Chapter 5
The Potential of Various Alcohol Fuels for Low-Temperature Combustion Engines

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5.1 Introduction

Due to higher compression ratio, better thermal efficiency, and good torque characteristics of diesel engine compared to its counterpart spark ignition (SI) gasoline engines, the diesel engines have become indispensable to meet the power demands for on-road and off-road applications. However, the oxides of nitrogen (NO_x) and smoke emission from the diesel engine are its major concerns. To surmount the depletion of fossil fuel resources and harmful emissions from these sources, the emission norms are tightened. Currently, the stringent emission norms keep the researchers in active mode to establish feasible solutions to mitigate the emissions from conventional fossil fuels. Several alternative strategies, namely alternate fuels, advanced combustion technology, and after treatment techniques, are practiced. In this regard, the alternate fuels from biomasses like alcohol and biodiesel are proved to be effective alternate fuels for internal combustion engines. Alcohol fuels have many advantages like renewable in nature, higher latent heat of evaporation (beneficial in NO_x reduction), and fuel-bound hydroxyl (OH) group (reduces smoke emission). However, direct usage of alcohols in compression ignition (CI) engines needs ignition aids due to their lower cetane and viscosity characteristics. Therefore, the alcohol–diesel blends or dual-fuel mode is preferred in CI engines. Biodiesel fuel is an efficient alternative fuel for CI engines. The biodiesel fuels have several advantages like renewable in nature, the presence of fuel-bound oxygen, and high miscibility with diesel. However, many

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researchers have reported an increase in NO_x emission from biodiesel compared to that of diesel fuel. Blending alcohol with biodiesel fuels decreases the NO_x emission by reducing in-cylinder temperature. In diesel engines, the NO_x and soot emissions' formation is influenced by flame temperature and equivalence ratio, respectively. Hence, the simultaneous reduction of these emissions is possible by controlling the flame temperature and local equivalence ratio. This is achieved in an advanced low-temperature combustion (LTC) strategy. Numerous articles are available in the open literature on the effect of LTC on performance, combustion, and emission characteristics of CI engines (Amorim et al. 2017; Carlucci et al. 2014; Fang et al. 2013a). The LTC could be attained with the help of advanced combustion strategies like homogeneous charge compression ignition (HCCI), partially premixed combustion (PPC), premixed charge compression ignition (PCCI), and reactivity-controlled compression ignition (RCCI). In LTC mode, preparing homogeneous mixture is one of the primary tasks, which can be done effectively with alcohol fuels because of its higher volatility (Kumar and Rehman 2017). Alcohols are one of the favorable alternative fuels for LTC due to their higher octane number, wide equivalence ratio range, and widened operational range with emissions reduction capabilities (Pachiannan et al. 2019). Moreover, alcohol and biodiesel fuels are used in an internal combustion engine with minimal or without major modifications (Çelebi and Aydın 2019). Numerous articles on the use of alcohol fuels with diesel and biodiesel in both the SI and CI engines are accessible from the literature (Nour et al. 2019; Yusri et al. 2017; Shirazi et al. 2019). Hence, an effort is made to comprehend the outcome of alcohol fuels on combustion and emission characteristics of low-temperature combustion engines as shown in Fig. 5.1.

5.2 Overview of Alcohol Fuels

Methanol, ethanol, and butanol are the extensively utilized alcohols in both SI and CI engines. The chemical structure of alcohol is represented as $C_nH_{2n+1}OH$. The higher octane number of alcohol can reduce the knocking tendency in spark-ignition (SI) engines, whereas the presence of fuel oxygen content in alcohol diesel blends lowers the soot formation tendency in compression ignition engines. Concomitantly, blending alcohol results in lower emissions in both the version of internal combustion engines (Çelebi and Aydın 2019; Yusri et al. 2017).

5.2.1 Types of Alcohol Fuels

Among the oxygenated fuels, methanol came into the spotlight as a clean alternative fuel supplementing conventional fossil fuels and is produced from fossil or bioenergy resources. The merits of blending methanol with gasoline include high research octane number and hence higher engine efficiency, higher latent heat, and wider
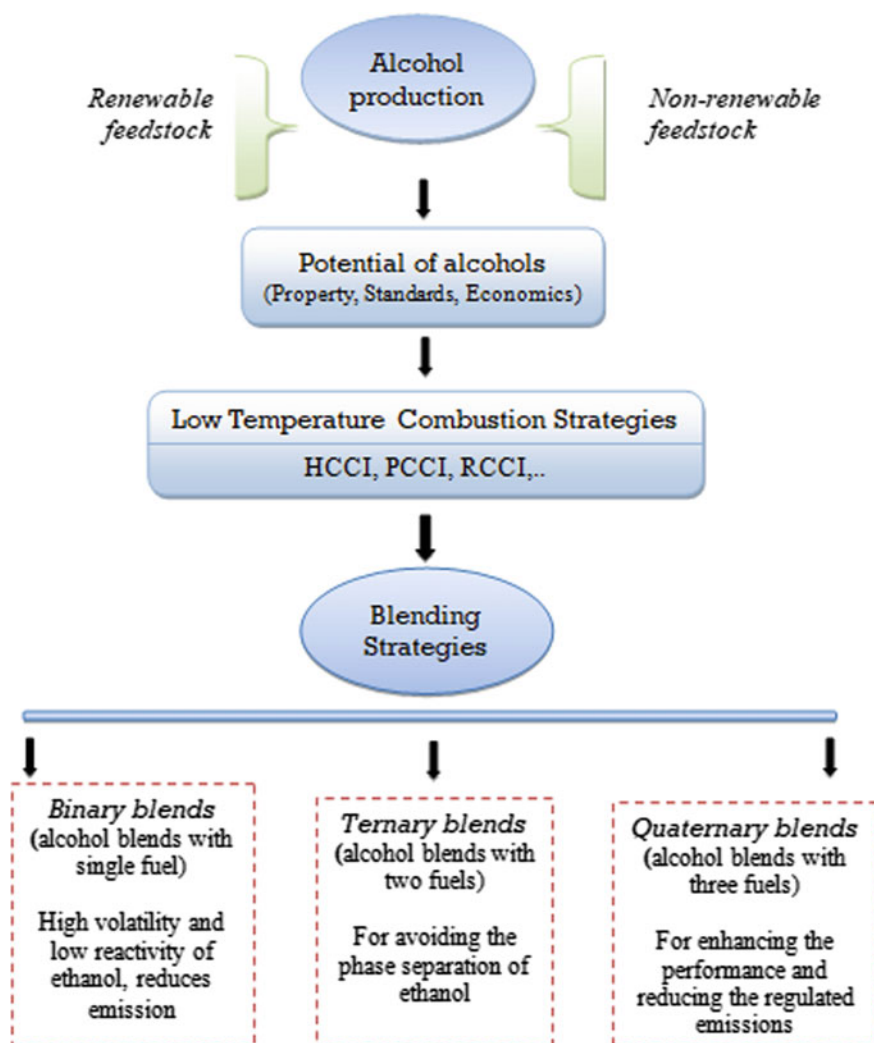
Fig. 5.1   An outline of the chapter

flammability limits than those of gasoline result in lower combustion temperature and thus lesser pollutant formation. Ethanol is a clear, colorless liquid and also known as grain alcohol. The USA and Brazil produce 85% of the world's ethanol as shown in Fig. 5.2. In USA, corn is used to produce the majority of ethanol, while in Brazil sugarcane is the preferred feedstock. *n*-propanol (1-propanol) and isopropanol (2-propanol) are the two isomers of propanol (C_3H_7OH). Though the energy density of propanol is higher than ethanol, they are not recommended in the automotive fuel segment due to their higher production cost. Hence, only very few studies are attempted in comparison to ethanol and butanol isomers (Shirazi et al. 2019). Among
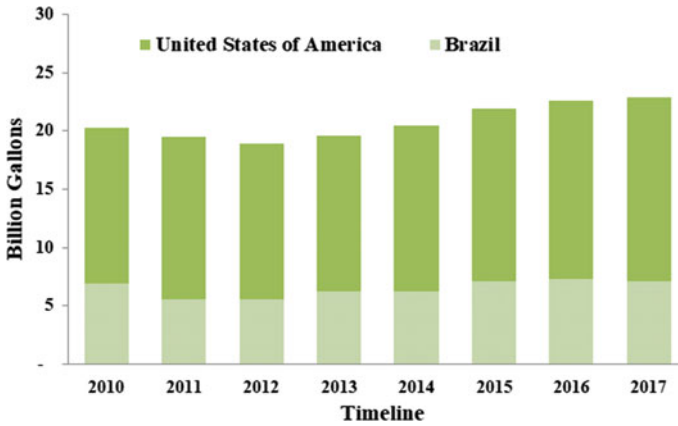
Fig. 5.2 Major ethanol-producing countries in the world (Annual Fuel Ethanol Production 2020)

the different isomers of butanol (C_4H_9OH), *n*-butanol and isobutanol are the potential blends for spark-ignition engines.

The other isomers, viz. secondary butanol and tertiary butanol, are not recommended due to their extremely low motor octane rating (32) and higher melting point (about 25 °C), respectively. Though butanol can be obtained from both fossil and renewable resources, production through biological pathways is highly preferred to mitigate greenhouse gas emissions. Biobutanol is produced through fermentation of straw, sorghum, sugar beets, wheat, corn, sugar cane, and cassava (Shirazi et al. 2019). In comparison with propanol and butanol, methanol is toxic and less volatile (Yusri et al. 2017). Table 5.1 provides the property comparison of methanol, ethanol, propanol, and butanol fuels. In particular, the four alcohols have higher octane number, heat of evaporation, and auto-ignition temperature than those of fossil fuels, and also they contain fuel-bound oxygen.

Among the alcohol groups, butanol has higher boiling point, thus requires higher temperatures for the evaporation. Longer ignition delay periods could be observed in the case of methanol and ethanol due to their higher heat of vaporization. Due to their higher heating values, propanol and butanol lower the fuel consumption for the same power output. The higher flash point of propanol and butanol offers safer storage and fuel transportation.

5.2.2 Standard Requirements

Flexible-fuel vehicles (FFVs) are designed to operate on alcohol and gasoline in any combination from a single fuel tank. As shown in Table 5.2, ASTM Standards provide

Table 5.1 Physicochemical properties of fuels (Yusri et al. 2017; Shirazi et al. 2019)

Properties	Fossil fuels		Alcohol fuels			
	Gasoline	Diesel	Methanol	Ethanol	Propanol	Butanol
Chemical formula	C_8H_{18}	$C_{12}H_{26}$	CH_3OH	C_2H_5OH	C_3H_7OH	C_4H_9OH
Molecular weight (g/mol)	114	170	32.04	46.07	60.10	74.12
Oxygen content (% wt.)	–	0	49.93	34.73	26.62	21.6
Cetane number	0–10	40–55	3.8	5–8	12	25
Research octane number	80–99	20–30	136	129	112	96
Boiling point (°C)	40–200	143	65	79	97	117
Density (kg/m^3)	~740	840	791.3	789.4	803.7	810
Viscosity @ 40 °C (mm^2/s)	~0.6	2.43	0.59	1.13	1.74	2.22
Lower heating value (MJ/kg)	42.7	42.5	20.01	26.08	29.82	33.01
Heat of vaporization @ 25 °C (kJ/kg)	349	243	1162.64	918.42	727.88	585.40
Flash point (°C)	−13 to 45	65–88	12	13	22	35
Auto-ignition temperature (°C)	257	~300	463	420	350	345
Stoichiometric air–fuel ratio	14.7	14.3	6.47	9.01	10.35	11.19

the specification for methanol fuel blends (M51–M85), ethanol fuel blends (E51–E83), butanol for use in automotive spark-ignition engines equipped with flexible-fuel and dedicated spark-ignition engines. For optimum vehicle operation, the alcohol content in the fuel blend is a vital parameter to ascertain the proper air–fuel ratio by the fuel metering system of the FFVs.

5.2.3   Economic Benefits of Alcohol Fuels

The pricing policy of biofuels is a crucial parameter to sustain their growth in comparison to conventional fossil fuels. European Union has set a goal to consume 10% of biofuels by 2020, and the USA is aiming for 36 billion gallons of biofuels by 2022 (Çelebi and Aydın 2019). Gallagher et al. (2005) emphasized the relation between capital costs and plant size for the economical production of biofuels. Typical biofuel

Table 5.2 Comparison of standard requirements of the alcohol fuel blends (ASTM Standard D5797-18 2018; ASTM Standard D5798-20 2020; ASTM Standard D7862-19 2019)

Properties	Methanol blends	Ethanol blends	Butanol
ASTM standard	D5797-18	D5798-19	D7862-18
Alcohol content (% by vol.)	51–85	51–83	94
Vapor pressure (kPa)	62–83	48–65	
Methanol content (% by vol., max)	–	0.5	0.4
Ethanol content (% by vol., max)	–	–	1.0
Lead (mg/L, max)	2.6	–	–
Phosphorus (mg/L, max)	0.2	–	–
Sulfur (mg/kg, max)	80	80	30
Acetic acid (mg/kg, max)	50	50	56 (mg/L)
Unwashed gum content (mg/100 mL, max)	20	20	–
Solvent washed gum content (mg/100 mL, max)	5	5	5
Total inorganic sulfate (mg/kg, max)	4	–	–
Water (% by mass, max)	0.5	1.0	1.0 (by vol.)
Total inorganic chloride (mg/kg, max)	1.0	1.0	8.0
Copper content (mg/L, max)	–	0.07	–
Existent sulfate (mg/kg, max)	–	–	4

productions in large scale were assumed to be 245 million L/year for ethanol and 110 million L/year for biodiesel (Pimentel and Patzek 2005). Lin et al. (2013) recommended utilizing waste feedstock (such as food waste or reused cooking oil) to lower the production cost of biofuels. Considering the Indian scenario, Thangaraja and Srinivasan (2019) found that the price of coconut biodiesel blend (B20) is slightly higher (0.017 $) in comparison to fossil diesel. Figure 5.3 summarizes the price variation between fossil and biofuel blends (E85 and B20) in major clean cities of the USA. It is interesting to observe that the price of biofuel blends is converging closer to fossil fuels in recent years.

5.2.4 Implementation of Alcohol Fuels in Combustion Engines

The current stringent emission norms led the researchers to shift their focus toward establishing alternative fuels and to develop advanced combustion strategies for subsiding the fossil fuel dependency and mitigating the deleterious emission from the internal combustion engines. In this regard, one of the promising alternate fuels such as alcohol deemed to be a suitable source to overcome the adverse impact of emission caused by internal combustion engines. However, the concurrent decrease
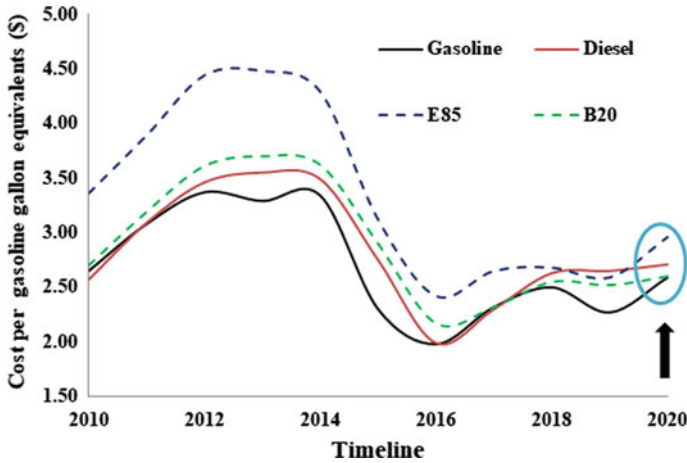
Fig. 5.3 Average retail fossil and biofuel blend prices in the USA (Clean Cities Alternative Fuel Price Reports 2020)

of NO$_x$ and soot emissions is one of the major inherent drawbacks of the diesel engine. LTC is one of the advanced combustion strategies which show the potential of reducing NO$_x$ and soot emissions. The LTC is accomplished with the help of altering the injection timing, a higher rate of exhaust gas recirculation (EGR), varying the fuel reactivity, etc. To abate the consequences of high rate of EGR and retarded injection timing, it is desirable to implement a fuel which has lower cetane number and higher volatility, like alcohol fuel (Zhang et al. 2012; Fang et al. 2013b). Moreover, alcoholic fuels are considered as suitable in LTC due to their desirable properties, namely high auto-ignition resistance and enhanced ignition delay, which helps in allowing adequate time for mixing the air and fuel and evaporating the fuel faster. Its hydroxyl group and higher latent heat of vaporization reduce the smoke emission especially at high loads (Lapuerta et al. 2010) and NO$_x$ emission significantly vis-à-vis diesel fuel (Doğan 2011). Therefore, the next section describes the potential of alcohol fuels in achieving low combustion strategies and their effect on combustion and emission characteristics of internal combustion engines.

5.3 Usage of Alcohol Fuels in LTC Strategies

It is well known that the simultaneous reduction of NO$_x$ and PM emissions necessitates avoiding both the high-temperature stoichiometric regions and local fuel-rich regions which are inherent in diesel combustion. It is informed that the low-temperature combustion improves fuel atomization and mixing, lowers the local equivalence ratio and reduces combustion temperature (Leermakers and Musculus

2015; Yousefi et al. 2018) which can abate the NO_x and particulate matter (PM) emissions simultaneously (El-Asrag and Ju 2014; Niemeyer et al. 2015). The alcohol fuels make use of the full merits of HCCI combustion due to their desirable properties such as higher octane number, wider range of equivalence ratios with a reduction in emissions (Maurya and Agarwal 2014). The alcohol fuel used in other mode of LTC such as RCCI engine increases the thermal efficiency along with decrease in harmful exhaust pollutants (Dou et al. 2017; Jamrozik 2017). As this chapter discusses the effect of alcohol fuels on LTC, for the sake of brevity the LTC concept is not explained in detail. Though several papers published on alcohol fuels, this work provides the effect of alcohol fuels which is characterized in terms of number of fuels used for blending. This section describes the suitability of alcohol fuel for LTC strategies and their effect on performance, combustion, and emission characteristics of engines under LTC mode.

5.3.1   Binary Blends

The binary blends consist of alcohol fuels blended with gasoline–diesel–biodiesel. This section describes the use of binary blends on LTC mode.

5.3.1.1   Diesel–Alcohol Blends

In the normal mode of combustion, it is reported that the alcohol fuels increase the intensity of premixed combustion phase due to increase in ignition delay period and heat release which in turn increases the combustion temperature (Ning et al. 2020). However, the high volatility and low reactivity of ethanol fuel suit LTC operation in diesel engines (Asad et al. 2015). Increasing the quantity of ethanol reduces the premixed phase of combustion and NO_x and soot emissions but it increases HC emission. The reduction of NO_x is attributed to the reduction in combustion temperature due to charge cooling. The higher premixed ratio (increase in ethanol fraction) increases the delay period and retards combustion due to higher resistance to auto-ignition of ethanol fuel and lower cetane number which in turn affects the auto-ignition process, respectively (Mancaruso and Vaglieco 2015). The binary blend diesel–ethanol (15% of ethanol) in a double-injection strategy reduced the NO_x and smoke emissions by 85% and 33%, respectively (Srihari and Thirumalini 2017). The reduced heat release rate, and combustion temperature and the higher latent heat of evaporation of ethanol fuel caused the NO_x reduction. The smoke reduction is attributed to the fuel-bound oxygen of ethanol fuel and improved fuel–air mixing. However, the HC and CO emissions are observed to increase at all the load conditions. It is suggested that increasing the inlet air temperature can decrease CO and HC emissions with a trade-off in NO_x emission (Maurya and Agarwal 2011).

The use of diesel with higher alcohols like isobutanol and *n*-pentanol blends (Rajesh Kumar and Saravanan 2016) established an increase in ignition delay and rate

of premixed combustion phase with retarded occurrences. Butanol blends increased the ignition delay, peak pressure, and combustion efficiency vis-à-vis pentanol blends which is attributed to low cetane number and higher oxygen content of butanol fuel compared to those of pentanol. The viscosity and density of isobutanol are lower compared to those of *n*-pentanol which enhance the spray behavior. While the butanol blends are noted to be comparable with the performance of diesel fuel, it is observed to be better than pentanol. In emission standpoint, butanol offered a huge reduction in NO_x than pentanol blends due to longer delay period, reduction in combustion flame temperature, and lower oxygen content of butanol blend. However, the lower oxygen content of butanol increased the smoke emission.

The RCCI strategy is one of the LTC variants, which addresses the several problems associated with HCCI and PCCI mode such as extending LTC to higher load, combustion phasing for a wide range of engine load conditions and excessive pressure rise rates at higher loads. Since the homogeneity of the fuel plays a major role in LTC, the use of port injected low reactivity fuel (LRF) and earlier direct injection of high reactivity (HRF) fuel is suggested for RCCI engines. The proper fuel blending provides the required fuel reactivity which can be changed by varying the quantity of LRF and HRF. These varying reactivities between LRF and HRF help control the various parameters of LTC for extending the range of engine load and speed conditions (Splitter and Reitz 2014). It is proved that the spatial stratification of the fuel reactivity influences the duration of combustion. For obtaining the necessary fuel reactivities, alcohol fuels, namely methanol, ethanol, and butanol, qualify as LRFs in the RCCI combustion concept. Among the variety of alcohol fuels, butanol is one of the potential low-reactivity fuels for RCCI mode due to its higher heating value, more energy density, low hydrophilicity, and non-corrosiveness (No 2016; Pan et al. 2017). The use of alcohol fuels achieves stable and extends the operation of RCCI engine (Dempsey et al. 2013; DelVescovo et al. 2015) due to their low reactivity and higher latent heat of evaporation. A small fraction of ethanol (about 10–20%) reduces the NO_x and smoke emissions in compliance with EURO VI emission norms with enhanced HC and CO emissions for a wide range of engine loads (Benajes et al. 2015). However, higher premixed ratios of ethanol are observed to increase CO and HC emission, while lowering NO_x and soot emissions significantly due to enhanced cooling effect and reduction in in-cylinder temperature, respectively (Qian et al. 2015). It is stated that the increasing the ethanol premixed ratio delays the phasing of combustion and reduces NO_x emission to an extremely low level, and hence the alcohol fuel becomes a good choice as LRF for RCCI engine (Zhu et al. 2015). The methanol–diesel combination in the RCCI engine emits low NO_x emission vis-à-vis gasoline–diesel pair (Li et al. 2016) which is attributed to reduced local combustion peak temperature and equivalence ratio. However, in general, CO and HC emissions increase (Tutak 2014; Işık and Aydın 2016) with ethanol fuel. In RCCI mode, it is found that the isobutanol–diesel blend is capable of mitigating CO, HC, NO_x, and particulate matter emissions vis-à-vis gasoline–diesel combination (Pan et al. 2020). The isobutanol–diesel retards the combustion phase with higher mean in-cylinder temperature along with the longer ignition delay and lower rate of pressure rise vis-à-vis gasoline–diesel. Recently, alcohol fuels are more focused as LRF for the RCCI

engine because of their superior physical and chemical properties (Liu et al. 2018; Zheng et al. 2018).

5.3.1.2 Biodiesel–Alcohol Blends

Biodiesel and higher alcohols have gained popularity among the other alternative fuels for diesel engines due to their renewable characteristics. It is concluded that adding the higher alcohols to biodiesel fuel lowers the density and viscosity of biodiesel and hence enhances the atomization and auto-ignition characteristics. It also assists the combustion process to occur in semi-LTC with reduced NO_x emissions (Atmanli and Yilmaz 2020). As shown in Fig. 5.4, the combination of higher alcohols has lowered the NO_x emission significantly than that of diesel (D) and waste cooking biodiesel (WB).

It is showed that the particle number concentrations are significantly reduced when two fuel-bound oxygen fuels, namely biodiesel and ethanol are used (Su et al. 2013). This explains the benefit of the fuel oxygen content in decreasing the PM emission. n-butanol reduced the NO_x and soot emissions by 75% and 98%, respectively, compared to those of diesel fuel in LTC mode due to low-combustion temperature and oxygen content. However, it is reported that an incomplete combustion during the premixed phase of combustion increased the CO and HC emissions (Soloiu et al. 2013). Use of *n*-butanol with high-pressure direct injection is suggested for LTC operation compared to diesel fuel (Han et al. 2013). The *n*-butanol decreases soot emission due to low boiling point, low viscosity, and higher latent heat of evaporation and significant improvement in the fuel–air mixing. As n-butanol easily blends with diesel (Rakopoulos et al. 2010; Merola et al. 2014) because of its less hydrophilicity
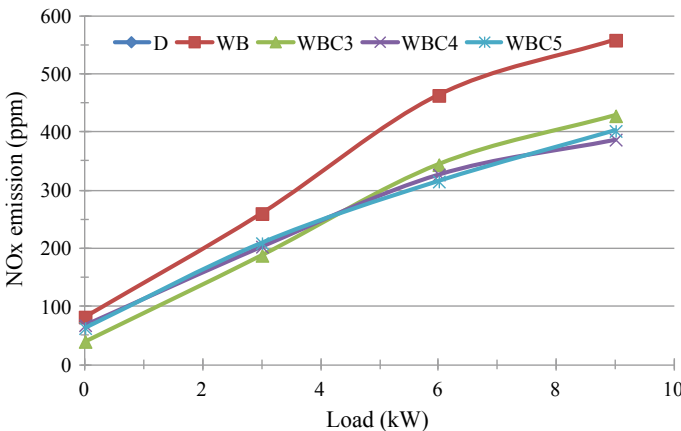

Fig. 5.4 NO_x emission from the various fuels (Atmanli and Yilmaz 2020). Legend: D—Diesel, WB—waste cooking biodiesel, WBC3—biodiesel + propanol, WBC4—biodiesel + *n*-butanol and WBC5—biodiesel + *n*-butanol

and higher miscibility nature compared to ethanol, n-butanol has good potential for LTC engines. Usage of alcohol fuels like n-butanol reduces the particulate matter emission to nearly zero levels (Han et al. 2013) and also reduces PM emission significantly even at a higher rate of EGR rate (Huang et al. 2016).

5.3.1.3 Gasoline–Alcohol Blends

The most important drawback of the HCCI engine is the extension of its operating range over a wide range of engine loads. This can be surmounted by employing alcohol–gasoline fuel blends with the optimal start of injection and blend ratio (Turkcan et al. 2014). In this study, ~80% of the total fuel (of the ethanol–gasoline blend) is injected in suction stroke, and the balance fuel is injected towards the later stage of compression stroke to control the ignition timing. It is concluded that for the fixed start of injections, the blend ratio affected the control of HCCI combustion phases significantly. However, *n*-butanol–gasoline blend auto-ignites earlier vis-à-vis ethanol–gasoline blends and reduced the combustion duration (He et al. 2015). *n*-butanol–gasoline blends also decreased the indicated mean effective pressure (IMEP) and indicated thermal efficiency (ITE).

5.3.2 Ternary Blends

In order to avoid the separation of ethanol from diesel fuel, an emulsifier or a surfactant is essential for increasing the premixed ratio of ethanol (Satgé De Caro et al. 2001; Xing-Cai et al. 2004). Fortunately, biodiesel stabilizes the diesel and ethanol mixture and helps in achieving a homogeneous mixture of ethanol–diesel blends (Fernando and Hanna 2005; Kwanchareon et al. 2007). The increase in smoke emission at higher load during LTC operation can be mitigated with the help of oxygenated fuels like biodiesel, and hence, it extends the higher operational load limit of LTC engines (Ickes et al. 2009). It is proved that biodiesel and ethanol blends reduce the smoke emission vis-à-vis conventional diesel combustion (Xue et al. 2011; Zhu et al. 2011). In an investigation, with the blends of ethanol–diesel–biodiesel (waste cooking oil) and EGR (Fang et al. 2013b), among the various blends of biodiesel–ethanol–diesel, it is observed that the ethanol blends lower the NO_x and smoke emissions about 8.55 and 31.79% (for BDE10—blend of 10% ethanol + 10% biodiesel + remaining diesel) and 23.08 and 73.44% (for BDE20—blend of 20% ethanol + 10% biodiesel + remaining diesel) due to lower energy release and higher latent heat of evaporation of alcohol fuel, respectively. Similar kinds of results, i.e., decrease in NO_x and smoke emissions and increase in HC and CO emissions, are also reported with diesel–rape seed biodiesel–ethanol blends (Pidol et al. 2012).

In ethanol RCCI combustion mode, it is observed that the engine knock is completely eliminated with reduced heat losses (Işık and Aydın 2016). Increase in quantity of ethanol reduced NO emission for all the tested fuel blends. BSFC is

found to increase in 30% ethanol RCCI operation for all fuels vis-à-vis 50% ethanol RCCI operation. In 50% ethanol RCCI operation, the BSFC is comparable to that of single fuel mode. This shows the effect of blending modes on the performance of the engines. It is shown that 5% rice wine alcohol with 75% diesel and 20% neem methyl ester increases the brake thermal efficiency by 8% and decreases the brake specific fuel consumption by 3.33% compared to those of diesel fuel. However, NO_x emission increased because of the presence of oxygenated biodiesel. The NO_x emission of 20, 5, and 10% biodiesel fuel (with 5% rice wine and remaining fraction is diesel) are noted to be 6.4%, 4.26%, and 2.14% higher than vis-à-vis base line diesel fuel (Reang et al. 2020).

5.3.3   Quaternary Blends

The experimental investigation (Appavu et al. 2019) established that the use of higher alcohol like pentanol as a quaternary blend with diesel, biodiesel, and vegetable oil overcomes the demerits involved with neat biodiesel operation. It is noted that at full load condition, the quaternary blends reduced the NO_x emission by 11.23%. This is ascribed to higher latent heat of vaporization of the blends which caused LTC, eventually decreasing the NO_x emission. The NO_x emission is found to be less for all the pentanol blends (from DBOP10 to DBOP40) compared to that of B100 (neat biodiesel—refer Fig. 5.5). However, increasing the pentanol concentration increased the NO_x emission while it decreased hydrocarbon, carbon monoxide, and smoke emissions. In another experimental investigation (Yesilyurt et al. 2020), the various fuel blends such as binary (diesel and biodiesel), ternary (diesel,
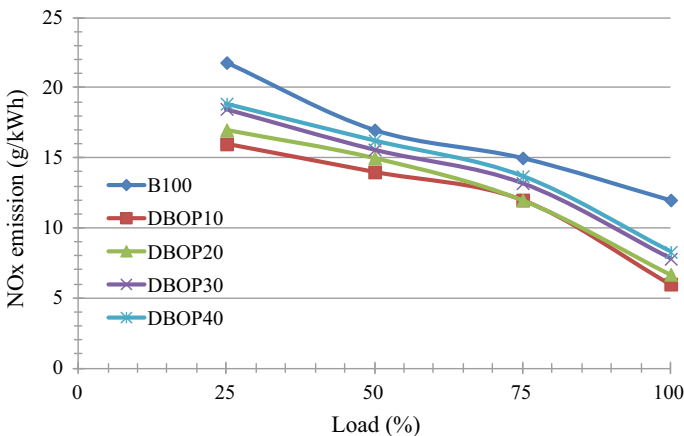

Fig. 5.5 NO_x emission variation for various tested fuels (Appavu et al. 2019)

biodiesel and vegetable oil) and quaternary blends (diesel, biodiesel, vegetable oil and isopentanol/isopropanol/n-butanol) are considered for the study.

The brake thermal efficiency of all quaternary blends is observed to be higher than B100, which increases with increasing the pentanol concentration. Increasing the concentration of pentanol in blend increased NO_x emission and reduced CO, HC, and smoke emissions vis-à-vis diesel fuel. It is also observed that diesel–gasoline–n-butanol blends increased the brake-specific fuel consumption, CO and HC emissions and reduced NO_x and soot emissions (Huang et al. 2016). In RCCI mode, diesel–biodiesel–ethanol–gasoline blends increased the peak pressure at higher loads, decreased both the NO_x (below EURO VI) and smoke emissions and increased CO and HC emissions (Benajes et al. 2015). The effect of alcohol blends on LTC engines is summarized and shown in Table 5.3.

Table 5.3 Summary of the effect of alcohol fuel on LTC engines

Blend types	Key inferences
Binary blends	• Decrease in peak cylinder pressure and heat release for lean mixture (Maurya and Agarwal 2014) • *n*-butanol gasoline blends shortens the combustion duration (less than 15° CA) and advances the auto-ignition • Decrease in NO_x and increase in CO and HC emission are observed • Increase in combustion efficiency (8.3%) and decrease in NO_x (26%), soot (71%), CO and HC emissions (~one third) in RCCI mode (Pedrozo et al. 2016) • Gasoline-n-butanol blends decrease NO_x, smoke, CO, HC emissions (Huang et al. 2016)
Ternary blends	• Ethanol–diesel–biodiesel (waste cooking oil) blends result in a decrease in BSFC and similar brake thermal efficiency • A decrease in NO_x and soot emission and an increase in CO (maximum of 100%) and HC (by 600 ppm) emission • Ethanol RCCI reduced engine knocking (Işık and Aydın 2016) • Increase in fuel consumption, BTE, peak cylinder pressure, and peak heat release rate in RCCI mode (Işık and Aydın 2016) • Shorter combustion duration and ignition delay, however, combustion duration increases with increase in premixed ratio • It is possible to decrease CO and HC emission by increasing alcohol content
Quaternary blends	• Higher brake thermal efficiency can be obtained • In RCCI mode, it is possible to achieve NO_x emission comply EURO VI norms • It is possible to decrease CO and HC emission by optimizing the alcohol content

5.4   Summary

The detailed discussion on alcohol fuels reveals that the alcohol fuels are capable of achieving low-temperate combustion by utilizing the entire advantages of this combustion concept. The oxygen content of alcohol fuel helps solve one of the major drawbacks of LTC such as higher CO and HC emissions. The alcohol fuels are reported to widen the operating load range of LTC. Thus, the various alcohol fuels become more suitable for LTC, and the conclusion of the chapter is presented in the next section.

5.5   Conclusions

This chapter provided the essential details of the alcohol fuel as alternate fuels for internal combustion engines. Alcohol fuels are characterized by their renewability, closer to the properties of gasoline, better adaptability with diesel and advantages of emission reduction. This chapter explained the potential of various alcohol fuels in terms of emission reduction when it is adapted to low-temperature combustion techniques. The alcohol fuel is found to be suitable for any mode of LTC such as HCCI, PCCI, PPC, and RCCI. The fuels are used without major or no modification of the existing engines. Moreover, alcohol fuels are one of the appropriate alternate fuels for the HCCI engine which effectively utilizes the full merits of LTC. The higher octane number, oxygen content, and lower latent heat of evaporation of alcohol fuels suit the requirement of reactivity stratification in RCCI engines. Alcohol fuels are capable of overcoming the major drawback of extending the operational range of LTC engines. Therefore, it is concluded that the alcohol fuel has the potential as effective alternative fuels and for reducing the harmful emissions from internal combustion engines especially in the LTC mode.

Nomenclature

B20	80% diesel and 20% biodiesel blend
BSNO	Brake-specific nitric oxide
BTE	Brake thermal efficiency
CI	Compression ignition
CO	Carbon monoxide
CO_2	Carbon dioxide
EGR	Exhaust gas recirculation
FFV	Flexible fuelled vehicles
HC	Hydrocarbon
HCCI	Homogeneous charge compression ignition

HRF   High-reactivity fuel
IMEP   Indicated mean effective pressure
ITE   Indicated thermal efficiency
LRF   Low-reactivity fuel
LTC   Low-temperature combustion
MTBE   Methyl tertiary butyl ether
PCCI   Premixed charge compression ignition
PPC   Partially premixed combustion
NO_x Oxides of nitrogen
RCCI   Reactivity-controlled compression ignition
SI   Spark ignition
WB   Waste cooking biodiesel.

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