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An experimental study on the effects of bioethanol-Gasoline blends on spark-ignition engine performance

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Abstract

Bioethanol is a clean fuel, renewable energy source that can be used in place of fossil fuels. Bioethanol has similar characteristics to gasoline fuel, making it an excellent alternative fuel for SI engines, contributing to the reduction of air pollution, the increased use of biofuels, and the removal of fossil fuel consumption. Analysis of the SI engine performance using gasoline fuel with an octane rating of 90 and gasoline-bioethanol blends containing up to 20% bioethanol concentration, each fuel blended at 5% by volume fraction. The purpose of this study is to present the experimental results for a spark ignition (SI) engine with a single injector that operates by using a gasoline-bioethanol blend as fuel. Analysis of the SI engine performance by using gasoline fuel with an octane rating of 90 and gasoline-bioethanol blends containing up to 20% bioethanol concentration. Each fuel was blended with bioethanol at an interval of 5% by volume fraction. The test was conducted on an SI engine with a capacity of 1500 cc, four cylinders, and a single injector was used to distribute fuel to each cylinder through the intake manifold. The shaft of the engine is connected to a 75 kW of eddy current dynamometer shaft to measure the engine torque. The engine load is controlled using an interface computer system. Load on an engine is done by increasing braking on the dynamometer, and real-time signals from the sensors are recorded. Each fuel sample is operated at full load or wide-open throttle (WOT) at speeds ranging from 1000 to 5500 revolutions per minute (rpm). The experiments show that adding bioethanol to gasoline fuel can have a significant effect on the single injector SI engine performance. When the bioethanol concentration of 10% (E10) by volume is used, it is possible to maintain engine power with lower fuel consumption or lower the energy supply to the engine cylinder, thereby increasing the thermal efficiency of the single-injector SI engine by 6.33% compared to gasoline fuel.

Keywords:
bioethanol, single injector, brake power, efficiency, brake fuel consumption.

1. Introduction

Energy consumption increases drastically every year, which affects fossil fuel availability. This is caused by the increasing number of human beings, industrialization, and transportation. The main cause of energy scarcely is the increasing energy needed in various sectors, which causes fossil fuel exploitation to continue [1]. The rapid increase of energy demand causes a rising price of world energy fuel, resource depletion of fossil fuel, and raised toxic gas emissions. These increase concern about future global warming and encourage researchers to develop alternatives to reduce fossil fuel use [2-4].

There have been many studies on developing alternative fuels. One of them is using natural gas and biofuel as alternative solutions to increase the use of new energy resources as vehicle fuels. Bioethanol is an alternative new fuel for Spark Ignition (SI) engine that are being studied dan keep being developed [5, 6]. It was chosen for having similar characteristics to gasoline that contribute to decreasing greenhouse emissions and increasing the quality of the environment [7].

Ethanol and bioethanol, also called ethyl alcohols, were originally found from biomass, which can be used as new fuels and oxygenated additive fuels for gasoline. They potentially reduce emissions. [8]. Ethanol which consists of carbon, oxygen, and hydrogen, has good properties in SI engine. Its automatic high ignition temperature, speed ignition, and latent heat of vaporization make it possible to be used in a higher compression ratio than gasoline fuels to increase torque and energy conversion efficiency [9-11].

Bioethanol has a high-octane value, around 108.61–110, resulting in a high autoignition temperature of approximately 424–434 °C [10], compared to gasoline fuels, which are around 257 °C [12]. Octane number is one of the quality fuel parameters [13]. A high-octane number can avoid detonation or engine deterioration. Furthermore, the engine can operate with a higher compression ratio, which increases its thermal efficiency [14-18]. A mixture of gasoline and ethanol showed that the addition of 10% ethanol with an octane number of 88 increased the octane number of that mixture to 92.5. Gasoline with an octane number of 92 increased to 95.6, while the addition of 30% ethanol to the volume fraction yielded an octane number of 100.6 [19].

Another characteristic to increase engine combustion efficiency is flame speed/burning speed, which has different values for each fuel [15]. The laminar flame speed plays an important role when an engine is operated at a higher speed, where the amount of fuel injected into the cylinder is greater than when the engine is operating at a low speed, but the availability of time to complete fuel burning is shorter at high engine speed. This becomes important to consider the high flame speed of the fuels to finish the combustion in a short time or shorter combustion duration [12].

Based on the higher laminar flame speed of bioethanol compared to gasoline fuel, as shown in Table 1, it can be stated that the addition of ethanol fraction into the gasoline fuel contributes to increasing the flame speed of the fuel, resulting in the combustion duration being shorter, especially at high engine speed [20].

Table 1. Fuel properties [22-24]

Characteristics	Gasoline	Ethanol
Chemical formula	C_4 - C_{12}	C_2H_5OH
Density (kg/m^3)	720 - 775	785 - 809.9
Ignition energy (MJ)	0.24	0.7
Auto ignition temperatures (℃)	>257	365 - 425
Adiabatic flame temperature (K)	2270	1920
Low calorie value (MJ/kg)	43	26.9
Latent heat vaporization (kJ/kg)	340	841 - 900
Flame ability limit (vol.%)	0.6 - 8	3.3 - 19
Ignition speed (m/s)	0.4	0.61
Stoichiometry of air-fuel	14.2 - 15.1	8.93 - 9
Octane value	95	103 - 108
Vaporization pressure @37.8 ℃ (kPa)	53-60	17
Laminar speed ignition @100 kPa, 325 K (cm/s)	33	39
Laminar speed combustion (cm/s)		39

The effects of the flame speed of gasoline, iso-octane, and ethanol have been compared on the SI engine. In comparison to pure gasoline and isooctane, the duration of combustion was shorter when ethanol was used [21]. This is possible due to the high flame speed of ethanol, which affects the increase in fuel burn rate in the cylinder. Table 1 shows the comparison of fuel characteristics.

Flame speed is also influenced by the fuel-air equivalence ratio, the amount of residual gas that is trapped inside a cylinder from a previous cycle, and spark timing [25]. The experimental result of natural gas fuel at 0.6–1.4 fuel-air equivalence ratio, the maximum burning speed, was obtained close to stoichiometry [26].

The higher burning speed can cause increasing in flame ignition propagation, so it can stabilize the combustion process and shorten combustion duration [27]. The combustion stability could be achieved while the engine is operated at a lower fuel-air equivalence ratio than stoichiometry and produces a higher cylinder pressure compared to gasoline at a similar fuel-air equivalence ratio. Improved combustion stability as the ethanol fraction in gasoline increases. This phenomenon is an effect of decreasing combustion duration. In addition, the engine could be operated at a lower fuel-air equivalence ratio, which reduces nitric oxide emissions (NOx). This method increases thermal efficiency and decreases exhaust gas emission, also engine fuel consumption [20]. Generally, the addition of a small fraction of oxygen-containing fuels to gasoline produces a higher flame speed of fuel mixture compared to pure gasoline [28].

The effects of mixed bioethanol into gasoline have been observed for 5%, 10%, 15%, dan 20% operated on SI engine controlled by an engine control unit (ECU) system. The fuel is injected by using the injectors for each cylinder. The results show the fraction of 20% obtaining the highest power, thermal efficiency, volumetric efficiency, and decreasing specific fuel consumption. The emission of carbon monoxide (CO) and hydrocarbon (HC) also decrease, whereas carbon dioxide (CO_2) and NO_x increase [29]. Similar results were reported by using an ethanol-gasoline mixture of up to 15% on SI engine with an electronic fuel injection (EFI) controlled system. The experiment shows the result of the maximum power, torque, and thermal efficiency on 15% of the fuel mixture. CO emissions were produced lower compared to gasoline fuel. [30].

The advantages of using ethanol as fuel for internal combustion engines are that it is a renewable energy resource and sustainable that can be produced using simple technology. In another hand, the ethanol has the high anti-knocking characteristic to substitute Tetra Ethyl Lead (TEL) or Tetra Metil Lead (TML), high flame speed, and low fuel-air equivalence ratio [31].

Considering those advantages, this study examined the effects of mixing gasoline-bioethanol E5, E10, E15, and E20 as fuels on a single-injector SI engine to inject the fuels into four cylinders distributed through an intake manifold. A single injector was fitted to the throttle body in a position further than the entry valve to increase the homogeneity of the mixture by increasing the flow turbulence of the fuel-air mixture in the intake manifold to each cylinder, which can improve the engine's performance.

2. Research Methods

2.1. Experimental design

The study used a four-stroke engine with four cylinders and a single injector fitted into an intake manifold to distribute the fuel to all cylinders with a water-cooled, 10:1 compression ratio in a 1.500 cc capacity. Maximum power of 66 kW at 5,000 rpm and maximum torque of 145 Nm at 5.000 rpm. To measure engine operating conditions, several sensors are equipped to detect intake air temperature, exhaust gas temperature, fuel temperature, lubricant temperature, and cooling water temperature as shown in Table 2. For accurate measurement of fuel flow rate, the variable area flowmeter magnetic sensor was used during the experiment. The volume of air intake and exhaust gas were measured using an orifice plate sensor. Sensor positions are shown in Fig. 1.

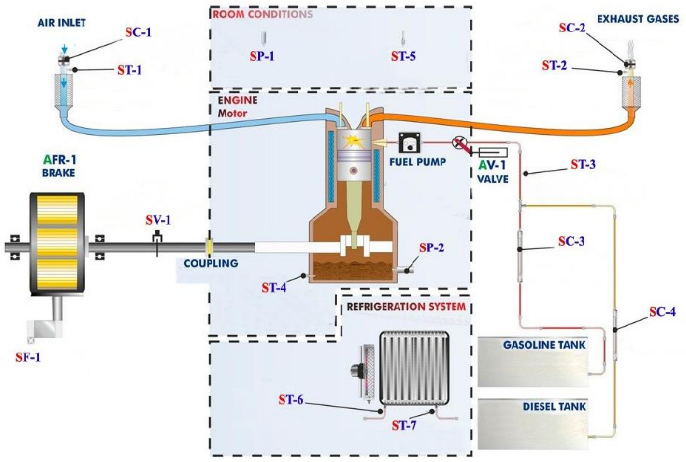

Fig. 1. Schematic diagram of engine [32]

Table 2. Sensor specification used

Sensor Code	Sensor	Type/Range
ST1-7	Temperature	-210°C - 1200°C
SV-1	Engine speed	0- 6000 rpm
SF-1	Load cell	0 - 350 N·m
SC-1	Flow meter air intake	0 - 600 m³/h.
SC-2	Flow meter exhaust gas	0 - 600 m³/h.
SC-3	Flow meter fuel rate	0 - 350 ml/min
SP-1	Environmental pressure	0 - 1 Bar
SP-2	Lubricant pressure	0 - 8 Bar.

Engine torque was measured by using a 75 kW eddy current dynamometer designed by EDIBON, Spain. The engine shaft was connected directly to the dynamometer shaft which braking was controlled using a personal computer. The real-time data from the sensors were recorded during the experiment.

The experiment was conducted on a single-injector engine operated at full load or wide-open throttle (WOT) with a maximum engine speed of up to 5500 rpm. Engine loading by the dynamometer was applied while the engine speed closed to the maximum of 5500 rpm and the rotation decreased to around 1000 rpm. During the experiment, all parameters were recorded at 0.25 second intervals.

The experimental procedure of SI engine performance by using a bioethanol-gasoline fuel blend of up to 20% was simultaneous with the 5% interval of bioethanol concentration in the gasoline as shown in Fig. 2.

The bioethanol concentration was used up to 20% for the experiment. The gasoline had a 90 octane number was used, namely Pertalite, produced by Pertamina. The bioethanol used was 99.5%, or fuel-grade bioethanol.

The experiment began with pure gasoline (E0) as the first measurement, then continued with adding 5% bioethanol to 95% gasoline (E5), 10% bioethanol to 90% gasoline (E10), 15% bioethanol to 85% gasoline (E15), and 20% bioethanol to 80% gasoline (E20) based on volume. The fuel properties are shown in Table 3.

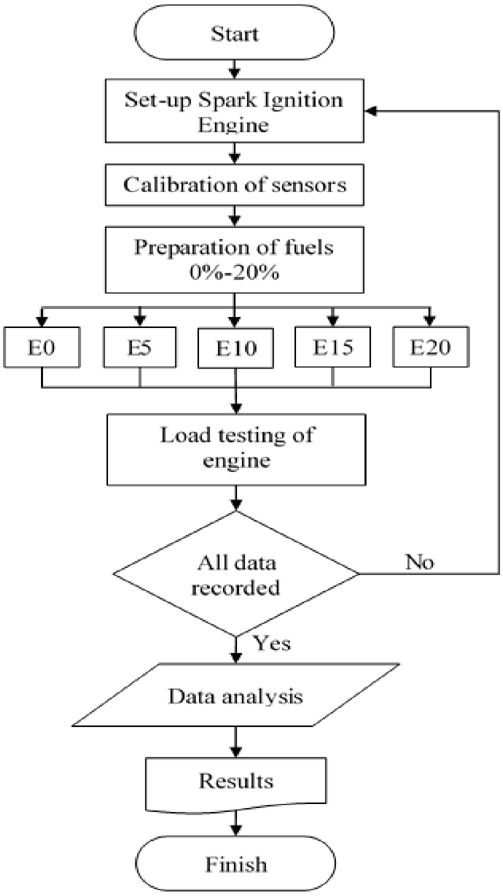

Fig. 2. Flowchart of the experimental design

Table 3. Fuel properties

Properties	Bioethanol concentrations				
	0% (E0)	5% (E5)	10% (E10)	15% (E15)	(20%) E20
Density (kg/m^3)	744.00	745.95	747.90	749.85	751.80
LHV (kJ/kg)	44000	43145	42290	41435	40580
RON	90	90.9	91.8	92.7	93.6
AFR stoich	15.051	14.923	14.787	14.641	14.486
Lat. Heat (kJ/kg)	349	377.7	406.4	435.1	463.8
Ignit. speed (m/s)	0.4	0.4105	0.421	0.4315	0.442

2.2 Data Analyses

The performance of an SI engine is related to the fuel consumption, air-fuel ratio, volumetric efficiency, air consumption, brake power, specific fuel consumption, thermal efficiency, fuel density, stoichiometry of air-fuel mixture, and lower heating value (LHV) of the fuel.

The energy of bioethanol was measured using gasoline and bioethanol LHV ratio, from Equations 1 and 2 based on volume and mass, respectively [23].

$$EER = \frac{\dot{v}_e \rho_e LHV_e}{\dot{v}_e \rho_e LHV_e + \dot{v}_g \rho_g LHV_g} \quad (1)$$

Mass based

$$EER = \frac{m_e LHV_e}{m_e LHV_e + m_g LHV_g} \quad (2)$$

Brake power is the actual power output produced by the engine shaft [33, 34]. Brake power is obtained using the equation 3.

$$bP = \frac{2\pi N bT}{60000} \quad (3)$$

bP is defined as brake power (kW), engine speed N (rpm), and bT is brake torque (N.m) obtained from the load cell (SF-1). Therefore, brake thermal efficiency η_{bth} (%) was calculated by using equation 4.

$$\eta_{bth} = \frac{bP}{\dot{m}_f \times LHV} \times 100 \quad (4)$$

$$(LHV)_b = \sum \left(\frac{\rho_i v_i}{\rho_b} \right) (LHV)_i \quad (5)$$

$\dot{m}_f$ is the mass flow rate of fuel (kg/s) calculated using the equation 6.

$$\dot{m}_f = \dot{V}_f \times \rho_f \quad (6)$$

$\dot{V}_f$ is fuel flow rate (m^3/s) obtained from fuel flowmeter (SC-3) sensor, ρ_f is density (kg/m^3). Brake specific fuel consumption *bsfc* (*gram/kW.h*) can be calculated by the equation 7.

$$bsfc = \frac{\dot{m}_f}{bP} \quad (7)$$

Brake-specific fuel consumption is the ratio of fuel mass flow rate to the brake power of the engine, or the required mass of fuel to produce 1 kW of the engine's power.

3. Result and Discussion

The effects of the gasoline-bioethanol mixtures on the engine torque are shown in Fig. 3 and Fig. 4. The result shows the engine torque decreasing along with increasing engine speed for all various fuel mixtures. Fig. 3 shows the closest value of torque was obtained at 5% bioethanol concentration, and the lowest value was obtained at 20% concentration of bioethanol at all various engine speeds. The trend of the engine torque for all various bioethanol concentrations is shown in Fig. 4, which clearly shows the decreasing engine torque affected by increased bioethanol concentration at all various engine speeds.

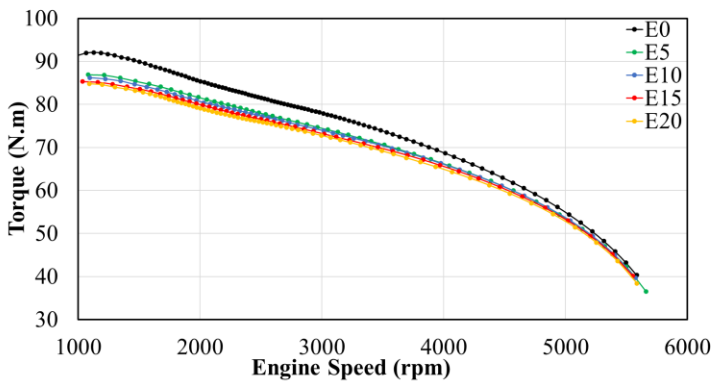

Fig. 3. Bioethanol addition effects on torque in various engine speed

The lowest torque is 5 N.m, obtained at 1000 rpm and decreasing along with the increase up to 5000 rpm of engine speed with a difference of about 3.3 N.m. The decrease in torque caused by the addition of bioethanol is due to a decrease in input energy, or lower energy from the fuel inducted into the cylinder during the intake process. The torque difference obtained at low engine speed is higher compared to the engine operated at high engine speed. This is affected by increasing friction losses of engine components proportional to the increase in engine speed [15,16].

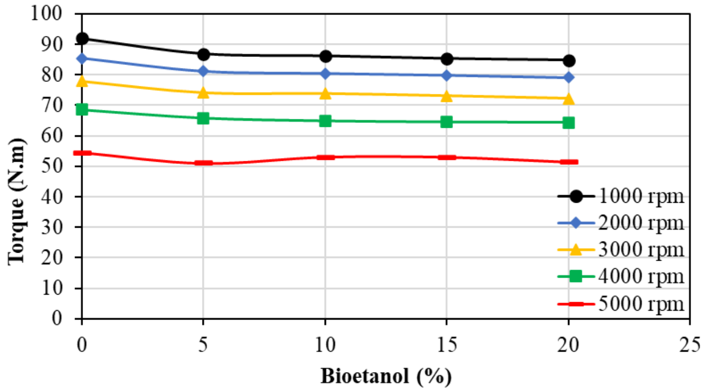

Fig. 4. Bioethanol addition effects on torque

The power refers to the load given on an engine and holding it at a specific engine speed. The increased power is proportional to increase engine speed [33]. This is due to more cycles occurring at the same time. According to equation 3, the power is proportional to the torque and the engine speed. Fig. 5 shows the power increases proportionally to the increase in engine speed. Compared to pure gasoline, all concentrations of fuel mixture generated less engine power. Fig. 6 shows the power significantly decreases when the engine is operated by using E5 fuel.

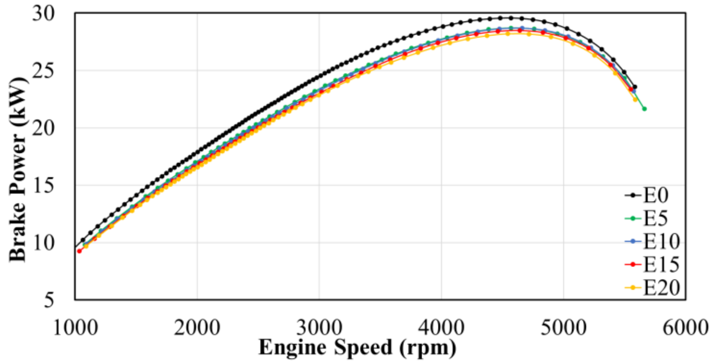

Fig. 5. Bioethanol addition effects on brake power deviation

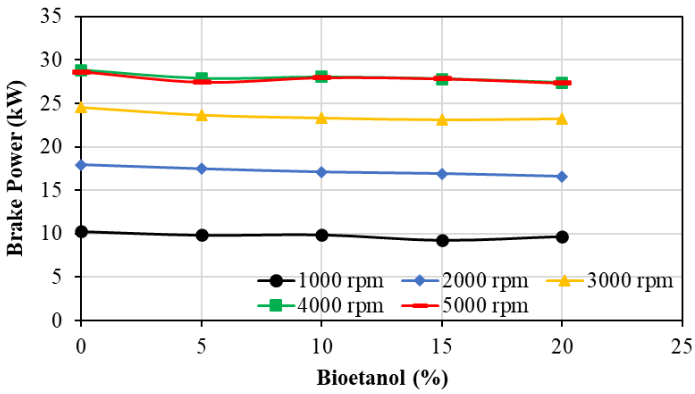

Fig. 6. Bioethanol addition effects on brake power

However, the higher concentration of bioethanol maintains the power more stable at various engine speeds. The E5 fuel produces the closest power to the power generated by pure gasoline fuel, with the highest power produced at an engine speed of about 4,500–4,600 rpm, which is 28.685 kW, decreasing by 0.89 kW, about of 3%. The existence of bioethanol reduces the energy content of the fuel mixture, which has a negative effect on power output. Table 3 shows, decreasing energy is proportional to increasing bioethanol concentration, resulting in a decreasing LHV of the various fuel mixtures. At the same time, the lowest power is produced by using E20 fuel with 28.2 kW, which is 1.373 kW about 4.6% lower than E0 fuel. The decreasing power was also obtained in the experiment conducted by A. Verma et. al. [34] with an ethanol concentration of 20% in gasoline, while the highest power was achieved at 6.25 % of concentration.

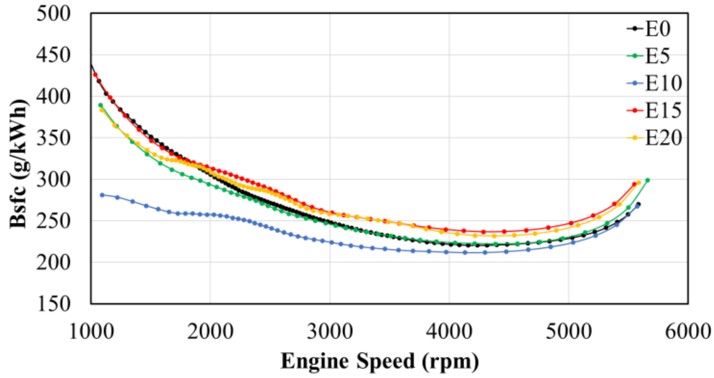

Fig. 7. Brake specific fuel consumption of engine speed

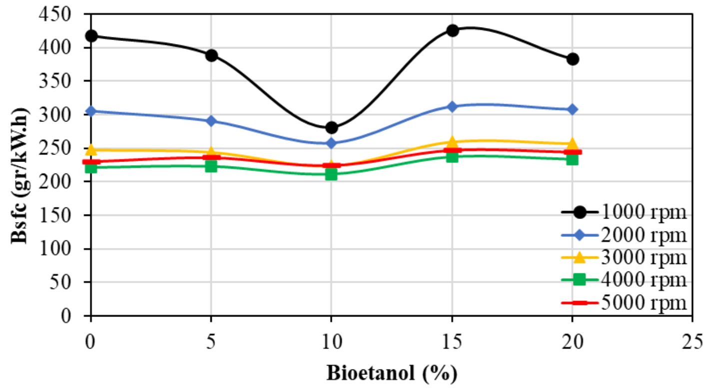

Fig. 8. Bioethanol addition effects on brake specific fuel consumption

Brake specific fuel consumption (bsfc) is a measure of the amount of fuel efficiently converted into engine power [16]. Fig. 7 shows decreasing bsfc as increasing engine speed up to 4,500 rpm, and it increases again at higher speeds for all fuel mixtures. The lower the bsfc is obtained, the higher the energy conversion efficiency of the SI engine. The increase in bsfc is caused by friction losses at a higher rotational speed of the engine [15].

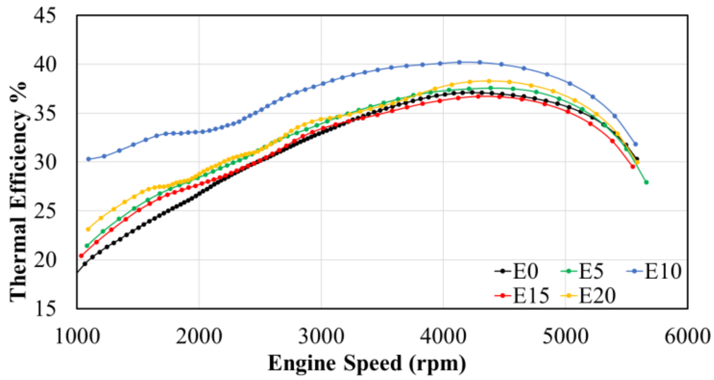

Fig. 9. Bioethanol addition effects on the highest Thermal efficiency

The highest bsfc was obtained from a 10% concentration of bioethanol, and the concentration of 5% was closer to gasoline fuel at the engine speed above 2,000 rpm, as shown in Fig. 8.

On the other hand, bioethanol concentrations of 15% and 20% required higher fuel mass to generate the engine power at the same speed rotation due to the low energy content in bioethanol fuel [35].

Thermal efficiency is the ratio of engine power produced to the energy input of fuel, converted through the combustion process [34]. The higher thermal efficiency is obtained in a cycle, the greater thermal energy can be converted to mechanical energy. Fig. 9 shows the maximum thermal efficiency achieved of 40.2% by using E10 fuel at various engine speeds, followed by the mixtures of E20 and E5.

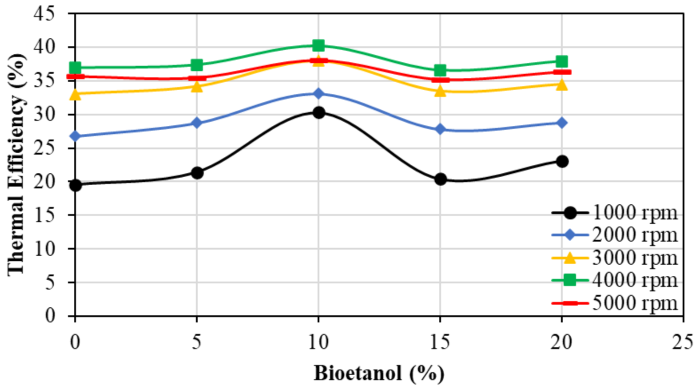

Fig. 10. Bioethanol addition effects on thermal efficiency

On the other hand, E15 produced lower efficiency when the engine was running at above 3500 rpm. However, the higher thermal efficiency of E15 fuel generated at engine speeds below 3,500 rpm compared to pure gasoline fuel.

At various engine speeds, increasing thermal efficiency was obtained for all bioethanol concentrations, as shown in Fig. 10. This is caused by the higher flame speed possessed by bioethanol compared to gasoline, which causes an increase in the combustion rate that affects decreasing combustion duration and produces higher cylinder pressure [12]. Furthermore, bioethanol consists of oxygen that contributes to complete combustion [28].

4. Conclusion

The results of an experimental study on the effects of bioethanol addition to gasoline operated in a single-injection SI engine with a concentration of mixture of E5 to E20, the following can be concluded:

1. The effects of flame speed and oxygen contained in bioethanol contribute to the increasing thermal efficiency of the single-injection SI engine.
2. The increasing of bioethanol concentrations in gasoline, decreases energy contained of fuel mixture, so that increasing the fuel consumption to produce power output.
3. The E10 fuel mixture is the best mixture used on a single-injection SI machine to produce higher power with lower mass fuel consumption.

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