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Characterization of n-butanol diesel blends on a small size variable compression ratio diesel engine: Modeling and experimental investigation

Ashish Nayyar[a,b,*], Dilip Sharma[b], Shyam Lal Soni[b], Alok Mathur[a]

[a] Department of Mechanical Engineering, Swami Keshvanand Institute of Technology, Management & Gramothan, Jaipur, India
[b] Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, India

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ABSTRACT

The continuous rise in environmental pollution has attracted the attention of researchers in clean alternative fuels for internal combustion engines. In the present study, experimental investigations were carried out on a small size, modified, variable compression ratio diesel engine with n-butanol-diesel blends (10–25% by volume) as fuel to determine the optimum blending ratio and operating parameters for reduced emissions. Full Factorial design approach was employed for modeling and analysis of experimental data. The experiments were planned and performed in three distinct phases at a constant speed of 1500 rpm and at varying engine load (12, 16, 20 and 24 Nm). The engine loads, blending ratio, compression ratio, injection timing and injection pressure were taken as input parameters and their effects on engine performance and emissions were investigated experimentally and analytically. In the modeling work, reduced quadratic and cubic prediction models were developed, checked for normality and homogeneity and parameters were optimized for desired responses. The optimum results were observed with twenty percent n-butanol-diesel blend (B20) at a higher compression ratio of 19.5 as compared to 18.5 for diesel under similar operating conditions. Brake thermal efficiency improved by 5.54% and smoke & nitrogen oxides decreased by 59.56% & 15.96% respectively for B20 in comparison to diesel at full load condition. Results of the study show that n-butanol-diesel blend is a potential fuel to reduce emissions from diesel engines with improved performance. A close match between experimental results and prediction results reveals that the developed models can be used with adequacy to optimize similar type of diesel engines using n-butanol-diesel blends.

1. Introduction

Development of clean and alternative 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, 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 [1,2].

A variety of alternative fuels and additives such as alcohols [3–9], biodiesels [10–12] and vegetable oils [13–16] can be used in compression ignition (CI) engines with adequate performance and reduced emissions. Improved fuels can also be obtained by adding suitable percentages of these alternatives to diesel. Among these, oxygenated additives have drawn more attention because of their capability to reduce emissions without much affecting the engine performance [17–19]. Oxygenated additives are renewable in nature and support the local agriculture industry [20,21]. Alcohols are bio-oxygenated compounds. The presence of oxygen; low viscosity and high 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 as compared to methanol and ethanol, and it is completely miscible with diesel. The calorific value of n-butanol is also higher than methanol and ethanol. This implies that same amount of n-butanol produces higher power from the same engine running on ethanol/methanol-diesel blends [22–26]. n-Butanol can be produced by fossil matter as well as by waste biomass (namely biobutanol), however, the properties of n-butanol produced from both sources are same [27,28].

In an experimental study, it was reported that smoke and NO_x can

Abbreviations: BTE, brake thermal efficiency; BSFC, brake specific fuel consumption; CA btdc, crank angle before top dead centre; CI, compression ignition; CN, cetane number; CO, carbon monoxide; CR, compression ratio; DI, direct injection; HC, unburned hydrocarbon; IC, internal combustion; Inj. Pr., injection pressure; Inj. T., injection timing; max, maximum; NO_x, nitrogen oxides; PM, particulate matter; TC, turbocharged

* Corresponding author at: Department of Mechanical Engineering, Swami Keshvanand Institute of Technology, Management & Gramothan, Jaipur, India.
E-mail addresses: ashishnayyar@skit.ac.in (A. Nayyar), dsharma.mech@mnit.ac.in (D. Sharma), slsoni.mech@mnit.ac.in (S.L. Soni), ashoom@gmail.com (A. Mathur).

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Table 1
A literature review of different blends of n-butanol, biodiesel and other oxygenated additives with diesel.

S. no.	Author	Engine setup used	Fuel used	Observations and results
1	Chen et al. [30]	Modified, 4-stroke, water-cooled, single cylinder research diesel engine with EGR	n-Butanol 40% on volume basis (v/v) in diesel	Lower smoke, higher NO_x, butanol with medium EGR has resulted in increased thermal efficiency
2	Yamamoto et al. [31]	Single cylinder, water cooled, naturally aspirated, Direct Injection (DI), YANMAR Co. Ltd., NFD 170-(E)	Ethanol and n-butanol 30%, 40% and 50% (v/v) in diesel	Lower smoke, higher NO_x, butanol is better than ethanol
3	Lopez et al. [32]	4-cylinder, 2.5 l, turbocharged (TC), DI, diesel engine	Ethanol and n-butanol10% (v/v) in diesel	Reduced particulate matter and NO_x
4	Zoeldy et al. [33]	4 Cylinder, 4 stroke, indirect injection PSA XUD 9A/L, diesel engine	n-Butanol 2.5–10% (v/v) in diesel	Up to 5% butanol is very effective in reducing NO_x and PM under 50 nm size
5	Choi et al. [22]	4 cylinder, common rail fuel injection, cooled EGR and intercooler turbocharged, diesel engine	n-Butanol 10% and 20% (v/v) in diesel	Reduced PM (30–80%) and reduced NO_x slightly in European Stationary Cycle tests
6	Sahin and Aksu [34]	4 cylinder, 4-stoke, water-cooled, TC, common-rail injection, 1.461 L Renault DI, diesel engine	n-Butanol in diesel 2–6% (v/v) in diesel	The maximum smoke reduction is 21.75% with B4 and max NO_x reduction is 5.03% with B2.
7	Sahin et al. [35]	4 cylinder, 4-stoke, water-cooled, TC, common-rail injection, 1.461 L Renault DI, diesel engine	n-Butanol and fumigated n-butanol 2–6% (v/v))	Reduced smoke, NO_x reduced for all combinations except 4% and 6% blends
8	Merola et al. [36]	4-cylinder, TC, water cooled, DI, diesel engine	n-Butanol in diesel 20% (v/v)	The best trade-off between smoke-NO_x at higher Injection Pressure (Inj. Pr.), B20 reduced smoke drastically with a slight increment in NO_x and a small increment in BSFC at moderate Inj. Pr.
9	Siwale et al. [37]	4-cylinder, 1Z type, 1.9 L-66 kW Turbo-Direct Injection (TDI) Volkswagen, diesel engine	n-Butanol 5–20% (v/v) in diesel	At B20 maximum smoke reduction is 85.1% with significant increment in NO_x
10	Fushimi and Kinoshita [38]	Single cylinder, 4-stroke, DI diesel engine	1-butanol, 2-butanol and isobutanol (10–50%, by mass)	Up to 40% blend BTE unchanged, smoke reduced (up to 85%), up to 30% blend NO_x unchanged and at 40% blend NO_x reduces slightly
11	Chen et al. [39]	High-speed, TC- inter-cooled, direct injection (DI), diesel engine	n-Butanol 20–40% (v/v) in diesel	Increased BTE to 2.7%, decreased smoke to 50.3%, increased NO_x to 15.8% at rated power
12	Zhang et al. [40]	Single cylinder, four-stroke, DI, diesel engine (L70AE, Yanmar Corporation), 4.5 kW	Butanol and pentanol (10–20% v/v) in diesel	same BTE, B20 is better in reducing PM
13	Ibrahim [41]	Single cylinder, 4-stroke, DI, air-cooled, TD212, diesel engine	Butanol–diesel–biodiesel, Biodiesel	Increased brake thermal efficiency (BTE) 6.5%, slightly increased NO_x
14	Liu et al. [42]	Modified single-cylinder, 4-stroke, water-cooled, diesel engine, EGR (0–62%)	n-Heptane, iso-octane, n-butanol, 2-butanol and methyl Octynoate (20% v/v) in diesel	Reduced smoke (32.8%) for B20, same BTE and NO_x at different blends, increased EGR results in reduced thermal efficiency
15	Zheng et al. [43]	4-Cylinder, 4-stroke, re-configured to single cylinder, common rail	n-Butanol with high- pressure direct injection	NO_x and smoke reduced substantially without EGR, earlier Injection Timing (Inj. T.) causes very high rates of pressure rise while delayed injection timings prone to make engine misfire
16	Huang et al. [44]	4-cylinder, variable-geometry TC, EGR, DI, high-pressure common rail fuel injection, diesel engine	n-Butanol (20–30% v/v) in diesel	Reduced smoke and NO_x with the addition of n-butanol Reduced smoke and NO_x with the advance pilot injection
17	Rakopoulos et al. [45]	Single-cylinder, 4-stroke, water cooled, Ricardo–Cussons, "Hydra", high-speed engine (steady state condition)	n-Butanol (8%, 16%, 24% v/v) in diesel	Reduced smoke significantly and reduced NO_x slightly, BTE improved
18	Rakopoulos et al. [46]	4-stroke, 6-cylinder, Mercedes-Benz, OM 366 LA, DI, TC, water-cooled, diesel engine (steady state condition)	n-Butanol (8% and 16% v/v) in diesel	Reduced smoke significantly and reduced NO_x slightly, BTE improved
19	Rakopoulos et al. [47]	4-stroke, 6-cylinder, Mercedes-Benz, OM 366 LA, DI, TC, water-cooled, diesel engine (steady state condition)	Ethanol (5% and 10% v/v/), n-butanol (8% and 16% v/v) in diesel	Reduced smoke significantly and reduced NO_x slightly, BTE increased slightly
20	Rakopoulos et al. [48]	4-stroke, 6-cylinder, Mercedes-Benz, OM 366 LA, DI, TC, water-cooled, diesel engine (transient conditions)	Biodiesel (30% by vol.) n-butanol (25% by vol.) in diesel	Reduced Smoke for butanol and increased for biodiesel, increased NO_x for both fuels
21	Rakopoulos et al. [49]	4-stroke, 6-cylinder, Mercedes-Benz, OM 366 LA, DI, TC, water-cooled, diesel engine (transient conditions)	Biodiesel (30% by vol.) n-butanol (25% v/v) in diesel	Increased NO_x mainly because of turbo charging irrespective of fuel, NO_x is higher for biodiesel than butanol, Reduced Smoke (max 57.9% for butanol)
22	Zhou et al. [50]	A constant volume chamber bore 110 mm, height 65 mm. This chamber can imitate spray and combustion practice of a diesel engine	Butanol 12% (v/v) and other compounds 8% (v/v)	Better combustion efficiency and emitted approximately zero smoke as compared to diesel
23	Atmanli et al. [51,52]	4-cylinder, 4-stroke, TC, DI, Land Rover 110, diesel engine	Vegetable oil 20% vol. and n-Butanol 10% vol.	Increased NO_x, increased BSFC, decreased BTE
24	Atmanli et al. [53]	4-cylinder, Onan DJC type, indirect injection, diesel engine	n-Butanol (20%-60% v/v) in diesel-vegetable oil	Decreased BTE, increased NO_x
25	Atmanli [54]	4-cylinder, Onan DJC type, indirect injection, diesel engine	Propanol, n-butanol and 1-pentanol (20% v/v) in diesel–biodiesel blends	BTE improved to 5.58% for 20% butanol, NO_x reduced for all alcohols blends as compared to diesel-biodiesel
26	Imtenan et al. [55]	Inline 4-cylinder, water-cooled, TC, diesel engine	Jatropha biodiesel–diesel blend with n-butanol and diethyl ether 5–10% (v/v)	10% n-butanol reduces smoke and NO_x by 27% and 8.8% as compared to biodiesel (20%)-diesel blend, 10% diethyl ether reduces smoke and NO_x by 38.58% respectively and 12% as compared to biodiesel (20%)-diesel blend
27	Giakoumis et al. [56]	Diesel engines (transient conditions)	Ethanol and n-butanol	Reduced smoke/PM, increases or decreases NO_x depending on the specific alcohol ratio, the engine calibration, and the operating conditions

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