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REVIEW ARTICLE

Improved Performance, Combustion and Emissions of SI Engine Fuelled with Butanol: A Review

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ABSTRACT – Several studies on ethanol as a biofuel have been comprehensively carried out. Today, a growing interest in longer chain alcohols has emerged due to their favourable physical and thermodynamic properties. Butanol or butyl alcohol with 4-carbon structure (C_4H_9OH) is a more promising biofuel as it outweighs methanol and ethanol in several ways. The production cost of butanol has been gradually reduced, and rapid progress in the development of its production technology has allowed butanol to be produced more effectively. However, studies on the effect of butanol on gasoline or spark ignition (SI) engines are not as comprehensive as the abundant research of ethanol. This paper highlights recent novelty and contribution of butanol addition in SI engine. Results of new approaches on the engine's performance, combustion and emission characteristics are summarised. Reviews from this paper suggest that there are some gaps in the addition of butanol found in the literature. Thus, several encounters and forthcoming research directions are outlined in the final section of this review article, highlighting several possible contributions that have not yet been carried out using butanol as a biofuel in a gasoline engine.

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KEYWORDS
Butanol; Ethanol; Gasoline; Spark ignition engine; Performance; Emission.

INTRODUCTION

Research in biofuels aims to achieve two essential goals. The first goal is to improve energy security as current fossil-fuel reserves are decreasing rapidly, while at the same time global energy consumption is increasing enormously [1-5]. The second goal is to reduce emissions to meet more rigorous emission protocols imposed by governments and authorities all over the world [6-8]. These two reasons have led researchers to explore alternative fuels that can reduce both fossil-fuel dependency and engine harmful emissions [9, 10]. Some alternative fuels from renewable resources have been investigated extensively in the last two decades such as biodiesel [11-15] and bioalcohol (ethanol and butanol) [16]. A derivative alcohol fuel such as fusel oil [17, 18] and other oxygenated biofuels such as 2,5-dimethylfuran (DMF) [19, 20] have also been investigated. Biodiesel is a promising biofuel due to its similar physico-chemical substances to petrol diesel [21], but it can only be used in diesel engines. A more versatile biofuel that can be used both in gasoline and diesel engine is needed.

Biofuels derived from alcohols arise as a more favourable alternative [22-24]. Alcohols, such as methanol and especially ethanol, have attracted many research groups [25, 26]. Methanol production is very limited [27, 28], while ethanol, on the other hand, can be manufactured straightforwardly by the fermentation of sugar from a wide variety of sources [29-31]. Ethanol is gaining more attention as it has superior octane number, approximately 108, and is thus often mixed with the gasoline to improve its properties quality [32, 33]. The high octane of ethanol has also allowed it to be run using greater compression ratio, i.e. diesel engines [34]. Furthermore, it is oxygenated, thereby providing the possibility to achieve complete combustion and reduce emissions [35-40]. Several studies have demonstrated that the ethanol-biodiesel blends can solve the trade-off between Particulate Matter (PM) and Nitrogen Oxides (NOx) in CI engines [41, 42]. As a result, ethanol is extensively used throughout the world [2, 43, 44]. Brazil can produce affordable ethanol fuel from the fermentation of sugarcane to supply its transportation sector [45-50], whereas the US produces ethanol from corn grain to supply its domestic demands [51-53]. However, the use of feedstock from first-generation biofuels such as sugarcane and corn grain to produce ethanol has raised some concerns as it can compete with human food supply [43, 54].

It is generally known that alternative fuel is often separated into first and second-generation [55-58]. First-generation biofuels are typically from edible sources such as sugar cane and corn [59, 60]. These biofuels offer great promises to replace fossil fuel, but since they are extracted from edible sources, these biofuels may contend with human agriculture supply and potentially escalate the food costs [61-64]. This dilemma has resulted in the extensive research of biofuels that can be produced from non-edible plants or waste. This type of fuel is commonly known as the second generation of biofuels [65, 66]. Therefore, the development of ethanol has shifted towards non-edible plants or waste such as cellulosic matter [67-69]. The main benefit of using agriculture waste is the abundant supply of cellulosic biomass compared to that of edible resources [70, 71]. The idea of using cellulosic waste has also enabled local people to produce ethanol in several regions whose climates are not suitable for crops production.

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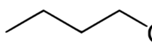
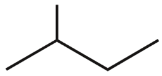
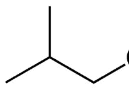
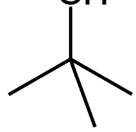
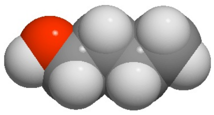
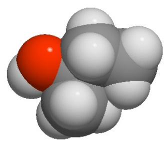
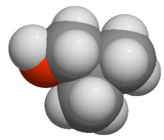
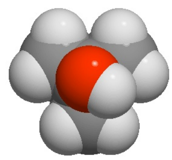
Despite the promising of ethanol as biofuel, recent investigations have revealed that ethanol has some major issue to consider before applying it on the engines. It is corrosive and may, therefore, cause disadvantages to both existing fuel pipelines distribution and fuel injection system [72]. Ethanol has also far low flash point and higher vapour formation, resulting in extra caution for its usage [73]. In addition to these drawbacks, ethanol may worsen local air quality and thus deteriorating human health. Compared to ethanol, a more promising option is offered by butanol [72, 74-76]. Butanol has four carbons whose atoms can form a straight or a branched-chain [77]. The more carbon atoms, the higher the energy content of alcohol fuel. Moreover, butanol is also less toxic and more energy dense compared to ethanol [72, 78]. It can also be produced from cellulose waste from agriculture products or even left-over fibre after sugar crops are harvested [79-81].

Unlike ethanol, butanol is far less corrosive allowing it to be delivered using the existing facilities to ship conventional fuel [72, 82]. Being less corrosive means that butanol can also be used without any modification to the vehicle [83, 84]. If it is contaminated with water, it is hard to separate from the base fuel (gasoline/diesel). It also contains a similar energy content to gasoline with 25% more energy density per litre than ethanol [72]. All these superior characteristics have resulted in higher performance of the engines, allowing the cars to achieve better mileage on butanol without any problem. Table 1 highlights the properties and application of butanol and its isomers.

Table 1. Properties and application of butanol [80].

	1-butanol	2-butanol	Iso-butanol	Tert-butanol
Density (kg/m^3)	809.8	806.3	801.8	788.7
Research Octane Number (RON)	96	101	113	105
Motor Octane Number (MON)	78	32	94	89
Boiling temperature (°C)	117.7	99.5	108	82.4
Enthalpy of vaporisation (kJ/kg) at T_{boil}	582	55.1	566	527
Self-ignition temperature (°C)	343	406.1	415.6	477.8
Flammability limits vol.%	1.4-11.2	1.7-9.8	1.2-10.9	2.4-8
Viscosity (mPas) at 25°C	2.544	3.096	4.312	-
Molecular structure	 OH	 OH	 OH	 OH
Sketch map				
Main application	Solvents, plasticizers, chemical intermediate, cosmetics, gasoline additive	Solvent, chemical intermediate, industrial cleaners, perfumes or in artificial flavours	Solvent and additive for paint, gasoline additive, industrial cleaners, ink ingredient	Solvent, denaturant for ethanol, industrial cleaners, gasoline additive for octane booster

It is known that fuel derived from longer chain alcohol fuel have not been widely used due to its production complexity. Today, the associated cost to produce butanol has been gradually reduced. Rapid progress in the development of production technology has allowed butanol to be produced more effectively [85]. Despite its increasing number of publications, studies regarding butanol on gasoline engine are not as comprehensive as the research in methanol or ethanol. This article aims to comprehend the effect of blending butanol with gasoline fuel in gasoline engine's performance, combustion and emission characteristics. Reviews from this paper suggest that there are several gaps where butanol addition in gasoline engine needs more investigating.

CONCENTRATION AND BLENDS

This section presents how much percentage of butanol have been successfully used in several studies. Due to its expensive production cost, some studies have only added a small percentage of butanol, whereas others have used a high concentration. Note that the results regarding the performance, combustion and emission characteristics will be discussed in the subsequent section. This section only highlights the use of various butanol's concentrations that have been successfully applied in the experiments so that a better understanding of the blends can be understood.

Elfasakhany [86] used low percentage n-butanol with Bu0, Bu3, Bu7 and Bu10 blends in SI engine with carburettor system. Despite its old technology, the carburettor system was selected as it could produce a homogenous mixture. The fuel system was not modified, and the engine was a single-cylinder performed in various working speeds from 2600 to 3400 rpm. Although a small percentage of butanol addition was successfully conducted in this study, the addition of butanol into gasoline fuel needs more investigating at a higher percentage. To be used in large scale for road transport, butanol should be added to a more significant percentage. More investigations need to be carried out from low to high percentage to clarify its addition on SI engine. Singh et al. [87] used various butanol blends from 5% to 70% into gasoline fuel. This study was performed in a medium-duty SI engine under various speeds and loads without hardware modifications. In another study, Sayin and Kemal [88] used 10%, 30% and 50% iso-butanol blends with the focus being given on the effects of three Compression Ratios (CR). The experiments were performed at the speed of 2600 rpm. One remarkable approach was done by Venugopal and Ramesh [89] by utilising a dual injection system using parallel injection of 50% n-butanol and 50% gasoline.

The studies mentioned above focused only on the butanol addition. To have a better understanding of the position of butanol in comparison with other alcohol fuels, direct comparison with other bio-alcohol such as methanol and ethanol is needed. Karavalakis et al. [90] tried to clarify the effects of butanol blend concentration compared to other alcohol fuel on the exhaust emissions using 16%, 24% and 32% of iso-butanol. Ethanol was used in this study for comparison. However, to have a complete understanding regarding the effect of butanol as a renewable alcohol fuel, a comparison between butanol and ethanol is not sufficient. More comprehensive studies comparing butanol with various alcohol fuels is required. Gravalos et al. [91] used various molecular alcohol, from lower to higher, to investigate their emission characteristics on the SI engine. The alcohols used in this study were methanol, ethanol, propanol, butanol and pentanol. Butanol concentration was only used at just 1.5% for the entire experiments. The percentage of methanol, propanol and pentanol were also fixed at under 2%, but the concentration of ethanol was varied from 2% to 22%. The rest, the dominant concentration, was unleaded gasoline fuel (70% - 90%).

As discussed above, most studies used n-butanol and iso-butanol only. Study of 2-butanol and tert-butanol in SI engine are rarely found. Yusri et al. [92] investigated 2-butanol addition with concentration ranging from 5%, 10% to 15%. The idea of using small portions of 2-butanol (up to 15%) are based on two reasons. First is because a low percentage of butanol addition can be directly used [93]. The second reason is due to butanol's higher price than gasoline. In addition to that, only one study tried to include thermal analyses. The data, however, were from 20 years ago and used 30% n-butanol. This finding implied that there was inadequate information in terms of thermal balance analyses for 2-butanol addition on SI engine. The butanol addition discussed so far was mainly evaluated as a standalone fuel. Most research groups used n-butanol or iso-butanol, but no one had used both butanols simultaneously at the same time. Elfasakhany [94] initiated the research of using two butanol fuels together. This study revealed the possibility to apply two butanol blends into the gasoline fuel. This was the first study that employed dual butanol blends in SI engine.

Another interesting approach was performed by adding H_2O and hydrogen. Feng et al. [95] investigated butanol-gasoline blend with H_2O addition in SI engine with a composition of 35% butanol-gasoline blend and 1% volume H_2O. Moreover, Raviteja and Kumar [96] investigated the same approach at stoichiometric conditions. As an additive in alcohol fuel, hydrogen enrichment in SI engines has been previously conducted and revealed some benefits [97, 98]. In ethanol-gasoline blends, the hydrogen addition was found to improve combustion efficiency, but the NOx was reported to be higher [99].

One challenging factor to be solved so that butanol can be mass-produced is by reducing its production cost. Its low production efficiency and high recovery costs have made butanol more expensive than ethanol and gasoline [16]. The recovery cost and dehydration processes could be eliminated if the Acetone Butanol Ethanol (ABE) or Isopropanol Butanol Ethanol (IBE) mixtures are directly used. Several research groups have been interested in exploring ABE as the next biofuel. Some were carried out in diesel engines such as Refs [76, 100-102]. Nithyanandan et al. [103] found that adding ABE up to 40% affected the combustion considerably. Li et al. [104] introduced hydrous ABE in PFI SI engines. Compared to ABE, IBE mixture is more promising [105] as acetone content is known for its corrosiveness [106, 107]. Isopropanol also has a higher energy density compared to acetone (23.9 MJ/L vs 22.6 MJ/L). Another study [108] proposed the use of IBE and reported that isopropanol could be used as an enhancer due to its greater energy density and octane number.

PERFORMANCE

Most published papers have reported that the butanol blends could deteriorate the engine performance due to its inherent properties. This reduction is understood since butanol's calorific value and saturation pressure were lower than gasoline fuel, resulting in lower torque, power and volumetric efficiency and higher fuel consumption. Engine performance is expected to worsen with the addition of butanol. However, some studies have proposed an innovative approach to improving engine performance fuelled with butanol.

Fuel Consumption and Thermal Efficiency

Brake Specific Fuel Consumption (BSFC) and Brake Thermal Efficiency (BTE) are the two essential characteristics in engine performance. Both parameters are used to indicate how efficient the fuel to produce work. BSFC (g/kWh) measures the fuel mass to generate one-unit power. In general, BSFC of alcohol blends in SI engine tends to increase due to its lower LHV values compared to gasoline fuel. Another important parameter to determine the fuel economy is Brake Thermal Efficiency (BTE). It is the ratio between the effective power and the rate of energy introduced by the fuel. BTE is used to indicate how efficient the fuel energy is utilised to produce power.

The BTE is related to BSFC and LHV. Alcohol blends normally have higher thermal efficiencies than pure gasoline because of their oxygen content, leading to the improvement of fuel-air mixing, thus resulting in rapid energy release and increasing combustion efficiency. In general, fuel with lower calorific value and saturation pressure consumes more fuel than that of higher value. Since butanol's calorific value and saturation pressure are relatively lower than gasoline, it is expected that the fuel consumption and engine efficiency from butanol addition will increase. However, several studies have been able to cut fuel consumption and improve the efficiency of SI engine fuelled with butanol addition.

The increase in fuel consumption was reported by Singh et al. [87]. They used various butanol blends from 5% to 70% into gasoline fuel and suggested that butanol addition to gasoline fuel slightly increased the BSFC. In other words, to obtain the same equivalence ratio as gasoline fuel, the amount of butanol should be added as butanol has lower LHV than gasoline. BTE of the butanol was reported to be lower compared to gasoline at the entire tested speeds, particularly at lower speeds. Furthermore, Sayin et al. [88] focused on the effects of three compression ratios of 9:1, 10:1 and 11:1 of a gasoline engine fuelled with 10%, 30% and 50% iso-butanol. It was found that the BSFC increased with the increasing amount of iso-butanol in the mixture due to its lower LHV than gasoline. As a result, adding more iso-butanol into the blend would increase the BSFC as shown in Figure 1a. However, increasing compression ratio was found to decrease the BSFC. For compression ratio of 9:1, the BSFC of 50% iso-butanol was 16.12% higher than that of pure gasoline, but when the CR was increased to 11:1, it was only 3.04% higher. Theoretically, BSFC and BTE are inversely proportional, the addition of more percentage iso-butanol was expected to increase BSFC and decrease BTE. However, this study found that higher iso-butanol ratio in the blends would increase BTE (Figure 1b), owing to the iso-butanol’s higher latent heat. Moreover, as the CR and iso-butanol content increased, the BTE also increased significantly, resulting from its high octane number.

Despite the reduction in fuel consumption, several studies have reported some improvements. Li et al. [108] proposed the use of IBE-gasoline blends and showed that 30% IBE addition (IBE30) to gasoline fuel enhanced BSFC and BTE. Compared to pure gasoline under two engine loads, 300 and 500 kPa BMEP, the IBE30 offered higher BTE. Raviteja and Kumar [96] investigated hydrogen enrichment with butanol at stoichiometric circumstances. Better engine efficiency and reduced fuel consumption were found using hydrogen as an additive. The high adiabatic flame velocity of hydrogen allows the engine to have high brake thermal efficiency. Hydrogen, however, suffers from low power outputs if it is used as a pure fuel. This is because its energy density is far lower than gasoline. Note that the high diffusivity of hydrogen allows it to replace the air, resulting in lower volumetric efficiency. Feng et al. [95] investigated H_2O addition in SI engine (neat gasoline, 35% butanol-gasoline blend, and 1% volume H_2O). It was reported that the BSFC of 35% butanol and 1% H_2O addition were lower than gasoline.

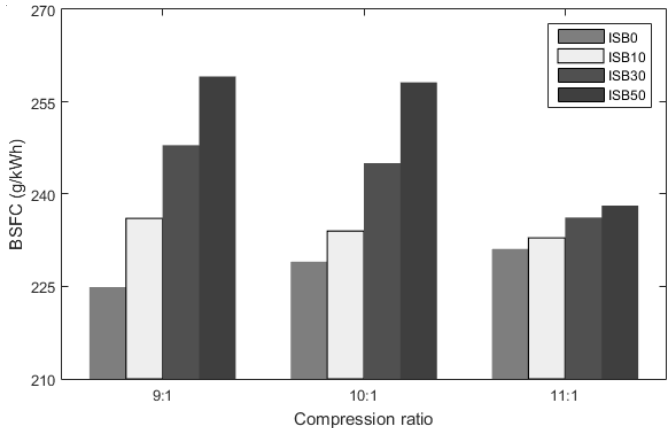
Power and Torque

In general, brake power and torque using butanol are relatively lower than gasoline fuel. These results are due to the lower calorific values of butanol. Theoretically, to obtain higher torque, additional fuel should be supplied. However, this will advance the start of the main combustion and may cause knocking.

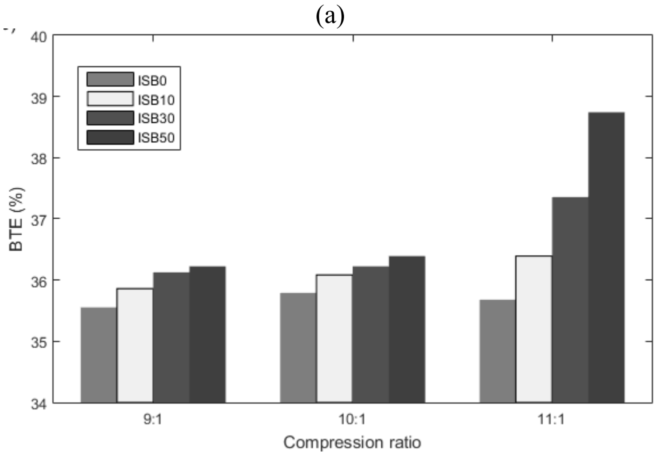
Elfaskhany [86] observed that the n-butanol addition gave a slight reduction in the output power and torque as shown in Figure 2. The author also found that the higher the percentage of n-butanol in the blends was used, the lower the engine performance was reported. This reduction was understood since butanol's calorific value and saturation pressure was lower than gasoline, leading to lower volumetric efficiency. The experiment was conducted using a low percentage butanol with 0, 3, 7 and 10 vol.%. The fuel system was not modified, and the engine was a single-cylinder performed in various working speeds from 2600 to 3400 rpm. The addition of n-butanol more than 10 vol.% would dramatically decrease the performance without a substantial decrease in exhaust emissions. The author proposed that the engine performance could be enhanced by changing the ignition time and raising the compression ratio as n-butanol is more resistant to knocking than gasoline.

An interesting finding was found by Elfasakhany [94]. His study was conducted using dual butanol fuel; n-butanol and iso-butanol. The outcomes revealed that dual butanol/gasoline blends gave a higher performance compared to a single one. There were, however, reduction in volumetric efficiency, brake power, torque, in-cylinder pressure and exhaust gas temperature than gasoline. As the percentage of the dual-fuel increased, its performance could exceed the gasoline. Feng et al. [95] investigated butanol-gasoline blend and H_2O addition in SI engine (gasoline, 35% butanol-gasoline blend, and 1% volume H_2O). The engine torque of 35% butanol and 1% H_2O addition were higher than gasoline. It is concluded from this study that operating parameters tend to influence the engine torque. Li et al. [104] introduced the water-containing ABE in PFI SI engines. It was found that the addition of 1% water and 29% ABE into gasoline fuel gave higher engine torque by 3.1% – 8.2%.

It is nearly impossible to achieve the best performance using pre-blended alcohol-gasoline fuels at the entire operation. A system that can change the fuel ratio is needed. A dual-injection system that can vary the ratio of each fuel could solve the problem. Only a few studies can be found investigating two independent fuel injection systems using butanol and gasoline. The dual-injection system allows butanol and gasoline to be independently injected using two different injection systems. Butanol is supplied from the intake ports, whereas gasoline is injected directly into the cylinders or vice versa. In this way, the amount of fuel can be ordered independently depending on engine load and speed.

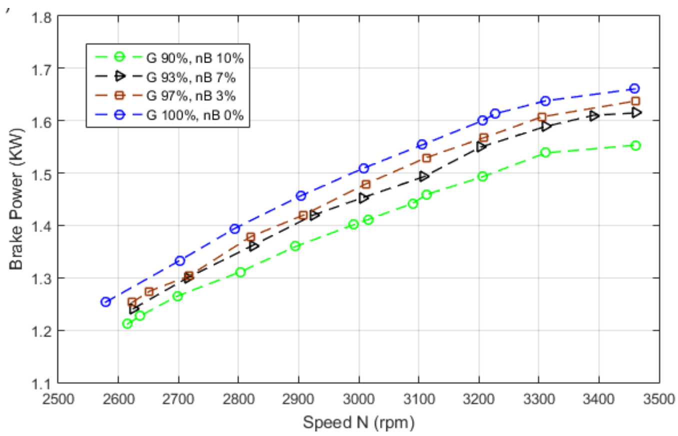


(a)



(b)

Figure 1. Variations of (a) BSFC and (b) BTE on CR, adapted from [88].



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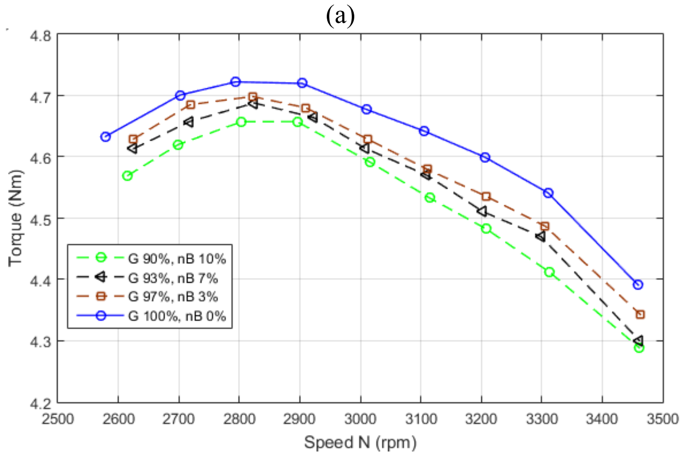

(b)

Figure 2. Power and torque against engine speed, adapted from [86].

He et al. [109] tried to examine the n-butanol using independent intake port injection and direct injection. The results showed that IMEP was marginally influenced by spark timing at stoichiometry. In lean situations, the influence from late spark timing on IMEP was stronger. Moreover, the higher n-butanol percentage was found to increase both IMEP and indicated thermal efficiency. In addition to that, IMEP was not found to be much difference between PFI n-butanol-DI gasoline and PFI gasoline-DI n-butanol. Venugopal and Ramesh [89] utilised butanol with a dual injection system. They examined the parallel injection of 50% n-butanol and 50% gasoline. The percentage of n-butanol, throttle position and injection timing were found to affect the torque and efficiency of the engine. This study showed that the dual injection could straightforwardly change the ratio of butanol and gasoline, allowing a higher butanol ratio to be used at part loads. At full load, engine torque could be enhanced with n-butanol. When the alcohol fuel supply was limited, the application of a dual injection system could be used only if high torque is needed. Moreover, the use of pure n-butanol (Bu100) was also reported to reduce the tendency of detonation at full load by charge cooling. Overall, the simultaneous dual injection system was considered as an effective approach to improve the gasoline engine's performance fuelled with butanol blends.

COMBUSTION

This section discusses the effect of butanol addition on the combustion of SI engine. In general, butanol addition is expected to improve the combustion process due to the presence of oxygen found in butanol. The extra oxygen will not only enhance the combustion inside the cylinder but also reduce the emissions in the exhaust system. The addition of butanol will assist the formation of CO into CO_2 thus decreasing the CO and HC emissions. Both the fuel properties and operating parameters are found to influence the combustion process that in turn affects the performance and emissions of the gasoline engine.

Spray

To examine butanol's effect on the flame front propagation of DI SI engine, Irimescu et al. [110] used a thermodynamic and optical investigation analysis. A constant 2000 rpm was selected to represent moderate load, with two throttles being partially opened. The results showed that the engine performance of butanol improved slightly than that of gasoline. Li et al. [111] investigated the spray of butanol blends using a high-pressure DI injector. To evaluate the penetration of the spray and the atomization of the droplet, high-speed imaging and Phase Doppler Particle Analyser (PDPA) techniques were employed. The experiments were performed in a high-pressure constant volume chamber. The injection pressure was varied from 60 to 150 bar and ambient pressure was changed from 1 to 5 bar. It was found that the butanol gave shorter penetration length than gasoline. This was caused by gasoline's small density and lower viscosity. The higher viscosity of n-butanol resulted in the fuel to have larger Sauter Mean Diameter (SMD). However, increasing ambient pressure could reduce the SMD by 42% and 37% for gasoline and n-butanol, respectively. The droplet velocity development indicated that the strong relationship among the fuel jets could influence the fuel distribution in the nozzle area. This phenomenon may have been initiated by two conditions; the cavitation inside the nozzle and the vacuum near the nozzle produced by the high-speed fuel jets.

Marchitto et al. [112] compared the atomization of n-butanol blend using a six-hole injector nozzle. To investigate its spray characteristic, the technique of Phase Doppler Anemometry was employed. The results showed that gasoline and n-butanol gave different droplets size and velocity where n-butanol provided higher viscosity and surface tension. The difference in size and velocity became narrower when the injection pressure was decreasing, and the distance was further from the nozzle.

To investigate the effect of split injection of DI gasoline engine fuelled with butanol, Merola et al. [113] carried out an experiment using six-holes injector in an optical accessed turbocharged single-cylinder engine. The results showed that two injections per cycle gave insignificant effect for gasoline, whereas the n-butanol gave substantial differences when changing from single to double injection. The discrepancies were caused by different mixture formation process particularly due to the dissimilar evaporative properties between those two fuels.

In-cylinder Pressure (ICP) and Heat Release Rate (HRR)

ICP and HRR are the two most vital indicators to evaluate engine combustion. The ICP is normally measured directly using pressure transducer. It gives detailed cycle by cycle combustion phenomena inside the cylinder, thus providing valuable insight into the characteristics of the whole combustion process. As for the HRR, it mirrors the rate of combustion reactions inside the chamber. When exactly the mixture starts to combust and how fast it occurs can be analysed using HRR. The HRR data is generally given relative to the crank angle position. The HRR-crank angle diagram is an important tool to determine the combustion irregularities such as misfire and knock. Therefore, both the ICP and HRR play a significant role in the combustion study.

Elfaskhany [86] used low percentage n-butanol with 0, 3, 7 and 10 vol.% n-butanol-gasoline blends in SI engine with carburettor system. The fuel system was not modified, and the engine was a single-cylinder performed in various working speeds from 2600 to 3400 rpm. The results indicated that adding n-butanol could substantially enhance the combustion caused by a partially oxidized nature of n-butanol and leaning effect resulted from its lower stoichiometric air fuel ratio. However, the n-butanol addition gave a slight reduction in ICP and the exhaust gas temperature. This reduction was understood since butanol's calorific value and saturation pressure were lower than gasoline fuel.

Singh et al. [87] used various butanol blends from 5% to 70% into gasoline fuel to be compared with pure gasoline fuel in a medium-duty SI engine. The engine test was conducted with no hardware modifications. Of all the investigated blends, the addition of 5%, 10%, and 20% of butanol had similar combustion characteristics with that of gasoline. However, the heat release of butanol blends began late with slightly longer combustion duration than gasoline. At higher loads, however, the duration was shorter since the combustion was faster for richer mixtures.

The effect of compression ratio is rarely investigated on the combustion of gasoline engines fuelled with butanol blends. Sayin and Kemal [88] focused on the effects of three compression ratios of 9:1, 10:1 and 11:1 on SI engine fuelled with 10%, 30% and 50% iso-butanol/gasoline blends. The experiments were performed at the constant engine speed and load at 2600 rpm. Results showed that the ICP increased as the concentration of iso-butanol increased. Moreover, the ICP and HRR of iso-butanol blends increased earlier than pure gasoline fuel.

He et al. [109] tried to investigate the butanol blends using independent intake port injection and direct injection systems. The results showed that different injection methods affect combustion events where n-butanol promotes the ignition and shortens the combustion duration. Therefore, the increase of n-butanol percentage was found to advance the ignition timing and shorten the combustion duration. It was also reported that the combustion processes were influenced by fuel injection methods. Overall, high n-butanol percentage provided enhanced combustion stability.

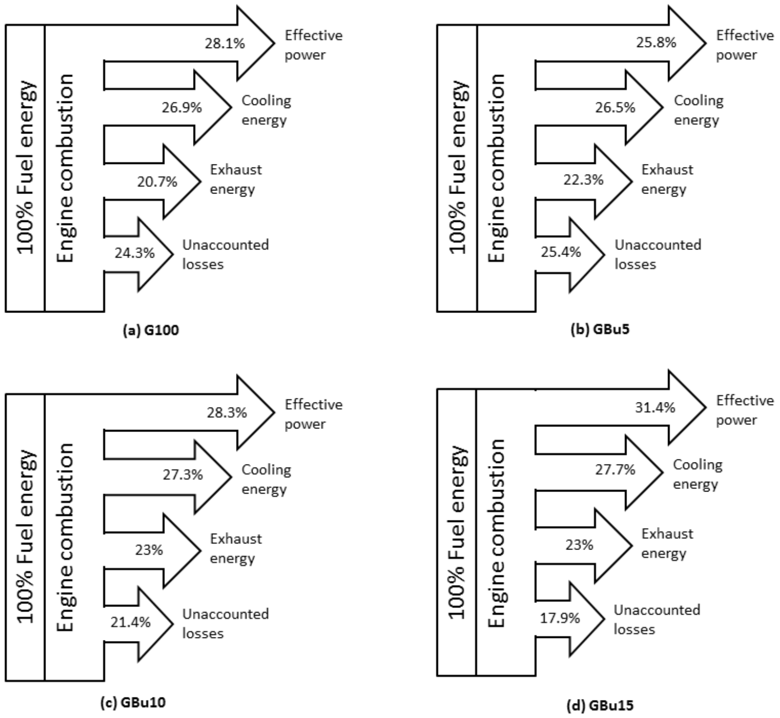

Figure 3. Sankey diagram of energy distribution for gasoline engine fuelled with (a) pure gasoline, (b) 5% butanol, (c) 10% butanol and (d) 15% butanol, adapted from [92].

The study of 2-butanol-gasoline blends is infrequently carried out, especially in small percentage addition. Yusri et al. [92] investigated 2-butanol addition to gasoline fuel with 5%, 10% and 15% at 50% by volume. In an internal combustion engine, the result of the combustion process is not converted 100% to produce work. Some are wasted in unaccounted losses due to lubrication and friction process. It is thus imperative to comprehend the energy distribution to reduce energy losses [114]. Yusri et al. used a Sankey diagram to describe the energy distribution of their work. Figure 3 shows the calculated percentage of its energy distribution using the Sankey diagram.

In their study, Yusri et al. [92] could easily visualise the inside of the engine system. The results of combustion analysis revealed that 2-butanol-gasoline blends had lower ICP, HRR and Pressure Rise Rate (PRR). As the percentage of 2-butanol increased, those three combustion characteristics also increased but were still lower than pure gasoline. Furthermore, even with low 2-butanol concentration, the COV of IMEP was enhanced. This improvement in COV indicated that the addition of 2-butanol was able to stabilise the combustion process of the SI engine. Moreover, the ability to estimate the energy distribution of internal combustion engines would enable us to have better approaches for energy management of the entire engine system.

As mentioned in the introduction, butanol can be produced from ABE fermentation. However, acquiring pure butanol from the ABE fermentation mixture needs a considerable amount of money and energy. To solve the problem, ABE is proposed to be used directly as a biofuel. Several studies have paid their attention to investigate ABE as an alternative fuel. Some were carried out in diesel engines such as Refs [20–23]. Nithyanandan et al. [52] investigated an SI engine using ABE-gasoline blends and found that adding 40% ABE or less affected the combustion substantially.

Knock Phenomena

The performance and efficiency of an internal combustion engine can be enhanced by raising both the compression and intake pressure ratios. However, the increase of those two ratios is limited by knock phenomena. Furthermore, to improve fuel economy and power density of gasoline engine, downsizing is often selected as an efficient approach to achieve those two objectives. Yet, it will increase the temperature and pressure inside the cylinder resulting in abnormal combustion including the knock. Therefore, the first issue to be addressed to increase both the performance and efficiency is eliminating the knock problem. Using alternative fuels that have anti-knock properties such as butanol offers a promising outcome as a result its high octane number.

Wei et al. [83] examined the knocking combustion of n-butanol blends in DI SI engine. It was found that n-butanol has better knock resistance characterised by improving the Knock Limited Spark Timing (KLST) from 27 to 32 ºbTDC as shown in Figure 4. Bu20 blend gave a slight reduction of knock resistance than gasoline. Furthermore, knock oscillation frequency tends to depend on combustion chamber resonance modes. This study used the probability distribution to assess the knock intensity variation.

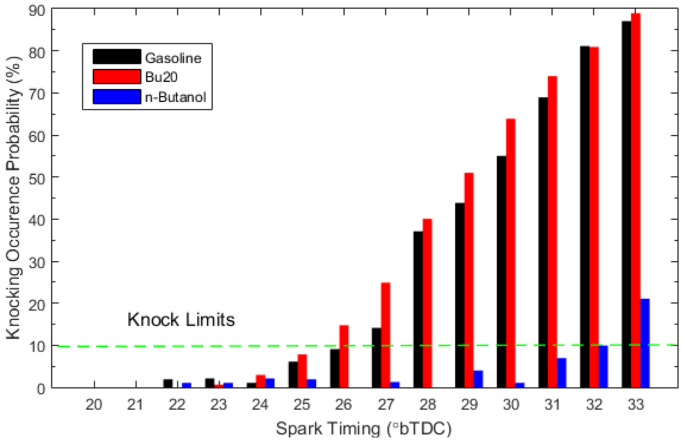

Figure 4. Knocking occurrence probability of butanol/gasoline blends, adapted from [83].

Wei et al. [115] tried to understand the effect of Exhaust Gas Recirculation (EGR) on knocking combustion behaviours of n-butanol as well as the sensitivity of n-butanol knocking phenomena to intake pressure and compression ratio. The results showed that EGR, due to cooling and dilution effects, could decrease knock intensity and delay knock start timing. Low EGR rate (3%) provided a significant reduction in the knock intensity, while the negligible outcome was observed in the combustion pressure. Under a given EGR rate, the addition of n-butanol had smaller combustion variations. This was because the probability distribution of its knock intensity was more concentrated than that of gasoline. This study indicated that the use EGR on high intake pressure and a high compression ratio of SI engine fuelled with n-butanol could successfully suppress the knock occurrence and stabilise the combustion process inside the chamber.

Zhang et al. [116] studied the anti-knock ability of ethanol/gasoline and n-butanol/gasoline blends in DI SI engine equipped with EGR. It was found that the addition of ethanol and butanol decreased the combustion duration from 10 to 90% MFB and improve combustion stability. The octane number, charge cooling effect and EGR improved the anti-knock ability, with butanol giving poorer anti-knock ability compared to ethanol.

Some studies have been investigated on the performance and combustion of gasoline engine fuelled with butanol blends. Results on the combustion behaviours are, however, still limited regarding several key operating parameters such as EGR rate and Knock Index (KI). Liu, et al. [117] aimed to find the common trends of both parameters in various engine speed. Simulation using GT-Power software was carried out under different EGR rate and compression ratio combined with KI. It was found that the butanol gave better knock resistance thus allowing earlier ignition timing. As the butanol blend ratio was increasing, the Peak Cylinder Pressure (PCP) and the peaks of the Rate of Heat Release (ROHR) were also increasing. As a result, improved thermal power conversion efficiency could be achieved since the locations of peak cylinder pressure and ROHR were advanced.

Furthermore, the engine load was found to affect the heat release greater than the engine speed did. As the engine load was increasing, the gross Indicated Thermal Efficiency (ITE) was increasing slightly with the net ITE increasing sharply. Moreover, the change of EGR rate was observed to influence the burning rate of butanol-gasoline more than that of pure gasoline. This was caused by the oxygen content and in-cylinder temperature of butanol fuel. By increasing the compression ratio, the in-cylinder maximum combustion temperature was found to increase resulting in improved in-cylinder temperature gradient and net ITE. However, as the compression ratio was increased, the rate of net ITE rise was steadily decreasing.

EMISSION

This section presents the effect of butanol on SI engine emissions. Pollutants in terms of Carbon Monoxide (CO), Hydrocarbons (HC) and Nitrogen Oxides (NOx) emissions are critically discussed. Moreover, Particulate Matter (PM) and unregulated emissions are also covered at the end of this section.

CO Emission

CO emissions indicate the incompleteness of combustion inside the chamber. Incomplete combustion if often occurs in modern internal combustion and by adding butanol, the CO emissions can be reduced since the oxygen content in butanol can increase the combustion temperature, thus helping the formation of CO_2. However, the increase in combustion temperature from complete combustion can also increase NOx emissions. Therefore, it is important to conduct a comprehensive emissions analysis to balance such trade-off.

Gravalos et al. [91] examined the emission of various molecular mass alcohol at various percentages. The result showed that the level of CO emissions from the alcohol-gasoline blends was lower than gasoline as shown in Figure 5. This study indicated that the reduction of CO emissions could be achieved by adding not only butanol but also by other alcohol fuels. Furthermore, in another study, Karavalakis et al. [90] found that a higher percentage of ethanol and butanol could reduce CO emission even further.

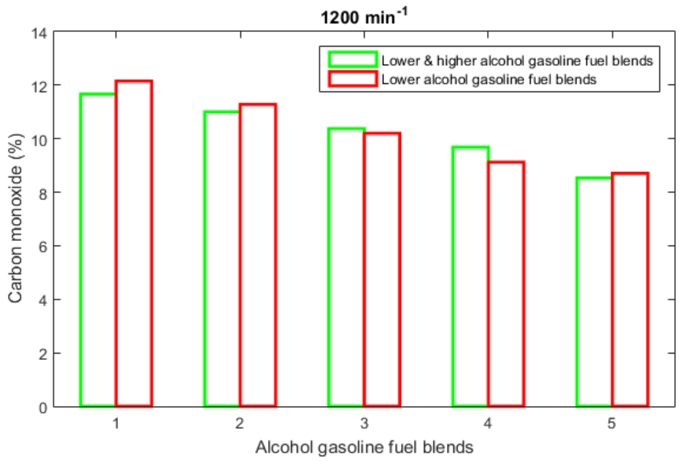

Figure 5. CO emission of various alcohol blends, adapted from [91].

Majority of published papers were tested using the fuel injector system. Although it is an old technology, carburettor provides homogeneous mixture formation that will improve engine performance and emissions. Elfaskhany [86] used low percentage n-butanol with 0, 3, 7 and 10 vol.% n-butanol. It was found that the n-butanol blends led to a dramatic decrease in CO emission than gasoline fuel. The fuel system was unchanged, and the engine was a single-cylinder performed in various working speeds from 2600 to 3400 rpm. Overall, the reduction in CO emission was achieved caused by the enhanced combustion resulted from the presence of extra O_2 in butanol. The extra oxygen assists the formation of CO_2 thus decreasing the CO.

HC Emission

The HC emission provides detailed information regarding the flame range inside the cylinder. Most sources of HC emissions come from the mixture found in the crevice and unburned fuel vapours that are absorbed by the oil due to the quenching close to the cylinder walls. The butanol blends may give a substantial reduction in HC emissions. The enhancement in HC emission was achieved due to the improved combustion owing to the presence of additional oxygen in n-butanol. Thus, besides helping the formation of CO_2 leading to CO emission reduction, the extra O_2 of butanol also helps to reduce HC emissions.

In an experiment using dual butanol fuel, HC emissions were successfully reduced. Elfasakhany [94] used dual n- and iso-butanol and found that the blends could burn cleaner and produce fewer HC pollutants than regular gasoline. Another study by Karavalakis et al. [90] revealed that a higher ratio of ethanol and butanol could reduce the HC emission. The HC emission also reduced with the increasing of iso-butanol as reported by Sayin and Kemal [88]. They investigated the effects of three compression ratios of 9:1, 10:1 and 11:1 with 10%, 30% and 50% iso-butanol blends. The experiments were carried out at the constant engine speed and load at 2600 rpm.

When hydrogen was added on the butanol blends, the delay period and combustion duration become shorter. As a result, the combustion was more complete owing to the presence of hydrogen and alcohol. Raviteja and Kumar [96] found that HC emissions decreased and with 10% hydrogen addition, HC emissions reduced on average by 60%. Feng et al. [95] found a reduced HC emission when 35% butanol-gasoline blends were added with 1% volume H_2O. The authors believe that fuel properties affected HC emissions. In another study, Feng et al. [118] revealed that the 35% butanol, even without H_2O addition, could lower the HC emission.

HC reduction from 27.4% to 78.2% was realised when Li et al. [104] introduced hydrous ABE in PFI SI engines. In another study, Li et al. [108] used another butanol fermentation product namely Isopropanol Butanol Ethanol (IBE). They found that 30% IBE addition (IBE30) could lower the HC emissions. HC emission was also successfully reduced using butanol and gasoline engine in a dual injection SI engine. Venugopal and Ramesh [89] performed a simultaneous injection of 50% n-butanol and 50% gasoline. It was found that such a strategy could reduce HC emissions by 13-15%. The vaporisation and reduction of HC emissions could be enhanced by appropriate directing the sprays. This study implied that the dual injection could change the ratio of fuel, allowing higher butanol percentage fuel to be used at part loads. Overall, the simultaneous injection system was a practical approach to utilise alcohol fuels and gasoline blends.

NOx Emission

In general, NOx emission is produced at high in-cylinder temperature. The cooling effect found in butanol fuel can enhance the combustion process resulting in high combustion temperature. Also, butanol's adiabatic temperature and heat value is relatively low, these two properties may help to reduce NOx emissions even further. As a result, the formation of NOx can be significantly reduced by adding butanol.

Karavalakis et al. [90] reported that the iso-butanol blended with a higher percentage of another alcohol fuel (ethanol) could reduce the NOx emissions. In another study, NOx reduction from 4.1% to 39.4% was realised when Li et al. [104] introduced water-containing ABE in an SI engine. Li et al. [108] used another butanol fermentation product which was IBE. They found that 30% IBE addition could lower the NOx emissions. This study was conducted in a PFI SI engine under two engine loads; 300 and 500 kPa BMEP. Significant NOx reduction was also reported by Irimescu et al. [110] when they combined thermodynamic analysis with the optical investigation.

NOx was also successfully reduced using butanol and gasoline engine in a dual injection SI engine. Venugopal and Ramesh [89] performed a simultaneous injection of 50% n-butanol and 50% gasoline. The results showed that such a strategy could decrease NOx emissions when the fuel ratio was raised at high throttles (35% and 100%). This is because butanol has high latent heat of vaporisation that is effective to reduce the mixture temperature or known as the charge cooling effect. This effect can lower NOx emissions.

Varying the inlet and exhaust valve events are often preferred to compromise between performance, fuel economy and emission. One established approach is Variable Valve Timing (VVT). This method can improve the fuel economy of a gasoline engine by several techniques. The first method is by delaying valve overlap to increase the trapped residuals and reduce engine pumping losses by allowing less vacuum to be used in the inlet system at part load. Another method of VVT is by applying Late Inlet Valve Closure (IVC). This approach will decrease pumping losses by letting more intake pressures. The next method is the Late Exhaust Valve Opening (EVO). This is done to improve the expansion work.

While most findings reported that butanol addition could reduce NOx emission in SI engine, Feng et al. [95] found an increase of NOx emission when 35% butanol-gasoline blends were added with 1% volume H_2O. The NOx emissions had the same tendency at both full and partial load as well as at 6500 and 8500 rpm. The author believed that the operating parameters affected the engine combustion process, thus increasing the NOx emissions. The rise in NOx emission was also reported in another study. Unlike Venugopal and Ramesh [89] who observed significant NOx emissions reduction at high throttles, Cairns et al. [119] found the highest NOx reduction at moderate loads by adopting Early Inlet Valve Closing (EIVC) with internal EGR during port fuel injection. Different amount of 1-butanol and ethanol were blended with gasoline and iso-octane. This study indicated that variable valve timing might be an alternative solution to meet stringent emission regulations, but attention should be paid to the high formation of NOx at high throttles. While Cairns et al. [119] found the highest NOx reduction at moderate loads by adopting EIVC, Feng et al. [118] found that the 35% of butanol increased the NOx emissions at full load. This is because when the engine load is increased, the heat release rates become faster and the combustion duration becomes longer. Its peak value rises, and the temperature inside the cylinder increases, thus producing more NOx emissions.

Particulate Matter (PM) Emission

Regulations on PM emission are imposed stricter in diesel engines [120-122]. In gasoline engines, however, laws and protocols have not been set up for PM emission. Due to its adverse effect on the human respiratory system, the attention to enact regulations of PM emission in gasoline engines has raised recently [123-128]. Generally, the use of butanol has successfully decreased the Particle Number (PN) emissions in SI engine. Moreover, the use of EGR was able to decrease the PM emissions further.

Particle Number (PN) emissions have gained more attention in SI engines as stringent regulations are being imposed stricter throughout the worlds. However, many studies investigating the PN and size distribution were only found in diesel engines [129-131]. Reports on PN and size distribution in gasoline engine are limited, especially using butanol/gasoline blends. Moreover, compared to direct injection, port-fuel-injection SI engines are known to produce less PN emissions caused by its better air-fuel mixture preparation. Many of initial studies investigating PM emissions in gasoline engine were performed on the PFI system.

DI-SI engine is known to produce more particle number emissions than PFI engine. Zhang et al. [116] found that the peak particle number concentration progressively decreased in DI-SI engine. Furthermore, as the EGR rate was increasing, the distribution of PN concentration became smaller. Similarly, as the alcohol content increased, the concentration of peak PN concentration decreased, and a higher proportion of finer particles were formed. Considering that DI-SI engine is more likely to emit higher PN emissions than PFI SI engine, several approaches need to be used simultaneously. Using high octane number fuels and knock reduction strategy can be combined.

CONCLUSION AND FUTURE RESEARCH DIRECTIONS

The use of alcohol fuel can achieve a net reduction in CO_2 emissions. Although the most popular and widely available alcohol fuel is ethanol, butanol is a more promising alternative. Butanol has comparable properties to gasoline such as higher energy density than ethanol. Understanding butanol's chemical reaction kinetics is an important step to understand its combustion characteristics. Moreover, it is also essential to determine the optimum operating parameters so that a more efficient combustion process can be achieved. This review article has critically discussed several strategies investigating butanol addition and its effect on gasoline engine's characteristics. Table 2 in Appendix 1 summarises the contribution and novelty proposed by research groups mentioned in this review article.

Some of the studies discussed in this article were carried out using optical investigation. The use of optical equipment in engine studies has offered some competitive benefits in understanding the combustion of the tested fuel and its operating conditions. Despite its relatively expensive equipment, more researches need to be conducted using optical investigation. Furthermore, to maximise the advantages of butanol in today's internal combustion engine, optimised engine design and calibration were needed so that it can be used directly in a gasoline engine. The characteristics of spray formation and combustion of the fuel also need to be quantified so that both injector design and operating strategies in a direct injection gasoline engine can be improved.

Several studies have tried to use various butanol concentrations to clarify its effect on the gasoline engine, from small, medium to a high percentage of butanol addition. A small percentage of butanol (less than 30%) was initially chosen considering its relatively high production cost an unknown behaviour on the engine characteristics. As more and more methods have been successfully established to reduce its cost of production, some researchers have attempted to increase the concentration of butanol up to 50%, 70% and even 100%. It was observed that most published papers have used a high percentage of butanol, only very few studies focused on a blended range of less than 10% butanol. Furthermore, to compare its relative advantage with other alcohol fuels, butanol has also been investigated and compared head to head with methanol, ethanol, propanol and pentanol.

Of all four butanol's isomers (n-butanol, 2-butanol, iso-butanol and tert-butanol), most studies were mostly conducted using n-butanol and iso-butanol. This is because the production of n-butanol and iso-butanol have been widely developed using various methods. Furthermore, several research groups have also found new techniques to enhance the production of n-butanol and iso-butanol. Meanwhile, 2-butanol and tert-butanol have not been studied extensively due to their unestablished production process. However, some studies have tried to use them in their investigation to evaluate these isomers on engine characteristics.

It is important to note that despite much effort have been done to reduce its production cost, the use of butanol intermediate fermentation product such as ABE and IBE has been gaining considerable attention as they can eliminate the recovery cost and dehydration processes of butanol. In addition to that, the use of hydrogen and H_2O addition into the butanol blends have appeared as promising approaches where researches have not yet extensively conducted in this area. Moreover, various approaches in the application of different fuel injections strategies and the investigation of some critical operating conditions have been discussed. Although some studies have been conducted using butanol in spark ignition engines, there are, however, many aspects need to be investigated more thoroughly. These include the examination of the cold start operating condition, application of different injection techniques, and comparison between several engine load conditions. Furthermore, strategies such as VVT, modifying EGR rate and altering compression ratio were found to have some rooms for improvements.

In terms of injection strategy, both port injection and direct injection system are currently available on modern vehicles. However, using both systems in one vehicle has not been studied thoroughly. Applying different fuel injection techniques can change the time for mixture preparation in the cylinders and affect the distribution of different fuels. This will subsequently affect the combustion process. This means that there is a two-way relationship between the distribution of fuel into the cylinder and combustion characteristics. To improve SI engine's thermal efficiency, it is essential to examine the effect of different fuel injection methods on combustion behaviours at various conditions.

The laminar burning velocity of butanol was found to be relatively higher than that of gasoline. It did, however, not guarantee a faster burning speed. Some operating parameters, mainly ignition timing may not be suitable for new fuels or different butanol volume ratio. The higher the butanol addition, the higher the oxygen content and anti-knock ability thus improving combustion efficiency. The heat release was reported to be more influenced by the engine load than the speed or fuel type. As for the fuel oxidation rate, it was more affected by the fuel-air ratio than fuel type.

Regarding the irregular combustion phenomena, knock problem is also worth investigating. Studies have shown that butanol has better knock resistance compared to gasoline. This finding can be further explored so that common principles can be agreed upon. In downsized SI engines particularly, knock tend to limit the compression ratio and turbocharger pressure. Knock is undoubtedly hindering the developments of engine performance and thermal efficiency. It can also damage the engine to some extent. Therefore, several approaches have been anticipated to solve the knock problem. The addition of butanol and EGR are found to successfully eliminate the knock phenomena. In general, the addition of butanol can successfully stabilise the combustion process of SI engine by giving higher resistance to detonation thus improving the ignition timing so that more efficient combustion can be achieved.

As for the exhaust emissions, the extra oxygen found in butanol can enhance the combustion which consequently decreases the CO and HC emissions. As the butanol concentrations increase, the oxygen content also increases, thus increasing the temperature reaction rapidly. The increase of combustion temperature not only reduces the CO emission by helping the formation of CO_2, but it also decreases the HC. Nevertheless, higher CO and HC emissions were also reported when some parameters of engine operating conditions were varied. Another vital aspect to consider is NOx emissions. Although the increased temperature may help to reduce CO and HC emissions, thoughtful consideration should be given as NOx emission will be produced at high combustion temperature.

Most studies on butanol/gasoline blends have primarily focused on regulated emissions only. Despite being considered as a promising fuel to replace ethanol, emissions from SI engine fuelled with a high percentage of butanol may increase the level of non-regulated emissions. CO_2 and oxygen are rarely investigated as a harmful gas emission. Very few studies were directed to analyse the CO_2 emissions of butanol blends on SI engine. Numerous earlier studies merely focused on the effect of butanol on regulated chemicals such as CO, HC and NOx. Although CO_2 is a non-hazardous and not considered as an emission, it can increase the global temperature due to the greenhouse effect. Oxygen is also often neglected although it can reflect other emissions. As emission regulations are becoming stricter, PM and unregulated emissions such as BTEX (benzene, toluene, ethylbenzene and xylene) are also worth considering in SI engine. Even though laws have not been set up for PM in the gasoline engine, their harmful effects on the human respiratory system and environment have raised some concerns. Further investigations are needed to examine the addition of butanol in a gasoline engine.

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REFERENCES

[1] Imdadul H, Masjuki H, Kalam M, Zulkifli N, Alabdulkarem A, Rashed M, Teoh Y, How H. Higher alcohol–biodiesel–diesel blends: an approach for improving the performance, emission, and combustion of a light-duty diesel engine. Energy Conversion and Management 2016; 111: 174-185.

[2] de Mattos Fagundes P, Padula AD, Padilha ACM. Interdependent international relations and the expansion of ethanol production and consumption: the Brazilian perspective. Journal of Cleaner Production 2016; 133: 616-630.

[3] Ghosh P, Westhoff P, Debnath D. Biofuels, food security, and sustainability. Biofuels, Bioenergy and Food Security: Elsevier; 2019. p. 211-229.

[4] Ingle AP, Ingle P, Gupta I, Rai M. Socioeconomic impacts of biofuel production from lignocellulosic biomass. Sustainable Bioenergy: Elsevier; 2019. p. 347-366.

[5] Ashwath N, Kabir Z. Environmental, Economic, and Social Impacts of Biofuel Production from Sugarcane in Australia. Sugarcane Biofuels: Springer; 2019. p. 267-284.

[6] Gaurav N, Sivasankari S, Kiran G, Ninawe A, Selvin J. Utilization of bioresources for sustainable biofuels: A review. Renewable and Sustainable Energy Reviews 2017; 73: 205-214.

[7] Grigoratos T, Fontaras G, Giechaskiel B, Zacharof N. Real world emissions performance of heavy-duty Euro VI diesel vehicles. Atmospheric Environment 2019; 201: 348-359.

[8] Campagnolo D, Cattaneo A, Corbella L, Borghi F, Del Buono L, Rovelli S, Spinazzé A, Cavallo DM. In-vehicle airborne fine and ultra-fine particulate matter exposure: The impact of leading vehicle emissions. Environment International 2019; 123: 407-416.

[9] Mahmudul H, Hagos F, Mamat R, Adam AA, Ishak W, Alenezi R. Production, characterization and performance of biodiesel as an alternative fuel in diesel engines–A review. Renewable and Sustainable Energy Reviews 2017; 72: 497-509.

[10] Mofijur M, Rasul M, Hyde J, Bhuyia M. Role of biofuels on IC engines emission reduction. Energy Procedia 2015; 75: 886-892.

[11] Erdoğan S, Balki MK, Sayin C. The effect on the knock intensity of high viscosity biodiesel use in a DI diesel engine. Fuel 2019; 253: 1162-1167.

[12] Lam MK, Jamalluddin NA, Lee KT. Production of biodiesel using palm oil. Biofuels: Alternative Feedstocks and Conversion Processes for the Production of Liquid and Gaseous Biofuels: Elsevier; 2019. p. 539-574.

[13] Piloto-Rodríguez R, Díaz Y, Melo-Espinosa EA, Sánchez-Borroto Y, Goyos L, Canoira L, Lapuerta M. Conversion of fatty acid distillates into biodiesel: engine performance and environmental effects. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 2019: 1-12.

[14] Chen B, Wang J, He T, Jie F, Chen B. Impact of biodiesel on engine oil quality: Role of methyl oleate and performance of sulfonate detergent additive. Fuel 2019; 244: 454-460.

[15] Rosha P, Mohapatra SK, Mahla SK, Cho H, Chauhan BS, Dhir A. Effect of compression ratio on combustion, performance, and emission characteristics of compression ignition engine fueled with palm (B20) biodiesel blend. Energy 2019; 178: 676-684.

[16] Veza I, Said MFM, Latiff ZA. Progress of acetone-butanol-ethanol (ABE) as biofuel in gasoline and diesel engine: A review. Fuel Processing Technology 2019; 196: 106179.

[17] Solmaz H. Combustion, performance and emission characteristics of fusel oil in a spark ignition engine. Fuel Processing Technology 2015; 133: 20-28.

[18] Calam A, Solmaz H, Uyumaz A, Polat S, Yilmaz E, Içingür Y. Investigation of usability of the fusel oil in a single cylinder spark ignition engine. Journal of the Energy Institute 2015; 88: 258-265.

[19] Sindhu R, Binod P, Pandey A, Ankaram S, Duan Y, Awasthi MK. Biofuel Production From Biomass: Toward Sustainable Development. Current Developments in Biotechnology and Bioengineering: Elsevier; 2019. p. 79-92.

[20] Liu H, Wang X, Zhang D, Dong F, Liu X, Yang Y, Huang H, Wang Y, Wang Q, Zheng Z. Investigation on Blending Effects of Gasoline Fuel with N-Butanol, DMF, and Ethanol on the Fuel Consumption and Harmful Emissions in a GDI Vehicle. Energies 2019; 12: 1845.

[21] Arun SB, Suresh R, Yatish KV. Biodiesel Production and Investigation of Fuel Properties. Materials Today: Proceedings 2019; 17: 186-190.

[22] Balki MK, Sayin C, Canakci M. The effect of different alcohol fuels on the performance, emission and combustion characteristics of a gasoline engine. Fuel 2014; 115: 901-906.

[23] Tutak W, Lukács K, Szwaja S, Bereczky Á. Alcohol–diesel fuel combustion in the compression ignition engine. Fuel 2015; 154: 196-206.

[24] Kumar BR, Saravanan S. Use of higher alcohol biofuels in diesel engines: A review. Renewable and Sustainable Energy Reviews 2016; 60: 84-115.

[25] Tosun E, Yilmaz AC, Ozcanli M, Aydin K. Determination of effects of various alcohol additions into peanut methyl ester on performance and emission characteristics of a compression ignition engine. Fuel 2014; 126: 38-43.

[26] Zou X, Wang H, Zheng Z, Reitz R, Yao M. Numerical study of the RCCI combustion processes fuelled with methanol, ethanol, n-butanol and diesel. SAE Technical Paper 2016; 2016-01-0777.

[27] Su Y-C, Sathyamoorthy S, Chandran K. Bioaugmented methanol production using ammonia oxidizing bacteria in a continuous flow process. Bioresource Technology 2019; 279: 101-107.

[28] Dalena F, Senatore A, Marino A, Gordano A, Basile M, Basile A. Chapter 1 - Methanol Production and Applications: An Overview. In: Basile A, Dalena F, editors. Methanol: Elsevier; 2018. p. 3-28.

[29] Ho DP, Ngo HH, Guo W. A mini review on renewable sources for biofuel. Bioresource Technology 2014; 169: 742-749.

[30] Molaverdi M, Karimi K, Mirmohamadsadeghi S, Galbe M. High titer ethanol production from rice straw via solid-state simultaneous saccharification and fermentation by Mucor indicus at low enzyme loading. Energy Conversion and Management 2019; 182: 520-529.

[31] de Araujo Guilherme A, Dantas PVF, de Araújo Padilha CE, dos Santos ES, de Macedo GR. Ethanol production from sugarcane bagasse: Use of different fermentation strategies to enhance an environmental-friendly process. Journal of Environmental Management 2019; 234: 44-51.

[32] Qian Y, Liu G, Guo J, Zhang Y, Zhu L, Lu X. Engine performance and octane on demand studies of a dual fuel spark ignition engine with ethanol/gasoline surrogates as fuel. Energy Conversion and Management 2019; 183: 296-306.

[33] Foong TM, Morganti KJ, Brear MJ, da Silva G, Yang Y, Dryer FL. The octane numbers of ethanol blended with gasoline and its surrogates. Fuel 2014; 115: 727-739.

[34] Tutak W. Bioethanol E85 as a fuel for dual fuel diesel engine. Energy Conversion and Management 2014; 86: 39-48.

[35] Herreros J, Schroer K, Sukjit E, Tsolakis A. Extending the environmental benefits of ethanol–diesel blends through DGE incorporation. Applied Energy 2015; 146: 335-343.

[36] Lim C-S, Lim J-H, Cha J-S, Lim J-Y. Comparative effects of oxygenates-gasoline blended fuels on the exhaust emissions in gasoline-powered vehicles. Journal of Environmental Management 2019; 239: 103-113.

[37] Sharma N, Agarwal AK. Effect of Fuel Injection Pressure and Engine Speed on Performance, Emissions, Combustion, and Particulate Investigations of Gasohols Fuelled Gasoline Direct Injection Engine. Journal of Energy Resources Technology 2020; 142.

[38] Kumar N. Study of oxygenated ecofuel applications in CI engine, gas turbine, and jet engine. Advanced Biofuels: Elsevier; 2019. p. 405-441.

[39] Geo VE, Godwin DJ, Thiyagarajan S, Saravanan C, Aloui F. Effect of higher and lower order alcohol blending with gasoline on performance, emission and combustion characteristics of SI engine. Fuel 2019; 256: 115806.

[40] Dhamodaran G, Esakkimuthu GS. Experimental measurement of physico-chemical properties of oxygenate (DIPE) blended gasoline. Measurement 2019; 134: 280-285.

[41] Júnior LCSS, Ferreira VP, da Silva JA, Torres EA, Pepe IM. Oxidized biodiesel as a cetane improver for diesel–biodiesel–ethanol mixtures in a vehicle engine. Journal of the Brazilian Society of Mechanical Sciences and Engineering 2018; 40: 79.

[42] Vijayashree P, Ganesan V. Oxygenated Fuel Additive Option for PM Emission Reduction from Diesel Engines—A Review. Engine Exhaust Particulates: Springer; 2019. p. 141-163.

[43] Ajanovic A, Haas R. On the future prospects and limits of biofuels in Brazil, the US and EU. Applied Energy 2014; 135: 730-737.

[44] Suarez-Bertoa R, Zardini A, Keuken H, Astorga C. Impact of ethanol containing gasoline blends on emissions from a flex-fuel vehicle tested over the Worldwide Harmonized Light duty Test Cycle (WLTC). Fuel 2015; 143: 173-182.

[45] Jonker J, Junginger H, Verstegen J, Lin T, Rodríguez L, Ting K, Faaij A, van der Hilst F. Supply chain optimization of sugarcane first generation and eucalyptus second generation ethanol production in Brazil. Applied Energy 2016; 173: 494-510.

[46] Jonker J, Van Der Hilst F, Junginger H, Cavalett O, Chagas M, Faaij A. Outlook for ethanol production costs in Brazil up to 2030, for different biomass crops and industrial technologies. Applied Energy 2015; 147: 593-610.

[47] Khatiwada D, Leduc S, Silveira S, McCallum I. Optimizing ethanol and bioelectricity production in sugarcane biorefineries in Brazil. Renewable Energy 2016; 85: 371-386.

[48] Oliveira DM, Cherubin MR, Franco AL, Santos AS, Gelain JG, Dias NM, Diniz TR, Almeida AN, Feigl BJ, Davies CA. Is the expansion of sugarcane over pasturelands a sustainable strategy for Brazil's bioenergy industry? Renewable and Sustainable Energy Reviews 2019; 102: 346-355.

[49] Méndez J, Passos DdF, Wischral D, Modesto LF, Pereira Jr N. Second-generation ethanol production by separate hydrolysis and fermentation from sugarcane bagasse with cellulose hydrolysis using a customized enzyme cocktail. Biofuels 2019: 1-7.

[50] Lemos SV, Salgado Jr AP, Duarte A, de Souza Jr MAA, de Almeida Antunes F. Agroindustrial best practices that contribute to technical efficiency in Brazilian sugar and ethanol production mills. Energy 2019; 177: 397-411.

[51] Locker CR, Torkamani S, Laurenzi IJ, Jin VL, Schmer MR, Karlen DL. Field-to-farm gate greenhouse gas emissions from corn stover production in the Midwestern US. Journal of Cleaner Production 2019; 226: 1116-1127.

[52] Dutta A. Forecasting ethanol market volatility: New evidence from the corn implied volatility index. Biofuels, Bioproducts and Biorefining 2019; 13: 48-54.

[53] Wang Z, Wlodarz M, McCarl B. Asset fixity and economic competitiveness of US ethanol production. Biomass and Bioenergy 2019; 122: 37-44.

[54] Ge J, Lei Y, Tokunaga S. Non-grain fuel ethanol expansion and its effects on food security: A computable general equilibrium analysis for China. Energy 2014; 65: 346-356.

[55] Lennartsson PR, Erlandsson P, Taherzadeh MJ. Integration of the first and second generation bioethanol processes and the importance of by-products. Bioresource Technology 2014; 165: 3-8.

[56] Garlapati VK, Tewari S, Ganguly R. Life Cycle Assessment of First-, Second-Generation, and Microalgae Biofuels. Advances in Feedstock Conversion Technologies for Alternative Fuels and Bioproducts: Elsevier; 2019. p. 355-371.

[57] Sydney EB, Letti LAJ, Karp SG, Sydney ACN, de Souza Vandenberghe LP, de Carvalho JC, Woiciechowski AL, Medeiros ABP, Soccol VT, Soccol CR. Current analysis and future perspective of reduction in worldwide greenhouse gases emissions by using first and second generation bioethanol in the transportation sector. Bioresource Technology Reports 2019; 7: 100234.

[58] Maga D, Thonemann N, Hiebel M, Sebastião D, Lopes TF, Fonseca C, Gírio F. Comparative life cycle assessment of first-and second-generation ethanol from sugarcane in Brazil. The International Journal of Life Cycle Assessment 2019; 24: 266-280.

[59] Smeets E, Tabeau A, van Berkum S, Moorad J, van Meijl H, Woltjer G. The impact of the rebound effect of the use of first generation biofuels in the EU on greenhouse gas emissions: A critical review. Renewable and Sustainable Energy Reviews 2014; 38: 393-403.

[60] Dutta K, Daverey A, Lin J-G. Evolution retrospective for alternative fuels: First to fourth generation. Renewable Energy 2014; 69: 114-122.

[61] Weng Y, Chang S, Cai W, Wang C. Exploring the impacts of biofuel expansion on land use change and food security based on a land explicit CGE model: A case study of China. Applied Energy 2019; 236: 514-525.

[62] Bosch C, Zeller M. Large-scale biofuel production and food security of smallholders: Evidence from Jatropha in Madagascar. Food Security 2019: 1-15.

[63] Taghizadeh-Hesary F, Rasoulinezhad E, Yoshino N. Energy and food security: Linkages through price volatility. Energy Policy 2019; 128: 796-806.

[64] Shrestha D, Staab B, Duffield J. Biofuel impact on food prices index and land use change. Biomass and Bioenergy 2019; 124: 43-53.

[65] Patinvoh RJ, Taherzadeh MJ. Fermentation processes for second-generation biofuels. Second and Third Generation of Feedstocks: Elsevier; 2019. p. 241-272.

[66] Gupta R, Yadav G, Kumar G, Yadav A, Saini JK, Kuhad RC. Second Generation Bioethanol Production: The State of Art. Sustainable Approaches for Biofuels Production Technologies: Springer; 2019. p. 121-146.

[67] Kim TH, Kim TH. Overview of technical barriers and implementation of cellulosic ethanol in the US. Energy 2014; 66: 13-19.

[68] Xia J, Yang Y, Liu C-G, Yang S, Bai F-W. Engineering Zymomonas mobilis for robust cellulosic ethanol production. Trends in Biotechnology 2019.

[69] Lou H, He X, Cai C, Lan T, Pang Y, Zhou H, Qiu X. Enhancement and mechanism of lignin amphoteric surfactant on the production of cellulosic ethanol from high solid corncob residue. Journal of Agricultural and Food Chemistry 2019.

[70] Soccol CR, Faraco V, Karp SG, Vandenberghe LPS, Thomaz-Soccol V, Woiciechowski AL, Pandey A. Chapter 14 - Lignocellulosic Bioethanol: Current Status and Future Perspectives. In: Pandey A, Larroche C, Dussap C-G, Gnansounou E, Khanal SK, Ricke S, editors. Biofuels: Alternative Feedstocks and Conversion Processes for the Production of Liquid and Gaseous Biofuels (Second Edition): Academic Press; 2019. p. 331-354.

[71] Madhu S, Ramteke PW. Cellulose as Potential Feedstock for Cellulase Enzyme Production: Versatility and Properties of Various Cellulosic Biomass–Part II. Approaches to Enhance Industrial Production of Fungal Cellulases: Springer; 2019. p. 117-125.

[72] No S-Y. Application of biobutanol in advanced CI engines–A review. Fuel 2016; 183: 641-658.

[73] Singh GN, Bharj RS. Study of physical-chemical properties for 2nd generation ethanol-blended diesel fuel in India. Sustainable Chemistry and Pharmacy 2019; 12: 100130.

[74] Babu V, Murthy M. Butanol and pentanol: The promising biofuels for CI engines–A review. Renewable and Sustainable Energy Reviews 2017; 78: 1068-1088.

[75] Galloni E, Fontana G, Staccone S, Scala F. Performance analyses of a spark-ignition engine firing with gasoline–butanol blends at partial load operation. Energy Conversion and Management 2016; 110: 319-326.

[76] Wu H, Nithyanandan K, Zhou N, Lee TH, Chia-fon FL, Zhang C. Impacts of acetone on the spray combustion of Acetone–Butanol–Ethanol (ABE)-Diesel blends under low ambient temperature. Fuel 2015; 142: 109-116.

[77] Chen Z, Wu Z, Liu J, Lee C. Combustion and emissions characteristics of high n-butanol/diesel ratio blend in a heavy-duty diesel engine and EGR impact. Energy Conversion and Management 2014; 78: 787-795.

[78] Tian Z, Zhen X, Wang Y, Liu D, Li X. Combustion and emission characteristics of n-butanol-gasoline blends in SI direct injection gasoline engine. Renewable Energy 2020; 146: 267-279.

[79] Gao K, Boiano S, Marzocchella A, Rehmann L. Cellulosic butanol production from alkali-pretreated switchgrass (Panicum virgatum) and phragmites (Phragmites australis). Bioresource Technology 2014; 174: 176-181.

[80] da Silva Trindade WR, dos Santos RG. Review on the characteristics of butanol, its production and use as fuel in internal combustion engines. Renewable and Sustainable Energy Reviews 2017; 69: 642-651.

[81] Procentese A, Raganati F, Olivieri G, Russo ME, Marzocchella A. Pre-treatment and enzymatic hydrolysis of lettuce residues as feedstock for bio-butanol production. Biomass and Bioenergy 2017; 96: 172-179.

[82] Killol A, Reddy N, Paruvada S, Murugan S. Experimental studies of a diesel engine run on biodiesel n-butanol blends. Renewable Energy 2019; 135: 687-700.

[83] Wei H, Feng D, Pan M, Pan J, Rao X, Gao D. Experimental investigation on the knocking combustion characteristics of n-butanol gasoline blends in a DISI engine. Applied Energy 2016; 175: 346-355.

[84] Kumar BR, Saravanan S. Effects of iso-butanol/diesel and n-pentanol/diesel blends on performance and emissions of a DI diesel engine under premixed LTC (low temperature combustion) mode. Fuel 2016; 170: 49-59.

[85] Zheng J, Tashiro Y, Wang Q, Sonomoto K. Recent advances to improve fermentative butanol production: genetic engineering and fermentation technology. Journal of Bioscience and Bioengineering 2015; 119: 1-9.

[86] Elfasakhany A. Experimental study on emissions and performance of an internal combustion engine fueled with gasoline and gasoline/n-butanol blends. Energy Conversion and Management 2014; 88: 277-283.

[87] Singh SB, Dhar A, Agarwal AK. Technical feasibility study of butanol–gasoline blends for powering medium-duty transportation spark ignition engine. Renewable Energy 2015; 76: 706-716.

[88] Sayin C, Balki MK. Effect of compression ratio on the emission, performance and combustion characteristics of a gasoline engine fueled with iso-butanol/gasoline blends. Energy 2015; 82: 550-555.

[89] Venugopal T, Ramesh A. Effective utilisation of butanol along with gasoline in a spark ignition engine through a dual injection system. Applied Thermal Engineering 2013; 59: 550-558.

[90] Karavalakis G, Short D, Vu D, Villela M, Asa-Awuku A, Durbin TD. Evaluating the regulated emissions, air toxics, ultrafine particles, and black carbon from SI-PFI and SI-DI vehicles operating on different ethanol and iso-butanol blends. Fuel 2014; 128: 410-421.

[91] Gravalos I, Moshou D, Gialamas T, Xyradakis P, Kateris D, Tsiropoulos Z. Emissions characteristics of spark ignition engine operating on lower–higher molecular mass alcohol blended gasoline fuels. Renewable Energy 2013; 50: 27-32.

[92] Yusri I, Mamat R, Azmi W, Najafi G, Sidik N, Awad OI. Experimental investigation of combustion, emissions and thermal balance of secondary butyl alcohol-gasoline blends in a spark ignition engine. Energy Conversion and Management 2016; 123: 1-14.

[93] Elfasakhany A. Experimental investigation on SI engine using gasoline and a hybrid iso-butanol/gasoline fuel. Energy Conversion and Management 2015; 95: 398-405.

[94] Elfasakhany A. Experimental study of dual n-butanol and iso-butanol additives on spark-ignition engine performance and emissions. Fuel 2016; 163: 166-174.

[95] Feng R, Yang J, Zhang D, Deng B, Fu J, Liu J, Liu X. Experimental study on SI engine fuelled with butanol–gasoline blend and H2O addition. Energy Conversion and Management 2013; 74: 192-200.

[96] Raviteja S, Kumar G. Effect of hydrogen addition on the performance and emission parameters of an SI engine fueled with butanol blends at stoichiometric conditions. International Journal of Hydrogen Energy 2015; 40: 9563-9569.

[97] Ji C, Zhang B, Wang S. Enhancing the performance of a spark-ignition methanol engine with hydrogen addition. International Journal of Hydrogen Energy 2013; 38: 7490-7498.

[98] Zhang B, Ji C, Wang S. Combustion analysis and emissions characteristics of a hydrogen-blended methanol engine at various spark timings. International Journal of Hydrogen Energy 2015; 40: 4707-4716.

[99] Akansu SO, Tangöz S, Kahraman N, İlhak Mİ, Açıkgöz S. Experimental study of gasoline-ethanol-hydrogen blends combustion in an SI engine. International Journal of Hydrogen Energy 2017; 42: 25781-25790.

[100] Chang Y-C, Lee W-J, Lin S-L, Wang L-C. Green energy: Water-containing acetone–butanol–ethanol diesel blends fueled in diesel engines. Applied Energy 2013; 109: 182-191.

[101] Chang Y-C, Lee W-J, Wu TS, Wu C-Y, Chen S-J. Use of water containing acetone–butanol–ethanol for NOx-PM (nitrogen oxide-particulate matter) trade-off in the diesel engine fueled with biodiesel. Energy 2014; 64: 678-687.

[102] Zhou N, Huo M, Wu H, Nithyanandan K, Chia-fon FL, Wang Q. Low temperature spray combustion of acetone–butanol–ethanol (ABE) and diesel blends. Applied Energy 2014; 117: 104-115.

[103] Nithyanandan K, Chia-fon FL, Wu H, Zhang J. Performance and emissions of acetone-butanol-ethanol (ABE) and gasoline blends in a port fuel injected spark ignition engine. ASME 2014 Internal Combustion Engine Division Fall Technical Conference. Columbus, IN, USA American Society of Mechanical Engineers; 2014. p. 1-11.

[104] Li Y, Nithyanandan K, Lee TH, Donahue RM, Lin Y, Lee C-F, Liao S. Effect of water-containing acetone–butanol–ethanol gasoline blends on combustion, performance, and emissions characteristics of a spark-ignition engine. Energy Conversion and Management 2016; 117: 21-30.

[105] de Vrije T, Budde M, van der Wal H, Claassen PA, López-Contreras AM. "In situ" removal of isopropanol, butanol and ethanol from fermentation broth by gas stripping. Bioresource Technology 2013; 137: 153-159.

[106] Jang YS, Malaviya A, Lee J, Im JA, Lee SY, Lee J, Eom MH, Cho JH, Seung DY. Metabolic engineering of Clostridium acetobutylicum for the enhanced production of isopropanol-butanol-ethanol fuel mixture. Biotechnology Progress 2013; 29: 1083-1088.

[107] Dusséaux S, Croux C, Soucaille P, Meynial-Salles I. Metabolic engineering of Clostridium acetobutylicum ATCC 824 for the high-yield production of a biofuel composed of an isopropanol/butanol/ethanol mixture. Metabolic Engineering 2013; 18: 1-8.

[108] Li Y, Meng L, Nithyanandan K, Lee TH, Lin Y, Chia-fon FL, Liao S. Combustion, performance and emissions characteristics of a spark-ignition engine fueled with isopropanol-n-butanol-ethanol and gasoline blends. Fuel 2016; 184: 864-872.

[109] He B-Q, Chen X, Lin C-L, Zhao H. Combustion characteristics of a gasoline engine with independent intake port injection and direct injection systems for n-butanol and gasoline. Energy Conversion and Management 2016; 124: 556-565.

[110] Irimescu A, Marchitto L, Merola S, Tornatore C, Valentino G. Combustion process investigations in an optically accessible DISI engine fuelled with n-butanol during part load operation. Renewable Energy 2015; 77: 363-376.

[111] Li Y, Guo H, Wang J-X, Xu H. The comparative study of gasoline and n-butanol on spray characteristics. SAE Technical Paper; 2014.

[112] Marchitto L, Merola S, Tornatore C, Valentino G. Experimental study on the spray atomization of a multi-hole injector for spark ignition engines fuelled by gasoline and n-butanol. SAE Technical Paper; 2014.

[113] Merola SS, Irimescu A, Tornatore C, Marchitto L, Valentino G. Split injection in a DISI engine fuelled with butanol and gasoline analyzed through integrated methodologies. SAE International Journal of Engines 2015; 8: 474-494.

[114] Javaheri A, Esfahanian V, Salavati-Zadeh A, Darzi M. Energetic and exergetic analyses of a variable compression ratio spark ignition gas engine. Energy Conversion and Management 2014; 88: 739-748.

[115] Wei H, Feng D, Pan J, Shao A, Pan M. Knock characteristics of SI engine fueled with n-butanol in combination with different EGR rate. Energy 2017; 118: 190-196.

[116] Zhang Z, Wang T, Jia M, Wei Q, Meng X, Shu G. Combustion and particle number emissions of a direct injection spark ignition engine operating on ethanol/gasoline and n-butanol/gasoline blends with exhaust gas recirculation. Fuel 2014; 130: 177-188.

[117] Liu K, Li Y, Yang J, Deng B, Feng R, Huang Y. Comprehensive study of key operating parameters on combustion characteristics of butanol-gasoline blends in a high speed SI engine. Applied Energy 2018; 212: 13-32.

[118] Feng R, Fu J, Yang J, Wang Y, Li Y, Deng B, Liu J, Zhang D. Combustion and emissions study on motorcycle engine fueled with butanol-gasoline blend. Renewable Energy 2015; 81: 113-122.

[119] Cairns A, Zhao H, Todd A, Aleiferis P. A study of mechanical variable valve operation with gasoline–alcohol fuels in a spark ignition engine. Fuel 2013; 106: 802-813.

[120] Veza I, Said MFM, Latiff ZA, Hasan MF, Jalal RIA, Ibrahim NMIN. Simulation of predictive kinetic combustion of single cylinder HCCI engine. AIP Conference Proceedings. Pahang, Malaysia: AIP Publishing; 2019. p. (020017-020011)-(020017-020019).

[121] Lapuerta M, Sánchez-Valdepeñas Js, Barba J, Fernández-Rodríguez D, Andrés JP, García Ts. Analysis of soot from the use of butanol blends in a Euro 6 diesel engine. Energy & Fuels 2019; 33: 2265-2277.

[122] Serrano JR, Piqueras P, Abbad A, Tabet R, Bender S, Gómez J. Impact on Reduction of Pollutant Emissions from Passenger Cars when Replacing Euro 4 with Euro 6d Diesel Engines Considering the Altitude Influence. Energies 2019; 12: 1278.

[123] Catapano F, Di Iorio S, Luise L, Sementa P, Vaglieco BM. Influence of ethanol blended and dual fueled with gasoline on soot formation and particulate matter emissions in a small displacement spark ignition engine. Fuel 2019; 245: 253-262.

[124] Yang J, Roth P, Zhu H, Durbin TD, Karavalakis G. Impacts of gasoline aromatic and ethanol levels on the emissions from GDI vehicles: Part 2. Influence on particulate matter, black carbon, and nanoparticle emissions. Fuel 2019; 252: 812-820.

[125] Lemaire R, Boudreau A, Seers P. Performance and emissions of a DISI engine fueled with gasoline/ethanol and gasoline/C-4 oxygenate blends–Development of a PM index correlation for particulate matter emission assessment. Fuel 2019; 241: 1172-1183.

[126] Qian Y, Li Z, Yu L, Wang X, Lu X. Review of the state-of-the-art of particulate matter emissions from modern gasoline fueled engines. Applied Energy 2019; 238: 1269-1298.

[127] Yang J, Roth P, Ruehl CR, Shafer MM, Antkiewicz DS, Durbin TD, Cocker D, Asa-Awuku A, Karavalakis G. Physical, chemical, and toxicological characteristics of particulate emissions from current technology gasoline direct injection vehicles. Science of the Total Environment 2019; 650: 1182-1194.

[128] Ge H, Ye Z, He R. Raman spectroscopy of diesel and gasoline engine-out soot using different laser power. Journal of Environmental Sciences 2019; 79: 74-80.

[129] Zhu R, Wang X, Miao H, Huang Z. Combustion and particulate emission characteristics of a diesel engine fuelled with diesel—dimethoxymethane blends. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 2010; 224: 521-531.

[130] Di Y, Cheung C, Huang Z. Experimental study on particulate emission of a diesel engine fueled with blended ethanol–dodecanol–diesel. Journal of Aerosol Science 2009; 40: 101-112.

[131] Zhang Z, Cheung C, Chan T, Yao C. Experimental investigation on regulated and unregulated emissions of a diesel/methanol compound combustion engine with and without diesel oxidation catalyst. Science of the Total Environment 2010; 408: 865-872.

[132] Deng B, Fu J, Zhang D, Yang J, Feng R, Liu J, Li K, Liu X. The heat release analysis of bio-butanol/gasoline blends on a high speed SI (spark ignition) engine. Energy 2013; 60: 230-241.

[133] Merola SS, Valentino G, Tornatore C, Marchitto L. In-cylinder spectroscopic measurements of knocking combustion in a SI engine fuelled with butanol–gasoline blend. Energy 2013; 62: 150-161.

[134] Yu X, Guo Z, He L, Dong W, Sun P, Shi W, Du Y, He F. Effect of gasoline/n-butanol blends on gaseous and particle emissions from an SI direct injection engine. Fuel 2018; 229: 1-10.

APPENDIX 1

Table 2. The novelty of recent studies using butanol blends in a gasoline engine.

Fuel	Engine	Operating Condition	Novelty / Contribution	Reference
5 blends consisting of 6 fuels; unleaded gasoline, ethanol, methanol, propanol and pentanol	Single cylinder, carburetted, air-cooled, non-road gasoline engine	Full throttle opening at a compression ratio of 6/1	Comparing lower-higher alcohol thoroughly (methanol, ethanol, propanol, butanol and pentanol)	Gravalos et al. [91]
95 RON ULG, i100, E100, E85, Bu100	Single-cylinder port fuel injection (4 bar)	1. Warm idle engine 2. Moderate speed and load	Combining the effects of EIVC (Early Inlet Valve Closing) with internal EGR	Cairns et al. [119]
Bu0, Bu35 and 1% volume H_2O	Single-cylinder motorcycle	Full and partial load of 6500 rpm and 8500 rpm	Performed at both full and partial load simultaneously and taking into account CO_2 emissions	Feng et al. [95]
Bu30 and Bu35	Single-cylinder high-speed	Various engine speed from 3000 to 8500 rpm	Extending the heat release data of butanol blends to the high-speed operating conditions	Deng et al. [132]
Bu60, Bu80, Bu100	Single cylinder, air-cooled	Various fuel ratios and throttle positions at an equivalence ratio of 1.	Examining the effect of dual injection system using butanol blends	Venugopal and Ramesh [89]
Bu20	Port fuel injection, optical engine with the head of commercial SI turbocharges engine	Stoichiometric mixture at 2000 rpm, medium boosting and wide-open throttle	Improving comprehension of in-cylinder phenomena with butanol in different operating conditions.	Merola et al. [133]
E10, E15, E20, Bu16, Bu24, Bu32 and E20Bu16	Five light-duty gasoline vehicles (passenger cars and trucks)	The FTP and the Unified Cycle (UC) including effects of both cold-start and transient operation.	Clarifying the effects of fuel type and blend concentration for ethanol and iso-butanol on the exhaust emissions.	Karavalakis et al. [90]
Bu3, Bu7, Bu10	Single-cylinder with a carburetted fuel system	2600-3400 rpm without any tuning or modification	Performed with less than Bu10 (the first time using Bu3 and	Elfasakhany [86]

			Bu7) and tested with the carburettor system. The carburettor is believed to promote homogeneous mixture formation	
Bu10, Bu10, E10, E20	Four-cylinder direct injection	Low-pressure loop EGR system	One of the earliest studies investigating the effect of EGR and Particulate Number (PN) emissions on direct injection SI engines using alcohol fuels.	Zhang et al. [116]
Bu0, Bu30, Bu35	Single-cylinder high-speed motorcycle engine	Full load and partial load at 6500 and 8500 rpm	Comprehensively investigating the influence of several variables (ignition timing, engine load) on SI engine fuelled with butanol-gasoline blends.	Feng et al. [118]
Bu0 and Bu100	Single-cylinder Direct injection of 100 bar	2000 rpm with various loads under stoichiometric mixture conditions	Investigating the effect of butanol on flame front propagation	Irimescu et al. [110]
Bu10, Bu30, Bu50	Single-cylinder, four-stroke, KG-type, 389 cc and air-cooled	Constant engine speed at 2600 rpm with a wide-open throttle.	Investigating both the effects of compression ratio and iso-butanol blended gasoline fuel on SI engine.	Sayin and Balki [88]
Bu10, Bu20, Bu30, Bu100 and hydrogen (5% and 10%	Single-cylinder with manifold electronic fuel injected (EFI) engine	3000 rpm at full load condition	Utilising the benefits of hydrogen in a butanol fuelled engine	Raviteja and Kumar [96]
Bu5, Bu10, Bu20, Bu50, Bu75	Four-cylinder, four-stroke, water-cooled, Multi-Point-Port-Fuel-Injection (MPFI) medium-duty engine	Four different engine speeds (1500, 2500, 3500 and 4500 rpm) and various engine torque (0 Nm – 66 Nm in an interval of 11 Nm)	Exploring the possibility of using lower (<20%) and higher butanol blends (> 50%)	Singh et al. [87]
Bu0, Bu22, Bu44, Bu66	Four-cylinder with independent port fuel injection and direct injection systems	Butanol and gasoline were injected independently with PFI and DI systems	The injection amount of butanol and gasoline into cylinders and intake ports were flexibly controlled independently according to engine load and speed	He et al. [109]
IBE0, IBE10, IBE30, IBE60	Single-cylinder port fuel injection	Constant engine speed at 1200 rpm with a	Proposing the use of IBE gasoline blends	Li et al. [108]

		fully opened throttle plate.	in a PFI gasoline engine	
Bu5, Bu10, Bu15	Four-cylinder with ECI-Multi (Electronically Controlled Multi-point) fuel injection	50% throttle wide open	Taking into account the thermal energy balance analyses of butanol addition	Yusri et al. [92]
niB3, niB7 and niB10,	A single-cylinder, four strokes, air-cooled	Engine speeds of 2600–3400 rpm	Demonstrating the possibility to apply dual butanol simultaneously, i.e. n-butanol and iso-butanol.	Elfasakhany [94]
G100, ABE30, ABE85, ABE29.5W0.5 and ABE29W1	Single-cylinder port fuel injection	Constant engine speed at 1200 rpm with a fully open throttle.	Evaluating the hydrous ABE blends in a gasoline engine	Li et al. [104]
Bu0 and Bu100	A single-cylinder, four-stroke, intake port injection	Constant engine speed at 1500 r/min (±5 r/min), full load, and under ambient temperature at 20 ± 2ºC.	Investigating the effect of EGR, intake pressure and compression ratio on butanol's knocking combustion behaviours .	Wei et al. [115]
Bu0, Bu30, Bu35	Single-cylinder and four-stroke, port-injected	Full and partial load. Engine speeds of 3000-8500 rpm at an interval of 500 rpm (full load)	Evaluating the addition of butanol in SI engine at high speed (3000 – 8500 rpm)	Liu et al. [117]