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Performance and Exhaust Emission of a SI Engine Fuelled with Potato Waste Ethanol and Its Blends with Gasoline

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Abstract *– The main aim of this study is to investigate the performance and the pollutant emissions of a four stroke SI engine operating on different ethanol-gasoline blends (0-20%). Fuel properties of ethanol–gasoline blended were examined by the standard ASTM methods. The results showed that increasing the ethanol content in the blend fuel will decrease the heating value of the blended fuel and increase the octane number. Exhaust gas emissions were evaluated and analyzed for Unburned Hydrocarbons (UHC), Carbon Dioxide (CO_2), Carbon Monoxide (CO), Oxygen (O_2) and Oxide of Nitrogen NO_x at different engine speeds and loads (1000-5000 rpm). The results revealed that using ethanol-gasoline blended fuels will marginally increase the brake power and the torque output, the brake thermal efficiency, the relative air–fuel ratio and the volumetric efficiency. Moreover, using ethanol-gasoline blends will decrease the brake specific fuel consumption, CO and HC emissions concentration. This improvement was due to the high oxygen percentage in the ethanol. However the CO_2, NO_x concentration and the exhaust gas temperature was noticed to be increased.*

Keywords **–** Engine performance, ethanol-gasoline blends, exhaust emissions, SI engine.

1. INTRODUCTION

Petroleum fuels play a critical role in industrial development, transportation and agriculture. However, the world energy demands are rapidly increasing. Due to the excessive use of the fossil fuels, alternative fuels are being sought. Another serious problem, associated with the use of petroleum fuel, is the increase of the pollutants emissions. Developing renewable energy has become an important worldwide energy policy to reduce greenhouse gas emissions caused by fossil fuel [1]. Alternative transport fuels such as hydrogen, natural gas, and biofuels are an option for the transport sectors. On the other hand, biofuels may mitigate both the economic vulnerability, associated with fossil fuel dependence, and the adverse environmental effects associated with the use of fossil fuels. Several developed countries introduce policies encouraging the use of biofuels obtained from grains, vegetable oil, and biomass. Alternative energy policy in those countries aims to prevent environmental degradation by using cleaner fuel. In addition to that, it assists to reduce dependence on imported fuels by replacing them with renewable domestic sources, and provide new demand for crops to support producer income and rural economics.

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One of the most promising candidates of biofuels is ethanol. According to [2]-[12], using ethanol-gasoline blended fuel in a spark ignition (SI) engines improves the engine performance depending on the ethanol content. The effects of ethanol–gasoline blends (0-60%) on engine exhaust emissions have been previously investigated showing high reduction in the engine emission [3]. It has been found that 40%-60% blends reduce significantly CO and HC emissions. In another attempt [4], the additives of ethanol and methyl tetra-butyl ether (up to 20% MTBE) in various blend ratios produced lower regulated engine-out emissions than MTBE, and reduce the knock at high compression ratio [5]. In [6], engine power has been increased by about 29%, when 50% ethanol fuel was used at high compression ratio. Moreover, the specific fuel consumption, and CO, CO_2, HC emissions have been found to be reduced by approximately 3%, 53%, 10% and 12%, respectively.

Furthermore, it has been reported that using ethanol as a fuel additive to unleaded gasoline enhanced the engine performance and exhaust emissions [7]. This was due to the fact that increase the ethanol content in the gasoline fuel increases the octane number. However, it has been found that NO_x emission depends on the engine operating condition more than the ethanol content [8] due to rising in the cylinder temperature at high ethanol percentage [8]. In [10], blending unleaded gasoline with ethanol increased the brake power, torque, volumetric efficiency, brake thermal efficiency, and fuel consumption. Meanwhile, it decreased the brake specific fuel consumption. In related work, using ethanol–unleaded gasoline blends decreased the coefficient of variation in indicated mean effective pressure [11], especially in 10 vol% ratio. Regarding the effect of air fuel ratio (λ) on the engine run by blended fuel, it has been found that using 10% blended fuel, at λ slightly greater than one, reduced pollutant emission components [12].

From another point of view, fuels with more than 10% ethanol are not compatible with non E85-ready fuel system components and may cause corrosion of ferrous components [16]. Ethanol affects the electric fuel pumps by increasing internal wear, which causes undesirable spark generation. Moreover, it is not compatible with capacitance fuel level gauging indicators, which may cause erroneous fuel quantity indications. In addition to that, increasing the cost of food and diverting human food resources to the costly inefficient production of ethanol fuel raise are major ethical questions [17].

From the above, the current study strongly recommends the usage of waste products and food processing waste materials to produce the ethanol. The main aim of this work is to study the effect of using ethanol, produced from waste material of potato, on the performance and emission of spark ignition engines. A V4 spark ignition engine was used for the experiments and the tests were performed at different engine speeds.

2. EXPERIMENTAL INVESTIGATION

Bioethanol preparation and characterization

The starch and sugar content in the raw materials determines the quantity of the material needed to produce bioethanol. The quality of bioethanol produced varies with the raw materials used in the production process. However, from a chemical point of view, there is no difference between ethanol produced from sugar beet, grains, fruit or even residues. The crucial factor is the degree of purity. For the current work, ethanol was produced from potato waste. In the preparation process, the potato waste was first passed through a chopper, mixed with water and alpha-amylase, and then through cookers where the starch is liquefied. The mash from the cookers was cooled and the secondary enzyme (gluco-amylase) was added to convert the liquefied starch into fermentable sugars (saccharification). In the next step, yeast was added to the mash to ferment the sugars into ethanol and carbon dioxide. Using a continuous process, the fermenting mash flowed through several fermenters until the mash was fully fermented and then transferred to a distillation tank (batch fermentation process). Before the distillation process starts, the mash remained in one fermenter for about 48 hours. The mash was pumped to a continuous flow, multi-column distillation system, to remove alcohol from the solids and the water. Alcohol was at the top of the final column at about 96% strength. Meanwhile, the residue mash was transferred from the base of the column to the co-product processing area. In spite of the boiling point of ethanol is 78.3ºC, which is significantly lowers than the boiling point of water, these materials could not be separated completely by distillation [17], [18]. The collected alcohol was passed through a dehydration system to remove the water and to gain the ethanol. Figure 1 shows the schematic diagram of production process of bioethanol from potato's waste. The properties of ethanol fuel are given in Table 1.

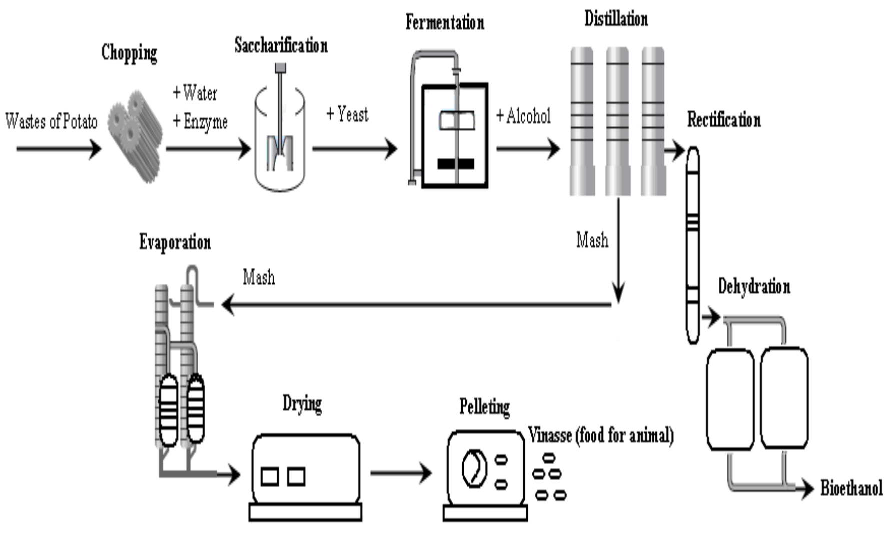

Fig. 1. Schematic diagram of bio ethanol production process.

Table 1. The properties of potato's wastes ethanol.

Property	Method	Ethanol (E100)
Density (kg/m3)	ASTM D 4052	785
Viscosity (cSt)	ASTM D 88	1.1
Calorific value (KJ/kg)	ASTM D 240	27000
research octane number	ASTM D 2699	108.6
Pour point (° C)	ASTM D 97	<<-50
Flash point (° C)	ASTM D 93	14
Ash content (mass %)	ASTM D 482	0

Description of the experimental setup

The experiments were conducted using a V4 spark ignition (SI) KIA 1.3 SOHC, four cylinders gasoline engine. The engine specification is given in Table 2. A 190 kW SCHENCK-WT190 eddy-current dynamometer was used to determine the torque of the engine. Fuel consumption rate was measured in the range of 0.4-45 kg/hr by using laminar type flow meter (Pierburg model). Air consumption was measured using laminar calibrated air flow meter. The relative air fuel ratio, exhaust gas emission components and the exhaust gas temperature were accurately measured using accurately calibrated exhaust gas analyser DIGAS 4000. Five separate fuel tanks were integrated into the gasoline engine containing gasoline/ bioethanol-gasoline blends.

Table 2. Main characteristics of the test engine.

Engine Type	8Valves –4 Cylinder-inline-SOHC
Combustion Order	1-3-4-2
Bore ×Stroke(mm)	71 x 83.6
Displacement Volume (cc)	1323
Compression Ratio	9.7
Max. Torque (N.m/rpm)	103 / 2750
Max. Power(kW/rpm)	47 / 5200
Max. Speed (rpm)	6200
Cooling System	Liquid, enclosed, with forced circulation of a cooling fluid

The Engine Control Unit (ECU) was a Johnson Controls JCAE S2000 adopted with seven sensors. ECU function is to control the quantity of fuel, injection timing, ignition timing and engine speed by the digital sensors. These sensors are oxygen, knock, manifold air pressure, intake air temperature, throttle position, water temperature and engine speed. A multi-point fuel injection (MPFI) system with top-feed injectors was used to inject the fuel. The ignition system was semi-static Distributor Less Ignition (DLI). A schematic diagram of the experimental setup is shown in Figure 2. A calibration of the ECU and pulse width with the injection amount was made by the manufacturer. For engine, calibration system optimized following items by ECU:

- Fuelling control
- Air to Fuel Ratio control
- Injection timing
- Ignition timing and knock control
- Electronic throttle control
- Variable valve actuation
- Variable cam phasing

The gas analyzer was calibrated separately using the special sample of gases. Using the appropriate calibration curve (provided by the manufacturer), the measurement error of the gas analyzer was calculated to be less than 2%, as suggested by the gas analyzer bench manual.

The load on the dynamometer was measured by using digital strain gauge load sensor which was calibrated using standard weights prior each experiment. An inductive pickup speed sensor was used to measure the speed of the engine, and it was also calibrated by an optical tachometer.

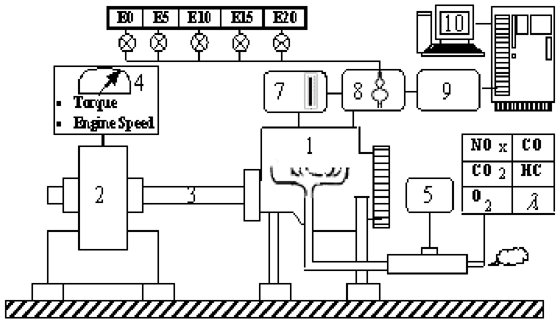

Fig. 2. Schematic diagram of experimental setup.
1. Engine; 2. Dynamometer; 3. Drive shaft; 4. Dynamometer control unit, load and speed indicator; 5. Temperature indicators; 6.Gas analyzer; 7. Air flow meter; 8. Fuel measurement system; 9. Measuring boom; 10.Computer

Experimental procedure

The performance and emission from the engine running on ethanol (derived from potato waste) and blended with gasoline (5-20%, E5-E20) were evaluated and compared with pure gasoline fuel (E0). Fuel properties were evaluated and tabulated at the laboratories of Research Institute of Petroleum Industry (RIPI) in Iran. The properties of the blended fuels at different ratio are given in Table 3. It was noticed that the engine was not running smoothly when ethanol percentage increased above 20%. Therefore, the experimental results were limited to a maximum of E20. The fuel blends were prepared just before starting the experiment to ensure that the fuel mixture was homogenously mixed and prevent any possible reaction between ethanol and water. A series of experiments were carried out under various engine speeds and loads.

The engine was operated using gasoline fuel until it reached the steady state condition. The engine speed, fuel consumption, and load were measured, while the brake power, Brake Specific Fuel Consumption (bsfc), brake thermal efficiency and volumetric efficiency were computed. After the engine reached the stabilized working condition, emission parameters such as CO, CO_2, HC, NO_x and the exhaust gas temperature were recorded. All experiments have been carried out at full throttle setting. To adjust ignition timing, electronic ignition system was used. Each fuel ratio was tested for four times under the same condition and averages value were adopted.

3. RESULTS AND DISCUSSION

Engine performance

Brake power

Figure 3 shows the effect of various fuel blends on the engine brake power. When the ethanol content in the blend fuel is increased, the engine brake power is slightly increased at all engine speeds. At higher engine speeds, it was found that E20 produce higher brake power compared to the other blend ratios. The gain of the engine power is due to the increase of the indicated mean effective pressure and cylinder pressure due to the high ethanol content in the blends [13]. Moreover, the evaporation heat of ethanol is higher than gasoline, which provides fuel-air charge cooling and increases the density of the charge, thus higher power output is produced [6], [14]. It has been reported that with the increase of the ethanol percentage, density of mixture and engine volumetric efficiency increases [10], [14], this will contribute to the increase in the power.

Torque output

Figure 4 shows the influence of ethanol-gasoline-blended ratio on the engine torque. The increase of ethanol content in the blends led to increases the engine torque and power at all engine speeds. This is due to the fact that adding ethanol to the gasoline produces lean mixture that increases the relative air-fuel ratio (λ) to a higher value, which increases the combustion efficiency [8]. Moreover, the gain in the torque can be attributed to better anti-knock behaviour (raised the Octane Number, Table 3) and the improvement in engine volumetric efficiency [7], [15].

Fuel consumption and brake specific fuel consumption

Figure 5 displays the variations of the fuel consumption against engine speed for different blended fuels. In general, the fuel consumption rate was slightly increased as the ethanol percentage was increased at all engine speeds. This behaviour is attributed to the lower heating value (LHV) per unit mass of the ethanol (Table 3. Therefore, the amount of fuel introduced into the engine cylinder for a given desired fuel energy input has to be greater than the gasoline fuel [10].

The relationship between engine speed and brake specific fuel consumption (BSFC) is shown in Figure 6. The BSFC decreases as the ethanol percentage increases. This is a normal consequence of the brake thermal efficiency.

At the lower range of engine speeds below 3000 rpm, the BSFC seems to be decreased. This is due to the increase in brake thermal efficiency. However, further increase in engine speed increases the BSFC, since the brake thermal efficiency decreases [10].

Table 3. Properties of different ethanol/gasoline-blended fuels.

Property item	Test fuel E0	E5	E10	E15	E20	Test Method
Vapour pressure (KPa), read@37.8°C	48.26	55.16	55.16	55.16	55.16	ASTM-D323
Octane number (research)	85.3	89.7	92.3	94.0	99.4	ASTM-D2699
Gross heat of combustion (MJ/kg)	45.12	44.15	42.87	41.61	40.51	ASTM-D340
Distillation range (°C) @760mmHg						
IBP	35.8	40.9	38.9	44.0	40.8	ASTM-D86
10 vol%	58.6	54.3	53.1	57.2	55.4	
50 vol%	93.3	93.5	71.9	71.4	71.6	
90 vol%	146.0	147.9	143.9	144.7	142.1	
End Point	176.7	184.1	175.1	182.4	176.6	

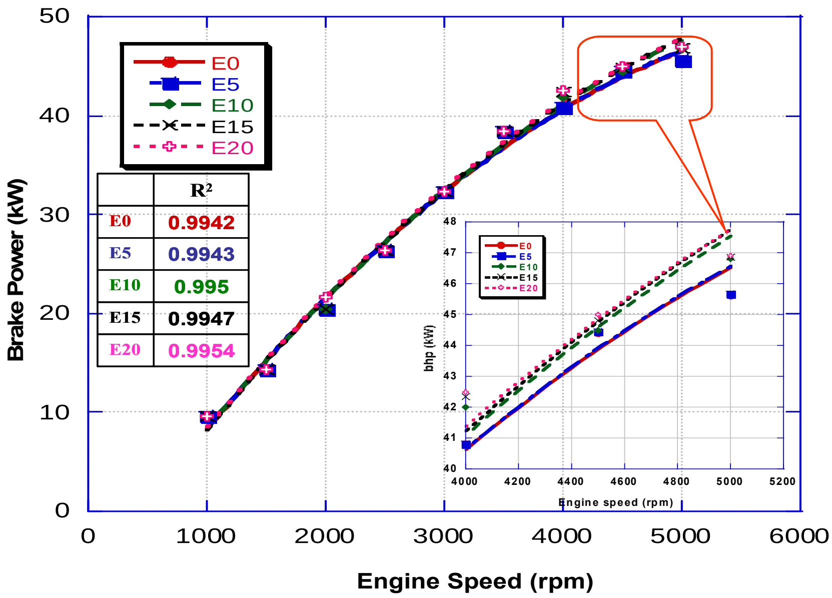

Fig. 3. The variation of engine power with engine speeds for different ethanol- gasoline fuel blends and full throttle setting condition.

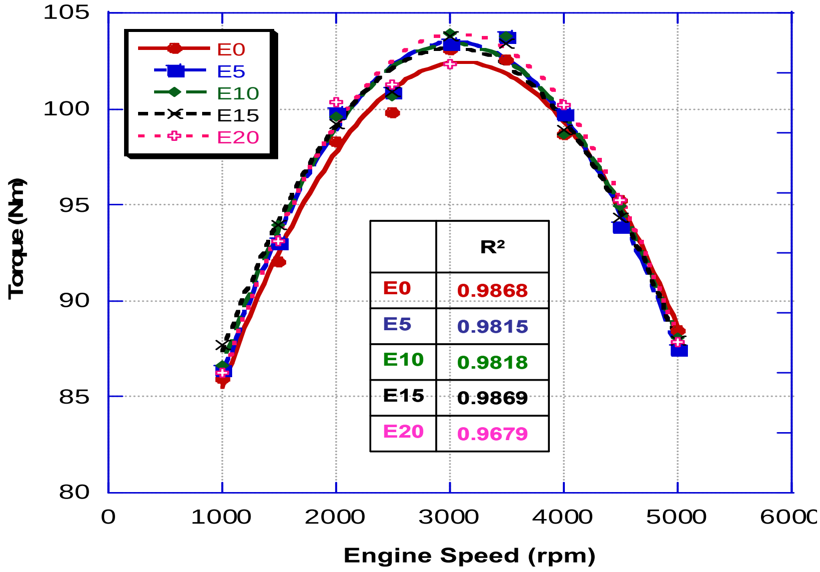

Fig. 4. The variation of engine torque with engine speeds for gasoline fuel and for the blend of ethanol and gasoline fuel at full throttle setting (WOT).

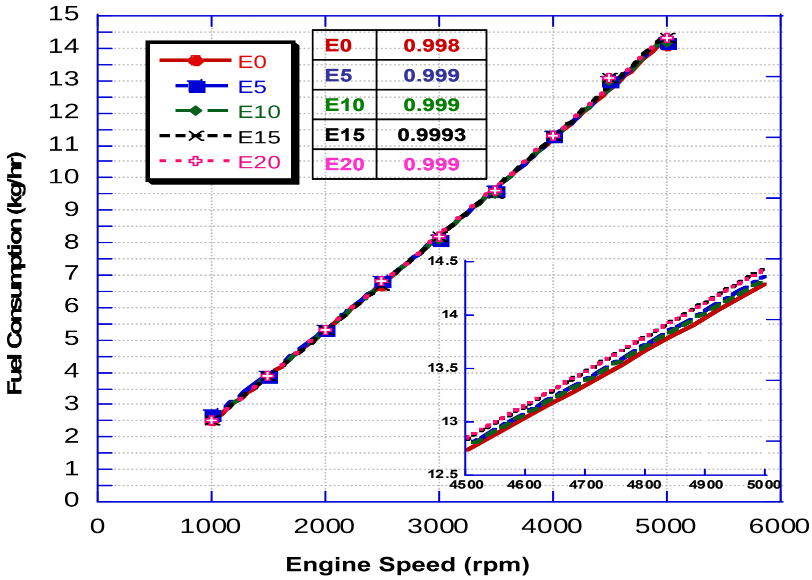

Fig. 5. The variation of fuel consumption with engine speed for gasoline-ethanol fuel blends.

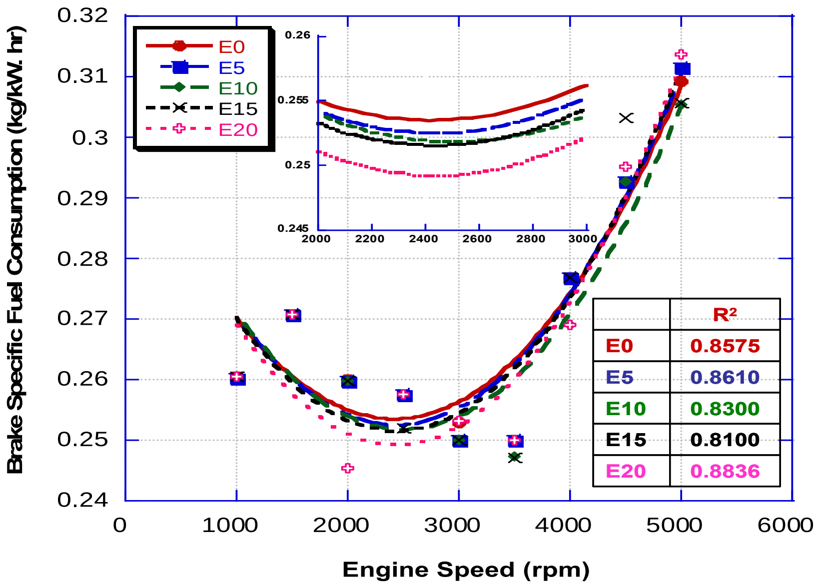

Fig. 6. The variation of brake specific fuel consumption with engine speed for gasoline-ethanol blends.

Lubricating oil temperature

The temperature of the lubricant oil at various engine speeds using different ethanol-gasoline blends is presented in Figure 7. Generally, when the engine speed the lubricant oil temperatures is increased due to the increase of the friction energy among the engine components. Meanwhile, the increase of the ethanol ratio in the blends contributed to increases the lubricant oil temperature which was attributed to the fact that ethanol may give better combustion leading to higher combustion energy [13].

Brake thermal efficiency

In Figure 8, it can be seen that the brake thermal efficiency increases as the ethanol percentage increases. The maximum brake thermal efficiency was approximately 35% when 20% ethanol was used in the fuel. The effect of engine speed on the brake thermal efficiency can be explained through its effect on the relative air–fuel ratio (λ) and volumetric efficiency (η_v). As the engine speed increases up to 3000 rpm, brake thermal efficiency increases. However, increasing the engine speed leads to a reduction in the brake thermal efficiency ($\eta_{b.th}$); whereas λ and volumetric efficiency decreased [10].

Relative air-fuel ratio

The relationship between the ethanol–unleaded gasoline blends and the relative air–fuel ratio is shown in Figure 9. The relative air–fuel ratio (λ) increases at high ethanol percentage. Ethanol produces lean combustion that increases the relative air-fuel ratio to a higher value where better combustion efficiency can be achieved [8].

Volumetric efficiency

Figure 10 shows the relationship between the volumetric efficiency and the percentage of ethanol in the fuel blends. The volumetric efficiency increased as the ethanol percentage increased at all engine speeds. Besides, at 3000 rpm, high volumetric efficiency can be achieved. Further increase in the engine speed results in a reduction in the volumetric efficiency, where the amount of air decreases as a result of choking in the induction system [10].

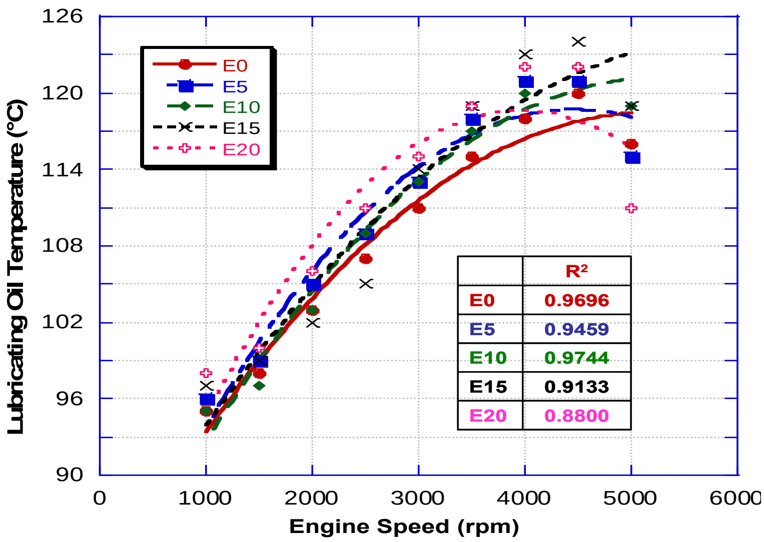

Fig. 7. Lubricating oil temperatures versus engine speeds for neat gasoline and gasoline-ethanol blends.

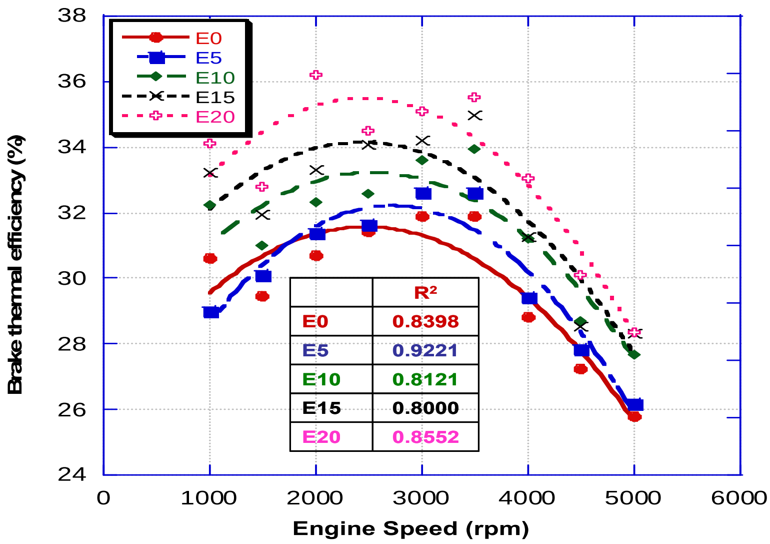

Fig. 8. Brake thermal efficiency versus engine speeds for the ethanol blends and gasoline fuel.

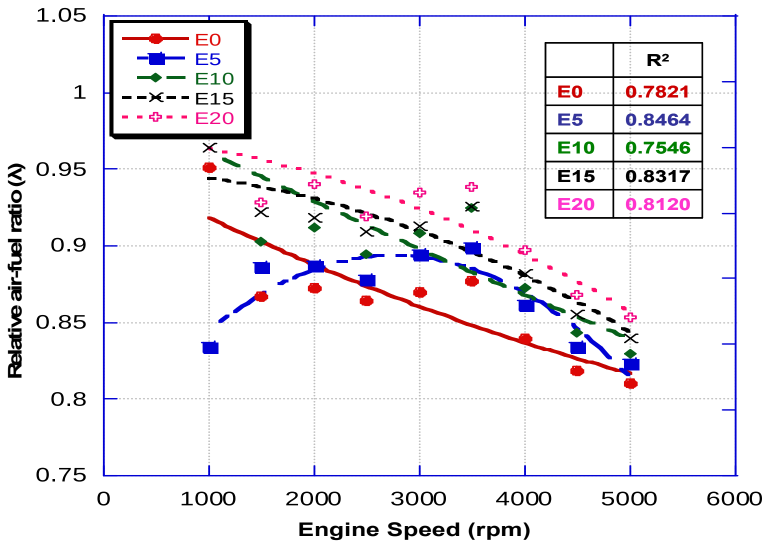

Fig. 9. Relative air-fuel ratio (λ) versus engine speeds for the gasoline-ethanol blends.

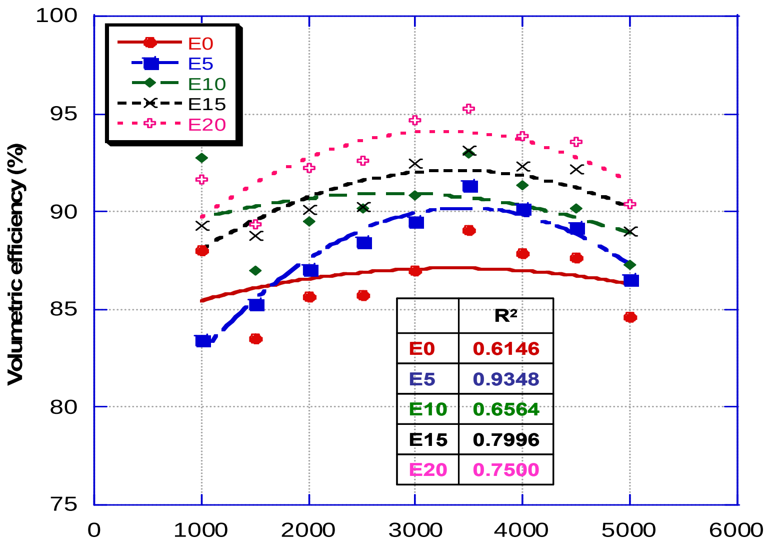

Fig. 10. Volumetric efficiency for blends of ethanol and gasoline fuel with those of neat gasoline fuel at various engine speeds.

Engine emission studies

CO emission

Figure 11 shows the concentration of CO emission at different engine speeds and ethanol ratios. It can be seen that when ethanol percentage increases, the CO concentration decreases, i.e. the combustion is nearly completed. The CO concentration in the exhaust gas emission at 3000 rpm using ethanol found to be decreased by about 13.7- 45.42%. Moreover, the higher the ratio of ethanol is the lower the CO concentration. This trend is due to the fact that ethanol has less carbon than gasoline. Also, given the same fuel dispersion pattern as for gasoline, the oxygen content of the blended fuels helps to increase the oxygen-to-fuel ratio in the fuel-rich regions.

The most significant parameter affecting the CO emission concentration is the relative air-fuel ratio [6], [12]. Relative air-fuel ratio approaches 1 as the ethanol content of the blended fuel increased (Figure 9), consequently combustion becomes completed and flame temperature rises due to stoichiometric combustion [10]. CO emission is likely to be reduced due to oxygen enrichment coming from ethanol; this result can be regarded as a "pre-mixed oxygen effect" to make the reaction completed [8], [12].

CO_2 emission

Figure 12 shows the relationship between the CO_2 concentration and engine speeds at different blends percentage. The CO_2 concentration was recorded to be increased as the ethanol percentage was increased. CO_2 emission depends on relative air-fuel ratio [6], [12]. The CO_2 concentration has an opposite behaviour compared to the CO concentration (c.f. Figure 11). This is due to the improvement in the combustion process as a result of the oxygen content in the ethanol fuel [10]. However, high ethanol ration increases the CO_2 compared to gasoline fuel. When the engine condition is leaner, the combustion process is more completed and the concentration of CO_2 emission becomes higher. As a result of the leaning effect caused by the ethanol, CO_2 emission was increased [8], [12].

HC emission

HC emissions for different engine speeds are illustrated in Figure 13. The HC concentration in the exhaust gas emission at 3000 rpm using E5, E10, E15 and E20 was found to be decreased by about 16.94%, 24.04%, 25.14% and 31.69%, respectively. This indicates that ethanol can significantly reduce HC emissions. The concentration of HC emission decreases with the increase of the relative air-fuel ratio. The reason for the decrease of HC concentration is same reasons of CO concentration as described previously. Ethanol does not contain lead, so formation of porous deposits is avoided. In addition, ethanol molecules are polar, which would not be absorbed easily by un-polar molecule in lubricating oil layer. Therefore, ethanol reduced the HC emission [12].

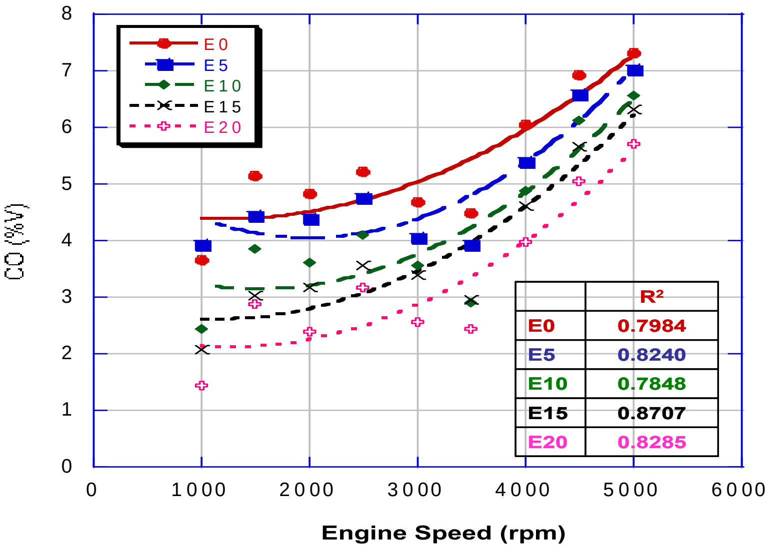

Fig. 11. Comparison of CO emissions for the blends of ethanol and gasoline fuel with those of neat gasoline fuel at various engine speeds.

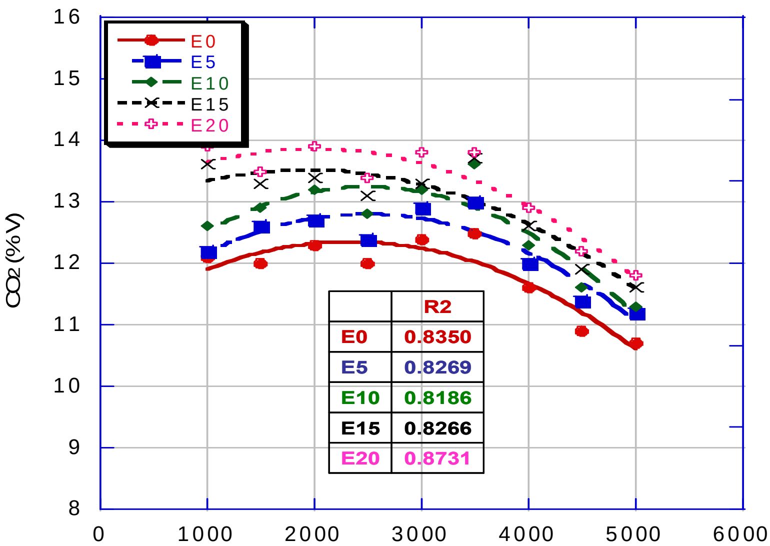

Fig. 12. Comparison of CO_2 emission for the blends of ethanol and gasoline fuel.

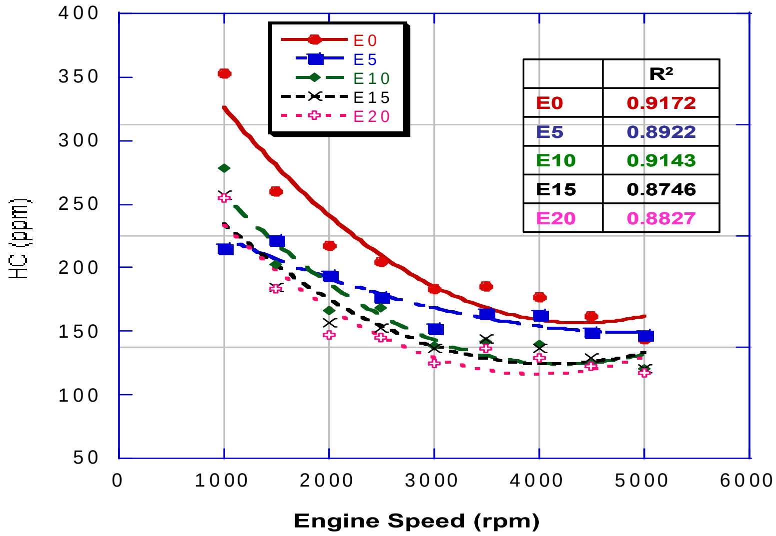

Fig. 13. Comparison of HC emission for the blends of ethanol and gasoline fuel.

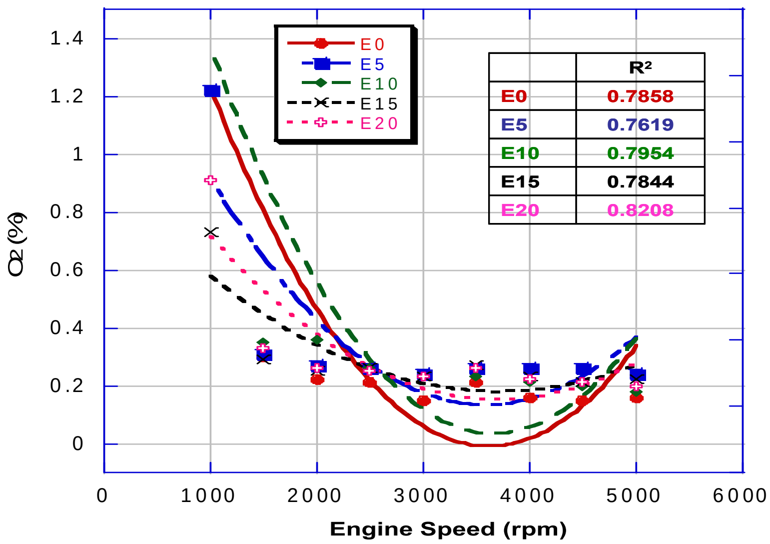

Fig. 14. The variation of O_2 emissions in relation to the engine speed for the blends of ethanol and gasoline fuel with those of neat gasoline fuel.

O_2 emission

O_2 emissions concentration for different speed is illustrated in Figure 14. It seems that increase the engine speeds reduces the amount of the O_2 in the exhaust. In addition, blending the gasoline fuel with ethanol enhances the combustion efficiency resulting in high O_2%.

Exhaust gas temperature

The relationship between exhaust gas temperature and engine speed for different ethanol-gasoline blends is shown in Figure 15. In general, the exhaust gas temperature increases when the engine speed was increased. Furthermore, the exhaust gas temperature increases as the percentage of ethanol in the blend was increased. The maximum value is about 800°C at maximum speed for E20 fuel.

NO_x emission

Considering the NO_x emission, Figure 16 shows that the NO_x concentration is high at high ethanol percentages. When the combustion process is closer to stoichiometric, flame temperature is increased, therefore, the NO_x emission was increased [8], [13].

The manufacturer's published engine performance curves displayed in Figure 17. The figure can be compared with the summarized experimental results shown in Figure 18. It is clear that experimental results are in high agreement to the specification curves and variations are very little. The maximum difference between these two series of curves is 1.98%.

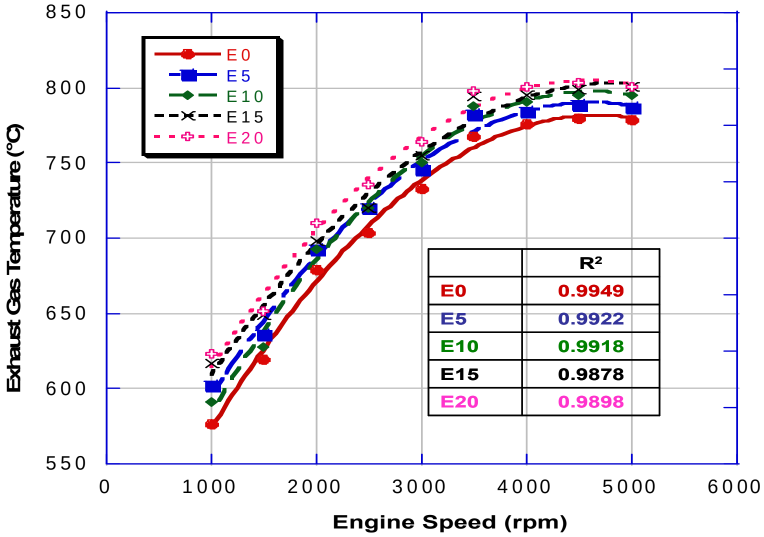

Fig. 15. Exhaust gas temperatures for the blends of ethanol and gasoline fuel.

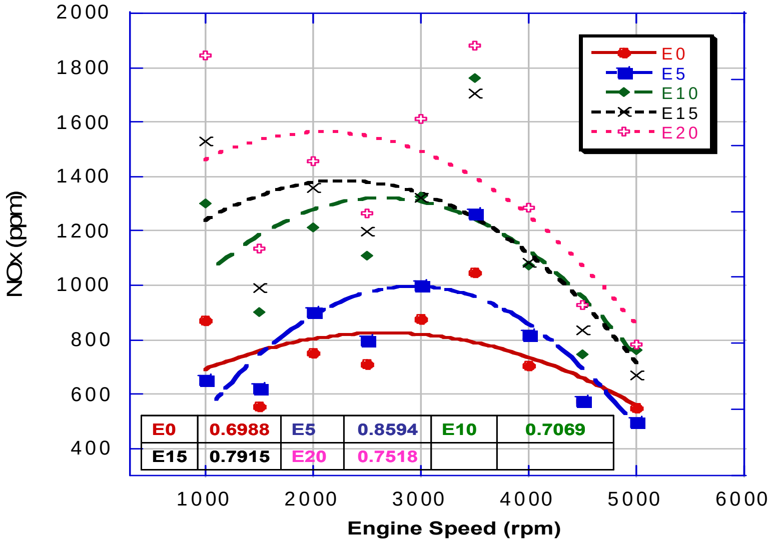

Fig. 16. The variation of NO_x emissions in relation to the engine speed for the blends of ethanol and gasoline fuel with those of neat gasoline fuel.

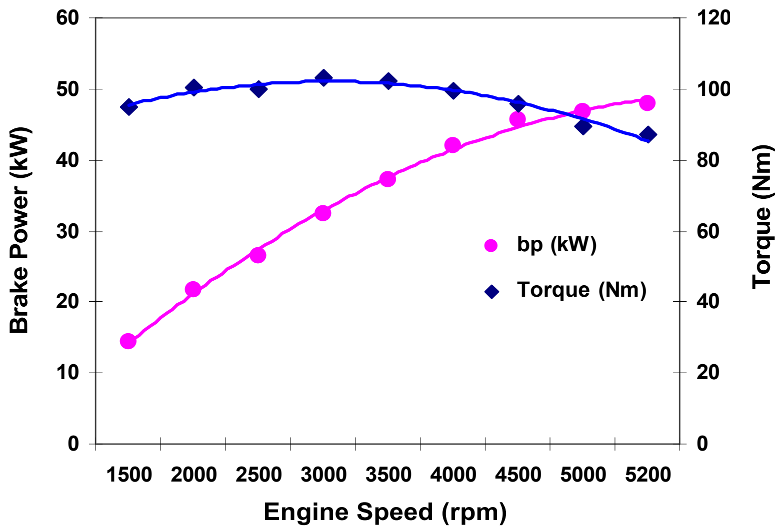

Fig. 17. Manufacturer's published engine performance curves for neat gasoline fuel.

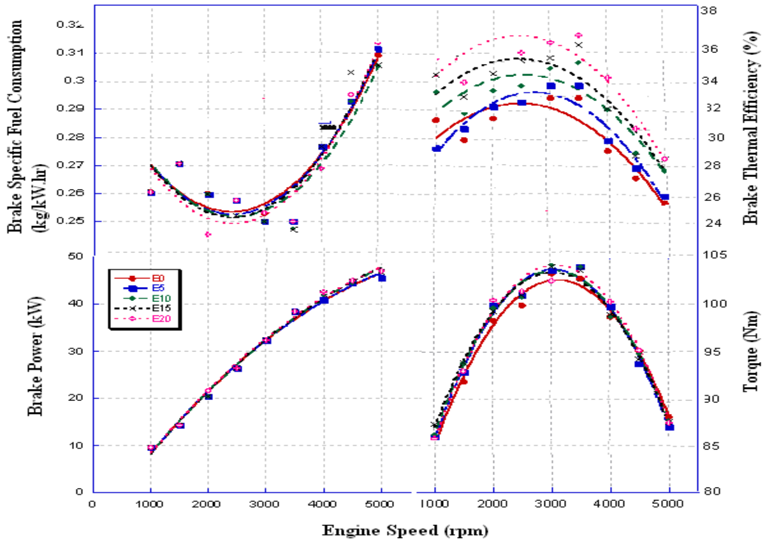

Fig. 18. The variation of engine performance parameters in relation to the engine speed for the blends of ethanol and gasoline fuel with those of neat gasoline fuel.

4. CONCLUSION

From the results of the study, some points can be withdrawn as follows:

1. Adding ethanol to gasoline improves the combustion efficiency. Ethanol ratio has a significant influence on the engine performance and emission. 20% ethanol increased the engine brake power, torque and brake thermal efficiency, and decreased the brake specific fuel consumption. On the other hand, brake thermal efficiency, relative air–fuel ratio and volumetric efficiency increased when the ethanol ratio increased.
2. Ethanol assisted to reduce the CO emission. This was due to the fact that the oxygen enrichment generated from ethanol increased the oxygen ratio in the charge and lead to lean combustion.
3. As a result of the leaning effect caused by the ethanol addition, the CO_2 emission increased.
4. It is found that adding ethanol to the blends reduces the HC emission because of oxygen enhancement.
5. The exhaust gas temperature was increased as the percentage of ethanol in the blend was increased. When the combustion process was closer to stoichiometric, flame temperature increased, which in turn increased the NO_x [18].

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