 to 4000 | Ethanol and gasoline | ↑ | – | ↑ | ↑ | – |
| [8] | 1 | 196 | – | – | – | 1600 to 3600 | Gasoline, ethanol and methanol | ↑ | ↑ | ↓ | ↓ | ↑ |
| [18] | 4 | 1297 | – | 43 | 98 | – | Ethanol and gasoline | ↓ | ↑ | ↓ | ↑ | ↓ |
| [37] | 1 | 573 | A | – | – | 1500 | Methanol, ethanol, butanol and propanol | ↑ | – | ↓ | ↑ | – |
| This research | 1 | 124.8 | A | 6.8 | 9.7 | 2000 to 4500 | Gasoline and ethanol | ✓ | ✓ | ✓ | ✓ | – |

## 2. Methods

This experiment uses a Honda Supra X125 PGM-FI motorcycle engine with the specifications shown in **Table 2**. Modifications have been made to the electronic fuel injection (EFI) system. The addition of the intake ethanol fuel injector (henceforth referred to as the ethanol injector) was mounted closer to the engine and towards the location of the gasoline fuel injectors. **Figure 1** shows the location of the ethanol injectors on a motorcycle engine. Fuel injection was controlled by adjusting fuel pressure, and engine speed was measured by adjusting the air throttle valve position. In contrast, the injection time was controlled by an electronic control unit (ECU).

The fuel pressure specification of this motor is 294 kPa (3.0 kgf/cm$^2$ or 2.43 psi). The addition of ethanol fuel is injected at the inlet with variations in ethanol injector pressure of 1.0 bar, 1.2 bar, and 1.4 bar. While the pressure on the gasoline injector is 2 bar, the pressure variation of the two injectors is obtained based on the calculation of the motor's combustion. All fuel variations will be tested at several engine speeds ranging from 2000 to 4500 rpm with 500 rpm increments. The process flow scheme of the modified fuel system with the addition of ethanol is shown in **Figure 2**.

A dynamometer and emissions test rig was used to test the fuel and ethanol mix test results (**Figure 3**). A dynamometer is used to measure the amount of braking force. A Tequipment brand engine dynamometer was used in this study. The data for analysis obtained from this engine dynamometer are engine speed and torque. The amount of power can then be calculated from this information. A fuel measuring cup (burette) can be used to calculate fuel consumption (ml/second).

The emissions testing equipment utilized in this study was the Stargas MOD 898 four-gas analyzer. **Table 3** shows the specifications of the emission test equipment. As one of the combustion products in the cylinder, it will produce exhaust gas emissions that are released through the exhaust pipe. The amount of exhaust gas emissions that come out should be limited as much as possible not to endanger the environment or health. To measure the amount of emission from combustion in the motor, a test instrument is needed to decompose the released gases in CO, HC, NOx, SOx, $CO_2$, and $O_2$.

**Table 4** presents the experimental parameters employed in the study. The study comprises four scenarios, labeled as case A-01, which involves pure gasoline under 3 bar pressure. The next case is a blend of gasoline and ethanol under varying pressures, with 2 bar and 1 bar for case A-02, 2 bar and 1.2 bar for case A-03, and 2 bar and 1.4 bar for case A-04. The study uses premium 88 fuel provided by PT Pertamina Indonesia and ethanol ($C_2H_5OH$) as the co-solvent liquid. The total mixture of fuel and ethanol for all four cases is 10 mL, with pure fuel (10 mL) for case A-01, and a fuel-ethanol blend (9 mL-1 mL) for cases A-02 to A-04. The study involves testing each scenario on a modified motorcycle engine, as shown in **Figure 1**.

The engine torque is obtained from the dynamometer, but the actual torque is not based on the dynamometer in this study. The actual torque (Ta) can be calculated by Equation (1):

$$T_a = \frac{T_0}{GR} \tag{1}$$

where $T_0$ and GR are the torque measured in the dynamometer (Nm) and gear ratio, respectively,

**Table 2.** Specifications of motorcycle engine

| | |
|---|---|
| Engine type | Honda Supra X 125, single-cylinder, 4-stroke |
| Fuel system | PGM-FI (Programmed Fuel Injection) |
| Displacement (cc) | 124.8 |
| Bore x Stroke (mm) | 52.4 x 57.9 |
| Compression ratio | 9.0 : 1 |
| Output (HP/rpm) | 9.18/7500 |
| Max. torque (kgm/rpm) | 0.99/5000 |
| Lubrication | Oil pump rotor (Trochoid) |
| Lubricant | Federal Oil, SAE 10W-30 |
| Ignition system | Full transistorized |
| Fuel | Gasoline |

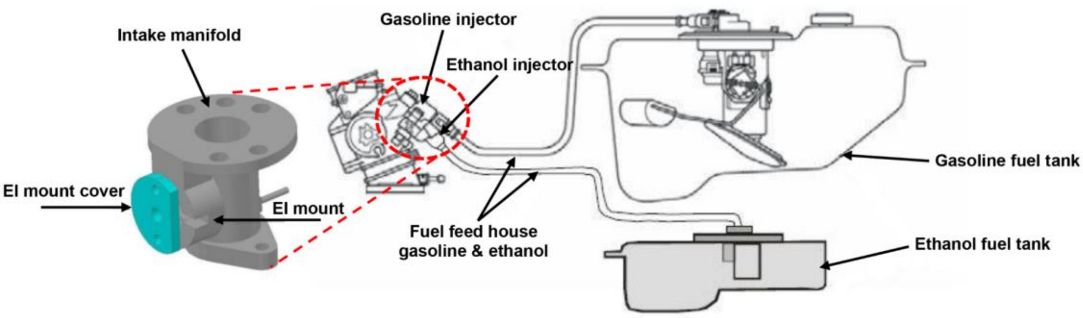


**Figure 1.** EFI system and intake manifold modification with the addition of ethanol injector

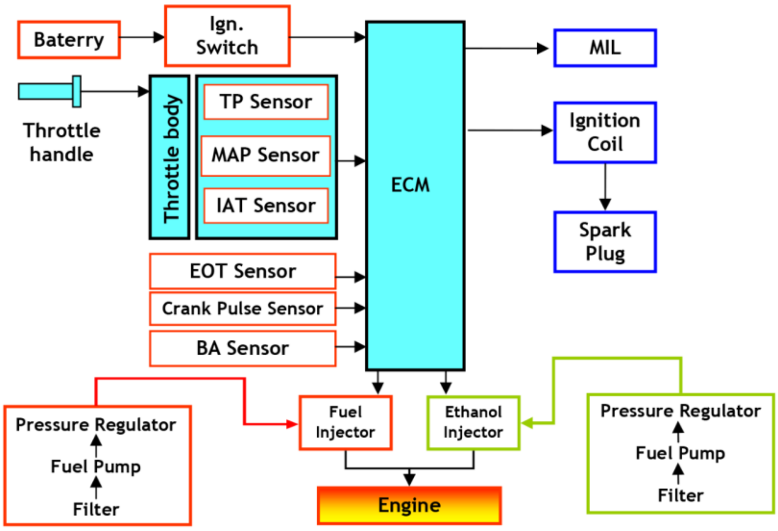


**Figure 2.** Schematic of modification of the fuel system with the addition of ethanol

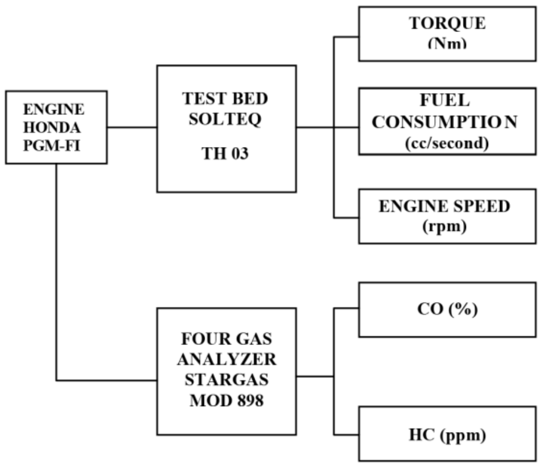


**Figure 3.** Schematic of combustion and emissions test performance with ethanol addition

**Table 3.** Specifications of the Four Gas Analyzer Stargas Mod 898

| Parameters | Scale | Resolution |
|---|---|---|
| CO | 0 % – 15.000 % Vol. | 0.001 % Vol. |
| $CO_2$ | 0 % – 20.00 % Vol. | 0.01 % Vol. |
| HC | 0 ppm – 30.000 ppm Vol. | 1 ppm Vol. |
| Lambda ($\lambda$) | 0.5 – 2.00 | 0.001 |
| $O_2$ | 0 % – 25.00 % Vol. | 0.01 % Vol. |
| Oil temperature | 0°C – 200°C | 1°C |
| Engine speed | 250 rpm – 7200 rpm | 1 rpm |

**Table 4.** Experimental and fuel blend conditions

| Case number | Fuel pressure (bar) | Ethanol pressure (bar) | Gasoline (mL) | Etahnol (mL) |
|---|---|---|---|---|
| A-01 | 3.0 | 0 | 10 | 0 |
| A-02 | 2.0 | 1.0 | 9 | 1 |
| A-03 | 2.0 | 1.2 | 9 | 1 |
| A-04 | 2.0 | 1.4 | 9 | 1 |

while $T_a$ is the actual torque (Nm). Engine power (P) is a function of engine speed and torque. Motor power cannot be measured by the tool, but is calculated using Equation (2):

$$P = \frac{2\pi N T_a}{60} \tag{2}$$

where P, N, and $T_a$ are engine power (kW), engine speed (rpm), and actual torque (Nm). To produce power, the engine requires a supply of fuel. While fuel efficiency is one of the benchmarks of an engine or commonly known as specific fuel consumption (SFC). SFC can be calculated using Equation (3):

$$SFC = \frac{\dot{m}_f}{p} \tag{3}$$

where SFC is the specific fuel consumption (gr/kWh), f is the mass flow rate of fuel (gr/h), and P is engine power (kW).

## 3. Results and Discussion

### *3.1. Engine Performance*

Engine performance in this study is derived from torque and engine power for several case variants. Torque is measured with a dynamometer. To get the actual value, the torque value read by the dynamometer must first be transformed based on the gearbox and engine clutch transformations. Torque undergoes many changes as the fuel system develops. Eventually it will go up, but at some point the engine revs will also drop. Also, varying the ethanol fuel injector pressure and the gasoline injector pressure to replace ethanol will produce different torques. Figure 4 shows the trend of torque change.

Compared to the engine torque of the gasoline injection system, replacing the ethanol injection reduces the average torque by 1.72%. On the other hand, replacing ethanol with an ethanol injection pressure of 1 bar produces better torque than other pressures at engine speeds between 2000 and 4500 rpm. This corresponds to 0.82%. Therefore, the ability of fuel penetration by pressure affects the distribution of the fuel pattern within the cylinder.

On the other hand, substitution of 1.2 and 1.4 bar ethanol injection pressures had the lowest reduction under the torque produced by the 1 bar ethanol injection system. This can occur because the fuel is too permeable, so unburned ethanol fuel flows in large quantities into the cylinder, but no power is produced [38]. This condition is also reflected in the high proportion of hydrocarbons in the exhaust gas.
Therefore, replacing ethanol fuel injection tends to reduce torque compared to gasoline fuel systems, albeit by a small percentage. For example, Surisetty et al. [39] reported several studies using mixtures of gasoline and alcohol fuels with a proportion of 10% ethanol to produce higher power in gasoline carburetor engines, but a mixture of 25% ethanol was used. Adding it reduced the engine power.

The level of engine power is obtained by calculation using existing formulas. The change in engine power with the magnitude of the torque rise obtained from the dynamometer. Engine power with a gasoline fuel system is available in the range of 0.135 kW to 1.311 kW. The power range of the ethanol injection alternative engine is

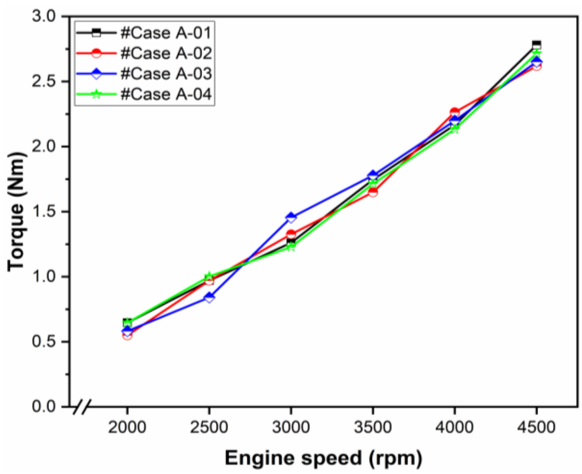


**Figure 4.** Torque vs. engine speed

0.135 kW to 1.280 kW. There was no significant increase in power, but changing the engine power by replacing the ethanol fuel injection resulted in a minimal drop of 0.82% at 1 bar of ethanol injection pressure.

Changes in engine torque also affect the level of engine power. Replacing the ethanol injection with a pressure of 1 bar gives better performance than other pressures. The air flow pattern in the cylinder therefore affects the fuel distribution and therefore the amount of combustion in the cylinder. The reduction in engine power under gasoline operation with ethanol injection pressure variations of 1.2 and 1.4 bar shows a rather large voltage drop (**Figure 5**). Higher fuel pressure allows for smaller droplet diameters. This allows more fuel to flow into the cylinder, but the ethanol is not fully mixed, making it harder to burn and reducing engine performance.

Changes in injection pressure affect torque and engine power, improving combustion by improving fuel-air mixing time in the cylinder. Advances in injection timing from uncontrolled electronic control units and contributions from airflow patterns over the pistons are believed to influence the mixing process and impact engine performance. At the same time, the fuel pressure can affect the penetration of fuel from the injector and penetrate the air pressure in the cylinder [40].

Based on the calculations, it can be seen that the use of gasoline fuel injection has the effect of reducing engine power due to variations in ethanol injection pressure. An ethanol injector pressure change of 1 bar resulted in the least engine power drop, while ethanol injector pressure changes of 1.2 and 1.4 bar resulted in significant voltage drops. This is because the calorific value or low calorific value of ethanol is lower than that of gasoline, so the heat of combustion generated in the cylinder is also lower [41]. Therefore, if a large amount of ethanol is injected into the gasoline fuel, the combustion heat of the gasoline engine is further reduced, resulting in a decrease in the power output. According to the results of Pikūnas et al. [42] that the addition of ethanol may lower the calorific value of the fuel mixture and increase the octane rating.

The molecular interactions between gasoline and ethanol can be impacted by the injection pressure in the fuel injection system. When the injection pressure is increased, it improves the fuel atomization process, leading to an increase in the surface area of fuel droplets. This, in turn, facilitates better mixing of the gasoline and ethanol molecules, ultimately enhancing their intermolecular interactions [43]. Consequently, this promotes more efficient combustion. The presence of OH groups in ethanol makes it a polar molecule that can engage in hydrogen bonds, but it also has nonpolar hydrocarbon chains that cause it to be slightly soluble in nonpolar solvents. The polar and nonpolar characteristics of ethanol can have an impact on its interaction with oxygen when combusted. The reaction can be facilitated by the polar OH groups, but the nonpolar hydrocarbon chains can draw in impurities that lower the efficiency of combustion [44]. This can have an effect on the engine's torque and power output.

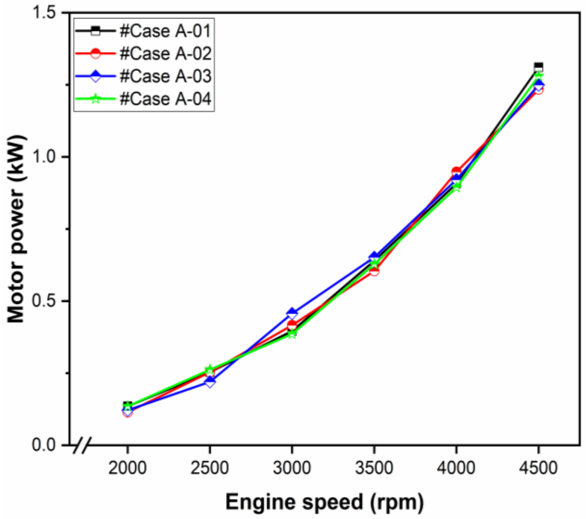


**Figure 5.** Power vs. engine speed for pressure variations

### 3.2. *Emissions*

Engines with ethanol injection systems significantly reduce all engine pressures and speeds. An engine with a gasoline fuel system has a CO content ranging from 0.693% to 2.388%, while replacing the ethanol fuel injection results in a CO content ranging from 0.209% to 2.257% (**Figure 6**). An average decrease of 29.51% occurred across all variations in ethanol injector pressure.

Higher injection pressures produce less CO gas, but the CO load from engine products in gasoline fuel systems is still low. An ethanol injector pressure of 1 bar is therefore the lowest for

CO gas even with varying engine speeds. At the ethanol injector pressure, the maximum CO content reduction is 42.54% at 1 bar pressure. This indicates that it is better to use this system and that the fuel particles can be reliably atomized and mixed with the air.

A decrease in carbon emission levels is caused by an increase in intrinsic oxygen content with increased mixing. Intrinsic oxygen is dissolved oxygen in ethanol compounds. This oxygen can increase the need for combustion in gasoline engines. The same result was also reported by Elfasakhany [45], the addition of ethanol allows him to reduce CO emissions at speeds of 2600–3500 rpm.

Hydrocarbon readings for engines with premium fuel injection systems range from 10ppm to 90ppm (**Figure 7**). On the other hand, replacing fuel injection with ethanol produces HC in the range of 6ppm to 88ppm. At some point there is an increase, at some point there is also a decrease. An ethanol injection pressure of 1 bar therefore produces the lowest HC at engine speeds between 2000 and 4500 rpm. However, the average increase for all pressure and velocity variations is 61.71%.

The fuel pressure setting affects the amount of HC level drop in the injector. Pressure affects the penetration of fuel into the cylinder, thus determining the direction of fuel particle flow and ultimately affecting engine characteristics. Higher ethanol pressures of 1.2 bar and 1.4 bar also increase fuel penetration, allowing it to reach the cylinder wall, where it accumulates and fuel particles are less likely to burn. This increases the HC load that can be measured through the exhaust duct.

Calculations show that adding ethanol injection to premium fuel can reduce hydrocarbon emissions in gasoline engines. Adding ethanol injection did not lead to a reduction in emissions. Adding ethanol at an injection pressure of 1 bar reduces HC with every increase in engine speed. On the other hand, at ethanol injection pressures of 1.2 bar and 1.4 bar, the largest increase in HC emissions was due to ethanol with slower volatility values, hence the atomization process when reacting with oxygen in vapor form. is started. Ethanol burns out and comes out with it. With vehicle exhaust. This waste carbon can take the form of particulate hydrocarbons and low-grade carbon.

Based on engine emissions test results, effective emissions reduction can be achieved with an ethanol injection pressure of 1 bar. This means that the aromatic components of the premium fuels used can be replaced with ethano substitutes to increase the octane rating (octane expanders). The aromatic compounds in this fuel are a series of ring bonds that are difficult to decompose and increase hydrocarbon air pollution. There is a positive relationship between aromatic content and hydrocarbon emissions: the lower the aromatic content, the lower the emissions. The results of this experiment are consistent with findings reported by other investigators [38], [46].

Increasing the injection pressure can also enhance the pressure and temperature in the combustion chamber, thereby leading to more

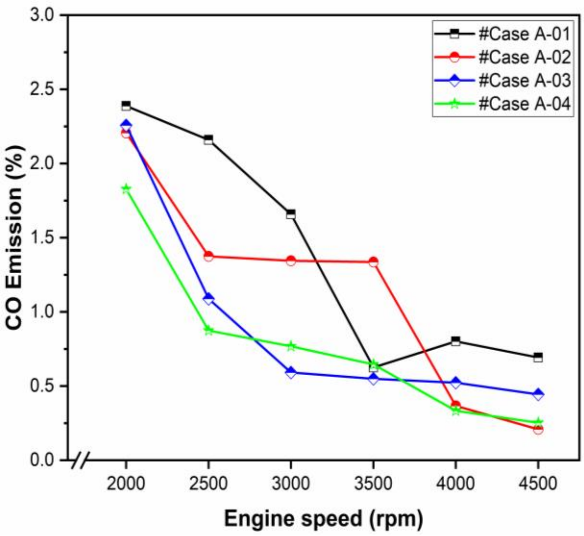


**Figure 6.** CO Emissions vs. engine speed

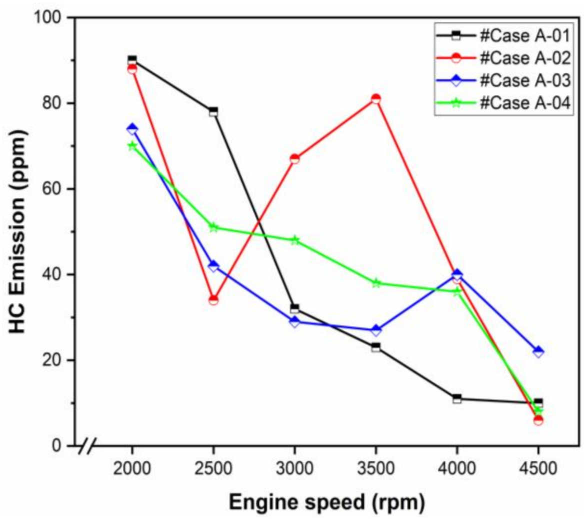


**Figure 7.** HC Emissions vs. engine speed

thorough combustion of the fuel mixture. Moreover, injection pressure can influence the uniformity of air-fuel mixing and the distribution of fuel droplets inside the combustion chamber. If the fuel droplets are not evenly distributed, certain regions may experience a fuel-lean mixture, while others may experience a fuel-rich mixture, resulting in lower emissions [47].

Toxic emissions can be affected by the hydroxyl group (-OH) in ethanol. Ethanol is an oxygen-rich fuel due to the presence of hydroxyl groups, which makes it more effective than hydrocarbons like gasoline in providing oxygen to support fuel combustion in the engine [48]. This results in a more complete combustion process and reduced emissions of carbon monoxide and unburned hydrocarbons. Moreover, ethanol's polar nature enables it to dissolve in water, which can help reduce hazardous emissions by increasing the production of water vapor during combustion.

### 3.3. *Fuel Consumption*

Specific Fuel Consumption (SFC) measures the amount of fuel consumed per unit of power produced by the engine in one hour and is expressed in units of g/kWh (see **Figure 8**). In this study, fuel economy tends to increase for all variations in ethanol fuel pressure. When he increased SFC as an alternative to ethanol infusion, improvement was obtained with an average increase of 8.89%. This indicates that fuel consumption is too high for the same engine performance.

As can be seen from the **Figure 8**, fuel consumption increases with pressure variation for ethanol-injected alternative fuels compared to gasoline-injected systems at all fuel pressures. The lowest average SFC increase occurs at 7.97% at 1 bar ethanol injector pressure, followed by 8.84% at 1.2 bar pressure and the maximum consumption increase at 1.4 bar pressure is 9.85%.

Higher fuel pressure appears to improve fuel efficiency or increases SFC at a higher rate. This is understandable because the higher the pressure, the higher the penetration capacity of the fuel, and the droplets can reach the walls and accumulate in a thin layer (film). In this situation the fuel burns less and produces more HC gas in the exhaust. Computational analysis of the graphs shows that the increase in SFC is minimal compared to others for ethanol fuel injection pressure fluctuations of 1 bar. This is due to the different performance of internal combustion engines and the amount of fuel drawn.

The amount of fuel depends on several factors, one of which is the density of the fuel. Ethanol (0.794 kg/l) is denser than gasoline (0.74 kg/l), resulting in different densities for each gasoline-ethanol mixture. The increased specific fuel consumption is also attributed to the low calorific value of the fuel and the increased density of the mixed fuel density. As the density increases, the flow rate of the fuel mixture in the fuel system decreases. Therefore, it is less fuel efficient and consumes more fuel [38].

Gasoline and ethanol can interact through different types of intermolecular forces such as van der Waals forces. Both fuels consist mainly of hydrocarbon chains, but ethanol also contains a polar hydroxyl group (-OH). Gasoline is predominantly composed of hydrocarbons, with small amounts of other compounds like oxygenates, olefins, and aromatics. When ethanol and gasoline are mixed, the polar hydroxyl groups in ethanol can form hydrogen bonds with the oxygenates in gasoline or other ethanol molecules [49]. Meanwhile, the nonpolar hydrocarbon chains in gasoline can interact with the hydrocarbon chains in ethanol via van der Waals forces. The exact molecular interactions between gasoline and ethanol will depend on the gasoline's composition and the ethanol concentration in the mixture. Optimizing the fuel ratio and combustion process can lead to more efficient fuel use in the engine.

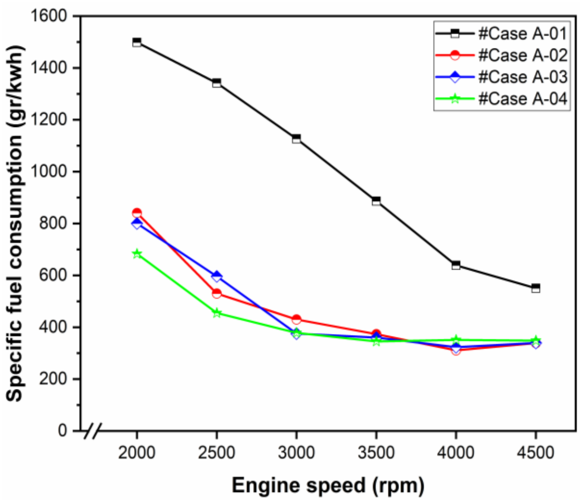


**Figure 8.** Specific fuel consumption vs. engine speed

### 3.4. Charging Efficiency and Air-Fuel Ratio (A/F)

Engines with ethanol-injected fuel systems achieve better charging efficiency than gasoline-injected engines. The pressure of ethanol fuel injection versus gasoline fuel increases charging efficiency with each change in engine speed. The largest increase in filling efficiency occurred at an injector pressure of 1.4 bar and was 29% (**Figure 9a**). This increase occurs from low spin to high spin. Efficiency gains also affect the fuel-air mixture entering the cylinder. This can be represented on a graph of air-fuel ratio mass known as air-fuel ratio (A/F) (**Figure 9b**). It can be seen from the graph that almost all variations in ethanol fuel injection pressure are increasing. The higher the engine speed, the richer the mixture in the intake manifold.

Almost all A/F lines tend to cross the gasoline fuel chart for changes in ethanol injection pressure. This represents a leaner mixture compared to petrol and injects more fuel than petrol fuel systems because heat is needed to generate electricity. The hydroxyl groups in ethanol, due to their polar nature, can cause ethanol to absorb moisture from the environment, which can create issues such as fuel system corrosion and phase separation. Moreover, ethanol has a lower energy density than gasoline, which means that it requires a larger volume of ethanol to produce the same amount of energy as gasoline [34]. This lower energy density can lead to lower fuel efficiency and a reduced driving range for vehicles.

## 4. Conclusion

The dual injection system of gasoline and ethanol was utilized in an experimental study to evaluate engine performance and emissions. Four different cases were examined, which involved testing fuel-ethanol mixtures at various engine speeds and injection pressures. The findings of this investigation revealed that engine torque and power did not differ significantly across the four cases, while exhaust emissions produced were also similar. However, the results highlighted that ethanol injection pressure could significantly reduce fuel consumption for case A-04 and increase the air-fuel ratio. Further research is required to explore the potential benefits of this dual injection system by examining various fuel and ethanol mixtures with different variations and exploring the use of other cosolvent variations, such as methanol. Injection pressure plays a critical role in atomization and enhances the pressure and temperature in the combustion chamber, thereby producing higher engine power compared to the single injection system.


## Acknowledgements

This research is supported by the Mechanical Engineering Laboratory, Universitas Gadjah Mada.


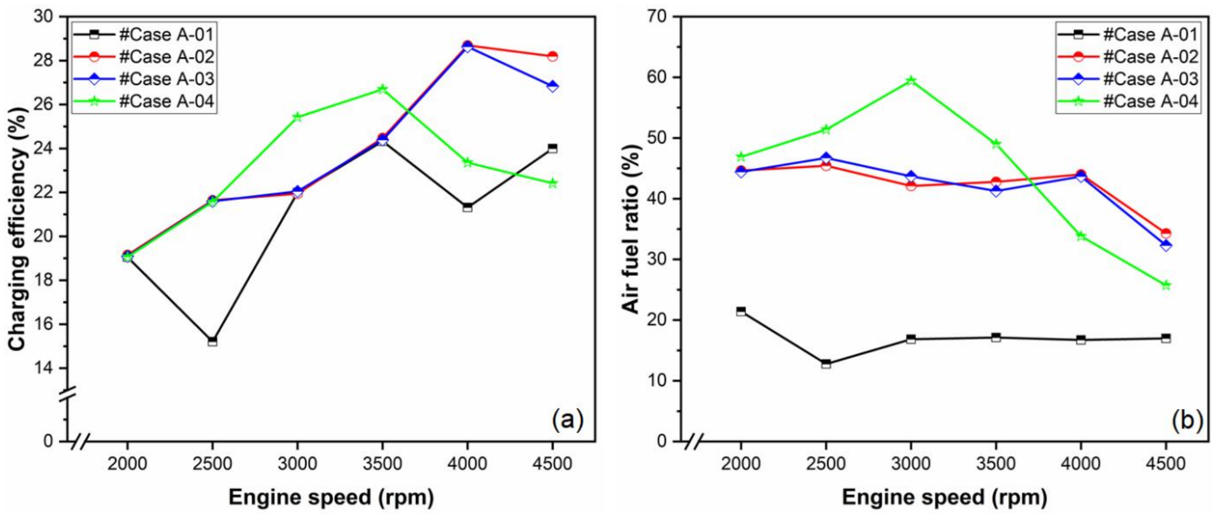


**Figure 9.** (a) Charging efficiency and (b) air-fuel ratio (A/F) vs. engine speed for pressure variations

## Author's Declaration

### Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript

### Funding

No funding information from the authors.

### Availability of data and materials

All data are available from the authors.

### Competing interests

The authors declare no competing interest.

### Additional information

No additional information from the authors.

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