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Mohan, Sumesh
Department of Mechanical Engineering, Amrita School of Engineering

Kotebavi, Vinod
Department of Mechanical Engineering, Amrita School of Engineering

Sahu, Debjyoti
School of Mechanical Engineering, KIIT Deemed to be University Bhubaneshwar

Shetty, Divakara
Engineering Department, University of Technology and Applied Sciences IBRI

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Investigations on N-Butanol and Biodiesel Blends Performance in Stationary Engine

Sumesh Mohan[1], Vinod Kotebavi[1,*], Debjyoti Sahu[2], Divakara Shetty[3]
[1]Department of Mechanical Engineering, Amrita School of Engineering, Bengaluru, Amrita Vishwa Vidyapeetham, India
[2]School of Mechanical Engineering, KIIT Deemed to be University Bhubaneshwar, India
[3]Engineering Department, University of Technology and Applied Sciences IBRI, Oman

*Author to whom correspondence should be addressed:
E-mail: k_vinod@blr.amrita.edu

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Abstract: The experimental study described here evaluated the emission and performance characteristics of a stationary diesel engine fueled with different blends, including diesel, biodiesel, and n-butanol, across various loads. This work was conducted on a single-cylinder, four-stroke, direct ignition, water-cooled CI engine at a constant speed, indicated a reduction in brake specific fuel consumption (BSFC) with an increase in the proportion of n-butanol in the fuel blend. Among the biodiesel blends, only the 10% blend showed lower BSFC compared to pure diesel, which was recorded at 0.25 kg/kWh. Moreover, it was observed that n-butanol combustion led to a significantly higher smoke density (HU) of approximately 33% compared to biodiesel, which showed around 15% at full load. Despite this, the But20 blend stood out by emitting lower levels of CO (~0.02%), CO_2 (~3%), HC (~8 ppm), and NO_x (~500PPM) at full load compared to diesel or any other blends. N-butanol blend resulted in higher smoke density. However, But20 blend offered a promising balance by emitting lower levels of harmful emissions compared to other blends and pure diesel.

Keywords: Biodiesel blend; N-butanol; brake specific fuel consumption; Smoke density.

1. Introduction

Biofuel can be used as an alternative fuel in diesel engines without making any major modifications in the engine[1)]. The different categories of biofuels available are biodiesel, biogas, alcohol etc. The different alcohols that can be used are ethanol, methanol, propanol, butanol etc. Biofuel research has mainly resulted in two major outcomes. First, decrease in harmful pollutant emissions such as unburnt hydrocarbon (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), carbon dioxide (CO_2)[2)]. Also, less dependency on petroleum brings energy security to many countries. Diesel is the most commonly used transportation fuel because of its benefits over other alternatives like low cost, availability, not so volatile, high thermal efficiency etc[3)]. Biodiesel as a blend is a good retrofit with its own limitations. Apart from vegetable oil biodiesel can be obtained from micro algae[4)]. Precipitation formation occurs in the biodiesel, which depends on outdoor temperature and biodiesel fraction[5)]. However, the best replacements are the use of oxygenated fuels in their refined stage or blended with traditional fuels like diesel or petrol. This, in fact, supplies sufficient oxygen and helps to improve combustion while decreasing particulate matter (PM) and NO_x emissions[6)].

Alcohols are considered as oxygenated fuels where oxygen atoms are chemically bonded within the fuel structure. These bonds will result in a chemical energy with no loss of efficiency while combustion is taking place. They are often available as ethers or as alcohols, in which ethanol and methanol are widely used. Ethanol and methanol are more volatile than diesel, hence the mixed fuel also becomes more volatile as well.

Many investigations on the CI engine have been carried out with different blends. Merola *et al.*[7)] have reported an experimental investigation with blend of 20% butanol and 80% diesel in a CI engine. The test report shows that BUT20 reduces NO_x and smoke without any loss in engine efficiency. Baskar *et al.*[8)] have tested Diethylene glycol, dimethyl ether and Diphenyl ether. They observed a significant reduction in CO and HC emissions, with a slight increase in NO_x emissions. Kannan et al.[9)] observed through their experimental investigation that adding ethanol to fossil fuel will yield less smoke, CO and HC; but there is an increase in NO_x emissions. Fernandez *et al.*[10)] have experimented with n-butanol and diesel, with blend ratios ranging from 10% to 30% by volume and with 1-pentanol and diesel, with blend ratios of 10% to 25%.

The experimental results showed that blends with n-butanol performed better than blends with 1-pentanol. Armas *et al.*[11] observed through an experiment that CO, smoke density (HU) and PM emissions decrease with a marginal increase in NO_x and HC emissions. They also reported that the emissions in hot and cold start conditions are different. In the cold start case HC, NO_x and CO emissions are inconsistent. And in hot or warm start condition, alcohol blends yield consistent emissions.

Rahman *et al.*[12] experimented on the effects of injection timing of CI engine's emissions and performance with bio-diesel, neat diesel, alcohol and other alternatives. They observed that alcohol blended with diesel yields better performance and less emissions than others. Wang *et al.*[13] and Banapurmath *et al.*[14] observed that NO, NO_x, HC, CO and PM emissions increases with ethanol addition with diesel along with increase in BTE. Varun *et al.*[15] conducted experiments on a kerosene stove using waste cooking oil kerosene blends. They concluded that 20 to 30% blend is most efficient and CO emission reduces with increases in waste cooking oil percentage.

Gnanamoorthi *et al.*[16] observed that the peak in-cylinder heat release and pressure increase close to TDC for ethanol -blended fuel and it gets increased as alcohol content in blends increased. CO and HC emissions are lower up to 30% blend but emission level increased beyond 30% blending. Murcak *et al.*[17] observed peak engine power for 10% blend at 3000 rpm and peak engine torque at 1400 rpm. Nabi *et al.*[18] reaffirmed that combustion with oxygenated blends is faster than with traditional fossil fuels. Miyamoto *et al.*[19] observed through experimentation that different oxygenated blends reduce smoke density, PM, NO_x, HC emissions along with knocking effects. Rathinam *et al.*[20] and Chaudhary *et al.*[21] observed reduction in HC and CO emissions while experimenting with waste cooking oil biodiesel mustard oil biodiesel blends. Chavan *et al.*[22] conducted experiments with mahua biodiesel blends. They also used ethanol and propanol as additives. They obtained lower emissions and better performance with 10% ethanol. In most of the research work carried out with alcohol and biodiesel blends it was observed that the HC and CO emissions reduces and NO_x increases with these blends[23, 24, 25]. Bhat *et al.*[26] experimented with shock- treated biodiesel and observed a decrease in emission levels. Hidayat *et al.* [27] in their study observed higher carbon deposits on the metal surfaces when they ran the engine with biodiesel as fuel.

In the present work, the load response of a diesel engine fuelled with n-butanol and biodiesel blends is experimentally investigated. In the experiment, n-butanol is used because it does not have any solubility issues while blending with diesel, and cheaper than ethanol. It has lower volatility, a high heating value, and is less hydrophilic than ethanol. Except cetane number, other qualities make n-butanol better suited for use as a blend.

2. Material and Methodology

2.1. Fuel blend preparation

In this experimental investigation, n-butanol is blended with diesel fuel in different percentages to check its performance and emissions characteristics in Diesel engine. Biodiesel is prepared using trans esterification of Waste cooking oil in the laboratory[3]. Fuel characterization process is well reported in the literature. N-butanol, diesel and other reagents are procured locally. After blending fuel properties are measured as per ASTM and Indian standard in the laboratory. These standards also include the processes of error analysis and the corrected values are considered here for further calculation.

2.2. Engine performance study

The experimental investigations are conducted on a single-cylinder, four-stroke diesel engine in the laboratory. The experimental setup is as shown in Fig. 1. For loading the test rig, eddy current dynamometer was used. All emission contents were recorded using a gas analyzer and a smoke meter. Steady-state has been maintained throughout the experiment. The engine specification is given in Table 1.

The percentage blends used in this study were 10%, 20%, 30% and 40% by volume. The butanol blends are designated as But10, But20, But30 and But40 respectively. Biodiesel prepared from waste cooking oil was blended with diesel in similar proportion and named as BD10, BD20, BD30 and BD40.

Table 1. Specifications of CI engine.

Sl No.	Parameters	Specification
1	Engine make and type	Kirloskar, Direct injection, naturally aspirated, Water cooled
2	Rated power	7.5 HP at 1500 RPM
3	Bore diameter and Stroke length	87.5 mm and 110 mm
4	Compression ratio	17.5:1

Fig.1: Experimental set up photograph

2.3. Uncertainty analysis

Table 2 contains information about the accuracy of various engine parameters and the uncertainties associated with the data collected during testing. Error size was reduced by averaging multiple readings to improve data quality and reliability. Here experiment with diesel fuel is repeated 5 times to calculate the uncertainty in brake specific fuel consumption estimation and the value remained within 3%[28, 29].

Table 2: Error analysis

Sl. No.	Parameter	Accuracy (+/-)	Uncertainty
1	Load (kg)	0.05	
2	Speed (RPM)	5	
3	Fuel flow (cc/min)	0.01	
4	Brake specific fuel consumption (kg/kWh)		3%
5	Hydrocarbon emission, ppm		1%
6	Oxides of nitrogen (ppm)		3%
	Carbon monoxide (%)		1%
7	Carbon dioxide (%)		1%
8	Oxygen (%)		2%

3. Results and discussions

3.1 Fuel properties

Biodiesel is chemically methyl ester of waste cooking oil. When biodiesel or N-butanol is added with diesel the oxygen content in the fuel increases which can be aiding better combustion[1]. Biodiesel slightly is more viscous than diesel however in the blend much difference is unexpected. Biodiesel had lesser calorific value than diesel therefore the blend too had less calorific value[2]. Butanol like methanol or ethanol are more suitable for petrol engine combustion due to high octane number (>93) and they are reported having less cetane number. However, N-butanol when mixed with diesel may result in comparable cetane number as diesel[11]. Butanol or biodiesel when blended with diesel the calorific value becomes almost similar to the proportional value as can be approximated mathematically. Table 3 here shows summary of property results where the N-butanol and diesel cetane numbers are taken from reported literature[28].

Table 3: Important fuel properties

Property	Diesel	Biodiesel	N-butanol
Viscosity at 40 ºC, cst	3.1	3.256	2.573
Specific Gravity at 25ºC	0.82	0.863	0.794
Flash Point ºC	54	124	29
Fire point ºC	57	133	33
Cetane number	45	49	25
Calorific value, kJ/kg	43544	42910	33630

3.2. Fuel Consumption

This study confirms that n-butanol and biodiesel blended up to 40% with diesel can be used in a CI engine directly under laboratory conditions. Even in a multi-cylinder high-speed engine, n-butanol blended fuel does not require any engine modification, including the programming of the electronic control unit[19,20]. As already established in the literature report, compared to pure diesel, improvement in efficiency is expected as the percentage of n-butanol in the mix increases the increased availability of oxygen during combustion. The presence of oxygen improves the combustion process in the engine, as the time available for combustion is very short. Typically, n-butanol helps limiting heat loss due to its low flame temperature property. Since n-butanol has a lower cetane number than neat or pure diesel fuel, longer ignition delay occurs, resulting in low heat loss from the engine. This factor helps the blends to have lower brake-specific fuel consumption than pure diesel/biodiesel, and the pattern is as shown in Fig. 2. Among biodiesel blends, BD10 reached lowest value at full load (0.25 kg/kWh). Anyway, all fuels get least consumed only at full load (0.2 to 0.3 kg/kWh).

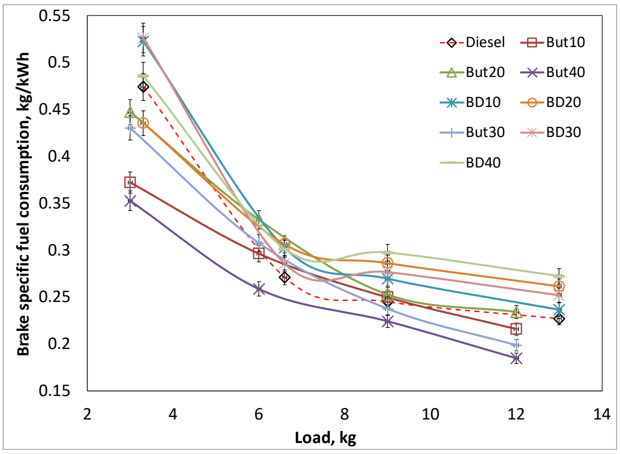

Fig. 2: BSFC variation with respect to load

3.3 Emission characteristics

Diesel alternatives are regularly subjected to emission measurement because of its exhaustive contribution in environmental pollution and global warming. Biodiesel addition decreases all harmful gas emissions except NO_x. Hence, an additive like n-butanol, which has the capability to reduce NO_x emissions, may find its way to be used in biodiesel/diesel blends in the future.

3.3.1 Smoke density

Diesel engines emit white, blue, or black smoke. Smoke opacity or smoke density measured in Hartidge units (HU) and the results from the present experiment are shown in Fig. 3. Among all the n-butanol blends BUT20 blend exhibits a lower smoke density (HU) whereas BUT40 shows the highest smoke density. From smoke opacity point of view, it is noticeable that smoke density reduces with an increased n-butanol proportion in blend fuel up to 20%, but later the opacity increases with increased alcohol concentration (~40%). The biodiesel blends provide a remarkably low smoke density, as seen in Fig. 3. Therefore, biodiesel blend smoke is apparently cleaner than those of n-butanol blend.

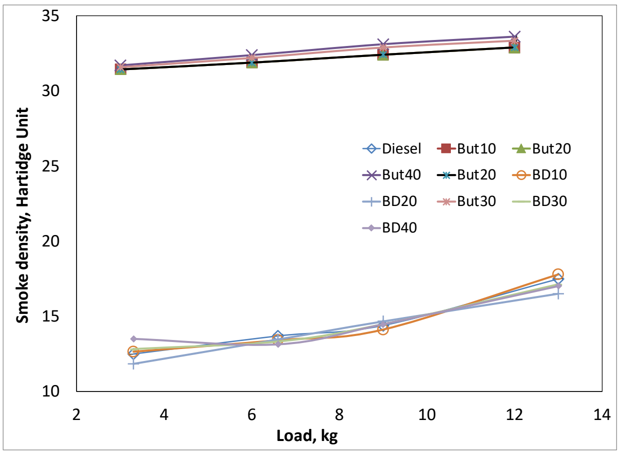

Fig. 3: Smoke density (HU) emission vs. Load

3.3.2 Unburnt HC emissions.

HC or hydrocarbons are unburned fuel emissions. In transport sector, engines run on high speed therefore less time is available for fuel combustion. Figure 4 shows HC emission with respect to load on engine for different fuel blends. Here, the BUT20 blend exhibits lower HC emissions, while the BUT40 blend exhibits the highest HC emissions. Compared to pure diesel, HC emissions reduces with increase in n-butanol are blend proportion by about 20%. However, HC emissions increase with n-butanol blend percentage. Interestingly, for biodiesel blends, the HC emission is almost similar as diesel. This suggests that blending n-butanol enhances the engine's efficiency and cleanliness.

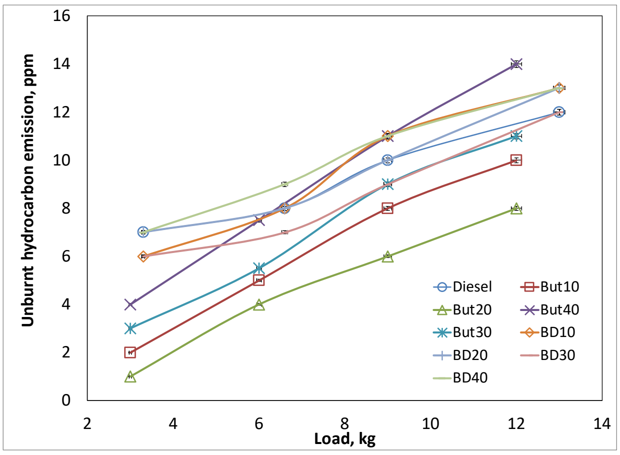

Fig. 4: Unburnt hydrocarbon vs. Load

3.3.3 CO emission

Carbon-monoxide emission is a major concern for IC engine related pollution. More the incomplete combustion, more happens to be CO emission. In experiments using biodiesel derived from waste cooking oil, we observed that a 20% blend gives competitive efficiency and also it reduces CO emissions. Results show here that n-butanol blends are better than biodiesel. BUT20 blend exhibits the lowest CO emission (0.01 to 0.03%). CO emission is reduced with increased n-butanol proportion in diesel blend upto 20% and gets increased with increased n-butanol proportion in diesel blend above 20% upto 40% as shown in Fig. 5. Anyway, CO emission decreases at increased load conditions for all fuels, probably because of lean burning. Favorable temperature and oxygen fuel interaction leads to complete combustion.

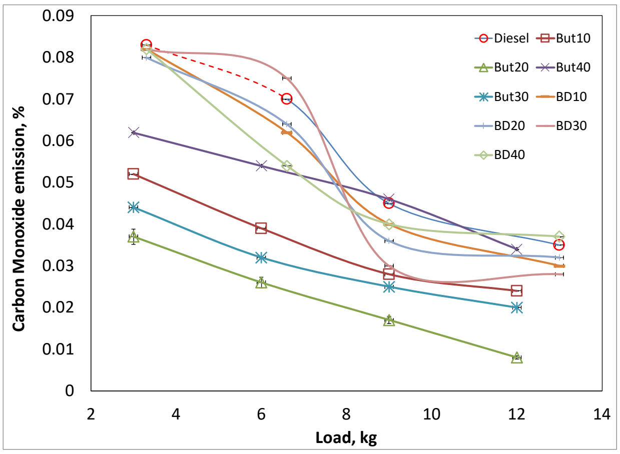

Fig. 5: CO emission vs. Load

3.3.4 NO_x emission

Nitrogen present in air generally does not take part in combustion however high temperature and pressure in presence of metallic surface leads to oxide formation. A high-speed engine yields oxides of nitrogen which is also a pollutant. In experiments on diesel engine using biodiesel derived from waste cooking oil, we observed that a 20% blend gives higher efficiency but NO_x was found to increase as the load increased[3]. Here Figure 6 shows the NO_x emission of various blends with respect to load. The result shown that blend BUT20 is best with lowest NO_x emission among the fuels considered (~500PPM). Probably the BUT20 has the perfect flame speed for this engine, which may not unnecessarily increase the pressure or temperature so that NO_x forms more[7]. All blends have much higher NO_x emission than pure diesel (>600PPM).

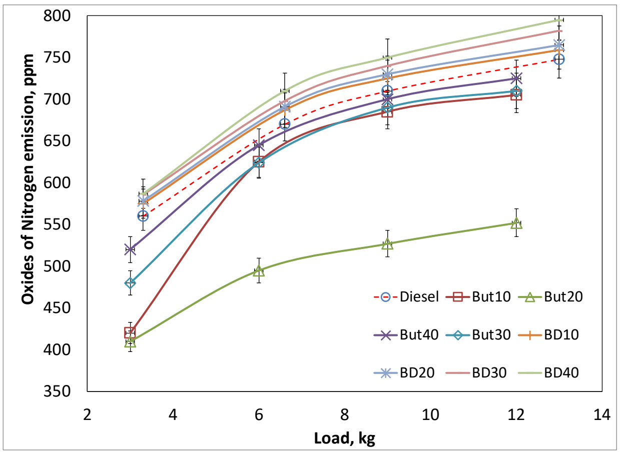

Fig. 6: NO_x emission vs. Load

3.3.5 CO_2 emission

If there is combustion there will be CO_2 formation. CO_2 is a greenhouse gas. Biodiesel blending generally increases the CO_2 levels in flue gas compared to pure diesel. It is interesting to see for n-butanol blending what should be the effect on CO_2 emission vis-à-vis diesel. Here, the BUT20 blend exhibits similar CO_2 emissions at higher load as shown in Fig. 7. CO_2 emission in biodiesel blend is higher at all load conditions. However, at low load conditions, all n-butanol blends emit less CO_2 than diesel (~3%) and biodiesel (~4%). The oxygen content in pure biodiesel is 10-11%, whereas in n-butanol it is 21.59% therefore the probability of oxygen supply during combustion is higher in case of n-butanol.

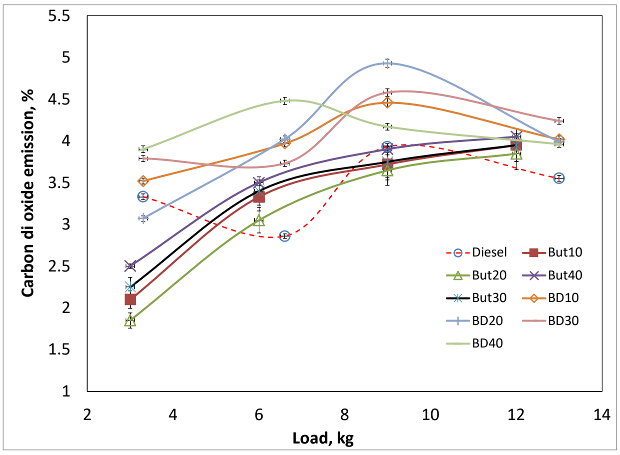

Fig. 7: CO_2 emission vs. load

3.3.6 Excess O_2 in exhaust

Excess air is provided in engine to make sure all fuel molecules get sufficient oxygen molecule for combustion process. However, the unutilized oxygen mixes with combustion gas may give after-burning effect i.e., CO molecules may get opportunity to form CO_2. However, that may lead to excess heat at the exhaust because CO oxidizing to CO_2 is an exothermic process. We already reported BD20 to have least exhaust gas temperature due as well as least excess O_2. Excess air supply may put off the flame, hence incoming air should have just enough oxygen. Figure 8 shows O_2 emissions with respect to load and overall trend remains stable (14 to 16%). Here, BUT10 and BUT20 blends exhibit marginally lower O_2 in exhaust whereas BUT30 and BUT40 blend exhibits the higher value (~20%).

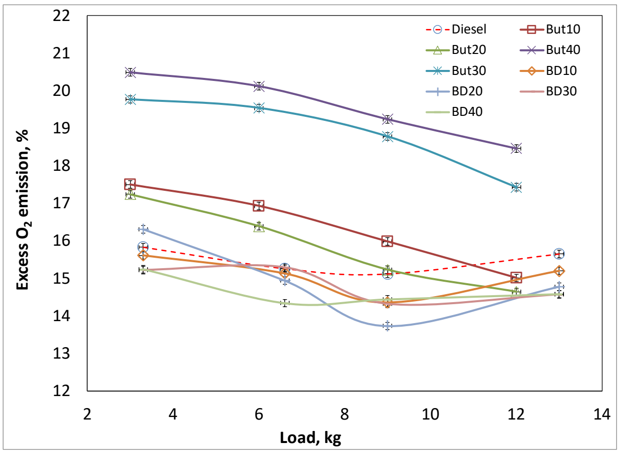

Fig. 8: Excess O_2 present in Exhaust vs. Load

3.3.7 Load and Exhaust emission

By this experimental investigation, the effects of blends on performance and emissions on diesel engine at different loading conditions are explored. Variation of CO_2 (%), HC (PPM), Excess O_2 (%) and Smoke density at full load are shown in Fig.9.

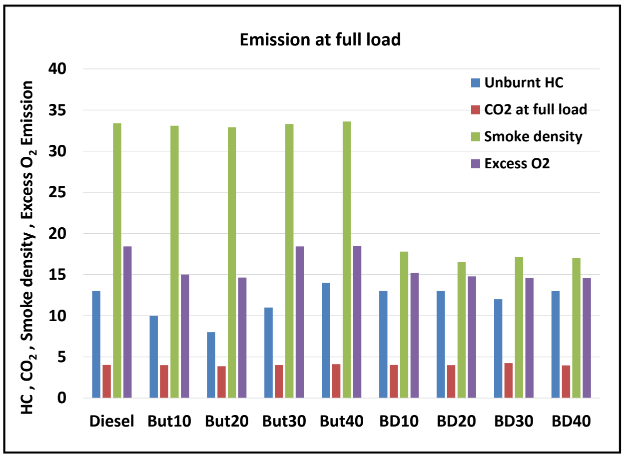

Fig. 9: Emission at full load

Since transport engines are used at full load condition hence a closer look at the same is important. Butanol has low cetane number, which means it will run the engine noisily. At the same time, the smoke density remains very high. Therefore, from the perspective of smooth operation of engine, butanol is not a good fuel. But with respect to the unburnt hydrocarbon emission, which is a major reason for smog formation in cities, butanol proves to be better choice than biodiesel especially the 20% blend.

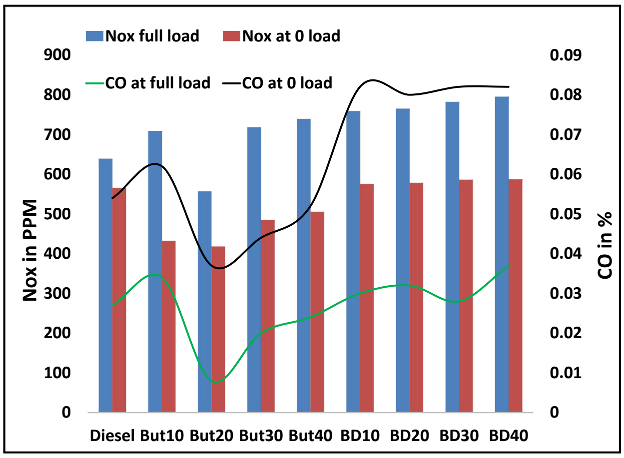

Fig. 10: Emission of NO_x and CO at full load and at no load

Many a times biodiesel blends are proposed to give cleaner combustion with respect to CO emission because NO_x emissions are anyway higher (see Fig.10). If CO emission is the main criteria, then both at no load (idling of transport vehicle engine is substantial in the entire driving cycle) or full load n-butanol blend yields low CO as well as NO_x especially the 20% blend. Therefore n-butanol if blended with diesel may require cetane improver to be more effective transportation fuel. However, in overall pollution level BUT20 is as good as BD10 therefore if biodiesel is preferred blending at 10% then for n-butanol it can be double i.e. 20%. Running the engine at full load is less polluting.

4. Conclusions

The single cylinder diesel engine was operated at near diesel working conditions in laboratory. Diesel is the viable transportation fuel so far and here the effectiveness of n-butanol and biodiesel (prepared from waste cooking oil) blending are evaluated systematically. From this experiment it can be concluded that emission of transport fuel combustion is matter of utmost concern at full load condition. Substantial amount of emission happens at no load condition as well. Following points can summarize the findings:

- Oxygenated fuels such as biodiesel and n-butanol show improved performance and lower emissions compared to traditional fuels like diesel.
- These fuels offer potential benefits in terms of combustion efficiency and emissions reduction.
- Biodiesel exhibits higher cetane rating than n-butanol, contributing to smoother engine operation.
- However, n-butanol blends outperform biodiesel in terms of reducing carbon monoxide (CO) and nitrogen oxides (NO_x) emissions.
- The combustion of n-butanol results in higher smoke density (HU) compared to biodiesel.
- Among the tested blends, a 20% n-butanol blend shows the least emissions of CO, CO_2, HC, and NO_x, surpassing other blend combinations.

Nomenclature

NO_x	Oxide of Nitrogen
CO	Carbon Monoxide
CI	Compression Ignition
HC	Hydrocarbon
CO_2	Carbon Dioxide
PM	Particulate Matter
BSFC	Brake specific fuel consumption
BTE	Brake Thermal Efficiency
But10	Butanol 10%
BD10	Biodiesel 10%

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