Chapter 4
Combustion and Emission Characteristics of Oxygenated Alternative Fuels in Compression Ignition Engines

Tomesh Kumar Sahu and Pravesh Chandra Shukla

Abstract Environmental pollution from petroleum products for energy generation is of grave concern nowadays. Oxygenated alternative fuels like biodiesels, alcohols, etc., have gained much popularity for internal combustion (IC) engines. Due to their inherent oxygen content, these oxygenated alternative fuels possess lower carbon-to-hydrogen (C/H) ratio for same heating value. Supporting the road map towards decarbonization of mobility, there has been a recent uptick in curiosity about the possibility of alcohols in compression ignition (CI) engines. Biodiesel contains ~10% inherent oxygen (*m/m*), and alcohols may contains up to 50% oxygen (*m/m*), affecting the CI engine's combustion, performance, and emission. An overview of CI engines fuelled with oxygenated fuels (biodiesel and alcohol blends) on combustion characteristics, engine performance, and exhaust emissions are presented in this study. Biodiesel and alcohol fuels (methanol, ethanol, and butanol) have been compared to evaluate the impact of different blend ratios, oxygen mass fraction content based on in-cylinder combustion pressure trace, heat release rate, and engine performance as brake thermal efficiency and carbon dioxide (CO_2) emission. Up to 25% lowered CO_2 emission was recorded for oxygenated fuel compared to diesel, with significantly lower particulate emission.

Keywords Oxygenated alternative fuels · Alcohols · Waste cooking oil (WCO) based biodiesel · Compression ignition (CI) engines

Abbreviations

ABE	Acetone-butanol-ethanol
BDE	Biodiesel-diesel-ethanol
BTE	Brake thermal efficiency
CA05	5% of total burn fraction

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CA50	50% of total burn fraction
CA90	90% of total burn fraction
CAD	Crank angle degree
CI	Compression ignition
C/H	Carbon to hydrogen ratio
CO	Carbon monoxide
CO_2	Carbon dioxide
EGR	Exhaust gas recirculation
HC	Hydrocarbon
HRR	Heat release rate
IBE	Isopropanol-butanol-ethanol
IC	Internal combustion
ISEC	Indicated specific energy consumption
IMEP	Indicated mean effective pressure
ITE	Indicated thermal efficiency
LTC	Low-temperature combustion
NOx	Nitrogen oxides
PPC	Partially premixed combustion
SI	Spark ignition
TDC	Top dead center
ULSD	Ultra-low sulfur diesel

4.1 Introduction

Global population is likely to reach 9 billion by the year 2040, resulting in a 25% increase in energy demand (Ghadikolaei et al. 2018). Increased energy demand and a growing global urge to minimize carbon emissions impact the usage of conventional fuels and encourage the investigation and implementation of alternative fuels for existing engines (Sahu et al. 2021a, 2022a). Sustainable fuel production processes and utilization have drawn attention to environmental protection by reducing overall carbon dioxide (CO_2) emissions (Ianniello et al. 2021). Biofuels are produced from renewable and sustainable resources, which have proven their use in compression ignition (CI) engines and have been promising in recent years. In this context, biofuels (such as biodiesels, lower and higher alcohols, and their blends with conventional fuels) are extensively explored, showing exciting results regarding emissions reduction and increased efficiency compared with conventional fuels (Ianniello et al. 2021; Shamun et al. 2020; Luca et al. 2022; Sahu et al. 2022c). Innovative technologies for powertrain systems improved the overall engine efficiency and lowered emissions (Belgiorno et al. 2020; Di Blasio et al. 2019). Improved injector nozzle and fuel injection systems (Sequino et al. 2018; Beatrice et al. 2017; Di Blasio et al. 2019), in-cylinder air motion, and EGR systems (Dimitrakopoulos et al. 2019) are being implemented to meet stringent emission regulations and engine performance requirements. Different injection strategies (Sahu et al. 2022d) as well as advanced combustion modes (dual fuel, partially premixed combustion, etc.) (Belgiorno et al. 2019; Dimitrakopoulos et al. 2017; Sahu et al. 2021b) combined with alternative fuels could be an enabler towards clean combustion and reduce the overall CO_2 impact of the transportation sector (Sahu et al. 2022d). It has been observed that oxygenated alternative fuel blends in dual fuel mode lead to the air-fuel mixture in crevice volume showing higher hydrocarbon (HC) emissions (Fraioli et al. 2017; Monsalve-Serrano et al. 2020). Other studies have also reported this behaviour for heavy-duty and light-duty engines (Heuser et al. 2016; Pedrozo et al. 2018). These observations show that HC emissions are higher at lower engine loads and have a similar emission profile to conventional fuel at higher engine loads. Engine operating parameters such as maximum in-cylinder pressure and compression ratio (CR) can affect the air-to-fuel mass trapped in the crevice volume, primarily affecting the HC emission slip in dual fuel combustion (Di Blasio et al. 2015, 2017). Biodiesel-diesel-ethanol (BDE; 78%, 17%, and 5% v/v, diesel, biodiesel, and ethanol, respectively) blends were studied by Krishna et al. (2019) and a marginal decrease in efficiency with reduced carbon monoxide (CO) and comparable CO_2 emissions for BDE has been reported. Saravanan et al. (2020) have tested exhaust gas recirculation (EGR) on ethanol-diesel blends in CI engines and reported that an increase in EGR reduces the efficiency, reduces peak pressure ($P_{\max}$) and heat release rate (HRR) compared to ethanol-diesel fuelled conditions. This is due to a drop in thermal efficiency caused by replacing a large quantity of combustion air with recirculated exhaust gases. Verma et al. (2020) have tested hybrid fuel (ethanol-methanol-diesel-microalgae blends) in a CI engine and observed that the presence of spirulina microalgae shortens the ignition delay while increasing efficiency and decreasing the exhaust gas temperature. Another study shows that EGR is an effective technique to reduce the oxides of nitrogen (NO_x) associated with alcohol fuel where Duan et al. (2021) have observed an advancement in injection timing which advances the HRR and $HRR_{\max}$ decreases with increasing the EGR ratio. Li et al. (2019) reported that utilization of isopropanol-butanol-ethanol blend with diesel (IBE30) reduces $HRR_{\max}$ value and NO_x emissions. Higher molecular weight alcohols (butanol, pentanol, hexanol, or octanol) blends with Ultra-low sulfur diesel (ULSD) were tested and investigated by Rajesh Kumar et al. (2016). They observed that butanol served promising with the lowest emission levels of smoke, NO_x, and CO; however, it showed longer ignition delay, higher $P_{\max}$ and $HRR_{\max}$, and shortest combustion duration among tested alcohols. Neat methanol was tested for varying intake air temperature, resulting in longer ignition delay and lowering the $P_{\max}$ with decreasing the intake air temperature (Zincir et al. 2019). Shamun et al. (2018) examined NO_x and Indicated mean effective pressure (IMEP) in a Partially premixed combustion (PPC) engine with methanol and *iso*-octane. They compared the charge-cooling impact of methanol and *iso*-octane using a single injection technique and observed that methanol resulted in lower nitrogen oxide (NO_x) emissions. Higher latent heat of methanol vaporization results in lower NO_x emission (Shamun et al. 2018). It has been observed that a reduction in the fuel injection rate reduced the NO_x and CO_2 emissions and increased the smoke and HC emissions (Sayin et al. 2009). According to the research summarised in the literature survey, it can be noted that biodiesel, methanol, ethanol, and butanol have been tested and compared extensively with varying volume fractions under various injection techniques, blends dual fuel modes, and PPC techniques. Researchers found that the lower carbon-to-hydrogen (C/H) ratio and inherent oxygen content may be the reasons for reduced exhaust emissions. In this framework, this study provides a thorough literature review on comparing different oxygenated alternative fuels (biodiesel, methanol, ethanol, and butanol) blended with diesel, keeping almost constant the oxygen fraction of blends. The analysis includes the comparative study of the main combustion analysis parameters and efficiencies. The first part of the chapter discusses the characteristics of oxygenated alternative fuels. The later part of the chapter discusses the combustion and performance behaviours of oxygenated fuels. This discussion emphasized in-cylinder pressure, heat release rate (HRR), ignition delay, and engine efficiencies.

4.2 Fuel Properties of Oxygenated Alternative Fuels

This section discusses the selected fuel properties of diesel and some of the alternative oxygenated fuels. Table 4.1 reports various fuel properties such as density, kinematic viscosity, heating value, latent heat of vaporization, autoignition temperature, carbon, hydrogen, oxygen content, and cetane number for different alcohols and biodiesels. Alcohols (methanol, ethanol and butanol) show a lower carbon-to-hydrogen ratio (up to 50%) with 50–21% inherent oxygen content (*m/m*). Primarily, alcohols and biodiesel are being used as oxygenated alternative fuels due to the ease of their production, availability, and renewable nature. Alcohol properties significantly change with increasing molecular weight, which can be observed in Table 4.1. For example, the kinematic viscosity of methanol, ethanol, and butanol are 0.59 mm^2/s, 1.2 mm^2/s and 2.51 mm^2/s, respectively. Similarly, heating values are 20.2, 27.1, and 33.1 MJ/kg for methanol, ethanol, and butanol.

Table 4.1 show that the stoichiometric air-fuel ratios for methanol, ethanol, and butanol are 6.6, 9.0, and 11.1 kg of air/kg of fuel, which are significantly lower than diesel, i.e., 14.49 kg of air/kg of fuel. Lower air requirement for chemically complete combustion increases the chances for a higher degree of complete combustion and reduces unburnt hydrocarbon emission. Alcohols show a lower cetane number, higher autoignition temperature, and higher latent heat of evaporation, increasing the ignition delay and decreasing the autoignition characteristics of the fuel.

4.3 Combustion and Performance of Oxygenated Fuels

CI engines are more widespread than SI engines in the farming and heavy-duty transportation sectors owing to their higher durability, performance, and fuel economy. Using oxygenated fuels (mainly alcohols and biodiesels) in CI engines

Table 4.1 Fuel properties of diesel, biodiesel, methanol, ethanol, and butanol (Verhelst et al. 2019; Labeckas et al. 2017a; Pipicelli et al. 2022; Zhang et al. 2011; Alemahdi and Tuner 2020)

Property parameters	Diesel	Methanol	Ethanol	Butanol
Density at 15 °C, kg/m^3	832.7	790	785	810
Kinematic viscosity at 40 °C, mm^2/s	2.13	0.59	1.2	2.51
Net heating value, MJ/kg	43.0	20.2	27.1	33.1
Autoignition temperature, °C	250	363	385	343
Latent heat of vaporization, kJ/kg	270	1178	838	585
Flashpoint, °C	57	12	12	37
Oxygen, max wt%	0	50	34.7	21.6
Carbon, max wt%	86.08	37.5	52.1	64.8
Hydrogen, wt%	12.99	12.5	13.0	13.6
Carbon-to-hydrogen ratio (C/H)	6.5	3.0	4.0	4.7
Stoichiometric air-fuel ratio, kg/kg	14.49	6.6	9.0	11.1
Cetane number	51.4	4	8	25

might offer a more environmentally friendly and viable alternative to conventional diesel (Sahu and Shukla 2022). Despite having renewable nature and superior fuel properties, specific challenges still need to be investigated for alcohols and biodiesels. Since alcohol has a lower cetane number (CN) value than diesel, the autoignition temperature value is higher, resulting in a longer ignition delay in contrast to diesel. In order to avoid this, it is essential to make modifications to the fuel design, and injection strategy or adding ignition improver additives (Sahu and Shukla 2022). Also, hardware modifications like increasing the compression ratio, increasing the intake temperature, and optimizing the EGR rate are ways to make combustion possible for alcohols. In this section, the combustion and performance of oxygenated fuels are discussed and compared with conventional diesel. Jamrozik et al. have tested butanol diesel fuel for oxygen fractions of 0–14.2% (m/m), corresponding to 60% butanol energy fraction (66% in mass fraction) in diesel. Figure 4.1 shows the carbon-hydrogen and oxygen mass fractions of prepared butanol blends. Higher peak pressure and HRR (Fig. 4.2) were observed for butanol blends (till 30% energy fraction of butanol). Further increase in butanol energy fraction showed reduced peak pressure and reduced HRR with retarded location of $P_{\max}$ and $\text{HRR}_{\max}$. It is attributable primarily to the rising latent heat of vaporization of the blend, which deteriorates the fuel evaporation process, and the low cetane number of n-butanol, which weakens the autoignition characteristics.

Ghadikolaei et al. (2018) investigated CI engines' combustion, performance, and emissions parameters fueled with five distinct alternative fuel mixtures. They used seven different fuels, diesel (D), waste cooking oil (B), methanol (M), ethanol (E), 2-propanol (Pr), n-butanol (Bu), and n-Pentanol (Pe) labeled as DB, DBM, DBE, DBPr, DBBu, and DBPe. These blends were prepared so that the oxygen content of 5% can be retained in the blend and the calorific value remained constant. They

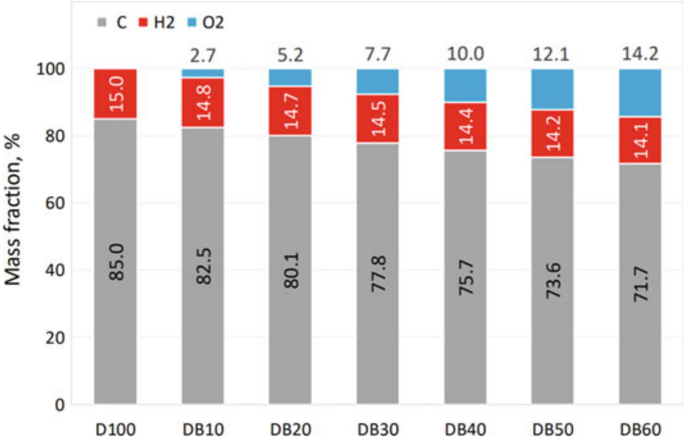


Fig. 4.1 Carbon, hydrogen, and oxygen mass fractions at different diesel-butanol blend ratios (Jamrozik et al. 2021). Copyright © 2021 MDPI. Reprinted with copyright permission

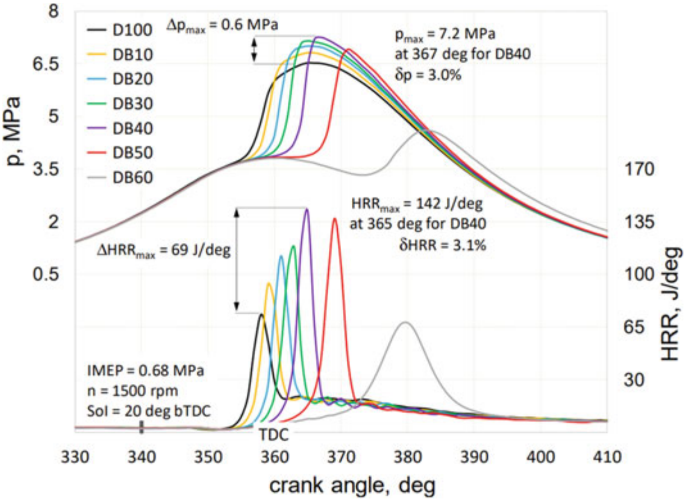


Fig. 4.2 In-cylinder pressure and HRR traces at part-load at different diesel-butanol blend ratios (Jamrozik et al. 2021). Copyright © 2021 MDPI. Reprinted with copyright permission

reported that the peak in-cylinder pressure of all tested blends shows a 1% higher $P_{\max}$ than conventional. Peak HRR was elevated by 22.1% for higher alcohols and 14.8% and 5.9% for lower alcohols (DBE and DBM), respectively. Moreover, 5% oxygenated biodiesel showed a lower peak of HRR by 3%. Labeckas et al. (2017a) have studied the variation of ethanol oxygen fraction and biodiesel oxygen fraction for five different oxygen fractions (0, 0.91, 1.81, 2.71, 3.61 and 4.52%). They observed a slightly higher ignition delay for ethanol blends than biodiesel blends when oxygen

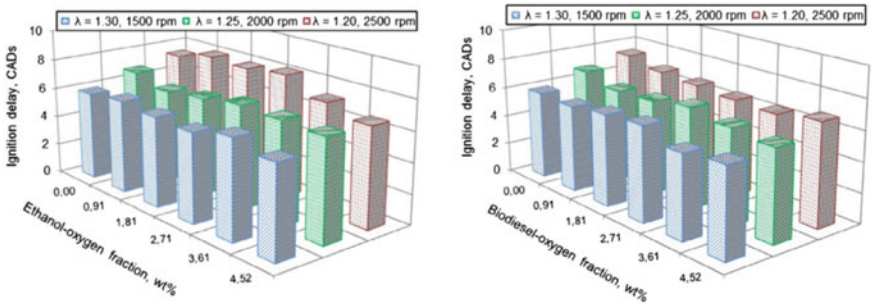


Fig. 4.3 Ignition delay for ethanol and biodiesel oxygen fraction (Labeckas et al. 2017a). Copyright © 2017 Elsevier. Reprinted with copyright permission

fraction (*m/m*) was maintained at 3.61%. However, ethanol showed 1.7 CAD higher ignition delay for 2.71% oxygen at $\lambda = 1.2$ (Fig. 4.3) at 2500 rpm of engine speed.

Nour et al. (2019) tested 10% pentanol/octanol with ethanol—diesel blend (10:10:80) and reduces the peak in-cylinder pressure compared to diesel. Diffusion phase of HRR is enhanced with a diminished premixed phase. Break specific fuel consumption (BSFC) was observed to be higher for pentanol substitution and lower for octanol substitution. Both pentanol and octanol report better stability for blends of ethanol-diesel with significantly lower NO_x and CO_2 emissions. Guedes et al. (Mendes Guedes et al. 2018) have suggested advancing the fuel injection timing by 1 CAD for an increase of every 5% ethanol in the blends of diesel-biodiesel-ethanol, which resulted in a maximum increase of 9% in peak pressure. Prakash et al. (2018) examined the performance of ternary mixtures of bioethanol, diesel, and castor oil. 30% bioethanol demonstrated a longer ignition delay, leading to higher fuel collection and a rapid increase in in-cylinder pressure and HRR. Shamun et al. (2018) tested diesel, biodiesel, and ethanol in a light-duty diesel engine; they underlined the fact that greater oxygen content in the fuel leads to complete combustion and elevates the temperature of the combustion process. Ignition delay was increased when ethanol was present, which resulted in a greater amount of fuel being consumed during the premixed phase of combustion and an increase in the creation of thermal NO_x. Pradelle et al. (2019) experimented with a Euro 3 CI engine and reported that the decreased density and heating value of ethanol caused a rise in specific fuel consumption of around 2% for every 5% increase in that anhydrous ethanol was included in the blend. Ethanol possesses a higher latent heat of vaporization, heat capacity at constant pressure, and a lower cetane number than conventional fuel causes an increase in the ignition delay. Despite these limits, useful thermal energy increased with ethanol content. This improved the engine's efficiency, especially at low loads. Shrivastava et al. (2021) investigated that the ternary blend (Biodiesel 20%—Ethanol 10%-Diesel 70%) delivered superior performance than the conventional diesel. Their study shows a 2% reduction in break thermal efficiency (BTE), a 3% rise in BSFC, a 3% increase in EGT, a 0.86% increase in CO_2, a 0.02% reduction in CO, an 8% reduction in NO_x, and 12 ppm reduction in HC compared to baseline diesel (Shrivastava et al.

2021). Authors of this chapter too performed an experiment to understand the effect of oxygen variation for different alcohol fuels, and an investigation was performed for 2.5% and 5% oxygenated blends in a twin-cylinder water-cooled CI engine for 1600 rpm at 20 Nm engine loading, schematic of the experimental setup shown in Fig. 4.4. The engine was fitted with a piezoelectric pressure sensor for measuring in-cylinder pressure. Engine was operated at desired operating load for a minimum of 15 minutes to reach the steady state condition. Upon reaching the steady state, combustion data were taken for 120 thermodynamic consecutive cycles for a given blend of fuel. Performance and emissions data were measured multiple times, and average data were used for analysis. Methanol, ethanol, and butanol were used for preparing the oxygenated blend, named as M2.5, E2.5, and B2.5 for 2.5% oxygen *m/m* fraction and M5, E5, and B5 for 5% oxygen *m/m* fraction. It contains 5.2% methanol, 7.4% ethanol, and 11.7% butanol respectively for a 2.5% oxygenated blend and 10.3% methanol, 14.8% ethanol, and 23.3% butanol respectively for a 5% oxygenated blend. Figure 4.5 shows the measured in-cylinder pressure and calculated HRR for tested fuels at 20 Nm loading conditions. For 2.5% oxygenated case (Fig. 4.5a), pressure and HRR pattern were similar with slightly higher peak pressure for M2.5, HRR curve was observed to shift away from top dead center (TDC) for all three tested fuels, E2.5 resulted in 2 CAD retarded location of HRR_{max} compared to diesel. Figure 4.5b shows the pressure and HRR pattern for 5% oxygenated fuel. M5 showed the advanced location of peak pressure; however, E5 and B5 showed the retarded location of peak pressure than diesel. E5 and B5 also showed a higher ignition delay and higher HRR_{max} and compared to diesel, the location of HRR_{max} was also retarded by ~3 CAD.

Figure 4.6 shows the value of combustion phasing (CA05, CA50, and CA90 correspond to total heat release of 5, 50, and 90%), combustion duration, and BTE

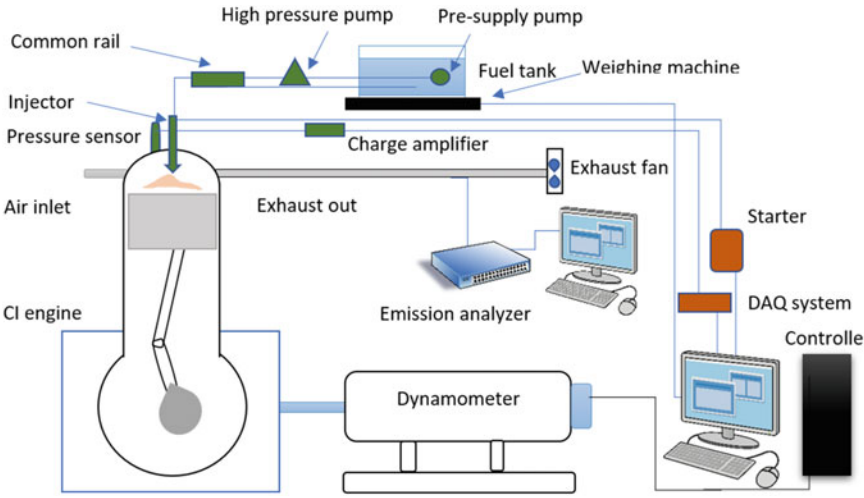


Fig. 4.4 Schematic representation of the experimental setup

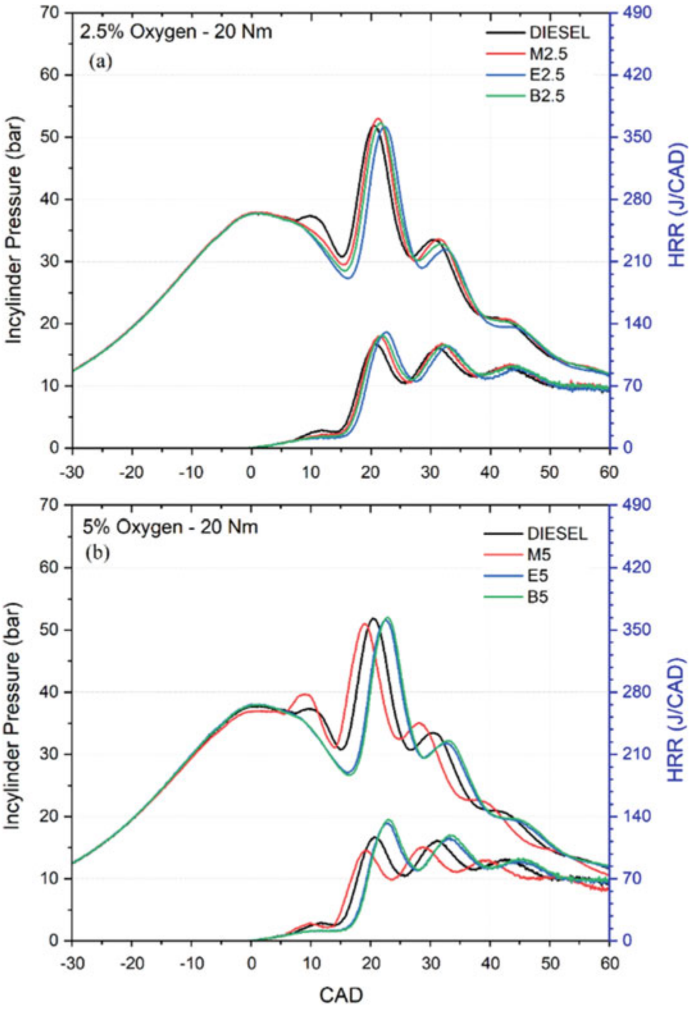


Fig. 4.5 In-cylinder pressure and HRR for 2.5 and 5% oxygenated fuel at 20 Nm

for 2.5 and 5% oxygenated blends at 20 Nm engine loading condition for 1600 rpm. It was noted that all three fuel CA05 locations were advances for 5% oxygenated fuel than 2.5% oxygenated fuel. A similar pattern was also observed for CA50 and CA90 locations. Early CA05 and CA90 of oxygenated fuel resulted in a lower combustion duration (lowered by ~2–3 CAD) for both 2.5 and 5% oxygenated fuel compared to baseline diesel. BTE was observed comparable for both 2.5 and 5% oxygenated fuel, with maximum efficiency of 22% was achieved for M5 and a minimum efficiency of 18.9% was achieved for E2.5 observed for the tested condition (Fig. 4.6).

Labeckas et al. (2017b) reported that BTE is higher after 2.71% oxygen fraction; further, it is intensified with a higher oxygen fraction for ethanol-oxygen mass content (shown in Fig. 4.7) for higher engine rpm of 2000 and 2500 rpm. Biodiesel oxygen

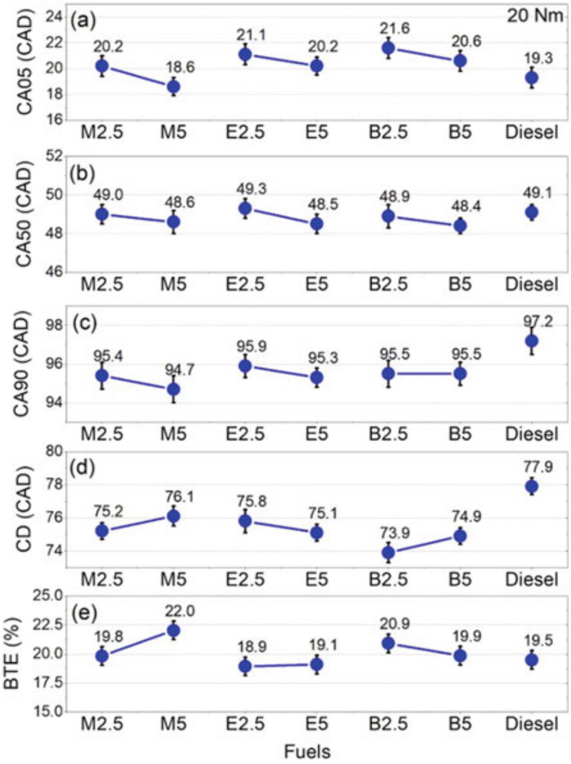


Fig. 4.6 Combustion phasing, combustion duration, and BTE for 2.5 and 5% oxygenated fuel at 20 Nm

mass fraction showed a similar comparable efficiency for 2500 rpm; moreover, it is a slightly increasing trend with an increase in oxygen fraction for 2000 rpm. Compared to both cases, ethanol oxygen fraction is more beneficial than biodiesel oxygen fraction as it showed a relatively higher BTE for tested conditions. Variations of BTE are shown in Fig. 4.8 for the experiment performed by Ghadikolaei et al. (2018) for different fuel blends with a 5% oxygen mass fraction. Figure 4.8 shows that the highest BTE of the tested fuels was observed at 199.5 Nm, resulted in the best engine performance. Low load operations caused lower combustion temperatures, which possibly resulted to incomplete combustion. At high loads, fuel/air ratio is richer, and combustion temperature is higher; however, there is insufficient time for mixing, leading to incomplete combustion and a decrease in BTE. Five loads show that the BTE of DBM (3.5%) and DBBu (1.5%) is higher than that of diesel fuel, while the BTE of other blended fuels is comparable [Ghadikolaei et al. (2018)]. Lower fuel viscosity, improved fuel atomization, and higher oxygen content etc. Improved BTE by enhancing the combustion process, which transforms fuel chemical energy into useful engine work. DBM showed the highest BTE of all the evaluated fuels. Among the investigated alcohols, methanol indicated the shortest chain and lowest molecular weight, which promotes better combustion and the highest BTE (Fig. 4.8). Methanol showed the lowest boiling point, which lowered heat losses and raises BTE.

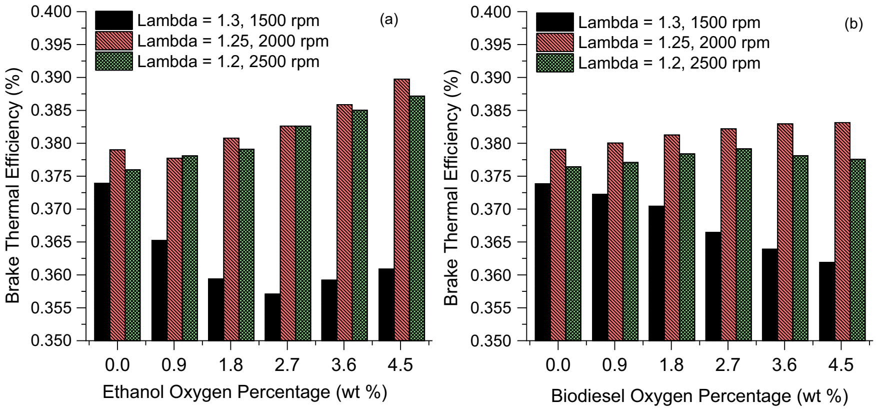
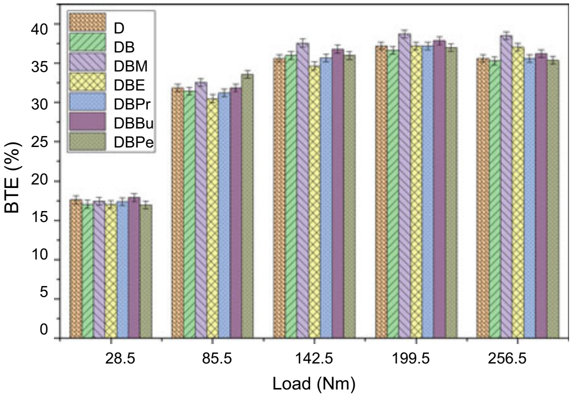


Fig. 4.7 BTE for an ethanol-oxygen mass fraction (left) and biodiesel oxygen mass fraction (right) (Labeckas et al. 2017b). Copyright © 2017 Elsevier. Redrawn with copyright permission

Fig. 4.8 BTE for 5% oxygen mass fraction for different alternative fuels (diesel (D), waste cooking oil biodiesel (B), methanol (M), ethanol (E), 2-propanol (Pr), n-butanol (Bu), and n-pentanol (Pe)) (Ghadikolaei et al. 2018). Copyright © 2018 Elsevier. Redrawn with copyright permission



Jamrozik et al. (2021) reported that DB40 (40% butanol energy fraction in diesel) showed maximum efficiency of 41.3% (Fig. 4.9) with the lowest energy consumption among the tested butanol-diesel blends which is approximately 11% higher than diesel. Higher efficiency is achieved possibly due to the acceleration of chemical oxidation with the higher butanol fraction, however, a further increase in butanol fraction shifted the HRR curve away from TDC resulting in lower useful work and lower efficiency.

Nour et al. (2019) demonstrated that pentanol (10%) increased the BTE by 3% at lower loads for ethanol-diesel blends (10:10:80). Adding octanol to diesel raises BTE by 5% at low and mid loads, whereas at higher loads, diesel is 1% more efficient. The ternary blends' oxygen concentration improved combustion and boosted BTE, especially with octanol.

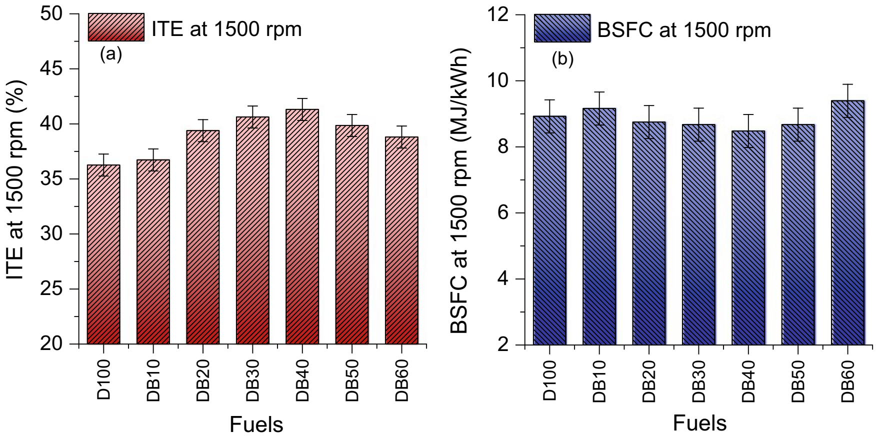


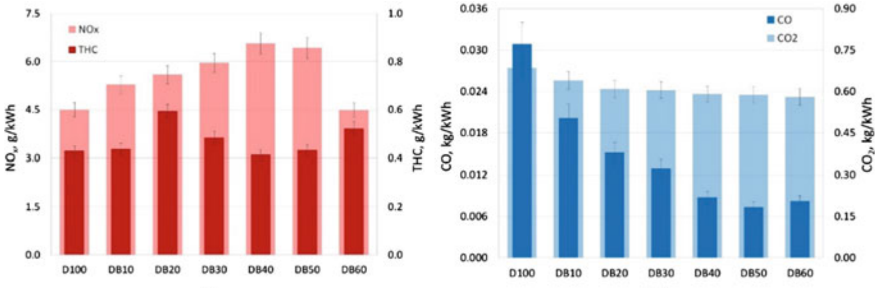
Fig. 4.9 Indicated thermal efficiency (ITE) and indicated specific energy consumption (ISEC) for diesel-butanol blends (Jamrozik et al. 2021). Copyright © 2021 MDPI. Redrawn with copyright permission

Overall, it can be observed that using oxygenated fuel in a limited fraction improves the combustion and enhances the performance characteristics of the engine, however, a much higher fraction also led to retard the peak pressure and offered higher ignition delay. Considering conventional CI engines up to 15% of alcohols can be utilized with diesel, a further higher fraction requires alterations in engine hardware and fuel injection systems.

4.4 Exhaust Emissions Characteristics of Oxygenated Fuels

Locally peak in-cylinder temperature locations and a high degree of pyrolysis lead to NO_x and PM emissions in CI engines. It has been reported that alcohols are beneficial in reducing PM emissions in diesel combustion drastically with almost no/slight change in NO_x emissions. Jamrozik et al. (2021) tested butanol blends with oxygen percentages of 2.7–14.2% (shown in Fig. 4.1, mentioned as DB10 to DB60). They reported NO_x is an increasing trend from DB10 to DB40; moreover, DB60 shows significantly lower NO_x (Fig. 10a) compared to DB50 and similar to diesel D100. This is mainly due to the higher amount of alcohol present in DB50 and DB60 blends, resulting in higher latent heat of vaporization, and reducing the peak cylinder temperature lowers the NO_x formation. CO and CO_2 emissions are in decreasing trend with an increase in butanol fraction; CO shows a sharp decline (Fig. 10b) with an increase in oxygen fraction due to improving combustion quality and lower C/H ratio of overall blends with an increase in butanol.

Kumar et al. (2022) tested the particulate matter (PM) in diesel engines fueled with ethanol-diesel blends and reported that 5–10% of ethanol with diesel fuel reduced

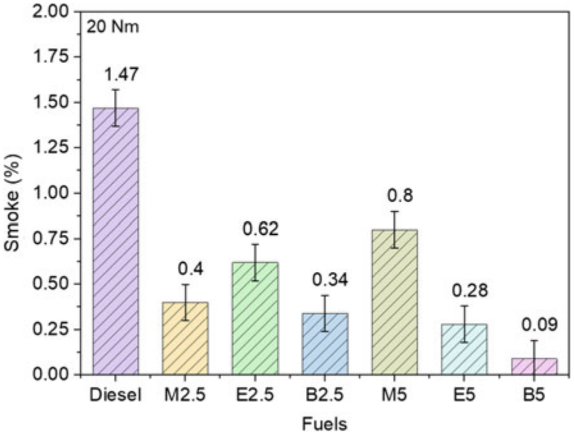


(a) (b)

Fig. 4.10 NO$_x$, THC, CO, and CO$_2$ emissions for different butanol-diesel blends (Jamrozik et al. 2021). Copyright © 2021 MDPI. Reprinted with copyright permission

significant particulate emissions. 50% reduction in PM was observed using ethanol compared to diesel fuel. This may be due to the use of ethanol fuel with diesel improving the combustion and increasing the combustion temperature which resulted in a reduction in soot formation. Smoke results shown in Fig. 4.11 were performed by authors, which show the emission characteristics of diesel engine fueled with different alcohols with the same oxygen fraction (2.5 and 5% inherent oxygen). Butanol blends with 5% oxygen mass fraction showed a higher reduction compared to diesel and 2.5% butanol oxygenated fuel blend. It was observed that E5 and B5 resulted in significantly higher HRR$_{max}$ and lower combustion duration (Figs. 4.5 and 4.6), which showed that a higher degree of complete combustion resulted in lower smoke emissions.

Fig. 4.11 Smoke emissions for 2.5 and 5% oxygenated alcohol fuel (methanol, ethanol, butanol blends) at 1600 rpm, 20 Nm loading



4.5 Summary

A comparative study was performed to study the combustion and performance characteristics of oxygenated alternative fuels in CI engines. In addition to this, an engine experiment was also performed with the same oxygen concentration for different fuels. Butanol blends resulted in a promising way compared to mineral diesel and lower molecular alcohol blends. Biodiesel and light alcohols have a high oxygen content that is chemically inherited in their molecular structure helps to boost combustion efficiency. Apart from that, the following conclusions can be drawn:

- Alcohols (methanol, ethanol, and butanol) with the same oxygen mass fractions showed different results due to different volume fractions of alcohol, ethanol, and butanol. Ethanol and butanol showed higher HRR than methanol blends (keeping the oxygen mass fraction same). Higher volume fraction of ethanol/butanol is required to make the same oxygen mass fraction.
- Methanol blends showed improved efficiency due to the shortest chain and lowest molecular weight among investigated alcohols, leading to better combustion and higher thermal efficiency.
- In general, higher alcohol fraction addition showed increased in-cylinder pressure and higher HRR, which may be damped using ignition improver additives, or higher alcohols such as the use of pentanol or octanol.
- The incorporation of alcohol into diesel fuel led to a considerable decrease in CO and smoke emissions.

The present study indicated that alcohols are promising alternative fuels in terms of PM reduction. Alcohols (especially butanol) indicated significantly higher efficiency compared to diesel due to better combustion. Overall, utilization of these alcohol fuels is also beneficial in terms of total CO_2 reduction in the environment as it is considered as green alternative fuel produced by first-generation or second-generation vegetation/agro products.

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