Performance Emission & Noise Characteristics Evaluation of n-Butanol/Gasoline Blend in Constant Speed SI Engine

Eshan Singh*, Mritunjay Kumar Shukla, Sunil Pathak , Vineet Sood, Nishan Singh
CSIR-Indian Institute of Petroleum
Dehradun
India

***Abstract*: There has been a recent interest in bio-based n-butanol as a fuel supplement due similar properties to gasoline. However, test data available in the literature for its behavior in SI engines are limited. Therefore, in present work, a comparative evaluation of physico-chemical properties, stability and corrosion properties, engine performance, emissions and noise of 10 % blend of n-butanol in gasoline (v/v), with pure gasoline and 10 % blend of ethanol in gasoline (v/v) has been carried out. Results show that 10 % blend of n-butanol in gasoline (v/v) offers a comparable performance and lesser tail pipe emissions than gasoline. N-butanol blended fuel is better than ethanol blended fuels in corrosion tests and overall emissions, currently used worldwide.**

Keywords— Biofuels, n-Butanol, emissions, noise, corrosion

I. INTRODUCTION

Pollution and depleting fossil reserves have been the two buzzwords that have been the driving force for all the research in the automobile industry in recent times. This has led to search for alternative fuels that may levitate the burden off the conventional fuels whilst reducing emissions. Biofuels are carbon neutral fuels derived from biomass [1]. Bio-based fuels like alcohols, ethers, biodiesel, green diesel, and algae based biofuels have been researched as alternatives or supplements to conventional fuels. The amount of engine modifications required for successful implementation of the movement towards biofuels has been a limiting factor in total conversion to biofuels, hence their use has been in blends upto a limit where the engine modification are minimal and easier for current crop of vehicles to adapt to the change in fuel [2].

So far, alcohols have been the most successfully used as blended biofuels currently employed across the globe. Alcohols such as methanol and ethanol are known to burn cleaner than regular gasoline and produce lesser carbon monoxide, HC and oxides of nitrogen. Moreover, their resistance towards knocking is higher than conventional gasoline, which provides scope for more efficient engines [3.4]. However, high corrosion tendency, water affinity and lower volumetric energy of ethanol and methanol make them less attractive as an alternative fuel. In recent time n-butanol has emerged as a potential futuristic biofuel due to its high energy density, better miscibility and less corrosiveness [5]. Moreover, its better volatility, lesser causticity, coupled with its compatibility to existing fuel storage and distribution infrastructures, promote it as a next gen biofuel candidate [6,7]. Higher flash point signifies that butanol is safer to transport compared to its counterpart and is less prone to accidental fire risks. Human inhalation exposure to n-butanol (20-50 ppm) is irritating to eyes, nose and throat, but no systemic effects occur at this exposure level. There is no report of carcinogenicity with Butanol-1 and it is classified under Group-D chemicals by EPA [8]. n-Butanol can be produced from the same bio feedstock used for ethanol by ABE fermentation, used to make acetone, butanol and ethanol in the ratio 3:6:1 [9,10,11]. The economics of butanol fermentation are favorable [12], and considerable improvements in every single step of production are foreseeable with stringent and consistent research and development efforts [13,14].

While significant research has been carried out regarding the use of methanol and ethanol blended gasoline in engines, limited experimental work has been reported regarding the use of n-butanol is SI engine, which has held back its global use as blends in gasoline. Alasfour carried out the initial research with 30% blends on butanol in gasoline. His work concluded reduction in maximum NO and HC emissions from butanol-gasoline fuelled engine [15,16,17,18]. Spray and combustion characteristics of butanol in DISI engine were later studied where butanol flame development was found to be very similar to that of gasoline [19]. Szwaja et al obtained similar results in their combustion study of increasing butanol content in gasoline [20]. Rice et al, studied 20% butanol-gasoline blend in single cylinder 4-stroke engine and reported lower CO emission and comparable UBF emission than those for gasoline [21]. Similar experiments performed by Norhisam Misron et al showed a performance increase by 8% compared to that using gasoline [22]. Williams et al. [23] evaluated isomers of butanol in an Atkinson cycle 1.5 L and prototype 1.8 L lean boosted engine and concluded that thermal-efficiency, combustion and emissions were not adversely affected as a result of adding butanol to gasoline.

Yang et al. [24] discussed the feasibility of fueling gasoline engines with butanol–gasoline blends, ranging from 10% to 35% butanol by volume. They found comparable engine power upto 20% blends and lower HC and CO emissions for all blends while NOx emissions went up. Experiments performed on a turbocharged multi-cylinder DI–SI engine equipped with an external exhaust gas recirculation (EGR) circuit showed that the 10% ethanol and 16% butanol fuels with the similar oxygen content produced similar values of

BSFC and similar MBT spark timings at the same conditions [25]. Yacoub, et al. examined blends of alcohols and gasoline and found that all alcohol blends had lower CO and UHC emissions and the blends with oxygen contents of 5% had higher NO emissions due to the lower enthalpies of vaporization and higher flame temperatures of the fuels [26]. Wigg et al investigated the use of neat butanol using a single cylinder Port Fuel-Injected, Spark-Ignition Engine and found comparable engine performance with butanol but producing slightly less brake torque while the emission of unburned hydrocarbons was found to be two to three times those of gasoline suggesting that butanol is not atomizing as effectively as gasoline and ethanol [27].
It is evident that, more studies based on different engine setup are required to bring n-butanol to forefront and bring about its global acceptance. Present work focuses on understanding performance, emission characteristics of 10% n-butanol/gasoline blend in a constant speed four stroke carbureted S.I. engine. Physico-chemical properties and corrosion behavior of the blended fuel were also studied. The effect of n-butanol addition to gasoline on exhaust and noise emissions have been experimentally investigated and results are compared to those of gasoline and ethanol-gasoline blend.

II. Material and Methods

The nomenclature followed by the results abbreviates the alternate fuel followed by its percentage in the blend followed by G for unleaded gasoline. For the current study two blends are attributed with names E10G and B10G referring to 10% ethanol+90% gasoline and 10% n-Butanol+90% gasoline. Commercially available unleaded gasoline, ethanol (99.99% pure, 0.1% H_2O, RFCL limited) and butanol (99.99 % pure, 0.2% H_2O, RFCL limited) were used for the study. Physico- chemical properties of pure compounds are given in Table 1.
10 % (v/v) blend of ethanol (E10G) and butanol (B10G) were prepared by splash blending method. Samples of these blends were then observed for 90 days for any visible phase separation under gravity. Samples of blends were then centrifuged at 1200 rpm for 30 minutes. Low temperature stability of the blends was also studied. The important physico-chemical properties of test fuels were analyzed as per ASTM standards. Density was measured by density meter (Anton Paar, DMA 4500M) following the ASTM 4052 standards. RVP of blends were calculated using RVP measuring instrument (ISL Company) following the ASTM D 323 standards. D-86 distillation property was measured by automatic distillation instrument (Precision, ADA IV, CEL, D-86-13). Calorific values were measured by a Bomb calorimeter (Paar industries, 6300Calorimeter). Corrosion characteristics were determined using ASTM G31 Static Immersion Test for piston metal.
A single-cylinder, constant speed (3000rpm) forced air-cooled spark ignition engine (compression ratio of 5.1) coupled with 2.2 KVA AC was used for the experiments. The details of the engine and electrical generator are listed in Table 2. The engine output was measured in terms of electrical power by measuring output current and voltage at constant frequency (50 Hz). K-type thermocouple was used to monitor the temperature of engine oil and exhaust gases.

Table 1: Physico-Chemical Properties of Pure Substances

Fuel	Gasoline	n-Butanol	Ethanol
Molecular Weight	114.15	74.12	46.07
Oxygen content (%)	<2.7	50	21.6
Energy density (MJ/L) [36]	32	29.2	19.6
Stoichiometric A/F Ratio [36]	14.6	11.2	9
Specific energy (MJ/kg) [37]	2.9	3.2	3
Latent heat of Vaporization [37]	0.36	0.43	0.92
RON [37]	91-99	96	129
MON [37]	81-89	78	102
Kinemetic Viscosity at 20°C in cSt [37]	0.4-0.8	3.64	1.52
RVP (psi)	4.5	2	0.33
Flash Point (F)	45	95	61.88
Laminar Burning Velocity (cm/s) [38]	51	58.5	63.6
Adiabatic Flame Temperature (K) [38]	2370	2340	2310
Solubility in Water at 20^oC (mL/100mL H_20) [38]	<0.1	Fully miscible	7.7
Self Ignition Temperature (^oC) [38]	~300	343	420

Fuel consumption was measured by recording the time of consumption for 100 ml of fuel. Figure 1 shows a schematic diagram of the setup used in our study.

Table 2: Birla Ecogen Genset Specifications.

Engine Specifications	
Engine type	4-Stroke,Forced air cooled, single valve engine
No of cylinder	One(1)
Bore X Stroke (mm)	73 X 61
Displacement (mm)	256
Comp. ratio	5.1:1
Rated O/P (HP/HR)	4.0/3000
Lube oil sump capacity	950ml
Ignition system	TCI
Generator Specifications	
Rated AC O/P	2200VA
Max. AC output	2400 VA
Voltage	220V
Current	10A
Frequency	50 HZ

Automotive emission analyzer (MEXA-584L) was used to measure engine tail pipe emissions. Details of the analyzer are given in Table 3. Measurement distance of exhaust gas analyzer was 1 meter from the engine block. The system was calibrated at the beginning of each test series. Cold start emissions were also measured for each fuel. Specific fuel consumption and concentration of Carbon monoxide (CO), Hydrocarbon (HC), Nitrogen monoxide (NO) and Carbon dioxide (CO_2) in engine emission were measured. HC emissions were measured in terms of propane equivalent, hence the correct value would be thrice the value measured by the analyzer.

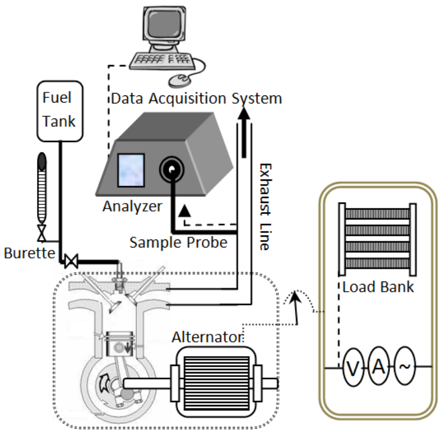

Figure 1: Schematic diagram of setup

Table 3: Analyzer Specifications

Species To Be Measured		Type Of Analyzer
CO	Molar concentration in dry exhaust (%)	Non-dispersive infrared absorption (ndir)
CO_2	Molar concentration in dry exhaust (%)	Non-dispersive infrared absorption (ndir)
HC	Molar concentration in wet exhaust (ppm)	Heated flame ionization detector (hfid)
O_2	Molar concentration in dry or wet exhaust (%)	Paramagnetic (pmd)
NO	Molar concentration in dry or wet exhaust (ppm)	Chemiluminescent detector (cld)

The engine was run for a period of 15 minutes to reach steady state operating conditions till the engine oil temperature reached 75°C. The tests were conducted 3 times for each test fuels Noise measurement was conducted according to ISO-3744-1981 (E) standards by Sound level precision instrument (Bruel & Kjaer, type 2209). Noise level was measured at different 9 different locations on a cube around the engine as shown in Figure 2.

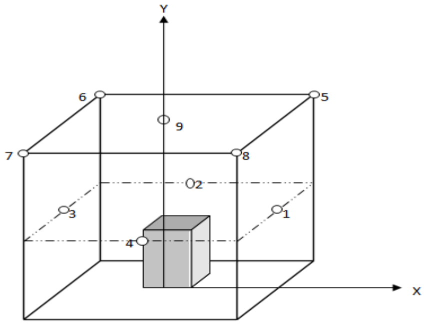

Figure 2: Testing points for noise emissions.

III. Results and Discussion

A. Fuel Properties

Results of stability test are given in Table 4. No phase separation occurred under gravity for 90 days observation period. Furthermore, no phase separation took place on centrifugal test up to 1200 rpm. B10G remained stable till -3°C during low temperature stability test.

Table 4: Stability Test Results

Fuel	Gasoline	E10G	B10G
Gravity Separation	Stable	Stable	Stable
Centrifuge Separation	Stable	Stable	Stable
Sub-Zero stability	Stable	Stable	Stable

The results of various fuel properties tested along with respective ASTM standards are given in Table 5. B10G has a calorific value close to gasoline. This can be attributed to the calorific values of the pure compounds as shown in Table 1. This ensures that no adverse effects on engine performance take place with B10G blends. B10G has a higher density compared to E10G and gasoline. It means that more charge can be inducted in the combustion chamber, which may compensate for the decrease in calorific value of the biofuels, as can be seen in the values of specific energy density of the three fuels. The research octane number of pure gasoline and B10G are comparable. B10G offers slight better knock resistance and combustion than gasoline, however the improvement is not as much as that in E10G.

Table 5: Properties of Blended Fuels

Property	Gasoline	E10G	B10G
Calorific Value (Cal/gm.)	11263.3	10932.3	10939.2
Density at 15 °C, g/cc (ASTM 4052)	0.7453	0.7529	0.7586
RON	88.5	92.7	88.7
T_{10}	61.1	54.7	62.3
T_{50}	101.6	85.9	98.6
T_{90}	151.4	146.9	150.7
Distillate	98	98.5	97.5
Residue (% vol)	0.5	0.5	0.5
Loss (% vol)	1.5	1.0	2.0

Distillation curve, given in Figure 3, provides an insight into the boiling range of the fuel and is used to predict its operation in engines. Front end volatility is related to evaporative emissions, engine start-up, engine warm-up, and vapor lock tendencies. Better front end volatility of B10G means that it is easier to cold start compared to gasoline and E10G. As compared to E10G, B10G follows the gasoline distillation curve closely providing smooth engine operation over all the operating range.

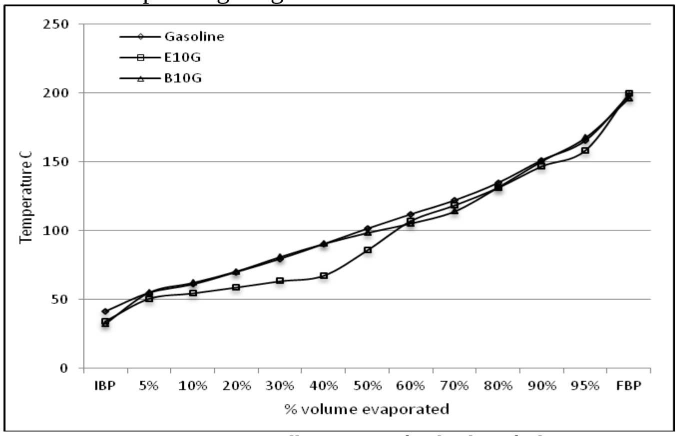

Figure 3: D-86 Distillation curve for the three fuels

Comparative results for corrosion test of piston material are given in Table 6 for E10G, B10G and Gasoline. Weight loss in piston material in case of B10G is lower than that of E10G. Also, lower corrosion rate and penetration rates were recorded for B10G, when compared to E10G. It is evident that B10G is less corrosive when compared to E10G, however the corrosiveness is slightly higher than those with pure gasoline, which is still a matter of concern.

Table 6: Results of corrosion test.

Fuel	Gasoline	E10G	B10G
Weight Loss (mg)	0.3	0.7	0.5
Corrosion Rate (mdd)	0.223	0.5203	0.3717
Penetration Rate (mpi)	0.1005	0.2344	0.1641

B. Engine Performance

The maximum brake power attained for all three fuels is plotted in Figure 4. Slight power drop is observed in case of B10G; however the power drop is negligible when compared to that in case of E10G. The values are in accordance with the calorific values of the three samples as calculated in Table 5.

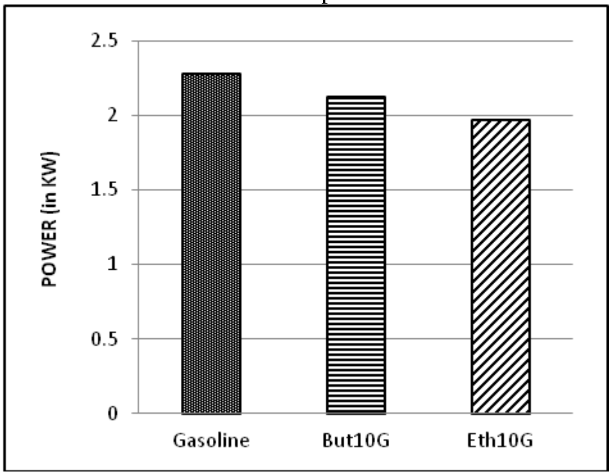

Figure 4: Maximum brake power for each fuel

Figure 5 shows a comparison of specific fuel consumption for B10G with gasoline and E10G. At all loads, brake specific fuel consumption of B10G is similar to that of gasoline and superior to E10G. This may be attributed to the comparable calorific value and higher density of B10G. To obtain the same output power, lower calorific value fuel is consumed more. For this reason E10G shows higher brake specific fuel consumption at all loads.

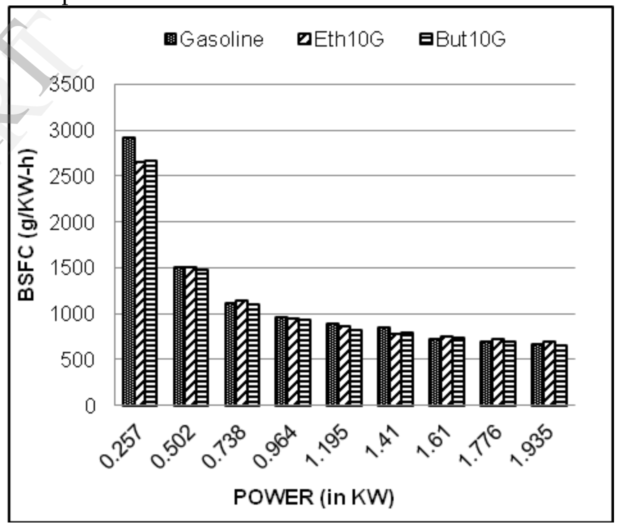

Figure 5: BSFC VS Power at different loads

C. Engine Emissions

Figure 6 shows the comparison of CO emissions for B10G with pure gasoline and E10G fuels. CO emissions from B10G are lower than that of pure gasoline. CO is a toxic gas that is the result of incomplete combustion. Alcohols are naturally oxygenated compound. When blended with gasoline, the combustion of the engine improves due to the inherent leaning effect of alcohols and therefore, at every load, CO emission is reduced. Oxygen content, in case of Ethanol is 50%, while for n-butanol, it is 21.62%, which explains the disparity in CO emissions between E10G and B10G.

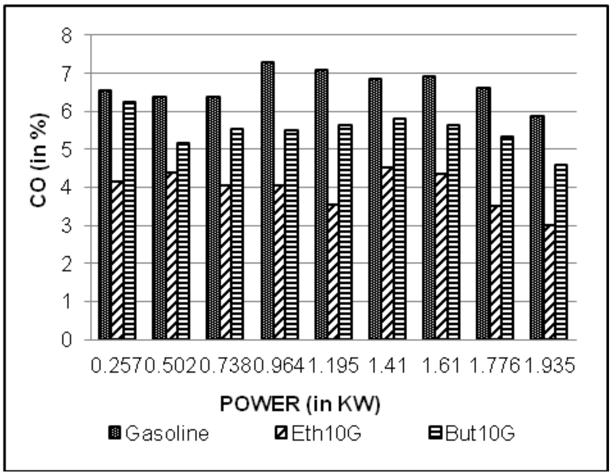

Figure 6: Carbon Monoxide emission at different loads

UHC emissions from different fuels are compared in Figure 7. UHC emissions from B10G are lower than those from gasoline. Because of oxygen contained in E10G and B10G fuels, alcohols may be considered as partially oxidized hydrocarbons, which results in lesser UHC emissions from tailpipe [28,29,30]. Reduction of UHC emissions is higher in E10G compared to B10G. This may again be attributed to the higher oxygen content when considering ethanol-blended gasoline.

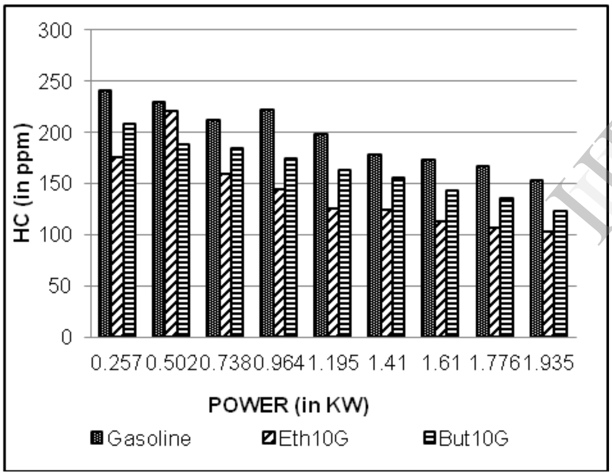

Figure 7: Hydrocarbon emissions at different loads

The effect of engine load on NO emissions from the three test fuels is given in Figure 8. NO increases with load due to increase in in-cylinder temperature. At all loads, NO emissions from B10G are comparable to those from pure gasoline and much lower than those from E10G. It may be a consequence of comparable energy densities, laminar flame velocities and flame temperature of gasoline and B10G. NO is formed as a result of nitrogen and oxygen reaction under high temperature and pressure in the engine cylinder. E10G is the biggest culprit when it comes to NO emissions. This can be attributed to higher flame speeds of ethanol, which results in faster combustion and sudden increase in overall chamber temperature, which is in accordance with previous works [31,32].

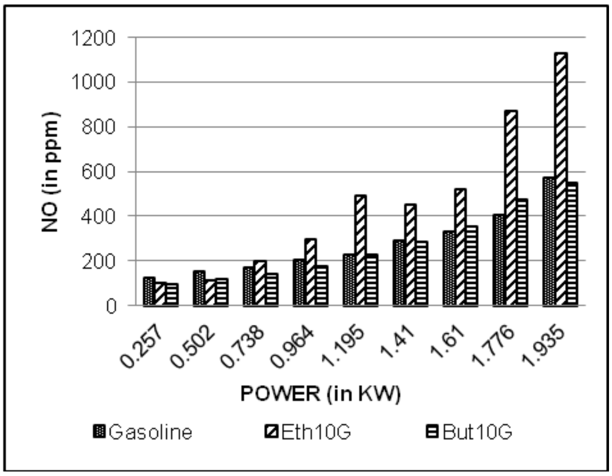

Figure 8: Nitrogen oxide emission at different loads

Figure 9 compares the CO_2 emissions for the three test fuels. B10G emits lowest CO_2 among the three fuels. CO_2 is a product of complete combustion and hence, CO and CO_2 have complementary correlation. Lesser CO_2 emissions during combustion indicate a better well-to-wheel efficiency. Due to better flame speed and yet comparable calorific value of B10G, a superior combustion process without a penalty in BSFC is witnessed, which translates to lower CO_2 emissions [33].

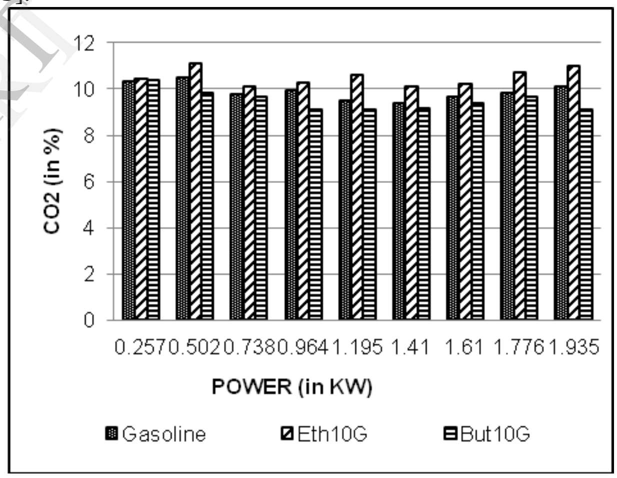

Figure 9: Carbon dioxide emission at different loads

Cold start emissions for B10G are plotted in Figure 10 and compared to E10G and gasoline emissions. CO emissions from B10G are comparable to those from pure gasoline; however, they are higher than CO emissions from E10G. HC emissions for B10G are lowest during cold starts. Lowest NO emissions were observed in case of B10G compared to E10G and pure gasoline. Cold starting requires more fuel injection into the combustion chamber due to reduced vaporization at low temperature. CO and HC emissions are of particular interest during cold start as they rise drastically at such high fuel-air ratio [34]. Overall, B10G provides lower cold start emissions compared to gasoline.

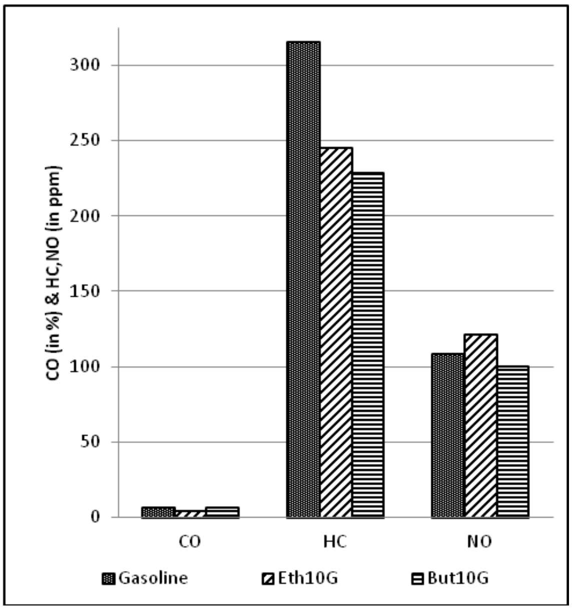

Figure 10: Cold Start Emissions

The noise level in dB at different points around the engine at 75% load is plotted in Figure 11. Noise emission for B10G blend was slightly higher than the gasoline. Both the alcohol blended fuels, B10G and E10G, show similar noise level. This is due to the increase in flame speed and hence, the increase in the rate of mass burning due to high burning speed of alcohol-air mixture, which is higher than that of the gasoline-air mixture. n-Butanol blending also improves combustion efficiency and therefore the point of maximum rate of heat release is increased due to faster flame front propagation [35].

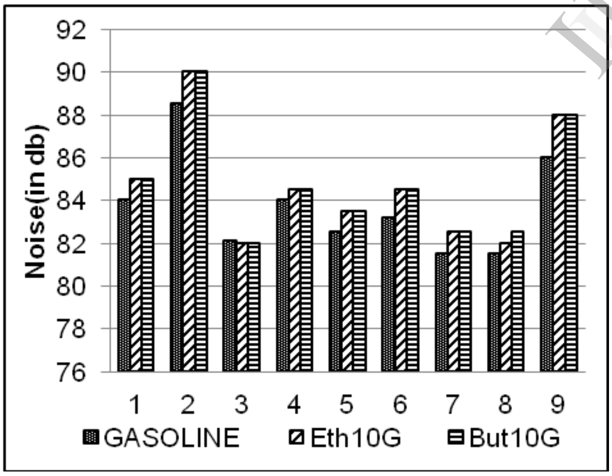

Figure 11: Noise emissions at 9 points

D. Conclusions

n-Butanol is a futuristic bio-fuel candidate, which can be produced from waste biomass. In order to understand the feasibility of its use as a blend component in gasoline in S.I. engines, evaluation of physico-chemical properties, corrosion behavior, engine performance and emission characteristics of 10% blend of n-butanol in gasoline (v/v) was carried out in a small-carbureted S.I. engine. Results were compared to those of pure and ethanol-blended-gasoline, which is a commonly used biofuel. Based on experimental results following conclusions may be drawn:

- 10% n-butanol-gasoline blend exhibits similar distillation curves as gasoline with a slightly better front end volatility, which means lesser problems of cold start than 10% ethanol-gasoline blend.
- 10% n-butanol blend is found to be less corrosive than 10% ethanol-gasoline blend. However corrosiveness of butanol-gasoline blend is higher than pure gasoline.
- n-Butanol-blended-gasoline offers engine performance comparable to gasoline and better than ethanol-blended-gasoline. The tailpipe emissions of CO and HC also reduce drastically with n-butanol-blended-gasoline; however, the quantum of reduction is slightly inferior to ethanol-blended-gasoline.
- Slightly lower NO emission level than gasoline is observed at all loads. CO_2 emissions are also lower than both ethanol-blended-gasoline and gasoline.
- Cold start emission level of HC and NO also decreases with 10% n-butanol-gasoline blend.

It may be concluded that n-butanol has a capability to serve as a S.I. engine fuel as a blend component with gasoline without any engine modification and is advantageous to be used in blend when compared to ethanol blends, in terms of engine performance and emission behavior. However, further studies related to material compatibility are required in this regard.

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