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Full Length Research Paper

An analytical study of NOx discharge on croton oil – 1-butanol – diesel in compression ignition (CI) engine

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Vegetable oils as fuel have received attention in recent years due to their advantages including renewable nature and domestically produced energy resources. Achieving reduced emission is important subject, as it enhances sustainability of biofuels. General factorial experimental design and analysis of variance (ANOVA) is used to analyze how NOx emission is influenced by alcohol content in vegetable oil-diesel fuel blends. Fuel samples 20% croton oil – 80% diesel (20%CRO-80%D2), 15% croton oil – 5% 1-butanol – 80% diesel (15%CRO–5%BU–80%D2), and 10% croton oil – 10% 1-butanol – 80% diesel (10%CRO–10%BU–80%D2) were investigated. Four-cylinder compression-ignition (CI) engine was run at constant speed 3000 RPM, loaded at different loading conditions: low idle as 0 to 100% load condition. The specific fuel consumption and exhaust temperature of fuel blend containing butanol was measured. It was observed that nitrogen oxides (NOx) emission decreases as percentage of butanol alcohol content increases in fuel samples.

Key words: Vegetable oil, butanol, NOx emissions, fuel blends, factorial design, analysis of variance (ANOVA).

INTRODUCTION

Vegetable oils, have received attention in recent years as alternative fuels for diesel engines. This is due to their advantages as renewable and domestically produced energy resources. Furthermore, there has been an increase in effort to reduce reliance on petroleum fuels for electricity generation and transport sectors throughout the world. Diesel engines in vehicles have the advantage of achieving lower fuel consumption and reduced emissions than their equally rated spark-ignition counterparts (Rakopoulos et al., 2010).

Vegetable oils consist of mostly triglycerides. These are inherently viscous. High viscosity and poor volatility are major challenges to run modern diesel engines on vegetable oils. Compression Ignition (CI) engines that run on vegetable oils display a number of unwanted behaviours. These are lower peak power and torque, low engine speeds, injector cocking, filter clogging, ring sticking, and thickening of lubrication oil (Demirbas, 2008, 2009; Ma and Hanna, 1999; Pinto et al., 2005). Different methods can be used to remedy these deficiencies of vegetable oils. Various methods are mainly focused on correcting its viscosity. These methods are transesterification, pyrolysis and catalytic cracking, microemulsions, and dilution with diesel fuel (Balat and Balat, 2008; Demirbas, 2008).

It can be seen from the study by Balat and Balat (2008), that microemulsions or blends of vegetable oils and diesel fuels were a useful method to improve vegetable oils fuel properties. In the review paper by Shahid and Jamal (2008), it was concluded that vegetable oil and diesel blends can be used to run on diesel engines, preferably heavy duty CI engines. The study by Chotwichien et al. (2009) show that that the diesel-palm oil methyl ester-butanol fuel blends (85% diesel to 10% palm oil methyl ester-5 % butanol) have shown better fuel properties. Hydrocarbon (HC), smoke, and particulate matter (PM) were reported to decrease when three components fuel (ethanol-biosiesel-diesel) was used to run on diesel engine (Rakopoulos et al., 2006). Emission reduction were also reported by Shi et al in their experimental works on three component fuel (alcohol-bioiesel-diesel) (Shi et al., 2005, 2006, 2008).

NOx and other emissions were reported to be reduced when petroleum diesel is blended with alcohols (Hansen et al., 2005). The study by Rakopoulos (2013) show reduction of NOx emissions in cottonseed oil and its (methyl ester) bio-diesel in blends with 20% by vol. of either n-butanol or diethyl ether as compared to diesel and 100% vegetable oil run in CI Engine. Researchers, Armas et al. (2012) investigated emissions of CI engine run on ethanol and butanol diesel blends, results show reduced NOx emission on blends containing butanol. It can also be observed from other studies that reduced NOx emission can be achieved when CI engine run on fuel blends containing alcohol such as butanol (Lin et al., 2012; Rakopoulos et al., 2012). Other intervention to achieving NOx emissions reduction is Exhaust Gas Recirculation (EGR) as reported in the study by Venkateswarlu et al. (2012).

Several studies reported that 1-butanol is a good candidate for vegetable oil – diesel blends as it makes a stable blends with diesel (D2) than ethanol, have high calorific value, butanol has future as it can be produced renewably from biomass (Ezeji et al., 2007; Qureshi et al., 2008; Thaddeus et al., 2007). The main objective is to determine the influence of butanol in croton oil – Diesel blends (diesel fuel fixed at 80%) on NOx emissions in CI engine. Fuel properties, NOx emissions, specific fuel consumption and exhaust temperature of fuel blend containing butanol are also investigated.

METHODOLOGY

Test fuels

Croton Megalocarpus oil (CRO) was supplied by Diligent Tanzania Limited. 1-butanol (BU) (CAS number 71-36-3) was purchased from chemical shop, and Diesel fuel (D2) purchased from local petrol station (Budapest, Hungary) was used for making blends and as the base fuel for comparison.

Butanol-oil-Dieslel blends were prepared by mixing the constituents at room temperature. In volumetric basis, D2 was fixed at 80% for all blends; remaining 20% consisted of vegetable oil and 1-butanol was varied from 0 to 10% 1-butanol in steps of 5%. The blends were made in batches, where the components were poured into 1000 ml beaker and steered until they mix. Diesel fuel (D2) sample and samples from uniform mixture of 20% croton oil – 80% diesel (20%CRO-80%D2), 15% croton oil – 5% 1-butanol – 80% diesel (15%CRO–5%BU–80%D2), and 10% croton oil – 10% 1-butanol – 80% diesel (10%CRO–10%BU–80%D2) were then taken for further analysis.

Equipments setup

Engine tests were done on a four cylinder Audi, 1.9 L, TDI engine (Table 1 shows engine technical details, Figure 1 and Table 2 show components/equipment connections and descriptions respectively). The engine (1) was coupled with dynamometer (2) to provide break load, engine throttling and dynamometer settings were controlled by computer (6). Fuel was introduced from fuel tank (3) equipped with flow measurement system. During fuel switching, fuel tank was drained from the engine fuel filter, new fuel was introduced to the tank until fuel filter is full, and engine was then started and allowed to run for few minutes to clear fuel lines and stabilise. Emission was measured by Horiba emission analyser system (5) equipped with analyser module H.CLDC (CLA-53m), for (NOx) measurements. The emission measurement system, fuel flow and thermocouple (8) were connected to the computer (7), and emission data were recorded. Table 2 show equipment descriptions.

Test cycle

During the engine test, the engine was run at constant speed 3000 RPM. The engine was loaded at different loading conditions, from idle as 0 to 100% load condition. This was done by varying engine load in the difference of 25% of full load as indicated by European Stationary Cycle (ESC) where each cycle was run for minimum of 2 min. Five points engine load measurement was then achieved and measurements of NOx, fuel consumption and exhaust temperature were made.

General factorial methodology

General factorial method (Karuppasamy et al., 2012; Mumtaz et al., 2012) was used to analyze the results (Tables 3 and 4). Fuel samples as a factor was divided into three levels according to the percentage of butanol in the blends (A). Variations were 0, 5 and 10% of butanol alcohol in the croton oil and diesel which was fixed at 80%. Five levels of Engine loading in percentage (B) were used as another factor. Design- Expert 6.0.6 software was employed to analyze the effects of Butanol percentage on the resulting NOx emissions at different load levels. Analysis of variance (ANOVA) (Saravanan et al., 2011) was used to analyze data; the model equation for NOx production was generated. The statistical significance of percentage of butanol in percentage on NOx emission was estimated by means of an F-test.

RESULTS AND DISCUSSION

Analysis of variance (ANOVA)

Table 4 shows the summary of ANOVA results indicating the significance of the control factors to NOx emission.

Table 1. Audi, 1.9 L TDI Engine Details.

Engine model	Audi, 1.9 L, TDI
Capacity	1896 cm^3
Bore	79.5 mm
Stroke	95.5 mm
Compression ratio	19.5:1
Maximum power	66 kW, at 4000 rpm
Maximum torque	202 Nm ,at 1900 rpm
Fuel system	Direct Injection with electronic distributer pump

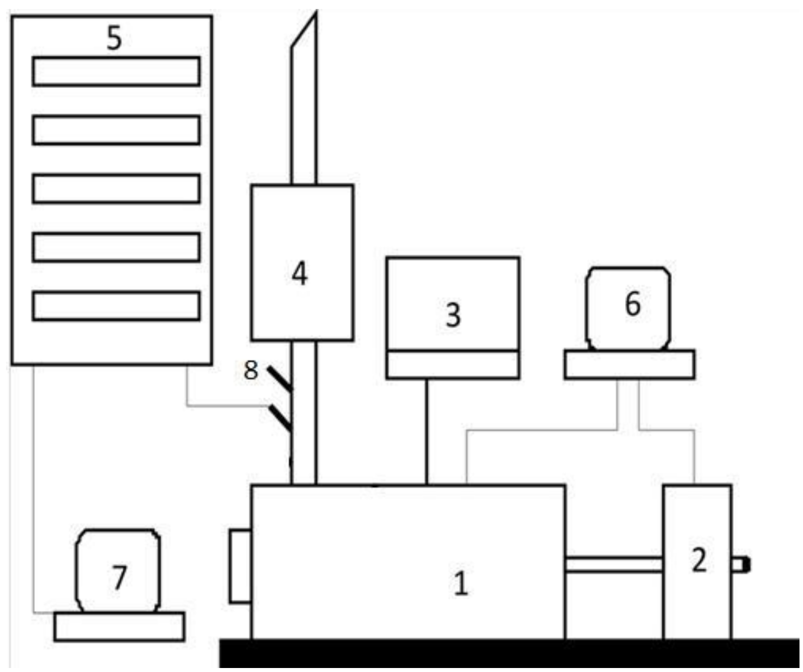

Figure 1. Engine test experimental set up. 1 Engine, 2 Dynamometer, 3 Fuel tank and fuel flow meter, 4 Exhaust pipe, 5 Gas analyser, 6 Computer-1, 7 Computer-2, and 8 Temperature sensor: Source: Lujaji et al. (2011).

Table 2. Description of the engine test experimental set up.

Equipment	Description
Engine	Audi, 1.9 L, TDI
Dynamometer	Type: FE350S-BORGBI & SAUERI
Fuel tank and fuel flow meter	Type: AVL 7030
Exhaust pipe	Connected to the laboratory exhaust system
Gas analyser	Type: Horiba system (Mexa-812)
Computer	PC-installed with engine loading controls program
Computer	PC-recording emission data
Temperature sensor	Type K Thermocouple

Control factors are butanol blending (A) and engine loading (B) (Table 3). The model (Equation 1) F-value of 290.94 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large, could occur due to noise.

Final Equation in Terms of Actual Factors:

Table 3. Experimental data.

Run	Factor 1 A:%BU in a Sample [x10%]	Factor 2 B:Engine Loading [x 25%]	Response 1 NOx [ppm]	Response 2 T_exhaust [°C]	Response 3 SFC [kg/kWh]
1	2	4	930	522	0.2278
2	2	3	565	449	0.2311
3	0	0	83	222	1.2063
4	1	4	966	532	0.2318
5	1	1	181	335	0.3034
6	0	1	204	302	0.3000
7	2	1	184	286	0.3145
8	1	0	87	234	1.2250
9	0	3	585	478	0.2363
10	0	2	388	400	0.2426
11	0	4	956	568	0.2239
12	1	2	332	404	0.2514
13	1	3	537	478	0.2363
14	2	0	36	198	1.3438
15	2	2	330	368	0.2626

Table 4. ANOVA table.

Response: Nox						
ANOVA for Response Surface Quadratic Model						
Analysis of variance table [Partial sum of squares]						
Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	1446213	5	289242.5	290.9415	< 0.0001	significant
A	2937.796	1	2937.796	2.955052	0.1197	
B	1369261	1	1369261	1377.304	< 0.0001	
A^2	102.3053	1	102.3053	0.102906	0.7557	
B^2	73819.44	1	73819.44	74.25305	< 0.0001	
AB	91.592	1	91.592	0.09213	0.7684	

$$\mathrm{NOx\ [ppm]} = 104.12762 - 32.5 \times A + 43.80476 \times B + 5.54 \times A^2 + 41.92381 \times B^2 + 2.14 \times A \times B$$

Where:

A = %BU in a sample [×10%]

B = Engine Loading [×25%]

Fuel properties

Fuel properties of components and the blends were measured by standard methods as shown in Table 5. It can be observed that Croton oil (CRO) – 1-Butanol (BU) – Diesel (D2) blends have comparable fuel properties as D2 fuel. 0% Butanol (20%CRO-80%D2) blend has density and viscosity 842.56 kg/m^3 and 8.5 mm^2/s respectively (Table 5), density and viscosity highest among the blends, but it is about 8% less dense and 75% less viscous than Croton oil. The presence of butanol; 5 and 10% in 15%CRO-5%BU-80%D2 and 10%CRO-10%BU-80%D2 blends respectively, improves density and viscosity. Cetane number (CN) and Lower heating value (LHV) are very similar among the blends but slightly lower than that of D2.

Fuel consumption

Figure 2 shows specific fuel consumption (SFC) of different fuel samples at different load levels. It can be observed that the SFC is generally high at 0% loading

Table 5. Fuel properties.

Test	Viscosity at 40°C [mm^2/s]	LHV [MJ/kg]	Density at 28°C [kg/m^3]	Cetane Number	%C, %H, %O
Method	ASTM D 445	ASTM D 240	ASTM D 1298	ASTM D 613	
1-Butanol (BU)	2.63	33.94	811.95	17.0	65.0,14.0, 22.0
20%CRO-80%D2	8.50	41.73	842.56	51.8	85.2, 12.0, 2.8
15%CRO-5%BU-80%D2	4.33	41.58	837.16	50.6	84.6, 12.1, 3.3
10%CRO-10%BU-80%D2	3.82	41.43	831.76	49.4	83.9, 12.2, 3.9
100%CRO	33.38	36.98	920.00	40.7	78.0, 12.0, 10.0
Diesel (D2)	2.30	42.92	823.20	54.6	87.0, 12.0, 0.0

Source: Lujaji et al. (2011).

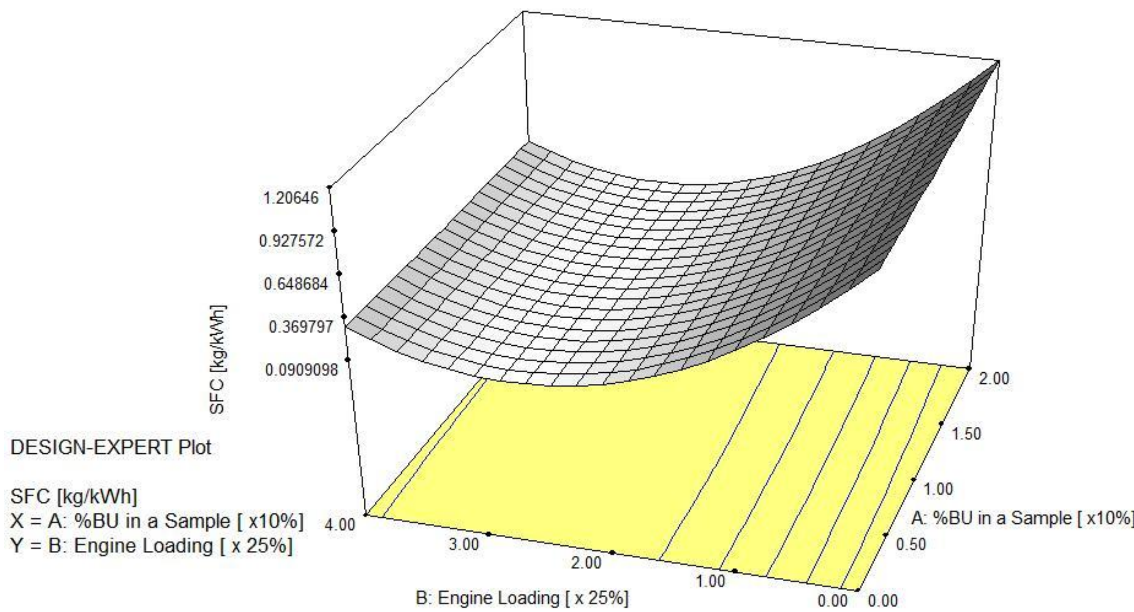

Figure 2. Specific fuel consumption (SFC) of fuel samples under different load levels.

condition. SFC decreases sharply to 50% load level, flattens and then rises slightly as load increased to 100%. At 0% load (idling) 0% butanol sample show the minimum value of SFC of 0.21 kg/kWh and 10% sample shows highest value of 1.34 kg/kWh. The trend is similar for all load levels. This may be attributed by the high HHV of blend sample containing 0% of butanol. It can be deduced therefore that, addition of more butaol to fuel blends containing croton oil and 80% diesel fuel increases SFC (Karuppasamy et al., 2012; Siwale et al., 2012).

Exhaust temperature

Figure 3 depicts exhaust temperature variations of different fuel samples at different load levels. It can be observed that the exhaust temperature generally increases as load level and increases from 0% loading condition to 100%. Furthermore, it can be observed that at higher levels of butanol percentage, exhaust temperature slightly decrease under all loading conditions. This could be attributed by the presence of more intrinsic oxygen from fuel samples containing more butanol percentage. More oxygen contents in fuel may lead to lower flame temperature as observed by the researchers Siwale et al. (2012).

Nitrogen oxides (NOx)

Figures 4 and 5 show nitrogen oxides (NOx) emissions. It can be observed that it is slowly increases as the load increase at steady engine speed. The Figure 4 shows

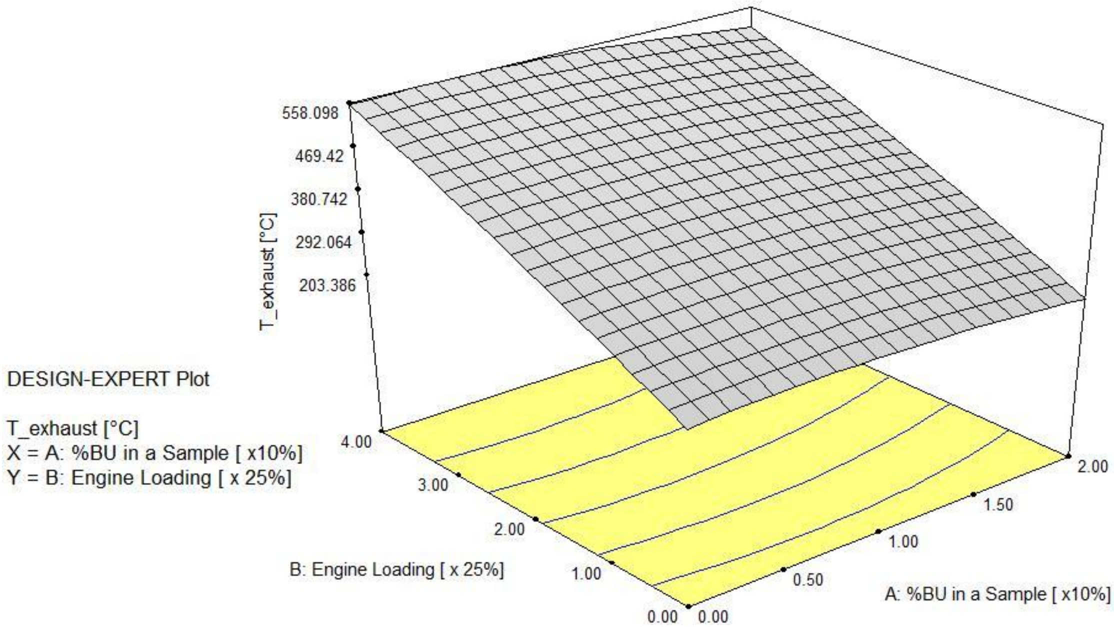

Figure 3. Exhaust temperature of fuel samples under different load levels.

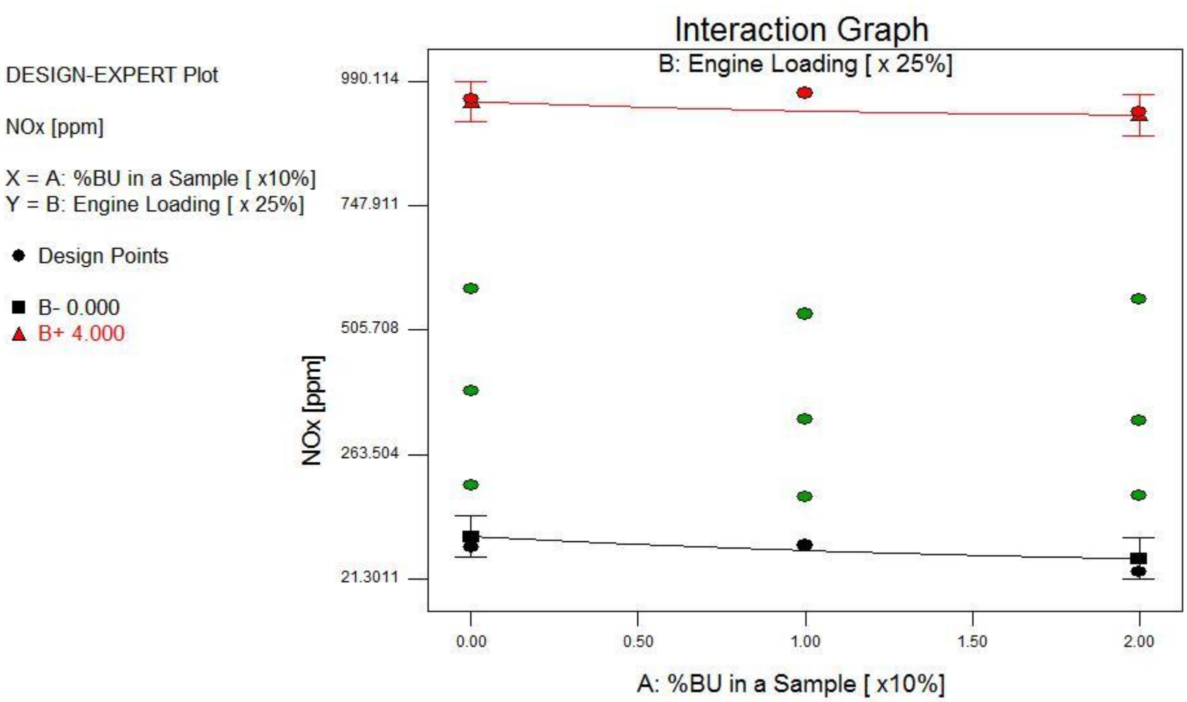

Figure 4. Interaction of fuel samples and engine load levels on NOx emissions.

interactions of engine loading and percentage variations of butanol in fuel samples, as they influence NOx emissions. No direct interactions of two factors are observed. Based on the interaction results, it can be noticed that there is a slight decrease of NOx emissions as percentage of butanol alcohol is increased in fuel samples. This could be associated by low exhaust temperatures which were observed in samples with higher percentages of alcohol. From the theory, this could be explained by the dominance of thermal NOx formation

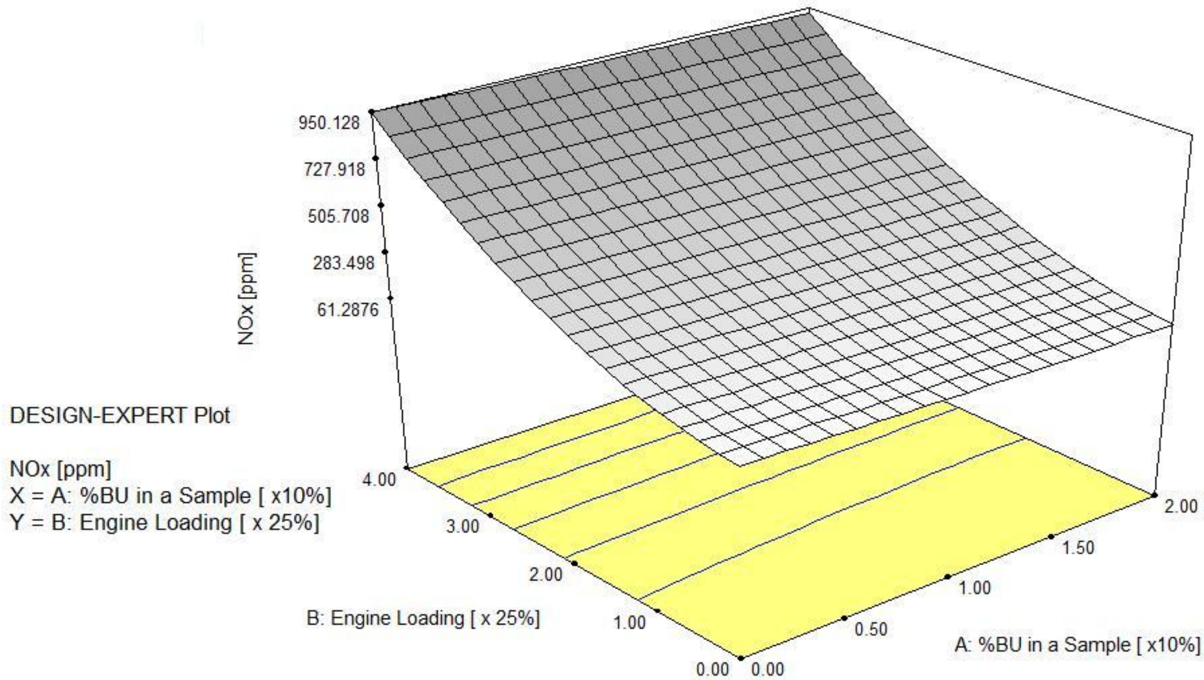

Figure 5. Exhaust temperature of fuel samples under different load levels.

at higher temperatures. The presence of alcohol in fuel tends to lower flame temperature, consequently reduction of NOx (Purushothaman and Nagarajan, 2009a, b).

Conclusions

Four cylinder direct injection compression ignition (CI) engine was operated by vegetable oil-diesel and alcohol blends without problem. Engine specific fuel consumptions, exhaust temperature and NOx emissions from blends were investigated. The investigation focused on how engine loading and percentage of butanol in fuel sample affects NOx emissions. From the results and discussions, the following conclusions can be drawn:

1. Addition of butanol on croton oil – diesel (CRO-D2) blend improves fuel properties.
2. Specific fuel consumption (SFC) increases as percentage of butanol in fuel blends increased.
3. Exhaust temperature increases as percentage load level increases. And higher content of butanol percentage in samples leads to lower exhaust temperature.
4. Nitrogen oxides (NOx) emission values decreases as percentage of butanol alcohol content increases in fuel samples.

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