Influence of N-Butanol-Diesel Fuel Blends on the Performance Characteristics of a Four Stroke, Compression Ignition Engine

ABSTRACT

Aims: This study investigates the impact of blending n-butanol with diesel fuel on the performance of a single-cylinder, 4-stroke diesel engine under varying engine loads.
Study design: The performance assessment followed SAE J1349 on a Tec-Quipment TD110-115 4-stroke engine at 1500 rpm with varying loads and fuel samples.
Place and Duration of Study: The study was conducted for 2 months the at Automotive Engineering Technology Workshop, Federal Polytechnic, Bauchi Nigeria
Methodology: The SAE J1349 test protocol was followed, using diesel fuel (D95) and different blended fuel samples (D90, D85, D80, D75, and D70). While diesel fuel generated higher brake power due to its higher calorific value, the D95 blend demonstrated comparable performance to diesel fuel across all parameters.
Results: The brake power of the D95 blend initially decreased by 69.7% and then increased as the load increased to 2500g and 3000g, indicating improved combustion due to oxygenation. The D95 blend exhibited lower fuel consumption compared to diesel fuel, although blends with higher n-butanol percentages showed increased brake-specific fuel consumption due to lower calorific values, densities, and viscosities. Under maximum load, the D95 blend exhibited higher exhaust gas temperature and heat loss, reflecting the increased fuel quantity required for additional power. Lower heat losses at lower loads were attributed to factors such as lower calorific values, n-butanol's heat of vaporization, temperature differentials between the exhaust and ambient conditions, and engine size.
Conclusion: The engine load has diverse effects on parameters across different fuel samples. D95 exhibits similar performance to diesel, yet discrepancies arise, especially with higher n-butanol content at lower loads.

Keywords: Diesel engine, n-butanol, engine performance characteristics, and emissions

1. INTRODUCTION

Diesel engines are widely used around the world because they are efficient, adaptable, and reliable in generating affordable electricity, especially in rural areas where they serve as either a backup or primary power source [1,2,3]. However, diesel combustion produces pollutants such as carbon dioxide (CO2), nitrogen oxides (NOx), and particulate matter (PM), which harm air quality and contribute to environmental damage. In addition, concerns about the depletion of traditional fossil fuels and the uncertainty of diesel prices underscore the need for alternative fuel options [4].

Biofuels have emerged as promising replacements for traditional fossil fuels due to their biodegradability, renewability, and eco-friendliness [5,6,7]. Alcohols such as n-butanol have attracted considerable attention for their potential to partially substitute fossil fuels and produce cleaner combustion [8,9,10,11,12]. N-butanol, in particular, is of interest as a versatile renewable biofuel because its properties closely resemble those of diesel fuel, making it a potential biofuel additive for diesel engines [13].

The transportation sector plays a pivotal role in the global economy, with over 1.5 billion vehicles on the road. However, the engines and power boilers in this sector emit harmful substances, including nitrogen oxides (NOx), hydrocarbons (HC), and particulate matter (PM), which have adverse effects on both human health and the environment [14,15]. The excessive consumption of diesel fuel to meet energy requirements contributes to pollution emissions, global warming, and the depletion of oil reserves. This escalating demand for energy affects global economic stability and results in fluctuations in global oil prices [16,17]. In response to these concerns, stringent regulations have been enforced globally to curb diesel emissions in compression ignition (CI) engines through various strategies [18]. These strategies encompass advancements in fuel injection systems, modifications in engine design, and the use of exhaust gas aftertreatment systems such as catalysts and filters [19]. Improvements in diesel fuel composition, involving the integration of oxygenated fuels and the addition of nanoparticles, have also exhibited promise in reducing emissions and enhancing combustion characteristics [20].

In recent decades, bio-alcohols have gained traction as alternatives to conventional diesel fuels and have found applications in CI diesel engines. Butanol, in particular, has shown promise due to its higher cetane number, better solubility in diesel fuel, and superior properties compared to shorter-chain alcohols [21,22,23]. Moreover, butanol is environmentally friendly, renewable, and free of sulfur, making it an appealing alternative fuel source derived from renewable sources like sugar beets, sugar cane, and maize, which helps in meeting stringent emission regulations and improving air quality [20]. Combustion studies have revealed that the use of alcohol blends, including butanol-diesel blends, leads to reduced CO, NOX, hydrocarbons, and PM emissions compared to conventional diesel fuel combustion [24]. The challenges of PM emissions are well documented in previous studies, as they manifest in diverse sizes and shapes in diesel engines, necessitating an understanding of their characteristics to enhance capture in diesel particulate filters (DPFs). Fuel injection (FI) pressure and timing have been identified as pivotal factors influencing PM characteristics. Elevated FI pressure results in reduced PM size and number, along with faster combustion, leading to smaller soot particles. Hence, post-injection of fuel can assist in DPF regeneration, contributing to reduced PM emissions [24]. A profound understanding of the impact of fuel blends on engine combustion, emissions, and particulate matter characteristics is crucial for optimizing their utilization in compression ignition engines.

Although research on n-butanol as a diesel fuel additive is ongoing, the sustainable use of diesel-n-butanol blends is still being investigated as a fuel for internal combustion engines. Hence, the objective of this paper is to evaluate the influence of n-butanol-diesel fuel blends on the performance characteristics of a four-stroke, single-cylinder compression ignition engine under constant speed and variable loading conditions. It is hoped that further research and development in this realm will continue to pave the way for a more sustainable and environmentally friendly future.

2. MATERIALS AND METHODS

2.1 Materials

The source of materials and properties of n-butanol used for this study are presented in Tables 1 and 2 below.

Table 1. Source of fuel and n-butanol additive.

S/N	Material	Product Manufacturer /Distributor
1	Diesel	Nigerian National Petroleum Corporation, Nigeria
2	N-Butanol	Solventis, Surrey, UK.

Table 2. Technical properties of n-Butanol

Properties	Specifications
Description	Colourless liquid, medium volatility, banana-like odour
Synonyms:	butan-1-ol, 1-butanol, normal butanol, and n-butyl alcohol
Cas Number	71-36-3
Molecular Formula	$C_4H_{10}O$
Molecular Mass	74.12
Flashpoint (closed cup)	29 °C (84.2 °F) - 35 °C
Autoignition temperature	343 °C (649.4 °F)
Boiling Point	117 °C (242.6 °F)
Melting Point	-90 °C (-130 °F)
Vapour Pressure	0.58 kPa at 20 °C (68 °F)
Density	0.81 at 20 °C (68 °F)
Log P	0.88

Source: [24]

The use of personal protective equipment, such as; gloves, coveralls, and recommended respirators of >20ppm –full face piece APR with organic vapor cartridges, >200ppm-supplied air to deal with health and safety concerns against; inhalation, and eyes and skin contact would be encouraged when handling n-butanol and preparing fuel samples in the laboratory [25]

2.2 Preparation of Fuel Samples.

To prepare the samples for the study, different compositions of diesel and n-butanol were mixed with the aid of a mechanical magnetic stirrer. The blends were prepared at an ambient temperature of 36^0C, and stirred for 60 minutes to obtain a homogeneous consistency. Each blended fuel sample was prepared on a volumetric basis of 500ml using the prescribed volumetric proportion of the mixtures in Table 3.

Table 3: N-butanol -Diesel Blends

S/N	**Samples**	**Fuel Constituents (%)**	
		N-butanol	**Diesel**
1	D100	0	100
2	D95	5	95
3	D90	10	90
4	D85	15	85
5	D80	20	80
6	D75	25	75

2.3 Fuel Characterizations.

ASTM Standard test protocols as prescribed in Table 4 below were used for the fuel property determination [26].

Table 4. ASTM D975 test specifications for fuel samples.

Fuel Property	**ASTM Specification**
Density at 40^oC (kg/m^3)	ASTM D4052

Specific gravity	ASTM D4052
Kinematic viscosity at 40^{0}C (mm^2/s)	ASTM D445
Flash Point (^{o}C)	ASTM D93
Cloud Point (^{o}C)	ASTM D2500
Derived Cetane Number	ASTM D613
Calorific Value (kJ/Kg)	ASTM D975
Autoignition temperature (^{o}C/^{o}F)	ASTM E659-14

2.4 Uncertainty analysis

Design Expert 13.1 was used to conduct an uncertainty analysis of the effect of the diesel-n-butanol blending ratio on engine performance at an optimal engine load of 1500 g. The uncertainty analysis was conducted using a face-centred cubic design with five levels of diesel-n-butanol blending ratio: 100% diesel, 80% diesel/20% n-butanol, 60% diesel/40% n-butanol, 40% diesel/60% n-butanol, and 30% diesel/70% n-butanol, at an optimal engine load of 1500g.The data collected from a dynamometer was imported into Design Expert for regression analysis, ANOVA, and response surface analysis to determine how the uncertainty in the input variables affects the uncertainty in the output variables.

2.5 Engine Performance Test.

The performance test was conducted in conformity with the SAE J1349 [27] test protocol on a Tec-Quipment TD110-115 single-cylinder, 4-stroke air-cooled engine test rig coupled to a horizontal hydraulic dynamometer (refer to figure 1 and table 4 for engine technical specifications). The engine was operated at a constant speed of 1500 rpm with variable loads of 500g, 1000g, 1500g, 2000g, 2500g and 3000g. The time taken by an engine to consume 8 ml of fuel, torque, exhaust temperature and barometric pressure for all fuel samples were recorded. Engine performance test on diesel fuel was also conducted as a basis for comparison. As the percentage of blend and load were varied, engine performance measurements such as brake specific fuel consumption, air flow rate, brake power, volumetric efficiency, brake thermal efficiency, percentage heat loss and air/fuel ratio were computed and recorded.

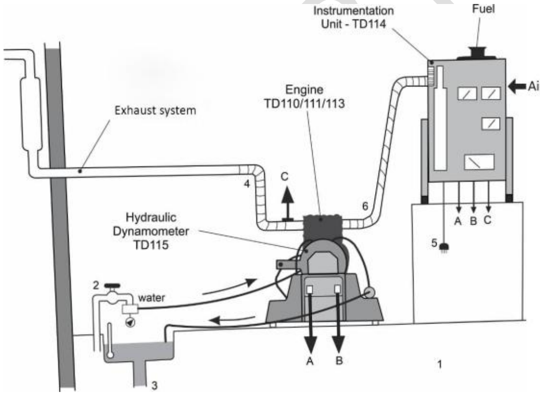


Fig.1. An illustration of a complete TD110-TD115 TQ small engine test rig [28].

Table 5: Test Engine Technical Specifications

Parameters	Specifications
Model	TD110-115
Number of cylinders	1
Method of starting	Manual starting
Engine type	Single-cylinder, 4-stroke diesel
Bore	79.5× 95.5 mm
Piston stroke	115mm
Displacement	1896mm
Rated speed	3600 rpm
Maximum output	5.6kW
Compression ratio	12:1 to 17.5:1
Maximum MEP	1400kPa
Cooling method	Air-cooled
Fuel and Lube oil	filter Present
Injection pump	Bosh VE VP 37

Source: [28].

3.0 RESULTS AND DISCUSSIONS

3.1 Fuel properties of fuel and blended samples.

The results of the properties of the fuel samples are presented in Table 4 and are briefly discussed in the ensuing paragraph.

The result in Table 4 has shown that the Diesel fuel sample demonstrated a relatively higher fuel density and relative density at room temperature, with a value of 0.8367. It could be seen that the density of the fuel samples decreases as the proportion of N-butanol additive in the fuel mixture increases. In terms of kinematic viscosity, Diesel fuel samples demonstrated the highest viscosity (2.98 mm^2/s. The lower the fuel viscosity, the more efficient fuel injection, atomization, and combustion behaviour of the fuel samples.

From the results presented in Table 4, Diesel fuel samples could be seen to demonstrate the highest flash point (54 ^{o}C), while the blended fuel samples; B100, D95, D90, D85, D80, and D75 progressively drop from 37^{o}C, 34^{o}C, 32^{o}C, 31^{o}C,31^{o}C, to 30^{o}C accordingly. The cloud point of the fuel samples analyzed revealed that Diesel fuel samples exhibited the highest pour point (-24 ^{o}C), and the value decreases as the volumetric proportion on-butanol increases in the fuel mixture. It is important to note that low-temperature behaviour is required for the engine at cold start and low load conditions.

Cetane number (CN) is one of the most important parameters affecting diesel fuel behaviour. It is related to the time that elapses between fuel injection and the beginning of combustion [30]. It generally depends on fuel composition and can influence engine stability, noise level and exhaust emissions [29, 30]. A fuel with high CN depicts a short ignition delay, which causes the combustion to begin shortly after being injected into the combustion chamber, thereby increasing its efficiency [31]. The cetane number results showed that Diesel fuel samples exhibited the highest cetane number (56.9), while N- butanol blended fuel samples D95, D90, D85, D80, and D75 exhibited relative lower pour points with values of 52.7, 49.9, 49.1, 44.1, and 41.9 respectively, and the cetane number of B100 fuel sample was observed as the least (i.e., 17.6).

Table 6: Fuel properties of n-butanol and Diesel fuel blends

Fuel Property	D100	B100	D95	D90	D85	D80	D75
Density at 40^{o}C (kg/m^{3})	835.6	813	833.79	832.78	831.03	829.62	828.70
Specific gravity	0.8367	0.813	0.83379	0.83278	0.83103	0.82962	0.82870
Kinematic viscosity at 40^{0}C (mm^{2}/s)	2.980	2.22	2.895	2.817	2.798	2.776	2.762
Flash Point (^{o}C)	54	37	34	32	31	31	30
Cloud Point (^{o}C)	-24	-	-34	-35	-36	-37	-37
Derived Cetane Number	56.70	17.6	52.70	49.90	47.10	44.10	41.90
Calorific value (KJ/Kg)	45530.6	37025	44728.4	44126.9	43532.0	43321.5	42579.7
Autoignition temperature (^{o}C/^{o}F)	210 °C (410 °F)	343 °C (649.4 °F)	-	-	-	-	-

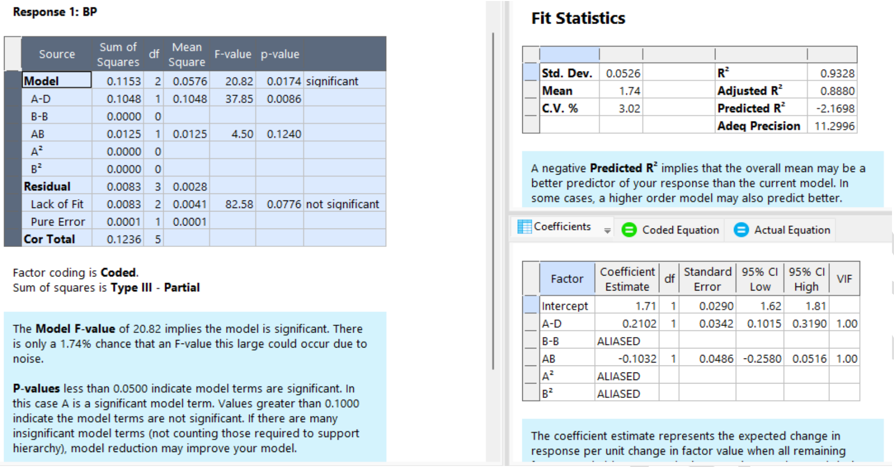
The calorific (heating) value of the fuel samples under consideration showed that Diesel fuel samples exhibited the highest heating value of 45530.6kJ, while N- N-butanol blended fuel samples D95, D90, D85, D80, and D75 exhibited relatively lower heating values of 44728.4 kJ, 44728.4 kJ, 44126.9 kJ, 43532.0 kJ, 43321.5 kJ, and 42579.7 kJ respectively, and the calorific value of B100 fuel sample was observed as the least (37025 kJ).

In terms, of auto-ignition temperature (AIT)- i.e., the lowest temperature at which the fuel will ignite spontaneously under ambient conditions without an external source of ignition such as a spark or flame, it could also be seen that the AIT value is higher for butanol (343 °C /649.4 °F) than diesel fuel sample (210 °C /410 °F). The implication is that the temperature required to supply the activation energy needed for combustion is higher for butanol and its blend than for the Diesel fuel sample. Hence, more rapid compression is required to raise the temperature of the butanol and blends to self-initiate combustion of the fuel samples, as such, butanol and its blended samples are much safer to handle in terms of storage and transportation.

3.2 Influence of Blending Ratio on Engine Performance

The effect of the diesel n-butanol blending ratio on brake power was considered by uncertainty analysis (refer to table 7). The response table shows the predicted mean and standard deviation for each level of the input variables. A p-value less than 0.05 indicates that the model is statistically significant, meaning that the input variables are likely to produce the best results. The fit statistics show how well the model fits the data. A higher R-squared value (0.9328) indicates a better fit, meaning that the model explains a greater portion of the variation in the output variable. The ANOVA table shows that a p-value less than 0.05 indicates that the model is statistically significant, which confirms the results of the response table. This means that the relationship between the input variable and the output variable is likely to be real, and the model can be used to predict the output variable for different levels of the input variables. The coefficients represent the change in the output variable (1.71) for a one-unit change in the input variable, while the other input variables are held constant.

Table 7. Uncertainty Analysis



Response 1: BP

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.1153	2	0.0576	20.82	0.0174	significant
A-D	0.1048	1	0.1048	37.85	0.0086	
B-B	0.0000	0				
AB	0.0125	1	0.0125	4.50	0.1240	
A^2	0.0000	0				
B^2	0.0000	0				
Residual	0.0083	3	0.0028			
Lack of Fit	0.0083	2	0.0041	82.58	0.0776	not significant
Pure Error	0.0001	1	0.0001			
Cor Total	0.1236	5				

Factor coding is **Coded**.
Sum of squares is **Type III** - **Partial**

The **Model F-value** of 20.82 implies the model is significant. There is only a 1.74% chance that an F-value this large could occur due to noise.

P-values less than 0.0500 indicate model terms are significant. In this case A is a significant model term. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

Fit Statistics

Std. Dev.	0.0526		**R^2**	0.9328
Mean	1.74		**Adjusted R^2**	0.8880
C.V. %	3.02		**Predicted R^2**	-2.1698
			Adeq Precision	11.2996

A negative **Predicted R^2** implies that the overall mean may be a better predictor of your response than the current model. In some cases, a higher order model may also predict better.

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	1.71	1	0.0290	1.62	1.81	
A-D	0.2102	1	0.0342	0.1015	0.3190	1.00
B-B	ALIASED					
AB	-0.1032	1	0.0486	-0.2580	0.0516	1.00
A^2	ALIASED					
B^2	ALIASED					

The coefficient estimate represents the expected change in response per unit change in factor value when all remaining

The 2D linear interaction and 3D surface response plots (refer to figure 2) show how each pair of variables relates to each other. The 2D linear interaction plots revealed a strong interaction between engine brake power (BP) and diesel-n-butanol blending mixtures, while the other variables are held constant. This means that the BP of diesel fuel (D100) increases as the blending proportion of n-butanol decreases, and the BP of the D75 blend also increases as the variable on the X-axis increases. However, at the beginning of the plot, the D75 fuel blend seems to have a higher BP than the D100 diesel fuel counterpart. This could be due to the improved combustion behaviour ascribed to the relatively higher cetane number and higher oxygenation potential on n-butanol.

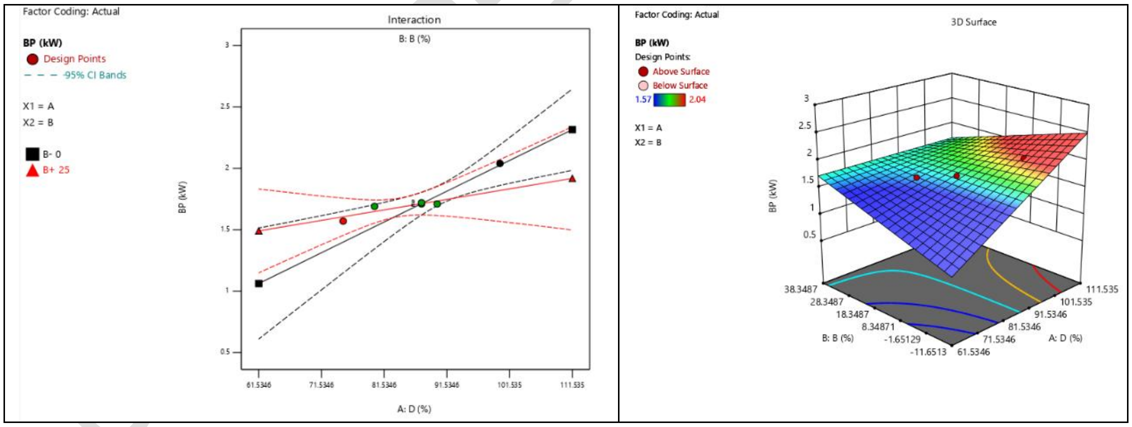


Fig 2. 2D linear interaction and 3D surface response plot

3.3 Influence of Fuel Samples on Engine Performance.

3.3.1 Effect on brake power.

The variation of BP with load increase for diesel and its blends with n-butanol is presented in Figure 3. An increase in BP was observed for both diesel and its blends as the load increased to maximum load [32]. The comparatively higher BP supplied by the engine running on diesel fuel is attributed to its higher calorific (heating) values (refer to table 4).

The BP performance of D95 was comparable to diesel fuel. At the load of 2500g, the BP for D95 reduced by 69.7% and peaks further to 72.8% at 3000 g, but lower than the diesel fuel sample. The relatively higher BP increased to maximum load [33]. The comparatively higher BP supplied by the engine running on diesel fuel is attributed to its higher calorific (heating) values (refer to table 4). The BP performance of D95 was comparable to diesel fuel. At the load of 2500g, the BP for D95 was reduced by 69.7%.

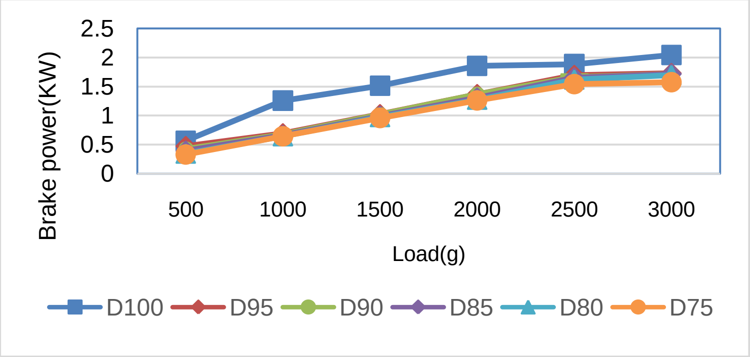


Fig 3: Variation of BP with load increase for fuel samples

and peaks further to 72.8% at 3000 g, but lower than the diesel fuel sample. The relatively higher BP can be attributed to the improved calorific value of n-butanol when blended with diesel. D85, D80 and D75 blends showed decreased BP as a consequence of the decrease in heat release due to their low calorific values. This can also be attributed to higher heat of vaporization of n-butanol which causes a decrease in power and torque [34, 35]. In all, the increase and decreasing trend in brake power as it relates to the engine load could be explained in terms of the influence of engine speed, fuel quality (i.e., cetane number, viscosity, density), and engine condition. It has been observed that higher engine speed leads to increased brake power by burning more fuel and producing more power; fuels with a higher cetane number, lower viscosity, and higher density result in greater brake power and; well-maintained engines tend to produce more brake power compared to worn or damaged ones. This also explains the engine performance characteristics behaviour of brake thermal efficiency and air-fuel ratio against engine loads [36].

3.3.2. Effect on brake specific fuel consumption.

It could be observed from Figure 4 that as the load increased, brake specific fuel consumption (BSFC) decreased to a minimum value at 3000g engine load. The BSFC of the blended samples is also closely comparable to Diesel fuel at loads at 2000g, 2500g and 3000g engine loads. At a load of 1000g, the BSFC for D95 rose above the diesel fuel sample by 11.17% and dropped below the diesel fuel sample fuel at 3000g by 0.024%. This improvement in BSFC can be attributed to efficient combustion due to the presence of additional oxygen molecules in the n-butanol in the blended fuel samples [37]. The BSFC values of Diesel fuel were noticed to be lower when compared with the blended samples. In other words, BSFC increased as the n-butanol percentage in the blends increased. The increased BSFC in blends with higher n-butanol percentages can be linked to the combined effects of lower calorific values, densities and viscosities resulting in low fuel flow rate (refer to table 4)., Kuszewski, [38] opined that a slight decrease in the density of n-butanol -diesel blends with the increase in the n-butanol fraction could in itself create a marginal problem in modern Diesel engines. Hence, mass fuel delivery at lower fuel density can easily be increased by modifying the control system. surmount this challenge.

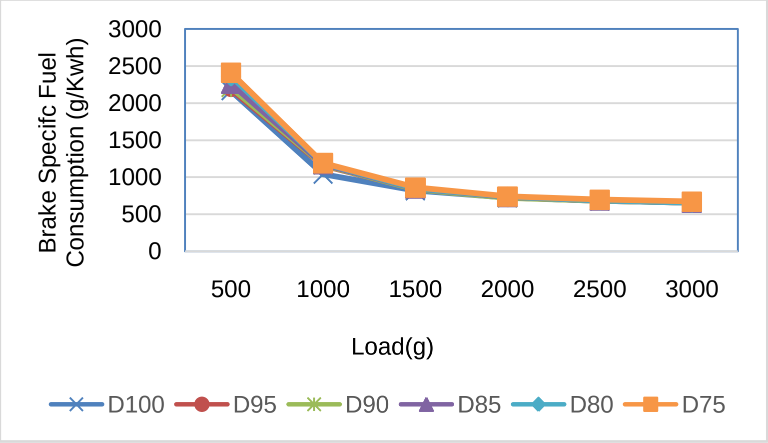


Fig 4: Variation of BSFC with load increase for fuel samples

3.3.3 Effect on air-fuel ratio

With the increase in engine load an increase in air-fuel ratio (AFR) was observed for all tested fuel samples (refer to figure 5). Blends with low n-butanol percentage i.e., D95 and D90 exhibited higher AFR values than Diesel fuel at all engine loading conditions. At a load of 2500g, the brake power for D95 increased by 0.21% and peaks further at 3000g to 0.53 % higher than the diesel fuel sample. This implies that blending n-butanol oxidizes the fuel samples thereby inducing a lean effect on the stoichiometric values of the mixture in blended fuel samples [38, 39,40, 41]. Blends with higher n-butanol percentage i.e., D85, D80 and D75 exhibited lower AFR in comparison to Diesel fuel. This too could be linked to the poor auto-ignition property of n-butanol which causes ignition delay thereby lowering cylinder walls and combustion temperatures. This performance could have been compensated by the higher oxygenation behaviour, lower density and viscosity of n-butanol blended fuel samples to enhance the combustibility of the fuel samples under study.

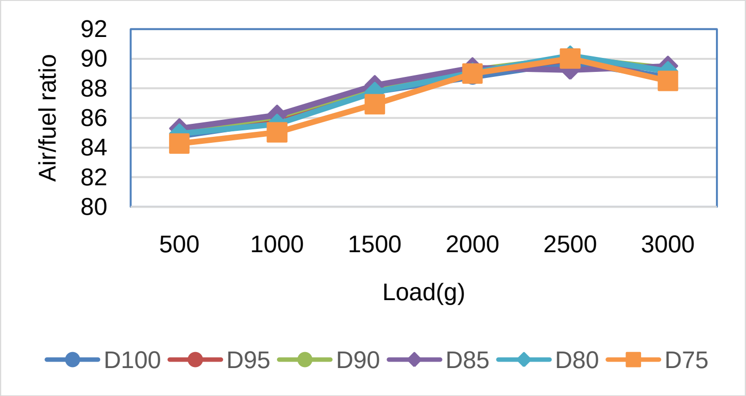


Fig 5: Variation of air-fuel ratio with load increase for fuel samples

3.3.4 Effect on Exhaust Gas Temperature.

The exhaust gas temperature (EGT) increases with an increase in load for both Diesel fuel and the blended fuel sample (refer to figure 6). This increase in EGT with load is obvious from the simple fact that more amount of fuel was required in the engine to generate that extra power needed to take up the additional loading. The Diesel fuel sample exhibited higher EGT

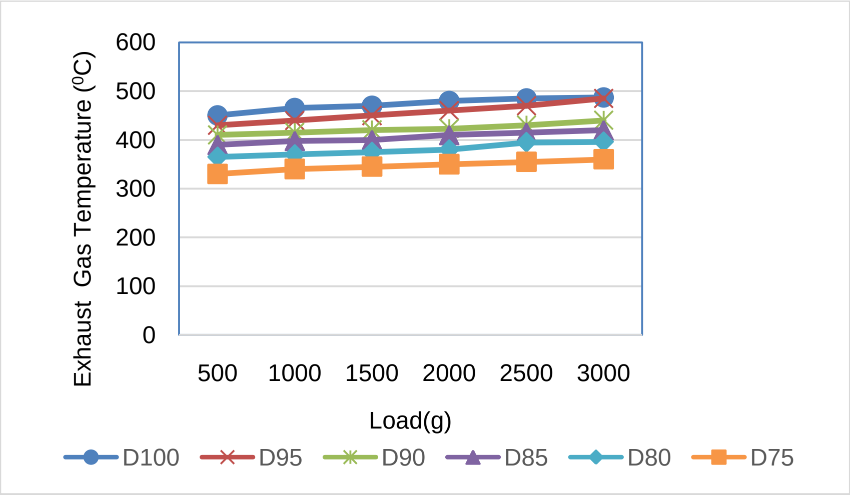


Fig 6: Variation of EGT with load increase for fuel samples.

compared to blended fuel samples. The EGT of the D95 blend is comparable with the Diesel fuel sample. The EGT for D95 rose from 4.44% for 500 g to 0.41% at maximum load (3000g) but was lower than the diesel fuel sample as the most comparable in the group. This implies that increasing the n-butanol content in the blends leads to a decrease in EGT values due to the effect of its diminishing calorific values in the blends (refer to Table 4). This shows that the n-butanol – like any alcohol- absorbs more heat to evaporate and burn, consequently decreasing the in-cylinder temperature at the end of the compression stroke and so the EGT at the end of the combustion process [30,40,41]. Agarwal [42] had reported that by increasing the concentration of n-butanol in a blended fuel sample is likely to lower the EGT in an operational internal combustion engine, and could probably explain the cause of the drop in the EGT values in this case.

Although this research work did not examine the influence the n-butanol in diesel blends on PM and NOx emissions, however, studies have shown that n-butanol blending can significantly impact PM and NOx emissions from diesel engines [43,44,45,46,47]. It has been reported that n-butanol blending can reduce PM emissions but increase or decrease NOx emissions. The effect of n-butanol blending on NOx emissions is more complex and depends on a variety of factors, including the engine type, operating conditions, and fuel blend ratio. The decreased NOx levels in the blends with n-butanol were explained by the diminished average chamber temperature resulting from n-butanol's lower heating value. Moreover, the surplus oxygen content in n-butanol contributed to the reduction in NOx emissions. The decline in the level of PM emissions could also be associated with the inclusion of n-butanol in the blends, as was, particularly observed in the blends during low-load conditions [48]. Hence, blends containing n-butanol exhibit favourable engine performance and lower CO2 and PM emissions, establishing them as a promising fuel choice.

3.3.5 Effect on Brake Thermal Efficiency.

It can be seen from Figure 5 that for all tested fuel samples, the brake thermal efficiency (BTE) increases with an increase in load. This could be attributed to the consequent increase in brake power occasioned by the improved combustion behaviour with an increase in engine load to a maximum of 3000g. Oxygen present in the blends could have enhanced the combustion of fuel samples at low engine load. At high loading conditions, the change of state from molecule oxygen to atomic oxygen perhaps led to a decrease in BTE [49]. The BTE provides an idea of the output generated by the engine concerning heat supplied by the fuel.

Diesel fuel showed higher BTE than other tested blends under varying load conditions (refer to Figure 7). This could be attributed to the higher calorific value of the Diesel fuel (refer to table 4). At a load of 2500g, the BTE for D95 reduced drastically by 1.67% and dropped further to 0.11% but higher than the diesel fuel sample at an engine load of 3000g. The fact that the BTE values at loads of 2000g, 2500g and 3000g for D95 are closely comparable to Diesel fuel, does suggest an improved stoichiometric mixture and enhanced combustion behaviour of the fuel samples in the combustion chamber due to the further oxygenation effect of n-butanol in the fuel mixtures. The lower BTE obtained in of D80 and D75 blends could probably be attributed to the obvious drop in their calorific values on one hand (refer to Table 4), and the increase in fuel consumption on the other. The higher latent heat of vaporization of n-butanol might also be responsible for inhibiting proper air-fuel mixing, thereby leading to inferior fuel combustion and lowering the BTE values [49].

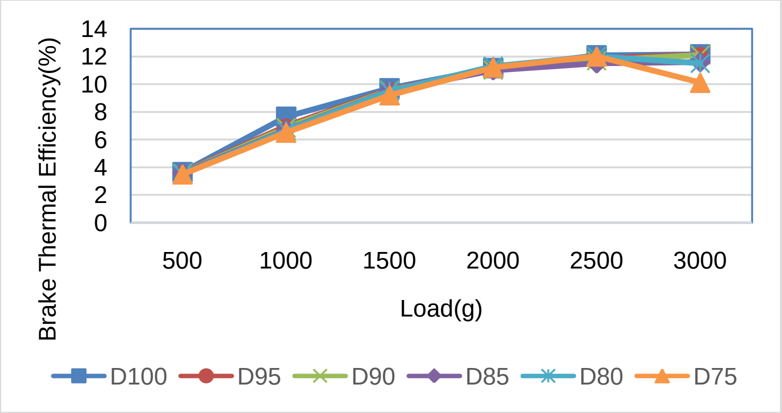


Fig 7: Variation of BTE with load increase for fuel samples

3.3.6 Effect on brake specific energy consumption

Figure 8 presents the variation of brake specific energy consumption (BSEC) for diesel and its blends with n-butanol with an increase in load. At a load of 1000g the BSEC for D95 rose drastically to 9.22 %, and dropped further to 1.78 % lower than the diesel fuel sample at a load of 3000g. Decreases in BSEC with an increase in load were observed up to 2500g load, after which a slight increase was experienced at 3000g load. This could be due to the percentage increase in fuel required to operate the engine being less than the percentage increase in brake power. The initial decrease in BSEC could be attributed to the complete and improved combustion of the fuel. Above 2500g engine load, the time taken for complete combustion of fuel decreased, hence a slight increase in BSEC was observed. It was also observed that the increase in n-butanol percentage in the blends was due to the decrease of calorific values of tested fuel samples, while the specific fuel consumption increased, this is responsible for the lower BSEC of all blends than that of diesel. The further oxygenation of the n-butanol blended fuel samples might well explain the progressive lowering of the BSEC values from D95 to D75 fuel samples. Topgül [50] mentioned that BSEC expressed as the total energy supplied by fuel to generate per engine power over an hour. The BSEC is also related to thermal efficiency, the result showed that improved thermal efficiency was found with decreased energy consumption.

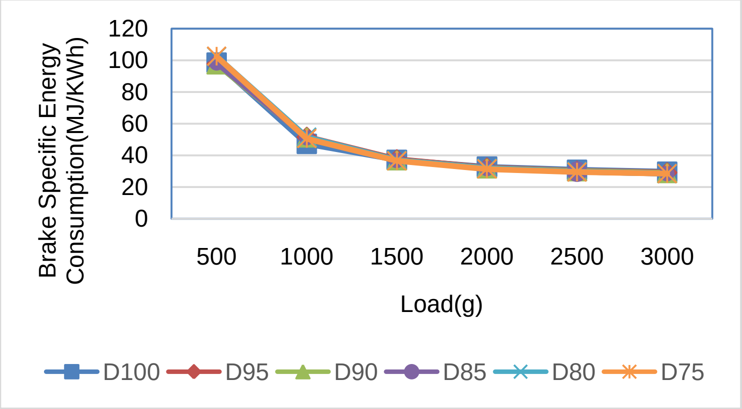


Fig 8: Variation of BSEC with load increase for fuel sample.

3.3.7 Effect on percentage heat loss

The variation of percentage heat loss (PHL) for diesel and n-butanol blended fuel samples with an increase in load is presented in Figure 9. All tested fuel blends showed evidence of lower heat loss in the engine than neat diesel fuel. At a load of 2500 g the PHL for D95 increased marginally dropped by 1.35 %, and rose further to 1.89 % higher than the diesel fuel sample at the load of 3000 g. The lower heat loss recorded in the blends at lower loading conditions can be explained in terms of lower calorific values, the heat of vaporization of n-butanol, the difference between the exhaust and ambient temperatures and the size of the engine. However, heat unaccounted for due to thermal losses is partly a function of the engine size. Hence, for smaller engines, considerable conductive and radiative heat losses are usually caused by inefficient combustion [51, 52].

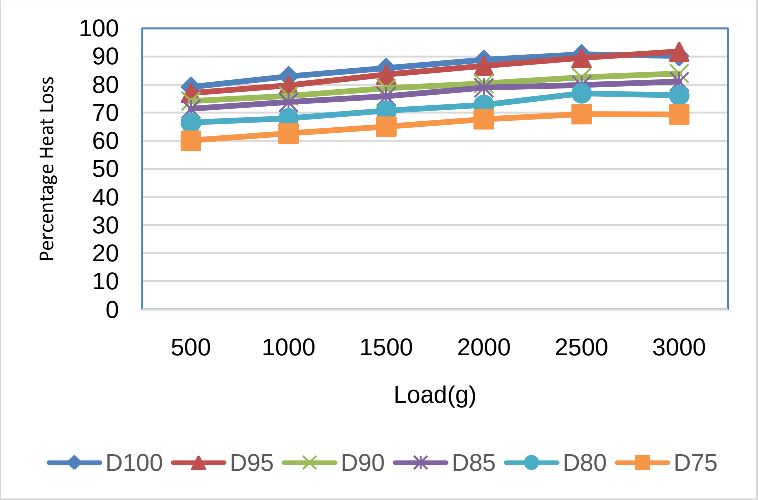


Fig 9: Variation of PHL with Load Increase for Fuel Samples

4.0 CONCLUSION

In all. this study sheds light on the intricate relationship between different fuel blends, and engine performance, and the following could be concluded:

i. The uncertainty analysis revealed that a strong interaction exists between engine brake power (BP) and diesel-n-butanol blending mixtures.
ii. Engine parameters such as BP, air-fuel ratio, EGT, BTE, and PHL increased as engine load increased.
iii. It was noted that blends with higher n-butanol content exhibited increased BSFC due to factors like additional oxygen molecules and lower calorific values, densities, and viscosities, resulting in a lower fuel flow rate.
iv. Despite these differences, the performance of the D95 fuel mixture closely resembled that of the diesel fuel sample, albeit with slightly lower BP, BTE, and BSEC values at higher loads.
v. The EGT for D95 showed a slight increase at the maximum load, while at lower loads, increasing n-butanol content led to decreased EGT values.

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