Engineering Science and Technology, an International Journal 19 (2016) 2053–2059

HOSTED BY

Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Full Length Article

Performance and emissions of spark-ignition engine using ethanol–methanol–gasoline, n-butanol–iso-butanol–gasoline and iso-butanol–ethanol–gasoline blends: A comparative study

Ashraf Elfasakhany

Department of Mechanical Engineering, Faculty of Engineering, Taif University, Box 888, Taif, Saudi Arabia

ARTICLE INFO

Article history:
Received 6 August 2016
Revised 10 September 2016
Accepted 14 September 2016
Available online 6 October 2016

Keywords:
Ethanol and methanol
n-Butanol and iso-butanol
iso-Butanol and ethanol
Gasoline
Comparison
Spark-ignition engine

ABSTRACT

The aim of this study, which is the first of its kind, is to compare experimentally the effects of different ternary blended fuels, e.g., ethanol–methanol–gasoline (EM), n-butanol–iso-butanol–gasoline (niB) and iso-butanol–ethanol–gasoline (iBE), on engine performance, combustion and pollutant emission characteristics to demonstrate the best potential one from these ternary fuel blends as alternative to fossil fuel. The experiments were performed at similar operating conditions and low content rates of fuel blends (3–10 vol% in gasoline) with varying engine speeds between 2600 and 3400 r/min at half throttle opening position of spark ignition engine. The results showed that the engine performance (volumetric efficiency, torque and brake power) increased, while pollutant emissions (carbon monoxide (CO) and unburnt hydrocarbons (UHC)) decreased at using EM fuel blends, compared to other blended fuels. It was also found that the highest emissions and the lowest performance among the blended fuels are introduced by niB, while iBE presented a moderate level of performance and emissions between niB and EM. On the other hand, the performance of niB and iBE is lower than the base fuel (neat gasoline) but EM showed a higher performance than the base fuel. The emissions of EM, niB and iBE are all lower than the base fuel.

1. Introduction

There is a growing realization worldwide that something constructive has to be done soon to reduce the environmental degradation due to gasoline fuel. Gasoline showed serious environmental problems such as acid rain, ozone depletion, greenhouse effect etc. [1–3]. Accordingly, researchers have focused their attention to replace gasoline by alternatives. Ethanol and methanol are the primary researched alternatives to gasoline in spark-ignition engines. Afterwards, other alcohols such as bio-butanol, e.g., n-butanol and iso-butanol, are researched. Many studies in literature investigated such single alcohol–gasoline blends, see e.g. [4–12]. Commonly, the studies have shown a significant reduction in pollutants emissions of such fuel blends, compared to neat gasoline. Besides, alcohol–gasoline blended fuels showed a superior engine performance, compared to neat gasoline, because of their oxygen content and higher octane numbers.

Recently, the effects of dual alcohols–gasoline blended fuels on engine performance and pollutant emissions are examined. In literatures, few publications are found as follows. Turner et al. [13] studied the effects of ethanol–methanol–gasoline blends on SI (spark-ignition) engine emissions using five different rates from 30–42 vol% gasoline and from 70–58 vol% ethanol–methanol; results showed that the dual fuel blends have reduced carbon dioxide (CO_2) and nitric oxides (NOx) emissions, compared to the neat gasoline. Sileghem et al. [14] examined ethanol–methanol–gasoline blends on carbon monoxide (CO) and NOx emissions using two different rates (71% ethanol–methanol blends and 63% ethanol–methanol blends) in gasoline; results declared that both fuel blends produced lower CO and NOx emissions than the neat gasoline. Elfasakhany [15] studied the effects of ethanol–methanol–gasoline blends using low rates (3–10 vol% ethanol and methanol) on performance and emissions of spark-ignition engine. Results have recommended the using of dual fuel blends than the neat gasoline. Nazzal [16] investigated the performance of gasoline engine using ethanol–methanol–gasoline blends at rate of 6, 6 and 88 vol% for ethanol, methanol and gasoline, respectively; the results showed significant improvements of engine performance (brake power, brake thermal efficiency and brake specific fuel consumption) at using dual fuel blends. Siwale et al. [17] studied methanol–n-butanol–gasoline blended fuels at rates of 53% methanol, 17% n-butanol and 30% gasoline on performance and emissions of spark-ignition engine. Results showed higher performance and

E-mail address: ashr12000@yahoo.com

http://dx.doi.org/10.1016/j.jestch.2016.09.009
2215-0986/

lower emissions of fuel blends than those of neat gasoline. Balaji et al. [18] examined ethanol–iso-butanol–gasoline blends using three different rates (10% ethanol–2.5% iso-butanol, 10% ethanol–5% iso-butanol and 10% ethanol–7.5% iso-butanol in gasoline) on engine performance and exhaust emissions of SI engine. Result showed that dual fuel blends increased the engine performance (brake power, volumetric efficiency and thermal efficiency) and decreased emissions (carbon monoxide and hydrocarbons) compared to pure gasoline. Elfasakhany [19] investigated bio-ethanol–iso-butanol–gasoline blends (3, 7 and 10 vol% bio-ethanol–iso-butanol in gasoline) in spark ignition engine and compared results with iso-butanol–gasoline blends as well as neat gasoline fuel. Results of dual fuel blends showed 15% and 20% lower UHC (unburnt hydrocarbons) and CO emissions, respectively, than those of neat gasoline; in addition, dual fuel blends introduced 9% and 14% lower UHC and CO emissions, respectively, than those of iso-butanol–gasoline blends. Engine performance of dual fuel blends demonstrated higher brake power, torque, volumetric efficiency and exhaust gas temperature than those of iso-butanol–gasoline; however, dual fuel blends showed a little drop in engine performance, compared to neat gasoline. Elfasakhany [20] examined in another study the effects on engine performance and pollutant emissions at using n-butanol–iso-butanol–gasoline blends; the author claimed that such blended fuel is the first of its kind in the internal combustion engines. The dual alcohols–gasoline blends, in addition, were compared with those of single alcohol–gasoline blends, e.g., iso-butanol–gasoline and n-butanol–gasoline blends, and pure gasoline. Results demonstrated a higher engine performance and lower emissions when engine was operated with dual alcohols–gasoline blends, compared to single blended ones. Besides, dual alcohols blended in gasoline showed lower emissions but with a minute drop in engine performance, compared to neat gasoline. Elfasakhany [21] in one more study examined the effects of n-butanol–methanol–gasoline fuel blends on the performance and pollutant emissions of spark-ignition engine. Four test fuels were investigated (namely: 0, 1.5, 3.5 and 5% for n-butanol and methanol in gasoline). The results showed that the addition of low content rates of n-butanol–methanol into gasoline adversely affects the engine performance and exhaust emissions, as compared to neat gasoline; however, higher rates of blended fuels in gasoline were observed to improve the SI engine performance and emissions. The performance and emissions of acetone-butanol-ethanol (ABE) blended in gasoline are examined in a number of studies, see e.g. [22,23], and results showed promising fuel blends.

In addition to single alcohol and dual alcohols blended in gasoline, as discussed above, researchers studied a comparisons between single alcohol with each others, see e.g. [4,5,13,14,24,25]; as well, single alcohol blends were compared with the dual alcohols blends, as shown early, see e.g. [15,19,20]. However, dual alcohols blended fuels were not compared with each others, according to the best of author knowledge. In the current study, this gap is filled by comparing performance and emissions of different dual alcohols blended fuels, e.g., ethanol–methanol, iso-butanol–n-butanol and iso-butanol–ethanol, in gasoline at similar rates (3–10 vol%) and similar engine working conditions. Given the increasing concern for acute pollution problems in the world, the study, in addition, aims at recommending the lowest fuel emissions among different dual alcohols blended fuels used in spark ignition engines.

2. Experiments overview

The experiments were carried out using a spark-ignition engine with four-stroke and air cooled type. The research engine contains a single cylinder with 17 kg weight, 65.1 mm bore, and 44.4 mm stroke. The output power is about 1.5 kW with operating compression ratio of 7. The single cylinder research engine is desirable here to avoid the complication of fuel/air mal-distribution ratio, where the variation in the fuel/air equivalence ratio from a cylinder-to-cylinder, in a multi-cylinder engine, could be of the order 210%. A pulley is mounted on the output shaft of the engine to couple the engine with a dynamometer. The engine is also mounted with vibration attenuators for dampening the vibrations that occur during the engine operation. For monitoring engine exhaust emissions, gas analyser of model Infralyt CL is applied. The gas analyser is capable of measuring the concentrations of CO, CO_2 and UHC using an infrared measurement technique, e.g., non-dispersive infrared. The CO and CO_2 emissions were measured in volume percentage bases; however, the UHC was measured in part per million (ppm). Detailed specifications of the exhaust gas analyzer and its measuring range are given in Table 1. Before starting up the gas analyzer and the engine, different fuels blends were first prepared. Three different dual alcohols blended in gasoline were arranged as: ethanol–methanol–gasoline, iso-butanol–n-butanol–gasoline and iso-butanol–ethanol–gasoline. The blended fuels were prepared in three different rates each. In particular, ethanol–methanol–gasoline blends were prepared as: 5:5:90 vol% in the first rate, 3.5:3.5:93 vol% in the second rate, and 1.5:1.5:97 vol% in the third rate for methanol, ethanol and gasoline, respectively. Other kinds of dual alcohols blended fuels, e.g., iso-butanol–n-butanol–gasoline and iso-butanol–ethanol–gasoline blends, were prepared in the same rates, e.g., 5:5:90 vol%, 3.5:3.5:93 vol% and 1.5:1.5:97 vol% for iso-butanol, n-butanol and gasoline, respectively, and/or for iso-butanol, ethanol, gasoline, respectively. The low rates of alcohols blended in gasoline were applied in the current study for some reasons; firstly, such low rate (up to 10 vol%) could be used in the current automobile engines without any modifications; secondly, alcohols are still more expensive than gasoline; thirdly, some of alcohols can cause corrosion in engine material and that increases in case of their high content rate in the fuel blends [15,26]; fourthly, the smaller the rate of alcohols in fuel blends, the easier typical blending problems (phase separation, etc.) can be solved; and fifthly, many countries (such as USA, Brazil, etc.) are currently using low blend rates (10 vol%.) of alcohols at their service stations. The properties of the fuels are summarized in Table 2 [27–32,10]. After preparing the fuel blends, it is introduced into the engine subsequently one by one. The experiments were performed at variable engine speeds from 2600 to 3400 r/min with 100 r/min interval. Engine speeds were controlled by engine dynamometer. During experiments, different parameters of engine performance and pollutant emissions were carried out. Engine performance measurements include volumetric efficiency, brake power and torque; however, pollutant emissions measurements include CO, CO_2 and UHC. The parameters of engine

Table 1
Gas analyser specifications.

Warm-up	10 min
Dimensions	294 mm × 430 mm × 260 mm
Weight	9 kg
Exhaust gas temperature	5–45 °C
Measurement Ranges	CO 0–10 vol% CO_2 0–20 vol% UHC 0–2000 ppm
Voltage	230 V
Frequency	50 Hz
Power	45 VA
Range of apparatus heating	0–130 °C
Accuracy	OIML class 1 and 0 ±1 °C, ±0.05 vol%, ±10 ppm

Table 2
Fuel properties [27–32,10].

Property	Gasoline	Ethanol	Methanol	iso-Butanol	n-Butanol
Chemical formula	C8H15	C2H5OH	CH3OH	C4H9OH	C4H9OH
Composition (C,H,O) (mass%)	86,14,0	52,13,35	37.5,12.5,50	65, 13.5, 21.5	65, 13.5, 21.5
Lower heating value (MJ/kg)	43.5	27.0	20.1	33.3	33.1
Heat of evaporation (kJ/kg)	223.2	725.4	920.7	474.3	582
Stoichiometric A/F ratio	14.6	9.0	6.4	11.1	11.2
Oxygen content, mass%	0.0	34.7	49.9	21.6	21.6
Density (kg/m^3)	760	790	796	802	810
Saturation pressure at 38 °C (kPa)	31	13.8	31.69	2.3	2.27
Flash point (°C)	−45 to −38	21.1	11.1	28	35
Auto-ignition temperature (°C)	420	434	470	415	385
Boiling point (°C)	25–215	78.4	64.5	108	117.7
Solubility in water (ml/100 ml H_2O)	<0.1	Fully miscible	Fully miscible	10.6	7.7
Vapor toxicity	Moderate Irritant	Toxic even In small doses	Toxic in only Large doses	Moderate Irritant	Moderate Irritant

performance were measured using appropriate actuators and sensors equipped with engine. The engine also is equipped with an electronic indicating system (EIS) to transfer the measured data into PC (personal computer). Tests were carried out initially using neat gasoline fuel (base fuel) to generate the reference line data. Then different fuel blends were tested under same operating conditions, e.g., the engine was not modified/tuned at using any fuel. In the beginning, the engine was allowed to run until reaching the steady-state operating conditions, and afterwards, the data were collected subsequently. The tests were repeated about three times and average values were considered as final results. Detailed information about the experimental setup and procedure can be found with complete description in the early publications [5–8,15,19–21,33] since we intended to provide here experiments overview.

3. Results and discussion

Since iso-butanol–ethanol–gasoline, n-butanol–iso-butanol–gasoline and ethanol–methanol–gasoline blends are already presented and discussed in our early publications [15,19,20], the present discussion is dedicated for a comparison between such fuel blends. In the figures, iBE, niB and EM represent iso-butanol–ethanol–gasoline, n-butanol–iso-butanol–gasoline and ethanol–methanol–gasoline blends, respectively; the number next to each fuel blend in the figures represents the rate value, e.g., iBE3 represents 3 vol% iso-butanol– ethanol in gasoline and so one. Figs. 1 and 2 show, respectively, a comparison of CO and UHC emissions for the blended fuels and neat gasoline (base line) at two different speeds (2600 and 3400 r/min); these speeds were applied since they are the extremes of our test engine. As seen, the lowest CO and UHC emissions at both speeds are introduced by the EM; iBE showed a moderate emissions and niB showed the highest CO and UHC emissions among all the blended fuels; besides, niB presented higher CO emissions than the base fuel. A comparison of CO_2 emissions for the blended fuels is presented in Fig. 3. Since CO_2 emissions are more-or-less a mirror of CO and UHC emissions, e.g., at low level of CO and UHC emissions we have high CO_2 emissions and vice versa, the EM provide higher CO_2 than those of other fuel blends and the neat gasoline. The niB and iBE fuel blends introduced reasonable lower CO_2 emissions than the neat gasoline. The reasons of such trends will be clarified later.

A general comparison between pollutant emissions (CO, CO_2 and UHC) of blended fuels and neat gasoline (base line) is summarized in Fig. 4. Such comparison is introduced in average basis within all our engine speed range (2600–3400 r/min) and all the blend rates (3–10 vol%). The comparison is useful in the sense of general evaluating of vehicle emissions in different speeds, as a real vehicle working condition. As shown in the figure, the lowest CO and UHC emissions are introduced by EM fuel blends and the lowest CO_2 emissions are introduced by niB blends, compared to other blended fuels; however, the highest UHC and CO emissions among all the blended fuels are provided by niB; a moderate level of all blended fuels emissions is introduced by iBE. Compared to neat gasoline fuel, all fuel blends provide lower CO, UHC and CO_2 emissions than those of the neat gasoline, except for CO_2 emissions for the EM fuel blends.

The reasons of such emissions trends make clear as follows. Blended fuels are considered as partially oxidized hydrocarbons due to their oxygen atoms in their basic content forms, as shown in Table 2. The oxygen content enhances the combustion process and that leads to decrease the CO and UHC emissions and increase the CO_2 emissions. Since EM fuel blends contain greater oxygen contains than other test fuels (oxygen contain for gasoline, ethanol, methanol, iso-butanol and n-butanol are, respectively, 0, 34.7, 49.9, 21.6 and 21.6 mass%), the CO and UHC emissions of EM are lower than the other fuels, as shown early. In addition, the leaning effect of EM is much greater than the other test fuels. The stoichiometric A/F ratio is respectively 6.4 and 9 for methanol and ethanol; however, it is 14.6, 11.1 and 11.2 for gasoline, iso-butanol and n-butanol, respectively, as shown in Table 2. When the combustion is leaner, more complete combustion and, in turn, lower CO and UHC emissions and higher CO_2 emissions are emitted. Consequently, EM showed the lowest CO and UHC emissions and the highest CO_2 emissions among all tested fuels, followed by iBE and then niB fuel blends.

The emissions are also significantly related to fuel boiling point. A high boiling point may comprise fractions or components that are not completely vaporized and/or burnt [15]. A low boiling point, on the other hand, can enhance the fuel combustion and thereby can decrease the CO and UHC emissions. The boiling points of methanol, ethanol, n-butanol, iso-butanol and gasoline are, respectively, 64, 78, 117, 108 and 25–215 °C, as shown in Table 2. As seen, the lowest boiling point is provided by EM, compared to the other fuel blends (niB and iBE), and that is one additional reason for gaining the lowest CO and UHC emissions by EM, followed by iBE and then niB. The latent heat of vaporization can also influence significantly on the pollutant emissions. The high latent heat of vaporization of EM (heat of vaporization for gasoline, ethanol, methanol, iso-butanol and n-butanol is, respectively, 223.2, 725.4, 920.7, 474.3 and 582 kJ/kg) can increase the intake air process and, in turn, more complete combustion and lower CO and UHC emissions of EM, compared to other test fuels.

One important observation on the emission results is that by using 10 vol% blended fuels, the emissions are lower than those of 7 vol% and 3 vol% of same fuel type. This refers to that the higher

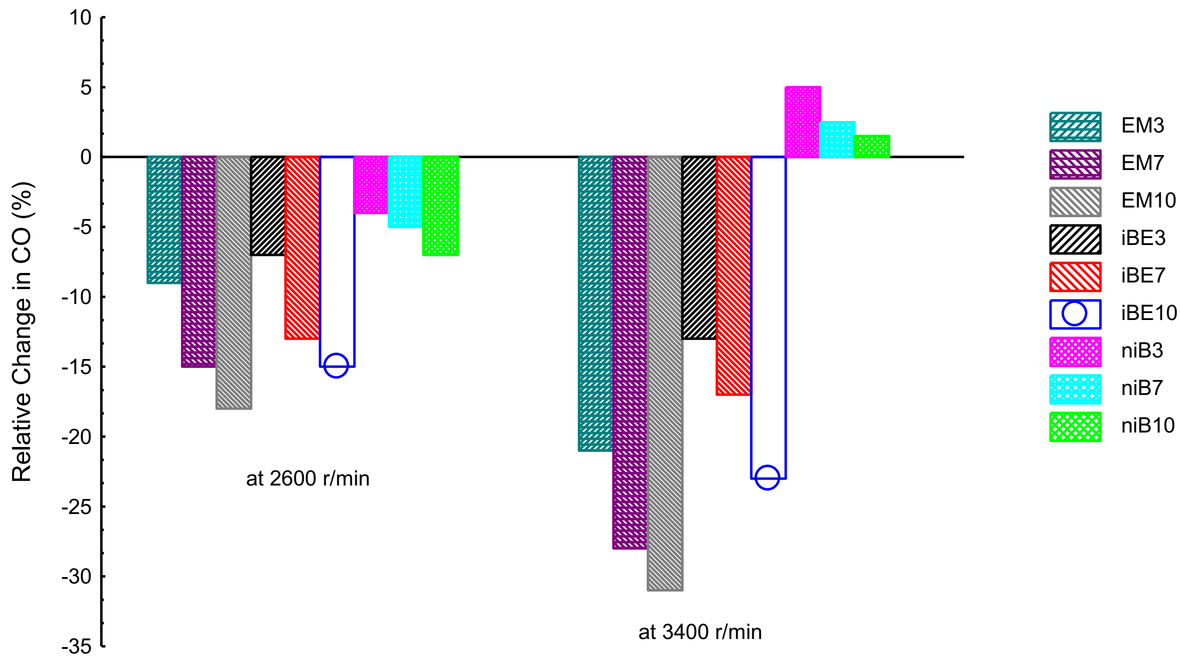

Fig. 1. Comparison of CO emissions from different blended fuels (EM3, EM7 and EM10: 3,7 and 10 vol% ethanol and methanol in gasoline; iBE3, iBE7 and iBE10: 3,7 and 10 vol % iso-butanol and ethanol in gasoline; niB3, niB7 and niB10: 3,7 and 10 vol% n-butanol and iso-butanol in gasoline) and neat gasoline (base line).

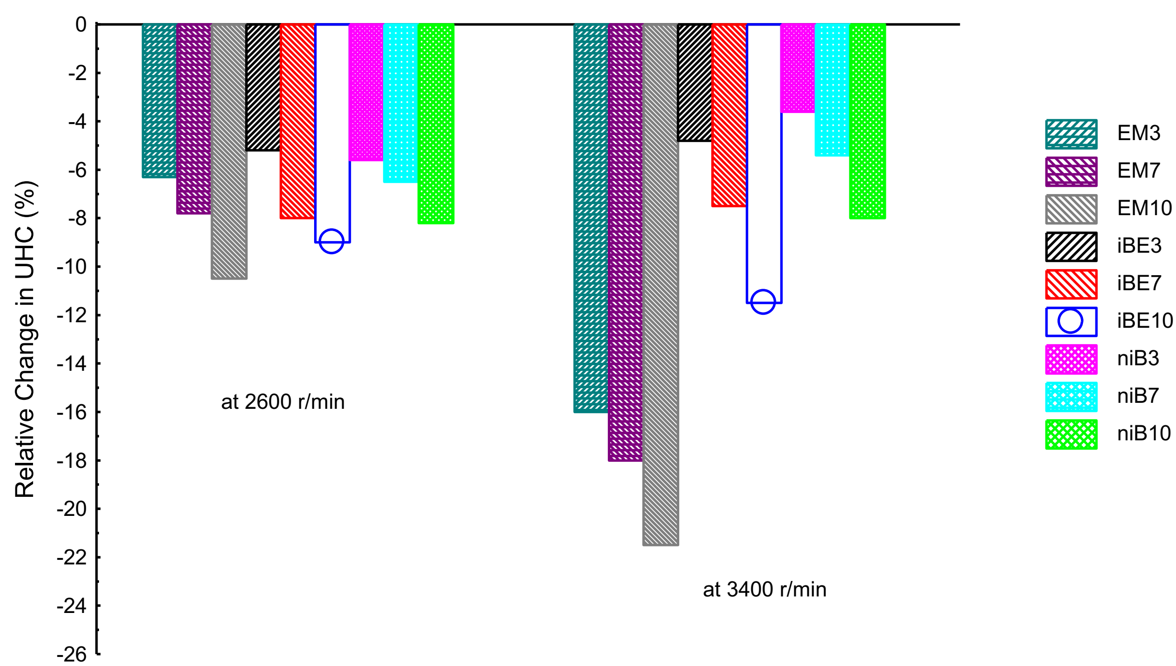

Fig. 2. Comparison of UHC emissions from different blended fuels and neat gasoline (base line), captions are similar to those in Fig. 1.

blend rates can lead to a higher oxygen content and latent heat of vaporization of the fuel. Consequently, a more complete combustion and lower CO and UHC emissions (higher CO_2 emissions) are gained. In addition, the higher blend rate, the further leaning effect is and, in turn, fuel can burn in a shorter duration of time, i.e., less CO and UHC emissions with higher CO_2 emissions.

A comparison of engine performance of different test fuels is presented in Figs. 5 and 6. In particular, Fig. 5 shows a comparison of volumetric efficiency (VE), torque (Tq) and brake power (BP) for the blended fuels (EM, niB and iBE) and neat gasoline (base line) in the two extremes of the engine speeds (2600 and 3400 r/min). Fig. 6 shows a general change in engine performance (VE, Tq and BP) for the blended fuels in average basis within all engine speeds (2600–3400 r/min) and all blend rates (3–10 vol%). As seen in the figures, the highest BP, VE and Tq within all speeds were presented by EM followed by iBE and niB. This refers to that the higher oxygen content of EM compared to other test fuels, as shown early, leads to a higher heat released, which that in turn increases Tq and BP. The higher latent heat of evaporation of the EM fuel blends, compared to others, also boosts its VE. On the other hand, the higher heat of evaporation of EM fuel blends, compared to iBE, niB and neat gasoline, as shown in Table 2, causes a lower temper-

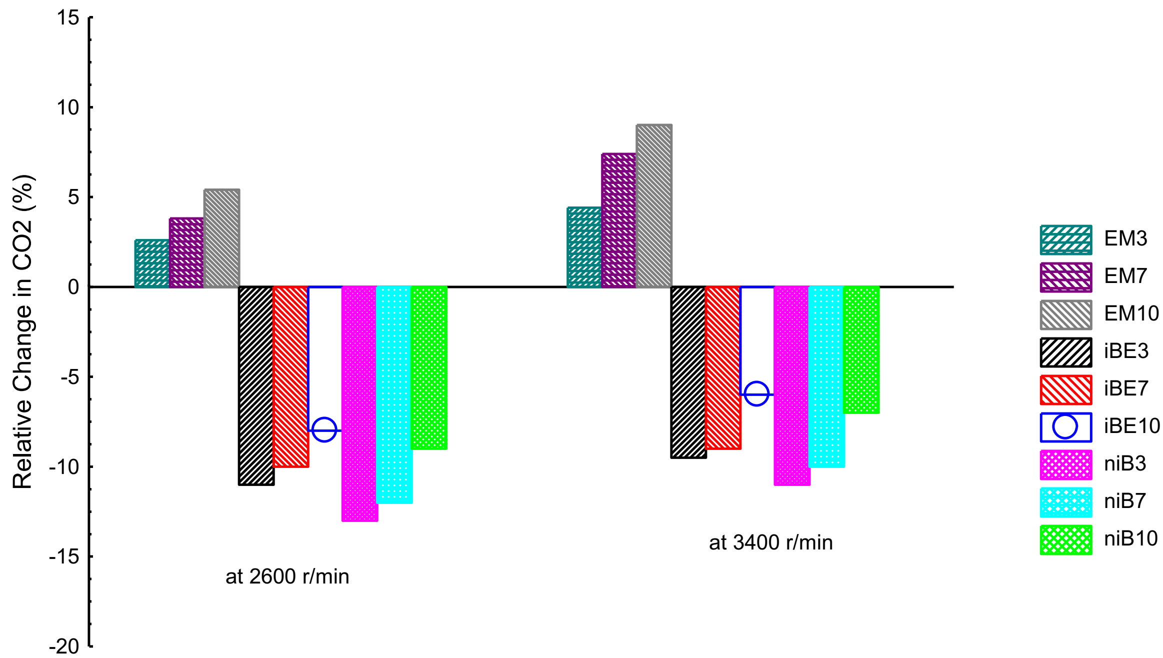

Fig. 3. Comparison of CO_2 emissions from different blended fuels and neat gasoline (base line), captions are similar to those in Fig. 1.

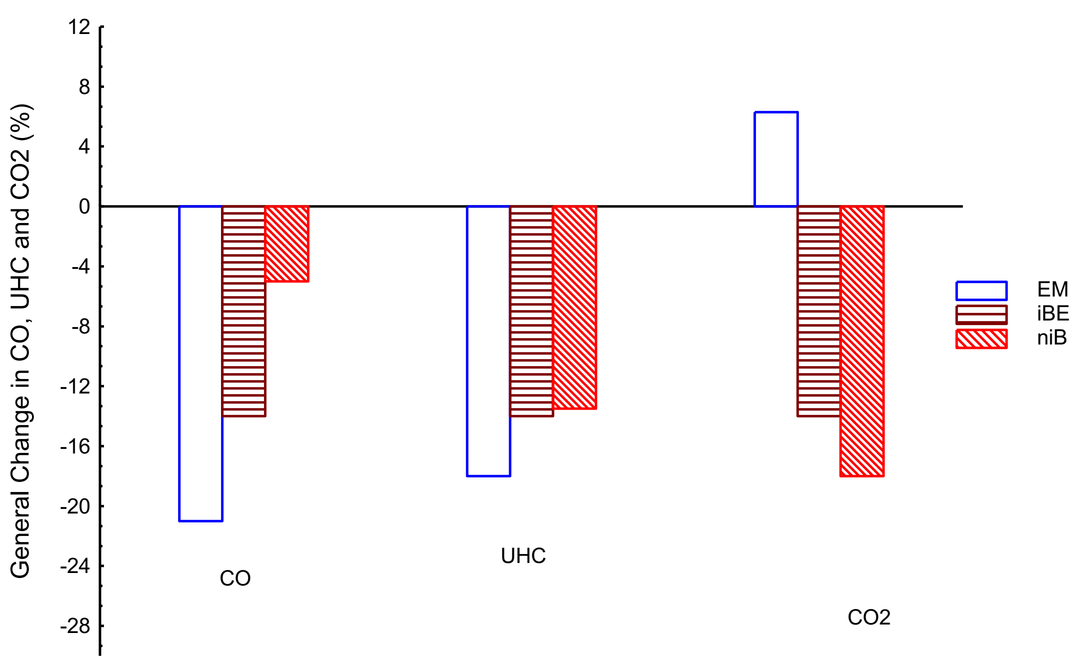

Fig. 4. General change of CO, CO_2 and UHC emissions for ethanol–methanol–gasoline blends (EM), iso-butanol–ethanol–gasoline blends (iBE), n-butanol–iso-butanol–gasoline blends (niB) and neat gasoline (base line) in average basis within all engine speeds (2600–3400 r/min) and all blend rates (3–10 vol%).

ature in the combustion chamber, hence decreases BP and Tq; but the higher VE of EM causes to improve fuel combustion and, in turn, increase BP and Tq. As a result of these conflicting factors, different fuel blends, e.g., EM, iBE and niB, have detractive effects on the BP and Tq, as shown in Figs. 5 and 6. It is also observed that both niB and iBE fuel blends slightly decreased the Tq and BP than those of neat gasoline due to the lower energy content of such fuel blends (43.5, 33.3 and 33.1 MJ/kg for gasoline, iso-butanol and n-butanol, respectively). It is also observed that VE of niB and iBE is lower than the gasoline fuel. This may attribute to their low saturation pressure (31, 2.3 and 2.27 kPa for gasoline, iso-butanol and n-butanol, respectively). The low saturation pressure leads to evaporate a great amount of fuel and, in turn, that lowers the VE. Since saturation pressure of niB is somewhat lower than iBE, the VE of niB is lower than that of iBE.

Finally, it is important to highlight that, EM showed the best performance and pollutant emissions, among all the blended fuels, followed by iBE and then niB. In addition, EM presented higher performance than the neat gasoline; however, iBE and niB showed lower performance (BP, Tq and VE) than those of neat gasoline. On the other hand, from other studies, ethanol and methanol showed to cause some engine performance problems in case of

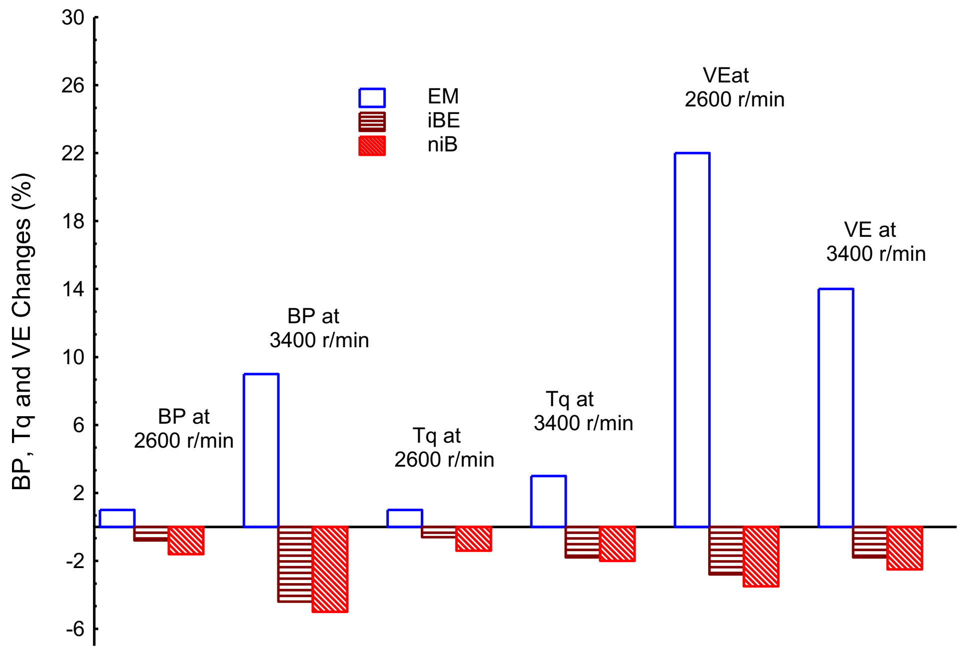

Fig. 5. Comparison of volumetric efficiency (VE), torque (Tq) and brake power (BP) for ethanol–methanol–gasoline blends (EM), iso-butanol–ethanol–gasoline (iBE), n-butanol–iso-butanol–gasoline blends (niB) blends and neat gasoline (base line) in average basis within the two extremes of engine speeds (2600 and 3400 r/min) and all the blend rates (3–10 vol%).

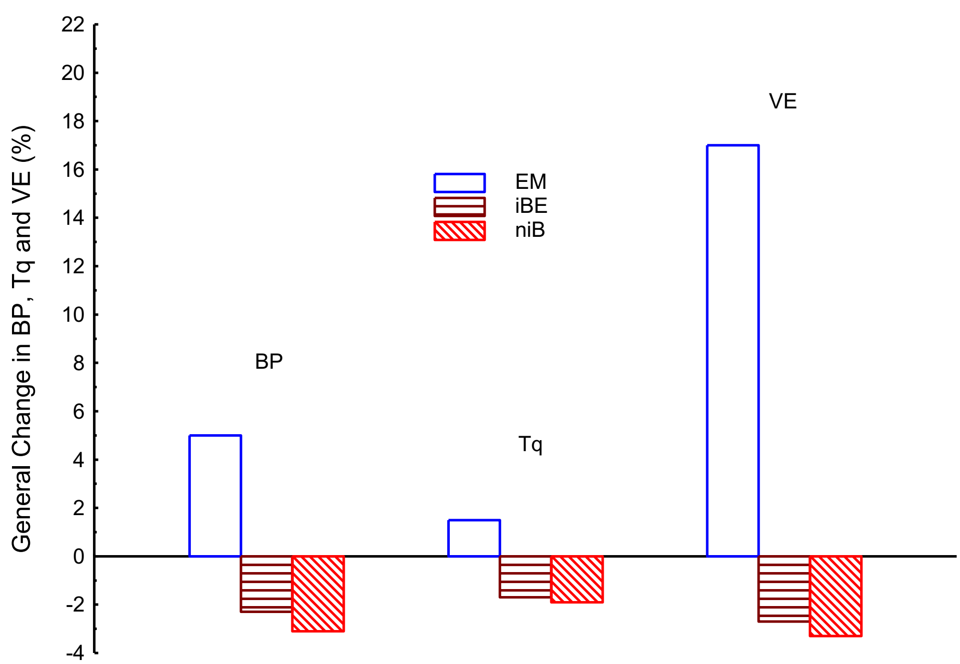

Fig. 6. General change in brake power (BP), torque (Tq) and volumetric efficiency (VE) for ethanol–methanol–gasoline blends (EM), iso-butanol–ethanol–gasoline blends (iBE), n-butanol–iso-butanol–gasoline blends (niB) and neat gasoline (base line) in average basis within all engine speeds (2600–3400 r/min) and all blend rates (3–10 vol%).

high blend rates conditions, which are not shown in our study since we apply low blend rates. In hot environmental working conditions, ethanol and methanol may cause vapor lock. In addition, they can cause engine starting up problem in cold environmental conditions due to their poor evaporation as a result of very high latent heat of ethanol's and methanol's [34,35]. They are also fully miscible in water and incompatible with some engine materials and systems. Compared with ethanol and methanol, iso-butanol and n-butanol showed advantages in case of their high content rate in gasoline. iso-butanol's and n-butanol's low vapor pressures improve cold engine starting condition; iso-butanol and n-butanol have the ability to be blended with gasoline in any concentrations without (or probably with minor) needs for system modifications [36]; they create less corrosions for engine material [37–42]; their solubility in water are significantly much lower than ethanol and methanol; also their higher boiling point and flash point make them safer to use than ethanol and methanol [43]. Finally, the higher heating values and energy densities of n-butanol and iso-butanol than those of methanol and ethanol, as shown in Table 2, lead to superior fuel economy of niB and iBE than the EM fuel blends. In conclusion, EM could be used in low blend rate conditions to avoid/limit drawbacks of cold starting, corrosion, vapor lock, etc., as shown from this study, where no drawbacks were observed. However, in case of applying high blend rates, iBE is preferable, followed by niB.

4. Conclusions

In this study, the effects of different ternary blended fuels at same rates and engine working conditions are compared for the first time. Engine performance (brake power, torque and volumetric efficiency) and pollutant emissions (CO, CO_2 and UHC) are measured for all tested fuels, e.g., ethanol–methanol–gasoline (EM), n-butanol–iso-butanol–gasoline (niB), iso-butanol–ethanol–gasoline (iBE) and neat gasoline. The results showed that the EM fuel blends can introduce the best performance and the lowest engine emissions (carbon monoxide and unburnt hydrocarbons) among all blended fuels, while niB fuel blends showed the worst performance and pollutant emissions (CO and UHC) among all blended fuels; iBE showed a moderate level of engine performance and pollutant emissions (CO and UHC) between the other two blended fuels. Besides, EM presented higher performance and lower CO and UHC exhaust emissions than the neat gasoline (base fuel), while niB and iBE presented lower engine performance than the base fuel. A comparison of carbon dioxide (CO_2) emissions showed that the EM introduced higher CO_2 than those of other fuel blends and the neat gasoline. The niB and iBE fuel blends introduced reasonable lower CO_2 emissions than the neat gasoline. One final observation is that the pollutant emissions are significantly improved at using higher rates of dual alcohols blended in gasoline.

References

[1] A. Elfasakhany, Modeling of pulverised wood flames. PhD thesis, fluid mechanics dept., Lund, Sweden, 2005; ISBN–13/EAN: 9789162864255.
[2] A. Elfasakhany, T. Tao, B. Espenas, J. Larfeldt, X.S. Bai, Pulverised wood combustion in a vertical furnace: experimental and computational analyses, Appl. Energy 112 (2013) 454–464.
[3] M. Ozcan, S. Öztürk, Y. Oguz, Potential evaluation of biomass-based energy sources for Turkey, Eng. Sci. Technol. JESTECH 18 (2015) 178–184.
[4] H. Bang-Quan, M. Liu, H. Zhao, Comparison of combustion characteristics of n-butanol/ethanol–gasoline blends in a HCCI engine, Energy Convers. Manage. 95 (2015) 101–109.
[5] A. Elfasakhany, Experimental investigation on SI engine using gasoline and a hybrid iso-butanol-gasoline fuel, Energy Convers. Manage. 95 (2015) 398–405.
[6] A. Elfasakhany, Investigation on performance and emissions characteristics of an internal combustion engine fuelled with petroleum gasoline and a hybrid methanol–gasoline fuel, Int. J. Eng. Technol. 13 (2013) 24–43.
[7] A. Elfasakhany, Experimental study on emissions and performance of an internal combustion engine fueled with gasoline and gasoline–n-butanol blends, Energy Convers. Manage. 88 (2014) 277–283.
[8] A. Elfasakhany, The effects of ethanol–gasoline blends on performance and exhaust emission characteristics of spark ignition engines, Int. J. Automot. Eng. 4 (2014) 608–620.
[9] S. Szwaja, J.D. Naber, Combustion of n-butanol in a spark-ignition IC engine, Fuel 89 (2010) 1573–1582.
[10] B. Deng, J. Yang, D. Zhang, R. Feng, J. Fu, J. Liu, K. Li, X. Liu, The challenges and strategies of butanol application in conventional engines: the sensitivity study of ignition and valve timing, Appl. Energy 108 (2013) 248–260.
[11] M. Al-Hasan, Effect of ethanol–unleaded gasoline blends on engine performance and exhaust emissions, Energy Convers. Manage. 44 (2003) 1547–1561.
[12] H.S. Yucesu, T. Topgul, C. Cinar, M. Okur, Effect of ethanol–gasoline blends on engine performance and exhaust emissions in different compression ratios, Appl. Therm. Eng. 26 (2006) 2272–2278.
[13] J.W.G. Turner, R.J. Pearson, E. Dekker, B. Iosefa, K. Johansson, K. Bergstom, Extending the role of alcohols as transport fuels using iso-stoichiometric ternary blends of gasoline, ethanol and methanol, Appl. Energy 102 (2013) 72–86.
[14] L. Sileghem, A. Coppens, B. Casier, J. Vancoillie, S. Verhelst, Performance and emissions of iso-stoichiometric ternary GEM blends on a production SI engine, Fuel 117 (2014) 286–293.
[15] A. Elfasakhany, Investigations on the effects of ethanol–methanol–gasoline blends in a spark-ignition engine: performance and emissions analysis, Eng. Sci. Technol. JESTECH 18 (2015) 713–719.
[16] I.T. Nazzal, Experimental study of gasoline –Alcohol blends on performance of internal combustion engine, Eur. J. Sci. Res. 52 (2011) 16–22.
[17] L. Siwale, L. Kristóf, A. Bereczky, M. Mbarawa, A. Kolesnikov, Performance, combustion and emission characteristics of n-butanol additive in methanol–gasoline blend fired in a naturally-aspirated spark ignition engine, Fuel Proc. Technol. 118 (2014) 318–326.
[18] D. Balaji, P. Govindarajan, J. Venkatesan, Influence of isobutanol blend in spark ignition engine performance operated with gasoline and ethanol, Int. J. Eng. Sci. Technol. 2 (2010) 2859–2868.
[19] A. Elfasakhany, Engine performance evaluation and pollutant emissions analysis using ternary bio-ethanol–iso-butanol–gasoline blends in gasoline engines, J. Cleaner Prod. 139 (2016) 1057–1067.
[20] A. Elfasakhany, Experimental study of dual n-butanol and iso-butanol additives on spark-ignition engine performance and emissions, Fuel 163 (2016) 166–174.
[21] A. Elfasakhany, A.F. Mahrous, Performance and emissions assessment of n-butanol-methanol-gasoline blends as a fuel in spark-ignition engines, Alexandria Eng. J. 55 (2016) 3015–3024.
[22] K. Nithyanandan, C.F. Lee, H. Wu, J. Zhang, Performance and emissions of acetone-butanol-ethanol (ABE) and gasoline blends in a port fuel injected spark ignition engine, ASME (2014), http://dx.doi.org/10.1115/ICEF2014-5644. 5644, V001T02A010.
[23] K. Nithyanandan, J. Zhang, Y. Li, H. Wu, T.H. Lee, Y. Lin, C.F. Lee, Improved SI engine efficiency using acetone–butanol–ethanol (ABE), Fuel 174 (2016) 333–343.
[24] I. Gravalos, D. Moshou, T. Gialamas, P. Xyradakis, D. Kateris, Z. Tsiropoulos, Performance and emission characteristics of spark ignition engine fuelled with ethanol and methanol gasoline blended fuels, Alternative Fuel, 2001, ISBN:978–953–307–372–9.
[25] J. Zhang, K. Nithyanandan, Y. Li, C. Lee, Comparative study of high-alcohol-content gasoline blends in an SI engine, SAE, 2015–01–0891, 2015, doi:http://dx.doi.org/10.4271/2015-01-0891.
[26] F. Pischinger, Alcohol fuels for automotive engines, 11th World Petroleum Congress, RTD 6(3), 1983, London.
[27] A.K. Agarwal, Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines, Prog. Energy Combust. Sci. 33 (2007) 233–271.
[28] L. Shenghua, E.R.C. Clemente, H. Tiegang, W. Yanjv, Study of spark ignition engine fueled with methanol–gasoline fuel blends, Appl. Therm. Eng. 27 (2007) 1904–1910.
[29] J. Chao, Y. Mingfa, L. Haifeng, F.L. Chiafon, J. Jing, Progress in the production and application of n-butanol as a biofuel, Renewable Sustainable Energy Rev. 15 (2011) 4080–4106.
[30] A. Irimescu, Performance and fuel conversion efficiency of a spark ignition engine fueled with iso-butanol, Appl. Energy 96 (2012) 477–483.
[31] F.N. Alasfour, NO_x emission from a spark ignition engine using 30% iso-butanol–gasoline blend: Part 1–Preheating inlet air, Appl. Therm. Eng. 18 (1998) 245–256.
[32] F.N. Alasfour, The effect of using 30% iso-butanol–gasoline blend on hydrocarbon emissions from a spark-ignition engine, Energy Sources 21 (1999) 379–394.
[33] A. Elfasakhany, Performance and emissions analysis on using acetone–gasoline fuel blends in spark ignition engine, Eng. Sci. Technol. JESTECH 19 (2016) 1224–1232.
[34] D.F. Kabasin, T. Hurter, R. Lamers, K. Hoyer, J.Kazour, Heated injectors for ethanol cold starts, SAE paper 2009–01–0615, 2009.
[35] C. Jin, M. Yaoc, H. Liuc, C.F. Leed, J. Jing, Progress in the production and application of n-butanol as a biofuel, Renewable Sustainable Energy Rev. 15 (2011) 4080–4106.
[36] A. Irimescu, Fuel conversion efficiency of a port injection engine fueled with gasoline–isobutanol blends, Energy 36 (2011) 3030–3035.
[37] X. Gu, Q. Li, Z. Huang, Laminar burning velocities and flame instabilities of butanol isomers– air mixtures, Combust. Flame 157 (2010) 2318–2325.
[38] B.Q. He, X. Wang, M. Hao, G. Yan, H. Xiao, A study on emission characteristics of an EFI engine with ethanol blended gasoline fuels, Atmos. Environ. 37 (2003) 949–957.
[39] R.H. Chen, L.B. Chiang, M.H. Wu, T.H. Lin, Gasoline displacement and NO_x reduction in an SI engine by aqueous alcohol injection, Fuel 89 (2010) 604–610.
[40] A.M. Liaquat, M.A. Kalam, H. Masjuki, M.H. Jayed, Potential emissions reduction in road transport sector using biofuel in developing countries, Atmos. Environ. 44 (2010) 3869–3877.
[41] C. Srinivasan, C.G. Saravanan, Study of combustion characteristics of an SI engine fuelled with ethanol and oxygenated fuel additives, Sustainable Energy Environ. 1 (2010) 85–91.
[42] M. Balat, H. Balat, C. Öz, Progress in bioethanol processing, Prog. Energy Comb. Sci. 34 (2008) 551–573.
[43] N. Abdehagh, F.H. Tezel, J. Thibault, Separation techniques in butanol production: challenges and developments, Biomass Bioenergy 60 (2014) 222–246.