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An Experimental Comparative Study of SI Engine Performance and Emission Characteristics Fuelled with Various Gasoline-Alcohol Blends

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***Abstract*—**This experimental investigation aimed to determine the influence of using different types of alcohol and gasoline blends such as ethanol - butanol - propanol on the performance of spark ignition engine. The experimental work studied the effect of various fuel blends such as ethanol – butanol/gasoline and propanol/gasoline with two rates of 15% and 20%, at different operating conditions (engine speed and loads), on engine performance emission characteristics. Laboratory experiments are carried out on a four-cylinder spark ignition (SI) engine. In this practical study, all considerations and precautions are taken into account to ensure the quality and accuracy of practical experiments and different measurements. The results show that the performance of the engine improved significantly in the case of ethanol/butanol-gasoline blends. The results also indicated that the engine emitted pollutants such as CO, hydrocarbon (HC) for alcohol fuel blends compared to base gasoline NOx emission increased for different fuel blends either ethanol/butanol-gasoline or propanol-gasoline fuel blend.

***Keywords*—**Gasoline engine performance, emissions, alcohol blends.

NOMENCLATURE

A/F	Air fuel ratio
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
C_3H_7 OH	Propanol
C_4H_9 OH	Butanol
C_7H_{15}	Gasoline
CO	Carbon monoxide
EB15	Ethanol/Butanol 15%
EB20	Ethanol/Butanol 20%
EGR	Exhaust gas recycle
Fc	Fuel consumption
G	Gasoline 100%
HC	Hydrocarbon
IC	Internal combustion
NOx	Nitrogen oxides
P	engine power
P15	Propanol 15%
P20	Propanol 20%
RON	Research octane number
SI	Spark ignition

I. INTRODUCTION

RECENTLY, there is an urgent need to find alternative fuels instead of conventional fuels such as gasoline or diesel fuel. It can be considered as a contribution to decrease the energy consumption over the global level as well as to protect the environment from pollution caused by internal combustion engines [1]-[3]. The topic of energy can be considered as one of the most significant research points at present and has received wide attention from researchers in various fields. Therefore, researchers have been using renewable and new alternative fuels to fossil fuels, whether gasoline or diesel in internal combustion (IC) engines [4]-[7]. These alternatives clearly contribute to filling the energy shortage gap of conventional fuels and contribute to reducing pollution from these engines.

The problem of air pollution from IC engines is one of the most important challenges in the last ten years, so researchers are paying great attention to the means and alternatives that lead to pollution reduction and preservation of the environment [8]-[11]. Sharudin [13] carried out an experimental work to compare the different types of fuel blends (gasoline and alcohol) when feeding a SI engine at different operating conditions of engine speeds and load. A number of experimental studies were done to investigate the performance and pollutant emission of IC engine fuelled with different rates of various types of alcohol/gasoline blends [12]-[15]. These researches were considered a significant attempt to determine the best fuel blend to operate gasoline engine from the view of performance characteristics and emissions of pollutants. They mentioned that the blending ratios used for different mixtures are considered the best ratios for IC engines according to previous studies [13]-[15].

The following is a summary of some of the available previous studies that investigated the effect of alcohol blends with gasoline on the performance of IC engines [16]. Costagliola et al. [17] studied the effect of bioethanol gasoline fuel blends on SI engine performance characteristics and exhaust gas emission for SI-engine four stroke. The motorcycle was tested on a two-wheeler chassis dynamometer, which simulated vehicle inertia and road load resistance. It was investigated the influence of bioethanol gasoline blends with rates from 5% to 30%. The results indicated a significant reduction in CO emission and PM emission at different operating conditions. Sharudin et al. [18] focused on the influence of the iso-butanol/methanol-gasoline fuel blends of SI engines. They used different fuel blends of methanol butanol gasoline with rates from 5% to 15% compared with base gasoline fuel. Experimental tests were carried out at full load with a different engine speed range from 1000 rpm to

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2500 rpm. The results showed that as for engine performance, M5B15 displayed improvement in engine brake power, brake thermal efficiency, and EGT (exhaust gas temperature) compared to other blended fuels. Furthermore, for all methanol-gasoline/iso-butanol blends, higher fuel consumption was observed compared to pure gasoline fuel. From the view of engine emissions, M5B15 gives a significant reduction in pollutants emissions of CO and HC compared to pure conventional gasoline fuel. At the other side, the different fuel blends gave high NO_x and CO_2 emissions with M5B15. Balki et al. [19] indicated that the use of ethanol and methanol increased the engine torque, brake specific fuel consumption (BSFC), thermal efficiency and combustion efficiency. In addition, carbon dioxide (CO_2) emission increased, while unburned hydrocarbon (UHC), carbon monoxide (CO) and nitrogen oxide (NO_x) emissions decreased. Li et al. [20] studied the comparative analysis on combustion, performance and emissions characteristics of a PFI SI engine single cylinder fueled with methanol, ethanol and butanol-gasoline blends under various alcohol ratios, equivalence ratios and engine loads. The engine had low BSFC at the use of butanol-gasoline blends as a fuel. Furthermore, alcohol-gasoline blends gave lower NO_x emission. Ethanol and methanol-gasoline blends produced the lowest HC and NO_x emissions respectively. Experimental results were recorded during engine operation with alcohol and gasoline blends under different operating conditions of engine speeds and loads.

The research objectives can be summarized in the following points. The gasoline engine can be operated with different fuel blends of ethanol - butanol – propanol/gasoline with different volume rates at different engine speeds and constant load. Furthermore, the effect of these mixtures on engine performance (engine torque, heat efficiency and specified fuel consumption and pollutant emissions (CO, HC and NOx)) can be determined. In addition, the best proportions of the mixture can be determined when the combustion engine is operated according to operating conditions and surrounding factors.

II. Materials and Methods

This section includes a detailed description of the test engine and all the measuring instruments used to complete the laboratory tests. In addition, it includes the alternative fuels of alcohols, and the mix of them with gasoline fuel. Physical and chemical properties of various fuel blend types were presented. Fuel blends are listed in Tables I and II.

A. Experimental Work Description

This section focused on the detailed description of the test engine and all the different measuring instruments. The tests are completed using a four-cylinder Hyundai engine, electronic injection, and electronic ignition systems and water-cooled system. The technical specifications of engine are shown in Table I. Table II illustrates the accuracies and uncertainties of the measured properties. Fig. 1 shows illustration of the test rig and all measuring devices used to measure different variables such as engine performance and the emission of pollutants. This test rig was designed and constructed in Mechanical Engineering Department, El-Minia University.

The measuring devices are used to measure the different performance parameters (engine torque, specific fuel consumption, brake thermal efficiency and engine speed) of the engine. The hydraulic brake system was attached with load cells and data acquisition system to measure the engine torque at different engine speeds. Thermocouples are connected at certain points on engine to measure different temperatures (exhaust, water, oil). There is also an exhaust gas analyser used to measure the emission values of various pollutants from the engine (CO, HC, NOx). To measure the fuel consumption of the engine, the fuel pump was installed in a tank and placed on a high precision balance. The amount of air entering the engine can be measured using the air flow meter placed on the air tank inlet port as illustrated in Fig. 1.

TABLE I
TECHNICAL SPECIFICATIONS OF THE SI ENGINE

Engine parameter	**value**
Engine model	G4eh
Engine type	SI-Gasoline
Displacement, cm^3	1341
Number of cylinders	4 inline
Compression ratio	9.5
Bore/Stroke, cm	7.15/8.35
Max. power kW@rpm	61.78@5500
Max. torque Nm@rpm	116.7@3000

TABLE II
ACCURACIES AND UNCERTAINTIES OF THE MEASURED PROPERTIES

Property	Accuracies	uncertainties
Load	± 0.2 N	± 0.2 %
Power	-	± 0.2 %
Fuel consumption	±2.0 g/h	± 1.5 %
Air flow rate	±1.0 cm^3/h	± 0.2 %
Brake thermal efficiency	-	± 2.5 %
Engine speed	±20 rpm	± 0.2 %
Temperatures	± 1 º C	± 0.1 %
CO	± 0.15 g/kWh	± 0.2 %
HC	± 0.10 g/kWh	± 0.2 %
CO_2	± 0.50 g/kWh	± 1.0 %
NO_x	± 0.10 g/kWh	± 0.2 %

B. Fuel Blend Preparation and Properties

Engine performance factors as well as pollutant emissions at different operating conditions were measured. Mixtures of gasoline/ethanol-butanol are two fuel blends with rates 15% and 20%. The fuel blend was mixed immediately prior to the experimental work. The fuel blend was carried out in the laboratory to ensure the mixing accuracy for precise practical results. Ethanol and butanol were mixed with gasoline evenly with the specified ratios of 15% and 20%. Also the propanol and gasoline mixtures were processed with the same proportions 15% and 20%, due to the different densities of fuel blends, they are mixed well before entering the engine to ensure fuel homogeneity. Table III illustrates the physical and chemical specifications of ethanol, propanol, butanol and gasoline fuel [22]-[27].

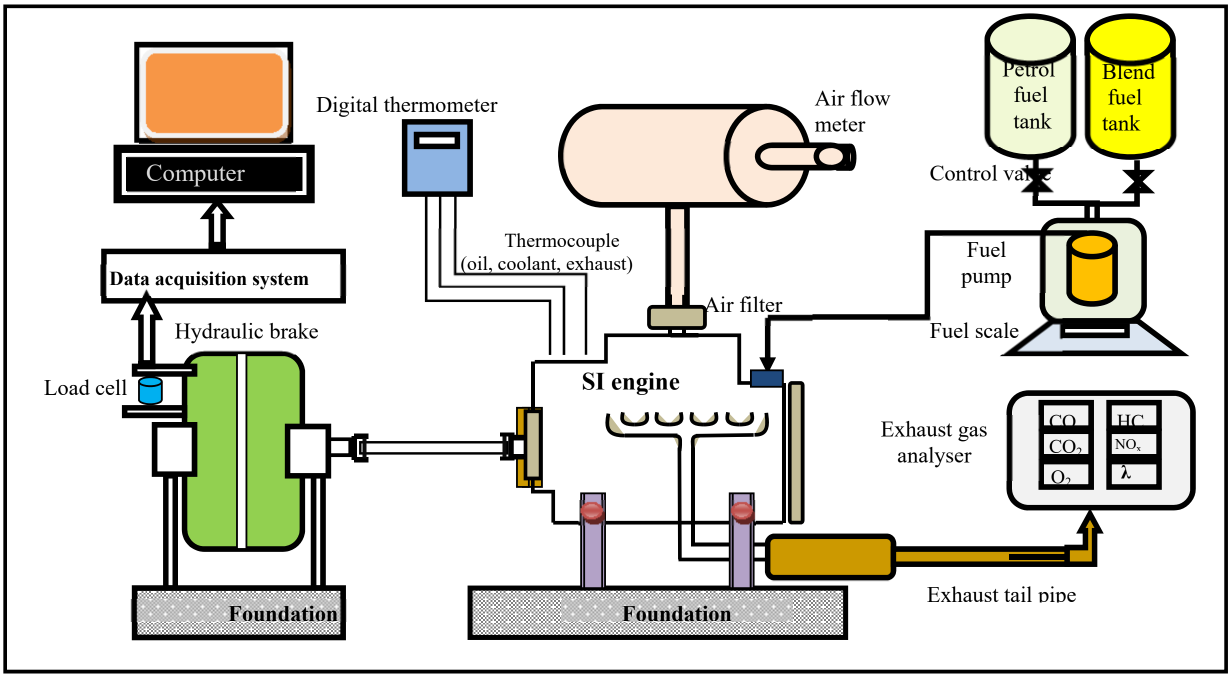

Fig. 1 Schematic diagram of an SI engine and experimental instrumentation [21]

TABLE III
CHEMICAL AND PHYSICAL PROPERTIES OF THE FUELS

Property	Gasoline	Ethanol	Propanol	Butanol
Chemical formula	C_8H_{15}	C_2H_5OH	C_3H_7OH	C_4H_9OH
Composition (C, H, O) (mass %)	86, 14, 0	52, 13, 35	29.81	65, 13.5, 21.5
Lower heating value (MJ/kg)	43.5	27.0	29.81	33.3
Heat of evaporation (kJ/kg)	223.2	725.4	585	474.3
Stoichiometric A/F ratio	14.6	9.0	10.28	11.1
Oxygen content, mass%	0.0 3	4.7	26.62	21.6
Density (kg/m^3)	750	790	804	802
Saturation pressure at 38 ºC (kPa)	31	13.8	6.3	2.3
Flash point (ºC)	-45 to -38	21.1	25.4	28
Auto-ignition temperature (ºC)	420	434	422	415
Boiling point (ºC)	25-215	78.4	82.3	108

C. Test Procedures

There is a systematic method used to carry out the investigation into this study. Laboratory work includes testing four-cylinder SI engines. In practical experiments, the gasoline engine runs at different operating conditions of engine speed and loads while using different types of fuel mix such as ethanol/butanol/propanol-benzene. All practical results, from external characteristics and emission contaminants from the gasoline engine, are recorded during operation with different types of fuel mixture. All engine temperatures, such as cooling water (inlet/outlet), engine exhaust, engine oil, are measured. All results are recorded in a systematic manner [28].

To measure the different engine pollutants emission, the engine is operated first until it reaches optimal operating conditions. During this time, measuring devices are also calibrated to measure different pollutants such as CO, HC and NO_x. These laboratory steps are performed in each measurement experiment for the different variables to ensure that the conditions surrounding the experiment are not changed. The error analysis of the experimental results is taken into consideration, and the precision and uncertainty of the measuring instruments are taken into account [29].

III. Results and Discussion

The results divided into two parts. The first part deals with all the results of engine performance coefficients such as engine torque - specific fuel consumption – brake thermal efficiency. These results show performance coefficients at different engine speeds and constant load. The second part shows the results of the emission of different pollutants from the engine at the same operating conditions.

A. Engine Performance Results and Discussion

Fig. 2 shows a comparison of the engine torque at different engine speeds for all fuel blends (G, P15, P20, EB15 and EB20). It is clear from the figure that, the engine torque in general is at highest value for all fuel mixtures at engine speed of 3000 rpm. When analysing engine torque results for different fuel blends at a specified speed, it is observed that, the torque of the engine in the case of fuel blends is higher than the torque of the engine in the case of pure gasoline. The engine's power increases due to more than one cause. The calorific value of fuel blends (P15, P20, EB15 and EB20) can be considered one of main parameters which increase the output power of engine [30]. Furthermore, the oxygen content of the different blends plays a significant role to enhance the behavior of combustion within the engine, which increases the output power of the engine. It is observed that the best fuel mixtures are the fuel mixture EB15, as it gives the highest torque at almost all engine speeds. The engine's torque is 116 Nm in the case of the use of the EP15 fuel mixture, while the engine's torque is only 111 Nm at gasoline fuel. The results show that the combination of EB and P at 15% gives better results than in fuel blends of 20%. This can be explained by the fact that the evaporation point of both mixtures is relatively high. The higher the fuel mixture, the higher the thermal energy required evaporating the fuel blend particles inside the engine combustion chamber, thereby reducing the overall engine output [31]. There is acceleration within the engine combustion chamber between several properties of the fuel blend and generally, affect the performance of the engine at different operating conditions. According to the most important characteristics of the combustion process within the engine room, the performance of the engine is in the same direction.

Fig. 3 indicates a comparison of the brake thermal efficiency (BTE) of different fuel blends for engine speeds from 1000 up to 5000 rpm. The BTE factor can be considered as one of the significant parameters of IC engine where it illustrates how well an IC engine can convert the fuel chemical energy into output power at flywheel of the engine [32]. According to the indicted results in Fig. 3, EB15 has the highest BTE of 27.6% at engine speed 3000 rpm. Therefore, it can be considered that the BTE is a significant feature to assess the engine performance under variant operating conditions. Particularly, the BTE of EB15 is higher than that of the other fuel blends due to the increased engine output power at high engine speeds. For the ethanol/butanol-gasoline blends, the BTE improved when the ratio increased to 15%, it can be considered due to the oxygen content in fuel blends, which plays a significant role to improve the burning behaviour into the combustion chamber of the engine [33], [34].

Fig. 4 shows the relationship between BSFC with different engine speeds ranging from 1000 rpm to 5000 rpm. It is clear from the figure that, the value of the specific fuel consumption is as low as 3000 rpm. This is because the torque of the engine at this point is at its highest value, as the spent fuel units give the greatest value of the engine at that point. It is observed that, pure gasoline is given less value than specific fuel consumption at all engine speeds. EB15 fuel mixture gives a reduced amount of BSFC than other fuel mixtures.

Fig. 5 indicates the difference percentage in engine performance characteristics (engine torque, BTE and BSFC) at engine speed of 3000 rpm (baseline: pure gasoline fuel) at full engine load. The figure shows that, the engine torque was affected with the different fuel blends compared to gasoline fuel where the difference percentages for the fuel blends P15 P20 EB15 EB20 are 1.8%, 4.5 %, 0% and 3.6% respectively and the highest value is for EB15. The figure also shows the different percentage of BTE for all fuel blends compared to conventional pure gasoline. The difference in the case of EB15 is the highest value and reaches up to 1.8% while the lowest value for EB20 is -1.4%. As for the specific fuel consumption, the figure shows that P20 has the highest percentage difference of fuel consumption and it is up to 15%, while EB15 gives a difference of up to 0.6%.

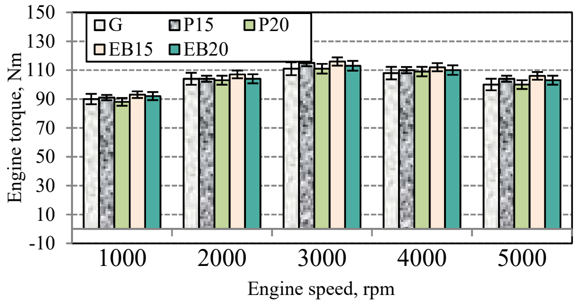

Fig. 2 Comparison of the engine power for various fuel blends at different engine speeds

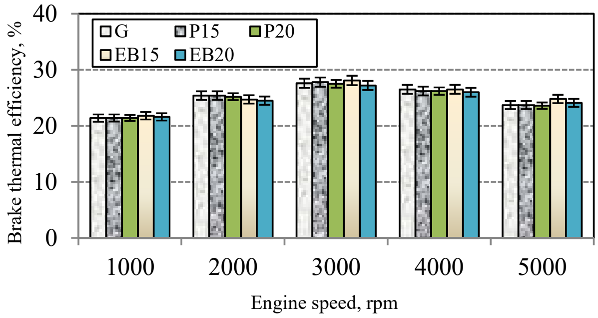

Fig. 3 Comparison of the BTE for various fuel blends at different engine speeds

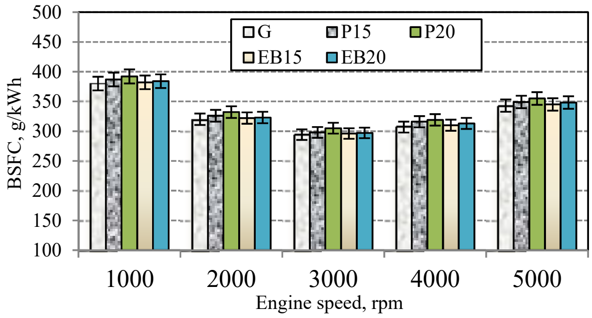

Fig. 4 Comparison of the BSFC for the various fuel blends at different engine speeds

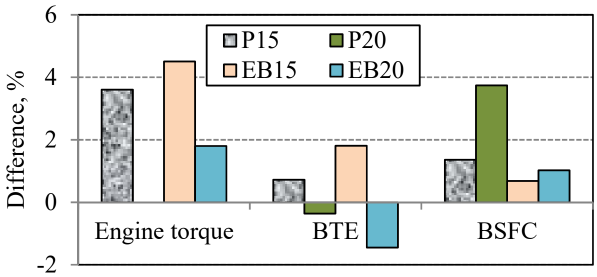

Fig. 5 Difference percentage in engine performance characteristics (Engine torque, BTE and BSFC) at engine speed of 3000 rpm (baseline: pure gasoline fuel) at full engine load

B. Engine Emission Results and Discussion

The effect of different fuel blends (G, P15, P20, EB15 and EB20) on CO emission from the combustion engine at different speeds is shown in Fig. 6. The CO emission of the combustion engine is a clear indication of the efficiency of combustion and the ratio of A/F within the combustion chamber. The full or almost complete combustion inside the combustion chamber emits a small CO emission, where the chemical reactions are closest to full complete reactions. It is clear that if combustion is incomplete within the combustion chamber of the engine, this increases carbon monoxide emissions. It can be seen from the figure that, the emission of CO in the case of pure gasoline is higher than in the case of the use of different blends of fuel (P15, P20, EB15 and EB20). A subtle observation of the figure shows that CO emission of fuel blends P15 and P20 is higher than that of EB fuel blends. The figure also indicates that, the CO emission is the lowest in the case of EB15 fuel blend. There is a direct relationship between engine load and rotational speed from side and the other side with CO emission so that the greatest the load, the greatest CO emission and the lowest CO emission during low and high engine speeds, provided that the load is low on the engine. It can be clarified at the high engine load that the fuel consumption of the engine will be increased and therefore there is a great opportunity for the emission of CO.

The low emission of CO from the combustion engine in the case of EB fuel blend is due to the high oxygen content of the fuel blend that contributes to increase the efficiency of combustion within the engine room and thus reducing the emission rate of CO in all engine-operating conditions. The oxygen content of EB fuel blends is high (29.6%) but in the case of fuel blend P is 16.9% and decreasing of oxygen content in pure gasoline fuel.

Fig. 7 shows a comparison of the HC emission for different fuel blends at different engine speeds and at high engine load. It can be seen from the figure that, the emission of all fuel blends is close and is limited to the values of 2 - 3 g/kWh for all engine speeds from 1000 to 5000 rpm. The emission ratio for different fuel blends is less than pure gasoline over the range of engine speeds. The low pollutant emission of HC is due to the quality of the combustion and its high efficiency within the combustion chamber of the engine. The oxygen content of the P and EB fuel blends assists to complete the chemical reactions between the fuel and the air reduces the overall emission of HC. It is clear from the figure that, EB15 fuel blend is given less value than HC because the oxygen content is higher than the propanol fuel blend.

Fig. 8 illustrates a comparison of NO_x emission for different fuel blends of ethanol/propanol/ butanil – gasoline at different engine speeds. NOx emissions increase with increasing engine load for all types of fuel blends due to the presence of the combustion gases in high pressure inside the combustion chamber. Emission pollutant of NO_x formation rises with rising of hydrogen ratio and oxygen content in the ethanol/ propanol/butanol-gasoline blends [35]. The NO_x pollutant emission of fuel blends is higher than that of NO_x emission for pure gasoline. This is due to several reasons, including high combustion temperatures within the combustion chamber of the engine, as well as the high pressure of burning gases, which gives the opportunity for the appearance of NO_x. The high temperature inside the combustion chamber is due to the presence of high oxygen content in different fuel blends, as well as the high heating value, which leads to a suitable atmosphere for the formation of NO_x [36]. It is clear from the figure that, the blend of fuel EB20 gives the highest value of a NO_x pollutant. It can be considered due to the improvement of combustion performance within the engine and thus increasing the combustion temperature, which increases the emission of NOx.

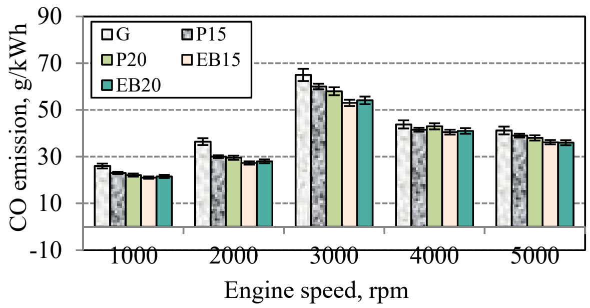

Fig. 6 Comparison of the CO emission for the various fuel blends at different engine speeds

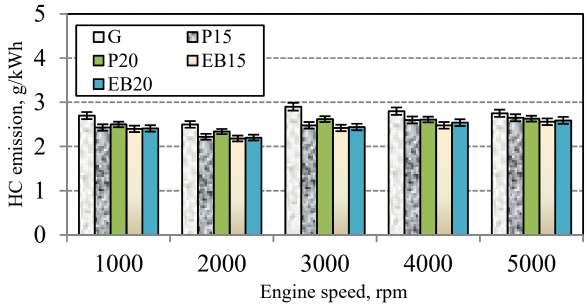

Fig. 7 Comparison of the HC emission for the various fuel blends at different engine speeds

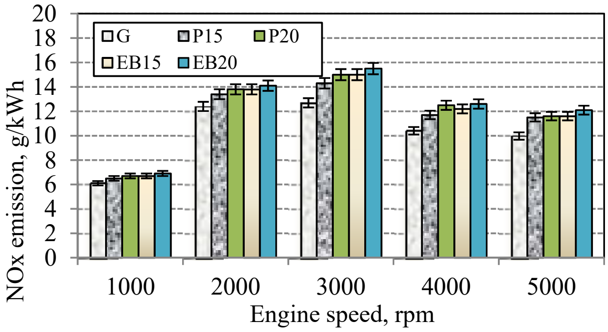

Fig. 8 The NOx emission for the various fuel blends at different engine speeds

Fig. 9 illustrates a comparison of the emission of CO, HC and NO_x for the different fuel blends (P15, P20, EB15 and

EB20) and pure gasoline fuel at an engine speed of 3000 rpm and high engine load. It is clear from the figure that CO pollutant emission is less for all fuel mixtures than pure gasoline. In the case of P20 fuel blend, the reduction is 10%. The decrease in the CO emission of EB15 fuel mixture reaches to 17%, which is the best ratio. A significant reduction of all pollutants for all fuel blends, especially EB15 fuel blend, is as high as 17%. This is due to improved burning within the combustion chamber due to oxygen content and high heating value, leading to better combustion in these conditions. This leads to a decrease in the appearance of CO and HC in the exhaust gases. The emission of NO_x increases for all fuel blends than pure gasoline. The value of the increase is more than 21% in the case of EB 20 due directly to the high temperature of combustion gases inside the engine room, which leads to the opportunity to build up NO_x significantly under different operating conditions of the engine.

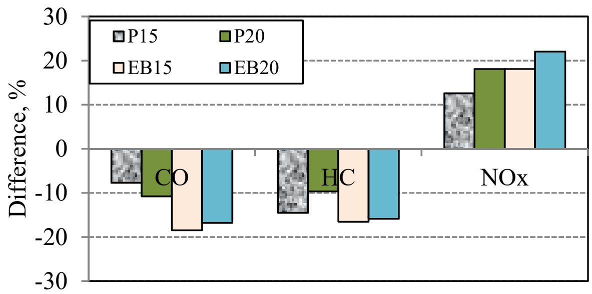

Fig. 9 Difference percentage in engine emission pollutants (CO, HC and NOx) at engine speed of 3000 rpm (baseline: pure gasoline fuel) at full engine load

IV. Conclusions

In this research, the characteristics of performance and emissions of SI engine fueled with, ethanol/butanol/propanol-gasoline blends were investigated. Several conclusions were formed in the following points:

- The test laboratory is equipped with IC engine and various measuring devices to conduct practical experiments for different types of fuel blends with P15, P20, EB15 and EB20 at different engine speeds ranging from 1000 up to 5000 rpm at high engine load to ensure the stability of all surrounding conditions of experiments.
- The fuel blends used in the practical experiments are P15, P20, EB15 and EB20 compared to pure gasoline, to determine the different performance parameters (engine torque, BTE and BSFC) of engine and pollutant emissions at different engine speeds and high load.
- It is clear from the practical results that while using ethanol-butanol/gasoline blends 15%, there is a clear improvement in the performance of the engine of the output power and BSFC and thermal efficiency compared to other fuel blends. In addition, the emission of pollutants, especially the CO and HC are less in the case of blends of ethanol-butanol with gasoline than the other cases of fuel blends. The improvement in engine performance for engine torque, BTE and BSFC are 4.5%, 1.8% and 0.7%, respectively.
- The results showed the influence of different fuel blends on the pollutant emission of engine, especially CO and HC; it is clear that all fuel blends are given a lower emission rate than pure gasoline. The decrease of engine emission in the case of a mixture of fuel EB15 can be reached to 18.46% and 16.55% for each CO and HC respectively, at the speed of engine 3000 rpm and high load.
- The NO_x emission of engines operating with alcohol blends is somewhat defective. The NO_x emission rate is higher in the case of fuel blends than in pure gasoline. The NOx emission rate increases up to 0.7% in the case of EB15 at engine speed of 3000 rpm.

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