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Performance and emission analysis of a multi cylinder gasoline engine operating on different alcohol-gasoline blends

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Abstract

Alcohols are potential renewable alternatives for gasoline because of their bio-based origin. Although ethanol has been successfully implemented in many parts of the world, other alcohols may also be utilized, such as methanol, propanol, and butanol. These alcohols contain much energy and a high octane number. Furthermore, they displace petroleum. Therefore, this study focuses on methanol, ethanol, propanol, and butanol as gasoline fuel alternatives. We conducted tests in a four-cylinder gasoline engine under the wide open throttle condition at varying speeds and results. This engine was fueled with 20% methanol/80% gasoline (M20), 20% ethanol/80% gasoline (E20), 20% propanol/80% gasoline (P20), and 20% butanol/80% gasoline (B20). M20, E20, P20, and B20 displayed brake specific fuel consumptions levels and break thermal efficiencies that were higher than those of gasoline at 7.78%, 5.17%, 4.43%, and 1.95% and 3.6%, 2.15%, 0.7%, and 1.86%, respectively. P20 and B20 showed better torque than E20, but they consumed more fuel. Moreover, the alcohol—gasoline blends generated a higher peak in-cylinder pressure than pure gasoline. As gasoline fuel alternatives, propanol and butanol were more effective than gasoline in engines. In addition, the alcohol–gasoline blends also emitted less carbon monoxide and hydrocarbon than gasoline. However, E20 emitted more nitrogen oxide than

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the other alcohol–gasoline blends. Thus, propanol and butanol are more effective options than ethanol for a gasoline engine in terms of fuel properties, engine performance, and emissions.

Key words: Ethanol; Alcohol gasoline, Performance, Emission, Gasoline engine.

Introduction

For researchers and manufacturers in the field of energy, the replacement of petroleum gasoline with alternative fuels is an important issue given rising petroleum fuel prices, environmental threats from engine exhaust emissions, fossil fuel depletion, the effects of global warming, and energy concerns.[1] Global energy consumption has increased sharply recently, and it will increase by approximately 53% by 2030, according to the International Energy Agency.[2] The United States Energy Information Administration projects that the liquid fuel consumption in the world will increase from 86.1 million barrels/day to 110.6 million barrels/day by 2035.[3] Furthermore, the burning of petroleum-derived fuel generates emissions that seriously affect both the environment and human health. In particular, the burning of fossil fuels is a main contributor to the increase in carbon dioxide (CO_2) emissions, which in turn aggravates global warming. If fossil fuel emissions are not strictly regulated soon, greenhouse gas (GHG) emissions from fossil fuels will increase by 39% by 2030. Hence, alternative fuel sources for clean combustion have received increased attention given several factors, such as worldwide environmental concerns, price hikes in petroleum products, and the expected depletion of fossil fuels.[4] Therefore, the development of clean alternative fuels that are locally available, environmentally acceptable, and technically feasible is a global concern. In the transport sector, biofuels can be a good substitute for fossil fuels because they can be adopted directly without altering the engine and fuelling processes.

The use of alcohols as substitutes for petrol in spark ignition (SI) engines has been investigated extensively. These alcohols enrich oxygen, enhance octane, and reduce carbon monoxide (CO) emission. As an alternative fuel, ethanol is the most widely used alcohol type.[5] It can be combined with gasoline because of its simple chemical structure, high octane number and oxygen content, and accelerated flame propagation.[6] Many experimental studies have confirmed that ethanol increases engine efficiency, torque, and power. However, its brake specific fuel consumption (BSFC) is higher than that of gasoline.[7]

Balki et al.[8] studied the performance, combustion, and emission characteristics of a single-cylinder gasoline engine fuelled by gasoline, ethanol, and methanol. Pure ethanol and methanol enhanced torque by 3.7% and 4.7%, at the expense of a 58% and 84% increase in BSFC, respectively, compared with those of gasoline fuel. Nitrogen oxide (NOx), CO, and hydrocarbon (HC) emissions by engines containing methanol and ethanol decreased by 49% and 47.6%, 22.6% and 21.25%, and 21.6% and 19.13%, respectively, compared with those emitted by gasoline. However, CO_2 emissions increased by 4.4% and 2.51%. Costa and Sodré [9] investigated the performance and emission of hydrous ethanol (6.8% water content) and a blend of 78% gasoline–22% ethanol (E22) at varying speeds. Hydrous ethanol displayed a higher break thermal efficiency (BTE) and BSFC than E22 throughout the entire speed range. However, torque and break mean effective pressure increased with engine speed. Moreover, hydrous ethanol reduced CO and HC emissions but increased CO_2 emissions. Koç et al. [7] experimentally investigated the performance and pollutant emissions of unleaded gasoline–ethanol blends. The torque and BSFC values of E50 and E85 were higher than those of gasoline by 2.3% and 2.8% and 16.1% and 36.4%, respectively. Moreover, the addition of ethanol to gasoline significantly reduced CO, HC, and NOx emissions. Ethanol–gasoline blends also accommodated high compression ratios without inducing knocking.

In many countries, governments mandate the integration of ethanol with gasoline. The Environmental Protection Agency (EPA) issued a waiver that authorizes the incorporation of up to 15% ethanol into gasoline for cars and light pickup trucks made in 2001 onwards.[10] The

US Renewable Fuel Standard mandates the production of up to 36 billion gallons of ethanol and advanced bio-fuels by 2022.[11] To meet the high demand for ethanol, alcohols with increased carbon numbers can be utilized as enhanced alternatives because the use of ethanol as fuel in gasoline engines is mainly limited by its low heating value (LHV). Hence, additional low-LHV fuel must be generated to match a certain power level.[12] Alcohols with high carbon numbers, such as propanol and butanol, have a higher LHV than ethanol. Therefore, they can overcome this shortcoming. Furthermore, all of these alcohols can be derived from coal-derived syngas, which is a renewable energy source.[13] Ethanol can also be converted into alcohols with high carbon numbers and fermented to enhance alcohol production through biorefinery.[14]

Some studies have compared different alcohol—gasoline blends. Gravalos et al.[15] integrated approximately 1.9% methanol, 3.5% propanol, 1.5% butanol, 1.1% pentanol, and variable concentrations of ethanol with gasoline in a single-cylinder gasoline engine. A total of 30% alcohol was incorporated into the gasoline. The alcohol—gasoline blend emitted less CO and HC but more NOx and CO_2 than pure gasoline. In the present study, multiple alcohol–gasoline blends also emit more acceptable levels of CO and HC than the ethanol—gasoline blend. Yacoub et al.[16] integrated methanol, ethanol, propanol, butanol, and pentanol with gasoline in an engine and analyzed its performance and emissions. Each alcohol was blended with gasoline containing 2.5% and 5% oxygen. The alcohol—gasoline blend displayed better BTE, knock resistance, and emissions than gasoline, but its BSFC was higher. Alcohols with low carbon content (e.g. C1, C2, and C3) contain high levels of oxygen. Hence, relatively less of these alcohols is required to reach the targeted oxygen percentage than alcohols with high carbon content (e.g., C4 and C5). Alcohol percentage and properties varied across blends. Thus, different alcohol—gasoline blends cannot be compared properly under optimized oxygen concentrations. Gautam et al. [17] prepared six alcohol—gasoline blends with various proportions of methanol, ethanol, propanol, butanol, and pentanol that total 10% alcohol. The alcohol–gasoline blends emitted lower brake specific CO, CO_2, and NOx than pure gasoline. However, these researchers did not blend specific volume percentages of alcohol or consider fuel properties.

Thus, few studies compare specific percentages of alcohols, such as methanol, ethanol, propanol and butanol, with respect to performance and emission characteristics in the gasoline of an SI engine. Moreover, very few studies focus on the partial replacement of gasoline with propanol as an SI engine fuel. Nonetheless, the derivation of alcohols with high carbon numbers from renewable sources has increasingly been investigated.[18-22] In particular, the application of such alcohols as gasoline engine fuel must be examined extensively. Thus, this research aims to determine the effect of methanol–gasoline, ethanol–gasoline, propanol–gasoline, and butanol–gasoline blends on engine performance, combustion, and exhaust emissions. The results obtained with these blends are compared with those of gasoline and the commonly used ethanol–gasoline blend in gasoline engines.

Materials and method

Fuel selection

In this study, we utilized methanol, ethanol, and branched isomers of propanol and butanol (99.8% purity) given their high octane numbers. We procured the ethanol from Chemical Industries (Malaya) Sdn Bhd., Malaysia and the other alcohols from QREC Chemical Company, Thailand. We obtained Primax 95 gasoline with research octane number (RON) 95 from PETRONAS, Malaysia as the base gasoline. We blended methanol, ethanol, propanol, and butanol with gasoline (M20, E20, P20, and B20, respectively) at volume concentrations of 20% alcohol and 80% gasoline. Table 1 lists the properties of the gasoline and the alcohol–gasoline blends.

Table 1: Properties of pure gasoline and different alcohol-gasoline blends.

Experimental setup

We experimented on a four-cylinder gasoline engine at the Engine Laboratory of the Mechanical Engineering Department in the University of Malaya. Table 2 details the engine, and Fig. 1 depicts the schematic of the experimental setup. The test engine was coupled with an eddy current dynamometer (Froude Hofmann model AG150, United Kingdom) with a maximum power of 150 kW. The engine was first operated on gasoline for a few minutes to stabilize the operating condition. The fuel was then changed to the alcohol blend. After sufficient amounts of the blend were consumed, data were acquired to ensure the removal of residual gasoline from the fuel line. Each test engine was again operated under gasoline to drain all of the blends in the fuel line.

The engine was operated between 1000 rpm to 6000 rpm with a step of 1000 rpm at 100% load condition. We measured fuel flow using a KOBOLD ZOD positive-displacement type flow meter (KOBOLD, Germany). The data were automatically collected using the CADET 10 data acquisition system. To analyze combustion, we applied a pressure sensor and crank angle encoder (RIE-360). Both sensors vary the in-cylinder pressure at a crank angle. The data were digitally recorded by a computer using the DEWESoft combustion analyzer software. Exhaust emissions were measured using the AVL DICOM 4000 exhaust gas analyzer (AVL DiTEST, Austria), where CO, NO, and HC are determined by non-dispersive infrared, heated chemiluminescence, and heated flame ionization detectors. Table 3 exhibits the accuracies of the measured parameters. In each test, performance and emission were measured in triplicate. These measurements were highly repeatable within the test series.

Fig. 1: Schematic diagram of the engine test bed

Table 2: Specification of the tested engine

Table 3: Specifications of the exhaust gas analyzer

Results and Discussion

Engine performance analysis

Torque

Torque is a turning force produced by the pressure from the crankshaft of the piston. Engine torque depends on engine stroke length, charge condition, and average effective cylinder pressure.[23] Under a constant engine condition, torque varies given different fuels as a result of the fuel properties and the effective pressure generated. Fig. 2 compares the engine torque given the test fuels. On average, M20, E20, P20, and B20 significantly increased the torque of gasoline by 5.02%, 3.39%, 10%, and 9.2%, respectively ($0.0003 < p < 0.011$). As indicated in this figure, torque was maximized at 4000 rpm in all fuels. The increased torque may be attributed to the high latent heat of vaporization (HoV). Fuel vaporizes in the intake manifold and in the combustion chamber. When the Latent heat of vaporization (LoV) of alcohol increases, charge temperature is lowered as the alcohol evaporates. Furthermore, charge density increases. Engine torque is also enhanced by associated fuel mass at the same air–fuel ratio. This result is consistent with those obtained by other researchers.[24, 25] Moreover, the incorporation of oxygenated alcohol produces a lean mixture that burns more efficiently than gasoline.[7] The maximum brake torque timing increases combustion pressure and torque as a result of the enhanced anti-knock behavior.[26] P20 obtained the ideal engine torque (138.2 Nm) at 4000 rpm. This improved torque may be attributed to the enhanced RON of propanol because high RON aggravates ignition delay, which decelerates energy release rate and limits heat loss from the engine because the heat from the cylinder is not transferred to the coolant in time.[13] Hence, engine torque decreases after it is maximized by engine acceleration.

Fig. 2. Variation of torque with engine speed.

Brake specific fuel consumption

Fig. 3 depicts the variation in the BSFC of the test fuels at different engine speeds. On average, the BSFC values of M20, E20, P20, and B20 were higher than that of unleaded gasoline by 7.58%, 5.17%, 4.43%, and 1.95%, respectively. This result is typically ascribed to the low energy content of the alcohols, which enhances engine BSFC when it is applied directly.[8] Therefore, increased amounts of fuel are required to produce the same level of engine power as that generated by low LHV fuel. The high BSFC of alcohol may also be induced by high alcohol density.[7] Nonetheless, the BSFC of B20 is closer to that of gasoline than the other alcohols. Furthermore, P20 and B20 displayed BSFC values that were 2% and 4% lower, respectively, than that of E20. Alcohols with high carbon number consumed less fuel because LHV increases with carbon number (Table 1). In all test fuels, BSFC decreased with engine acceleration because the volumetric and combustion efficiencies increased.[27]

Fig. 3. Variation of BSFC with engine speed.

Brake thermal efficiency

Fig. 4 displays the BTE values of the different test fuels. On average, the thermal efficiencies of M20, E20, P20 and B20 were significantly higher than that of gasoline by 3.6%, 2.15%, 0.7% and 1.86%, respectively ($0.001 < p < 0.04$). Alcohol—gasoline blends with low carbon numbers have higher BTE values than those with high carbon numbers. This condition can be attributed to the fact that blends with low carbon numbers contain more oxygen than those with high carbon numbers. As a result, combustion is improved, thereby enhancing thermal efficiency.[28] Moreover, fuel is vaporized in the compression stroke when latent HoV is high. Given that fuel absorbs heat from the cylinder during vaporization, the air—fuel mixture is compressed more easily, thus improving thermal efficiency. Balki et al.[8] noted that the HoV and oxygen content of alcohol enhances BTE in alcohol—gasoline blends.

Fig. 4. Variation of BTE with engine speed.

Exhaust gas temperature

Fig. 5 presents the effect of test fuels on the EGT of the test engine, which is a significant indicator of cylinder temperature. EGT can also be used to analyze exhaust emission, especially of NOx because NOx formation often depends on temperature.[29] In this figure, the addition of alcohol to gasoline reduces EGTs, with the exception of ethanol. The heating value of alcohol is lower than that of gasoline; thus, the combustion temperature and EGTs of alcohol–gasoline blends are lower than those of gasoline. However, the high latent HoV of ethanol induces ignition delay and increases its EGT relative to other fuels. In all fuels, EGTs increase with engine speed. Moreover, EGT and combustion temperature increase as increased amounts of fuel burn at high engine speeds.

Fig. 5. Variation of Exhaust gas temperature with engine speed.

In-cylinder gas pressure

We can compare the combustion characteristics of different fuels based on cylinder gas pressure and heat release rate. Fig. 6 compares the cylinder gas pressures of all of the test fuels at an engine in full throttle load at a speed of 4000 rpm. All of the fuels displayed similar inlet and exhaust pressure curves because throttle angle was almost constant. Furthermore, the maximum pressures for all test fuels were close to the top dead center (TDC). As observed in the figure, cylinder gas pressure increased earlier in alcohol—gasoline blends than in pure gasoline. Furthermore, this pressure was higher in the blends. According to Melo et al.[30] explained alcohol increase spark timing and avoid knocking as a result maximum pressure obtained for using alcohol. Balki et al.[8] , the increase in alcohol enhanced timing and prevented knocking, thus maximizing the pressure obtained using alcohol. Balki et al. [8] added that high latent HoV and oxygen content in alcohols increases cylinder gas pressure. Moreover, Fig. 6 shows that the addition of alcohol shortens combustion duration compared with that of gasoline This finding is attributed to high laminar flame speed and RON by Balki et al.[8] The peak in-cylinder was highest for P20. It because of, heat release started early for P20 than others fuel as P20 is having higher RON.

Fig. 6. Comparison of in-cylinder pressure at 4000rpm

Engine emission analysis

CO emission

CO emission represents a loss in the chemical energy that is not fully utilized in the engine. It is a product of incomplete combustion given either an insufficient amount of air in the air–fuel mixture or the interruption of combustion cycle time.[31] Fig. 7 depicts the variation in CO exhaust emissions in relation to engine speed. In M20, E20, P20, and B20, CO emissions are significantly lower than those of gasoline by averages of 16.6%, 13.9%, 9.6%, and 5.6%, respectively ($p < 0.01$). Alcohols are oxygenated fuels; therefore, they enhance oxygen content in fuel for combustion. This process generates the “leaning effect”, which sharply reduces CO emission.[32] Thus, alcohol—gasoline blended fuel emits less CO than gasoline fuel. Table 1 shows that the alcohols with low carbon numbers contain much oxygen and possess a simple molecular structure. Hence, CO emission from the alcohol—gasoline blend with low carbon number is lower than that from the blend with high carbon number. Nonetheless, all of the alcohol—gasoline blends emit less gas at overall engine speed than gasoline. At high engine speed, CO emission is lower in alcohol—gasoline blends than in pure gasoline fuel. Furthermore, the engine has limited time to complete the combustion cycle; thus, flame speed must be increased to complete combustion.[25, 33] As a result of this increased flame speed in alcohol, alcohol—gasoline blends emit less CO at high engine speeds. This finding is consistent with that of previous studies, which utilized ethanol–gasoline blends.[9]

Fig. 7. Variation of CO emission with engine speed.

HC emission

Emissions of unburned HC are primarily caused by unburned mixtures induced by improper mixing and incomplete combustion. These emissions are a main contributor to photochemical smog and ozone pollution.[34] Fig. 8 exhibits the emissions of unburned HC by all test fuels at speeds ranging from 1000 rpm to 6000 rpm. These emissions were slightly lower in all alcohol—gasoline blends than in pure gasoline. On average, emissions of unburned HC by M20, E20, P20, and B20 significantly decreased by 10.7%, 14.9%, 5.4%, and 2.9%, respectively ($0.03 < p < 0.05$). This result may be attributed to the leaning effect and the oxygen content in the alcohol.[7] Moreover, these emissions decrease as engine speed increases in all blends. At high speeds, the air—fuel mixture homogenizes to increase in-cylinder temperature. This condition in turn enhances combustion efficiency. Thus, HC emission decreases more at high engine speeds than at low speeds. This conclusion is consistent with that of Koc et al.[7]

Fig. 8. Variation of HC emission with engine speed.

CO_2 emission

CO_2 is a GHG produced by the complete combustion of hydrocarbon fuel. Its formation is affected by the carbon–hydrogen ratio in fuel. Stoichiometrically, hydrocarbon fuel combustion should generate only CO_2 and water (H_2O). Fig. 9 presents the variation in CO_2 emission across different fuels. As per the study results, CO_2 emission is higher in alcohol–gasoline blends than in pure gasoline; on average, CO_2 emissions by M20, E20, P20, and B20 are 15%, 12%, 6.5%, and 5.8% significantly higher ($0.01 < p < 0.03$). This finding can be attributed to carbon flow rate. To attain a certain level of engine power given a constant throttle position, the amount of alcohol–gasoline blended fuel consumed must be higher than that of gasoline. Therefore, the carbon flow rates of the alcohol–gasoline blends are higher than those of gasoline.[30] The oxygen ratio in alcohols also enhances the combustion efficiency of alcohol–gasoline blends, which enhances CO_2 emission in alcohol—gasoline blends.

Fig. 9. Variation of CO_2 emission with engine speed.

NOx emission

During combustion at high temperature, nitrogen in the air oxidizes to form NOx. Thus, the generation of NOx in an engine is closely related to combustion temperature, oxygen concentration, and residence time inside the combustion chamber.[35] Fig. 10 exhibits the variation in NOx emission at WOT and at different engine speeds. On average, NOx emissions by M20, E20, P20, and B20 are significantly higher than that by pure gasoline at 20%, 32%, 14.5% and 11% ($0.001 < p < 0.05$). This results may be ascribed to the high oxygen concentration in the alcohol—gasoline blend. Among all of the fuels, E20 displayed the highest EGT, which indicated that it emitted the most NOx. Moreover, NOx emission increased with the acceleration of engine speed in all of the tested fuels. At high speeds, increased amounts of fuel are burned. Furthermore, torque and BSFC increase, and as a result, in-cylinder temperature increases. This increase may also enhance NOx emission instead of lowering heating value.[35]

Fig. 10. Variation of NOx emission with engine speed

Conclusion

This study mainly compares the performance, combustion, and emission characteristics of M20, E20, P20, and B20 as engine fuels. Based on experimental observation, we can draw the following conclusions:

- Alcohol–gasoline blends displayed better engine torque and BTE than gasoline. Torque was also enhanced in alcohol blends with high carbon numbers compared with those with low carbon numbers given their improved fuel properties such as RON, LHV etc. In particular, P20 exhibits the best torque and BTE among all of the fuels. Moreover, the BSFC levels of P20 and B20 are more acceptable than that of E20 at 1.21% and 3.06% because of their high LHV.
- In-cylinder gas pressure increases earlier in all alcohol–gasoline blends that in gasoline fuel because of the high flame speed of alcohol. Furthermore, the combustion duration of alcohol–gasoline blends was shorter than that of gasoline. Peak in-cylinder pressure was also higher for alcohol–gasoline blends (particularly the P20 blend) than for pure gasoline.
- All alcohol–gasoline blends emitted less CO and HC than gasoline. Specifically, E20 emitted the lowest amount. However, these blends emitted more NOx and CO_2 than gasoline. Moreover, P20 and B20 emitted 5-6% less NOx and 11-14% less CO_2 than E20. Thus, alcohol–gasoline blends are more environment-friendly than gasoline.
- In general, the fuel properties of P20 and B20 were superior to the other alcohol–gasoline blends. Furthermore, these blends enhanced engine performance and lowered emissions more effectively than the ethanol–gasoline blend in an unmodified gasoline engine.

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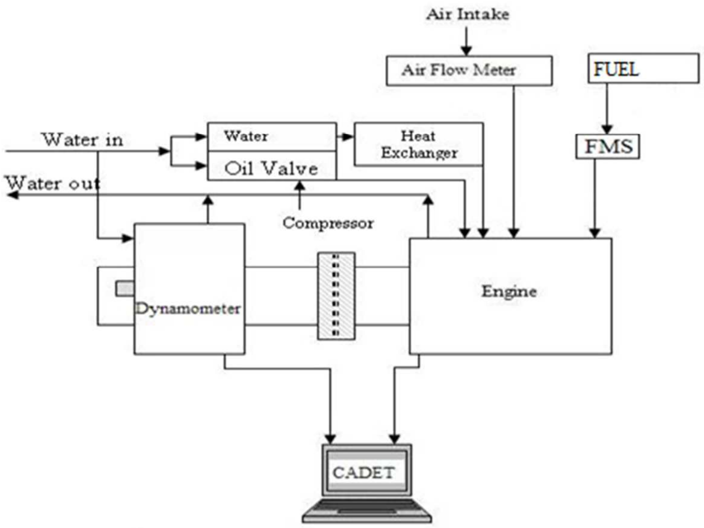

Fig. 1: Schematic diagram of the engine test bed

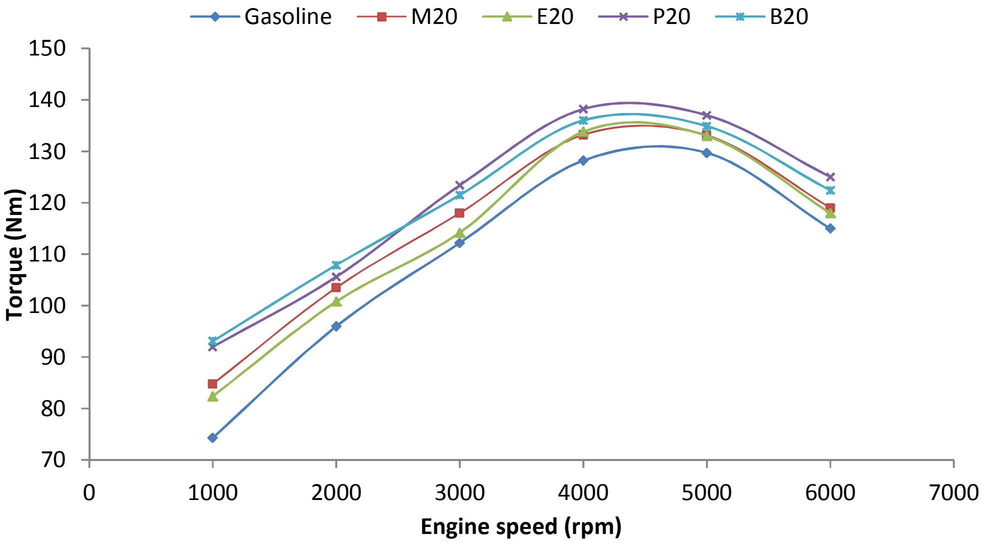

Fig. 2. Variation of torque with engine speed.

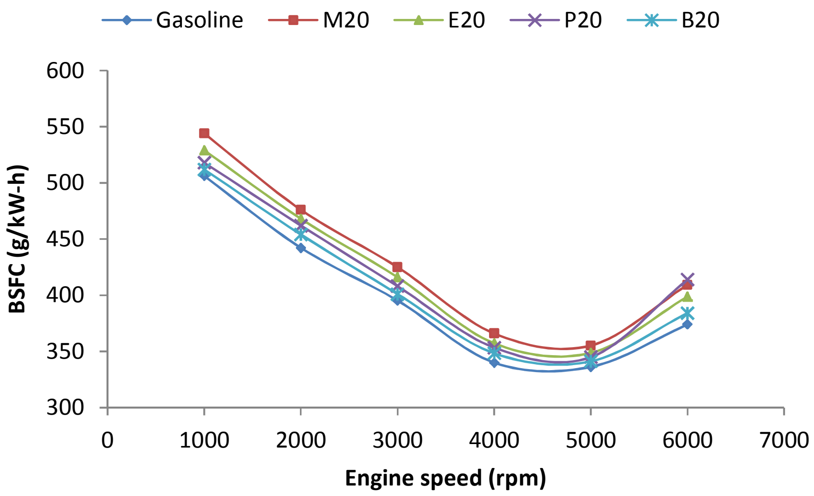

Fig. 3. Variation of BSFC with engine speed.

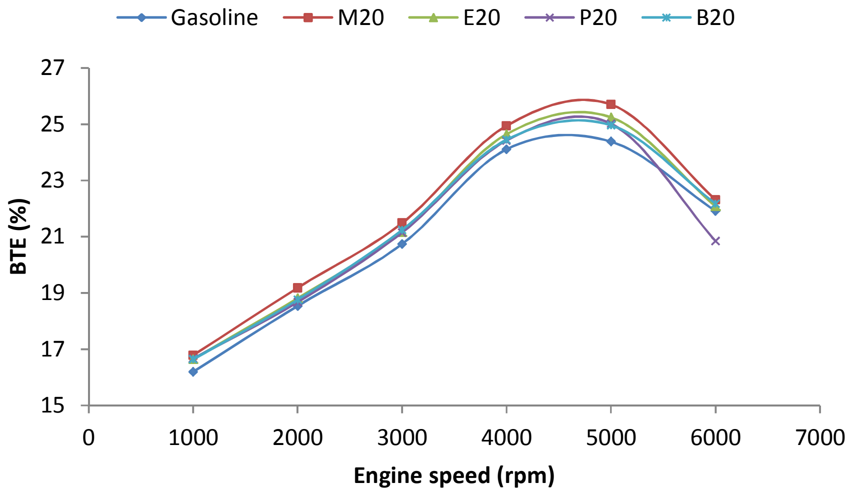

Fig. 4. Variation of BTE with engine speed.

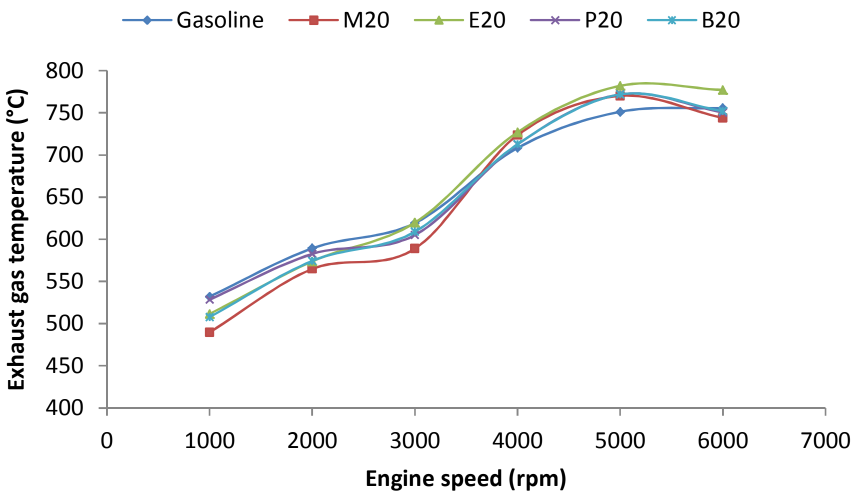

Fig. 5. Variation of Exhaust gas temperature with engine speed.

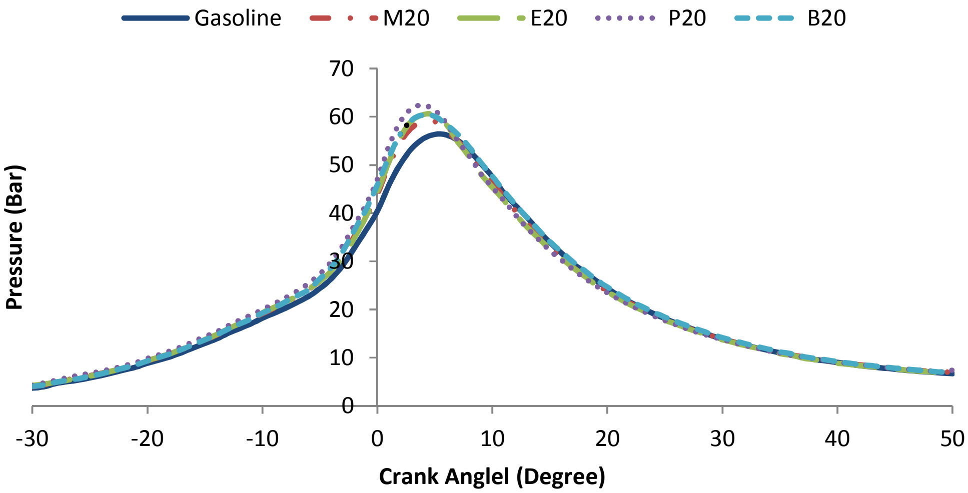

Fig. 6. Comparison of in-cylinder pressure at 4000rpm

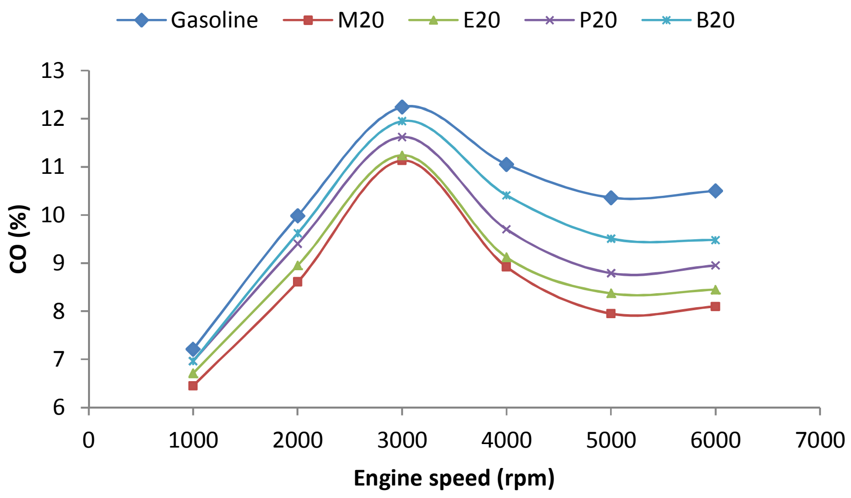

Fig. 7. Variation of CO emission with engine speed.

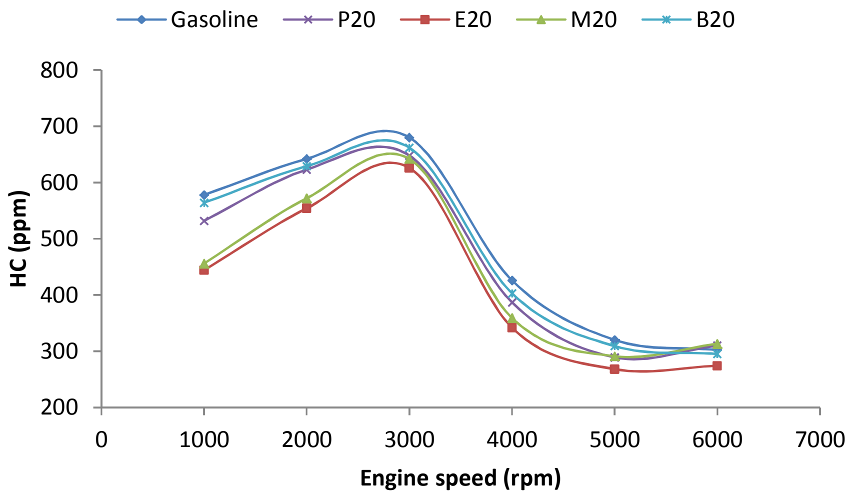

Fig. 8. Variation of HC emission with engine speed.

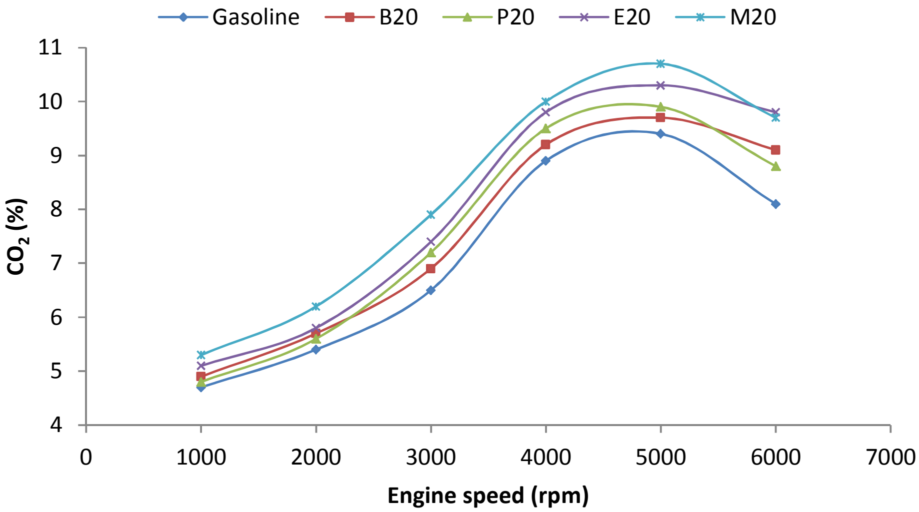

Fig. 9. Variation of CO_2 emission with engine speed.

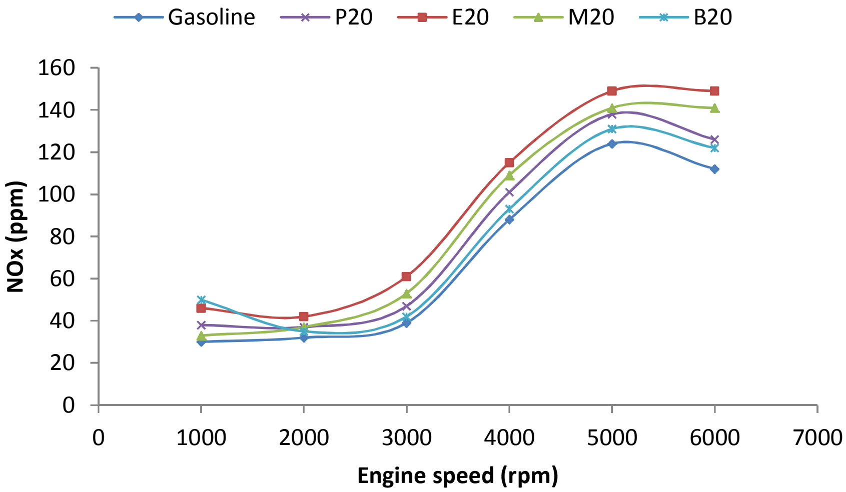

Fig. 10. Variation of NOx emission with engine speed

Table 1: Properties of pure gasoline and different alcohol-gasoline blends.

Property	Unit	Gasoline	M20	E20	P20	B20
Oxygen	wt.%	0	9.99	6.94	5.32	4.32
Density (at 15°C)	Kg/m^3	736.8	743.82	748.3	747.32	750.64
LHV	MJ/kg	43.919	39.434	40.799	41.725	42.273
RON	--	95	98.7	99.735	100.81	97.95
RVP (at 37.8°C)	kPa	63.9	55.2	67.7	58.9	55.5
LoV	kJ/kg	349	1178	923	761	683
Specific gravity (at 15°C)	--	0.7375	0.7967	0.795	0.7899	0.8067
Dynamic viscosity (at 20°C)	mPa.s	0.516	0.521	0.629	0.802	0.925

* Here, LHV= Lower heating value, ROM, Research octane number, RVP= Reid vapor pressure, LoV= Latent heat of Vaporization

Table 2: Specification of the tested engine

Engine parameter	Value
Number of cylinder	4
Displacement volume	1596 cm^3
Bore	78mm
Stroke	84mm
Connecting rod length	131mm
Compression ratio	10:1
Fuel system	Multi-point electric port fuel system
Max output (at rpm)	78kW at 6000rpm
Max torque (at rpm)	135N-m at 4000rpm

Table 3: Specifications of the exhaust gas analyzer

	Measurement range	Detection limit
CO	0-10% vol.	0.01 % Vol.
CO_2	0-20% vol.	0.1 % Vol.
HC	0-20.000 ppm vol.	1 ppm
NOx	0-5.000 ppm vol.	1 ppm
O_2	0-25 % vol.	0.01 % Vol.