Chapter 7

Combustion and Emission Characteristics of Blends: -n-Butanol-Diesel (D2); and Dual Alcohols: n-Butanol-Methanol with Gasoline in Internal Combustion Engines

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Additional information is available at the end of the chapter

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Abstract

A study of the effects of oxygenated alcohol/gasoline/diesel fuel blends on performance, combustion, and emission characteristics in conventional reciprocating engines is reported. On the one hand, in alcohol-gasoline blends, dual alcohols-gasoline blends have not yet been sufficiently proven as suitable alternatives to single alcohol-gasoline blends in engines as far as performance is concerned. On the other hand, n-butanol-diesel, although it has a better miscibility factor in diesel than methanol or ethanol, is limited with regard to extensive application in the diesel engines due to its low cetane number. Engine performance was compared using single alcohol-gasoline and dual alcohol-gasoline blends, where the dual blends were constrained to meet the vapor issues regarding fuels and regulations. The blends were selected in terms of a combination by volume of one being higher alcohol (n-butanol) and the other, lower alcohol (methanol). The engines used for this study included a single-cylinder and a four-cylinder, naturally aspirated, four-stroke spark ignition engines and a four-cylinder, four-stroke compression ignition turbocharged diesel engine. In the n-butanol-diesel studies, a comparison was made with other studies in order to determine how suitable n-butanol-diesel blends were across the biofuel family such as the biodiesel-ethanol-diesel blends. The findings were as follows: The dual alcohols-gasoline blends performed better than the single alcohol-gasoline blends depending on certain compositional ratios of the alcohols in gasoline regardless of vapor pressure consideration. The n-butanol/diesel alcohol blend (B5, B10, and B20, where B5 represents 5% n-butanol and 95% diesel) significantly reduced the regulated emissions in a turbocharged engine compared to other studies using biodiesel-diesel blends. The significant decrease in NO_x, CO emissions, and reduction of unburned hydrocarbons content using n-butanol/diesel fuel (DF) blends were found experimentally. The use of dual alcohol /

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gasoline blends was beneficial due to their shorter combustion duration in crank angles and their higher-energy content compared with single alcohol-gasoline blends. The n-butanol/diesel blend fired in the diesel engine showed a higher brake thermal efficiency and improved brake specific fuel consumption compared to the study by others where ethanol\diesel and methanol\diesel blends were used.

Keywords: compression ignition engine-diesel, emission reduction, butanol (-n) brake-specific fuel consumption (BSFC), brake thermal efficiency, combustion and emission, bioalcohols, spark ignition engine, global climate change

1. Introduction

The efforts of researchers worldwide have been and continue to be directed toward finding fuels that are cleaner than fossil fuels in internal-combustion engines. The goal is to replace or reduce the use of petroleum oil because conventional fuels such as gasoline degrade the environment. Use of petroleum oil in transportation greatly contributes to the deterioration of the environment through the emission of regulated emissions such as nitrogen oxides (NO_x), unburned hydrocarbon (UHC), carbon monoxide (CO), particulate matter (PM), and carbon dioxide (CO_2) [1].

A very strong debate on the gradual substitution of petroleum by using renewable alternatives such as biofuels dominates the political and economic agenda worldwide [2].

In their two articles, Andersen et al. [3, 4] reported on the vapor pressures (VP) of single bioalcohol-gasoline blends. They evaluated the VP for lower alcohols, methanol, and ethanol and higher alcohols including, n-butanol and propanol. Vapor pressure is an indirect way to measure the volatility of liquid fuels, which emit fuel vapors known as evaporative emissions. Evaporative emissions will cause vapor lock on restricted spaces in the fuel lines and the pump in spark ignition (SI) engines and carburetor fuel delivery systems. Port injection is also prone to this problem [3, 4].

	Molar mass Kg/kmol	RVP (kPa)	Density at 20°C (g/mL)	Normal boiling point (°C)
Gasoline	98.5	60-62	0.741	NA
n-butanol	74.12	2.2	0.81	117.8
Methanol	32.04	32	0.791	64.6
Ethanol	46.07	16	0.789	78.3

Source: Ref. [4].

Table 1. Typical physical properties of gasoline and alcohols.

Adherence to stringent regulation of the Reid's vapor pressure (RVP) for gasoline as presented in **Table 1** is required by many countries in order to limit evaporative emissions. Depending

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on the properties of the individual alcohols, it is possible to add another alcohol to the single alcohol-gasoline blend in order to reduce the evaporative emissions [4].

When alcohols are blended with gasoline or diesel fuel, the resulting mixture has more or fewer different properties than the conventional fuels on the basis of which the engines were designed to operate. This creates problems such as vapor lock, changes of viscosity, energy-content (low heating value), boiling point of the fuel blends, and different flame propagation hence limiting their application.

To mitigate the negative impacts caused by vapor lock of single alcohol/gasoline (SAG), Andersen et al [3] proposed the use of dual alcohols, one higher and the other lower alcohol blended in gasoline engines, as well as a method of determining the composition of dual alcohols/gasoline (DAG) blends. Based on this concept, the lower volatility of n-butanol (a higher alcohol) can be exploited by mixing n-butanol and another highly evaporative lower carbon alcohol (methanol) in gasoline. The expected net effect is to reduce problems in the fuel delivery system.

However, the researchers Andersen et al. did not formulate any list and conduct experiments using alcohol-gasoline blends, which satisfy the Reid's vapor pressure requirement for gasoline fueled engines. Thus, their performance in reciprocating engines remains unclear.

Although Andersen et al. studied VP issues of alcohol-gasoline blends in spark ignition engines only, alcohol-diesel blends also appear to be as promising as the former. Low carbon-content alcohols (C_1 and C_2) have a greater auto-ignition temperature than ($C_{4–5}$) ones. Therefore, methanol and ethanol have a much *higher auto-ignition* temperature than n-butanol. For this reason, C_1–C_2 alcohols may not be preferred to C_4–C_5 alcohols for blending with diesel fuel. This renders n-butanol or any other high carbon-content alcohols promising candidates for blending with diesel fuel.

This author has proposed a number of dual alcohols-gasoline blends, which were selected based upon the vapor pressure requirements as proposed by Andersen et al. The dual blends were experimentally tested in a laboratory using engines in order to determine whether they can satisfy the requirements of operation with different engine loads.

The research hypothesis is that the dual alcohols-gasoline and higher alcohol/diesel blends with the shared volume above the known limits may be applied satisfactorily to both spark and compression ignition engines, respectively. These may also comply with the most recent emission regulations as well as the engine performance requirements.

2. Objectives

The general objective of this research is to reduce the negative impacts of petroleum oil-based fuels in reciprocating engines on the environment through the use of oxygenated (alcohol) blends, while not deteriorating engine performance. The specific objectives include the following:

- To compare the performance, combustion, and emission characteristics of dual alcohol-gasoline with single alcohol-gasoline blends fired in a four cylinder naturally aspirated (NA) spark ignition (SI) engine.
- To compare the combustion and emission characteristics of dual alcohol (methanol-n-butanol-gasoline) blends with single alcohol (methanol-gasoline) blends in a single-cylinder SI engine.
- To evaluate the combustion and regulated emission characteristics of diesel fuel (DF) and n-butanol/diesel blends (B5, B10, and B20, where B5 represents 5% shared volume of n-butanol to 95% diesel fuel) fired in a high load turbocharged diesel engine and to compare the findings with a study that was conducted by others [5]. Detailed information on the advantages and disadvantages of using n-butanol, comparisons of ethanol or methanol, and heating value estimation of the blends can be found in Ref. [6].

3. Engine experimentation

The engine experiments and methodology, data collection process, and analysis software are all described in turn in Ref. [6].

3.1. Multipoint injection NA engine

3.1.1. Fuel mass flow rate

The electronic control unit (ECU) controls the fuel mass flow rate and changes the fuel delivery system. The change to the type of fuel is different from gasoline; in particular, the type of fuel (blends) affects the quantity of the mass of fuel delivered by the fuel pump.

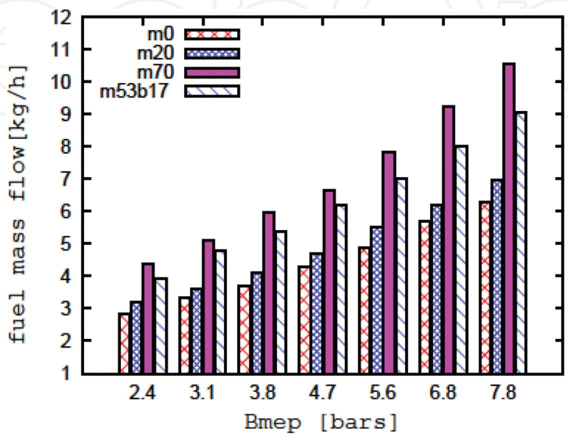

Figure 1. Effect of blends on fuel mass flow rate vs. Bmep.

Figure 1 depicts the increase of the fuel's mass-flow rate (m_f) for the blends with the load or brake mean effective pressure (BMEP). The raised fuel mass flow with the blends in comparison with GF is well known.

3.1.2. BSFC and BTE

Figure 2(a) demonstrates the effect of the blends on BSFC and **Figure 2(b)** on BTE. Improvement of brake thermal efficiency (BTE) as a result of the raising of the heating value and oxygen atoms of the blend is well understood (**Figure 2(b)**). A well-known relation between BTE and BSFC is such that as the BTE increases, the BSFC reduces as BMEP increases (see **Figure 2(a)** and **(b)**). It is well established that alcohol-gasoline blends indicate a higher BSFC than GF does at a given BMEP. Other factors that could contribute to the observed improvement of BTE are better atomization of the blend and effects on friction [7]. Atomization of a fuel is affected by the fuel's surface tension [7, 8]. The increased BTE when using M70 being greater than the BTE when using M53b17 indicates the improved combustion process of the single alcohol-gasoline blend in comparison with that of the dual alcohol-gasoline blend.

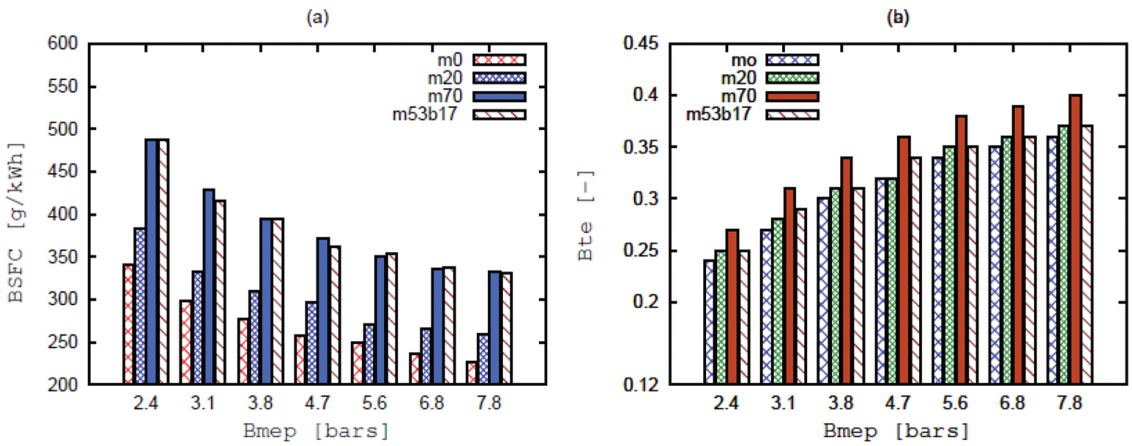

Figure 2. Effect of blends on (a) BSFC and (b) BTE.

3.2. Diesel (TDI) engine

3.2.1. BSFC and BTE

A study in which a small shared volume of ethanol to diesel (E5 and E10) was compared with methanol-diesel blends: M5, M10 (M5 represents 5% by volume of methanol in diesel fuel) was conducted [9].

The test was based upon the engine type Super Star 7710a, (age of the engine: year 2000) four-stroke, single-cylinder, naturally aspirated diesel engine, and displacement of 770 cc, with bore size of 98 mm and stroke 100 mm and compression ratio 17:1. The intake valve opens at 15° crank angle (CA) before top dead centre (BTDC), and the exhaust valve opens at 15° after top dead centre (ATDC), in the conditions of original injection timing of 27°CA BTDC, the injection nozzle with needle valve and four holes, a nozzle-valve lifting pressure of 150±0.5 bar; a maximum torque 39.8 Nm (at 1650 rpm), and maximum power 7.4 kW at 1900 rpm.

The minimum BSFC in the study carried out by Ref. [9] was 298 g/kWh when compared with 237 g/kWh on 1500 rpm in this study. This is expected, as n-butanol has a lower fuel consumption rate than ethanol or methanol blends, due to the higher-energy content of n-butanol. In this study, however, the lower-energy content of n-butanol blends than DF resulted in an increased mass flow rate with n-butanol /diesel blend as depicted by the increased BSFC in **Figure 3(a)** and **(b)**. In the writer's study, the BSFC, on low BMEP, was higher than that on high BMEP for all the test fuels.

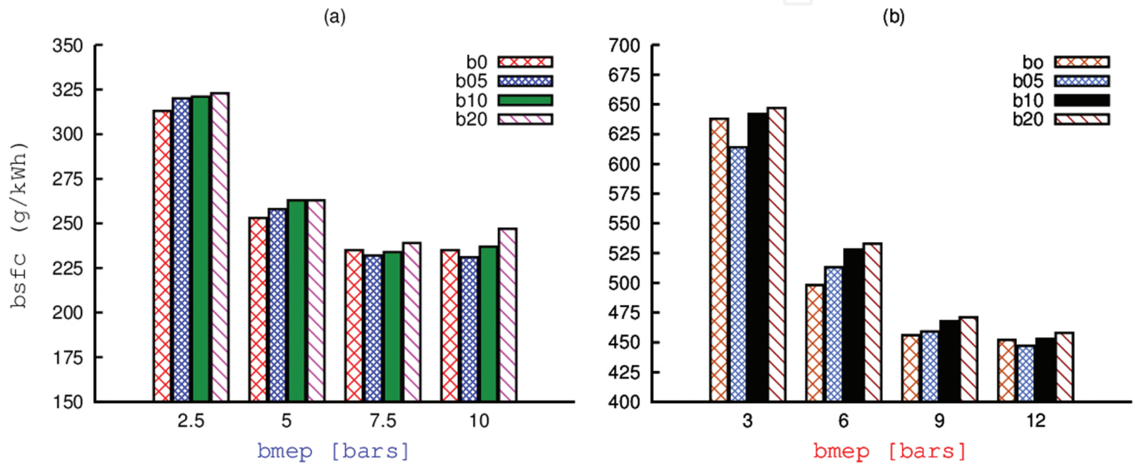

Figure 3. BSFC vs. BMEP (a) at 1500 rpm (b) at 3000 rpm.

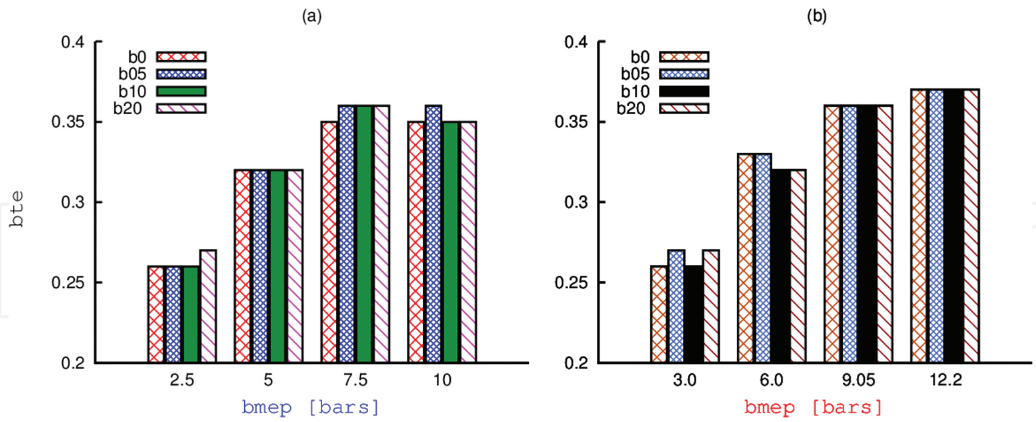

Figure 4. BTE vs. BMEP: (a) at 1500 rpm and (b) at 3000 rpm.

Figure 4(a) and **(b)** depicts the BTE at speeds 1500 and at 3000 rpm, respectively. The range of BTE in the study [9] was 0.22–0.28 in the speed range of 1000–1600 rpm. In the writer's study, the BTE fell into the range: 0.25–0.35 with 1500 rpm. The higher BTE of n-butanol/diesel blends than the ethanol/or methanol-diesel blends is attributed to the higher CN of n-butanol [10]. The energy content (LHV) of the blend decreases with the increase of the shared volume of n-butanol in DF. This causes fuel mass flow to increase the BSFC. Thus, the two effects compensate each other and maintain the same BTE. The effects of atomization of the blend and friction discussed in Ref. [10] could apply here; however, the BTE is not raised as much because of the slow evaporation of the blends.

3.3. Conclusions

3.3.1. Naturally aspirated engine

The purpose of this part of the study was to compare the performance characteristics of a single alcohol (methanol)/gasoline with a dual alcohol (methanol-n-butanol)/gasoline blend relative to gasoline fuel (GF) used in a four stroke and cylinder naturally aspirated SI engine. The dual alcohol blend M53b17 was chosen according to a technique developed by Andersen et al. [4] where the VP of M53b17 was a match to the VP for gasoline fuel. The test fuels were as follows: reference fuel GF, M20, M70, and M53b17. The following conclusions can be drawn:

- Blends had higher BSFC than that of GF for the same BMEP to compensate for their lower-energy content. As the thermal efficiency increases with BMEP, the BSFC drops.
- Blend M70 indicated a higher BTE than M53b17 did.

3.3.2. Diesel (TDI)

The purpose of this work was to evaluate the performance characteristics of n-butanol-diesel blends as fuel fired in a turbocharged, direct-injection, and diesel engine and to compare the performance characteristics with those found in literature [9] using ethanol-diesel and methanol-diesel blends. The n-butanol additive is an attractive biofuel to consider because it is readily miscible with diesel fuel and has a higher CN than ethanol or methanol. The blends tested were reference fuel, DF, and blends B5, B10, and B20 (where B5 represents 5% of n-butanol by volume 95% diesel fuel).

The results reported in a study conducted by Sayin [9] (regarding the BSFC and BTE of ethanol-diesel and methanol-diesel blends) with similar parameters were compared with n-butanol-diesel blends of this study. The following conclusions can be drawn:

- The BSFC was lower and BTE higher in this study than those in the cited study. The range of BTE in the cited study was 0.22–0.28 in the speed range of 1000–1600 rpm. In this study, the BTE fell into the range 0.25–0.35 for 1500 rpm. However, due to the lower-energy content of the n-butanol blends than that of DF, the BSFC increased. On the other hand, the BSFC reduced as a result of improved BTE when increasing the brake mean effective pressure.
- Smaller shared volumes of n-butanol to diesel fuel fired in a turbocharged diesel engine is recommended instead of ethanol-or methanol-diesel blends as a result of improved brake thermal efficiency and BSFC, including the benefits not requiring any engine modification.

4. Results of and discussion on combustion and emissions characteristics

4.1. Indicated pressure, HRR and emission of NO_x,

4.1.1. Effect of blends on octane rating SI engine

By inspection of the relevant heat release rate (HRR) (see **Figure 5(a)–(d)**), blends with the same combustion duration in CADs as that in GF, it was found to be SAG blend M10 (see **Figure 5(a)**) and for DAG blends M-nB 30:20. Both blends had the same indicated peak pressure. Blends with shortened combustion duration relative to GF were M25 in the category of SAG blends and M-nB 40:20, M-nB 25:35, and M-nB 80:10 in that of the DAG blends. Blends with slightly prolonged combustion duration such as SAG blends were M15, M20, M30, and M80, while in the DAG, blends were M-nB 10:20, M-nB 15:25, and M-nB 20:30. It can therefore be deduced that in the case of DAG blends, when the blending ratios or shared volumes of both methanol and n-butanol to GF were increased, the combustion duration was shortened, whereas increasing the methanol shared volume prolonged the combustion duration in the case of the SAG blends. This could be due to the improved combustion efficiency of oxygenated fuels resulting from the higher heating value in the DAG rather than in the SAG blends. **Figure 6** illustrates the effect of blends on HRR in stoichiometric mixtures for both the DAG and the SAG blends. The combustion duration was substantially more prolonged for the SAG than the DAG blends.

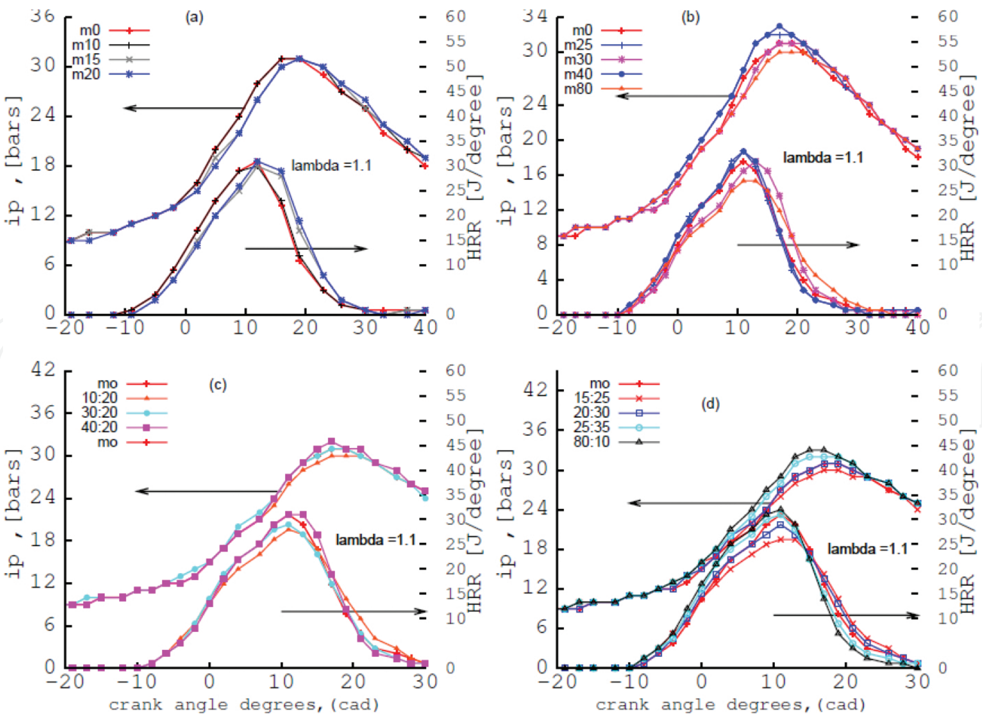

Figure 5. Effect of SAG (a, b) and effect of DAG (c, d) blends on mean indicated pressure (IP) and heat release rate (HRR) at $\lambda = 1.1$.

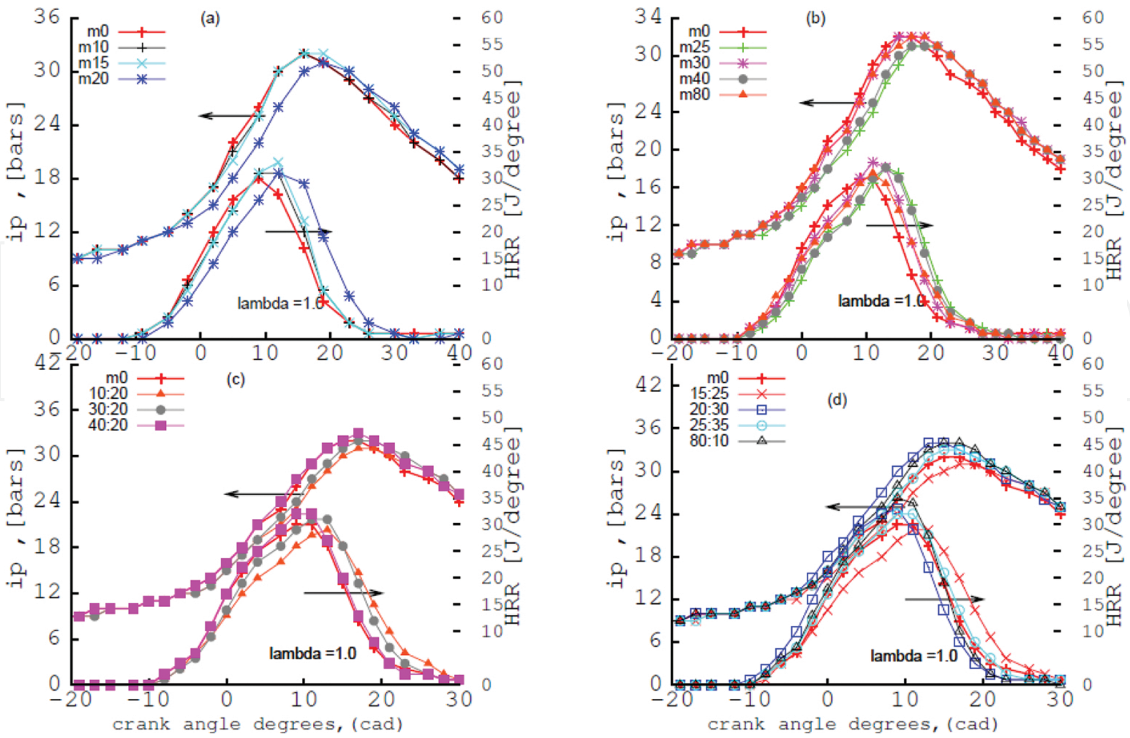

Figure 6. Effect of SAG (a, b) and DAG(c, d) blends on mean indicated pressure (IP) and heat release rate (HRR) at λ = 1.0.

Figure 7(a) and **(b)** indicates the effect of blends on the emissions of nitrogen oxides in the category of the SAG blends and **Figure 7(c)** illustrates the effect of DAG blends on the emissions of nitrogen oxides. Thermal NO_x is a by-product of combustion, and its exponential formation rate is dependent on temperature. Thermal NO_x formation, which is well studied and understood [5], depends upon the residence time and higher temperatures. The peak emission of NO_x for test fuels occurs at approximately: λ = 1.1. This means that its formation is more probable at very high temperatures as a function of heat release. **Figure 5(a)–(d)** illustrates the HRR and indicated pressure for methanol and DAG blends. The high latent heat of evaporation in alcohols results in an evaporative cooling of the mixture. Because of this any increase in the alcohol percentage of the fuel mixture causes NO_x to drop (see **Figure 7(a)** and **(b)**. For methanol blends up to M20, the maximum HRR and maximum indicated pressure at λ = 1.1 were all similar (**Figure 6(a)**); therefore, the peak NO_x emissions were also identical (see **Figure 7(a)**).

Figure 7(e) demonstrates the effect of blends on NO_x, which includes n-butanol. Blends of M30 and M-nB 10:20 both contain a total alcohol content of 30% (v/v), and by examining the relevant figures (**Figure 5(b)** and **(c)**), it is evident that the maximum HRR is lower for M-nB10:20 than for M30, although both produced about the same NO_x emission concentration. This result could be explained by the *difference in residence* time between the combustion products of the two blends, which absorb energy from the surrounding. Of the two blends, the faster burning mixture prolonged the residence time and had more time to absorb energy than the slower burning blend. So the net effect was the same.

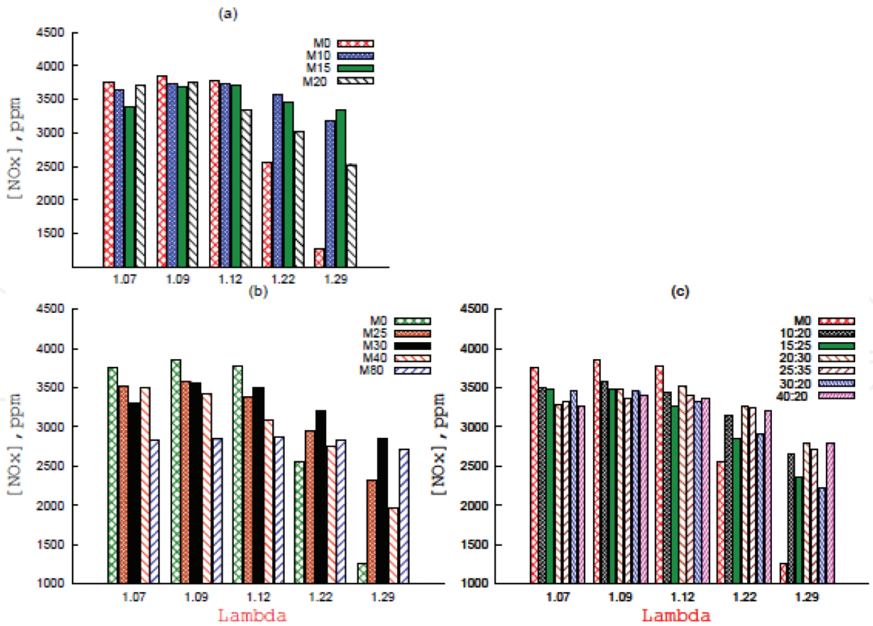

Figure 7. Effect on NOx: (a, b) single alcohol/gasoline (SAG) blends (c) dual alcohol/gasoline (DAG) blends.

4.1.2. Mean indicated pressure, HRR and effect of blends on multipoint injection NA engine

Figure 8(a) and **(b)** compares the effect of blends on combustion HRR and indicated pressure against different spark timings (STs). Both M70 and M53b17 revealed the same combustion duration at the ST of 24.5 CAD BTDC, (see **Figure 8(a)**). The blend M70 indicated a more shortened combustion duration compared with that of M53b17 when the ST (**Figure 8(b)**) was advanced, suggesting an improved combustion efficiency. The effect of knock limited how far the Injection timing of M20 could be advanced, which was 26.5 CAD BTDC. However, blend M53b17 could be advanced to 28.5 CA BTDC without any problems relating to knocking.

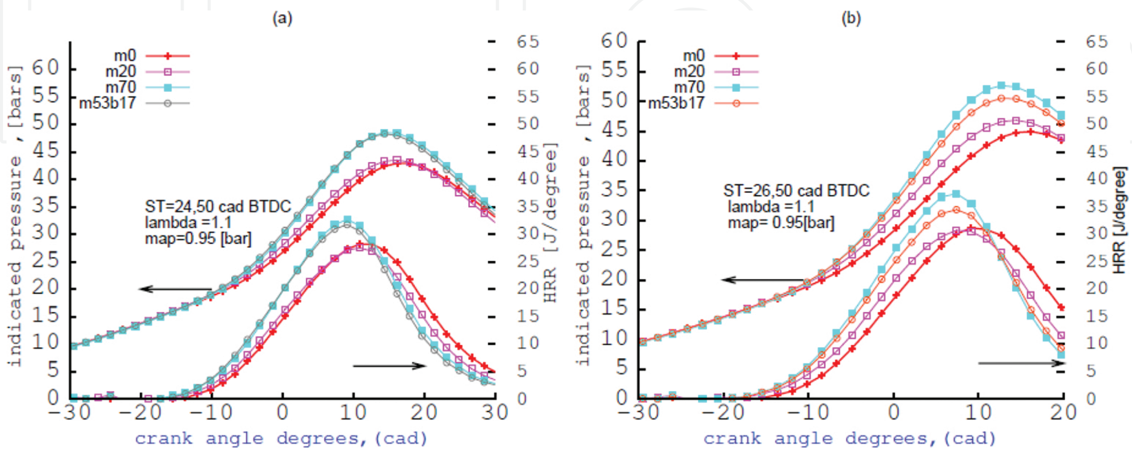

Figure 8. Effect of blends on heat release rate (HRR) and mean indicated pressure at 7.8 bars (BMEP).

Since the indicated peak pressure (**Figure 9(a)**) or HRR (**Figure 9(c)**) rises with an increase in the BMEP, the trend is to reduce the CAD at which these peaks occur (**Figure 9(b)** and **(d)**). The ST for M0, M20, M70, and M53b17 were suitably set to: 27.5, 28.5, 26.5, and 28.5 CAD BTDC, respectively. Therefore, blends M53b17 and M20 followed by M70 and M0, indicated early combustion, which resulted from high peak pressures or peak HRR (**Figure 9(a)** and **(c)**). Blend of M53b17 was, therefore, expected to produce the highest pressure peaks because its ST CAD BTDC was more advanced than that of M70 and GF, drawing the peak pressure and HRR closer to the top dead centre (TDC). The combustion duration is therefore, expected to shorten with the use of M53b17 when its ST is fixed at 28.5 CAD BTDC. The crank angles of the indicated peak pressure set at a medium BMEP of 5.5 bars for GF, M70, M53b17, and M20 were 17, 16, and 15 CAD after top dead centre (ATDC), respectively.

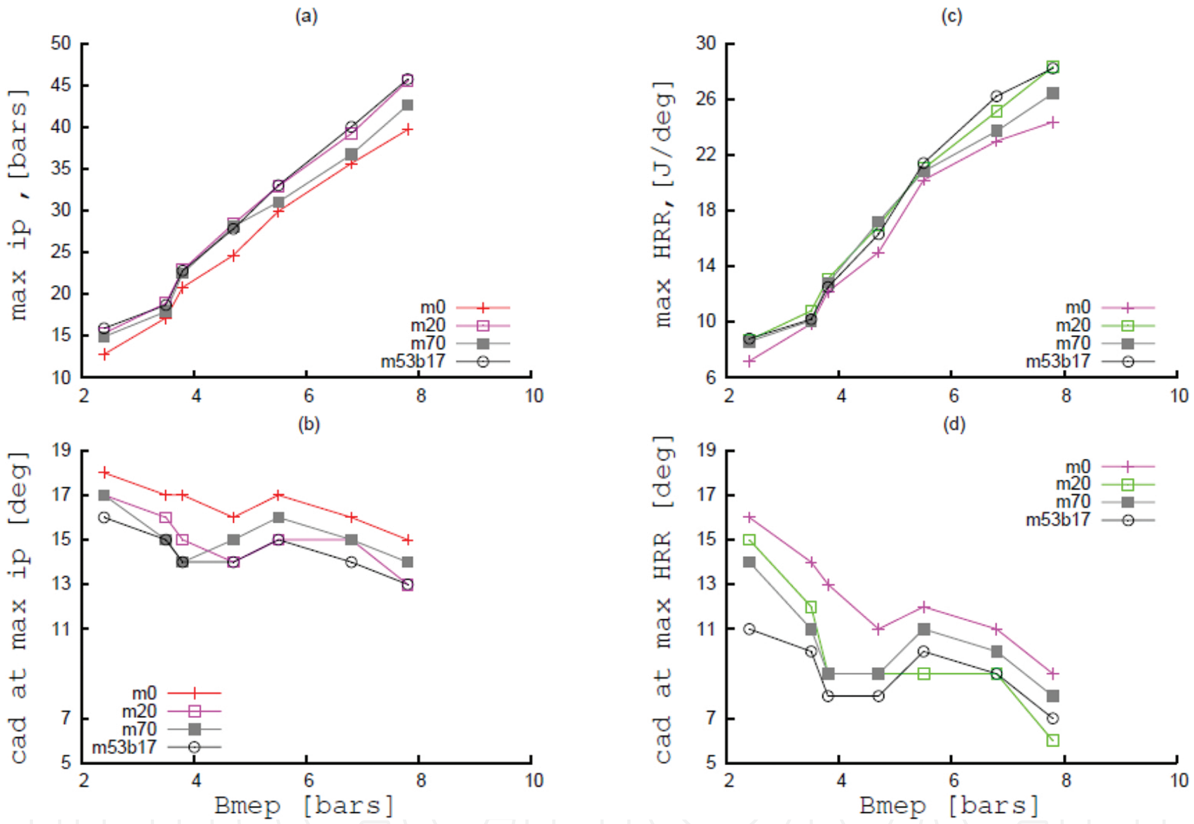

Figure 9. Relationship of cad at maximum mean indicated pressure (IP) and HRR for blends vs. BMEP.

4.2. Emission of CO

4.2.1. Effect of blends on (TDI) CI engine

The data in this section demonstrate that smaller shared volumes of n-butanol when using fuel fired in a light-duty, turbocharged, direct-injection diesel engine significantly reduce regulated emissions compared with the findings of a similar study using a naturally aspirated diesel engine using 30% biodiesel from rapeseed oil with admixes of E5 and E7.5 [5].

Researchers [5], studied multi component fuelling of a naturally aspirated diesel engine using biodiesel (BD), composed of a shared volume of 30 % (v/v) or BD30 (RMEs) from rapeseed oil and compounded with diesel fuel (DF), with properties similar to those of DF used in the current study. A third admix to BD30 that was tested in the cited study is ethanol 5 and 7.5% (E5 and E7.5). The BSFC values for the admixed blends B30 + 5E and B30 + 7.5E were similar to those of DF.

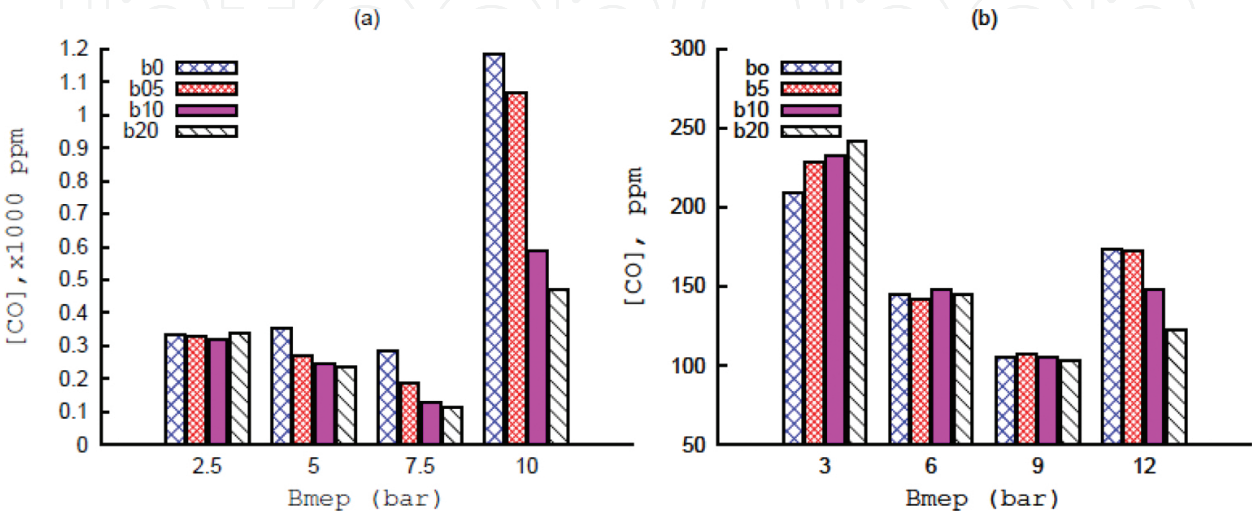

Figure 10. Carbon monoxide emissions (a) at 1500 rpm and (b) at 3000 rpm.

Figure 10 illustrates the effect of blends on the CO concentration at speeds: of 1500 and 3000 rpm. The CO measured in Ref. [5]: For DF: when the BMEP was 0.650, 0.325, or 0.1 MPa, the CO was 912, 351, and 634 ppm, respectively, while in the author's study, when the BMEP for DF was 0.751, 0.50, or 0.251 MPa, the CO was 286, 355, and 334 ppm, respectively. Furthermore, in the cited study, when the BMEP was 0.650, 0.325, or 0.100 MPa, for B30+E5-7.5%, the CO was 300, 575, and 280 ppm, respectively. On the other hand, in the author's study, when the BMEP was 0.751, 0.50, or 0.251 MPa for B20, the CO was reduced to 111, 234, and 338 ppm, respectively [10].

4.3. Emissions of UHC

In this section of the study, the emission of UHC using DAG blends is compared with the emission of UHC using SAG blends. The dual blends meet the VP requirement for GF, in internal-combustion engines. The blends do not require any engine modification.

4.3.1. Effect of blends on (TDI) diesel engine

The effect of the blends on the unburned hydrocarbon emission concentration at 1500 and 3000 rpm is illustrated in **Figure 11**. The amount of fuel injected during the ignition delay period has an influence on its concentration. For BD30, where CN was higher, the injection period was shorter, decreasing correspondingly, with the emission of UHC [5]. When the BMEP for DF was 0.650, 0.325, or 0.100 MPa, the UHC was 318, 347, and 406 ppm, respectively, while

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the UHC emission for B30+5-7.5E was 220, 240, and 280 ppm for the same range of BMEP. Conversely, in this study, when the BMEP for DF was 0.751, 0.50, or 0.251 MPa, the UHC was 14, 20, and 30 ppm, respectively, and, the UHC emission for B20 was 30, 37, and 55 ppm, showing a significant reduction in the UHC emissions in this study [10].

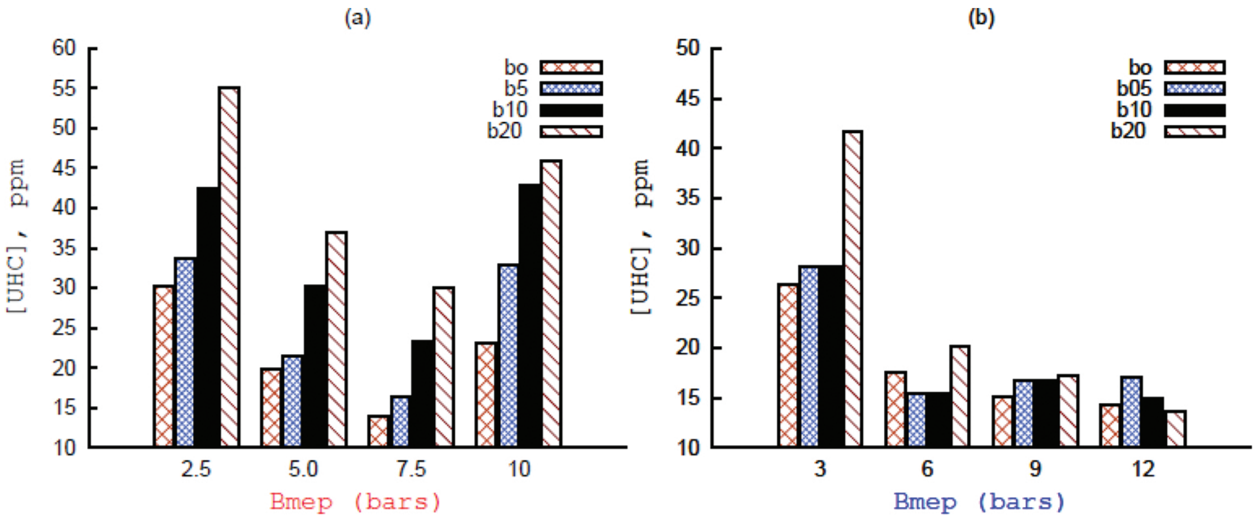

Figure 11. UHC emissions varying against BMEP (a) at 1500 rpm and (b) at 3000 rpm.

4.4. Conclusions

The combustion of the alcohol/conventional fuel blends in reciprocating engines indicate certain effects on the regulated emission and combustion characteristics as summarized later.

4.4.1. Octane engine

The experiments were conducted on a single-cylinder BASF octane rating SI engine at the constant speed of 600 rpm. The aim of this part of the study was to compare regulated emissions of DAG with SAG blends.

The combustion duration was shortened using the DAG blends as the total shared volume of methanol and n-butanol to GF was increased. However, the combustion duration was prolonged using the SAG blends as the methanol shared volume in GF was increased. The combustion duration was substantially more prolonged for the SAG blends than for the DAG blends in stoichiometric mixtures.

The SAG blends reduced the UHC emission concentration more than the DAG blends did (both with the same total alcohol content). Regarding the GF, the UHC emission was reduced by 9.2% for M-nB 10:30 and 20% for the M30 at $\lambda = 1.1$. Blend of M-nB 15:25 reduced the UHC emission by approximately 16.9% whereas M40 reduced the UHC emission by 26.9% at $\lambda = 1.1$.

Although, the SAG blends produced lower UHC emission than the DAG blends, in this study, the use of DAG blends is recommended. The combustion duration for the latter was shortened in crank angles due to their higher-energy content than the SAG blends. By either increasing the methanol or the n-butanol shared volume to GF, the UHC emission was improved.

4.4.2. Naturally aspirated engine

The purpose of this part of the study was to compare the combustion characteristics of a single alcohol (methanol)/gasoline with a dual alcohol (methanol-n-butanol)/gasoline blend relative to gasoline fuel (GF) based on a four-stroke and four-cylinder naturally aspirated spark ignition engine. The test fuels were as follows: reference fuel: GF, blends: M20, M70, and M53b17.

The following conclusion can be drawn from the engine experiments:

The same combustion duration was attained by both M70 and M53b17 at ST of 24.5 Crank angle degree (CAD) BTDC. However, the blend M70 exhibited slightly shorter combustion duration than M53b17 at ST of 26.5 CAD BTDC. However, when the ST for M53b17 was fixed at 28.5 CAD BTDC, its combustion duration was shorter than that for M70. All the test fuels indicated an increase in both the heat release rate and the indicated pressure when the ST CAD BTDC was advanced.

Blend M53b17 was recommended as a suitable substitute for M70 in the SI engine because the heating value and the combustion duration using M53b17 improved compared with using M70 blend.

4.4.3. Diesel (TDI)

The purpose of this part of the study was to evaluate the combustion characteristics and regulated emissions of pure DF and n-butanol/diesel blends: B5, B10, and B20 fired in a high load turbocharged diesel engine. A similar study was used as a basis for comparison and attenuation of the results from the current study in order to build understanding of the impact of fuel property on combustion and regulated emission.

A comparison of regulated emissions in this study using a turbocharged diesel engine with a similar study [5] (based on a naturally aspirated diesel engine) indicated an improvement in the reduction of UHC and CO using a turbocharged engine.

Unburned hydrocarbons emissions were more significantly reduced when using n-butanol/DF blends in this study than when using 30% RME and 5–7.5% bioethanol in the other study [5]. However, in both cases, the blends produced higher UHC emission than DF. In this study, the UHC emission concentration increased by 21.4, 71.4, and 214% regarding DF on a 75% load at 1500 rpm for B5, B10, and B20 respectively. Smaller shared volumes, up to 20% (v/v) of n-butanol added to DF are highly recommended to use especially in a turbocharged engine. These blends substantially reduce the regulated emissions requiring no engine modification.

5. Final conclusions

5.1. Accomplishments in this study

Dual alcohol-gasoline blends, in particular, burned in internal-combustion engines that meet the VP requirements do not make them entirely good performers in spark ignition engines.

The following dual alcohol-gasoline blends were analyzed as being suitable in spark ignition engines in terms of shortened combustion duration while maintaining the same reduction of important pollutants of single alcohol-gasoline blends in a spark ignition reciprocating engine.

- M53b17 (53% methanol and 17% n-butanol in gasoline)
- M-nB 40:20, M-nB 25:35 and M-nB80:10
- The following dual alcohol gasoline blends prolonged the combustion duration
- M-nB 10:20, M-nB15:25 and M-nB 20:30.
- On the part of the diesel engine, it was demonstrated that the reduction of emissions on a turbocharged engine was greater in this study than in another study carried out by others [5] who used 30% biodiesel (rape methyl esters, RME, derived from rapeseed oil). They blended with diesel fuel and operated at similar conditions except for the type of engines (a turbocharged one was used in this author's study and a naturally aspirated engine in the other study).

5.2. Future work recommendations

- To investigate additives to the dual alcohol-gasoline blends (that prolonged the combustion duration) in order to shorten their combustion duration although they meet the VP requirement as shown throughout this study.
- To *increase* the n-butanol blend percentage in pure diesel or biodiesel/diesel blend and to investigate performance in a diesel engine. This is to be supported by firstly, increasing the biodiesel fraction (which increases the cetane number) in the biodiesel/diesel blend. The advantage of doing this is that the calorific value of n-butanol is lower than that of biodiesel.

There is evidence in this study that bioalcohols have a significant role to play in achieving the goal of the reduction of regulated emissions although partially, in the search for alternative fuels to replace the conventional fuels used in the IC engines.

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