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Chapter 3

n-Butanol-Diesel (D2) Blend Fired in a Turbo-Charged Compression Ignition Engine: Performance and Combustion Characteristics

Lennox Siwale, Lukacs Kristof, Torok Adam,
Akos Bereczky, Makame Mbarawa,
Antal Penninger and Andrei Kolesnikov

Additional information is available at the end of the chapter

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Abstract

The use of biofuels that include n-butanol in diesel fuel (DF) is attracting attention in the search for the reduction of emissions into the environment due to the burning of fossil fuel. The performance and combustion characteristics were evaluated in this study using blends B5, B10, and B20 (B5: 5% n-butanol and 95% DF) in a turbo-charged direct injection compression ignition engine. In the n-butanol diesel studies, a comparison was made with other studies that also included biodiesel in order to determine how suitable n-butanol-diesel blends were to use in internal combustion engines. Combustion characteristics of B20 (n-butanol 20% and 80% DF) improved when the study was compared with a similar study that included 40% biodiesel added to B20. A higher value of the standard deviation for DF than the blends was observed from the standard deviation diagram, indicating a more stable combustion process for the blends than DF. Soot reduction relative to DF at 1500 rpm at 75% load for B05, B10, and B20 mixtures was 55.5, 77.8, and 85.1%, respectively. This reduction is a significant advantage of blending DF with smaller shared volumes of bioalcohol.

Keywords: compression ignition, n-butanol-diesel, performance, combustion

1. Introduction

A very strong debate on the gradual substitution of petroleum by using renewable alternatives such as biofuel dominates the political and economic agenda worldwide [1]. This has been driven by the global concern of the international governing bodies for countries to

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comply with the requirements for emission reduction. The energy independence and security act of 2007 (US) requires the production of 36 billion gallons of renewable fuels including ethanol-based fuels by 2022. This constitutes a 75% increase in their production over the next 14 years [2].

Biofuels constitute a renewable source of energy derived from biomass (the primary source). These include all three states of matter: solid, liquid and gas. They fall into the following categories, for liquid biofuels: (a) bioalcohols, (b) vegetable oils and biodiesel, and (c) biocrude and synthetic oils. It is expected that their demand in the future will rise because they replace petroleum [3]. Biofuels can be produced from bio-based materials through the biochemical processes such as pyrolysis, gasification, or liquefaction. Thermal chemical reforming of biomass concerns the process of catalytic or non-catalytic pyrolysis and gasification with a goal of maximizing in the production of energetically exploitable liquids or gases. Biofuels include bioethanol and biomethanol, Fischer-Tropsch liquids and biogas [4].

Oxygenated fuels including alcohols constitute one of the categories of the biofuels that have attracted research for many years due to their cleaner properties when blended with the conventional fuels [5]. Oxygenated fuels drew the attention of many researchers, due to their ability to drastically reduce the particulate matter (PM) emission without altering the emission levels of NO_x, UHC, and CO [6, 7]. Oxygenated additives such as ethers, esters, alcohols have been added to diesel fuel [8]. Alcohols are used in internal-combustion engines as alternative fuels. If the source of alcohol is based on biomass then one can reduce greenhouse gas emissions, and exhaust emissions as well as enhance the overall energy efficiency [1, 3, 9–11].

N-butanol possesses certain qualities that make it more suitable to use in internal combustion engines than ethanol or methanol. These include a higher heating value of (28.4 MJ/L) for n-butanol and (21.2 MJ/L) for ethanol; higher cetane number (CN), lower auto-ignition temperature, better flow ability. For ethanol-diesel blend, an emulsifying agent is used to satisfy the homogeneity of the ethanol-diesel fuel mixture to prevent phase separation [12]. However, n-butanol is easily miscible in diesel fuel [13]. Within the functional groups of butanol isomers, n-butanol has the highest flame speed which enhances the combustion process [14]. Some researchers have argued that n-butanol-diesel blends prolong the ignition delay (ID), thereby affecting the combustion duration in internal combustion engines. However, others have stated that burning n-butanol-diesel fuel blends reduces emissions [14]. Therefore, comparisons are necessary on how the combustion characteristics differ between blends of n-butanol and biodiesel in diesel fuel, respectively.

In internal combustion engines such as diesel engines, diesel fuel is atomized into droplets using injectors at high pressure. These droplets entrain air as they evaporate into proportions that are combustible in the combustion chamber. The air temperature and pressure are above the fuel's ignition point. Therefore, after a short while: or ID the mixture auto ignites. ID is a time lag that is influenced by the physical chemical properties of the fuels measured in time (s) or CADs in engine cycles. This affects the combustion process in internal combustion engines including combustion duration and in-cylinder pressure and temperatures.

The simultaneous use of biodiesel, ethanol, and butanol in diesel is an interest that has arisen recently by researchers. However, since biodiesel is characterized by high viscosity, lubricity,

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CN, and flash point relative to that of ethanol, the obstacles due to ethanol are partially overcome. Literature concerning the use of n-butanol/diesel fuel blends in diesel engines and their effect on the steady state performance and exhaust emission in engines is limited [15]. Most of the studies, however, have evaluated the potential of methanol and ethanol [16], while there is a need for more studies to be done on the characteristics of higher alcohols such as propanol, butanol, and pentanol [17].

2. Objectives

The general objective is to reduce the negative impacts of petroleum oil-based fuels in reciprocating engines on the environment through the use of oxygenated (alcohol) blends, without deteriorating the engine performance. The specific objective of the study is as follows:

- To evaluate the performance and combustion characteristics of n-butanol-diesel blends: B5, B10, and B20. It is given in the abstract in a direct-injection, turbo-charged diesel engine.
- To compare findings with studies that were carried out by others [18–20].

3. Engine experimentation

In this section the engine experimental set up, procedure and matrix are included.

The study was conducted on a four-cylinder piston 1Z 1.9 L-66 kW Turbo-Direct injection (TDI) Wolkswagen diesel engine. The engine was fully equipped with a turbocharger with all the necessary sensors and actuators for stable operation of engine. The engine was warmed up to about 94°C and the temperature was maintained. The engine was run for 20–30 min to warm up with the reference DF or test blend fuel. Once the new fuel was pumped in, the engine was made to run for about 20 min to allow for stable operation of the new blend at test fuel conditions. Typical fuel consumption data and brake specific consumption are shown in **Table 1**. The fuel injection timings for the blends and DF controlled by the electronic diesel control (EDC) for different speeds of 1500, 2500, 3000, and 3500 rpm were 11,11,12, and 15° crank angle BTDC, respectively. The fuel consumption was measured using the AVL 7030 dynamic fuel consumption measuring equipment. Torque was measured by a Borghi and Saveri FE-350S eddy current dynamometer. The study was carried out for 75, 50, and 25% load for engine operating a range of 1500, 2500, 3000, and 3500 rpm. The engine was made to run for each measuring point on steady-state condition for about 2 min before recording values. An average based on three measurements for each test fuel was recorded. The engine operating conditions are shown in **Table 2**. The in-cylinder indicated pressure (IP) was measured by a piezoelectric pressure transducer Kistler KIAG 600. The top dead center (TDC) crank angle position was measured by an Optical Encoder HENGSTLER RI 32-0/1024.ER.14KA [21].

	DF	B05	B10	B20
Fuel cons. (kg/h)				
(A) At 1500 rpm	5.47	5.47	5.43	5.63
(B) At 1500 rpm	3.0	3.06	3.12	3.12
(B) At 3000 rpm	7.13	7.34	7.56	7.62
λ (−)				
(A) At 1500 rpm	1.4	1.42	1.5	1.52
(B) At 1500 rpm	1.72	1.82	1.92	1.92
(B) At 3000 rpm	2.37	2.73	2.42	2.79
BSFC (g/kWh)				
(A) At 1500 rpm	235	231	237	248
(B) At 1500 rpm	252.9	258.02	263.09	263.08
(B) At 3000 rpm	249.4	256.75	264.4	266.54

Table 1. Typical fuel consumption, λ, BSFC with DF and blends at 1500 and 3000 rpm; A = 100%, and B = 75% load [21].

Torque (Nm)	Speed (rpm)	Exhaust temperature (°C)	*MAP (bar)
184.6	3004	562	0.82
136.4	3004	473	0.71
92	3002	419	0.56
45	3000	333	0.38
168.9	3504	584	0.79
187.8	2505	519	0.84
153.7	1502	532	0.35

Ambient air temperature 20°C, intake air temperature 25°C.
*Manifold (boost) air pressure (above atmospheric pressure).

Table 2. Operating conditions of engine for fuel D2 [21].

Typical fuel consumption and fuel air ratios are given in **Table 1** and operating conditions in **Table 2**.

4. Diesel (TDI) engine

4.1. Crank angle advance injection timing

The effect of injection timing of all the test fuels (B0, B5, B10, and B20) is indicated in **Figure 1**. The engine operating speeds selected for testing were 1500 rpm and 3000 rpm. When the operating speed was high the fuel was injected earlier than when the speed was reduced to allow for the correct retention time for the fuel to burn adequately. Running on partial load in

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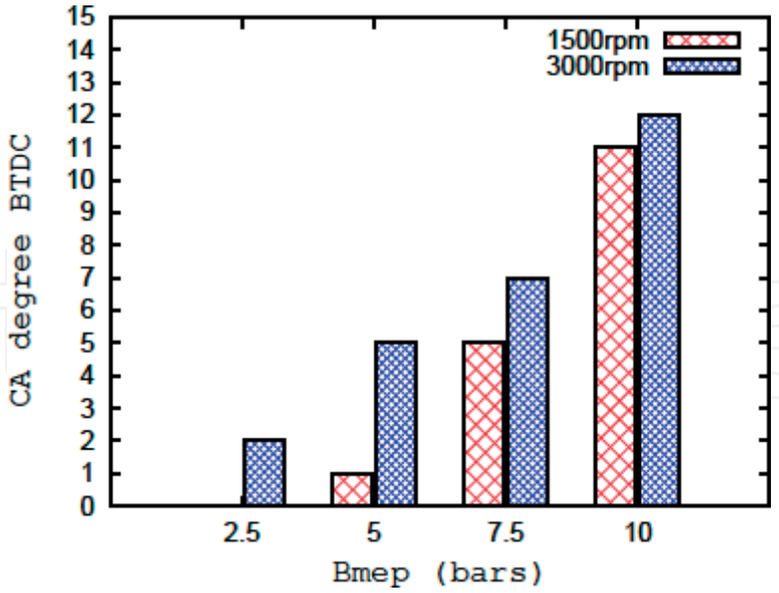


Figure 1. Effect of test fuels on injection timing.

terms of brake-mean effective pressure (BMEP), or when the engine was running at low speed, the engine's start of injection (SOI) timing was retarded by the EDC in order to meet the engine's operating conditions.

4.2. Manifold boost (air) pressure

Figure 2a and **b** depict the effect of the blends on manifold boost (air) pressure at 1500 rpm and 3000 rpm, respectively. The increasing boost (air) pressure (above atmospheric of 1 bar) level with BMEP is a measure that helps to improve the brake thermal efficiency (BTE) as the fuel-air ratio is reduced.

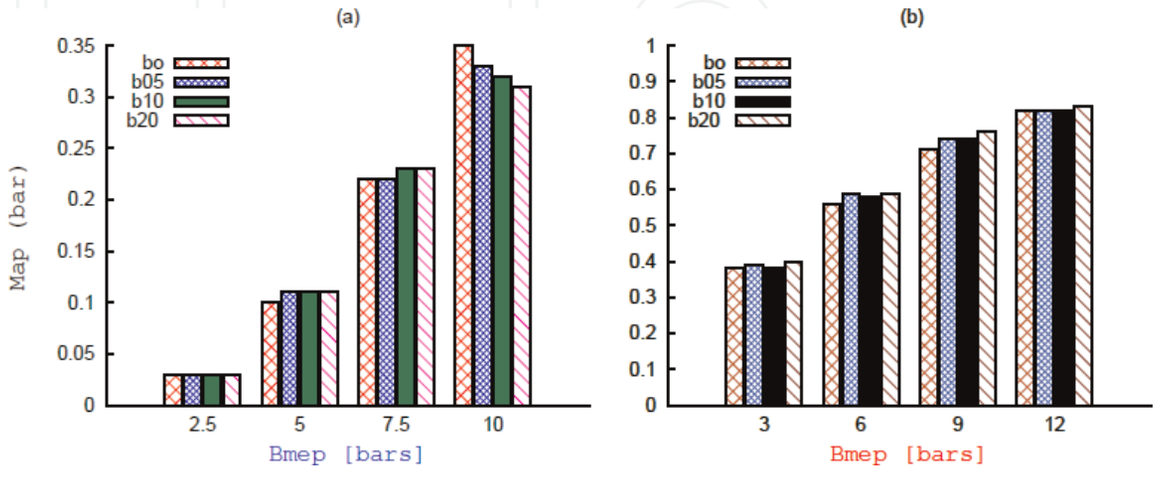


Figure 2. Manifold boost (air) pressure (MAP) vs. BMEP (a) at 1500 rpm (b) at 3000 rpm.

4.3. Torque, power, and EGT

The derated power and torque indicated in **Figure 3** is attributed to the fixed algorithm and set points in the EDC unit, which reads diesel as the reference fuel as programmed if not modified. In this case, the EDC was not calibrated for the n-butanol/diesel blends. When the diesel fuel was changed to n-butanol/diesel blend, the lower heating value due to the blend triggered the EDC to increase the mass flow of fuel to compensate for the drop in energy delivered; the heating value of n-butanol is lower than that of diesel fuel. This is achieved by altering the fuel-control ring position of the control system. However, the EDC set point for DF which controls the amount of diesel that can be delivered at different loads was fixed. Therefore, the mass flow of the blend could not be increased above this point. This explains the lowered power and torque output when using n-butanol/DF as shown in **Figure 3**.

The effect of exhaust gas temperature (EGT) on BMEP is indicated in **Figure 4a** and **b**. The trend shows an increase of EGT with BMEP for all the test fuels: DF, B5, B10, and B20. The

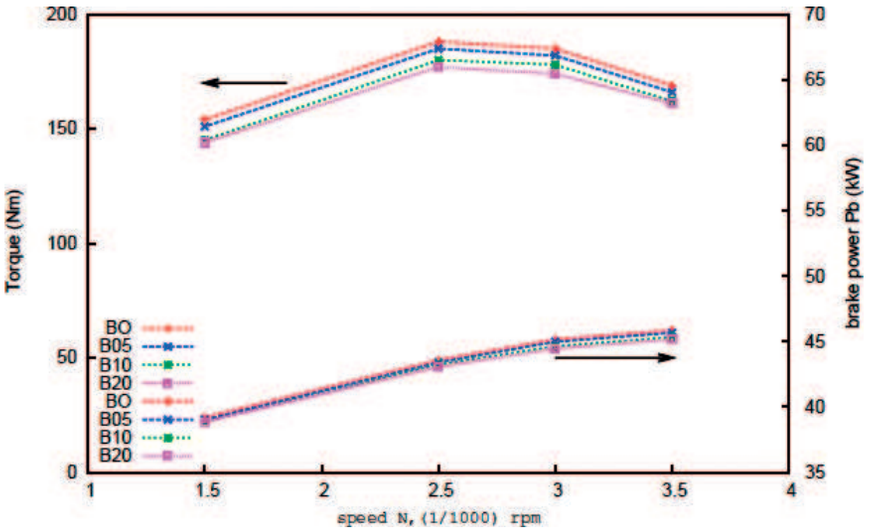


Figure 3. Effects of blends on torque, brake power vs. speed [21].

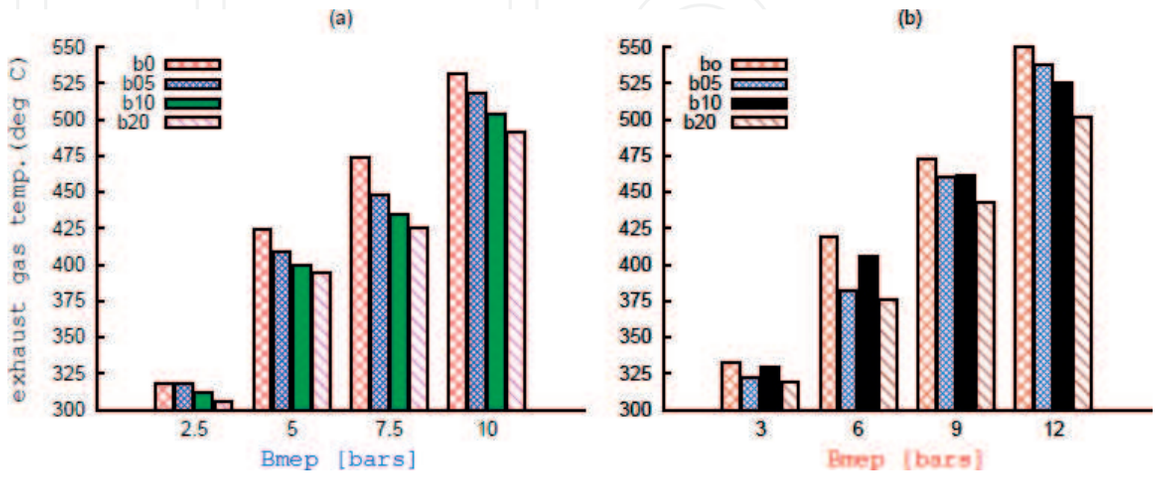


Figure 4. EGT vs. BMEP (a) at 1500 rpm and (b) at 3000 rpm [21].

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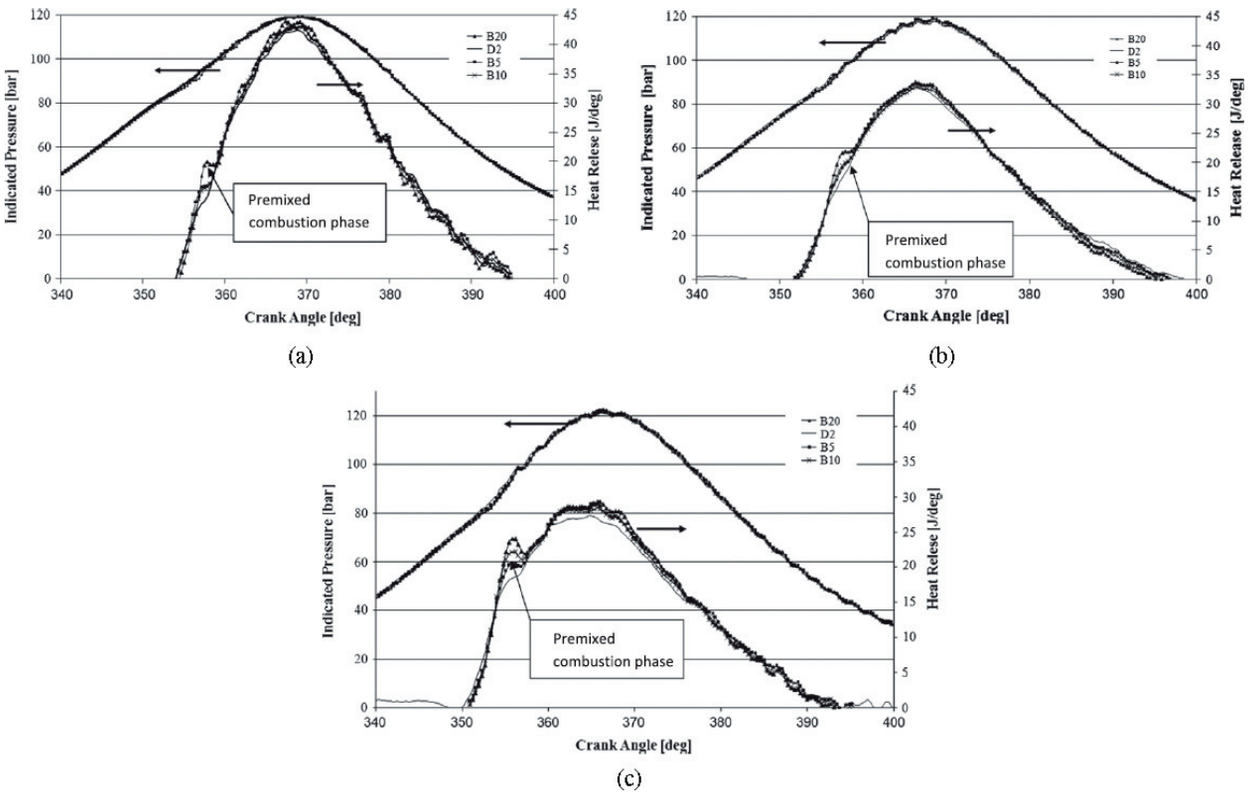


Figure 5. (a) Indicated pressure (ip) and HRR at 2500 rpm source [21]; (b) indicated pressure and HRR at 3000 rpm source [21]; (c) indicated pressure and HRR at 3500 rpm source [21].

higher heat of evaporation of the blends than DF resulted in evaporative cooling which lowers EGT. Furthermore, the increasing higher molecular oxygen content of the blends than DF is also a contributing factor in lowering EGT by reducing the energy content of the fuel. The irregularity for B10 at 25% and 50% load at 3000 rpm could be due to unstable combustion, which is also evident in the high standard of deviation for B10% in **Figure 6**.

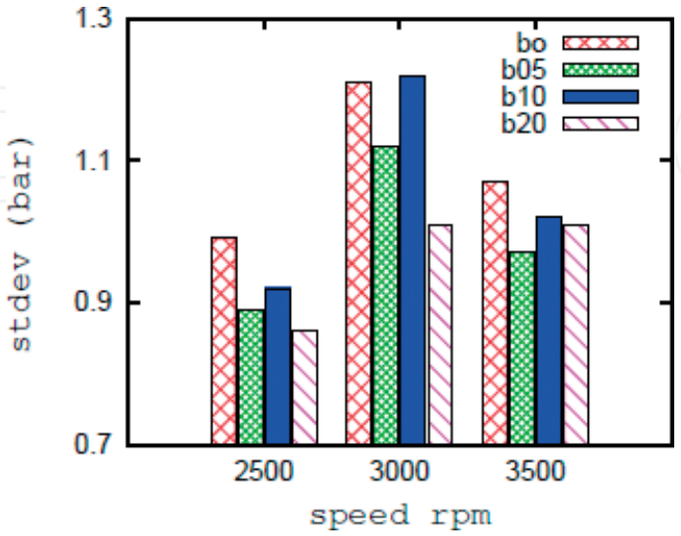


Figure 6. Standard deviation of indicated pressure [21].

5. Indicated pressure, HRR, and effect of blends on (TDI) CI engine

In combustion studies, the CN measures the ease with which a fuel auto-ignites. The CN is therefore a measure of a fuel's auto-ignition delay, the period between the start of injection and the first identifiable pressure increase during the combustion of the fuel. The heat release is the net heat of combustion generated by chemical reactions of the fuel affected by the fuel's physical and chemical properties in the combustion process of the fuel. The fuel is injected timely and periodically in the combustion chamber by means of fuel injectors. The mean pressure developed due to the heat released each cycle is termed as the IP, which is the pressure reading on an indicator diagram.

Figure 5a–c illustrates the effect of the mean pressure and the heat release rate at different speeds of 2500, 3000, 3500 rpm on blends compared with DF. The operating conditions depicted by brake mean effective pressure (BMEF) for the blends is given in **Table 3**. It is observed that there are very little differences in the peak pressures obtained at the different speeds. After the Ignition delay, there exists a rapid combustion phase that causes a steep rise in the in-cylinder pressure and heat release. This is known as the premixed phase where after atomization of the fuel, the fuel droplets are evaporated and ignited by the heated air from the compression process prior to the start of injection. The peak pressure is controlled by the ignition delay, the rate of fuel injection, the speed of the engine and including the compression ratio for the engine. The remaining oxygen of the air charge limits the final phase slowing down the combustion rate (see **Figure 5a–c** heat release curve) as the crank angles advance toward the beginning of exhaust process. Increasing the shared volume of n-butanol in DF as well as the engine speed coupled with the molecular oxygen content of the oxygenated fuel improves the mixing quality of the blend. This phenomenon is observed in the increasingly distinguishable premixed combustion phase with an increase of engine speed (see **Figure 5b** and **c** heat release curve). The premixed phase is similar for B5 and B10 at 2500 and 3000 rpm. Higher heat release rate is observed at 2500 rpm because of the more resident time (s) allowed for the mass of fuel to burn than at higher speeds of 3000 and 3500 rpm. The mixing controlled combustion or final phase just after the premixed stage indicated a steeper slope on the heat release curve for the blends than DF with increasing the shared volume of n-butanol in the blend. By this, the combustion efficiency of the blends was better than DF and the combustion duration shortened.

In past studies conducted by Ref. [19], the effect of using BD30 (30% biodiesel or methyl ester, from rapeseed oil (RME) blended with 70% diesel fuel) alone shortened the ignition delay (ID). By adding E10 (10% ethanol and 90% diesel fuel) in other words, BD30 + E10 prolonged the ID,

Speed [rpm]	B0	B05	B10	B20
2500	12.45	12.25	11.92	11.76
3000	12.23	12.09	11.8	11.50
3500	11.19	10.98	10.74	10.64

Table 3. Operating BMEP (bars) for **Figure 5a–c** [21].

which is not desirable as it results in a hard start of the test engine. When comparing the CNs, it was found that the CN for RMEs was 55 whereas for DF was 51. The CN for n-butanol was approximately 25 and CN for ethanol was approximately 8. Therefore, increasing the shared volume of n-butanol above 20% in Diesel fuel displaces richer components of CN in DF than in n-butanol prolonging start of combustion SOC and prompting the hard start of the engine. Therefore, this limits how many fractions of n-butanol can be blended with DF. A blend of greater than 20% shared volume of n-butanol in DF further reduces the CN of the blend. Therefore, the limiting point would be when the final CN of the blend is too low for the engine to start.

The combustion characteristics of blend B20 in the author's study is compared with Bu20 (n-butanol 20%, biodiesel 40%, and diesel 40%) by others [20]. In the latter study, B50 (biodiesel 50% and diesel fuel 50%) was the preferred fuel type over Bu20 in terms of maximum pressure and heat release rate. The operating conditions were: single cylinder, four strokes, direct injection, air cooled, TecQuipment TD212 diesel engine, naturally aspirated, maximum power 3.5 kW at 3600 rpm and maximum heat release rate (HRR) 15.5 J/deg. In the author's study using B20, the maximum HRR was 43.5 J/deg. for four cylinders, four strokes, direct injection, turbo-charged diesel engine as specified in section (1). In a study by others, B50 was recommended as the most suitable blend fired in a diesel engine. Combustion duration for DF is higher (within the range for the indicated power of 1.2 and 1.6 kW) than Bu20. Combustion duration in the author's study using B20 (n-butanol 20%, DF 80%) was reduced as observed by a steeper profile of the heat curve in comparison with DF (D2) see **Figure 5a–c**. **Figure 5a–c** illustrate the mean IP which did not change much in terms of peak pressure for the increase of HRR at lower speeds for all test fuels. The IP and HRR were evaluated at 2500, 3000, and 3500 rpm for the entire test fuels at full load respectively. The operating BMEP for the blends are presented in **Table 3**. It was observed that at 3500, 3000 and 2500 rpm within 5° CAD the premixed heat release was within 17–24 J/deg., 15–23 J/deg., and 10–20 J/deg., respectively. In the study by others [20], the maximum pressure was obtained by DF followed by B50 and then Bu20 [20] at a constant speed of 1500 rpm. This could be attributed to the effect of the EDC which could restrict the fuel flow of the blends when not modified (see Section 4.3).

These results concur with the findings of past study conducted by [19], who obtained a prolonged ID by adding an alcoholic admix of E10 to BD30 and the ID was shortened by reducing the alcohol fraction. In the previous study, the engine used was a type T40 M, D-144 diesel engine, which was newly acquired for research in 2003 and was used throughout the period 2004–2008 [22]. Further details of the engine include the following: (a) mechanical power of 37 kW on 1600 rpm, (b) naturally-aspirated; (c) direct-injection, (d) four-cylinders; (e) diameter of 110 mm; (f) stroke of 120 mm, (g) compression ratio was 16.5:1, (h) dished-piston; and (i) compression ignition engine. The fuel was delivered by a single-plunger, fuel-pump, and type: ND 21/4, through three-hole injection-nozzles; with initial fuel delivery starting at 25 ± 1° BTDC. The needle-valve lifting pressure on the injectors was set to 17.5 ± 0.5 MPa.

5.1. Analysis

Both biodiesel and n-butanol fractions in DF reduces the combustion duration of the blend. However, n-butanol has a limitation and may not be increased any further than 20% (v/v) in

DF due to its significantly low CN. Biodiesel, on the other hand, has a higher CN making it possible to increase fractions for blending in DF. Results obtained in the author's study involving only n-butanol in DF and comparing with a study by others [20] who included biodiesel in n-butanol/DF blend indicated enhanced combustion characteristics when biodiesel was added. It was observed that B50 performed better than Bu20.

Figure 6 illustrates the standard deviation of pressure cycles. It can be deduced that blends have less deviation of pressure from the mean value than diesel. In other words, blends have a more stable combustion characteristic than the reference fuel. The blend B10 revealed a less stable combustion quality than the other blends by indicating a higher standard deviation at all speeds. A similar study by others [20] measured the thermodynamic cycle-to-cycle variations for the in-cylinder pressure using the coefficient of variation (COV) to determine combustion stability for the blends Bu20 and B50. They found that the COV for the blends was below 5% for the engine loads, which agrees with the author's study where the standard deviation of the mean in-cylinder pressure cycles was below that of DF. **Figure 6** results should reconsider referring to other studies.

6. Soot concentration from (TDI) compression ignition engine

Figure 7 illustrates the soot concentration in the exhaust gas at 1500 and 3000 rpm. In a direct-injection diesel engine, the fuel-air distribution is not homogeneous. Therefore, in addition to the excess-air ratio, soot formation is also controlled by the mixing of air and fuel [19]. The formation of soot depends upon the condition of the engine, the type of the combustion chamber and differences in the physical and chemical properties of the fuel [19]. The soot emission is reduced when a shared volume of n-butanol is added to DF. This is because the oxygen atoms attached to the hydroxyl group of n-butanol hinder (through moderation) the production of the precursors responsible for the formation of soot [21]. The low C/H ratio of n-butanol also reduces soot formation. In Study P, as well as in the author's study, the soot concentration was substantially reduced. The soot concentration reduced when n-butanol/DF

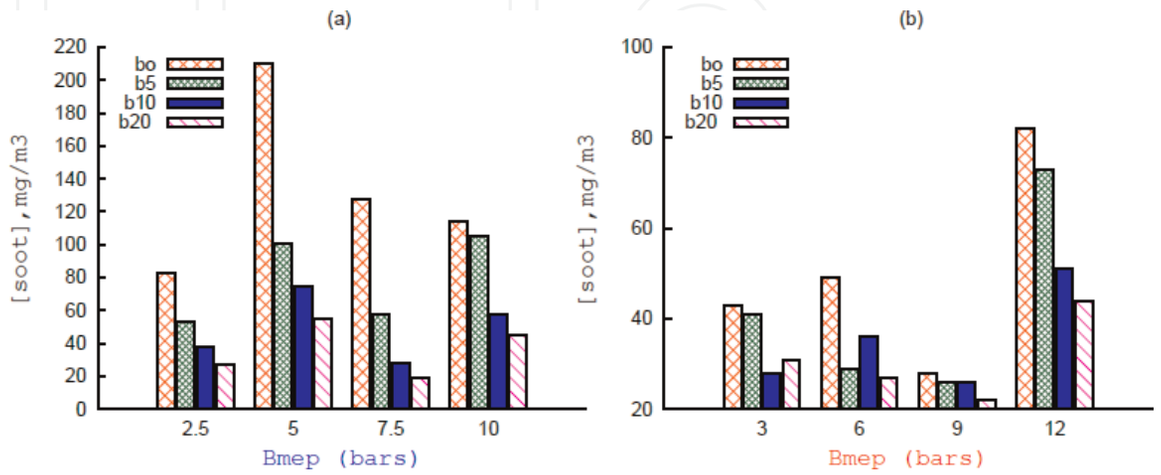


Figure 7. Soot emissions against varying BMEP (a) at 1500 rpm (b) at 3000 rpm [21].

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blends were used as indicated in **Figure 7**. The soot concentration for the blends was always lower than that of DF in both the speeds: 1500 and 3000 rpm, when measured against BMEP. The soot emission reduction with increasing the shared volume of n-butanol to DF was 55.5, 77.8, and 85.1% for B5, B10, and B20, respectively in the 75% load with 1500 rpm. The reduction of soot emission for all the test fuels was higher in the engine tests with 3000 rpm than with 1500 rpm. The reduction of soot emission was highest in the 75% load. The small deviation exhibited by the blends from the trend in the 25 and 50% load with 3000 rpm is not well known: it might be caused by the temperature distribution during the combustion process, as temperature also plays an important role in the formation and oxidation of soot.

7. Conclusions

A study was conducted to determine the performance and combustion characteristics of a mixture of n-butanol in diesel fuel in the ratios: 5,10, and 20% (B5:n-butanol 5% with diesel fuel 95%, B10 and B20) using a turbo-charged four cylinder compression ignition engine. The results were compared with studies by others using similar shared volumes of n-butanol (20%, v/v), including 40% (v/v) biodiesel. Combustion characteristics of B20 (n-butanol 20% and 80% DF) in the author's study improved when the study was compared with the study by others where 40% biodiesel was added to B20. A higher value of the standard deviation for DF than the blends was observed from the standard deviation diagram, indicating a more stable combustion process for the blends than DF. Soot emission was greatly reduced in both compared studies (in author's study and Ref. [19]). This was when bioethanol admix was introduced to BD30/DF blend in the other study [19]. In both cases, smaller proportions of bioalcohol were used. In the author's study, the soot reduction relative to DF at 1500 rpm at 75% load for B05, B10, and B20 mixtures was 55.5, 77.8, and 85.1% respectively. This reduction is a significant advantage of blending DF with smaller shared volumes of bioalcohol. The study has indicated a highly prospective fuel in n-butanol/DF bioalcohol to be promoted in the blending science to reduce particulate matter and improve combustion efficiency in the application of the diesel fuel in reciprocating internal combustion engines.

Moreover, the results should be compatible with figures. I cannot understand how authors say, for example, about ID using pressure development figures, premixed combustion period using HRR or combustion stability which requires a cyclic analysis. Certainly, pressure development and HRR curves are a indicator for such parameters, but the author should define, first, the terms based on the related quantity for better understanding of a reader. Moreover, the results should be discussed more.

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Nomenclature

ATDC After top dead center

CA Crank angle

BSFC Brake-specific fuel consumption

ID Ignition delay

CAD Crank angle degree or θ crank angle

EGT Exhaust gases temperature

BTDC Before top dead center

HRR Heat release rate

rpm Revolution per minute

NOx Nitrogen oxides

BTE Brake thermal efficiency

CO Carbon monoxide

BMEP Brake mean effective pressure

CN Cetane number

DF Diesel fuel

IP Indicated pressure

EDC Electronic diesel control

UHC Unburned hydrocarbon

MAP Manifold air pressure

Greek letter

λ Excess air ratio

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Author details

Lennox Siwale[1]*, Lukacs Kristof[2], Torok Adam[2], Akos Bereczky[2], Makame Mbarawa[3], Antal Penninger[2] and Andrei Kolesnikov[4]

*Address all correspondence to: zumbe.siw@gmail.com

1 Department of Mechanical Engineering, Copperbelt University, Kitwe, Zambia

2 Department of Energy Engineering, Budapest University of Technology and Economics, Budapest, Bertalan Lajos, Hungary

3 Ministry of Communication, Science and Technology, Dar es Salaam, United Republic of Tanzania

4 Department of Mechanical Engineering, Tshwane University of Technology, Pretoria, South Africa

References

[1] Demain A. Biosolutions to the energy problem. Industrial Microbiology and Biotechnology. 2009;**36**:319-332

[2] Nelson DK, Lapara TM, Norak PJ. Effects of ethanol-based fuel contamination: microbial community of regulated compounds, and methane generation. Environmental Science & Technology. 2010;**44**:4525-4530

[3] Demirbas A. Biofuels securing the planet's future energy needs. Energy Conversion and Management. 2009;**50**(9):2239-2249

[4] Mustafa B. Production of bioethanol from lignocellulosic materials via the biochemical pathway: A review. Energy Conversion and Management. 2011;**52**(2):858-875

[5] Dogan O. The influence of n-butanol/diesel fuel blends utilization on a small diesel engine performance and emissions. Fuel. 2011;**90**(7):2467-2472

[6] Zhang Y, Boehman AL. Oxidation of 1-butanol and a mixture of n-heptane/1-butanol in a motored engine. Combustion and Flame. 2010;**157**:1816-1824

[7] Zhang Y, Boehman AL. Oxidation of 1-butanol and a mixture of n-heptane/1-butanol in a motored engine. Combustion and Flame;**157**(10):1816-1824

[8] Yao M et al. Experimental study of n-butanol additive and multi-injection on HD diesel engine performance and emissions. Fuel. 2010;**89**(9):2191-2201

[9] Surisetty V et al. Alcohols as alternative fuels: An overview. Applied Catalysis A: General. 2011;**404**(1-2):1-11

[10] Sarathy SM et al. An experimental and kinetic modeling study of n-butanol combustion. Combustion and Flame. 2009;**156**(4):852-864

[11] Hsieh W-D et al. Engine performance and pollutant emission of an SI engine using ethanol–gasoline blended fuels. Atmospheric Environment. 2002;**36**(3):403-410

[12] Rakopoulos DC et al. Effects of butanol-diesel fuel blends on the performance and emissions of a high-speed DI diesel engine. Energy Conversion and Management. 2010;**51**(10):1989-1997

[13] Bryan W et al. Autoignition of n-butanol at elevated pressure and low-to-intermediate temperature. Combustion and Flame. 2011;**158**:809-819

[14] Karabektas M, Hosoz M. Performance and emission characteristics of a diesel engine using isobutanol-diesel fuel blends. Renewable Energy. 2009;**34**:1554-1559

[15] Kumar S et al. Advances in diesel-alcohol blends and their effects on the performance and emissions of diesel engines. Renewable and Sustainable Energy Reviews. 2013;**22**:46-72

[16] Broustail G et al. Experimental determination of laminar burning velocity for butanol and ethanol iso-octane blends. Fuel. 2011;**90**(1):1-6

[17] Laza T et al. Examination of burning processes regenerative liquid fuel and alcohol mixtures in diesel engine. Periodica Polytechnica Mechanical Engineering. 2006;**50**:11-26

[18] Sayin C. Engine performance and exhaust gas emissions of methanol and ethanolol-diesel blends. Fuel. 2010;**89**(11):3410-3415

[19] Raslavicius L, Bazaras Z. Variations in oxygenated blend composition to meet energy and combustion characteristics very similar to the diesel fuel. Fuel Processing Technology. 2010;**91**(9):1049-1054

[20] Ibrahim A. Performance and combustion characteristics of a diesel engine fuelled by butanol-biodiesel-diesel blends. Applied Thermal Engineering. 2016;**103**(Supplement C):651-659

[21] Siwale L et al. Combustion and emission characteristics of n-butanol/diesel fuel blend in a turbo-charged compression ignition engine. Fuel. 2013;**107**(2013):409-418

[22] Siwale L. (zumbe.siw@gmail.com) age of the engine used for research [email-to-], 2013 (Raslavicius L, (Laurencas.Raslavicius@gmail.com), Dept of transport engineering at kaunas, University of technology Luthiana, July 16)