


Experimental investigation of performance and emissions of a VCR diesel engine fuelled with *n*-butanol diesel blends under varying engine parameters

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Abstract The continuous rise in the cost of fossil fuels as well as in environmental pollution has attracted research in the area of clean alternative fuels for improving the performance and emissions of internal combustion (IC) engines. In the present work, *n*-butanol is treated as a bio-fuel and investigations have been made to evaluate the feasibility of replacing diesel with a suitable *n*-butanol-diesel blend. In the current research, an experimental investigation was carried out on a variable compression ratio CI engine with *n*-butanol-diesel blends (10–25% by volume) to determine the optimum blending ratio and optimum operating parameters of the engine for reduced emissions. The best results of performance and emissions were observed for 20% *n*-butanol-diesel blend (B20) at a higher compression ratio as compared to diesel while keeping the other parameters unchanged. The observed deterioration in engine performance was within tolerable limits. The reductions in smoke, nitrogen oxides (NO_x), and carbon monoxide (CO) were observed up to 56.52, 17.19, and 30.43%,

respectively, for B20 in comparison to diesel at rated power. However, carbon dioxide (CO₂) and hydrocarbons (HC) were found to be higher by 17.58 and 15.78%, respectively, for B20. It is concluded that *n*-butanol-diesel blend would be a potential fuel to control emissions from diesel engines.

Keywords Additive · *n*-Butanol-diesel blend · Emission · NO_x · Performance · Smoke

Nomenclature

BSEC	Brake specific energy consumption
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CA btdc	Crank angle before top dead centre
CI	Compression ignition
CO	Carbon monoxide
CN	Cetane number
CO ₂	Carbon dioxide
HC	Hydrocarbons
IC	Internal combustion
NO _x	Nitrogen oxides
PM	Particulate matter

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Introduction

Development of alternative and green fuels for IC engines has attracted substantial research in recent years. Diesel engines are more efficient than SI engines but suffer from high smoke emission. Smoke emission can be controlled by improving fuel, by improving the combustion process, or by suitable after-treatment. Out of these options, use of improved fuels would be an easy solution as it would be applicable for new as

well as old engines without structural modifications (Curran et al. 2001; Rahman et al. 2013).

In diesel engines, various alternative fuels/additives such as alcohols (Chen et al. 2012; Kumar et al. 2013; Putrasari et al. 2013; Lapuerta et al. 2008; Sayin 2010; Sayin et al. 2010; Can et al. 2004), biodiesels (Palash et al. 2013; Mohsin et al. 2014; Klein-Douwel et al. 2009), and vegetable oils (Agarwal and Agarwal 2007; Corsini et al. 2015; Bayindir et al. 2017; Jain et al. 2017) can be used to improve performance and emissions. Improved fuels can also be obtained by adding suitable percentages of these alternatives to diesel. Among them, oxygenated additives have drawn more attention because of the capability to reduce emissions without much affecting the engine performance (Rakopoulos et al. 2014; Rajasekar et al. 2010; Choi and Reitz 1999). Oxygenated additives are renewable in nature and support the local agriculture industry (Chen et al. 2012; Jang et al. 2012; Tutak 2014). Alcohols are bio-oxygenated compounds. The presence of oxygen, lower viscosity and higher volatility of alcohols make them suitable fuels for diesel engines. Among alcohols, *n*-butanol has a higher heating value and lower latent heat of vaporization. Its cetane number is higher than that of methanol and ethanol, and it is miscible with diesel completely. The calorific value of *n*-butanol is also higher than that of methanol and ethanol. This implies that the same amount of *n*-butanol produces higher power from the same engine running on a methanol/ethanol-diesel blend (Atmanli et al. 2013; Choi and Jiang 2015; Yilmaz et al. 2014). *n*-Butanol can be produced from fossil matter as well as from waste biomass (namely bio-butanol); however, the properties of *n*-butanol produced from both sources are the same (Jang et al. 2012; Dogan 2011; Qureshi et al. 2010). The overall emission of CO₂ due to combustion of *n*-butanol is reduced because of utilization of CO₂ by growing feedstock of biomass (Chen et al. 2014). On the whole, there is strong evidence from past research that the addition of *n*-butanol with diesel, biodiesel, vegetable oil, and diesel-biodiesel/vegetable blends results in improved emission.

In an experimental investigation, combustion characteristics were analyzed with 30, 40, and 50% blends of ethanol-diesel and butanol-diesel blends, and it was found that combustion and emission characteristics of butanol-diesel blends were better than that of ethanol-diesel blends. Also, the blending of butanol in diesel can be done without any surface-active agent (Yamamoto et al. 2012). Substitution of 10% ethanol and *n*-butanol in diesel on energy basis by the fumigation method resulted in reduced nitrogen oxides (NO_x) and particulate matter (PM), but with increased levels of carbon monoxide (CO) and hydrocarbons (HC). The engine performance was also found to have deteriorated. However, the *n*-butanol-diesel blend showed better emission results than the ethanol-diesel blend (Lopez et al. 2015).

Low-butanol blends with diesel (up to 5% by volume) are very effective in reducing NO_x and PM under 50 nm size

(Zoldy et al. 2010; Choi et al. 2015). Maximum smoke reduction of 21.75% was observed with 4% *n*-butanol blend, and maximum NO_x reduction of 5.03% was observed for 2% *n*-butanol blend (Sahin and Akshu 2015). Experimental investigations with *n*-butanol-diesel blends and *n*-butanol fumigation have been performed at low ratios of *n*-butanol (2, 4, and 6%) for engine performance and emission. The brake specific fuel consumption (BSFC) was found to increase for all combinations except 2% blending of *n*-butanol. Although smoke was reduced, there was an increase of HC and CO₂ for all combinations. The NO_x was reduced for all combinations except 4 and 6% blends. It was concluded that 2% blending of *n*-butanol in diesel has more potential for reducing emissions than that of fumigation of *n*-butanol in diesel (Sahin et al. 2015). The blending of butanol along with some cetane number (CN) improver to diesel has also been investigated. Such blends were reported to result in decreased smoke and CO and HC emissions and increased NO_x emission. However, with increased percentage of butanol in blends, NO_x was found to decrease with an associated increase in HC (Kumar et al. 2013). Experimental research with *n*-butanol-diesel blends (5–20%) recommends that blending of *n*-butanol should be equal to or less than 10% for reduced emissions. The result shows that for B5 and B10, PM size under 50 nm is reduced to 18.5 and 31.1%, respectively, whereas for B20 it increased to 20.5% (Choi et al. 2015). On a positive note, these blends have resulted in improved engine performance. Research has indicated that emissions of smoke, NO_x, and CO reduces while HC increases with *n*-butanol-diesel blends (Dogan 2011).

The blending of 20% butanol by volume in diesel (B20) has been reported to result in almost smokeless conditions with a slight increment in NO_x emission and a small increment in the BSFC (Merola et al. 2014). Maximum smoke and CO reductions reported for B20 were 85.1 and 71.4%, respectively. However, NO_x and HC increased significantly with B20 (Siwalea et al. 2013). It was reported that up to 40% mass blending of all isomers of butanol resulted in lesser smoke and higher HC and CO emissions than that of diesel (Fushimi et al. 2013). It was reported that the 40% *n*-butanol-diesel blend reduces smoke because of a lower equivalence ratio and higher NO_x due to longer time duration of the high-temperature zone in the combustion chamber. It was concluded that higher *n*-butanol-diesel blend with the medium rate of exhaust gas recirculation (EGR) is capable of maintaining a high brake thermal efficiency (BTE) with reduced smoke and ultra low NO_x emission (Chen et al. 2014). It was reported that emissions of diesel engines run on *n*-butanol-diesel blends (20–40%) varied with loads. The increment in BSFC and BTE was 7.3 and 2.7%, respectively, for B40 at rated power. For B40, smoke was found to reduce up to 50.3% and NO_x increased up to 15.8% at rated power than that of diesel (Chen et al. 2013). The blending of 20% *n*-

butanol resulted in significant reduction in PM with a negligible change in engine performance (Zhang et al. 2016; Ibrahim 2016; Liu et al. 2013). When neat *n*-butanol was injected in a diesel engine, the emissions of NO_x and smoke reduced substantially but HC and CO emissions were increased (Zheng et al. 2015). Experimental investigation on the effect of pilot injection mass and timing on performance and emission of a diesel engine running on *n*-butanol-diesel blends was done. It has been reported that addition of *n*-butanol increases BSFC and reduces BTE. The more the injection timing is advanced, more is the reduction in smoke and NO_x. Increasing the mass of pilot injection reduces smoke and increases NO_x emissions (Huang et al. 2015). Experimentally, reducing smoke and NO_x without affecting the engine performance was tried by management of blending of fuel, injection pressure, injection timing, and the EGR rate. It was found that for diesel at higher injection pressure and retarded injection timing, smoke reduced and NO_x increased. Better atomization and a high mixing rate were found as main factors leading to reduced smoke. Increased ignition delay and higher volatility of *n*-butanol-diesel blends (B20 and B40) provide sufficient time for better mixing of fuel with air before starting the combustion. The blending of *n*-butanol at advanced ignition and at low injection pressure creates conditions similar to those of premixed low-temperature combustion, in which approximately all fuel is injected before the start of combustion and this in turn reduces smoke and NO_x emissions (Valentino et al. 2012).

Experimental studies were conducted on a diesel engine at steady-state conditions with 8–24% (v/v) *n*-butanol-diesel and biodiesel (30%)-diesel blends and at transient conditions with *n*-butanol (25%)-diesel blends. For both the conditions, results indicate that *n*-butanol-diesel blends reduce emissions without much affecting engine performance. In steady-state conditions, emissions of smoke and CO reduced significantly and NO_x reduced slightly. On the other hand, increase in HC emissions was reported for *n*-butanol blends, this increment being higher and higher with increasing percentage of *n*-butanol in the blends (Rakopoulos et al. 2010a, b, c, 2011a, b). The results for transient conditions were found to be similar except that NO_x was reported higher for blends than that of diesel (Rakopoulos et al. 2010c, 2011b).

In an experimental work with 12% butanol and 8% other compounds blended with diesel exhibited better combustion efficiency and emitted approximately zero smoke as compared to neat diesel (Zhou et al. 2014). Investigations with 10% addition of butanol (by volume) with vegetable oil-diesel (20:70) resulted in decreased CO₂ and HC, but with increased BSFC, NO_x and CO. The performance of the engine was found to be affected by these ternary blends (Atmanli et al. 2013, 2014, 2015a). In an experimental work, as the percentage of *n*-butanol in diesel-vegetable oil blends increased, emission of NO_x increased while emission of CO and HC decreased drastically. However, the

performance of the engine deteriorated significantly (Atmanli et al. 2015b). Mixing of 20% *n*-butanol with diesel-biodiesel blend showed similar results to Atmanli et al. (2015b), but with an increment in CO and decrement in NO_x emissions (Atmanli 2016). It was found that butanol-biodiesel blends (5–10%) reduce the NO_x emission in comparison to biodiesel. Low concentration of butanol in biodiesel (5–10%) results in lower CO and higher NO_x while higher concentration of butanol in biodiesel (20%) results in higher CO and lower NO_x in comparison to diesel (Yilmaz et al. 2014). In another study, effects of mixing *n*-butanol and diethyl ether in biodiesel-diesel blends on engine performance and emissions were observed. It was reported that 10% blending was more effective than 5%. The mixing of 10% *n*-butanol with biodiesel-diesel reduces smoke, NO_x and CO, by 27, 8.8, and 30.7%, respectively, as compared with biodiesel (20%)-diesel blend. The BSFC for 10% *n*-butanol-biodiesel-diesel ternary blend was also found to be up to 3.9% lesser than that of biodiesel (20%)-diesel blend (Imtenan et al. 2015).

Majority of research agrees that with increasing *n*-butanol percentage in *n*-butanol-diesel blends, BSFC increases and BTE decreases. However, variations in BSFC and BTE also depend on base fuel and operating parameters. Literature review shows that in general, the addition of *n*-butanol in diesel or biodiesel/vegetable oil-diesel blends reduces smoke significantly, reduces CO, reduces NO_x marginally, and increases HC. Out of these, some of the studies reported higher NO_x emission for *n*-butanol-diesel blends. The NO_x emission mainly depends on two factors, namely (i) peak temperature in the combustion chamber and (ii) time duration of sustaining this peak temperature. The conflicting results pertaining to NO_x may be because of variations in the above two factors as well as other factors including *n*-butanol content, engine operating conditions, engine setup, and the use of different injection techniques, injection pressure, etc. (Huang et al. 2015; Valentino et al. 2012; Giakoumis et al. 2013). With these technical merits of *n*-butanol, several researchers have explored the use of *n*-butanol in diesel engines in the past few years. However, the study on the effect of *n*-butanol-diesel blend on engine parameters is limited. This is the motivation for the research work presented in this paper. Moreover, the extensive research on emissions with the use of various blends has shown to have a lot of variation, which makes it difficult to come to a conclusion about an optimal blend. This forms another motivation for current research.

The current research thus focuses on experimental investigation on the use of *n*-butanol-diesel blends in diesel engines to determine the optimum blending ratio and operating conditions of the engine that can be used universally with existing engines. The effect of blending of *n*-butanol in diesel on the compression ratio, injection timing, and injection pressure has been analyzed. This study therefore considers two variables: (i) *n*-butanol-diesel blends and (ii) engine parameters for optimum engine performance and emissions.

Experimental setup and methodology

Test engine

A single-cylinder, four-stroke, constant-speed, water-cooled, direct-injection, variable-compression-ratio (VCR) diesel engine was used for the experiments. The technical specifications of the engine and other measuring equipments are shown in Table 1 and Table 2, respectively.

The engine is coupled with an air-cooled eddy current dynamometer. A lifting and lowering cylinder block arrangement has been used for varying the compression ratio without stopping the engine and without altering the combustion chamber geometry. To analyze and display results on computer, LABVIEW-based software package is incorporated. The schematic layout and pictorial view of the experimental setup are shown in Fig. 1. Fresh lubricating oil was filled in the oil sump before conducting the experiments.

Emission measurements

Exhaust gas opacity was measured using a smoke opacimeter (make: AVL Austria, model: 437C). The exhaust gas composition was measured using an exhaust gas analyzer (make: I3SYS Bangalore, India; model: EPM1601). The basic principle for measurement of CO₂, CO, and HC emissions is non-dispersive infrared radiation (NDIR) and electrochemical method for NO_x measurement.

Fuel preparation

Different *n*-butanol-diesel blends on volume basis were prepared using a magnetic stirrer and glassware for blending and storage. The *n*-butanol used was of 99.0% purity. Several blends of varying concentrations were prepared to range from 0% (diesel only) to 25% (*n*-butanol) denoted by B0, B10, B15, B20, and B25. A listing of properties of diesel and *n*-butanol is given in Table 3. Table 4 shows the calculated cetane number of different *n*-butanol-diesel blends.

Table 1 Specification of the test engine

Engine make	Diesel-Kirloskar (TV1) (crank start and self-start)
No. of cylinder	01
Stroke	4 stroke
Cooling	Water cooled
Rated power	3.75 kW
Max. rpm	1500
Stroke and bore	110 and 87.5 mm
Capacity	660 cm ³

Test procedure

Experiments were performed at a constant engine speed of 1500 rpm and at eight engine loads varying from zero to maximum engine power output (100% of rated power). The engine was run with diesel-*n*-butanol blends for at least 30 min before each set of readings to obtain a constant value of exhaust gas temperature (This ensured steady-state condition of the engine). After completion of the tests with one blend, the remaining blend was purged from the fuel tank and fuel line in order to prevent mixing and alteration of the actual ratio of the blends.

The tests were conducted in two phases. In the first phase, the tests were conducted with diesel and *n*-butanol-diesel blends on normal settings of compression ratio (18.5), injection timing (23° CA btde), and injection pressure (210 bar) specified by the manufacturer. From this set of data, the optimum blend (B20) was selected. In the second phase, tests were conducted on varying compression ratios, injection pressures, and injection timings to optimize these parameters for B20.

Calculation of engine performance parameters and properties of *n*-butanol-diesel blends

The following formulae were used for the calculation of various performance parameters and properties of fuels. The formulae presented in Eqs. (1) and (2) were used to calculate the calorific value and cetane number of *n*-butanol-diesel blends, respectively. Formulae presented in Eqs. (3), (4), and (5) were used to calculate brake power, BTE, and brake specific energy consumption (BSEC), respectively, of diesel and blended fuels.

$$\begin{aligned} \text{Calorific value of blend } C_v \text{ (kJ/kg)} \\ = \left\{ \left(\frac{v_b}{v} \times \rho_b \times C_{vb} \right) + \left(\frac{v_d}{v} \times \rho_d \times C_{vd} \right) \right\} / \\ \left\{ \left(\frac{v_b}{v} \times \rho_b \right) + \left(\frac{v_d}{v} \times \rho_d \right) \right\} \end{aligned} \quad (1)$$

$$\begin{aligned} \text{Cetane number of blends (CN)} \\ = \left(\frac{v_b}{v} \times \text{CN}_b \right) + \left(\frac{v_d}{v} \times \text{CN}_d \right) \end{aligned} \quad (2)$$

$$\text{Brake power, BP (kW)} = T(2\pi N) / (60 \times 1000) \quad (3)$$

$$\begin{aligned} \text{Brake thermal efficiency, BTE (\%)} \\ = \left\{ \text{BP} \times 3600 / (m_f \times C_v) \right\} \times 100 \end{aligned} \quad (4)$$

Table 2 Specifications of measuring equipments and formulae used to calculate different quantities

Dynamometer	Make: Power MAG, torque rating available: 3.75 kW, speed: 1500 RPM
Torque/load measurement: torque (T) Nm = load (kg) $\times r$ (m) ($r = 0.16$ m) $\times 9.81$	Transducer: load cell
Fuel rate measurement	The principle of working of this unit is based on loss of weight. The microcontroller notes the amount of loss of weight for a known interval of time and calculates the rate of fuel.
Intake air measurement/air flow indicator: air flow (m^3/s): $Q = C_d A \{2gh(\rho_w - \rho_a)/\rho_a\}^{1/2}$, where C_d = coefficient of discharge = 0.62 A = area of orifice in m^2 (orifice dia. = 20 mm) $g = 9.81$ m/s^2 h = manometer deflection in m ρ_w = density of water ρ_a = density of air	The atmospheric air is sucked into the engine through an orifice provided in the intake side of the air box. The pressure drop across the orifice is measured using a differential pressure sensor (Piezo resistive type). The differential pressure sensor is calibrated for manometer deflection in mm. With this as input, the unit calculates air flow in m^3/s .
Temperature measurement (5-channel indicator)	Sensor: RTD (Pt100), range of temperature: 0–400 °C, resolution: 0.1 °C
High-temperature indicator (for exhaust gas)	Sensor: thermocouple (K-type), range of temperature: 0–800 °C, resolution: 1 °C
Water flow measurement	Type of transducer: turbine flow type, range: 0–99.9 cm^3/s , resolution: 0.1 cm^3/s
Unit for measurement of diesel injection pressure (DI)	Sensor: piezoelectric (10,000 PSI for DI), range: 0–2000 bar, resolution: 1 bar
Computer connectivity of instrument	All the indicators are attached to a RS232 to RS485 converter whose output is attached to Comm1 port of the computer.

$$\begin{aligned}
 & \text{Brake specific fuel consumption, } BSEC \left(\text{kg/kW-h} \right) \\
 & = m_f \times C_v / BP \tag{5}
 \end{aligned}$$

where

T = brake torque (i.e., load) (Nm), N = r.p.m., m_f = mass of fuel consumption (kg/h), v_b and v_d = volume percentage of *n*-butanol and diesel in blend, $v = v_b + v_d$, CN_b and CN_d = cetane

number of *n*-butanol and diesel, C_v = calorific value of blend (kJ/kg), C_{vb} and C_{vd} = calorific value of *n*-butanol and diesel (kJ/kg), ρ_b and ρ_d = density of *n*-butanol and diesel (kg/m^3), CN = cetane number of blends

Uncertainty analysis

During the observations, there were possibilities of error/uncertainty because of operating conditions, calibration of equipments, accuracy of measuring equipments, human errors, and planning of experiments (Moffat 1988; Plint and Martyr 1999). The uncertainties of various parameters were calculated and are shown in Table 5.

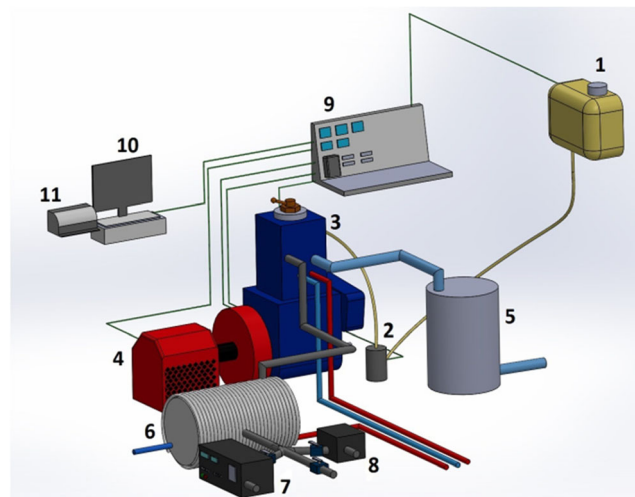


Fig. 1 Schematic of engine setup

Table 3 Properties of *n*-butanol and diesel (Kumar et al. 2013)

Property	<i>n</i> -Butanol	Diesel
Density at 20 °C	0.8098	0.829
Boiling point (°C)	117–118	187–343
Cetane number	≈25	40–55
Energy density (MJ/L)	27–29	46
Lower heating value (MJ/kg)	36.6	44.8
Heat of vaporization (MJ/kg)	0.43	0.23–0.60
Flash point (°C)	35	74
Viscosity (40 °C) (10^{-3} Pa s)	2.593	2.95

Table 4 Cetane number of *n*-butanol-diesel blends

S. no.	Fuel/blend	Cetane number
1	Diesel	55.50
2	<i>n</i> -Butanol	25.00
3	B10	52.45
4	B15	50.93
5	B20	49.40
6	B25	47.88

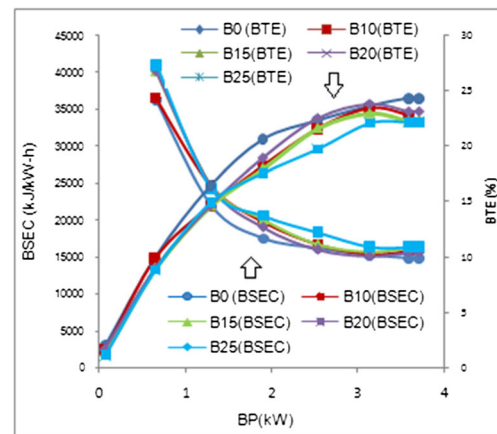
Results and discussion

Performance of engine with *n*-butanol-diesel blends

Tests were conducted with diesel and *n*-butanol-diesel blends with the following engine settings: 18.5 compression ratio (CR), 210 bar injection pressure, and 23° CA btdc injection timing. The variations in engine performance and emissions for diesel and blends noted at different load conditions (no load to 100% rated power) have been shown in Figs. 2, 3, 4, 5, 6, and 7. Figure 8 shows performance and emissions of the engine at full-load condition (100% rated power).

Performance characteristics with *n*-butanol-diesel blends

It can be seen from Fig. 2 that the BSEC reduces with increasing load and is lowest at full load. Figures 2 and 8 show that BSEC is higher for all *n*-butanol-diesel blends in comparison to diesel. The heating value of *n*-butanol is lesser than that of diesel. This means, for producing the same amount of power, more blended fuel is required. It can be observed from Table 4 that with an increase in *n*-butanol percentage in the blend, the cetane number of fuel decreases. Combustion of fuel with a lower cetane number increases the ignition delay period which increases accumulated fuel inside the cylinder before combustion starts. The increased delay period increases the time duration of fuel combustion at higher temperature. This in turn increases heat transfer to engine parts, and due to this, the

**Fig. 2** Variation of BSEC and BTE for *n*-butanol-diesel blends

effective energy conversion into brake power decreases. Thus, the lower heating value and the cetane number of *n*-butanol are the main factors that are responsible for increased BSEC of blended fuels (Atmanli et al. 2015a, b). At full load, the BSEC decreases for blends B10 to B20, but again increases for B25. A decrement in BSEC for blends from B10 to B20 can be attributed to better combustion with increasing *n*-butanol in diesel. On the other hand, the increase of BSEC at a higher blend is because of too high ignition delay, which leads to lower mean effective pressure. However, B20 exhibits better performance than other blends. The increment in BSEC was of 5.09% for B20 than that of diesel at full load condition (100% rated power).

Figure 2 shows the trends of BTE and Fig. 8 shows the value of BTE at full load condition. It can be observed that the BTE for *n*-butanol-diesel blends are lower as compared to diesel only. The blended fuels provide lesser heat release because of lower heating and a lower cetane number of *n*-butanol, which in turn reduces the BTE of the engine. It can be observed that for B20, the decrement in brake thermal efficiency (BTE) is lesser than that of other blends in comparison to diesel only. A loss of about 4.85% in BTE has been observed for B20 than that of diesel.

Table 5 Uncertainty of various parameters

Measured quantity	Range of experiments	Resolution	% uncertainty
BSEC	14,784–44,712 kJ/kW-h	–	±0.114
BTE	0–24.34%	–	±0.114
Smoke	1.3–98.9 HSU %	0.1%	±0.05
NO _x	15–650 ppm	1 ppm vol.	±3
CO	0.02–0.232%	0.001%	±3
CO ₂	1.8–7.75%	0.01%	±3
HC	19–72 ppm	1 ppm vol.	±5

Total uncertainty of measurements in experiment (Huang et al. 2015)

=square root of {(uncertainty of BSEC)² + (uncertainty of BTE)² + (uncertainty of smoke)² + (uncertainty of NO_x)² + (uncertainty of CO)² + (uncertainty of CO₂)² + (uncertainty of HC)²}

=√{(0.114)² + (0.114)² + (0.05)² + (3)² + (3)² + (3)² + (5)²} = 7.21%

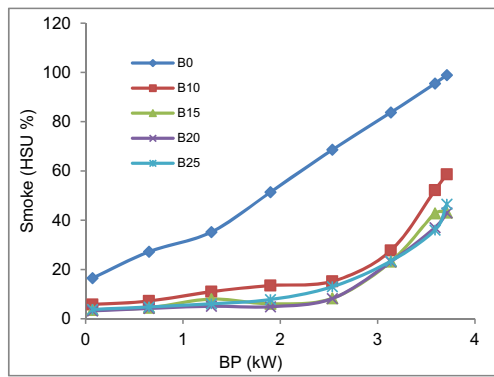


Fig. 3 Emission of smoke for *n*-butanol-diesel blends

Emission characteristics with *n*-butanol-diesel blends

Figure 3 shows the variation of smoke emission for *n*-butanol-diesel blends. Significant reduction in smoke has been observed. The increased ignition delay which provides sufficient time of fuel-air mixing and better volatility of *n*-butanol (boiling temp. 118 °C) in comparison to diesel (180–360 °C), both factors enhance the combustion quality. Also, the higher oxygen content of *n*-butanol provides enough oxygen in the fuel-rich zone which is helpful in oxidation of smoke. A reduction of 56.52% in smoke emission can be observed from Fig. 8 for B20 compared to that of diesel at full-load condition (100% rated power). However, for B15, the smoke value is the same as that of B20.

Figure 4 shows a slight decrement in NO_x for blends B10 to B20 compared to that of diesel. However, it can also be observed that there is a significant increment of NO_x for B25. The reduction in NO_x may be justified by two factors. Firstly, the blending of *n*-butanol in diesel reduces the cetane number of the blend and increases the ignition delay period. The increased delay may allow the fuel to have sufficient time to mix with air to reduce temperature in the cylinder. The reduction in the cylinder temperature results in low NO_x in comparison to diesel. Secondly, better combustion increases the peak temperature, but at the same time, the total span of diffusion combustion and total combustion reduces because of better

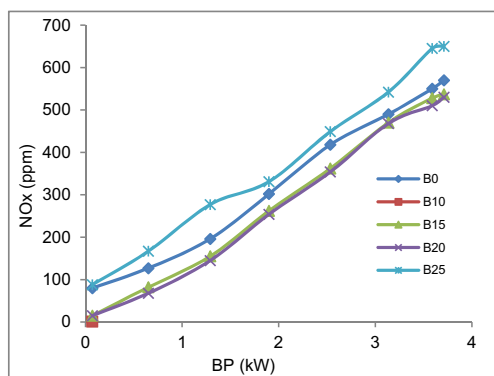


Fig. 4 Emission of NO_x for *n*-butanol-diesel blends

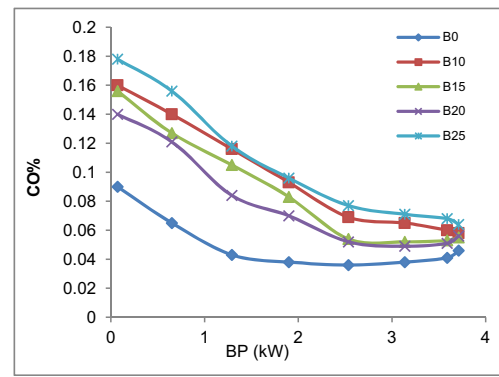


Fig. 5 Emission of CO for *n*-butanol-diesel blends

combustion flame speed. The later effect seems to be predominant in the case of *n*-butanol-diesel blends, thus reducing the retention period of peak temperature, which also reduces the NO_x emission. At a higher blend (B25), the ignition delay is too long such that a high quantity of fuel is available for combustion which results in higher peak temperature. From Fig. 8, a slight decrement of 7% in NO_x emissions can be noted for B20 compared to that of diesel only.

Figure 5 shows the CO emission for *n*-butanol-diesel blends. It can be observed that blending of *n*-butanol in diesel increases the CO emission initially and then decreases afterwards. The trends of CO are decreasing for B10 to B20 and then increasing for B25. From Fig. 8, a maximum reduction of 21.7% of CO emission can be noted for B20 compared to that of diesel at full-load condition (100% rated power). Deficiency of air at the fuel-rich zone is the most probable reason for higher CO at B25.

Figure 6 shows the CO₂ emissions for *n*-butanol-diesel blends at different load conditions. It can be observed that for B20 at higher loads, the CO₂ emission rate is higher than at low loads. From Fig. 8, a slight increment of 2.9% in CO₂ emission can be noted for B20 compared to that of diesel.

It can be observed from Fig. 7 that the emission of HC is higher for the lowest and highest blends (B10 and B25, respectively). However, it is lower for intermediate blends B15 and B20. However, the emission of HC for all blends is higher compared to that of diesel. Late combustion due to a longer

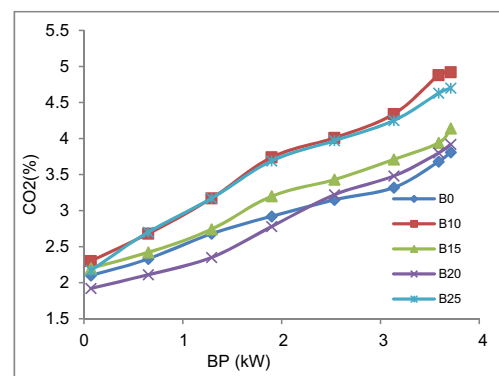


Fig. 6 Emission of CO₂ for *n*-butanol-diesel blends

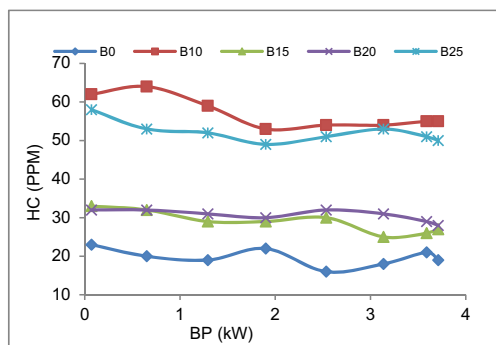


Fig. 7 Emission of HC for *n*-butanol-diesel blends

ignition delay and a low boiling point may be the reasons for higher HC emission. Because of the low boiling temperature of *n*-butanol, the amount of fuel boil off from the injector during exhaust stroke increases and in turn increases the HC emission. An increment of 47.36% in HC can be observed for B20 compared to that of diesel.

On the basis of the obtained results of performance and emissions, B20 was selected as the optimum blend of *n*-butanol with diesel.

Optimization of engine parameters for *n*-butanol-diesel blends

After selection of B20 as the fuel for further investigation, the engine was optimized for the compression ratio, injection timing, and injection pressure. The first set of tests was conducted for compression ratios ranging from 17.5 to 20.5, at constant injection timing of 23° CA bt dc, and 210 bar injection pressure. From the resulting observations, 19.5 CR was selected as optimum for B20.

The second set of tests was conducted with retarded injection timing of 21° CA bt dc at optimized CR of 19.5 and at 210 bar injection pressure. The readings were compared with data of 19.5 CR, 23° CA bt dc, and 210 bar injection pressure. The 23° CA bt dc setting was found optimum for B20 at 19.5 CR and 210 bar injection pressure.

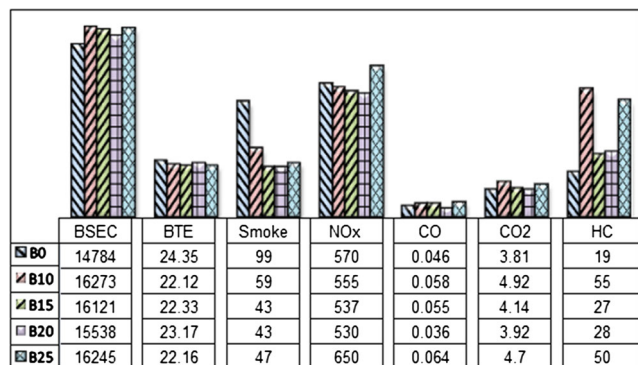


Fig. 8 Performance and emission of *n*-butanol diesel blends (100% rated power)

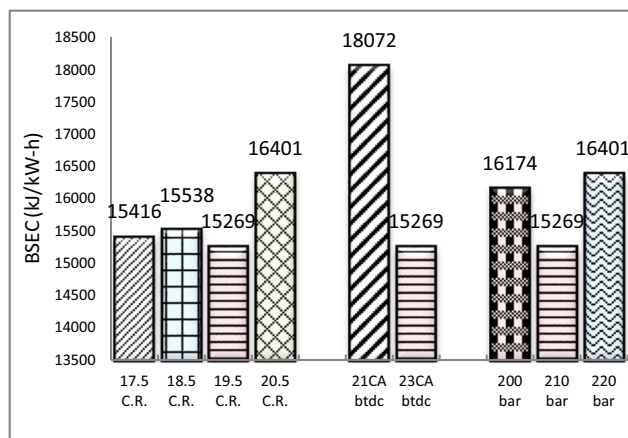


Fig. 9 BSEC at different CRs, injection timings, and injection pressures

The third set of tests was conducted with injection pressures of 200 and 220 bar at optimized CR of 19.5 and injection timing of 23° CA bt dc. These data were compared with data on 210 bar injection pressure, 19.5 CR, and 23° CA bt dc. The 210 bar injection pressure setting was found optimum at 19.5 CR and at 23° CA bt dc.

The results of these experiments are shown in Figs. 9, 10, 11, 12, 13, 14, and 15. Figures 9 and 10 show engine performance characteristics and Fig. 11 to Fig. 15 show emission characteristics for different CRs, injection timings, and injection pressures.

Performance and emission characteristics of B20 at different compression ratios

It can be observed from Fig. 9 and Fig. 10 that the engine performance at 19.5 CR is better than that of other CRs. The BSEC was lowest at 19.5 CR, and a slight increment of 1.8% in BTE was recorded at 19.5 CR compared to that of 18.5 CR at full-load condition (100% rated power). It can be observed from Fig. 11 that the smoke emission is the same for 18.5 and 19.5 CR. It can be seen from Fig. 12 that at 19.5 CR, NO_x

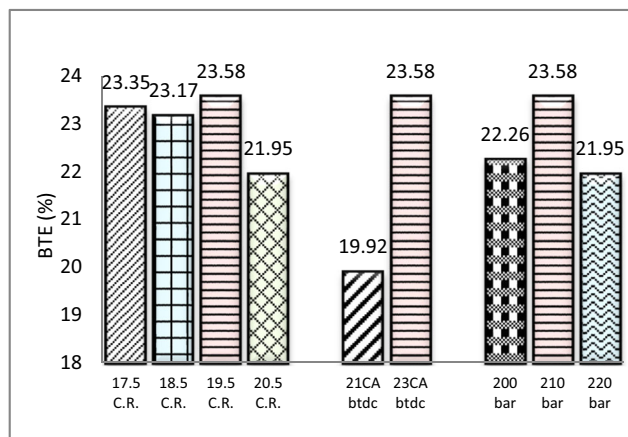


Fig. 10 BTE at different CRs, injection timings, and injection pressures

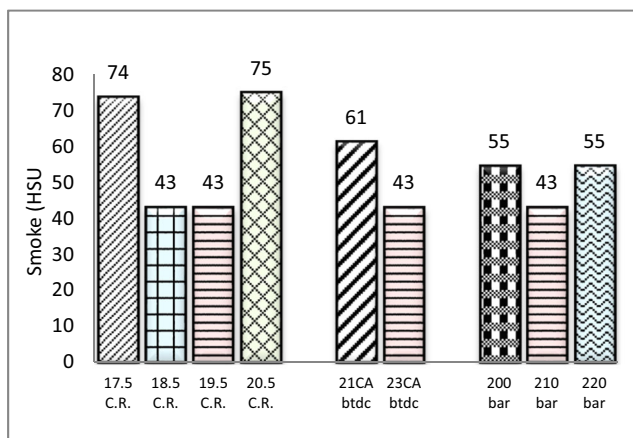


Fig. 11 Smoke emission at different CRs, injection timings, and injection pressures

emission is 10.9% lesser than that of 18.5 CR. From Figs. 13 and 15, it can be observed that at 19.5 CR, emissions of CO and HC are the lowest in the group. Moreover, at 19.5 CR, decrements of 11.1 and 21.4%, respectively, can also be noted against 18.5 CR. For 19.5 CR, CO₂ was slightly higher than that of 17.5 CR and 18.5 CR (14.3%), but less than that of 20.5 CR. On the basis of the above observations, the compression ratio of 19.5 was selected for further investigation with B20 fuel.

Performance and emission characteristics of B20 at retarded injection timing

At 23° CA btdc, BSEC was observed to be lower by 18.36% than that of 21° CA btdc and thermal efficiency was higher by 15.5% than that of 21° CA btdc at full-load condition (100% rated power). At 23° CA btdc, smoke and NO_x were lower by 42.56 and 8.5%, respectively, than that of 21° CA btdc. The CO and CO₂ were higher by 3.1 and 5.1%, respectively, for 23° CA btdc than for 21° CA btdc. The HC emission for 23° CA btdc was 9.1% lesser than that for 21° CA

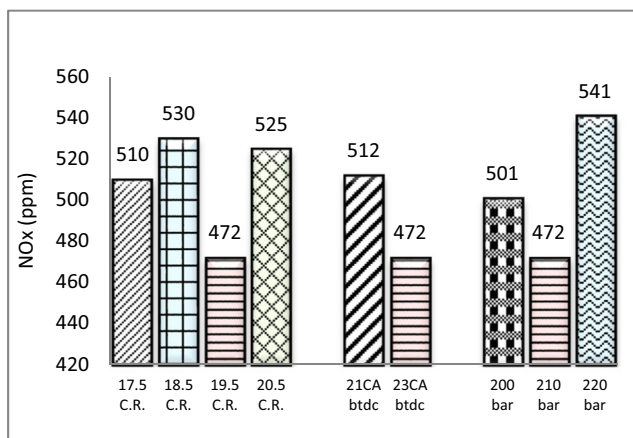


Fig. 12 NO_x emission at different CRs, injection timings, and injection pressures

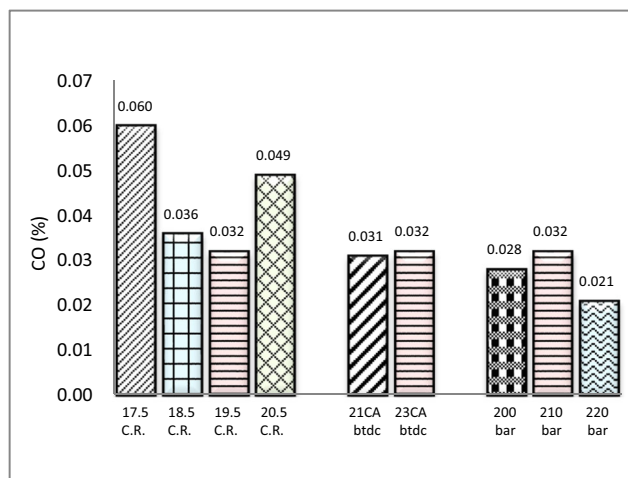


Fig. 13 CO emission at different CRs, injection timings, and injection pressures

btdc. On the basis of the above observations, 23° CA btdc was selected for further investigations.

Performance and emission characteristics of B20 at different injection pressures

BSEC at 210 bar injection pressures was found lower by 5.9 and 7.4% than that of 200 and 220 bar, respectively, at full-load condition (100% rated load). The BTE at 210 bar injection pressure was higher by 5.6 and 6.9% than that at 200 and 220 bar, respectively. Smoke at 210 bar was lower by 27% than that of 200 and 220 bar, respectively at full-load condition. There was no significant difference in NO_x emission for 210 and 200 bar; however, an increment of 14.6% in NO_x emission was noted for 220 bar compared to that of 210 bar injection pressure. Emission of CO at 210 bar injection pressure was higher by 12.5 and 34.37% than that of 200 and 220 bar, respectively. The CO₂ emission at 210 bar was almost the same as compared to 200 bar, and at 220 bar, it was higher

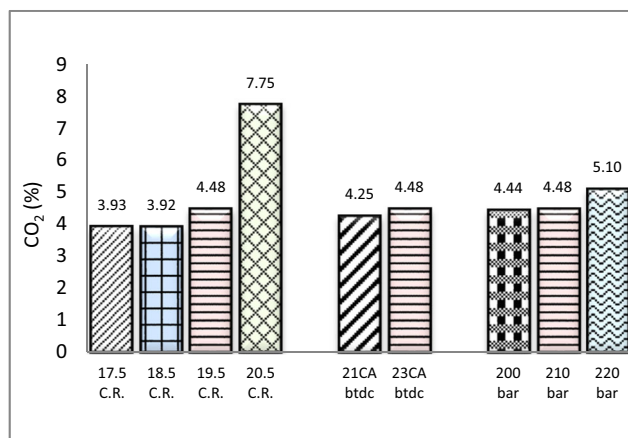


Fig. 14 CO₂ emission at different CRs, injection timings, and injection pressures

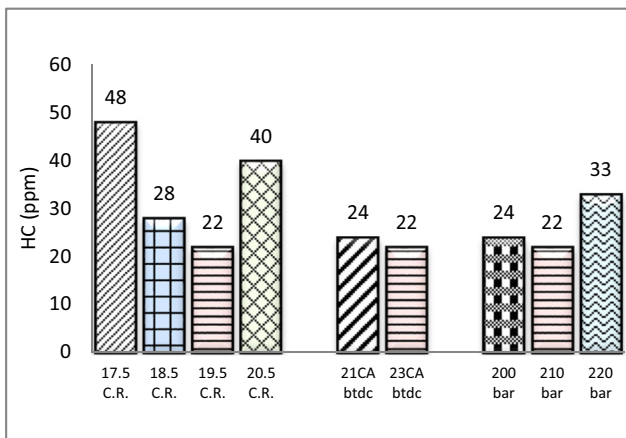


Fig. 15 HC emission at different CRs, injection timings, and injection pressures

by 13.8% than that of 210 bar. HC emission at 210 bar injection pressure was lower by 9.1 and 50% than that of 200 and 220 bar, respectively.

From the above observations, it was concluded that the existing engine is giving optimum results of performance and emissions for B20 at 19.5 CR, 23° CA bt dc injection timing, and 210 bar injection pressure.

Sample validation and optimization of results

To validate the results of the experimental investigation, the observations of NO_x emission were analyzed analytically through a sample test. Full factorial design was used for the development of the prediction model and optimization of engine operating parameters. Table 6 shows the engine input parameters and their levels, and Table 7 shows the design matrix for the experimentation according to the full factorial design. To analyze the NO_x emission as per design matrix, some more experiments were done with different combinations of CR, injection timing, and injection pressure. The CR, injection timing, and injection pressure were taken as input parameters, and NO_x emission was taken as a response. The observations of NO_x emissions obtained from the experiments performed as per the design matrix are shown in Table 7. These observations were fed into the Design Expert 8.0.4.1 software for further analysis.

Table 8 shows the analysis of variance (ANOVA) terms for the reduced quadratic model for NO_x using the backward elimination procedure to eliminate insignificant terms.

Table 6 Parameters and their levels according to the factorial design for B20

Parameter	Symbol	Type	Levels			
			1	2	3	4
CR	A (CR)	Numeric	17.5	18.5	19.5	20.5
Injection timing (CA bt dc)	B (Inj. T.)	Numeric	21	23	25	
Injection pressure (bar)	C (Inj. Pr.)	Numeric	200	210	220	

Table 7 Design matrix and experimental results for B20

S. no.	Run no.	Factor 1 A: CR	Factor 2 B: Inj. T. (CA bt dc)	Factor 3 C: Inj. Pr. (bar)	Response NO _x (ppm)
1	15	17.50	21.00	200.00	534
25	19	17.50	21.00	220.00	565
13	31	17.50	21.00	210.00	529
26	3	18.50	21.00	220.00	561
14	12	18.50	21.00	210.00	516
2	14	18.50	21.00	200.00	519
15	6	19.50	21.00	210.00	512
27	9	19.50	21.00	220.00	558
3	28	19.50	21.00	200.00	517
16	18	20.50	21.00	210.00	530
4	33	20.50	21.00	200.00	545
28	35	20.50	21.00	220.00	573
17	8	17.50	23.00	210.00	510
29	10	17.50	23.00	220.00	555
5	24	17.50	23.00	200.00	510
18	13	18.50	23.00	210.00	530
30	21	18.50	23.00	220.00	547
6	30	18.50	23.00	200.00	505
31	4	19.50	23.00	220.00	541
7	11	19.50	23.00	200.00	501
19	23	19.50	23.00	210.00	472
32	1	20.50	23.00	220.00	562
8	2	20.50	23.00	200.00	530
20	34	20.50	23.00	210.00	525
9	7	17.50	25.00	200.00	524
21	25	17.50	25.00	210.00	521
33	29	17.50	25.00	220.00	585
10	26	18.50	25.00	200.00	518
34	27	18.50	25.00	220.00	581
22	36	18.50	25.00	210.00	513
11	17	19.50	25.00	200.00	514
35	22	19.50	25.00	220.00	575
23	32	19.50	25.00	210.00	516
24	5	20.50	25.00	210.00	540
36	16	20.50	25.00	220.00	630
12	20	20.50	25.00	200.00	542

Table 8 Analysis of variance and interaction fit for the NO_x response

Source	Sum of squares	Degree of freedom	Mean square	F-value	p value	Prob. > F
Model	3428.68	8	428.58	43.64	<0.0001	Significant
A-CR	82.15	1	82.15	8.36	0.0075	
B-Inj. T. (CA bt/dc)	44.28	1	44.28	4.51	0.0430	
C-Inj. Pr. (bar)	1495.49	1	1495.49	152.26	<0.0001	
AB	31.60	1	31.60	3.22	0.0841	
BC	114.99	1	114.99	11.71	0.0020	
A ²	386.60	1	386.60	39.36	<0.0001	
B ²	422.13	1	422.13	42.98	<0.0001	
C ²	851.44	1	851.44	86.69	<0.0001	
Residual	265.19	27	9.82			
Cor total	3693.87	35				
Std. dev.		3.13	R-Squared		0.9282	
Mean	208.49	Adjusted R-squared			0.9069	
C.V. %	1.50	Predicted R-squared			0.8759	
PRESS	458.47	Adequate precision			25.724	

ANOVA was carried out for a significance level of $\alpha = 0.05$, i.e., for a confidence level of 95%.

In the table, the value of “Prob. > F” for the model is 0.0001 which is less than 0.05, indicating that the model is significant, i.e., the terms in the model have a significant effect on NO_x. In the same manner, the values of “Prob. > F” for the main effect of CR, Inj. T., and Inj. Pr.; interaction effect of CR and Inj. T., Inj. T., and Inj. Pr.; and the second order effect of CR, Inj. T., and Inj. Pr. were also found to be less than 0.05. So these terms are also significant model terms.

The R-squared (R^2) value, which is the measure of proportion of total variability explained by the model, is equal to 0.9282. Its nearness to 1 for the model is indicative of the accuracy and exactness of the model in finding the desired responses. The

adjusted R-squared ($Adj-R^2$) is a measure of variation about the mean described by the model and particularly useful when comparing models with different number of terms. Predicted R-squared ($Pred-R^2$) is an indicator of how effectively the model predicts a response value. For reliability of the model and data, the $Adj-R^2$ and $Pred-R^2$ should be within the range of 0.20 of each other. Table 8 shows that $Pred-R^2$ of 0.8759 is in reasonable agreement with the $Adj-R^2$ of 0.9069, i.e., the difference is less than 0.20. Adequate precision is the gauge of the range of predicted output relative to its allied error, i.e., signal to noise ratio. A value greater than 4 is desirable for significant precision. For the developed NO_x model, the value of adequate precision is 25.724, which shows the sufficiency of precision of the model. The final model for NO_x in mathematical form with actual factors and

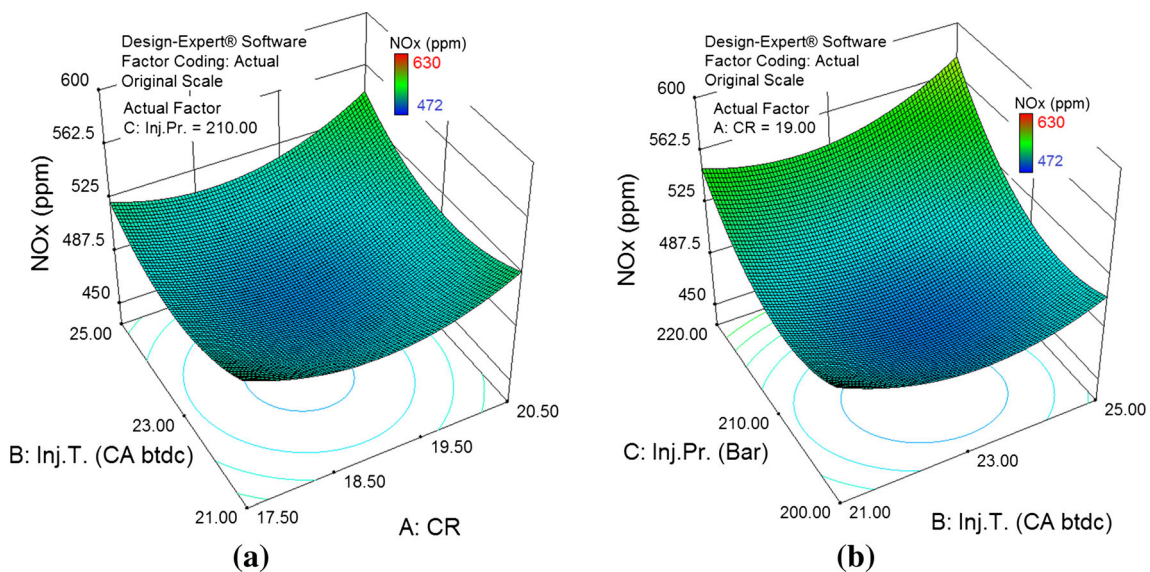
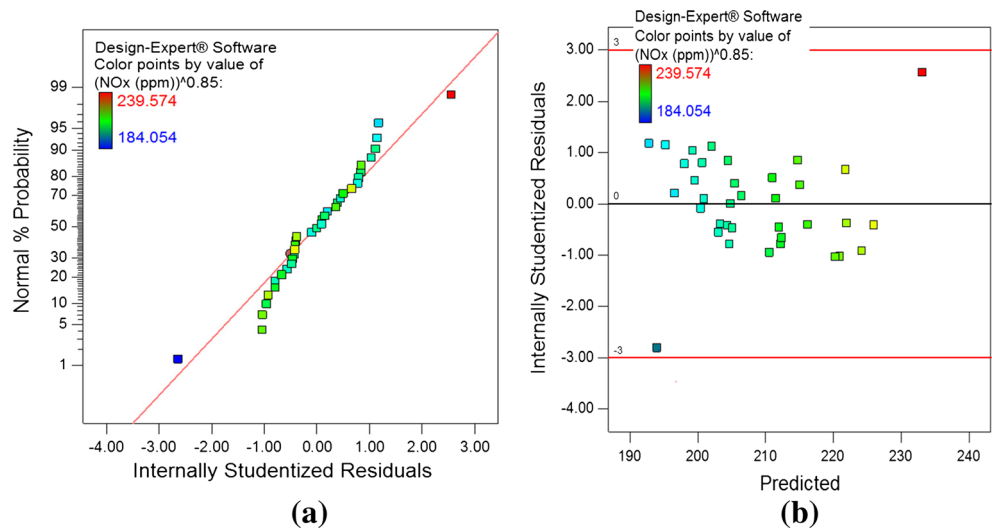


Fig. 16 Variation in NO_x due to the combined effect of **a** CR and injection timing and **b** injection timing and injection pressure

Fig. 17 Plots of **a** normal percent probability vs. internal residual and **b** internal residuals vs. predicted response for the NO_x model



graphical form is given by Eq. (6) and Fig. 16. The 3D surface curves shown in Fig. 16 a, b are consistent with experimental results as depicted in Fig. 12.

$$\begin{aligned}
 (\text{NO}_x)^{0.85} = & 7550.55 - 134.978 * \text{CR} - 120.756 * \text{Inj.T.} \quad (6) \\
 & - 45.623 * \text{Inj.Pr.} + 0.513162 * \text{CR} * \text{Inj.T.} \\
 & + 0.134043 * \text{Inj.T.} * \text{Inj.Pr.} + 3.27702 * \text{CR}^2 \\
 & + 1.81601 * (\text{Inj.T.})^2 + 0.103165 * (\text{Inj.Pr.})^2
 \end{aligned}$$

Figure 17 shows plots of normal probability vs. internal residuals and internal residuals vs. predicted values for smoke response.

In normal probability plots, it can be observed that most of the points are accumulated along a straight line which indicates that residuals follow normal distribution, and hence, the fitted model is adequate for actual systems. The internal residuals vs. predicted plots show no obvious patterns, thus indicating the validity assumption of ANOVA to be true. It is projected that for the desired response, the variance of the observed data is constant and hence is satisfactory.

The NO_x was optimized for input parameters. Table 9 shows the optimization analysis of the parameters and their predicted

Table 9 Optimum conditions of operating parameters and their predicted responses

	CR	Inj. T.	Inj. Pr.	NO _x (ppm)	Desirability
Predicted values from model	19.094	23.312	208.286	485.905	0.904
Experimental values	19.5	23	210	472	
Error percentage (×100)				2.86	

response (NO_x). It can be observed from Table 9 that the predicted values of optimized parameters and response are quite closer to experimental values, thus reflecting the reliability of experimental results.

Comparison of performance and emission characteristics of diesel and B20

After optimization of engine parameters for B20, comparison of performance and emission characteristics of diesel and *n*-butanol-diesel blend (B20) was done and is shown in Fig. 18.

Figure 18 exhibits only a negligible change in performance of the engine optimized for B20. It can be seen that the reduction in smoke and NO_x are 56.52 and 17.19%, respectively, for B20 compared to that of diesel at full load condition. Figure 18 shows a decline of 30.43% in CO emission for B20. However, for B20, the emissions of CO₂ and HC show increments of 17.58 and 15.78%, respectively, compared to that of diesel at full-load condition.

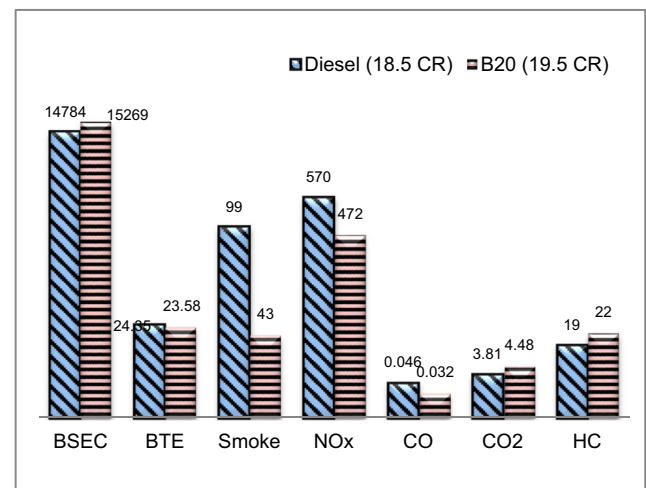


Fig. 18 Comparison of diesel and B20 performance and emissions

Table 10 Cost differences of diesel and B20

Fuel	Cost/L	Cost/kg	Average BSFC (kg/kW-h)	Cost (INR/kW-h)
Diesel	58.63	70.72	0.37	26.17
B20	59.86	73.92	0.41	30.31

Economical analysis

Literature gives evidence of numerous studies that have been done on production of *n*-butanol by different methods and with different substrates. An economical method of butanol production from glycerol and polysaccharides with elimination of acetone and other by product was established in Xin et al. (2016). The production of butanol through chemical conversion process is quicker and economical than the acetone-butanol-ethanol (ABE) process (Ndaba et al. 2015). The average price of *n*-butanol production (over 20 years, from 2007 (base year) to 2027) from corn or switch grass through ABE fermentation is estimated \$0.77 (INR 51.95) per kilogram (Pfromm et al. 2010).

n-Butanol is available in the local market at a cost of INR 80/kg (INR 64.78/L, specific gravity of *n*-butanol being 0.8098). The cost of B20 (20% *n*-butanol and 80% diesel) is INR 59.86/L (diesel cost is INR 58.63/L). Table 10 shows cost calculation of diesel and B20 on a per kilowatt hour basis. It can be clearly seen, when the engine is running on B20, the increased cost of the fuel is just INR 4.14/kW-h.

Conclusions

The results obtained in the present research are consistent with past studies, presented in literature. The sample modeling of NO_x emission shows that experimental observations and predicted results from the mathematical model are quite close. This is indicative of the fact that results obtained by experiments are significant and reliable. The following conclusions were drawn from the results of the experiments:

1. The existing engine gives the best performance at a compression ratio of 18.5, injection timing 23° CA btdc, and injection pressure of 210 bar for diesel. When the engine was fuelled with 20% *n*-butanol-diesel blend (B20), the best results of performance and emission were observed at a higher compression ratio of 19.5 under similar operating conditions. It may be because of a longer delay period with *n*-butanol-diesel blends. An increased compression ratio compensates the effect of the long delay period.
2. *n*-Butanol can be blended in diesel up to 20% without affecting the engine performance significantly. By blending 20% of *n*-butanol in diesel, smoke, NO_x, and CO emissions were decreased by 56.52, 17.19, and 30.43%, respectively, at

rated power. However, CO₂ and HC emissions were increased by 17.58 and 15.78%, respectively, compared to that of diesel at rated power.

3. Results of this experimental investigation show that 20% (v/v) *n*-butanol-diesel blend is a potential alternative fuel for diesel engines and can be used safely in engines similar to the one used in the experiments. The overall effect of using *n*-butanol-diesel blend is a reduction in emissions with negligible change in engine performance at a reasonable cost.
4. The developed model for NO_x emission is significant and is able to describe the effect of engine operating parameters on NO_x emission when the engine was fuelled with *n*-butanol-diesel blends.
5. The increased cost of fuel (B20) by INR 4.14/kW-h is justified by the reduction in emissions as stated above. Further, high feasibility of mass production by biomass and encouraging government policies to promote *n*-butanol as a biofuel will be helpful in cost cutting of *n*-butanol production.

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References

Agarwal D, Agarwal AK (2007) Performance and emissions characteristics of jatropha oil (preheated and blends) in a direct injection compression ignition engine. *Appl Therm Eng* 27:2314–2323

Atmanli A (2016) Comparative analyses of diesel–waste oil biodiesel and propanol, *n*-butanol or 1-pentanol blends in a diesel engine. *Fuel* 176:209–215

Atmanli A, Yuksel B, Ileri E (2013) Experimental investigation of the effect of diesel–cotton oil–*n*-butanol ternary blends on phase stability, engine performance and exhaust emission parameters in a diesel engine. *Fuel* 109:503–511

Atmanli A, Ileri E, Yuksel B (2014) Experimental investigation of engine performance and exhaust emissions of a diesel engine fuelled with diesel–*n*-butanol–vegetable oil blends. *Energy Convers Manag* 81:312–321

Atmanli A, Ileri E, Yuksel B, Yilmaz N (2015a) Extensive analyses of diesel–vegetable oil–*n*-butanol ternary blends in a diesel engine. *Appl Energy* 145:155–162

Atmanli A, Ileri E, Yuksel B (2015b) Effects of higher ratios of *n*-butanol addition to diesel-vegetable oil blends on performance and exhaust emission of a diesel engine. *J Energy Inst* 88(3):209–220

Bayindir H, Isik MZ, Aydin H (2017) Evaluation of combustion, performance and emission indicators of canola oil-kerosene blends in a power generator diesel engine. *Appl Therm Eng* 114:234–244

Can O, Celikten I, Usta N (2004) Effects of ethanol addition on performance and emissions of a turbocharged indirect injection diesel engine running at different injection pressures. *Energy Convers Manag* 45(15–16):2429–2440. doi:10.1016/j.enconman.2003.11.024

Chen G, Yu W, Li Q, Huang Z (2012) Effects of *n*-butanol addition on the performance and emissions of a turbocharged common-rail diesel engine. *SAE Technical Paper* 2012-01-0852. doi:10.4271/2012-01-0852

- Chen Z, Liu J, Han Z, Du B, Liu Y, Lee C (2013) Study on performance and emissions of a passenger-car diesel engine fueled with butanol-diesel blends. *Energy* 55:638–646
- Chen Z, Wu Z, Liu J, Lee C (2014) Combustion and emissions characteristics of high n-butanol/diesel ratio blend in a heavy-duty diesel engine and EGR impact. *Energy Convers Manag* 78:787–795
- Choi B, Jiang X (2015) Individual hydrocarbons and particulate matter emission from a turbocharged CRDI diesel engine fueled with n-butanol/diesel blends. *Fuel* 154:188–195. doi:10.1016/j.fuel.2015.03.084
- Choi CY, Reitz RD (1999) An experimental study on the effects of oxygenated fuel blends and multiple injection strategies on DI diesel engine emissions. *Fuel* 78:1303–1317
- Choi B, Jiang X, Kim YK et al (2015) Effect of diesel fuel blend with n-butanol on the emission of a turbocharged common rail direct injection diesel engine. *Appl Energy* 46:20–28
- Corsini A, Marchegiani A, Rispoli F, Sciulli F, Venturini P (2015) Vegetable oils as fuels in diesel engine. eEngine performance and emissions. *Energy Procedia* 81:942–949. doi:10.1016/j.egypro.2015.12.151
- Curran HJ, Fisher EM, Glaude PA, et al (2001) Detailed chemical kinetic modeling of diesel combustion with oxygenated fuels. SAE Technical Paper 2001-01-065. doi:10.4271/2001-01-0653
- Dogan O (2011) The influence of n-butanol/diesel fuel blends utilization on a small diesel engine performance and emissions. *Fuel* 90(7):2467–2472
- Fushimi K, Kinoshita E, Yoshimoto Y (2013) Effect of butanol isomer on diesel combustion characteristics of butanol/gas oil blends. SAE Technical Paper 2013-32-9097. doi:10.4271/2013-32-9097
- Giakoumis EG, Rakopoulos CD, Dimaratos AM, Rakopoulos DC (2013) Exhaust emissions with ethanol or n-butanol diesel fuel blends during transient operation: a review. *Renew Sust Energ Rev* 17:170–190
- Huang H, Liu Q, Yang R, Zhu T, Zhao R, Wang Y (2015) Investigation on the effects of pilot injection on low temperature combustion in high-speed diesel engine fueled with n-butanol–diesel blends. *Energy Convers Manag* 106:748–758. doi:10.1016/j.enconman.2015.10.031
- Ibrahim A (2016) Performance and combustion characteristics of a diesel engine fuelled by butanol-biodiesel-diesel blends. *Appl Therm Eng* 103:651–659
- Imtenan S, Masjuki HH, Varman M, Rizwanul Fattah IM, Sajjad H, Arbab MI (2015) Effect of n-butanol and diethyl ether as oxygenated additives on combustion–emission–performance characteristics of a multiple cylinder diesel engine fuelled with diesel–jatropha biodiesel blend. *Energy Convers Manag* 94:84–94
- Jain NL, Soni SL, Poonia MP, Sharma D, Srivastava A (2017) Performance and emission characteristics of preheated and blended thumba vegetable oil in a compression ignition engine. *Appl Therm Eng* 113:970–979
- Jang YS, Malaviya A, Cho C, Lee J, Lee SY (2012) Butanol production from renewable biomass by clostridia. *Bioresour Technol* 123:653–663
- Klein-Douwel RJH, Donkerbroek AJ, Van Vliet AP, Boot MD, Somers LMT, Baert RSG et al (2009) Soot and chemiluminescence in diesel combustion of bio-derived, oxygenated and reference fuels. *Proc Combust Inst* 32:2817–2825
- Kumar S, Cho JH, Park J, Moon I (2013) Advances in diesel–alcohol blends and their effects on the performance and emission of diesel engines. *Renew Sust Energ Rev* 22:46–72
- Lapuerta M, Armas O, Herreros JM (2008) Emissions from a diesel–bioethanol blend in an automotive diesel engine. *Fuel* 87(1):25–31
- Liu H, Li S, Zheng Z, Xu J, Yao M (2013) Effects of n-butanol, 2-butanol, and methyl octynoate addition to diesel fuel on combustion and emissions over a wide range of exhaust gas recirculation (EGR) rates. *Appl Energy* 112:246–256
- Lopez AF, Cadrazco M, Agudelo AF, Corredor LA, Vélez JA, Agudelo JR (2015) Impact of n-butanol and hydrous ethanol fumigation on the performance and pollutant emissions of an automotive diesel engine. *Fuel* 153:483–491
- Merola SS, Tornatore C, Iannuzzi SE, March L (2014) Combustion process investigation in a high speed diesel engine fuelled with n-butanol diesel blend by conventional methods and optical diagnostics. *Renew Energy* 64:225–237
- Moffat RJ (1988) Describing the uncertainties in experimental results. *Exp Thermal Fluid Sci* 1(1):3–17
- Mohsin R, Majid ZA, Shihnan AH, Nasri NS, Sharer Z (2014) Effect of biodiesel blends on engine performance and exhaust emission for diesel dual fuel engine. *Energy Convers Manag* 88:821–828
- Ndaba B, Chiyanzu S, Marx I (2015) n-Butanol derived from biochemical and chemical routes: a review. *Biotechnol Rep* 8:1–9. doi:10.1016/j.btre.2015.08.001
- Palash SM, Masjuki HH, Kalam MA, Masum BM, Sanjid A, Abedin MJ (2013) State of the art of NOx mitigation technologies and their effect on the performance and emission characteristics of biodiesel-fueled compression ignition engines. *Energy Convers Manag* 76:400–420
- Pfromm PH, Boadu VA, Nelson R, Vadlani P (2010) Bio-butanol vs. bio-ethanol: a technical and economic assessment for corn and switchgrass fermented by yeast or *Clostridium acetobutylicum*. *Biomass Bioenergy* 34:515–524
- Plint MA, Martyr A (1999) Engine testing theory and practice, Second edn. Butterworth-Heinemann, Burlington
- Putrasari Y, Nur A, Muharam A (2013) Performance and emission characteristic on a two cylinder DI diesel engine fuelled with ethanol-diesel blends. *Energy Procedia* 32:21–30
- Qureshi N, Saha BC, Dien B, Hector RE, Cotta MA (2010) Production of butanol (a biofuel) from agricultural residues: part I—use of barley straw hydrolysate. *Biomass Bioenergy* 34:559–565
- Rahman MM, Stevanovic S, Brown RJ, Ristovski Z (2013) Influence of different alternative fuels on particle emission from a turbocharged common-rail diesel engine. *Procedia Eng* 56:381–386
- Rajasekar E, Muragesan A, Subramanian R, Nedunchezian N (2010) Review of NOx reduction technologies in CI engine fuelled with oxygenated biomass fuels. *Renew Sust Energ Rev* 14(7):2113–2121
- Rakopoulos DC, Rakopoulos CD, Hountalas DT, Kakaras EC, Giakoumis EG, Papagiannakis RG (2010a) Investigation of the performance and emissions of bus engine operating on butanol/diesel fuel blends. *Fuel* 89:2781–2790
- Rakopoulos DC, Rakopoulos CD, Giakoumis EG, Dimaratos AM, Kyritsis DC (2010b) Effects of butanol–diesel fuel blends on the performance and emissions of a high-speed DI diesel engine. *Energy Convers Manag* 51(10):1989–1997
- Rakopoulos CD, Dimaratos AM, Giakoumis EG, Rakopoulos DC (2010c) Investigating the emissions during acceleration of a turbocharged diesel engine operating with bio-diesel or n-butanol diesel fuel blends. *Energy* 35(12):5173–5184
- Rakopoulos DC, Rakopoulos CD, Papagiannakis RG, Kyritsis DC (2011a) Combustion heat release analysis of ethanol or n-butanol diesel fuel blends in heavy-duty DI diesel engine. *Fuel* 90:1855–1867
- Rakopoulos CD, Dimaratos AM, Giakoumis EG, Rakopoulos DC (2011b) Study of turbocharged diesel engine operation, pollutant emissions and combustion noise radiation during starting with bio-diesel or n-butanol diesel fuel blends. *Appl Energy* 88:3905–3916
- Rakopoulos DC, Rakopoulos CD, Giakoumis E, Papagiannakis RG, Kyritsis DC (2014) Influence of properties of various common bio-fuels on the combustion and emission characteristics of high-speed DI (direct injection) diesel engine: vegetable oil, bio-diesel, ethanol, n-butanol, diethyl ether. *Energy* 73:354–366

- Sahin Z, Aksu ON (2015) Experimental investigation of the effects of using low ratio n-butanol/diesel fuel blends on engine performance and exhaust emissions in a turbocharged DI diesel engine. *Renew Energy* 77:279–290
- Sahin Z, Durgun O, Aksu ON (2015) Experimental investigation of n-butanol/diesel fuel blends and n-butanol fumigation—evaluation of engine performance, exhaust emissions, heat release and flammability analysis. *Energy Convers Manag* 103:778–789
- Sayin C (2010) Engine performance and exhaust gas emissions of methanol and ethanol–diesel blends. *Fuel* 89(11):3410–3415
- Sayin C, Ozsezen AN, Canakci M (2010) The influence of operating parameters on the performance and emissions of a DI diesel engine using methanol-blended-diesel fuel. *Fuel* 89(7):1407–1414
- Siwalea L, Kristófb L, Adamb T et al (2013) Combustion and emission characteristics of n-butanol/diesel fuel blend in a turbo-charged compression ignition engine. *Fuel* 107:409–418
- Tutak W (2014) Bioethanol E85 as a fuel for dual fuel diesel engine. *Energy Convers Manag* 86:39–48
- Valentino G, Corcione FE, Iannuzzi SE, Serra S (2012) Experimental study on performance and emissions of a high speed diesel engine fuelled with n-butanol diesel blends under premixed low temperature combustion. *Fuel* 92:295–307
- Xin F, Wang C, Dong W et al (2016) Comprehensive investigations of biobutanol production by a non-acetone and 1,3-propanediol generating clostridium strain from glycerol and polysaccharides. *Biotechnol Biofuel* 9:1–12. doi:10.1186/s13068-016-0641-8
- Yamamoto S, Agui Y, Kawahara N, Ueki H, Daisaku S, Ishida M (2012) Comparison of diesel combustion between ethanol and butanol blended with gas oil. SAE Technical Paper 2012-32-0020. doi:10.4271/2012-32-0020
- Yilmaz N, Vigil FM, Benalil K, Davis SM, Calva A (2014) Effect of biodiesel–butanol fuel blends on emissions and performance characteristics of a diesel engine. *Fuel* 135:46–50
- Zhang ZH, Chua SM, Balasubramanian R (2016) Comparative evaluation of the effect of butanol–diesel and pentanol–diesel blends on carbonaceous particulate composition and particle number emissions from a diesel engine. *Fuel* 176:40–47
- Zheng M, Li T, Han X (2015) Direct injection of neat n-butanol for enabling clean low temperature combustion in a modern diesel engine. *Fuel* 142:28–37
- Zhou N, Huo M, Wu H, Nithyananda K, Lee CF, Wanga Q (2014) Low temperature spray combustion of acetone–butanol–ethanol (ABE) and diesel blends. *Appl Energy* 117:104–115
- Zoldy M, Hollo A, Thernesz A (2010) Butanol as a diesel extender option for internal combustion engines. SAE Technical Paper 2010-01-0481. doi:10.4271/2010-01-0481