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ANALYSIS OF ETHANOL-BUTANOL-GASOLINE BLENDS INFLUENCE ON THE PERFORMANCE OF SINGLE-CYLINDER SI ENGINE AND EXHAUST EMISSIONS

ISAM E. YOUSIF*, ADEL MAHMOUD SALEH

Mechanical Engineering Department, University of Technology, Baghdad, Iraq
*Corresponding Author Email: me.20.30@grad.uotechnology.edu.iq

Abstract

Alcohols, such as ethanol and butanol, exhibit great promise as fuel potential replacements for spark ignition (SI) engines. These renewable, clean, and secure-to-transport fuels have garnered significant attention due to concerns regarding exhaust gas emissions and the pursuit of alternative energy resources for internal combustion engines. To address these challenges, researchers have explored the blending of traditional gasoline with specific alcohols to assess the performance of the PRODIT engine (single-cylinder) four-stroke SI combustion engine. The operation of the engine was simulated using LOTUS v.6.01 software with gasoline blends containing ethanol and butanol. Minimizing the time and cost of testing the performance and emission analyses of IC engines using alternative fuels, blended fuels, and neat fuels, as compared to experimental tests. So, performance simulation software would give an expected result as obtained by an actual procedure of testing IC engines. Pollutant emission levels are calculated using Olikara & Borman Equilibrium Routines. The tested blends consist of ethanol, butanol, and gasoline, respectively as 50%, 20%, and 30% (E50B20), 20% 50%, 30% (E20B50), 50% 0%, and 50% (E50), and 0%, 50%, and 50% (B50) volume fractions. The study revealed that blending 50% vol. of butanol with 50% gasoline resulted in optimal IC engine performance, while the other blends (E50B20, E20B50, and E50) exhibit acceptable performance rates, and about the pollutants, the results showed minimized levels of emissions of CO, UHC, and NOx, respectively.

Keywords: Butanol, Ethanol, Exhaust emissions, Lotus software, SI engine performance.

1. Introduction

The use of internal combustion (IC) engines has increased environmental concerns due to the release of hazardous exhaust pollutants. Carbon dioxide and methane stand out as two crucial greenhouse gases emitted by IC engines. These gases' high levels in the atmosphere have contributed to global climate change [1]. Escalating living standards and reduced public transportation interest, particularly in Iraq, have compelled people to increasingly rely on private vehicles for mobility. This shift has led to a surge in gasoline car numbers, resulting in environmental consequences [2-4].

As mitigation for pollutants emitted from diesel engines, biodiesel fuel derived from animals or plants has been introduced [5, 6]. Alcohols such as ethanol (E), methanol (M), and butanol (B) are incorporated into gasoline as additives due to their high-octane ratings compared to gasoline. Agricultural products rich in sugar, such as sugar beets, sugar cane, dates, wheat, barley, and oil derivatives, undergo fermentation to generate alcohol. The approach of blending alcohol with gasoline has emerged as an alternative to using lead compounds, which have adverse effects on organisms and the environment. This blending technique enhances the fuel's octane number [5, 7, 8].

Alcoholic fuels can directly power spark ignition engines. Engines using alcohol generally exhibit reduced brake loads compared to those using gasoline. Gasoline can also be blended with alcohols at specific ratios, approximately 50% [9, 10].

In a research conducted by Radwan [11] investigated blended gasoline with ethanol ranging from E10 to E70, determining E50 to have the best anti-knock performance. The utilization of ethanol-gasoline blends aims to reduce carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions.

In a research conducted by Alternate fuels committee of the engine manufacturers association [12] conducted experiments on various vehicles using a blend of 10% ethanol and 90% unleaded gasoline. Their study revealed that NOx concentrations decreased by 1.2 g/mile, compared to 1.62 g/mile for gasoline.

In a research conducted by Palmer [13] conducted engine tests using various ethanol-gasoline fuel mixtures. The findings showed that a 10% ethanol blend raised both the octane number and engine power by 5%, potentially reducing CO emissions by up to 30%.

In a research conducted by Abdel-Rahman and Osman [14] performed performance tests on an engine with a variable compression ratio, using fuel ethanol concentrations ranging from 0% to 40%. They observed an increase in octane number proportional to ethanol quantity in the base fuel while the heating value decreased. Adding 10% ethanol resulted in increased power at a 10:1 compression ratio. Optimal compression ratios of 10, 11, and 12 were determined for ethanol concentrations of 20%, 30%, and 40%, respectively, to achieve maximum indicated power.

In a research conducted by Hsieh et al. [15] conducted experimental research on spark ignition engine operation and exhaust pollutants using ethanol-gasoline blends with ratios of 5%, 10%, 20%, and 30%. The findings demonstrated that increasing ethanol led to a decline in heating values but an increase in octane numbers.

Using corn-based butanol as a transportation fuel resource can potentially result in energy savings of 39% to 56% compared to gasoline, along with a reduction of greenhouse gas emissions by 32% to 48%, according to comprehensive fuel analysis [16]. Alcohols burn with moderate flame temperatures due to their low combustion maximum temperature, leading to reduced NOx emissions and heat losses. Ethanol possesses a high latent heat of vaporization, which cools the suction air and increases the fresh charge density, enhancing volumetric efficiency.

However, ethanol's lower heating value compared to gasoline, due to its oxygen component, leads to a lower range per litter of fuel capacity. Butanol, with a heating value of 36.4 MJ/kg, outperforms ethanol with 24.8 MJ/kg and gasoline with 44.9 MJ/kg [17-19].

Unlike ethanol, butanol features a lower latent heat of vaporization, reducing fuel vaporization and combustion issues during cold starts typical of alcohol-based fuels. Butanol has advantages over ethanol in compression ignition (CI) engines, including lower vapour pressure, a higher cetane number, and enhanced diesel fuel miscibility. Due to its physical properties, butanol blends seamlessly with gasoline [20, 21]. Butanol, with its numerous advantages over ethanol and methanol, holds significant promise as an alternative fuel.

Butanol production can be derived from diverse biomass feedstocks such as corn, grass, cereals, sugar beets, potatoes, leaves of trees, and agricultural waste [22, 23]. The impact of employing ethanol-gasoline blends with three blending ratios (5%, 10%, and 15% by volume) on engine performance and exhaust emissions was studied by Hosseini et al. [24]. In comparison to other fuels, E10 provided the highest torque, while E15 exhibited the most power and the lowest CO and UHC emissions.

In a research conducted by Elfasakhany [25] compared the effects of blending gasoline with n-butanol and iso-butanol on engine performance and characteristics versus pure gasoline. The study also looked at a mixture of the isomer and regular butanol found in gasoline. Furthermore, the research compared UHC, carbon dioxide (CO_2) and CO_2 emissions between the studied blends and pure gasoline, with the results favouring ternary blended fuels.

In another study, compared five biofuel blends containing isomer and normal butanol, as well as bioethanol, normal butanol–bioethanol, and iso-butanol-bioethanol-gasoline [26]. The results indicated that ethanol blends exhibited higher brake power of 6.5%, torque of 1.5%, and volumetric efficiency of 25% compared to gasoline. However, the blends with butanol (nB, iB, nBE, and iBE) indicated lower engine performance values compared to gasoline. In terms of exhaust emissions (pollutants), ethanol blends presented a maximum CO_2 increase (4.7%) and minimum CO reduction (21%). Both nB and iB indicated substantial CO_2 reductions by 35% and 37%, respectively, and increased CO emissions (9% and 10.3%, respectively).

Butanol presents a promising option due to its more complex 4-carbon structure compared to ethanol. Butanol can be derived from agricultural products and cellulose waste, offering an advantage in terms of energy sources. Additionally, butanol is considered less corrosive, allowing for its use within existing infrastructure for shipping diesel or gasoline fuel. Another benefit is its compatibility with vehicles, requiring no modifications [27, 28]. In a research conducted by Singh et al. [29] conducted experiments across various engine loads within the rated engine speed. The relative engine performance of the gasoline engine is tested at variable engine operation speeds and loads.

The blending of alcohols with gasoline poses challenges due to variations in heating values, viscosity, fuel boiling points, vaporization heat, and flame spreads. As n-butanol is less volatile compared to other alcohols, it can be combined with isooctane to produce larger amounts of alcohol, potentially resulting in fewer problems within the petroleum distribution system [30, 31].

Alcohol-gasoline mixtures are known to cool the combustion chamber during injection, lowering cylinder temperature due to their high latent heat of evaporation. The relationship between exhaust gas temperature (EGT) and in-cylinder temperatures in spark engines' NOx emissions remains ambiguous [32-34].

To achieve effective combustion with minimal exhaust pollutants, researchers still use the old-fashioned approach of altering the fuel's composition with additives. One recommended approach is adding light alcohols to gasoline fuels, such as methanol and ethanol [35]. High-carbon alcohols possess superior fuel characteristics compared to light alcohols like methanol, ethanol, and propanol [36].

According to the literature, spark-ignition engines powered by two alcohols, such as ethanol-butanol, methanol-butanol, and propanol-butanol, can achieve good thermal efficiency and low exhaust emissions. Even though much research has been done on the efficiency and combustion properties of engines running on blends of petrol and ethanol and petrol and n-butanol, few studies simulation IC engine performance dealing with gasoline blends.

So, reducing the cost and time of analysis of the experiment data was the main point to motivate the paper to give simulation work. This study introduces a simulation study of the effects of blending a light alcohol, such as ethanol, with a heavy alcohol like 1-butanol with Iraqi regular gasoline. Using the LOTUS simulation software as the tool of the study to evaluate PRODIT engine performance, and emission parameters are obtained by Olikara & Borman Equilibrium Routines.

2. Methods and Materials

2.1. Samples preparation and characterization

The tests encompass four blending types alongside neat Iraqi gasoline. Iraqi gasoline fuel contains about 500 parts per million of Sulphur due to the presence of this substance in crude oil. Also, the old Iraqi oil refineries dating back to the 1990s are unable to reduce Sulphur to lower levels. Added alcohols do not contain Sulphur, and therefore any added amount reduces the proportion of this substance in the fuel and thus limits its harmful effects on the environment and humans.

The first blend consists of 50% vol. ethanol and 20% vol. butanol, the second blend involves 20% vol. ethanol and 50% vol. butanol, the third is composed of 50% vol. ethanol alone, and the fourth comprises 50% vol. butanol only. Table 1. shows the physiochemical characteristics of both neat gasoline and the blended gasoline tested in the engine.

Table 1. Features of neat gasoline and the selected alcohols [37].

Parameter	Ethanol	1-Butanol	Gasoline
Molar mass (kg/mole)	46.07	74.12	114.228
Density @ 15 °C (gm/cc)	0.789	0.810	0.692
Boiling point (°C)	78	117.7	99.30
The lower Calorific value (MJ/kg), LHV	26.952	34.37	44.3
(AFR)stoichiometric	9	11.1	15.1
The latent Heat of vaporization (kJ/kg)	840	430	308
Mixed octane number	99.15	86	100
Mass content of oxygen (% by weight)	34.8	21.6	0
Vapor pressure (kPa) @ 37 °C	15.9	2.3	5.5
Auto ignition temp. °C	365	314	220

Table 2 illustrates that B50 exhibits a lower vapour pressure value, approximately 45% less compared to other blends. However, butanol's lower heating value is about 22.4% less than gasoline. Despite this, B50's calorific value of butanol is 12.5%, greater, implying better engine performance.

Table 2. Physiochemical and thermal properties of alcohol-gasoline blends [37].

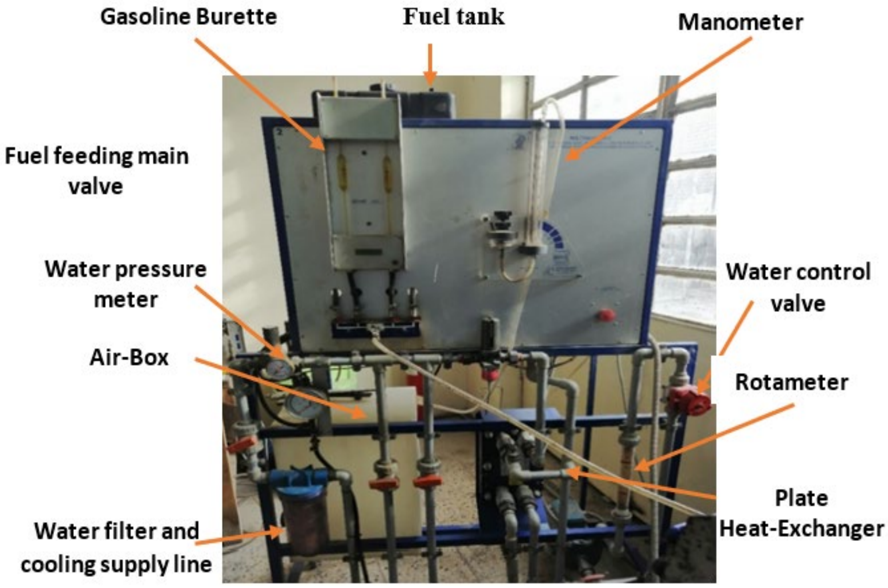
Blend	Density (g/cm^3)	LHV (MJ/kg)	AFR Stoichiometric	Vapour pressure (kPa)	Latent heat (kJ/kg)	Mixed ON	Oxygen content
E50B20	0.76	33.24	11.13	12.08	608.5	97.13	22.40
E20B50	0.77	35.53	11.77	7.175	481.1	92.97	18.20
E50	0.74	35.06	11.90	13.26	591.4	99.93	18.00
B50	0.75	38.94	12.99	3.38	373.8	93	11.00

2.2. Engine configuration and specifications

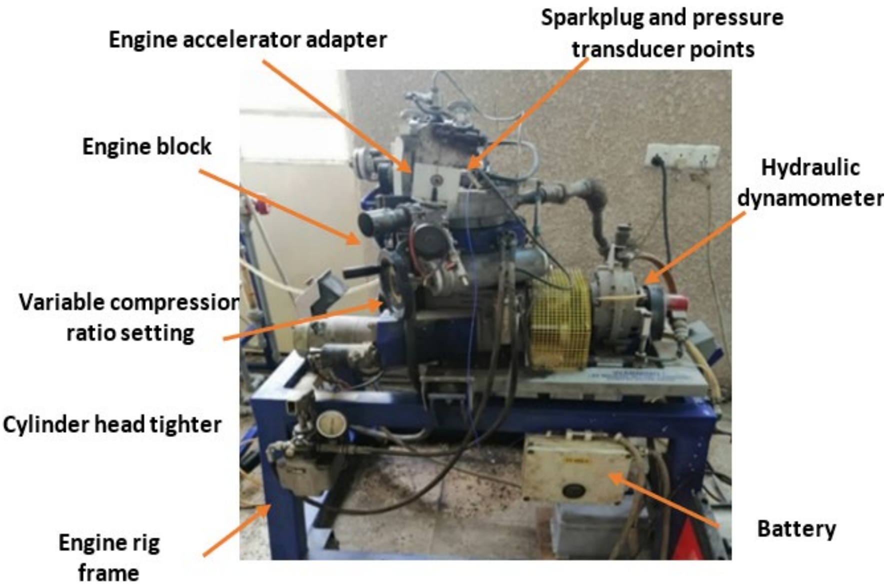
The simulation and experimental work utilized the PRODIT single-cylinder engine. The technical specifications are listed in Table 3. Figure 1 illustrates the experimental engine setup, with (a) representing the fuel and water supply units and (b) the engine components.

Table 3. Specifications of the test engine.

Engine specifications	Designed and measured values
Bore	90 mm
Stroke	85 mm
Swept volume	541 mm^3
No. cylinders	1
No. of valves	2
Compression ratio	8: 1



(a) Cooling and fuel/air metering.



(b) PRODIT single cylinder test rig.

Fig. 1. Experimental setup.

2.3. Performance parameters

The parameters of IC engine performance are itemized in Table 4 [23]. Also, the meaning of each item has been defined.

Table 4. Formulas and definitions of the performance parameters.

Parameter	Equation	Explanation
Brake power	$bp\ (kW) = \frac{2\pi * N * T}{60 * 1000}$	The net rate of work done by the engine with respect to a specified load.
Brake mean effective pressure	$BMEP\ (\frac{kN}{m^2}) = bp \times \frac{120}{V_{sn} * N}$	Exerted pressure according to net mean effective force of combustion on cylinder swept volume.
Actual Air mass flow rate	$\dot{m}_{a,act.}(\frac{kg}{s}) = \frac{12\sqrt{h_o * 0.85}}{3600} \times \rho_{air}$	Actual consumption of air by weight, which measured by using orifice meter.
Theoretical Air mass flow rate	$\dot{m}_{a_{theo.}}(\frac{kg}{s}) = V_{s.n} \times \frac{N}{60 * 2} \times \rho_{air}$	Calculated weight of air contained in swept volume cylinder
Mass flow rate of fuel	$\dot{m}_f(\frac{kg}{s}) = \frac{v_f \times 10^{-6}}{1000} \times \frac{\rho_f}{time}$	Fuel consumption rate of specified volume for each selected fuel density per time
Brake specific fuel consumption	$BSFC\ (kg/kWhr) = \frac{\dot{m}_f}{bp} \times 3600$	Fuel consumption specifically to develop one kilowatt load per hour.
Brake thermal efficiency.	$\eta_{bth.} = \frac{bp}{Q_t} \times 100$	The ability of the engine thermal system to convert the total fuel energy into actual applied load on the engine.
Volumetric efficiency	$\eta_{vol} = \frac{\dot{m}_{a,act}}{\dot{m}_{a,theo}} \times 100$	Air proportion which entered into engine cylinder with respect to swept volume space.

2.4. Simulation setup

The theoretical study of this paper occurred by the LOTUS Engine Simulation software of version 6.01a which is considered one of the most important software in design and analysis studies of internal combustion engines. This simulation program can calculate the complete engine system performance by completing the design requirements of the selected engine type and cycle operation. In this work, the single-cylinder IC engine model was created using options of this simulator. The engine layout and process flow of the simulation are presented in Fig. 2. The input parameters to the LOTUS software to simulate the engine performance are tabulated in Table 5.

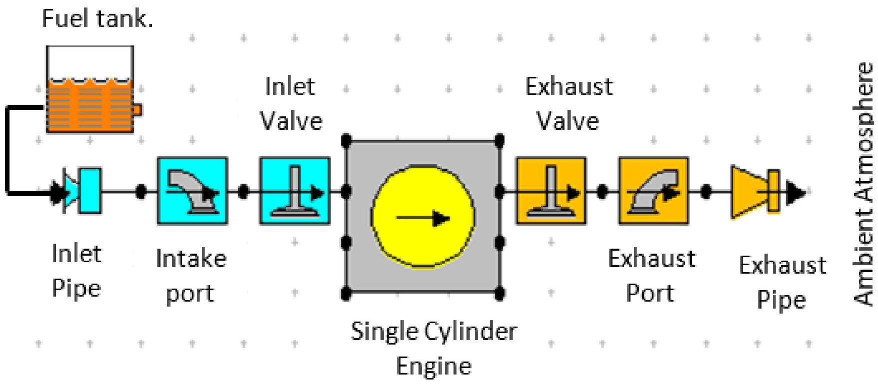


Fig. 2. Engine Layout by LOTUS software.

Table 5. Input parameters for LOTUS software simulation of the engine performance.

Input Data	Parameter
Engine Data	- Speed, RPM - Fuel Type - Fuel System - Engine Cycle - Heating Values
Engine Geometry Data	- Bore - Stroke - Compression Ratio - Valve Timing - No. of Cylinders - Connecting Rod Length
Operation Condition	-Equivalence Ratio -Atmospheric Pressure -Atmospheric Temperature

3. Results and Discussion

The results of the research are covered under two separate sections: the engine performance analysis and the environmental related issues created by the emissions.

3.1. Engine performance analysis

3.1.1. Brake specific fuel consumption

Due to the lower LHV of the mixture compared to gasoline, blending alcohols and gasoline results in high brake specific fuel consumption (BSFC). The BSFC for E50B20, E20B50, and E50 is observed to be high, while B50 exhibits lower BSFC than gasoline at medium speeds (2000 rpm).

Figure 3 shows the BSFC distribution for each blended fuel compared to gasoline across various engine speeds. Fuel consumption is higher for blended fuels at high speeds of 2400 and 2800 rpm compared to gasoline. At all engine speeds, B50 demonstrates lower consumption at low and medium speeds of 1200, 1600, and 2000 rpm and higher consumption at high speeds of 2400 and 2800 rpm. Generally, IC engines consume more fuel as speeds increase, and the BSFC for the B50 butanol-gasoline blend is 14.1% lower than gasoline at low speeds. At tested engine speeds, BSFC increased by about 8% for E50B20 compared to gasoline, with other blends showing increases of less than 5%.

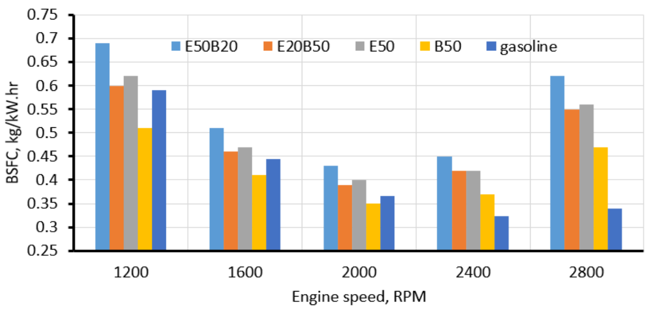


Fig. 3. Change in BSFC with engine speed for tested fuel blends.

3.1.2. Brake thermal efficiency

Improved combustion leads to greater brake thermal efficiency (BTE) for the utilized fuel, as less fuel is needed to produce the same braking power. Figure 4 demonstrates the gradual increase in BTE for blended fuel with changing engine speed compared to neat gasoline. Butanol's complete oxidation during combustion reduces cylinder cooling losses, resulting in faster combustion speeds. B50 exhibits favourable BTE, surpassing other tested fuels at low and medium speeds, although it decreases at high speeds due to increased fuel mass flow rate at these speeds.

Maximum BTE values ranging from 25% to 26.4% for all blend types are achieved at medium speeds compared to gasoline, with the B50 blend showing a 19% increase in BTE at 2000 rpm. Analysis indicates that blending gasoline with low alcohol volume fractions enhances overall IC engine performance, aligning with findings from [37, 38]. In addition, Elfasakhany [26] reported that butanol showed low performance as compared to gasoline, such as thermal efficiency, as agreed with this work.

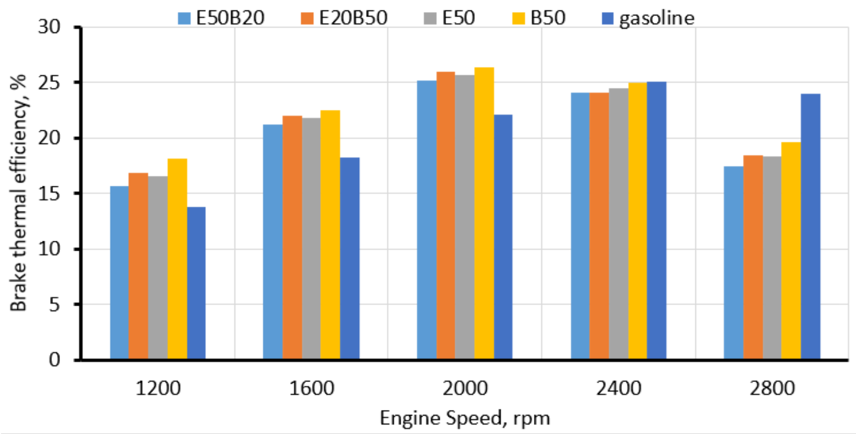


Fig. 4. Change in brake thermal efficiency vs. variation in engine speed with different tested fuel blends.

3.1.3. Volumetric efficiency

The volumetric efficiencies for various fuel blends at intervals of 1200-2800 rpm with 400 rpm intervals is displayed in Fig. 5. It can be observed that gasoline and ethanol-butanol-gasoline blends result in a gradual increase in volumetric efficiency from low to medium speeds (1200, 2000 rpm), followed by a decrease at high speeds (2400, 2800 rpm). The maximum ethanol volumetric ratio in gasoline, compared to butanol, shows the minimum volumetric efficiency.

Blending B50 develops maximum volumetric efficiency at a medium engine speed of 2000 rpm and minimum volumetric efficiency as a result of the E50B20 mixture at low engine speed. This decrease in volumetric efficiency with rising engine speed might be due to restrictions on fresh charge intake and charge flow into and out of the combustion chamber. Moreover, the lower saturation pressure of ethanol relative to gasoline leads to higher fuel evaporation rates, increasing the volumetric efficiency of the alcoholic fuel [39].

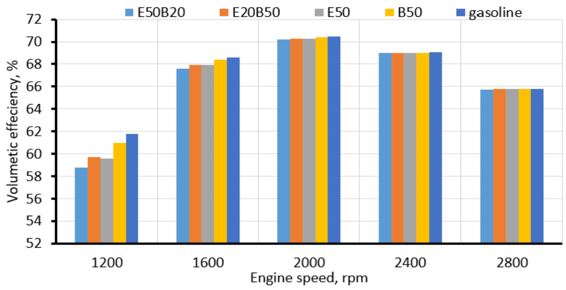


Fig. 5. Change in volumetric efficiency with engine speed for different tested fuel blends.

3.2. Emission analysis

Compared to gasoline, the GB blends exhibit better combustion quality and lower CO emissions due to their higher oxygen content, as shown in Fig. 6. CO concentrations are reduced by about 9.7 % and 7.9% for E50B20 and E20B50, respectively, while for E50 and B50 the reductions are about 7.5% and 4.8 %, respectively, compared to gasoline.

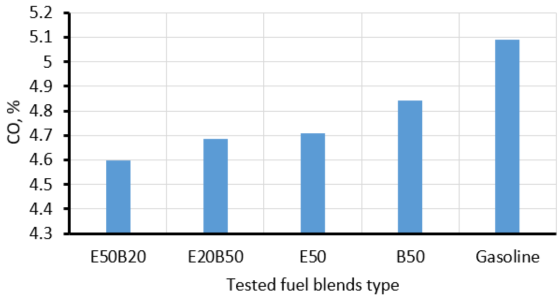


Fig. 6. CO emission by various tested blends.

Figure 7 illustrates the positive effect of Ethanol-Butanol blends on UHC emissions, where they are reduced by 11% and 9% compared to gasoline for E50B20 and E20B50, respectively. For E50 and B50, the reductions of CO and HC are 7.8% and 5.3%, respectively., which are comparable to [11] using ethanol as blending with gasoline and [26] using butanol, respectively.

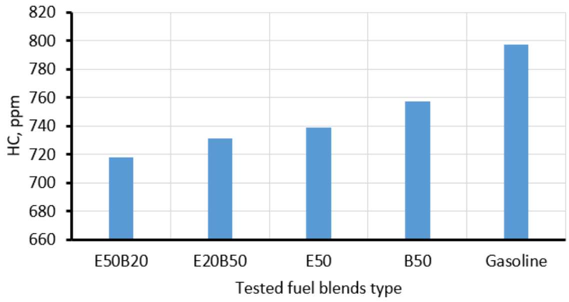


Fig. 7. UHC emission by various tested blends.

When gasoline is burned, nitrogen is given the time and heat required for oxidation, resulting in the production of NOx. Most researchers, including those in [35], agree that introducing oxygen into gasoline increases the release of NOx. From Fig. 8, it is evident that the oxygen content and influence of ethanol-butanol on NOx levels are ineffective.

On the contrary, their concentrations have somewhat decreased for various reasons (any or all of which could have contributed to this result). The researchers hypothesize that an increase in the mass percentage content of oxygen in the combustion chamber caused the increase in NOx. Despite the drop in calorific value, the combustion chamber produces less heat, minimizing NOx levels. The rates of NOx reduction for E50B20 and E20B50 were 22.2% and 19.3%, and for E50 and B50, they were 17% and 12.5% lower than gasoline, respectively.

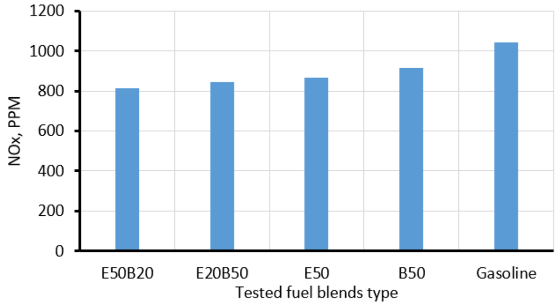


Fig. 8. NOx emission by various tested blends.

3.3. Validation and comparison

Figures 9 and 10 show the validations of the specified results of BSFC and the NOx emission levels, respectively. The results are distributed with respect to each tested fuel of E50B20, E20B50, E50, B50, and neat gasoline. The verification results show that the experimental data is slightly lower than the simulation data when compared, while the distribution trend remains the same. It has become clear from the comparison that the BSFC for the practical case is lower by about 3.38%. In comparison, the measured practical NOx concentrations are lower by about 4.56% than the theoretical readings. This convergence of results shows that the assumptions that were used in the model were close to practical reality.

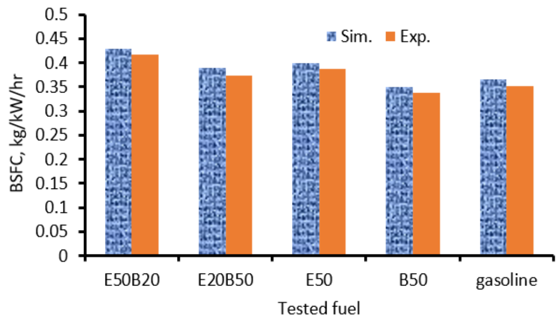


Fig. 9. Validation of simulation for brake specific fuel consumption for different tested fuels at 2000 rpm.

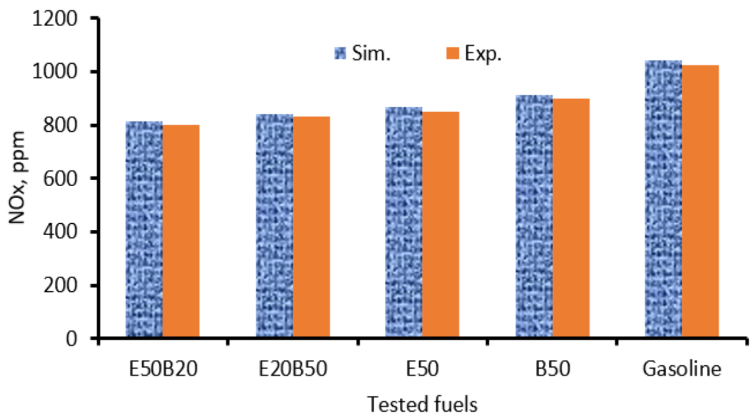


Fig. 10. Validation of simulation for NOx emission for different tested fuels at 2000 rpm.

4. Conclusions

The addition and blending of ethanol and butanol with Iraqi neat gasoline at variable volume fractions, including ethanol 50% and butanol 20%, ethanol 20% and butanol 50%, and ethanol 50% and butanol 50%, were tested. The simulation is performed using LOTUS Engine Simulation version 6.01a. The results indicate that the B50% blend exhibits lower BSFC compared to the other blends for all engine speeds, with a slight improvement in brake thermal and volumetric efficiencies.

Comparative results demonstrate a gradual decrease in CO emissions from B50 to E50B20 compared to gasoline. Additionally, there is a reduction in UHC levels. Although the NOx levels show a slight decrease compared to neat gasoline, the study's findings support the notion that any of the four fuel blends could potentially replace Iraqi gasoline successfully. The results found by simulation predicted that the experiment results were lower than previous, as a result of unexpected losses in the SI engine.

Nomenclatures

bp	Brake power, kW
h_o	Pressure difference, mmH_2O.
$\dot{m}_{(a,act.)}$	Actual air mass flow rate, kg/s.
$\dot{m}_{(a,theo.)}$	theoretical air mass flow rate, kg/s.
N	Engine speed, rpm.
Q_t	Fuel energy, kW.
T	Torque, N.m.
v_f	Fuel volume, m^3

Greek Symbols

ρ_{air}	Air density, kg/m^3
ρ_{fluid}	Fuel density, kg/m^3
η_{bth}	Brake thermal efficiency, %
ηvol	Volumetric efficiency, %

Abbreviations

BMEP	Brake mean effective pressure, kN/m^2
BSFC	Brake specific fuel consumption, kg/kW
B50	50% butanol + 50% regular gasoline
CO	Carbon monoxide
CO_2	Carbon dioxide
E50	50% ethanol + 50% regular gasoline
E20B50	20% ethanol + 50% butanol + 30% regular gasoline
E50B20	50% ethanol + 20% butanol + 30% regular gasoline
iB	iso-butanol
M10	10% methanol
MGT	Exhaust gas temperature
nB	Normal butanol
NOx	Nitrogen oxides
UHC	Unburned hydrocarbons

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