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ORIGINAL ARTICLE

Performance and emissions assessment of n-butanol–methanol–gasoline blends as a fuel in spark-ignition engines

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Engine performance

Abstract The sleek of using alternatives to gasoline fuel in internal combustion engines becomes a necessity as the environmental problems of fossil fuels as well as their depleted reserves. This research presents an experimental investigation into a new blended fuel; the effects of n-butanol–methanol–gasoline fuel blends on the performance and pollutant emissions of an SI (spark-ignition) engine were examined. Four test fuels (namely 0, 3, 7 and 10 volumetric percent of n-butanol–methanol blends at equal rates, e.g., 0%, 1.5%, 3.5% and 5% for n-butanol and methanol, in gasoline) were investigated in an engine speed range of 2600–3400 r/min. In addition, the dual alcohol (methanol and n-butanol)–gasoline blends were compared with single alcohol (n-butanol)–gasoline blends (for the first time) as well as with the neat gasoline fuel in terms of performance and emissions. The experimental results showed that the addition of low content rates of n-butanol–methanol to neat gasoline adversely affects the engine performance and exhaust gas emissions as compared to the results of neat gasoline and single alcohol–gasoline blends; in particular, a reduction in engine volumetric efficiency, brake power, torque, in-cylinder pressure, exhaust gas temperature and CO_2 emissions and an increase in concentrations of CO and UHC (unburned hydrocarbons) emissions were observed for the dual alcohols. However, higher rates of n-butanol–methanol blended in gasoline were observed to improve the SI engine performance parameters and emission concentration. Oppositely the higher rates of single alcohol–gasoline blends were observed to provide adverse results, e.g., higher emissions and lower performance than those of lower rates of single alcohol. Finally, dual alcohol–gasoline blends could exceed (i.e. provide higher performance and lower emissions) single alcohol–gasoline blends and pure gasoline at higher rates (> 10 vol.%) in the blend and, in turn, it is recommended to be used at high rate conditions.

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1. Introduction

Works on the use of alternative fuels instead of crude oil are vastly employed worldwide since crude oil reserves are depleting, in addition to its environmental problems. Researchers have focused their interest on the domain of bio-fuels, which offer benefits in terms of reduced emissions and their renewable nature [1]. Among those, bio-alcohols such as butanol and methanol are considered as very promising alternative fuels. Works on the use of butanol and methanol in spark-ignition engines either as blended with gasoline or as neat fuels have been reported in several studies, see e.g. [2–11].

Investigations of methanol in SI (spark ignition) engines, in early research groups, showed that methanol gives higher engine efficiency and lower emissions than gasoline. The methanol combustion can provide lower reactivity of organic emissions than the gasoline fuel and in turn lower ozone forming potential. In addition, methanol can present lower emissions of benzene and PAHs (polycyclic aromatic hydrocarbons). However, methanol showed some drawbacks as an alternative fuel in SI engines, compared to gasoline. The methanol–energy density and calorific value are very low and, hence, methanol–fueled vehicle required larger fuel tank. Methanol flame is invisible and it is likely to explode in enclosed tanks. Methanol, in addition, is toxic and has corrosive characteristics [12–14].

Compared to methanol, n-butanol showed some advantages. Butanol or butyl alcohol can be demonstrated to work in the internal combustion (IC) engine designed for use with gasoline with minor modifications [11,15]. Butanol is less corrosive than methanol and it could be distributed using the same infrastructure used to transport gasoline fuel. It is much less hygroscopic than methanol preventing it from water contamination. For ICE point of view, butanol is less corrosive to the materials in the fuel delivery and injection systems. It also has more desirable fuel properties such as higher energy density and miscibility with gasoline. However, when taking into account the latent heat of vaporization, butanol is less attractive than methanol (latent heat of methanol is much higher than n-butanol). For port fuel injection systems, when the fuel vaporizes in the inlet port it decreases a temperature of the intake charge. Therefore, fuel of higher latent heat of vaporization has larger decrease in temperature of intake charge with complete vaporization in the intake port. This increases the density of combustible mixture and also increases the charge mass. Furthermore, the cost of butanol production is higher in comparison with methanol [16]; butanol has physical properties that can lead to poorer spray atomization. Finally, butanol lags behind methanol in terms of commercial production.

In order to improve butanol and methanol as practical transportation alternative fuels in spark-ignition engines, it is therefore important to enhance their characteristics. One possible method is by blending methanol and butanol since the drawbacks of methanol would be limited by butanol and the same for the drawbacks of butanol; however, such mixture requires to be investigated prior to be practically recommended as alternative fuel, especially each of fuel (methanol and butanol) has different thermodynamic properties and, in turn, combustion characteristics of ternary n-butanol–methanol–gasoline blends are unidentified.

Investigation of ternary fuel blends in SI engines is examined in the literature and found not often. Turner et al. [17] presented the concept of ternary blends of gasoline, ethanol and methanol, but the work did not show how the engine performance or emissions will be with this new fuel blends. Nazzal [18] investigated the effects of ethanol–methanol–gasoline blends on the performance of gasoline engine at a variety of engine operating conditions. The study examined 6% ethanol–6% methanol–88% gasoline and the results showed that ternary blends improve the engine performance compared to neat gasoline. The study by Balaji et al. [19] examined iso-butanol–ethanol–gasoline blends using different blend rates in gasoline, e.g., 10% ethanol–2.5% iso-butanol, 10% ethanol–5% iso-butanol and 10% ethanol–7.5% iso-butanol. They demonstrated that ternary fuel blends can increase the engine performance and decrease the exhaust emissions compared to pure gasoline fuel; however, the fuel consumption for the ternary fuel blends increases significantly compared to pure gasoline. Sileghem et al. [20] studied ternary ethanol–methanol–gasoline blends and demonstrated an improvement in engine performance and emissions compared with neat gasoline. Elfasakhany [21] investigated ethanol–methanol–gasoline blends using low rates of fuel blends (3–10 vol.% ethanol and methanol) in gasoline. Results showed that ternary fuel blends provide better performance and lower emissions than those of pure gasoline. Elfasakhany [22] in another study investigated bio-ethanol–iso-butanol–gasoline blends in motorcycle engines and compared results with those of iso-butanol–gasoline blends (dual blends) and neat gasoline fuel. Results showed higher engine performance (brake power, torque and volumetric efficiency) of ternary fuel blends than those of dual bends, but ternary fuel blends showed a little drop of engine performance compared to neat gasoline. Results of emissions demonstrated lower UHC (unburnt hydrocarbons) and CO emissions by 15% and 20%, respectively, than those of neat gasoline and 9% and 14% lower than those of dual fuel blends. Elfasakhany [23] examined in one more study the n-butanol–iso-butanol–gasoline blends (such fuel blends are thought to be the first of its kind in internal combustion engines) on engine performance and pollutant emissions. The results were compared with those of iso-butanol–gasoline, n-butanol–gasoline blends and pure gasoline. Generally, the study came up with a recommendation of using ternary blends than the dual blends or neat gasoline. Siwale et al. [24] investigated methanol–n-butanol–gasoline blends (53% methanol, 17% n-butanol and 30% gasoline by volume) in SI engines and compared results with dual blends (70 vol.% methanol–30 vol.% gasoline, M70, and 20 vol.% methanol–80 vol.% gasoline, M20) and neat gasoline fuel. Results showed lower UHC emission of the ternary fuel blends than that of dual fuel blends or neat gasoline. But ternary blends showed higher CO, NOx and CO_2 emissions than those of dual blends. The performance was investigating via brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) and the results showed that the ternary blends provide lower BTE than M70 and higher BSFC than gasoline; however, other performance parameters, such as volumetric efficiency, brake power and torque, were not examined. Andersen et al. [25] discussed theoretically the mixing of methanol and n-butanol in gasoline and concluded that the fuel blends can reduce the evaporative emissions on the fuel delivery system; however, the study did not test any practical ternary fuel blends to determine whether or not these blends can be applied satisfactorily on spark ignition engines.

Table 1 Engine specifications.

Type	CT 150, spark-ignition engine
Bore (mm)	65.1
Stroke (mm)	44.4
Compression ratio	7.1
Engine displacement (cc)	147.7
Number of cylinders	Single
Engine configuration	Vertical configuration
Lubrication system	Splash
Valve arrangement	Two vertical over head valves
Max power	1.5 kW

The research presented in this work is focused on applying ternary n-butanol–methanol–gasoline mixture as blending agent fuel and compared with n-butanol–gasoline blends as well as neat gasoline. Engine performance includes volumetric efficiency, brake power and torque and pollutant emissions of CO, UHC and CO_2 are investigated and compared for the test fuels. The rates applied of n-butanol–methanol in gasoline are up to 10 vol.%. Such low rates were favorable for the following motivations; low blend rates could be used in the current engines without any modifications; n-butanol and methanol are still more expensive and fewer productivities than gasoline; methanol causes corrosion to some engine materials, as demonstrated early, and that increases in case of its high content rate in the blends. The novelty in the current study, compared to the early ones in the literature, e.g., Siwale et al. [24] and Andersen et al. [25], is that the current study investigates wider engine performance parameters (volumetric efficiency, brake power and torque), which are not investigated early; secondly, low rates of dual alcohols (up to 10 vol.%) are examined here; however, early studies investigated higher rates; thirdly, dual alcohols are investigated against single alcohol (n-butanol), which is not presented early.

2. Experimental setup

In this study, three different fuels were applied, namely methanol, n-butanol and gasoline. The methanol's and n-butanol's physical and chemical properties relative to gasoline are summarized in Table 2 [26–32]. The fuels were blended together to form four tested fuels, as 10% n-butanol–methanol (5% n-butanol and 5% methanol by volume) in gasoline, 7% n-butanol–methanol (3.5% n-butanol and 3.5% methanol by volume) in gasoline, 3% n-butanol–methanol (1.5% n-butanol and 1.5% methanol by volume) in gasoline, and pure gasoline.

The test fuels were charged into the intake system of the test engine. The engine is a single-cylinder and 4-stroke SI engine type, as specified in Table 1. The engine was operated during experiments on a full load from 2600 to 3400 r/min with an interval of 100 r/min. Engine performance parameters were measured, including intake pressure and temperature, in-cylinder pressure, exhaust gas temperature, output torque, brake power and volumetric efficiency. The engine was arranged with different instruments to provide the needed measurements; the engine is equipped with the electronic indicating system (EIS), which contains sensors for different engine parameter measurements. The EIS transfers the measured data to a personal computer (PC). The PC is equipped with software that allows for calculating and displaying engine performance parameters, such as volumetric efficiency and power. The in-cylinder pressure was measured by a pressure transducer, which was fitted together with spark plug; the torque was measured directly using the dynamometer.

In addition to performance parameters, engine-out raw emissions were measured for each test case. The samples of exhaust gases were taken from exhaust hose within gas analysis. An Infralyt CL model gas analyser was used to measure the exhaust of UHC, CO and CO_2 emissions. The engine air/fuel ratio (AF) was measured by analyzing the exhaust gas contents. Due to lack of AF ratio control because of the existing fuel system, the fuel mass flow per cycle was kept constant for all test fuels for a given condition. Since the stoichiometric AF ratio of gasoline is 14.7, and is 11.2 and 6.49 for n-butanol and methanol, respectively, the blend fuels always run at leaner fuel–air mixtures relative to pure gasoline. The environment temperature was about 25 °C ± 1 °C during the test cases. All of the measurements were performed after a fully warm-up of engine when the engine and analyser have a 30 s stable operating conditions. For n-butanol–methanol–gasoline blend fuels, all tests were performed without modifying anything on the engine, e.g., similar as in gasoline conditions. For further details about experimental setup and experimental method, you may see the early publications [2,11,15,21–23,33–34].

3. Results and discussions

In this section, the performance and pollutant emissions of the SI engine fueled with 3, 7 and 10 volumetric percentage of

Table 2 Properties of gasoline, methanol and n-butanol [26–32].

Parameters	Methanol	N-butanol	Gasoline
Molecular formula	CH_3OH	C_4H_9OH	C_8H_{15}
Octane number	111	96	90–99
Oxygen content (% weight)	50.0	21.6	–
Composition (C, H, O) (mass%)	37.5, 12.5, 50	65, 13.5, 21.5	86, 14, 0
Stoichiometric air/fuel ratio	6.49	11.21	14.7
Lower heating value (MJ/kg)	19.9	33.1	42.7
Density at 20 °C (g/cm^3)	0.796	0.810	0.745
Viscosity (mm^2/s) at 40 °C	0.59	2.63	0.4–0.8
Flash point (°C)	12	35	−45 to −38
Latent heating (kJ/kg) at 25 °C	920.7	582	223.2
Boiling point (°C)	64.5	117.7	25–215
Saturation pressure (kPa) at 38 C	31.69	2.27	31.01
Auto-ignition temperature (°C)	470	385	420
Flammability limits (vol.%)	6.0–36.5	1.4–11.2	0.6–8
Specific heat (kJ/kg K) LIQ	2.533	2.48	2.4
Vapor toxicity	Toxic in only Large doses	Moderate Irritant	Moderate Irritant

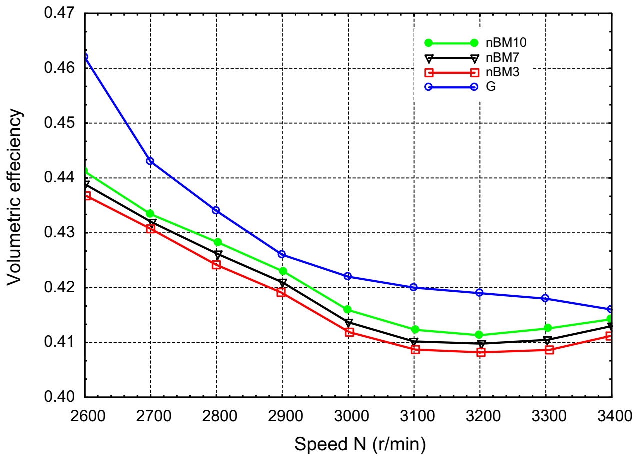

Figure 1 Volumetric efficiency versus engine speed for n-butanol–methanol–gasoline blends of 3, 7 and 10 vol.% (nBM3, nBM7 and nBM10, respectively) and neat gasoline (G).

n-butanol–methanol–gasoline fuel blends (namely: nBM3, nBM7 and nBM10, respectively) are studied and compared with results of neat gasoline (G) under similar conditions. The engine performance (volumetric efficiency, in-cylinder pressure, brake power, torque and exhaust gas temperature) of different test fuels is conducted in a speed range of 2600–3400 r/min. Fig. 1 shows the variations of engine volumetric efficiency with engine speed for various fuel blends and neat gasoline. As seen, increasing engine speed exhibits a reduction in engine volumetric efficiency for all test fuels as a result of flow choking and frictional losses in the induction system. For the blended fuels, the addition of n-butanol–methanol to gasoline results in a decrease in engine volumetric efficiency over gasoline at all engine speeds. The motivation of volumetric efficiency results is that the n-butanol's saturation pressure (2.27 kPa) is very low compared to gasoline (31 kPa), as shown in Table 2. Therefore, large amount of fuel is vaporized in the engine intake system when using fuel blends. As a result of fuel vapor formation in the intake charge, fuel vapor displaces some of the incoming induced air and this significantly reduces the engine volumetric efficiency [11,15]. In addition, the stoichiometric air/fuel ratio of methanol is 6.49 as compared to 14.7 for gasoline, see Table 2. Fuels with lower values of air/fuel ratio experience a greater loss in volumetric efficiency [35]. In summary, fuel evaporation due to low saturation pressure as well as low values of stoichiometric air/fuel ratio significantly reduces engine volumetric efficiency when engine charged with fuel blends compared to gasoline. However, n-butanol–methanol has higher heat of evaporation than gasoline (582, 920 and 223 kJ/kg for n-butanol, methanol and gasoline, respectively, as shown in Table 2) and this decreases the intake temperature of n-butanol–methanol and, accordingly, increases the volumetric efficiency of the blended fuels. At low blend rate (nBM3), saturation pressure dominates on volumetric efficiency than the heat of evaporation and lower air/fuel ratio; hence, nBM3 showed much lower volumetric efficiency than gasoline. As the blend rate increases, e.g. 7% and 10% of n-butanol–methanol, the heat of evaporation starts to dominate and thus charge temperature at the end of intake stroke decreases due to evaporation cooling. Accordingly, nBM7 and nBM10 exhibit higher volumetric efficiency than nBM3. By further increase in n-butanol–methanol rates in the blends, volumetric efficiency of fuel blends is expected to exceed the value of the gasoline fuel. Feng et al. [36] showed that the engine volumetric efficiency with 35 vol.% butanol–gasoline blended fuel is higher than that of pure gasoline due to higher latent heat of vaporization of fuel blends.

The temporal variation of in-cylinder pressure (pressure – crank angle degree) at an engine speed of 3000 r/min (mid range of engine speeds) is shown in Fig. 2 for various fuel blends and neat gasoline. In-cylinder pressure is considered to be one of the most important performance parameters as it measures the combustion characteristics of blended fuels as compared with pure gasoline. As illustrated in the figure, the effects of the fuel blends are limited, to some extent, to the peak in-cylinder pressure. Compared to that of pure gasoline, the nBM3 reduces the maximum in-cylinder pressure by about 8.5%. Increasing the rate of fuel blends from nBM3 to nBM7 results in a reasonable increase in the peak in-cylinder pressure. Further increase in the rates of nBM fuel content from nBM7 to nBM10 does not significantly affect (slightly increases) the value of the peak in-cylinder pressure. The reduction in the engine in-cylinder pressure of blended fuel nBM3, compared to that of pure gasoline, is attributed to the lower heating value of methanol and n-butanol fuels in comparison with that of pure gasoline (19.9, 33.1 and 42.7 MJ/kg, respectively, for methanol, n-butanol and gasoline, Table 2). Improvements gained in the in-cylinder charge pressure when firing the engine with nBM7 and nBM10 blends are due to the improvements obtained in the volumetric efficiency (Fig. 1) and also to the improved combustion due to increase in the percentage of oxygen content (Table 2), as it will be discussed later in further details.

Variations of engine brake power and torque are displayed in Figs. 3 and 4, respectively. As illustrated, adding small amount of n-butanol–methanol to gasoline (nBM3) significantly decreases both the engine brake power and torque over gasoline, particularly at high engine speeds. This is attributed to the decrease in the heat released by combustion as a result of lower calorific values of the blended fuels, as shown early. In addition, the heat of evaporation of n-butanol–methanol

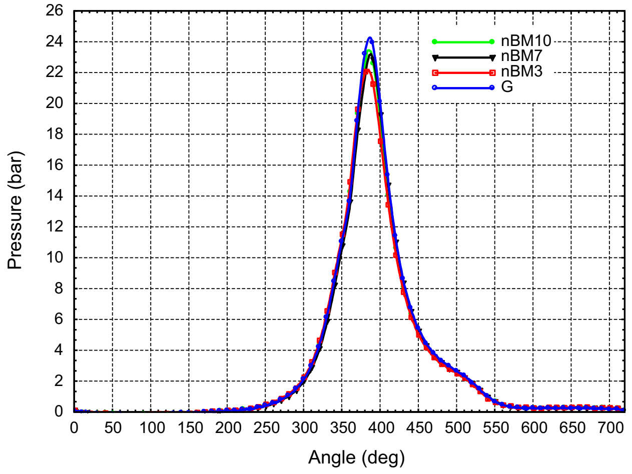

Figure 2 Effect of fuel blends on indicated mean effective pressure (IMEP) at engine speed 3000 r/min. Captions are seen in Fig. 1.

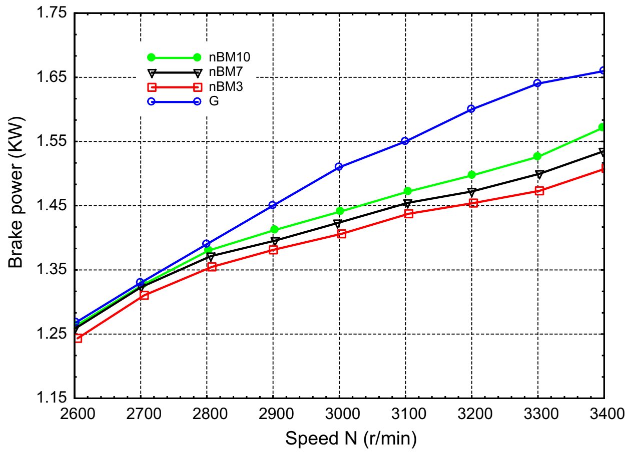

Figure 3 Brake power versus engine speed. Captions are seen in Fig. 1.

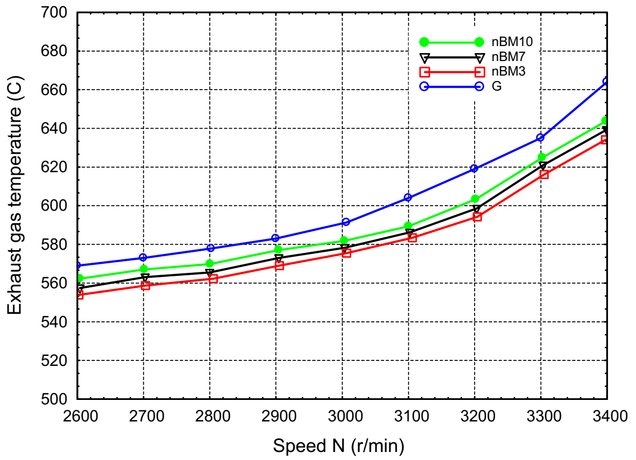

Figure 5 Exhaust gas temperature versus engine speed. Captions are seen in Fig. 1.

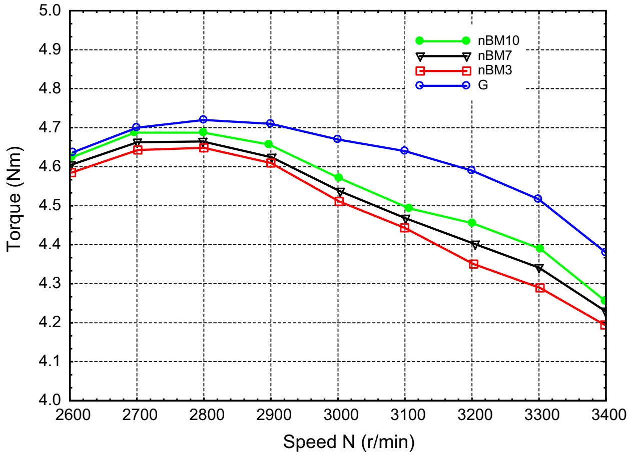

Figure 4 Torque versus engine speed. Captions are seen in Fig. 1.

is much higher than that of gasoline, as shown in Table 2, and that without doubt will decrease the power and torque. But, on the other hand, the high heat of vaporization of fuel blends will provide a cooling of intake fresh charge and that increases the density of the charge at the end of induction process [37]. The increase in the charge density results in an increase in the volumetric efficiency and, in turn, an increase in the engine torque and power output as the rate of fuel blending (nBM content) increases. Furthermore, improvements gained in the in-cylinder pressure due to the increase in the rate of fuel blending have a positive effect on the engine torque and brake power [38].

Fig. 5 shows exhaust gas temperature trends for all test fuels. As depicted, the exhaust gas temperature increases with an increase in the engine speed for all test fuels. Besides, engine fueled with neat gasoline shows the highest exhaust gas temperature, compared to blended fuel. Lower rates of nBM fuel blends exhibit lower trends of exhaust gas temperature. Increasing the rate of fuel blends, from nBM3 to nBM10, leads to an increase in the values of exhaust gas temperature. This may refer to that methanol and n-butanol having higher latent heats of vaporization than gasoline, as mentioned early. For this reason, vaporization of nBM blends produces a much larger temperature drop in the engine cylinder at the end of induction process. This consequently decreases the in-cylinder temperature at the end of compression stroke and so the exhaust gas temperature at the end of combustion process [38,39]. Increasing the volumetric efficiency while increasing the content of nBM in the fuel blend leads to a corresponding increase in the exhaust gas temperature. Compared to pure gasoline, having lower exhaust gas temperature, while firing the SI engine with fuel blends, may be beneficial to the environmental conditions. This is due to the lower amount of exhaust heat transferred to the ambient when fueling the engine with fuel blends. Thus, fuel blends may be considered as environmentally friendly fuels as they would have less contribution to global warming phenomenon. Furthermore the lower exhaust gas temperature means a lower compression work, e.g., beneficial in output power [24].

From the results presented so far, the performance parameters of SI engine are significantly affected by the addition of n-butanol–methanol to pure gasoline. A common negative effect on volumetric efficiency, in-cylinder pressure, brake power and torque is observed at low rates of nBM fuel blending. Increasing the volumetric percentage of nBM in the blend improves the engine performance significantly. A continuous improvement in the engine performance is expected while increasing the content of nBM in the blend, as demonstrated early and will be additionally investigated later. This conclusion is consistence with Abu-Zaid et al. [40] who investigated the performance of an SI engine using 3–15% alcohol blended gasoline and reported that the maximum power output was obtained from 15% fuel blend.

Fig. 6 illustrates the effects of fuel blends on the emissions of carbon monoxide and unburned hydrocarbons at different engine speeds. CO is mainly produced in the exhaust gases due to the incomplete combustion of fuel. Accordingly, the existence of carbon monoxide in the exhaust gas is a measure of loss in engine power. Increasing the engine speed causes an increase in engine power for all test fuels (see Fig. 3) and consequently decreases emissions of CO and UHC as depicted in Fig. 6. As compared to pure gasoline, blends of

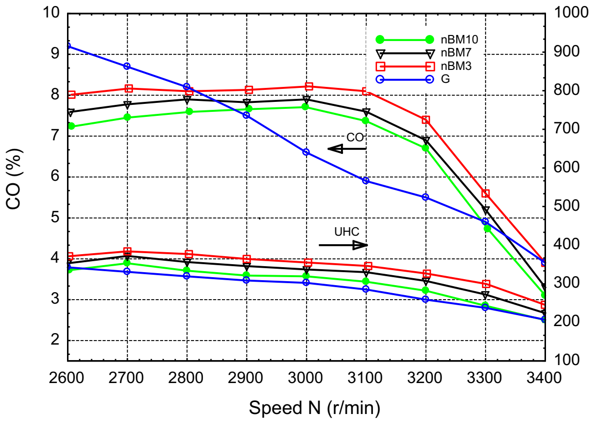

Figure 6 Carbon monoxide and unburned hydrocarbon (UHC) versus engine speed. Captions are seen in Fig. 1.

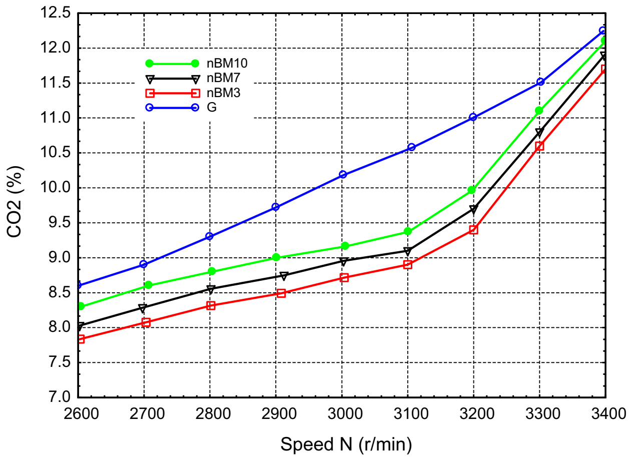

Figure 7 Carbon dioxide versus engine speed. Captions are seen in Fig. 1.

n-butanol–methanol with gasoline show lower CO emissions at lower engine speed, whereas differences in engine power and torque are insignificant. When engine uses fuel blends, increasing the engine speed does not significantly affect the emission of CO till a speed of 3100 r/min, and after that, an abrupt decrease in the CO emissions is observed. The presence of oxygen molecules in the blends, compared to pure gasoline fuel, may improve the combustion process and thus reduces the emissions of CO and UHC. Oxygen content by weight is 50% for methanol and is 21.6% for n-butanol, as shown in Table 2. However, lower calorific values of methanol and n-butanol blends, compared to neat gasoline, lead to lower peak in-cylinder pressure (Fig. 2) and temperature. This definitely affects the trends of CO and UHC emissions as shown in Fig. 6. Increasing the percentage of n-butanol–methanol in the fuel blend (from nBM3 to nBM10) leads to increase its oxygen content and therefore reduces the CO and UHC emissions. Moreover, higher volumetric efficiency gained when increasing the content of nBM from nBM3 to nBM10 (Fig. 1) leads to more access of air in the combustion chamber and accordingly lowers the CO and UHC emissions [21]. However, the investigated range of nBM test fuels still produces exhaust gas emissions with high concentration of CO and UHC emissions (in average) as compared to pure gasoline; further discussions will be demonstrated in a while.

The variation of CO_2 emission at different engine speeds and for various blends of test fuels is shown in Fig. 7. As seen, the trends of CO_2 emissions are being contrary to those of CO and UHC emissions (Fig. 6) since CO_2 emissions mainly depend on the air–fuel ratio as well as on the concentration of CO and UHC emissions. The leaner the in-cylinder charge, the more efficient the combustion of fuel and the higher the concentration of CO_2 emissions in the exhaust gas. As shown in Fig. 7, increasing the volumetric content of n-butanol–methanol in the fuel (from nBM3 to nBM10) leads to an increase in the emissions of CO_2, as opposed to emissions of CO and UHC, as depicted in Fig. 6. This is due to improvements gained in the combustion process as a result of higher oxygen content in the blends, as reported by many investigators under different conditions, e.g. Varol et al. [41] and Al-Hasan [42], and also due to higher volumetric efficiency at higher contents of n-butanol–methanol in the blended fuels. Further reason may refer to the leaning effect of fuel blends (stoichiometric air/fuel ratio for methanol and n-butanol is 6.49 and 11.2, respectively) compared to gasoline (14.7), as shown in Table 2.

Commonly, the high level of CO and UHC emissions of fuel blends (or alternatively the lower production of CO_2) compared to neat gasoline refers to, in addition to above reasons, the unconverted CO and UHC to CO_2 through the intermediate (secondary) step reaction during the later stages of combustion in the combustion chamber [43]. Such secondary step combustion depends on some factors such as the temperature in the combustion chamber, abundance of O_2 and the staying instance of fuel in the combustion chamber. In the case of fuel blends (oxygenated fuel), O_2 concentration does not limit this secondary reaction but the temperature does. Alcohols (methanol and n-butanol) have lower heating values and higher heat of vaporization than those of gasoline fuel, as shown in Table 2. Therefore, the temperature of the combustion products is lower (this is confirmed by the lower in-cylinder pressure and exhaust gas temperature of dual alcohols, as shown in Figs. 2 and 5) and that slows down the process of CO and UHC conversions to CO_2 or even freezes the reactions [43]. This causes the CO and UHC concentrations to increase and CO_2 to decrease. On the other hand, excess-air ratio and fuel leaning combustion conditions are important factors affecting the CO, UHC and CO_2 emissions. By increasing the blend rates in the fuel, excess-air ratio and leaning condition increase; accordingly, CO and UHC emissions decrease and CO_2 emission increases.

Engine performance and pollutant emissions of both dual alcohols (n-butanol and methanol) and single alcohol (n-butanol) each blended with gasoline were evaluated and compared with each other (at same blend rate conditions) as well as with those of pure gasoline at similar engine circumstances, e.g., without any tuning/adjustments for all test fuels. Comparisons of CO, CO_2 and UHC pollutant emissions for dual alcohols–gasoline blends (nBM), single alcohol–gasoline blends (nB) and neat gasoline at two different speeds are shown in Figs. 8 and 9. The case of neat gasoline has been chosen as the basis of the comparison, e.g., baseline in the figure. Fig. 8 compares the effects of blended fuels of nB and nBM on the CO, CO_2 and UHC emissions at the start and

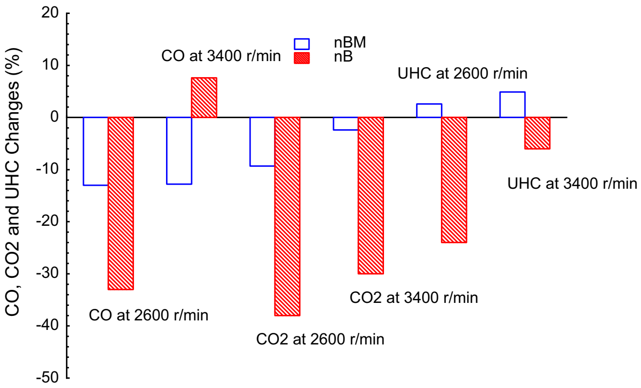

Figure 8 Comparison of CO, CO_2 and UHC emissions for n-butanol–methanol–gasoline blends (nBM), n-butanol–gasoline blends (nB) and neat gasoline (baseline) at two different speeds.

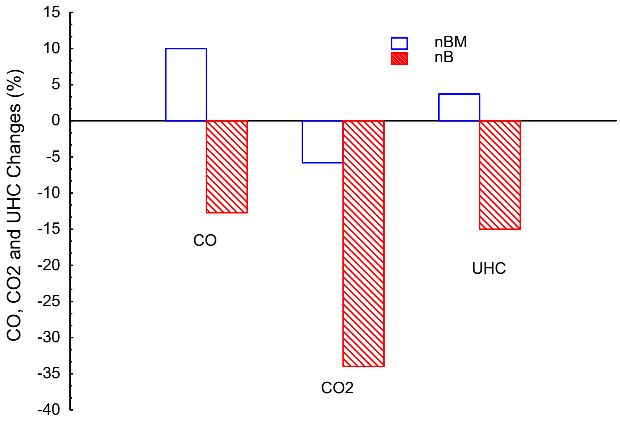

Figure 9 General change in emissions (CO, CO_2 and UHC) for n-butanol–methanol–gasoline blends (nBM), n-butanol–gasoline blends (nB) and neat gasoline (baseline) at two different speeds.

at the end of speed range (i.e. at 2600 r/min and at 3400 r/min) with respect to gasoline fuel. It is observed that the addition of only n-butanol alcohol to gasoline reduces the concentration of both CO_2 and UHC emissions as compared with neat gasoline and dual alcohols. With regard to the emission of CO pollutant, the engine fueled with n-butanol–gasoline produces lower CO emissions at the low r/min while it produces higher emissions at the upper limit of speed range (the reason of such trend is discussed in our early publications [11,15,23]). However, the general average concentration of CO emission is low when engine is fueled with the nB blended fuel as follows. On average basis, the results in Fig. 9 demonstrate that the engine pollutant emissions are better when engine fueled with n-butanol–gasoline fuel, compared to neat gasoline and n-butanol–methanol–gasoline blends, as the concentrations of CO, CO_2 and UHC emissions in the exhaust gas are reduced by about 13%, 34% and 15%, respectively, compared to neat gasoline. Generally, the addition of n-butanol to gasoline reduces the challenging pollutants from SI engines than the addition of n-butanol–methanol to gasoline. The motivations of such behaviors of both dual alcohols and single alcohol will be discussed later. However, there is an important observation on dual alcohols–gasoline blended fuels, which is that the emissions are significantly improved as the rate of n-butanol–methanol increases in the fuel blends; the reason(s) of such improvement, in addition to the early discussions, will be extra demonstrated afterward. Nevertheless the higher rates of single alcohol–gasoline blends were observed to provide adverse results, e.g., higher emissions and lower performance, as illustrated in our early publications [11,23].

The effects of different alcohols blended fuels (n-butanol–methanol–gasoline blends (nBM) and n-butanol–gasoline blends (nB)) on the performance parameters (brake power, torque output, volumetric efficiency and exhaust gas temperature) are compared in Fig. 10 at the speed limits of the investigated engine range (2600 r/min and 3400 r/min) as well as in average basis, as shown in Fig. 11. The results in both figures use pure gasoline as the base for the comparison, similar as in Figs. 8 and 9. Results in Fig. 10 show that fueling the engine with nBM fuel blends has a positive effect only on brake power at the low limit of speed range as well as on the volumetric efficiency at the high limit of engine speed, compared to the case of nB. In particular, with nBM blended fuels, a 50% more in brake power is gained at 2600 r/min while a 60% more in volumetric efficiency is achieved at 3400 r/min, compared to nB fuel blends. Except the two aforementioned benefits, running the engine with nB blended fuel exhibits a better performance than when running with nBM fuel blends. Overall, the average performance of engine fueled with nBM blended fuel is beneficial only to volumetric efficiency and exhaust gas temperature, as shown in Fig. 11.

By intensely analyzing the performance and emission results of single and dual alcohols–gasoline blends, we may emphasize that the physical/chemical properties of methanol could be the key of such dissimilarities of results for the both test fuels. The methanol's physical and chemical properties are very close to gasoline fuel, rather than the properties of n-butanol and gasoline. In particular, the density of methanol, n-butanol and gasoline is respectively 0.796, 0.810 and 0.745 g/cm^3; the viscosity of methanol, n-butanol and gasoline is respectively 0.59, 2.63 and 0.4–0.8 mm^2/s; the saturation pressure of methanol, n-butanol and gasoline is respectively 31.69, 2.27 and 31.01 kPa, as shown in Table 2. This implies that the properties of dual alcohols are closer to gasoline than the single alcohol. Since the engine is not tuned/adjusted for all

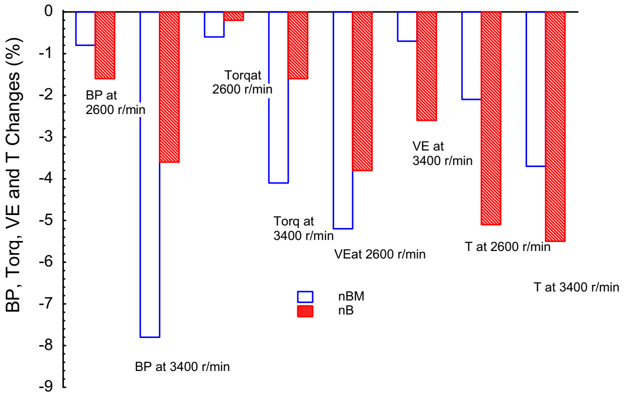

Figure 10 Comparison of brake power (BP), torque (Torq), volumetric efficiency (VE) and exhaust gas temperature (T) for n-butanol–methanol–gasoline blends (nBM), n-butanol–gasoline blends (nB) and neat gasoline (baseline) at two different speeds.

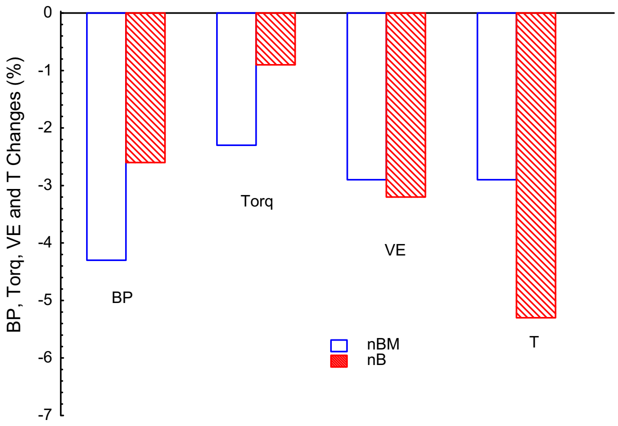

Figure 11 General change in engine performance (brake power, BP, torque, Torq, volumetric efficiency, VE, and exhaust gas temperature, *T*) for n-butanol–methanol–gasoline blends (nBM), n-butanol–gasoline blends (nB) and neat gasoline (baseline).

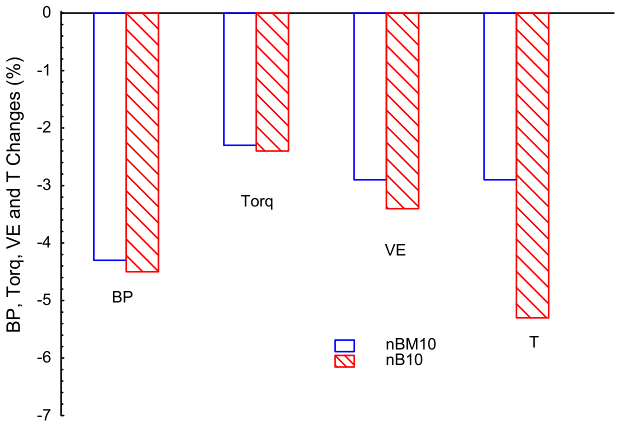

Figure 12 General change in engine performance (brake power, BP, torque, Torq, volumetric efficiency, VE, and exhaust gas temperature, *T*) for 10 vol.% n-butanol–methanol–gasoline blends (nBM10), 10 vol.% n-butanol–gasoline blends (nB10) and neat gasoline (baseline).

test fuels, as mentioned early, dual alcohols are more appropriate to be operated in the existing gasoline engines than the single alcohol does. Besides, the addition of methanol to n-butanol–gasoline blends slightly increases the oxygen content of dual alcohols as well as causes more leaning condition for the fuel blends resulted in higher performance and lower CO and UHC emissions of dual alcohols at higher rate conditions; however, at lower rate conditions (nBM3) the methanol is minute, which has no significance. Accordingly, as the dual alcohols increase in the blended fuels the combustion efficiency improved and the emissions are reduced. This outcome could be seen clearly by comparing single and dual alcohols–gasoline blends at high rate. Comparisons of engine performance for 10 vol.% nBM (nBM10) and 10 vol.% nB (nB10) show that as the blends rates increase, performance of nBM improves, while performance of nB comes worse, as shown in Fig. 12; the performance of nBM10 test fuel exceeds those of nB10 for all performance parameters. Furthermore, the dual alcohols at higher rates are expected to provide better emissions than single alcohols and neat gasoline (the figure is not presented). Siwale et al. [24] showed that the using of fuel blends containing 53% methanol, 17% n-butanol and 30% gasoline by volume can produce lower emission of UHC than the neat gasoline. Furthermore, composition of carbon to hydrogen (C/H) fuel ratio of methanol, n-butanol and gasoline is respectively 37.5/12.5, 65/13.5 and 86/14 mass%, as shown in Table 2; this limits the level of emissions for dual alcohols than those of single one and neat gasoline. Accordingly, we may emphasize that the flame propagations and combustion characteristics of the dual alcohols blended fuels are totally different from the single ones [23]. This means that dual alcohols–gasoline blends provide potential benefits to the combustion process rather than the single alcohol–gasoline blends do. Finally we may conclude that if one interested in low rate of alcohols, one should use nB fuel, however if one interested in high rate of alcohols in gasoline, one should use nBM fuel blends instead; such high fuel blends should be at least 10 vol.% n-butanol–methanol in gasoline.

4. Conclusions

As promising alternative fuels, the performance parameters and pollutant emissions of an SI engine fueled with dual alcohols (n-butanol–methanol, nBM) blended in gasoline were experimentally investigated. The test fuels were 0, 3, 7 and 10 volumetric percentage of n-butanol–methanol blended in pure gasoline. Within the investigated range of engine speeds (2600–3400 r/min), performance parameters of volumetric efficiency, in-cylinder pressure, brake power, torque and exhaust gas temperature and exhaust emissions of CO, UHC (unburned hydrocarbons) and CO_2 were investigated for each rate of the blended fuels as well as for the neat gasoline. In addition, performance and emissions of dual alcohols–gasoline blends were compared with those of single alcohol (n-butanol)–gasoline blends at same rate conditions, which is the first of its kind. The experimental results showed that the addition of n-butanol–methanol to gasoline at lower rate conditions ($\leqslant$7 vol.%) results in a sensible decrease in engine volumetric efficiency, brake power, torque, exhaust gas temperature and concentration of CO_2 emissions as compared with results of pure gasoline and single alcohol–gasoline blends; in addition, dual alcohols at lower rate showed higher emissions of CO and UHC compared to single alcohol and neat gasoline. On the other hand, increasing the volumetric content of n-butanol–methanol in the blends (10 vol.%) improves significantly the SI engine performance and exhaust emission concentration. At high rates of fuel blends ($>$10 vol.%), dual alcohols can exceed single alcohol as well as neat gasoline. The reason for this behavior may be attributed to the effects of physical/chemical properties of methanol in the dual alcohols blended fuel. Finally, the study may conclude that if one is interested in using lower rate of alcohol in gasoline, single alcohol (n-butanol) should be used; however, if one is interested in high rate of alcohol in gasoline, dual alcohol (n-butanol–methanol) is recommended.

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