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Review article

An overview of Higher alcohol and biodiesel as alternative fuels in engines

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ABSTRACT

Hydrocarbon based conventional fuels are considered as fast depleting and harmful to the environment as they release poisonous chemicals to the atmosphere. Higher Alcohols and Biodiesel are the most promising alternative fuels widely researched due to their availability, ease of production and environmental benefits. The use of alternative fuels such as alcohol and biodiesel in engines aims to reduce air pollution and energy costs. The most commonly used higher alcohol fuel are bio-ethanol, isopropanol, propanol, ethanol–methanol, butanol, n-butanol, tert-butanol and iso-butanol. The commonly used biodiesel are derived from the waste cooking oil, Pyrolysis oil, Palmoil, Jatropha oil, Karanja oil and Linn oil. The purpose of this review is to reveal engine performance and combustion characteristics using alternative fuels such as alcohol and biodiesel. Also summarized are the effects of alternative fuels on emission properties such as NO_x, CO and HC.

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1. Introduction

The internal combustion engine utilizing hydrocarbon fuels will continue to be the important transportation system for decades. 30% of the world's greenhouse emissions currently originates from the transportation sector (Awad et al., 2018; Dalkmann and Brannigan, 2007; Wright, 2004). The SI engine is environmentally friendly because fewer emissions come out from the combustion chamber (Berghorson and Thomson, 2015; Geng et al., 2017; Lal and Patil, 2001). Several types of harmful substances are present in the suspended particles emission, such as elemental carbon, inorganic ions, organic carbon and trace elements (Cheung et al., 2010; Chow, 2001; Francioso et al., 2005). These chemical compounds can threaten the health and ecosystem (Done, 2018; Gong et al., 2019; Lim et al., 2018; Tong et al., 2018; Wang et al., 2018; Zhou et al., 2015).

Demand for fuel that continues to increase from customers in recent years has resulted in the depletion of fossil fuels (Abas et al., 2015; David, 2018; Jia et al., 2018). Investigations about alternative fuels have been explained in the literature, where reservoirs can meet the demand for fuels such as oil, coal and natural gas (Kessel, 2000; Zucchetto, 2004). The growth of the automotive industry which continues to increase has had an impact on energy scarcity. The increasing demand for alternative fuels and the use of petroleum are the biggest challenges because people want to be ensured of energy security globally.

The average monthly retail fuel price in the United States (US) from 2000 to 2018 can be seen in the graph shown in Fig. 1. Gasoline and diesel fuel are the primary drivers for the price of liquid fuels. This is because vehicles that use liquid fuels cannot be replaced and are not dedicated to fuel oil, while electric vehicles are high in cost and not made to reach the lower income and middle-class groups of drivers. However, even electricity and natural gas fuels are denied from drivers because only a small portion is marketed for transportation.

Worldwide commercial vehicle uses from 2006 to 2015 is as shown in Fig. 2. More than 335 million commercial vehicles were used globally in 2015. One of the largest markets using commercial vehicles is in the United States. As a rapid increase in commercial vehicle use also has an impact on fuel, the United States has used alternative fuels to avoid scarcity and increasing demand for fossil fuels.

Besides, alternative fuels were used to overcome fossil fuels that are continually decreasing and prices that are continuously increasing all over the world (Agency, 2013).

The automotive industry has attempted to devote all its resources with the aim of achieving the requirements of standard emission reductions derived from their vehicles. Emission reduction from the combustion engine is focused to reduce environmental problems and air pollutions (Tamilselvan et al., 2017).

In this aspect, the use of sustainable fuel alternatives such as alcohol, natural gas and biodiesel is the best way to reduce NO_x, CO, HC, CO₂ emissions (Thakur et al., 2017; Yan et al., 2017a).

Some researchers have suggested alternative fuels such as alcohol and biodiesel in recent studies as the main keys to reduce greenhouse gases and harmful pollutants from the combustion chamber (Bhasker and Porpatham, 2017; Chen et al., 2018a; Ghadikolaei et al., 2018; Li et al., 2018a,b,c,d; Moula et al., 2017; Sathiyamoorthi et al., 2019).

Alternative fuels were widely used in SI and internal combustion engines to overcome fossil fuel declines and rising natural gas prices. Alcohol fuel, biodiesel and natural gas are alternative fuels that are very promising as a substitute for fossil fuels that have attracted users' interest because they are easily stored and very easy to handle (Chen et al., 2018a; Hoseinpour et al., 2018; Jamuwa et al., 2016; Yusri et al., 2017; Zaharin et al., 2017). SI can

be operated by using various mixtures of alcohol fuels with multiple ratios, both through modification and without modification to the engine (Deng et al., 2018; Doğan et al., 2017; Ghadikolaei, 2016; Li et al., 2018b; Liu et al., 2016). In the blended mode, the alcohol fuel is mixed first with gasoline before being injected into the cylinder (Elfasakhany, 2018; Iodice et al., 2018, 2016; Mourad and Mahmoud, 2018; Zhang and Sarathy, 2016). Blended stability with additive fuel is very necessary. The long carbon chain and also the normal HLB (Hydrophile–Lipophile Balance) of 1.6 to 6 contained in fatty alcohols are emulsifiers and co-solvents. The SI engine needs a little modification such as addition of separate fuel tank, fuel injector, low pressure components, the channel and the control system (Chen et al., 2018c; Najafi et al., 2016; Wu et al., 2016; Yilmaz and Taştan, 2018; Yusri et al., 2018). However, in this case, there is no need to use fuel additives because the engine can directly use alcohol fuel at all load conditions and speed (Awad et al., 2017; Bae and Kim, 2017; Jiaqiang et al., 2017; Noor et al., 2018; Sathiyamoorthi and Sankaranarayanan, 2017).

Another alternative that can be used for combustion engines as a substitute for fossil fuels is natural gas (Chen et al., 2018c; Du et al., 2018; Gogolev and Wallace, 2018; Li et al., 2018a,b,c,d; Liu et al., 2018a; Mehra et al., 2017; Nocera and Cavallaro, 2016). Natural gas has various mixtures of hydrocarbon molecules such as butanol, methanol, ethanol and inert diluents such as nitrogen and carbon dioxide molecules. However, the availability of natural gas throughout the year and geographically varies greatly. In addition, it requires special care during production and operation (Grigoratos et al., 2016; Hegab et al., 2017; Johnson et al., 2017; Korsakas et al., 2017; Mazyan et al., 2016; Ogden et al., 2018; Yan et al., 2017a). It can be mixed with air to create a homogeneous fuel / air mixture and significantly reduce engine exhaust emissions (Hegab et al., 2017; Khan, 2017a,b; Wang et al., 2015b). Raw materials such as corn, vegetables, sugar and wheat can be produced into biodiesel fuel (Chen et al., 2018c; Dimitriou and Tsujimura, 2017; Ghadikolaei et al., 2018; Ramli and Epplin, 2017; Şahin et al., 2018; Saravanan et al., 2018). The difference between biodiesel and fossil fuels lies in oxygen content (Baloch et al., 2018; Dominković et al., 2017; Trumbo and Tonn, 2016). Clean energy can be produced from biodiesel fuel because it is renewable energy. Thus, renewable and sustainable fuels such as biodiesel are more promising and also very environmentally friendly (Abbas et al., 2018; Patel et al., 2016; Thangavelu et al., 2016).

The effect of adding iso-butanol and bio-methanol to gasoline can improve the performance of engines such as EGT, BP, Torque and ICP by 0.9%, 2.6%, 1.47% and 6.2% respectively (Elfasakhany, 2018). Meanwhile, the addition of ethanol to gasoline shows a reduction in carbon dioxide (CO₂), carbon monoxide and nitrogen oxide (NO_x) emissions without significantly reducing the power. However, the temperature reduction in the cylinder increases hydrocarbon (HC) emissions (Doğan et al., 2017; Jerrett et al., 2010; McDonald et al., 2007; Peters et al., 2006). NO_x emissions are scattered in urban environments and mostly come from private vehicles or public transportations which lead to smog, thinning of the ozone layer and acid rain (Elfasakhany, 2018; Iodice et al., 2018; Ramalingam et al., 2018).

This review intends to reveal the performance, combustion and emission characteristics of IC engines using alternative fuels (such as alcohol, and biodiesel). The effects of alternative fuels on the performance, combustion characteristics and emissions such as NO_x, CO, HC, and CO₂ were also investigated.

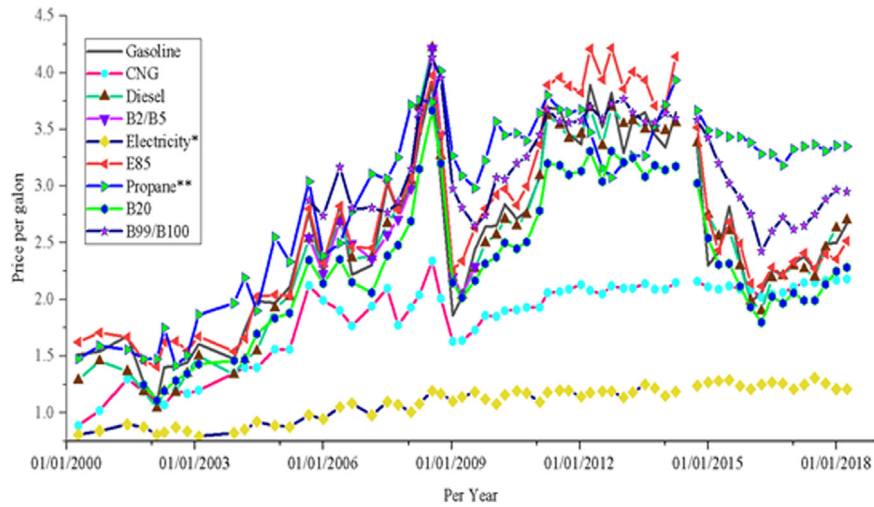


Fig. 1. Alternative fuel vehicles in use, 2000 to 2018 (Energy, 2018).

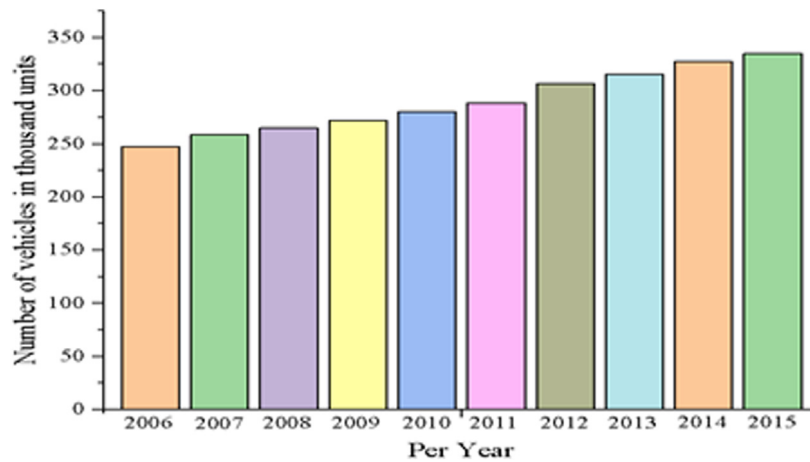


Fig. 2. Number of vehicles in thousand units (Energy, 2018).

| Nomenclature | | | |
|----------------------------------|---|----------------------------------|--------------------------------------|
| BSFC | Brake Specific Fuel Consumption | LHV | Low Heat Value |
| BTE | Brake Thermal Efficiency | BMEP | Brake Mean Effective Pressure |
| HCCI | Homogeneous Charge Compression Ignition | PCCI | Premixed Charge Compression Ignition |
| E | Engine's speed surface | PAH | Polycyclic Aromatic Hydrocarbon |
| NOx | Nitrogen Oxides | HC | Hydrocarbon |
| CO | Carbon monoxide | PM | Particulate Matter |
| HLB | Hydrophile–Lipophile Balance | EGR _s | Exhaust Gas Recirculation |
| BP | Brake power | BT | Brake torque |
| SI | Spark ignition | CO ₂ | Carbon dioxide |
| HRR | Heat release rate | CH ₃ OH | Methanol |
| C ₂ H ₅ OH | Ethanol | C ₃ H ₇ OH | Propanol |
| C ₄ H ₉ OH | Butanol | C ₈ H ₁₅ | Gasoline |

2. Literature review

2.1. Alcohol

Alcohol has been widely studied (especially ethanol and methanol) because it is an alternative fuel that can be readily mixed into gasoline. Alcohol is a renewable energy source and has oxygen properties that can reduce emissions from the combustion chamber (Schifter et al., 2017; Yerrenagoudaru et al., 2018b). A comparison of properties of alcohol and gasoline is shown in Table 1. Alcohol density is higher than that of gasoline; while the octane number of gasoline is higher than alcohol as the number of carbon molecules increases. Latent heat of evaporation and carbon content in alcohols are considered as an essential parameter in engine combustion. Ethanol and methanol are more desirable than other alcohols as alternative fuels because the resulting emissions are much lower and more affordable (Benajes et al., 2018; Pham et al., 2017; Ramasamy et al., 2017). In a recent study, ethanol–methanol fuel operated on a combustion engine with full load conditions significantly reduced emissions because it has a lower amount of carbon (Barrientos et al., 2016; Li et al., 2018b). Moreover, the use of ethanol–methanol–propanol, HC and CO emissions was found to decrease because alcohol tolerates higher exhaust-gas recirculation ratio (EGRs) (Liu et al., 2018b; Polat, 2016; Yusri et al., 2016).

Table 1
Comparison properties of gasoline and alcohol-based (Geng et al., 2017; Liu et al., 2016; Mourad and Mahmoud, 2018).

| Properties | Methanol | Ethanol | Butanol | Propanol | Gasoline |
|--------------------------------------|--------------------|----------------------------------|----------------------------------|----------------------------------|--------------------------------|
| Chemical formula | CH ₃ OH | C ₂ H ₅ OH | C ₄ H ₉ OH | C ₃ H ₇ OH | C ₈ H ₁₅ |
| Cetane number | 2 | 8 | 17 | 12 | 10–15 |
| Molecular weight (g/mol) | 32.04 | 46.07 | – | 60.10 | 96.5 |
| Density (kg/m ³) | 791.3 | 789.4 | – | 803.7 | 746 |
| Boiling point (°C) | 65 | 79 | 117 | 97 | 25–215 |
| Lower heating value (MJ/kg) | 20.01 | 26.08 | 32.01 | 29.82 | 42.7 |
| Vaporization latent heat (kJ/kg) | 1162.64 | 918.42 | – | 727.88 | – |
| Self-ignition temperature (°C) | 385 | 363 | – | 350 | – |
| Oxygen (%) (wt.) | 49.93 | 34.73 | 21.6 | 26.62 | – |
| Latent heating (kJ/kg) 25 °C | 1162 | 904 | 585 | 728 | 380–500 |
| Viscosity (mm ² /s) 40 °C | 0.59 | 1.13 | 2.22 | 1.74 | 0.4–0.8 ^a |

Table 2
Properties of biodiesel fuel.

| Properties | Biodiesel fuel |
|-------------------------------|----------------|
| Carbon content (wt %) | 77.0 |
| Specific gravity at 15 °C | 896 |
| Flash point (°C) | 105 |
| Stoichiometric air/fuel ratio | 12.33 |
| Oxygen content (wt %) | 10.32 |
| Hydrogen content (wt %) | 12.18 |
| Gross heating value (MJ/kg) | 40 |
| Cetane number | 53 |
| Viscosity at 40 °C (cSt) | 2.99 |

2.2. Biodiesel

Biodiesel is more prominent than other alternative fuels, and biodiesel production can be refined from various vegetable oils; for example, cotton seeds, soybeans, sunflowers, peanuts, palm oil and rapeseeds. Biodiesel has been widely used for combustion engines, especially in heavy-duty vehicles and marine engines (Amini et al., 2017; Arumugam and Ponnusami, 2019; Verma and Sharma, 2016). Table 2 shows the properties of biodiesel. Transesterification process involves the alcohol reaction of vegetable oil in the presence of alkali catalysts (KOH and NaOH) for biodiesel production.

This process is intended to reduce the viscosity and oxygen content of vegetable oils. The organic substances contained in biodiesel have high molecules such as alcohol, ketones, phenols and ether (Adewale et al., 2015; Chen et al., 2018b; Silva Filho et al., 2018). Biodiesel has a lower density than water. It can be stored for a longer duration in a stable form (Noor et al., 2018; Sajjadi et al., 2016; Veljković et al., 2018; Wang et al., 2016). Biodiesel does not have aromatic hydrocarbons, and the sulphur content is lower than diesel. Thus, emissions from the production of biodiesel do not endanger human health and are also more environmentally friendly. Moreover, biodiesel has a lower amount of cetane than diesel fuel which further improves engine combustion performance (Geng et al., 2017; Noor et al., 2018; Othman et al., 2017).

3. Methodology

3.1. Application of alternative fuel in Engines

There are two main application modes of alternative fuels in Engines: Mixed/blended fuel mode and dual fuel mode (Aklouche et al., 2018; Mustafi et al., 2013; Yang et al., 2014). In this review,

experiments carried out generally used the mixed/blended fuel mode. The alternative fuels used for testing include methanol, ethanol, butanol, propanol, n-butanol, n-propanol, isopropanol, and biodiesel (Akar, 2016; Li et al., 2016; Verma et al., 2016).

3.1.1. Fuel blend mode

Liquid alternative fuels such as alcohol and biodiesel are very suitable using the mixed fuel mode because they can be blended with gasoline (Turkcan et al., 2018; Yan et al., 2017a; Yao et al., 2017). Meanwhile, alcohol-based alternative fuels such as ethanol, methanol, butanol and propanol can be mixed with gasoline with emulsifiers and solvents (Yusri et al., 2018; Zhang and Sarathy, 2016). The schematic diagram of blended fuel mode is displayed in Fig. 3. The phase separation of alternative fuels for engine combustion is a problem faced by mixed fuel modes. However, this problem can be overcome by using solvents into mixed fuels. In addition, some ignition fuels such as methanol can be added to mixed fuels in order to reduce the number of cetane fuel. The fuel and engine supply systems do not need to be modified when the alternative fuels concentration is lower. Several previous studies investigated the use of alcohol fuels mixed with gasoline in spark ignition engines and the effects on engine performance, combustion and exhaust gas emissions. (Deng et al., 2018; Ghadikolaie, 2016; Gonca, 2017; Li et al., 2018a,b,c,d; Schifter et al., 2017; Verma et al., 2018; Yu et al., 2018; Yusoff et al., 2018). During this study, the different percentage of alternative fuels was chosen such as 5%, 10%, 20%, 30%, 40%, 50% for performing the experiment.

A schematic diagram of the fuel blend modes used by previous researchers is shown in Fig. 4. This is an illustration of the Campro PROTON four-cylinder engine used to operate alternative fuels. During the experiment, this engine is normally operated at a speed of 1000 to 5000 rpm, with different Alcohol and gasoline ratio. With the addition of alcohol to gasoline, engine performance and NO_x, CO and HC emissions increased. However, the combustion characteristics of the engine decreased, while CO₂ emissions were found to increase depending on the concentration of alternative fuel to gasoline. Moreover, the load and speed of the engine when using alternative-gasoline mixed fuels affects the engine performance and NO_x, CO and HC emissions.

3.1.2. Dual fuel mode

The dual combustion mode has several advantages and previous researchers have studied extensively (Jamrozik et al., 2018; Ramasamy et al., 2017; Saxena and Maurya, 2017; Zheng et al., 2018). Fig. 2 illustrates a schematic of a dual fuel combustion mode system. The mixing of alternative fuels was accomplished by inducing a homogeneous mixture into the manifold mixed with fresh air. (Ramasamy et al., 2017). Furthermore, the alternative fuel mixture was ignited with a spark plug, when the piston was at the top dead centre. The amount of diesel fuel remained constant when the operating load conditions were different, while the number of alternative fuel injections varied according to the output power of the engine (Wang et al., 2015b). Alcohol fuel and biodiesel were studied as the alternative fuels used in the dual fuel mode. In previous research (Chen et al., 2018a; Feng et al., 2018; Pan et al., 2018; Pedrozo et al., 2018; Song et al., 2018; Thiruvengadam et al., 2018; Yang et al., 2015), the use of dual fuel modes was very suitable for alcohol-based alternative fuels such as ethanol. This dual fuel mode can reduce NO_x emissions compared to using conventional combustion engines. However, dual fuel modes have several difficulties when the combustion is performed. When the engine is operated under low and medium load conditions, the combustion efficiency is much lower. Consequently, it increases NO_x, CO and HC emissions that do not significantly burn when using a dual fuel combustion

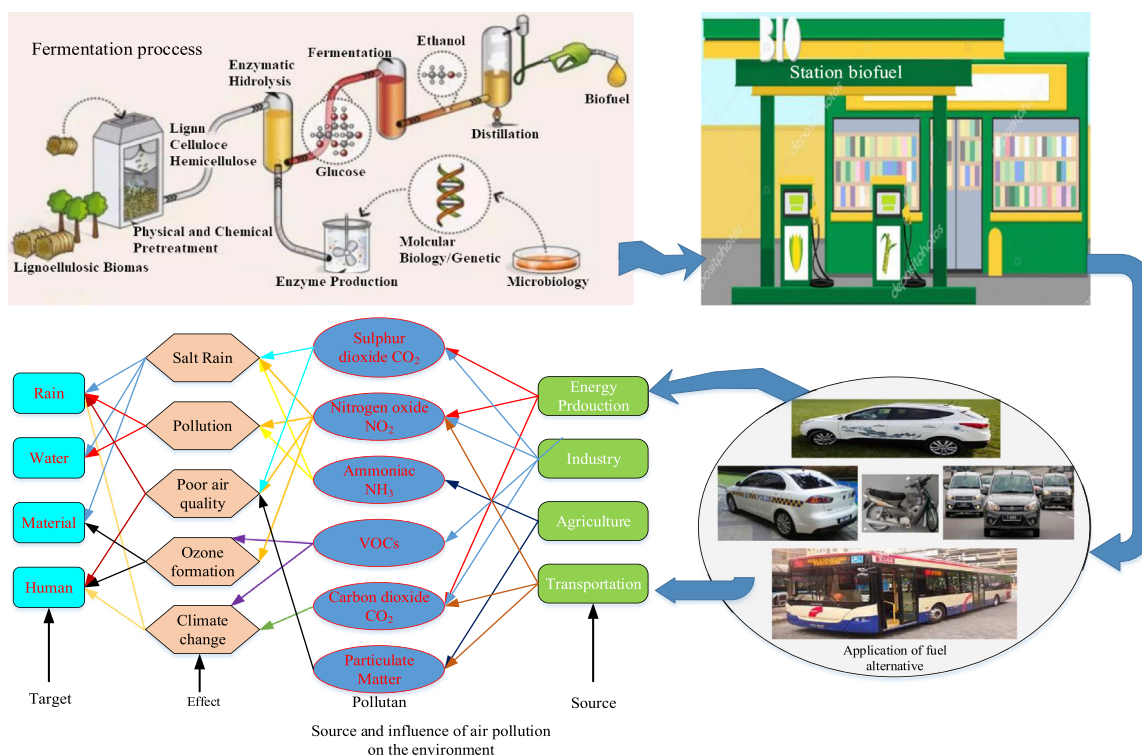


Fig. 3. Fermentation, station biofuel, application and source and influence of air pollution on the environment.

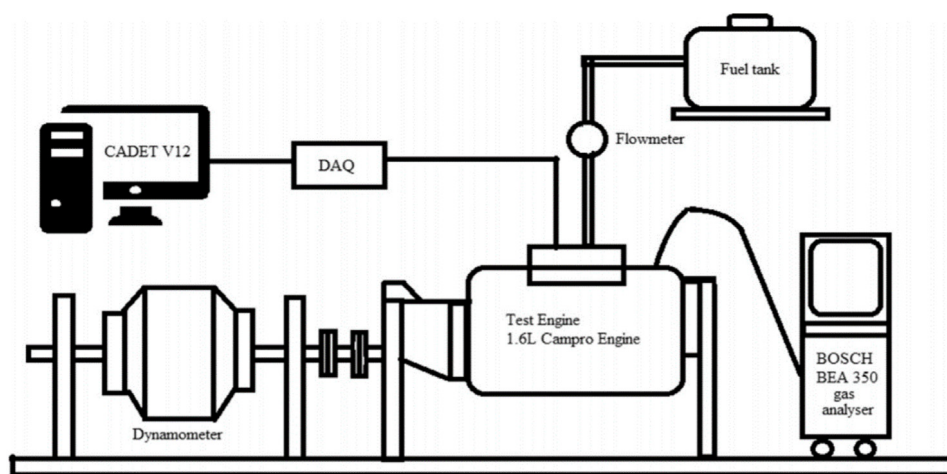


Fig. 4. Schematic diagram used of the engine test set-up (Yusoff et al., 2017).

mode (Kumar et al., 2017; Liu et al., 2015b,a; Sarjovaara and Larmi, 2015). Further research is therefore needed to assess the effects of combustion of engines using dual combustion methods. The schematic diagram is shown in Fig. 3 is an illustration of the Mitsubishi 4G93 SOHC four-cylinder engine. This engine can be operated using a variety of alternative fuels with speeds of 500 to 6500 rpm and various load conditions (see Fig. 5).

4. Result and discussion

4.1. Performance characteristics

4.1.1. Brake specific fuel consumption (BSFC)

Brake-specific fuel consumption (BSFC) using alcohol–gasoline blends increases for different engine loads and speeds compared to pure gasoline. This increase occurred for all engine test condition. It can be reported that increasing BSFC also increases engine

emissions. The maximum BSFC was obtained from the strength of the brakes when testing the engine using gasoline. Of course, the use of alcohol fuel is more stable because it has a lower energy content than gasoline. A significant increase in BSFC was also due to the increase in engine speed.

4.1.2. Brake torque and brake power

The main performance parameters for determining engine performance are brake-specific fuel consumption (BSFC), brake power (BP) and engine brake torque (BT).

The torque is a rotational force that results from the cylinder pressure inside the engine on the piston. The average effective cylinder pressure, stroke length and load of the engine affect the torque of the engine. The engine torque varies greatly when alternative fuels are operated at constant engine loads, due to the nature of the fuel and the effective pressure generated. BSFC

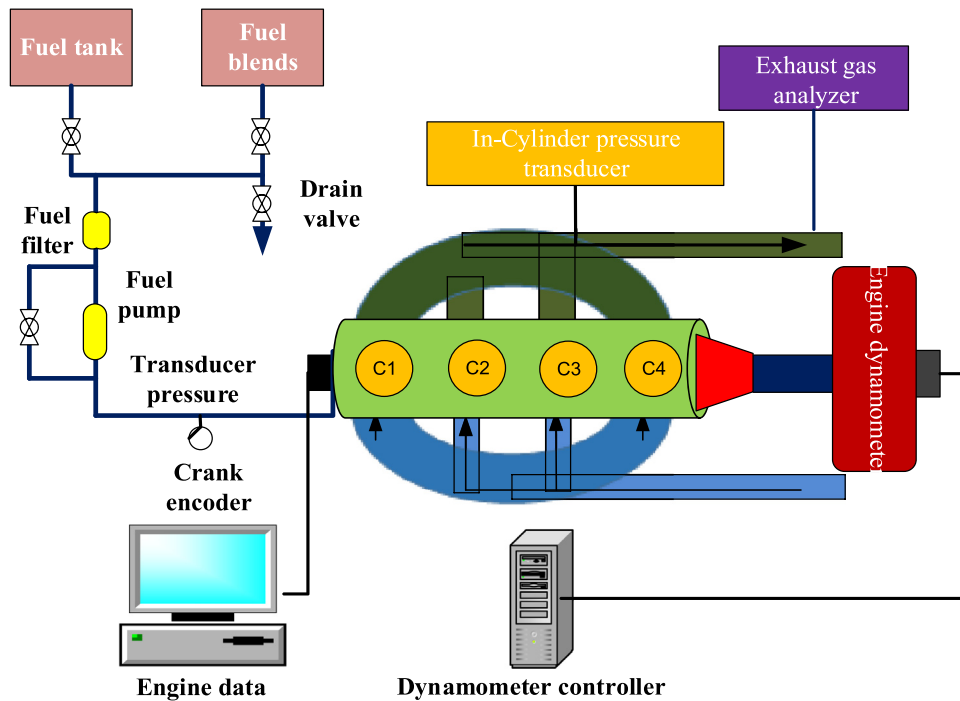


Fig. 5. Schematic diagram four-cylinder SI engine.

calculations can be done with the following equation:

$$BSFC = \frac{\text{Fuel consumption}}{\text{Power output}} \quad (1)$$

The effects of using various types of alternative fuels on BSFC, brake power and brake torque are shown in Table 3. Some studies (Deng et al., 2018; Elfakhany, 2018, 2016; Kumar et al., 2016; Yusoff et al., 2017), stated that the alternative fuels have the same results on the brake torque and power. The use of alternative alcohol-based fuels generally improves engine performance. However, when using alternative fuels with a low volume ratio, the engine performance decreases (Masum et al., 2015). Increasing the amount of carbon in alcohol fuel has significantly reduced engine losses. Using alcohol fuel in the combustion engine increases brake torque, brake power and brake specific fuel consumption (Elfakhany, 2018).

Moreover, the use of alcohol–gasoline fuel with a high ratio resulted in deteriorating engine behaviour. Findings from several previous studies on the performance of engine parameters such as BSFC, BP and BT have no significant impact when using alcohol fuel. However, compared to pure gasoline, alcohol fuel slightly increases engine performance (Ghadikolaei, 2016; İlhak et al., 2018; Imran et al., 2013; Thangavel et al., 2016). When the engine is operated under low and medium load conditions, engine performance is higher.

This increase is due to the low combustion temperature and the fuel–air ratio in the combustion chamber, which decreases the combustion rate in the engine, when compared to conventional combustion mode. The increased combustion temperatures and more mixtures are the two main factors that decrease the BSFC (Amirante et al., 2017; Boulahlib et al., 2018; Nadaleti and Przybyla, 2018; Yan et al., 2017a).

4.2. Combustion characteristics

The effects of combustion such as cylinder pressure and heat release rates from various types of alternative fuels were studied. The ignition delay is defined as the variation of the crank angle

between the starting of the injection and start of the ignition. Table 3 shows the effect of the release rate and pressure of alternative alcohol fuels in the cylinder. There are many differences in the rate of heat release and in-cylinder pressure from the use of alcohol fuels operated in mixed fuel modes and conventional fuels. Significantly, compression pressure decreased as the alcohol content in the fuel increased, compared to conventional combustion mode (Fajri et al., 2017; Hasan et al., 2018; Pischinger et al., 2017; Wang et al., 2015c). The latent heat of vaporization, which is higher than gasoline, caused this decrease. So, when intake ports were injected with alcohol fuels such as methanol and ethanol, they absorbed heat and evaporated from the incoming air, so that the cylinder pressure and temperature decreased.

The maximum cylinder pressure changed slightly with the low and medium ratios of premixed alcohol when the engine was operated under low load and speed conditions; however, the premix was high when the alcohol ratio decreased. Higher latent heat of vaporization of alcohol reduced the combustion temperature and cylinder pressure which delays the combustion phase. The ratio of alcohol fuel mixture increased with the engine load and speed compared to conventional fuels (Dudareva et al., 2017; Feidt, 2017; Tarabet et al., 2018). When the engine was operated with a low load using a mixture of alcohol, the combustion pressure in the cylinder decreased. This was because of the increased specific heat capacity of the combustion gasses, gas–air mixture leanness and lower ignition delay. At the beginning of combustion, heat cannot be released efficiently because of the amount of steam collected during the ignition; however, after that, it improved. After experiencing an ignition delay, the fuel–air mixture burnt very quickly.

In addition, engine load conditions can cause the combustion chamber to accumulate more gas fuel and decrease the ignition delay. The addition of biodiesel can speed up the initial combustion for all test engine loads because at the end of the compression the cylinder pressure increases rapidly (Dharma et al., 2016; Yerrenagoudaru et al., 2018a).

Furthermore, the combustion characteristics study of the engine with biodiesel mixture was carried out in comparison with

conventional fuels, especially diesel. The combustion of the biodiesel fuel mixture occurred a little earlier in the crank angle due to the bulk modulus, higher density and viscosity of biodiesel. With biodiesel mixture, the rate of heat release decreased during the combustion phase when the engine was operated in low and high engine load conditions. This decrease occurred because of the lower amount of fuel injection and shorter ignition delay. However, the biodiesel fuel mixture had a low heating value.

4.2.1. In-Cylinder pressure

Pistons do all the work during compression and produce energy through the combustion process of the gases in the engine. In an SI engine, when the cylinder gas pressure increases, it can significantly increase combustible fuel. Because the enthalpy of combustion has increased, the fuel energy increases. The combustion characteristics of mixed alcohol fuels can be compared with gasoline fuel through the gas pressure in the cylinder. The peak combustion pressure in the cylinder was significantly faster than the gasoline because the octane value of the fuel was lower as shown in Table 3. The higher the octane value, the greater the compression ratio that can be charged in the engine without observing the knock phenomenon in the engine. Thus, a significant increase in engine performance output can be provided with similar amounts of test fuels. This is a fairly positive aspect, while there is a lack of engine efficiency with the current gasoline engine (Masum et al., 2015).

4.2.2. Heat release rate

Combustion can produce heat release in the engine and provide precise information on fuel combustion. The calculation of heat release rate was carried out to get information on the combustion process inside the engine. The alcohol fuel mixture was compared with gasoline by investigation of the rate of heat release during their combustion process (Masum et al., 2015).

The increase in the heat release rate was observed when the piston reached the top dead centre using a gasoline–alcohol fuel mixture.

The heat release rate increased due to the higher enthalpy in the mixed fuel. In all engine speeds and loads tested, gasoline fuels had a higher heat release level compared to alcohol-based fuels. The main cause, in this case, was that oxygen contained in alcohol fuel can increase combustion, depending on the fuel concentration. Therefore, the release of increased heat in the engine can reduce emissions; in the beginning, if the combustion decreases, the emissions increase. This can be influenced by several factors, especially the heat value of gasoline which is higher than alcohol. More results about combustion characteristics are shown in Tables 3 and 4.

4.3. Emission characteristics

The use of ethanol resulted in lower HC, NO_x and CO emissions from the engine. In addition, the blends had a lower content of toxicity, since they were reported to be much cleaner compared to the conventional fuels. A detailed literature outcome, depicting the effect of ethanol blends on the various constituents of emissions, has been done in a previous study (Kessel, 2000).

4.3.1. Nitrogen monoxide (NO_x)

Several studies reviewed in this paper mentioned that NO_x emissions vary greatly and sometimes increase due to the combustion characteristics of the fuels in the engine. Conversely, if engine combustion increases, NO_x emissions decrease, this applies to all engine loads and fuel mixtures. Compared to the alcohol content, the water content of the fuel can significantly reduce emissions; however, it affects the engine output and torque.

NO_x emissions do not linearly increase with the compression ratio because the combustion temperature varies throughout the engine. This is because the fuel's water content reduces NO_x emissions. Furthermore, the peak combustion temperature in the cylinder decreases.

As reported, the reaction of nitrogen with engine fuel can form NO_x emissions. Moreover, it can create greenhouse gases which are very dangerous, because they cannot ignore oxidation from a fuel-rich environment with a lower temperature during the combustion process (Canakci et al., 2013; Doğan et al., 2017; Iodice et al., 2018; Masum et al., 2015; Suarez-Bertoa et al., 2015).

The exhaust gas temperatures at various speed and engine loads of the test engine have provided significant insight into the extent to which the fuel mixture can emit NO_x emission gas. From several studies reviewed, it was stated that the addition of alcohol fuel in various ratios could reduce NO_x emissions. However, there are also different studies that stated adding alcohol to gasoline can increase NO_x emissions. Meanwhile, the amount of gas emitted to gasoline burned enough for certain engine speeds. Conversely, greater alcohol content in the fuel can produce NO_x emission levels even at higher exhaust temperatures. This is a determining factor for the level of NO_x emission stressed from the engine. The increase and decrease of NO_x emissions in engines that are operated using a mixture of alcohol to gasoline with different engine loads and speeds are shown in Table 3.

The reduction of CO content to zero may not be possible because each combustion is imperfect and there is always a little of the fuel contained in the engine. Also affects the concentration of CO emissions in the engine during the when the engine operation.

In some cases, the amount of CO in the exhaust increases significantly due to the lower combustion temperature.

The changes in the engine compression ratio show highly varied levels of emissions. Any addition of alcohol fuel like ethanol to gasoline by 10% can reduce CO emissions by 30% (Chansauria and Mandloi, 2018; Deng et al., 2018). In this review, several proven statements that the use of alcohol fuels can reduce CO from various mixtures were tested (Deng et al., 2018; Elfasakhany, 2018, 2016; Elfasakhany and Mahrous, 2016; Jamrozik et al., 2018; Kumar et al., 2016; Mourad and Mahmoud, 2018; Yusoff et al., 2017). However, CO emissions also increased in some research, and more details can be shown in Table 3 (Elfasakhany and Mahrous, 2016; Hasan et al., 2018; Li et al., 2017, 2016, 2018a; Raj et al., 2018; Yan et al., 2017b).

The CO emission clearly showed that an increase in alcohol fuel could reduce CO, but the combustion characteristics slightly decreased and vice versa; if the combustion characteristics of the engine increase, CO emissions decrease. CO emission levels can also be affected by the low latent heat contained in alcohol fuel.

4.3.2. Hydrocarbon (HC)

HC that are not burned out are emitted after burning fuel in the engine. Some of the air–fuel mixtures inside the engine piston is hidden from the combustion in the cracks available on the piston ring grooves. Moreover, it is possible that from some combustion chambers, the flames are very weak and the combustion temperatures are low. As a result, when the fuel is not burned, the HC is formed from the steam emitted. Compared to gasoline, HC emissions from alcohol fuel are larger. This is because the alcohol fuel has a lower calorific value and molecular weight than gasoline. (Geng et al., 2017; Liu et al., 2016; Mourad and Mahmoud, 2018).

The effect of an alcohol-based alternative fuel mixture on hydrocarbon emissions is significantly increased. However, from some previous studies, not all HC experienced an increase, as shown in Table 3. Non-combustible HC emissions are one of the emissions in the engine discussed in this review. The engine

Table 3
Effect of alcohol on the engine performance, combustion and emission characteristics compared to gasoline.

| Speed RPM | Using fuel | Volume fraction | Engine type | Pressure | HRR | Temp | NOx | CO | HC | CO ₂ | BSFC | Power | Torque | Ref. |
|------------------------|---|--------------------------------|----------------------------|---------------|---------------|--------------|---------------|---------------|---------------|-----------------|--------------|--------------|--------------|---|
| 1000–5000 2600–3400 | Alcohol–gasoline Iso-butanol–bio-methanol–butanol, bio-ethanol–gasoline | All fuel 20% 3%, 7% and 10% | SI-Gasoline SI-Gasoline | N/A N/A | N/A N/A | High High | High Lower | High Lower | High Lower | N/A High | High High | N/A High | N/A High | Yan et al. (2017b) Yusoff et al. (2017) |
| 2600–3400 | n-butanol–methanol–gasoline | 0%, 3%, 7% and 10% | SI-Gasoline | High | N/A | High | N/A | Lower | Lower | Lower | N/A | High | High | Elfasakhany (2018) |
| 1500–5000 | Ethanol and gasoline | 10% and 20% | SI-Gasoline | Lower | N/A | Lower | N/A | High | High | Lower | Lower | Lower | N/A | Elfasakhany and Mahrous (2016) |
| 1500 | n-Octanol–Diesel | 10%, 20% and 30% | SI-Gasoline | High | N/A | N/A | Lower | Lower | Lower | N/A | Lower | Lower | Lower | Deng et al. (2018) |
| 1000–5000 | Propanol–gasoline | 0%, 5%, 10%, 15% and 20% | SI-Gasoline | N/A | High | High | Lower | Lower | Lower | N/A | High | Lower | N/A | Kumar et al. (2016) |
| 2600–3400 | Bio-ethanol–iso-butanol–gasoline | 0.8%, 1.2%, 0.4% and 0.6% | SI-Gasoline | N/A | N/A | N/A | High | Lower | Lower | N/A | High | High | High | Mourad and Mahmoud (2018) |
| 1200 | Methanol, ethanol and butanol | N/A | SI-Gasoline | Lower | N/A | High | N/A | Lower | Lower | High | Lower | High | High | Elfasakhany (2016) |
| 2600–3400 | n-butanol–methanol–gasoline | 1.5%, 3%, 3.5%, 5% and 7% | SI-Gasoline | High | N/A | N/A | Lower | High | Lower | N/A | Lower | Lower | Lower | Li et al. (2017) |
| 3000 | iso-octane/n-butanol | 10%, 20 and 30% | SI-Gasoline | High | N/A | High | N/A | Lower | Lower | High | High | Lower | N/A | Elfasakhany and Mahrous (2016) |
| N/A | 1-pentanol | 5%, 10%, 20%, and 40% | Kirloskar | High | N/A | High | N/A | N/A | N/A | N/A | N/A | N/A | N/A | Feng et al. (2016) |
| 1200 2000 | Acetone–alcohol Ethanol/gasoline | 30% and 60% 10% and 20% | SI-Gasoline SI-Gasoline | Lower High | Lower High | N/A High | High High | High Lower | High High | N/A Lower | High High | High High | High High | Raj et al. (2018) Jamrozik et al. (2018) |
| 2000 | Alcohol and gasoline | N/A | SI-Gasoline | N/A | N/A | High | High | High | High | N/A | High | High | High | Fajri et al. (2017) and Hasan et al. (2018) |
| 1500 | Alcohol and diesel | 15%, 30%, 45%, 55% and 70% | CI-engine | High | N/A | High | High | High | High | N/A | Lower | Lower | Lower | Li et al. (2018a) |

Table 4
Effect of biodiesel on the engine performance, combustion and emission characteristics compared to diesel.

| Speed RPM | Using fuel | Volume fraction | Engine type | Pressure | HRR | Temp | NOx | CO | HC | CO ₂ | BSFC | BTE | EGT | Ref. |
|-----------|--------------------------------|--------------------|--|-----------|-----------|-----------|--------|-------|-------|-----------------|-------|-------|-------|-----------------------------------|
| 1500 | Waste cooking methyl ester oil | B20, B40, B60, B80 | 4 stroke variable CI | Increases | Decreases | Increases | High | High | High | Low | N/A | High | Low | Muralidharan and Vasudevan (2011) |
| 1600±10 | Jatropha methyl ester | B100 | Direct injection | N/A | N/A | N/A | Lower | High | Lower | High | High | High | N/A | Jindal et al. (2010) |
| 1500 | Waste cooking methyl ester oil | B20, B40, B60, B80 | 4 stroke variable CI | Increases | Decreases | Increases | Lower | High | High | Lower | N/A | High | Low | Muralidharan and Vasudevan (2011) |
| 1500 | Cotton seed oil | B5, B20 | Single cylinder variable CI | Increases | Increases | Increases | High | Low | Low | N/A | Lower | Lower | N/A | Anand et al. (2009) |
| N/A | Rice bran and biogas | B100, B50 | Single cylinder DI | Decreases | Decreases | Decreases | High | Lower | Lower | High | N/A | Lower | N/A | Bora and Saha (2016) |
| 1500 | Tyre pyrolysis oil–biodiesel | Oil20 + B80 | Naturally aspirated DI CI | Increases | Decreases | N/A | High | Lower | Lower | N/A | Lower | High | Lower | Sharma and Murugan (2015) |
| 1500 | Waste Fried oil methyl ester | B50, B70 | 4 Stroke single cylinder CI | N/A | N/A | N/A | N/A | Lower | Lower | N/A | High | Lower | High | Hirkude and Padalkar (2014) |
| 1500 | Mustard oil methyl ester | B10, B20 | Single cylinder 4 stroke CI | N/A | N/A | N/A | Lower | Lower | Lower | N/A | N/A | High | Lower | Basavaraju and Jamunarani (2014) |
| 1500 | Sal methyl ester | B10, B20, B30, B40 | Single cylinder 4 stroke water cooled CI | N/A | N/A | N/A | High | Lower | Lower | N/A | High | Lower | N/A | Pali et al. (2015) |
| 1500 | Preheated Palm oil | B5, B10, B15, B20 | Single cylinder 4 stroke CI | N/A | N/A | N/A | N/A | Lower | Lower | N/A | N/A | N/A | Lower | Nagaraja et al. (2015) |
| 1000–2000 | Waste oil | B10, B20, B30, B50 | 4 Stroke single cylinder DI | Increases | N/A | N/A | Higher | Lower | Lower | High | High | High | N/A | ELKassaby and Nemitallah (2013) |
| 1500 | Jatropha oil | B10, B30, B50, B80 | 4 Stroke single cylinder VCR, DI | N/A | N/A | N/A | Lower | N/A | N/A | N/A | N/A | Low | N/A | De and Panua (2014) |
| 1500 | Honne oil | B20, B40, B60, B80 | Direct injection CI engine | N/A | N/A | N/A | Lower | Lower | N/A | High | Low | Low | Low | Channappattana et al. (2015) |
| 1500 | Tamanu oil | B100 | 4 Stroke single cylinder, VCR | N/A | N/A | N/A | High | Lower | Lower | High | N/A | Low | Low | Mohanraj and Mohan Kumar (2013) |
| N/A | Palm kernel and eucalyptus | B5, B10, B15 | 4 Stroke single cylinder CI | Increases | N/A | Increases | High | Lower | Lower | N/A | High | High | High | kommana et al. (2016) |

Table 5
Comparative study of alcohol and biodiesel.

| | Methanol | Ethanol | Butanol | Biodiesel |
|---------------|---|---|--|--|
| Advantages | <ul style="list-style-type: none"> • Higher cooling, hence less compression work • The high latent heat of vaporization • The high stoichiometric fuel-air ratio • High oxygen content, high hydrogen to the carbon ratio and low sulphur content • Reduced soot and smoke | <ul style="list-style-type: none"> • The use of ethanol could reduce carbon dioxide emissions, provided that a renewable energy resource was used to produce crops required to obtain ethanol and to distill fermented ethanol • Ethanol is a renewable resource • Ethanol produces less carbon (soot) and carbon monoxide | <ul style="list-style-type: none"> • Biomass is readily available for making butanol, and the process is simple and can be regionalized (from biomass production to fuel). Butanol is similar to gasoline so that it can be distributed through the same infrastructure and is much more user-friendly than oil-based fuel. • It can also be burned without water separation (as with diesel) or dehydration (as with ethanol) in most combustion engines made for it. | <ul style="list-style-type: none"> • Biodiesel fuel is a renewable energy source unlike petroleum diesel • Less polluting than petroleum diesel is one of the main advantages of biodiesel fuel. • Excessive biomass production in the world makes this surplus economic use for the production of biodiesel fuel • The lack of sulphur in 100% biodiesel extends the life of catalytic converters • It can be blended with other energy resources and oil • It can be distributed through existing diesel fuel pumps • The lubricating property may extend the lifetime of engines • Biodiesel fuel can also be used in existing diesel engines without making any alterations • It requires energy to produce biodiesel fuel from soy crops, plus there is the energy of sowing, fertilizing and harvesting • At present, Biodiesel fuel is about one and a half times more expensive than petroleum diesel fuel. • Another biodiesel fuel disadvantage is that it can harm rubber hoses in some engines. • Biodiesel fuel distribution infrastructure needs improvement, which is another disadvantage • As Biodiesel cleans the dirt from the engine, this dirt can then get collected in the fuel filter, thus clogging it. So, filters have to be changed after the first several hours of biodiesel use. |
| Disadvantages | <ul style="list-style-type: none"> • Poor combustion characteristics • Lower energy content • Longer ignition delay • More corrosive • Lower flash point | <ul style="list-style-type: none"> • Large amounts of arable land are needed to produce ethanol from plant sources. • Typical current engines would require modification to use high concentrations of ethanol • Ethanol has a lower heat of combustion (per mole, per unit of volume, and per unit of mass) than petroleum • Major environmental problems would arise out of the disposal of waste fermentation liquors. | <ul style="list-style-type: none"> • Butanol has an energy density lower than gasoline and an octane rating lower than gas, ethanol or methanol. • It has a gasoline-like air–fuel ratio (11.1 vs. 14.6) but a lower energy output overall. • While the manufacture of butanol is not new, it is difficult to produce it correctly as a fuel, so no real marketing has yet taken place. | |

efficiency decreases with the increasing HC emissions; on the contrary, if engine combustion increases, HC emissions decrease. In the case of an alcohol fuel mixture, it can provide better combustion and is quite clear because it can limit the unburned fuel trapped in a particular engine location. Alcohol fuels with B20 and B40 fuel mixtures increase HC emissions because of the lower cetane number causing delays in ignition (Hasan et al., 2018; Raj et al., 2018).

Meanwhile, a mixture of gasoline–ethanol and methanol HC emission was found to decrease, while the HC methanol–gasoline mixture increased. The increase in HC using methanol–gasoline is because too much fuel is injected, resulting in ignition delays (Li et al., 2017). The addition of ethanol fuel with a mixture ratio of E10W and E20W to gasoline reduces the HC emissions compared to E20W, E10W (Deng et al., 2018). The isobutanol–n-butanol–gasoline mixture produced the lowest HC emissions compared to pure gasoline when the engine load was high (Yusoff et al., 2017). The effect of oxygenated fuel tested on dual fuels showed that HC emissions were higher compared to conventional fuel modes (Jamrozik et al., 2018). An alcohol fuel mixture of 10% (IBE10%) increased UHC emissions by 12.4–25.1 and 4.4–6.1% compared to ABE. However, deteriorating combustion quality can increase UHC emissions (Li et al., 2018a). HC emissions decreased by 14.18% from the use of propanol–gasoline fuel mixture. Also, vehicle fuel consumption increased with decreasing hydrocarbons (Mourad and Mahmoud, 2018).

The use of alcohol-based fuel with mixtures in combustion engines has been widely investigated.

There are several benefits to alcohol fuels, such as methanol, ethanol, butanol, and biodiesel. The disadvantages of using alcohol fuels such as methanol are mainly for diesel engines because of lower calorific value, low flash point and smaller cetane number. The pros and cons of alcohol-based fuels are described in Table 4 (Ghadikolaei et al., 2018; Li et al., 2018b). Among several alternative fuels used for combustion engines, biodiesel has more advantages that offer some unique qualities and features. Biodiesel fuel has been tested in combustion engines, and it can meet the essential emission standards requirements of various regulations (see Table 5).

5. Conclusions

This review illustrates the effect of alcohol and biodiesel on SI / CI engine performance, combustion and emission characteristics. The addition of alcohol/biodiesel to gasoline/diesel engines can result in more varied performance. From the critical investigation of the literature, the following inferences had been drawn:

- The alcohol-based fuels have a high latent heat of vaporization and oxygen content which provides anti-knock qualities and better combustion efficiency.
- In general, with an increased % of alcohol fuel CO, HC emissions increase and NO_x emission decreases. However, it reduces the combustion characteristics; and engine performance.

- Due to lower heating values compared to conventional diesel, engine power decreases with the use of biodiesel blends.
- Using clean alternative fuels such as biodiesel in CI engines can reduce injection delays, improve air–fuel mixing and contribute to clean combustion.
- Alternative fuels such as alcohol and biodiesel have enormous potential in addressing the energy and environmental issues associated with conventional fuels.

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