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A Baseline Review on Effect of n-Butanol on the Performance and Emission Characteristics of CI and SI engines

Ravikumar R[1], Antony A J[2]
[1]Mechanical Engineering, CHRIST (Deemed to be University), Bangalore, Karnataka, India-560074
[2]Mechanical Engineering, Mangalore Marine College and Technology, Mangalore, Karnataka, India-574144
*Author for Correspondence E-mail: r.ravikumar64@gmail.com

***Abstract*—** *Internal combustion engines are the main members of the fast-growing in energy consumption. Fossil fuel consumption is the greater reason for maximizing in air pollution, which represented by the emission constituents such as oxides of nitrogen, unburnt hydrocarbon, oxides of carbon, emissions and some solid particulate matter delivered by the internal combustion engine. In few recent decades, biofuels, such as alcohol from the verity of feedstocks, biodiesel derived from various sources, natural gas, dimethyl ether, n-butanol, have been used in engines to achieve a reduction in total costs of energy utilization and environmental pollution. Non-conventional fuels have tempted the research scholars as alternative energy sources for internal combustion engines due to its greater reliability, possible physical properties, exhaustive combustion characteristics, and complete burning possibilities. Utilization of n-butanol as recommended biofuel for internal combustion engines from several years. Rich numbers of research scholars have investigated the effect of n-butanol presence in blends of n-butanol–gasoline as well as clear n-butanol fuel for gasoline engine and diesel engines in their research work. The mixtures of n-butanol-gasoline have a maximum potential to be used as supportive fuel can be easily obtained from various sources and can maximize the performance of the engine with the reduction of carbon monoxide, carbon dioxide, unburnt hydrocarbons, and other pollutants. This review paper illustrates various effective methods to produce n-butanol, the effects of n-butanol and its blends with gasoline as well as diesel fuel on combustion characteristics and emission constituents from internal combustion engines to meet future demand in emission regulations using n-butanol as a suitable biofuel.*

***Keywords*—** *Emission constituents, Fossil fuels, gasoline, n-butanol.*

I. INTRODUCTION

A. *Production of n-butanol*

Alcohol such as n-butanol is obtained chemically, adopting either the hydroformylation process begins from acetaldehyde or the aldol process begins from propylene. The important risk associated with the bio-production of n-butanol is the cost of substrate. Recent trends in the extraction of biobutanol or n-butanol from biomass have led to the fermentation process, in achieving better product yield [1]. A better suitable route to produce n-butanol is bacterial fermentation, it poised for re-commercialization. Now a day's n-butanol can compete in the area of alternative fuel. Biobutanol or n-butanol is also a superior biofuel in important contribution in the supply of the demanded fuels for next generation [2]. The oldest industrial fermentation process is known as clostridial acetone–butanol–ethanol (ABE) lining at second in scale only to produce ethanol by the yeast fermentation process. In 1920, Chaim Weizmann, who became Israel's president, identified the anaerobic bacterium Clostridium acetobutylicum which naturally produces acetone [3].

B. *Characterization of n-butanol*

I. M. Yusria and his team conducted an exhaustive review and they summarize the characterization of ethanol, methanol, and n-butanol. Their review summary showing that the properties of n-butanol are satisfying the ASTM requirements of fuel. The data are tabulated below [4].

Table 1: Physico-chemical properties of methanol and n-butanol

Properties	n-butanol	Methanol
Flashpoint (°C)	35	12
Boiling point (°C)	117-118	65
Heat of vaporization (kJ/kg)	585.4	1162.4
Low heating value (MJ/kg)	33.1	20.1
RON	96	136
CE	25	3.8
Auto ignition temperature (°C)	345	463
Stoichiometric air/fuel ratio	11.19	6.47

Dimitrios C. Rakopoulos has evaluated the properties of different biofuels such as vegetable oil, biodiesel, ethanol, n-butanol, and diethyl ether. The results obtained from his the experiments are tabulated below [5].

Table 2: Physico-chemical properties of ethanol and n-butanol

Properties	n-butanol	Ethanol
Density at 20ºC (kg/m^3)	810	713
KV at 40ºC (mm^2/s)	3.6	1.2
Bulk modulus of elasticity (bar)	15,000	13,200
BP (ºC)	118	78
Latent heat of evaporation (kJ/kg)	585	840
Stoichiometric air-fuel ratio	11.2	9
Oxygen % by weight	21.6	34.8

C. *Actions of n-butanol as fuel in CI engine*

Oxides of nitrogen and smoke opacity are the most familiar emissions from the compression ignition engines. Especially, diesel fuels containing the higher rate of oxygen content can reduce smoke emission with higher potential significantly. Oguzhan Dogan and his team members have investigated and evaluated the effect of n-butanol and n-butanol diesel fuel mixtures on compression ignition engine performance and exhaust emissions. Investigator selected five different test fuels such as B5, B10, B15, B20, and neat diesel fuel. The experimental test results indicating that oxides of nitrogen, smoke opacity, and carbon monoxide emissions reduced dramatically on the other hand emissions of hydrocarbon raised with the higher n-butanol content in the fuel mixture. Performance test results show that there is a gradual increase in the BSFC and in the brake thermal efficiency with a higher rate of n-butanol in the fuel mixture. Also, the gas temperature at exhaust reduces by adding more n-butanol in the fuel blends [6].

A team of research scholars has conducted an experimental investigation on compression ignition engine to determine the effects of using a mixture of n-butanol with high-speed diesel fuel. The fuel mixtures are prepared at the rate of 8% and 16% by volume of n-butanol. The parameters of performance and exhaust emissions of a 6 cylinder, water and air cooled, turbocharged direct injection Benz engine is examined under a fully instrumented facility. In each investigation, exhaust smoke and exhaust regulated emissions constituents such as oxides of nitrogen, carbon monoxide, and unburned hydrocarbons were measured. Thermal efficiency and BSFC are monitored from the volumetric flow rate of measured fuel as well as the heating value of fuel and density. The smoke opacity, NOx, CO were reduced significantly with an n-butanol mixture with respect to those of the neat diesel fuel. On the other hand, the UBHC emissions were dramatically increased with the use of the n-butanol and diesel fuel mixture with respect neat conventional diesel fuel, it is observed that the specific fuel consumption is gradually increased with corresponding to the little rise of brake thermal efficiency [7].

An investigation was conducted to determine the effects of utilization of diesel fuel with n-butanol and ethanol at the rate of 5 percent and 10 percent or n-butanol in 8 percent and 16 percent by vol, on direct injection, Mercedes-Benz engine. The observations are made such as, the ignition delay is increased considerably, cylinder pressures rise in engine cylinder are reduced. Operating temperatures of the engine quite decreased during the first part of combustion, smoke opacity decreases gradually, but higher with an increasing percentage of biofuels in the mixture. Oxides of nitrogen reduce with an increasing percentage of biofuels in the mixture [8].

D C Rakopoulos has conducted an investigation on high-speed direct injection engine fuelled with twenty percentage of n-butanol or diethyl ether with biodiesel obtained from cottonseed oil. Scholar compared combustion and emissions versus clear cottonseed oil and its neat biodiesel. Results show cylinder gas pressures decreases, and ignition delays increase with the mixture. Thick smoke, NOx, and CO reduce, and unburned hydrocarbon emission increase significantly with fuel mixtures. It is observed that specific fuel consumption reduces and higher thermal efficiency with the blends [9].

Nadir Yilmaz has investigated the influence of n-butanol–biodiesel mixture on the emissions parameters and performance characteristics of a 4S, naturally breathed, water and air cooled, indirect injection diesel engine. Preferred blends for the evaluation were 5%, 10%, and 20% n-butanol on a volumetric basis. Results show with respect to biodiesel, n-butanol blended fuels, fewer gas temperatures at exhaust and oxides of nitrogen (NOx) emissions while exhaustively higher carbon monoxide (CO) and hydrocarbons emissions (HC). Blends of n-butanol fuels release lower carbon monoxide and higher nitrogen oxide emissions with respect to conventional diesel fuel for a low percentage of n-butanol such as 5% and 10%. But the results were highlighted there was no rational change in terms of hydrocarbon emissions. When the biodiesel mixture with the highest percentage of n-butanol (20%) caused a greater range of carbon monoxide and hydrocarbon emissions and lesser nitrogen oxides emission than neat diesel fuel. It is observed that BSFC increased with biodiesel blended fuels as compared to neat diesel fuel [10].

Peng Geng and team has extracted results of emission and performance characteristics from dual fuel engine by using different sources of fuel. Investigations indicated that marginal reduction of regular gas constituents in the exhaust and particular matter emissions by the use of an alcohol-diesel dual fuel. Rare gas emissions such as acetaldehyde, ethanol, methanol, ketone, and formaldehyde are higher compared to neat diesel fuel. An emerging neat alternate for the compression ignition engine is the dimethyl ether, which provides a lengthy delay in injection, cylinder pressure in the cylinder is showing as less, In this context, alcohols, natural gas, biodiesel, and dimethyl ether can be a substitute as alternative fuels have a great future response in the energy shortage world [11].

Ertan Alptekin and his team have studied and concluded that break specific fuel consumption values of alcohol and diesel fuel mixtures were little greater than with respect to pure diesel fuel. Alcohol and diesel fuel blends give higher HC, NOx and CO emissions with respect to pure diesel fuel. Slightly maximum cylinder pressures observed with blends. Ethanol, diesel and isopropanol, diesel fuel mixtures shows simultaneous combustion characteristics and emissions. Investigators concluded that the injection of fuel characteristics was affected by the types of fuel with respect to the engine load and speed. Alternative fuels such as ethanol and isopropanol were preferred as additives with neat diesel fuel at the rate of five percent of ethanol with eighty-five percentage of diesel fuel, and fifteen percentage of isopropanol with eighty-five percentage diesel fuel [12].

Ravikumar R and team has conducted an exhaustive investigation on compression ignition engine to determine the influence of n-butanol in a diesel engine. Experiments were conducted on a single cylinder, four strokes, water-cooled common rail direct injection engine. Investigations were conducted for five different n-butanol and diesel fuel mixtures, results obtained from experimental tests conclude that n-butanol and their mixtures produce a higher rate of carbon monoxide (CO) emissions, nitrogen oxides and hydrocarbon (HC) emissions than diesel fuel. Performance of compression ignition varies with respect to the percentage of biofuel presence in the mixture [13].

C D Rakopoulos and team have investigated turbocharged compression ignition engine to evaluate pollutant formation, and combustion noise radiation by utilizing bio-diesel or n-butanol-diesel fuel blends. A variety of starting tests was conducted for different fuel blends, i.e. neat diesel fuel or diesel fuel with either bio-diesel or n-butanol, with blending ratios of 70–30% and 75–25% (by vol.), respectively. As expected, turbocharger lag was found to be the most notable Contributor, The low cranking speed appeared to have the dominant influence on combustion noise development and its absolute values. Smoke opacity increased notably (+40% in peak value) for the bio-diesel blend, while for n-butanol blend it decreased significantly For both bio-fuel blends, NO emission increased compared with the neat diesel fuel case; specifically, peak NO value increased by 30% and 51% for the bio-diesel and n-butanol blends, respectively. The bio-fuels blends had a minor effect on the transient performance of the engine (engine speed development, turbocharger response) and the overall combustion noise radiation [14].

I M Yusri and his team did the literature survey on the effect of n-butanol as additive fuel in a diesel engine. The summarized data are tabulated bellow [4].

Table 3: Performance and emissions of compression ignition engine with n-butanol blends.

Blends	Type of engine	Result history
B5, B10, B15	6-cylinders, 4S, DIDE.	BSFC↑, CO↓, Soot
B5, B10, B15,B20	Single cylinder, 4S, naturally aspirated DIDE.	BSFC↑, BTE HC while NOx↓, CO, smoke.
B5, B10, B15, B20	4-cylinder, TDI engine.	NOx↑ and HC CO↓, soot
B8, B16, B24	Single cylinder, CI, DI, naturally aspirated DE.	BSFC↑, BTE and HC↓ CO, NOx and soot
B20, B30, B40	Inter-cooled high-speed direct injection diesel engine	BSFC↑, BTE CO, HC and NOx↓, and soot
B10, B20, B30, B40	Single cylinder, DIDE.	BP↑, BTE, and BSFC

Lennox Siwale examines in a heavy load, light duty, turbo-charged CI engine by burning of 5 percent, 10 percent, and 20 percent on volume of n-butanol. Using n-butanol on a volume basis, B05, B10, and B20 considerably improved the less in regulated emissions compared to the other investigations. This investigation result shows for B5, B10, B20 blends, solid soot particular emission reduced by 55.5 percent, 77.8 percent, and 85.1 percent respectively. Carbon monoxide emission reduced by 35.7 percent, 57.1 percent, and 71.4 percent. It is observed that nitrogen oxide emission increased by 10.3 percent, 32.3 percent and 54.4 percent, unburnt hydrocarbon emission result shows an increase by 21.4 percent, 71.4 percent, 214 percent respectively [15].

D. Actions of n-butanol as fuel in the gasoline engine

M.A. Costagliola has carried out an investigation on the spark-ignition engine to determine the efficiency of combustion and engine emissions by using n-butanol as additive fuel. The engine was operated in the mode of conventional 1.6 l port injection engine under steady states with a bio-ethanol-gasoline mixture such as 0, 10, 20, 30, and 85 percent by volume of ethanol in gasoline fuel and with 10 percent of n-butanol by volume basis in gasoline fuel. A marginal reduction of PN and PM1 was observed with alcohol mixture compared to neat gasoline fuel. When the engine is fuelling by the alcohol mixture, the engine exhaust particulate emissions are highly decreased compared to neat gasoline. The PN decreases by the ranges between 60 percent and 90 percent. Some of the harmful emission constituents for human health, such as benzene and benzopyrene are observed in the reduction of almost 50 percent and 70 percent respectively [16].

Ashraf Elfasakhany was studied engine exhaust emissions and performance by experimentally for pure gasoline and gasoline and n-butanol mixture in a larger range of speeds such as 2500–3200 revolution per minute without any major modification on the gasoline engine. Results of the experimental studies on gasoline engine show that adding of n-butanol in gasoline fuel slightly reduces the torque developed, power output, volumetric efficiency, the gas temperature at the exhaust and inside cylinder pressure of the engine as a result of the n-butanol addition. CO, CO_2, and unburnt hydrocarbon emissions reduce gradually for mixed fuels compared to pure gasoline due to development in combustion since n-butanol consist more oxygen which significantly allows partial reduction of the CO and UHC through the formation of CO_2 [17].

Saravana Kannan Thangavelu has reviewed the influence of bioethanol fuel mixture on combustion characteristics such as pressure rise, temperature, flame speed, combustion efficiency, combustion duration, heat release rate, knocking and cold start. Engine performance parameters i.e. torque, brake power, brake specific fuel consumption, brake mean effective pressure, brake thermal efficiency, and volumetric efficiency. Finally emission characteristics such as carbon monoxide, oxides of nitrogen, carbon dioxide, unburned hydrocarbon and other unregulated emissions of spark ignition engine. The engine test results showed a dramatic improvement in engine power and increase combustion characteristics for bioethanol fuel. In addition, the CO and UHC emissions reduce. On the other hand, CO_2 and NO_X emissions, unregulated emissions such as aromatics, acetaldehyde, and carbonyls were not decreased [18].

Guisheng Chen has investigated on combustion and emissions characteristics of a multi-cylinder CI engine fuelled with DMF diesel, n-butanol-diesel, and gasoline-diesel mixtures, and fuel characteristics of DMF, n-butanol, and gasoline were compared. Experimental results indicating that compared to B30 and G30, D30 has lengthened in ignition delay reason of lesser cetane number, which leads to faster burning rate and higher pressure rate. With EGR facility provided, D30 gets the lesser soot particles emissions, In addition, D30 and B30 improve the reduction of NOx-soot particles gradually. As diesel additive, DMF is superior to n-butanol and gasoline for reducing soot particles emissions due to its prolonged ignition delay and presence of oxygen. Using DMF diesel mixture with a moderate level of EGR suits better for the diesel engine to meet emissions regulations with higher fuel economy and efficiency [19].

Ashraf Elfasakhany has experimentally investigated the effect of using dual alcohols such as n-butanol and iso-butanol mixtures into gasoline fuel on SI engine performance parameters and exhaust emissions. Studies conducted by using 3 different types of mixtures such as 3, 7 and 10 percent by volume of iso-butanol and n-butanol. Results demonstrate a reduction in volumetric efficiency, Brake power, and Torque when engine operated with the dual alcohols compared to single fuel. On the other hand dual alcohols burn completely than regular gasoline fuel and produce CO, CO_2, and UHC pollutants at the rate of 4.3 percent, 40 percent, and 11 percent respectively [20].

The researchers have studied the effects of dual alcohols such as n-butanol and methanol with single alcohol methanol mixtures in gasoline fuel to examine performance parameters, combustion rate and exhaust emissions of a naturally-aspirated, spark ignition engine. The experiments conducted for the mixtures of GF, blend B17M53, M20, and M70. The mixture M53b17 was considered to match the vapor pressure of gasoline fuel. The brake thermal efficiency increases gradually whereas the gas temperature at exhaust reduced. Investigators concluded that the mixture M53b17 is recommended in place of M70 because of shortened combustion duration, high energy density and its vapor pressure is also selectively matched to that of gasoline fuel [21].

Ahmet Uyumaz has conducted experiments in a single cylinder, 4S, port fuel injection test engine in order to obtain the influence of clear n-heptane, the mixtures of n-heptane and n-butanol fuels at rate of B20, B30, B40 and the mixtures of n-heptane and isopropanol fuels P20, P30, P40 respectively on Combustion and performance characteristics at constant engine speed of 1500 revolutions per minute. The influence of inlet air temperature was also examined. The investigation results concluded that the beginning of combustion was early with the increasing of inlet air temperature for all test mixtures. Initiation of combustion is delayed due to a higher percent of n-butanol and isopropanol in the test mixture. Reduction in combustion duration was noted in case of using B40 mixture. Oxides of nitrogen emission were observed that the dramatic reduction with test mixture B20. Another side the experiment results demonstrate that the level of CO and HC emissions reduces with the increase of inlet air temperature for all test fuels blend [22].

Haiqiao WeiIn has worked on the knocking characteristics with neat n-butanol as well as a mixture of 20 percent of n-butanol by volume in gasoline fuel was investigated experimentally in a DISI single cylinder engine. Compared with the neat fuel gasoline, pure n-butanol provides better anti-knock characteristics with more advance in spark timing to limit the knock, Bu20 mixture was shows gradually deteriorative knock resistance and higher-end gas temperature due to higher BMEP and fast burning rate [23].

Divakar Shetty A S and his team extracted fuels from waste municipal plastics and has conducted experimental investigations on a single cylinder, 4 strokes, oil, and water-cooled CI engine. Results show that the fuel obtained from waste municipal plastics and its mixtures meets the ASTM standards of fuel requirements. Engine shows a little greater level of exhaust emissions and has contributed to performance parameters almost equals to neat conventional fuels. Results project the possible future fuels for IC engines can be derived from many waste resources [24].

II. Conclusion

Biofuels are more responsible and attractive alternative energy resources for the internal combustion engine. Utilization of biofuel with conventional fuel in blended mode can be saved a million barrels of crude oil in a day. Production of n-butanol by using waste resources by adopting well suitable technique will solve the problem of waste accumulation in nature and helps in saving the conventional fuel for future use. Many research articles projecting that the obtained physio-chemical properties of n-butanol and its mixtures with gasoline as well as diesel fuels are satisfying the ASTM requirements of fuel. The experimental investigations conducted by many research scholars are indicating positive oriented result such as CO, CO_2, and UHC emission reduces for the blends B05 and B10. Oxides of nitrogen emission increased by 15 percent to 20 percent for the same fuel mixtures. On the other hand, it was observed that maximum cylinder pressure is improved due to the complete burning ability of the fuel mixtures. Knock limits during engine operation was very less as compared to neat conventional fuel in the case of both CI and SI engines due n-butanol assigned with a higher rate of octane number. Complete combustion of fuel was observed for blended fuels as compared to neat conventional fuels, which increase the overall performance of the engines.

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