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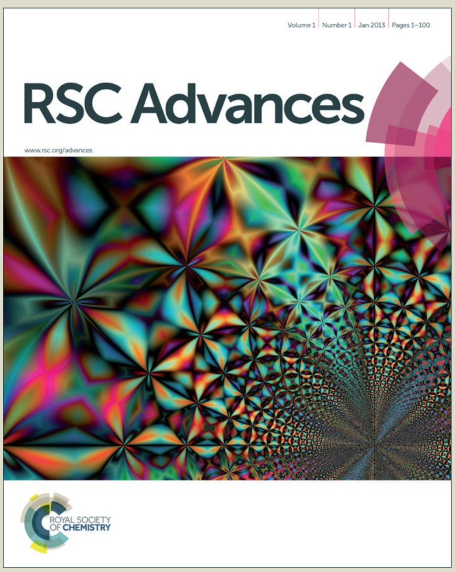

Experimental investigation on performance and emissions characteristics of waste cooking oil biodiesel and n-butanol blends in compression ignition engine

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Abstract

Experimental investigations were conducted to evaluate the effects of n-butanol in biodiesel/diesel blends on performance and emissions characteristics of a constant speed, direct injection diesel engine. The biodiesel/diesel blends were B20, B40 and B60 and diesel/biodiesel /n-butanol blends were D80-B10-nBu10 and D60-B20-nBu20 on volume basis. The performance parameters evaluated were brake thermal efficiency (BTE), brake specific fuel consumption (BSFC) and brake power (BP). Emission characteristics including carbon monoxide (CO), un-burnt hydrocarbon (UHC) and oxides of nitrogen (NO_x) with different blends ratio were also monitored. All the tests were performed at constant speed of 1500 rev/min and at different load conditions. At full load condition, results showed that nBu10 when compared to B0 increased the BSFC by 38.3% and HC content by 19.9%. In addition, CO emissions were reduced by 22.53%, while, NOx emissions increased by 3.6%. In view of reduction in exhaust emissions and comparable engine performance, n-butanol may be used along with biodiesel-diesel blends in a conventional diesel engine without any modification.

Keywords: Waste cooking oil biodiesel; Diesel; n-butanol; brake thermal efficiency.

Nomenclature	
BP	Brake power
BSFC	Brake specific fuel consumption
CI	Compression ignition
SN	Saponification number
IV	Iodine value
CN	Cetane number
CV	Calorific value of fuel
BTE	Brake thermal efficiency
IC	Internal combustion
kW	Kilowatt
HSU	Hartridge smoke unit
HC	Hydrocarbon
CO	Carbon monoxide
NOx	Nitrogen oxide
ppm	Parts per million
rpm	Revolution per minute
KOH	Potassium hydroxide
B0	Diesel
B20	20% biodiesel blended with 80% diesel
B40	40% biodiesel blended with 60% diesel
B60	60% biodiesel blended with 40% diesel
nBu10B10	10% n-butanol, 10% biodiesel blended with 80% diesel
nBu20B20	20% n-butanol, 20% biodiesel blended with 60% diesel
WCO	Waste cooking oil

1. Introduction

In view of current energy scenario, one of the principal routes of research in the past decade is focused on alternative fuels for diesel engines, due to depletion of petroleum resources and the increased environmental concerned caused by the conventional fossil fueled engines. Among those, bio-fuels have received increasing attention owing to their attractive features of being renewable in nature. In the recent years, the biodiesel is considered as an important alternative bio-fuel and it is produced from vegetable oils, animal fats or waste edible oils by transesterification with methanol or ethanol in the presence of catalyst that is the kind of methyl or ethyl ester. The idea of using oxygen rich fuels in comparison to conventional diesel in order to reduce emissions has been studied in the past. Pure biodiesel contains approximately 10% oxygen by weight[1] and its presences in the biodiesel leads to the reduction of emissions such as HC, CO_2 and so on[2]. In spite of this favorable impact, the economic aspect of biodiesel production is still a barrier in its utilization as the estimated cost of biodiesel is approximately 1.5 to 2 times higher than that of the petroleum based diesel fuel[3]. Therefore, exploring ways to minimize the cost of feedstock available for biodiesel production is the main interest in recent biodiesel research.

Huge quantities of waste cooking oils are generated per year by every country in the world and utilization of waste cooking oil (WCO) significantly reduced the production cost by 60-70%, which enhances the economic viability of biodiesel[4-5]. The management of such oils is significant because of their disposal problems and possible contamination of the water and land resources[6]. Many researchers compare the different characteristics of waste cooking oil biodiesel with diesel as a fuel in CI engine. Engine performance of WCO biodiesel and its blends was marginally poorer as NOx emissions were slightly higher[7], but significant reductions in particulate matter has been reported[8-9]. The un-burnt hydrocarbon (UBHC) emissions were lower for WCO biodiesel when compared to conventional fossil diesel with no loss of efficiency[10]. The indicated thermal efficiency increased by 1.8% at full load with B100, while soot peak volume fraction was reduced by 15.2%, with simultaneous reduction of CO and HC concentrations by 20 and 28.5%, respectively[11]. It has been observed that B25, B50 and B75 blends of WCO biodiesel have similar properties with diesel fuel, and exhaust emissions from biodiesel fuels were reported to be lower than those of fossil diesel fuels[12]. The major advantages of biodiesels are the higher flash point, lubricity and cetane number and disadvantages include low volatility and high viscosities which cause problems in long period engine performance tests.

Literature studies reveal that using straight vegetable oil as a diesel fuel lead to operational problems because of a very high viscosity, high pour point, lower cetane number and low calorific value[13]. Because of the emission benefits derived from the oxygen in the fuel molecules, the interest in the use of bio alcohols blends in diesel engine has been increased [14-15]. Diethyl ether may be produced from ethanol, that is produced itself from biomass[7], via a dehydrating process with strong dehydrating agents, thus being also a bio-fuels. Owing to some favorable properties including high cetane number, high oxygen content, low auto ignition temperature and high miscibility, it has been blended with diesel fuel. Also with certain limitation that include anesthetic effects, high viscosity and propensity for peroxidation in storage [16]. Butanol is a good fuel additive or alternative fuel for use in diesel engines with several advantages such as high heating value, higher cetane number, lower heat of vaporization and better miscibility with diesel. To achieve favorable conditions for ignition, butanol requires fewer heat and lower intake air temperature because it has low heat of vaporization. Moreover, its blends with biodiesel are to improve solubility and reduce viscosity to aid flowability[17]. Overall, butanol has physical properties close to diesel thus, butanol is an important additive or alternative fuel for use in CI engines[18].

From the open literature, it has been included that the main research is concentrated on the use of four promising bio-fuels mentioned above in diesel engine, viz. vegetable oil, biodiesels, diethyl ether and butanol, as blending agent in diesel engine[19]. The present research work is aimed to evaluate the influence of biodiesel/diesel and n-butanol/biodiesel/diesel blends on the performance and emissions characteristics in a commercially used direct ignition diesel engine and its comparison with the results of conventional fossil diesel fuel.

2. Material and methodology

2.1 Feedstock and chemicals

Waste cooking oil (WCO) was procured from hostel mess of Thapar University, Patiala. All the required chemicals such as methanol (Merck, 99.5%), n-butanol (Merck, 98%)and potassium hydroxide (KOH) of analytical grade were purchased from Lobachemie Pvt. Ltd. India. Biodiesel from waste cooking oil were produced in the laboratory. The fatty acid composition of waste cooking oil is shown in Table 1.

Table 1

Fatty Acid Composition of waste cooking oil

S.No	Fatty acid name	Structure	wt %age
1	Myristic	14:0	0.9
2	Palmitic	16:0	20.4
3	Palmitoleic	16:1	4.6
4	Stearic	18:0	4.8
5	Oleic	18:1	52.9
6	Linoleic	18:2	13.5
7	Linolenic	18:3	0.8
8	Arachidic	20:0	0.12
9	Behenic	22:0	0.3
10	Eicosenic	20:1	0.84
11	Erucic	20:1	0.07
12	Tetracosanic	24:0	0.04

2.2 Biodiesel production process

The FFA content of procured waste cooking oil was less than 1%. So, single stage alkaline transesterification process was chosen for production of biodiesel from waste cooking oil. The measured amount of waste cooking oil (250ml) was poured into a 500ml conical flask and put it into the hot plate with magnetic stirrer arrangement and heated for 15-20 minutes to lower its viscosity. Solution of methanol to oil molar ratio (6:1) and potassium hydroxide (KOH) 1% by weight were prepared separately, and poured into preheated waste cooking oil. The mixture was stirred continuously at a speed of 600 rpm and reaction flask was maintained at temperature of 60°C (below the boiling point of methanol) for 2 h. The final product was poured into a separating funnel and kept overnight for settling under the influence of gravity. Two layers were formed the upper layer consist of methyl ester of waste cooking oil and lower layer glycerol was formed. The waste cooking oil methyl ester was separated and washed with distilled warm water (10% by volume). After 5-6 washing, the pH of the methyl ester was found to be neutral. The obtained biodiesel was heated in the rotary evaporator to remove the traces of water vapors in the waste cooking oil based methyl ester. The ester was stored in the bottle for further analysis. The fuel properties were determined as per ASTM standards. The various properties of WCO methyl ester, n-butanol and diesel fuel were shown in Table 3.

2.3 Experimental setup

The test engine used in the experimentation was a single cylinder, water cooled, direct injection small utility commercially used diesel engine with a rated power output of 3.73 kW at 1500 rpm manufactured by Kirloskar Oil India Ltd. Table 2 presents the basic technical details of the engine used in the experimental setup. For measuring the power output of diesel engine used in the experiment, an eddy current (EC) dynamometer was coupled with engine shaft and it was loaded with the help of a resistive load bank. The exhaust gas analyzer consist of a group of analyzers for measuring carbon monoxide (CO), unburned hydrocarbons (HC) and nitrogen oxides (NO_x). The CO and HC concentration measured with HG-540 emission gas analyzer, the NO_x concentration was measured with KM19106 flue gas analyzer. The engine was operated at four load conditions corresponding to 0.9, 1.8, 2.7 and 3.6 bmep at a constant speed of 1500 rpm. The performance parameters evaluated were brake power, brake specific fuel consumption and brake thermal efficiency. In order to evaluate the exhaust emissions, the concentration of carbon monoxide, unburnt hydrocarbon and oxides of nitrogen were monitored.

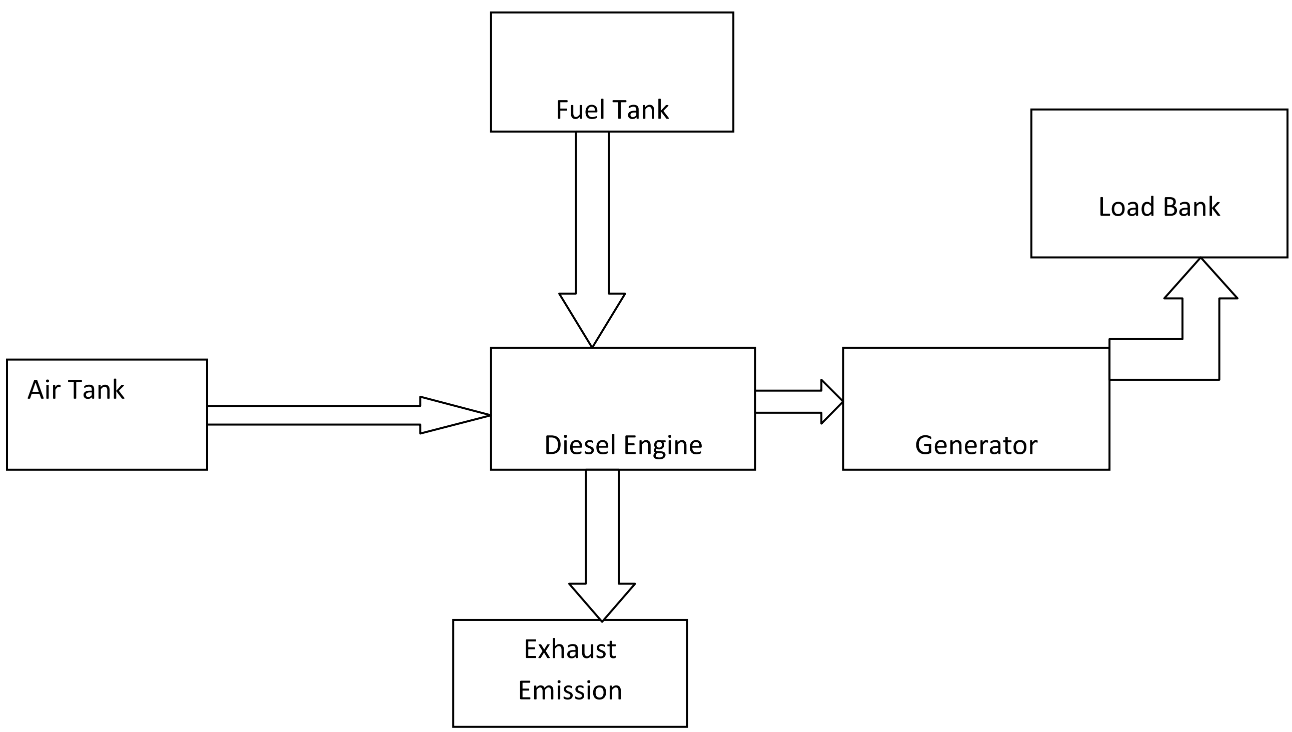

Fig.1: Schematic diagram of experimental setup

Table 2

Parameters of tested diesel engine

Parameter	Description
Manufacture	Kirloskar
Engine Type	Vertical, 4-Stroke
Rated power output (kW)	3.75
Engine Cooling	Air Cooled
Engine Speed (rpm)	1500
No of cylinder	1
Stroke length, (mm)	110
Bore (mm)	87.5
Compression ratio	16.5:1
Displacement volume (cc)	252.9
Injection pressure (kg/cm^2)	200

In this experimental study, three different blends comprising of WCO methyl ester and diesel and two blends of n-butanol-biodiesel-diesel were chosen for study. Biodiesel were mixed with diesel and blended fuels contained 20%, 40% and 60% by volume of biodiesel, and were identified as B20, B40 and B60 fuels whereas 10% and 20% of n-butanol, which were denoted as D80-B10-nBu10 and D60-B20-nBu20 on volume basis. The various blends were obtained by mixing on magnetic stirrer to ensure homogeneity of fuel blends.

3. Result and discussion

The following section illustrated the results of performance and emission characteristics of the diesel engine fueled by the biodiesel/diesel, n-butanol/biodiesel/diesel and pure diesel were tested under different load conditions. To ensure the accuracy of the results all the reading were replicated thrice and average value is taken for measurement.

3.1 Physico-chemical properties of fuels

The fuel characterizations were carried out as per ASTM standards and are shown in Table 3.

Table. 3

Physical properties of fuels

Property	Diesel	B100	n-Butanol	ASTM standard
Density (kg/m^3)	835	868	810	900
Viscosity (cSt)	2.72	4.38	3.64	1.9-6
Calorific Value (kJ/kg)	43400	39488.5	33000	>33000
Cloud Point (ºC)	-8	1		-2 to 12
Pour Point (ºC)	-6	-2	-45	-15 to 10
Flash Point (ºC)	78	155	29	>130
FFA %		0.12		<2.5
Saponification Number (SN)		202.5		
Iodine Value (IV)		79.67		
Cetane Number (CN)	50	55.32		

3.2 Uncertainty analysis

All measurements are subject to some errors and uncertainty regardless of the care which is exerted. Errors in experiments can rise from the instrument selection, observation, condition, environment, calibration, reading and test planning. Uncertainty analysis is needed to precise the accuracy of the experiments. Table 4 shows details of instruments and its range, accuracy and percentage uncertainties.

Table 4

Details of instruments, its range, accuracy and percentage uncertainties

Equipment name	Model	Measuring element	Measuring range	Resolution	Accuracy	% uncertainty
Neptune automotive gas analyzer	HG-540	HC	0-10000 ppm	1 ppm	± 10	± 0.2
	HG-540	CO	0.000-9.999 %	0.001%	±0.002%	± 0.2
Load indicator	------	------	0-3.75 kW	------	------	± 0.001
Burette for fuel measurement	------	------	1-30cc	------	±0.2cc	± 1.0

3.3 Performance characteristics

3.3.1 Effect on brake power

The variations of brake power (BP) at various engine load conditions for different tested fuels are shown in Fig.2. The brake power increased continual with increase in engine load from low load to full load condition. The results show that the biodiesel blends with conventional diesel fuel decreased brake power by 0.4, 0.5 and 0.8 KW for B20, B40 and B60, respectively, at full load condition, this dropped trend may be due to the 9.03% reduction in heating value of WCO based biodiesel which results in unstable combustion and consequently, lower brake power. However, some researchers found that the brake power initially increases with biodiesel blend and thereafter, decreases with increasing content of biodiesel beyond certain limit [20-21]. The brake power output of nBu10 blend was found to be very close to that of B20 with difference of 0.1 kW, but with increasing n-butanol proportion in the blends showed decreasing trends in the brake power profile due to reduced heating value of n-butanol in the tested fuels.

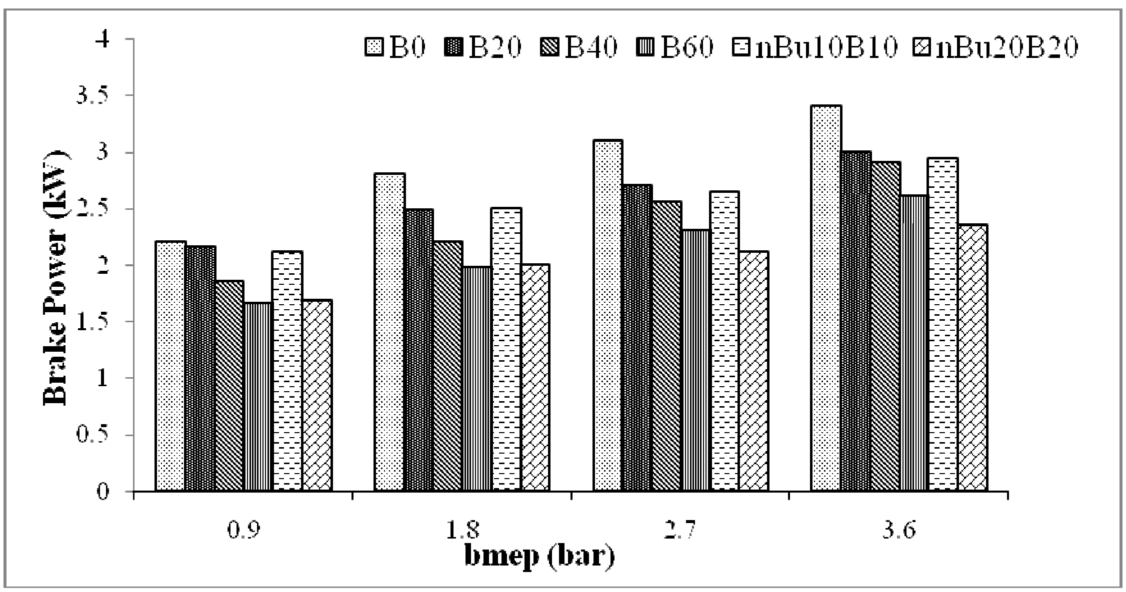

Fig. 2: Variation of brake power with bmep

3.3.2 Brake specific fuel consumption (BSFC)

BSFC is defined as the amount of fuel consumed for each unit of brake power per hour. It indicates the efficiency with which the engine develops the power from fuel. The fuel efficiency will tend to peak at higher engine loads at constant rated speed. Fig. 3 depicts that the BSFC increased with increasing proportion of biodiesel in the blends, however BSFC decreased with increasing load proportions due to better utilization of fuel. The BSFC decreased by 18.5 for B20, 21.8% for B40, 29.9% for B60, 9.6% for nB10 and 13.4% for nB20 as the b.m.e.p increased from 0.9 bar to 3.6 bar. This decrease in BSFC is understandable due to the increased total energy utilization[22]. For the blends B20, the BSFC is almost similar to fossil petro-diesel because of the presence of dissolved oxygen in the WCO methyl ester that enables complete combustion. However, as the biodiesel concentration in the blend increases, the BSFC increases due to the lower heating value of biodiesel when compared to that of conventional diesel. The study[20] indicated that more fuel needs to be injected for obtaining same power output of diesel, when operating with fuels of lower heating value such as biodiesel. An addition to this, n-butanol proportion in the biodiesel/diesel blends further increases this consumption, as n-butanol does not create a significant change in BSFC. Generally, the engine consumes more fuel with n-butanol/biodiesel/diesels than the reference diesel fuel because of the lower heat content of the fuel blends.

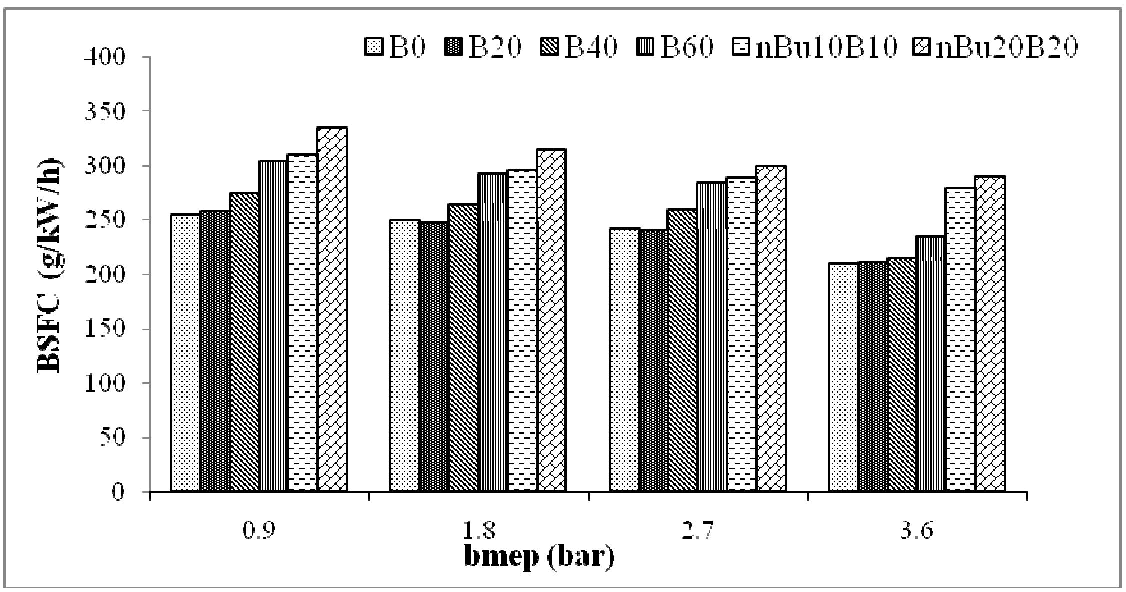

Fig. 3: Variation of brake specific fuel consumption with bmep

3.3.3 Effect on brake thermal efficiency

Brake thermal efficiency is defined as the ratio of the heat equivalent of the brake output to the heat supplied to the engine. It gives the efficiency with which the chemical energy of fuel is consumed into mechanical work. The variation of brake thermal efficiency for different test fuels at 3.6 b.m.e.p. load condition has been presented in Fig. 4. The maximum brake thermal efficiency observed were 25.4, 24.1, 22.4, 18.1 and 17.2% for B20, B40, B60, nBu10 and nBu20 blends, respectively, when compared to 24.3% for baseline fossil diesel. The maximum improvement in brake thermal efficiency was observed for B20, beyond which reverse trend was noticed due to lower calorific value and higher viscosity of biodiesel that leads to the lower brake thermal efficiency. The highest brake thermal efficiency was observed in B20 blend, which may be attributed to the enhanced combustion due to the presence of oxygen molecule in the blend. During fuel spray higher viscosity require more energy to pump the fuel which wears the fuel pump injectors, also cause poor fuel atomization[23]. However, at full load condition, the brake thermal efficiency were observed to be lowered with n-butanol concentration in the blends than that of diesel by 6.9 and 14.8% for nBu10 and nBu20, respectively while, at lower loads this variation was increased up to 13.8 and 20.4% because n-butanol generate the cooling effect which could be the reasonable factor for reduction in brake thermal efficiency.

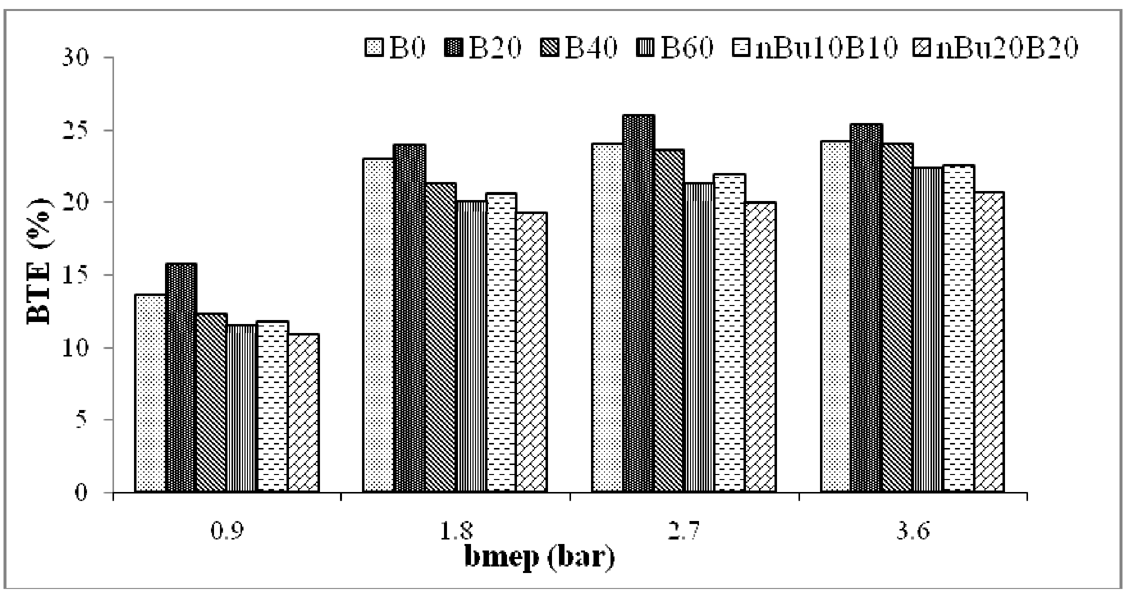

Fig. 4: Variation of brake thermal efficiency with bmep

3.4 Emissions characteristics

Engine exhaust emissions like NOx, unburned hydrocarbon (U.B.H.C.), Carbon monoxide were measured for diesel and tested fuel blends at constant speed of 1500 rev/min at different load conditions. All observations were replicated thrice to get a reasonable value.

3.4.1 Effect on NOx emissions

NOx emissions of diesel engine fueled with different fuel blends at different load condition are illustrated in Fig. 5. The NOx emissions of the biodiesel blends increased with increase in biodiesel content at same load which may be mainly due to higher combustion temperature of the biodiesel blended fuels. The NOx formation takes place mainly due to three factors: oxygen concentration, peak combustion temperature and residence time. Due to inherent oxygen molecules in biodiesel fuel, it promotes more NOx formation than conventional diesel fuel in tailpipe emission. The NOx emissions, at 3.6 b.m.e.p load condition for B60 blend was higher by 24.3% when compared with diesel, while n-butanol addition to biodiesel/diesel blends reduced NOx emissions by 16.5 and 18.04% for nBu10 and nBu20 blends, respectively when compared to B60. These results are in agreement with the previous findings[24]. The results reveal that addition of n-butanol in the diesel/biodiesel decreased the NOx level and this reduction increased with increase in n-butanol concentration in biodiesel/diesel blends because n-butanol increases the oxygen content and decreases the cetane number of blended fuel due to the cooling effect produced by n-butanol, which also lower the combustion temperature and subsequently, NOx formation is reduced[24]. However, at 0.9 b.m.e.p load condition, NOx emissions were reduced more significantly by 19.5% for nBu10 and 22.9% for nBu20, thus n-butanol addition give better results at part loads.

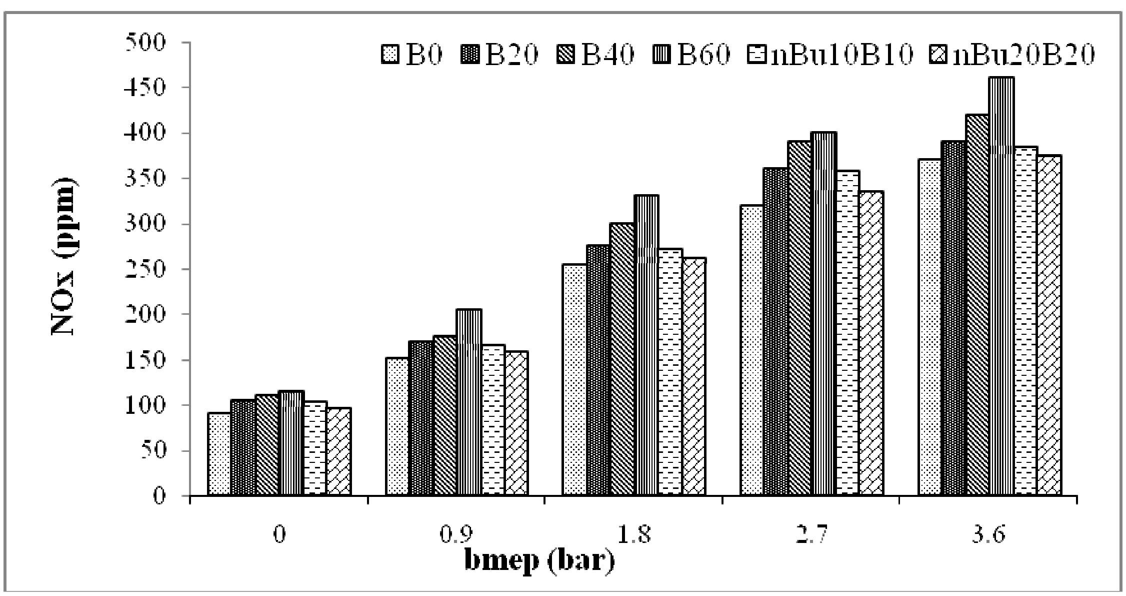

Fig. 5: Variation of NOx emissions with bmep

3.4.2 Effect on unburned hydrocarbon emissions

The variation of hydrocarbon emissions of tested fuels at various engine load conditions is plotted in Fig.6. For all the tested fuels, hydrocarbon emission increased with increasing engine loads. At 3.6 b.m.e.p load condition, the hydrocarbon emission was reduced by 17.30, 32.69 and 48.07 % for B20, B40 and B60 fuels, respectively. It is revealed that hydrocarbon emission reduction is higher with increasing proportion of biodiesel blends due to better oxidation because of presence of oxygen content in the fuel blends. While, nBu10 blend reduced the hydrocarbon emissions by 5.76%, but the hydrocarbon emissions increased by 19.23% for nBu20. This may be attributed to the fact that the combined effect of low cetane number and high heat of vaporization leads to longer ignition delay[24]. Hence, hydrocarbon emissions increase with increasing n-butanol concentration beyond 10% in the test fuel. It was also observed that opposite trend was observed in B20, B40 and B40 when compared with n-butanol blended fuels.

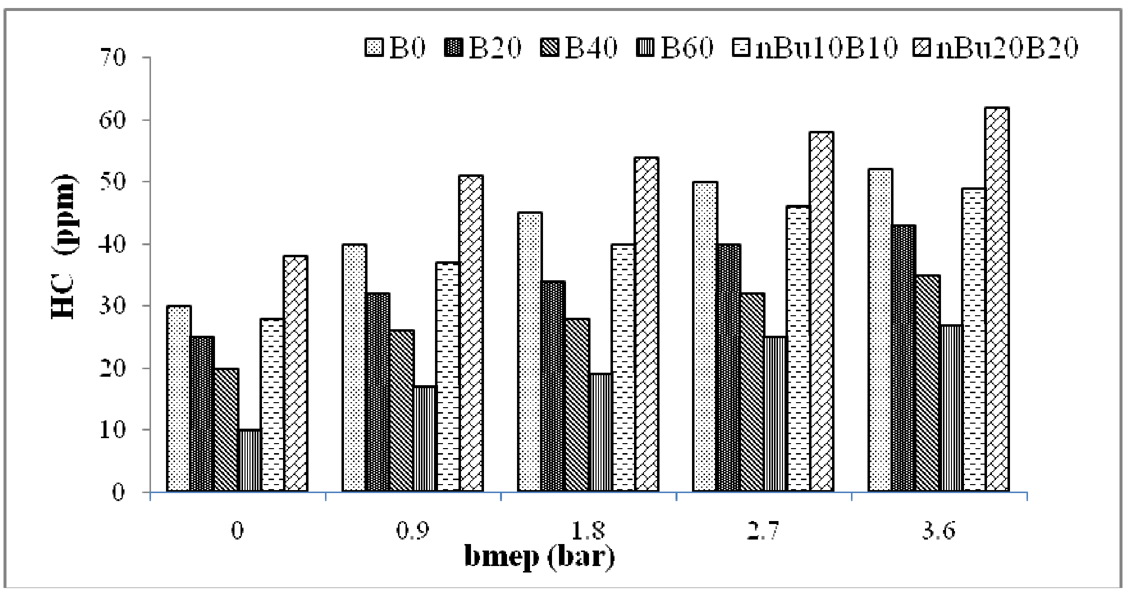

Fig. 6: Variation of HC emissions with bmep

3.4.3 Effect on carbon monoxide emissions

Fig. 7 illustrates the CO emissions versus b.m.e.p. trends for diesel fuel and various diesel-biodiesel and n-butanol fuel blends. The carbon monoxide is formed in engine cylinder due to incomplete combustion. The main sources of CO emissions are due to over mixing/ under mixing of fuel and moreover, rate of oxidation of CO is slow when compared to other hydrocarbon in tailpipe emissions. For diesel-biodiesel blend fuels, CO emission decreased with increasing biodiesel content at same load condition. The CO emission of diesel and tested fuels increased with increase in load. The increase in CO levels at higher loads is due to rich mixture than that of lower load which results in incomplete combustion of the tested fuels. At 3.6 b.m.e.p of full load condition, the carbon monoxide emission were lowered by 13.2, 15.9 and 22.2% for B20, B40 and B60 blends because of better combustion due to additional content of oxygen in the biodiesel fuel[25]. Increase in n-butanol fraction in biodiesel/diesel blends reduced the CO emissions by 22.5 and 19.4% for nBu10 and nBu20, respectively.

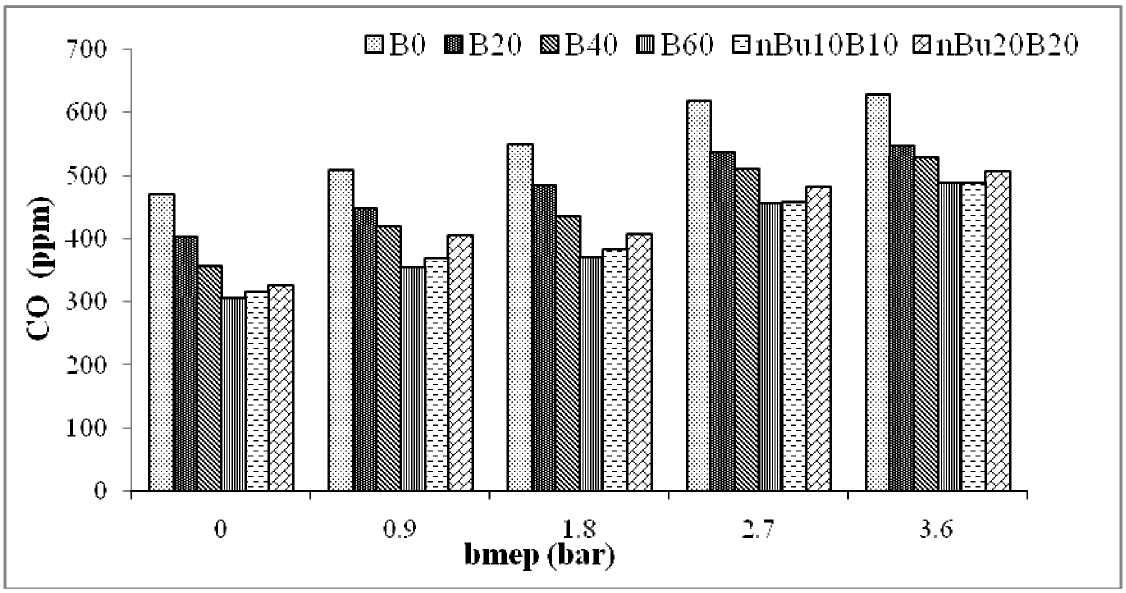

Fig. 7: Variation of CO emissions with bmep

4. Conclusions

Based on the experimental results of biodiesel and n-butanol-biodiesel blended fuels with diesel tested in single cylinder commercial diesel engine, the following conclusions have been drawn.

- The BTE of all biodiesel blended fuels followed decreasing trend except B20 which showed higher BTE than diesel.
- Addition of n-butanol content in biodiesel/diesel blends (nBu10 blend) lead to reduction in BTE by 22.5% and CO emissions by 6.9% with simultaneous increase of HC and NOx emissions by 5.7 and 3.8% respectively, at full load condition.

- The BSFC of B20 obtained was almost similar to diesel, however, a tangent increase in BSFC was observed in B40 and B60 blends, which may be mainly attributed to reduced BTE and lower CV of biodiesel.
- The carbon monoxide and hydrocarbon emissions significantly decreased with waste cooking oil biodiesel blends, whereas, significant increase in NOx emissions was observed, may be due to high oxygen content and advanced injection process with biodiesel.

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