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Modelling of engine performance and emissions fueled by biodiesel blends

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Abstract

The aim of this study is to investigate the modelling of engine performance and emissions fueled by biodiesel blends. Biodiesel blended with diesel, were introduced to mitigate its decreased power output, poor fuel atomization and increased nitrogen oxides emissions. Unfortunately, it has been difficult to obtain the best biodiesel blend level for optimal engine performance, since it sourced from a variety of vegetable oils whose fuel parameters and interactions differ considerably, causing variation in their combustion processes. The research has developed mathematical models, using Buckingham pi-theorem analytical method and experimental data to predict CI engine performance parameters {brake thermal efficiency (Bte) and carbon monoxide (CO) emissions, while, specific fuel consumption (sfc) and nitrogen oxides (NOx) emission fueled by different biodiesels' diesel blends. The experimental tests were performed on factorial design method using a 3.5 kW one cylinder four stroke CI engine on a test rig connected to an eddy current electric dynamometer, running on biodiesels (WVO, canola, sunflower, oleander and coconut) with their blends (mixed at ratios by volume of biodiesel: diesel;10:90, 15:85, 20:80, 25:75 and 30:70) using the ASTM procedures. The results showed that engine fueled with biodiesel and their blends had lower Bte and CO emissions, while, sfc and NOx emission were higher, as compared those of diesel fuel. The developed mathematical model predicted Bte, sfc, CO and NOx with error margins of 1.65, 15.98, 4.69 and 2.78 per cent respectively as compared to the experimental results.

Key words: Biodiesel blend, emissions, modelling, performance.

INTRODUCTION

Petroleum fuels from crude oil play a pivotal role in industrial growth, agriculture, domestic needs, transportation, and various other essential human activities. Diesel, produced from petroleum, has been one of the notable primary sources of fuel used to run compression ignition (CI) engines in the twentieth century due to its abundant supply, affordability, higher combustion efficiency, reliability and adaptability (Abed et al., 2019; Zheng et al., 2009). However, in recent years, the supply of petroleum has declined while the need for petroleum fuels has substantially increased; for instance, in the last few decades' global consumption of petroleum fuel has increased from 93 million barrels per day in 2018 to over 100 million barrels per day, increasing at the rate of 1.3 per cent annually (Mahmudul et al., 2017), causing significant depletion of crude oil reserves.

Besides useful power, CI engines emit considerable amounts of greenhouse gas (GHG) from their exhaust, consisting mainly of carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NO_x) (Heywood, 1988). GHG emissions have been emphasised in recent years because of their adverse effects on environmental pollution, global warming and human health risks (Burchart-Korol & Folęga, 2019). In overcoming these challenges, researchers have focused on numerous renewable energy options, with biodiesel emerging as a preferred fuel choice for CI engines due to its reliability and similar characteristics to diesel (Knothe & Razon, 2017); thus, it is used with little or no modification (Hoekman et al., 2012). Biodiesel is a renewable, non-toxic fuel made of a long chain of fatty acids and mono-alkyl esters produced from triglycerides of vegetable oils or animal fats, produced through a process of trans-esterification (Knothe & Razon, 2017). In addition, biodiesel has oxygen in its structure, which helps improve its combustion in engines compared to diesel. The vegetable oils are produced mainly from crops such as sunflower, soya beans, mustard, canola, peanut, cotton, *Jatropha curcas*, croton, castor seeds, Oleanders, palm, and any other odiferous vegetation (Verma & Singh, 2014). The use of biodiesel as a fuel is not a new development; rather, it is as old as the diesel engine itself, since Rudolph Diesel, the inventor of the engine in 1892, used peanut as fuel to run off one of the engines in the Paris exposition. Currently, the use of biodiesel in CI engines has been reported in several countries, with global production increasing tenfold from 2000 to 2008 (Verma & Singh, 2014), especially with government support.

LITERATURE REVIEW

Engines running on biodiesel fuel, unfortunately, have been associated with reduced performance, brake power, thermal efficiency, and increased fuel consumption (Verma & Singh, 2014). The reduced performance was attributed to biodiesel's lower heat value and higher viscosity as compared with diesel since a fuel with a lower heat value results in low brake power; in contrast, higher viscosity leads to poor atomisation, both leading to power loss in an engine. A low cetane number implies the energy release is reduced, as reported by studies by Gupta et al. (2007). Conditions that ensure good fuel economy and complete combustion typically lead to higher in-cylinder temperatures, which, unfortunately, create better conditions for the oxidation of nitrogen, thus increasing its oxide emissions (Zhang et al., 2016). Biodiesel blends have been used as a trade-off to achieve reduced toxicity of exhaust emissions and improved engine performance (Verma & Singh, 2014). However, the influence of biodiesel blends on engine performance varies depending on the quality and origin of biodiesel (Zhang et al., 2016).

The major challenge, though, is to locate the best biodiesel-diesel blend ratios for the different feedstocks that target global optimisations of the CI engine. For example, earlier studies have reported variability of test results in engine performances and emission characteristics for blends with similar fuel parameters (Lapuerta et al., 2008). These differences in reported results are attributed to the fact that biodiesel is produced from feedstock of different vegetable oils, which have different physical and chemical properties (Tveit, 2015), affecting combustion processes and mechanisms differently (Zhang et al., 2016) to impact the performance of diesel engines significantly. The fatty acid composition, higher oxygen content, chemical stability, and biodiesel blends compared to petroleum diesel results in improved combustion, reduced emissions, and decreased energy content (Burchart-Korol & Folęga, 2019). The composition of the fatty acids in biodiesel affects its properties, such as viscosity and energy content, which in turn impact its engine performance due to the unsaturated fatty acids content. However, (Agarwal et al., 2011) noted that efficiency strongly depended on the biodiesel feedstock, with sources high in unsaturated fats generally showing better performance. Similar conclusions were reached by (Mahmudul et al., 2017), who experimentally tested Jatropha, neem, and mahua biodiesel blends in a diesel engine.

The mathematical models use dimensional analysis to help reduce the number of independent parameters involved in modelling and experimental engineering problems by expressing them as dimensionless groups. These dimensionless groups represent ratios of important physical quantities involved in the problem of interest, some of which shall be constants, through simplifying the solution and generalisation of the results of engineering models and experiments. Particularly in situations where a comprehensive mathematical model of the process under investigation is unknown, dimensional analysis is a useful technique. Deshmukh et al. (2019) have used dimensional analysis to study factors influencing the performance characteristics of engines (Verma & Singh, 2014). With the advancement of high-performance computing, numerical models have rapidly grown in sophistication and scale by integrating computational fluid dynamics, weather forecasting, and even spacecraft trajectory optimisation. In the study by Zhang et al. (2016), biodiesel was used as an alternative diesel fuel in order to investigate the emission and combustion characteristics of a four-stroke diesel engine. The simulation model was validated by experimental findings under 50 per cent, 75 per cent and 100 per cent load conditions and blends with 10 per cent, 20 per cent, and 30 per cent of biodiesel by volume.

Therefore, to understand the effects of operational fuel properties, it was imperative to use experimental setups to accurately determine the relationship between engine performance and fuel properties for the biodiesel blends. Unfortunately, these can be expensive and time-consuming because they generate an infinite number of experimental conditions (Lapuerta et al., 2008). Modelling and simulation approaches have been effectively used to simulate engine operations since they isolate one variable while giving output results for the other variables (Tveit, 2015). Thus, modelling and simulation can be useful tools to study engine performance and emission trends of a biodiesel blend fueled engine since they are more precise in predicting the outcome of a specific test, easily pointing out cause-effect and relationships of input/output variables. Unfortunately, they require high-capacity computers. The research has proposed a simple, cost-effective, semi-analytical model to predict the CI engine's performance characteristics fueled by biodiesel blend.

METHODOLOGY

The mathematical model for predicting engine performance (brake thermal efficiency (Bte), specific fuel consumption (sfc)) and emission (carbon monoxide (CO), and nitrogen oxides (NOx)) as a function of equivalent brake power (Bp), fuel characteristics (density, kinematic viscosity, low heat value) and blend levels (B) for the given fuels were developed using the Buckingham's theory analytical methods with MATLAB.

In the development of the models. Assumptions were;

i. The biodiesel-diesel mixture remained homogeneous during the analysis.
ii. The engine operated under lean conditions, with constant compression ratio (CR) and ignition angle (ɯ); the air-fuel (AF) ratio had no influence on its performance. Environmental conditions were constant throughout the engine test runs.
iii. The low heat value, kinematic viscosity, and density fuel parameters had a significant effect on engine performance and emission.

Figure 1 below gives the engine input-out analysis. The subsections below outline the development of the mathematical models.

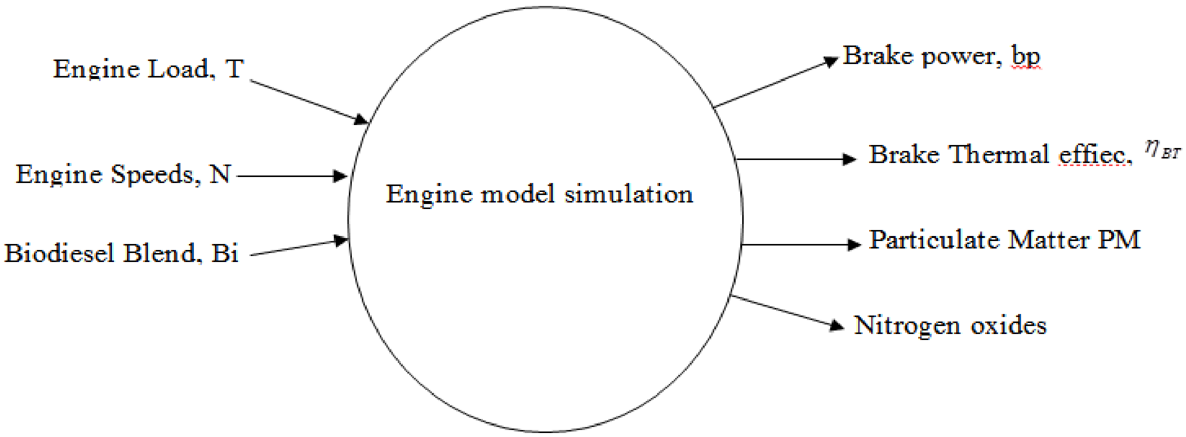

Figure 1: Engine Performance Analysis

Development of the Mathematical Models

Table 1 presents a concise overview of the parameters along with their respective dimensions deployed in the development of the brake thermal efficiency (Bte) mathematical model.

Table 1: Brake Thermal Efficiency Parameters

Dependent (Output)	**Parameter**	**Symbol**	**Dimension**
1	Brake thermal efficiency	Bte	$M^0L^0T^0$
2	Specific fuel consumption	Sfc	$M^0L^2T^{-2}$
3	Nitrogen oxide	NOx	$M^0L^0T^0$
4	Carbon monoxides	CO	$M^0L^0T^0$
Independent (Inputs)			
5.	Blend Ratio	B	$M^0L^{-2}T^{-2}$
6	Calorific value	Cv	L^2T^{-2}
7	Density	P	M^1L^{-3}
8	Kinematic viscosity	N	L^2T^{-1}
9.	Equivalent Brake power	Bp	$M^1L^2T^{-3}$

The standard form Bte equation derived from the Table 1 above are as given below;

$$\{Bte, B, Bp, Cv, \rho, v\} = 0$$

………………………………………………………… (1)

The Buckingham *pie* theorem used 3 π terms {No. of variables (n=6)-fundamental variables (m=3)} and selected as repeating variables (n= 3) Lower heat value (Cv), density (ρ), kinematic viscosity (ν) were, since fuel parameters were constant for fuel, to develop Bte models;

The three (3) *pie (π) terms* for the Bte equation;

$$\pi_1 = BCv^{a1}\rho^{b1}v^{c1},$$

$$\pi_2 = BpCv^{a2}\rho^{b2}v^{c2} \quad \text{and}$$

$$\pi_3 = (Bte)Cv^{a3}\rho^{b3}v^{c3} \text{ ……} \quad (2)$$

Where; a1, b1, c1, a2, b2, c2 were constants for the independent π_1 and π_2 and a3, b3, c3 for dependent *pie (π) term* respectively, determined by dimensions represented into equations 3.6.;

π_1= B Cv^{a1} ρ^{b1} ν^{c1}; $[M^0L^0T^0]$ = $[M^0L^0T^0]^1$ $[M^0L^2T^{-2}]^{a1}$ $[M^1L^{-3}T^0]^{b1}$ $[M^0L^2T^{-1}]^{c1}$

π_2= Bp Cv^{a2} ρ^{b2} ν^{c2}; $[M^0L^0T^0]$ = $[M^1L^2T^{-3}]^1$ $[M^0L^2T^{-2}]^{a2}$ $[M^1L^{-3}T^0]^{b2}$ $[M^0L^2T^{-1}]^{c2}$

$\pi_3 = (Bte)Cv^{a3}\rho^{b3}v^{c3}$ $[M^0L^0T^0]$ = $[M^0L^0T^0]^1$ $[M^0L^2T^{-2}]^{a3}$ $[M^1L^{-3}T^0]^{b3}$ $[M^0L^2T^{-1}]^{c3`}$

The constants were determined using the comparison method of the basic units as follows;

π_1; M: 0 = -c1; L: 0 = 2a1-3b1-2c1; T:0 = 2a1-c1; thus; a_1=0, b_1=0 and c1=0,

Therefore; Independent *pie term*

$$\pi_1 = B \text{ ………………………..………}(3)$$

π_2; M: 0 = 1+b2; L: 0 = 2+2a2-3b2+2c2; T: 0= -3-2a2-c2; then; a2= -½, b2= -1, c1= -2, were The results obtained for the indices were substituted and the final equation was be

Thus; Independent *pie term*

$$\pi_2 = \frac{Bp}{\rho Cv^{1/2}v^2} \text{ ………………………….}(4)$$

π_3 : M: 0 = b3; L: 0 = 2a3-3b3+2c3; T: 0 = -2a3-c3, thus, a3 = 0, b3 = 0, c3 =0;

This resulted in the Bte dependent *pie term* as

$$\pi_3 = \text{Bte ……………………….…. (5)}$$

Hence, from equations 3.7, 3.8, and 3.9, the Brake thermal efficiency (Bte) relationship is given as;

$$f\left\{BTE,\ \mathrm{B},\ \frac{Bp}{\rho Cv^{1/2}v^2}\right\} = 0;$$

Thus,

$$BTE = k_1\mathrm{B}^{p1}\left(\frac{Bp}{\rho Cv^{1/2}v^2}\right)^{q1} \text{ ……………………………………..................……...... (6)}$$

Where; k_1, p1, and q1 were constants for brake thermal efficiency (Bte),

The same method was used to develop the Sfc, NOx and CO equations:

$$sfc = k_2Cv^{-1}\,\mathrm{B}^{p2}\left(\frac{Bp}{\rho Cv^{1/2}v^2}\right)^{q2} \text{ …………………………………..…………... (7)}$$

$$[\mathrm{NOx}] = k_3\mathrm{B}^{p3}\left(\frac{Bp}{\rho Cv^{1/2}v^2}\right)^{q3} \text{ ……………………………………………….. (8)}$$

$$[\mathrm{CO}] = k_4\mathrm{B}^{p4}\left(\frac{Bp}{\rho Cv^{1/2}v^2}\right)^{q4} \text{ ……………………………………………… (9)}$$

K_2, p_2, q_2; k_3, p_3, q_3 and k_4, p_4, q_4 are constants for Sfc, NOx and CO

Determination of the Model Constants

The B, Bp, ρ, v an C_v were common to all the output parameters (Bte, sfc, NOx and CO) were outlined below in table below.

Table 2: The Pie Terms and their Usefulness

Pie Term	Physical Meaning	Variable
π_1= **B**	Biodiesel blend ratio, B, measures the amount of biodiesel added to the diesel	Blend level (B) = 0.10, 0.15, 0.20, 0.25, 0.30
$\pi_2 = \frac{Bp}{\rho Cv^{1/2}v^2}$	Measures the ability of an engine to convert the fuel energy into useful power	Equivalent Bp and fuel Load = 3, 6, 9, 12

		Speed = 1500 rpm Fuels = WVO, oleander, coconut, canola and sunflower.

Engine test runs were carried out using factorial design, shown in Table 2, to determine the constants for π_1 and π_2 for the models.

Thus, from equations 6, 7, 8 and 9 were generalised as;

$$\text{output parameters} = k_i \, \pi 1^{\,p_i} (\pi 2)^{q_i} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(10)}$$

log operation was applied to equation 10, and the equation of log (output parameters) with *pie terms* was obtained as;

$$\log(output\,parameters) = logk_i + p_i log\pi_1 + q_i log\pi_2 \quad \ldots\ldots\ldots\ldots\ldots \text{(11)}$$

The constants K_i, p_i, and q_i for equation 11 were determined using experimental data in 2 using MATLAB software for the non-linear curve-fitting method. The parametric statistical student t-test was used to compare the model and experimental results. The two-tailed paired t-test was performed using the "T.TEST" function of Microsoft Excel to compare simulated and experimental data for the BTE, SFC, NOx, and CO. The p-values were used to determine the statistical significance of the difference between the means; for instance, a p-value < 0.05 implied that the difference between the means of the two groups was significant and vice versa.

RESULTS AND DISCUSSION

Results for Fuel Properties

The selected biodiesel properties, density, kinematic viscosity and lower heating value were determined using ASTM D1298, ASTM D445-18 and ASTM D2015-18 procedures, respectively. ANOVA was used to analyse the data to determine their significant differences in comparison to diesel and presented in Table 3.

Table 3: Determined Properties of the Selected Biodiesels

Selected fuel Properties	Diesel	WVO	Oleander	Canola	Sunflower	Coconut	LSD
Density (p), kg/m3@23ºc	820.0^{f}	876.6^{d}	872.3^{e}	891.6^{b}	882.9^{c}	925.1^{a}	0.170
Kinematic viscosity, mm²/s@40ºc	3.2^{f}	4.2^{em}	4.4^{d}	4.7^{c}	5.2^{b}	5.5^{a}	0.033
heat value (Cv) kJ/kg	43906^{a}	39421^{b}	38736^{c}	37572^{e}	37818^{d}	36206^{f}	0.043

Key: The superscript letters (a, b ...f) represent specific property groups significantly different from each other, as ranked according to status; that is, 'a' has the highest value and 'f' is the lowest.

Coconut had the highest density, while WVO had the lowest density among the biodiesels, and diesel had the lowest density compared to all biodiesels. The small LSD of 0.170 indicates that the differences in density between any two fuel types are considered statistically significant. The P-value was found for the whole sets of data points to be <0.0001, implying that there was no significant difference at an 85 per cent confidence level. The Tukey pairwise comparison was employed to test the differences in kinematic viscosity among various biodiesel fuels, and diesel fuel had the lowest kinematic viscosity at 3.2 mm²/s. There was a significant difference in biodiesels from diesel but not from any other biodiesel according to a small LSD of 0.033 and P-value of 0.0001. the lower heating value of diesel was higher than that of biodiesel fuel, with WVO having the highest lower heat value and coconut having the lowest heat value. The small LSD of 0.043 and P-value of 0.001 show that there was a statistically different lower heat value among any two means compared.

Mathematical Models to Predict Engine Performance

In this research, the mathematical models for prediction of brake thermal efficiency (Bte), specific fuel consumption (sfc), carbon monoxide (CO), and nitrogen oxides (NOx) were developed as a function of the blending level (B), fuel parameters ($\rho\vartheta^2 C_v{}^{1/2}$), and equivalent brake power (Bp) using empirical equations, engine test results in Tables 4. A series of experiments were done using three biodiesels (soybean, linseed and jatropa) at three blend levels (B10, B20 and B30) to validate the mathematical model presented in Table 4.

Table 4: Engine Performance Results for Experimental Versus Prediction

no.	Fuel	Exp. Bte	Pred. bte	Exp sfc	pred. sfc	Exp Nox	pred Nox	Exp CO	pred CO
1	Linseed B10	28.5^a	29.2^a	0.39^a	0.31^b	171^a	175^a	1197^a	1246^a
2	Linseed B20	21.9^a	21.8^a	0.53^a	0.46^b	178^a	196^a	1291^a	1347^a
3	Linseed B30	18.3^a	18.4^a	0.60^a	0.58^a	191^a	209^b	1416^a	1421^a
4	Soybean B10	25.5^a	26.3^a	0.36^a	0.30^b	130^a	143^a	1421^a	1239^a
5	Soybean B20	20.5^a	19.7^b	0.47^a	0.45^a	152^a	160^a	1498^a	1308^b
6	Soybean B30	16.5^a	16.6^a	0.53^a	0.56^a	180^a	171^a	1643^a	1673^a
7	Jatropa B10	22.7^a	23.9^b	0.43^a	0.46^a	108^a	134^b	1378^a	1308^a
8	Jatropa B20	17.3^a	17.9^a	0.58^a	0.46^b	135^a	134^a	1860^a	1873^a
9	Jatropa B30	14.8^a	15.1^a	0.65^a	0.57^b	161^a	143^b	1963^a	1421^a

Brake Thermal Efficiency Model

The BTE model constants were determined using the empirical equation 6 in section 2, and the experimental result for the brake thermal efficiency (for blends in levels of 0.1, 0.15, 0.2, 0.25 and 0.3, brake power levels at speed 1500rpm and loads varying from 3, 6, 9 and 12 kg) in appendix 1, fuel property results in table 3. The developed equation for BTE is given below;

$$BTE = 1.2B^{-0.42}\left(\frac{Bp}{\rho\vartheta^2 C_v{}^{1/2}}\right)^{0.68} \quad \text{……………………………………………………} (12)$$

Where:

BTE = bake thermal efficiency; B = blend percentage of biodiesel

Bp = equivalent brake power;

ϑ = kinematic viscosity of the biodiesel

ρ = density of the biodiesel

Equation 12 clearly shows that as the biodiesel blend level rises, BTE decreases, while an increase in the ratio of Bp to fuel property leads to an increase in BTE. Analysis of variance (ANOVA) was used to provide a statistical validation of the model by comparing predicted BTE to experimental Bte data. ANOVA found no significant difference between predicted and experimental BTE means with a P-value of more than 0.01. This indicates the model predicts BTE accurately at a 95 per cent confidence level.

Figure 2 shows a plot for the predicted values versus experimental values. The graph has a positive gradient, but the gradient keeps changing at any particular point of the curve, indicating that it is not a straight line. Although it's not a straight line, the model predicts BTE with more than 95 per cent accuracy.

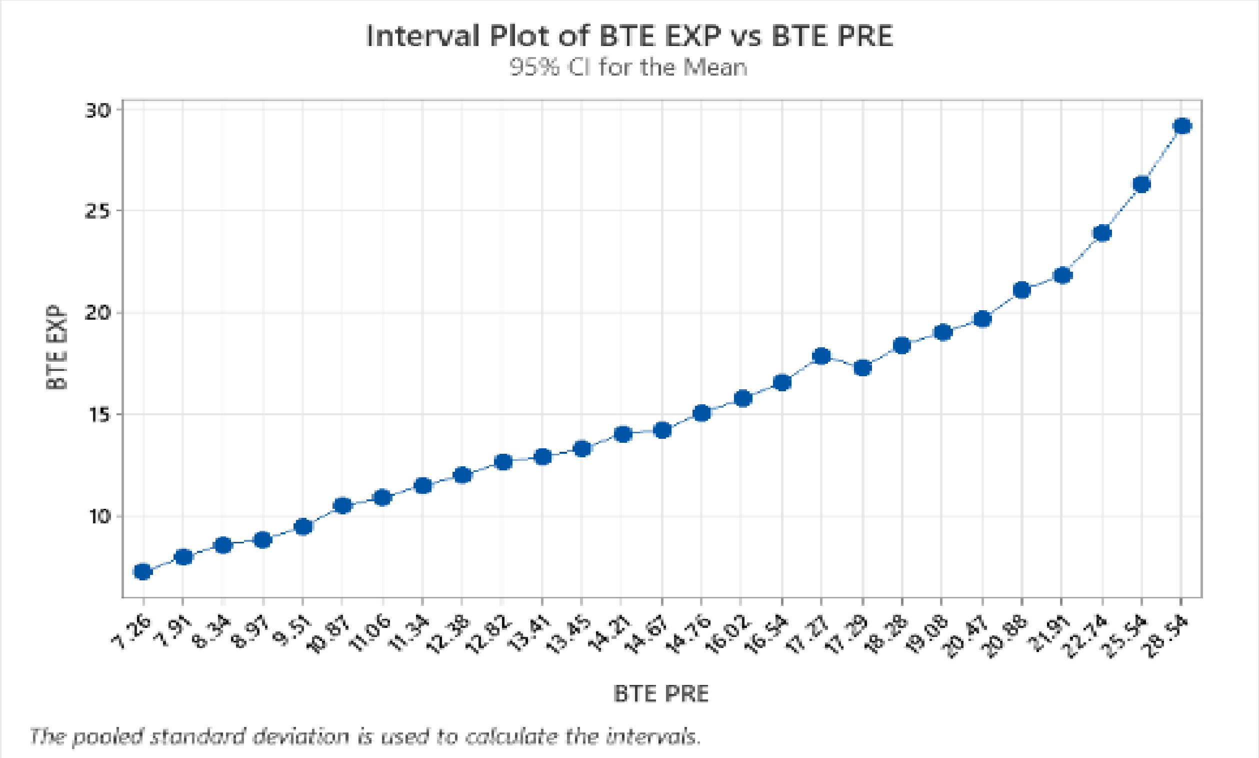

Figure 2: **Brake Thermal Efficiency of Experimental against Predicted**

Specific Fuel Consumption Model

The SFC model constants were determined using the empirical equation 7 in section 2, and the experimental result for the brake thermal efficiency (for blends in levels of 0.1, 0.15, 0.2, 0.25 and 0.3, brake power levels at speed 1500rpm and loads varying from 3, 6, 9 and 12 kg) in appendix 2, fuel property results in table 3. The developed equation for SFC is given below;

$$SFC = 2.55 * 10^{-9} C_v B^{0.55} \left(\frac{Bp}{\rho\, \vartheta^2 C_v{}^{1/2}}\right)^{-0.65} \qquad (13)$$

Where:

SFC is the specific fuel consumption, *B* is the blend percentage of biodiesel

Bp is the equivalent brake power ϑ is the kinematic viscosity of the biodiesel

ρ is the density of the biodiesel, *Cv* is the lower heating value

A one-way ANOVA was done to compare the predicted and experimentally measured SFC values from the model. The analysis found strong evidence of statistically significant differences between the two groups' means, with a p-value of 0.001. The model thus fails to fully capture the range and distribution of experimental outcomes.

While this initial ANOVA provides useful evidence of biases and limitations in the model's SFC predictions, the validation process would benefit from more rigorous statistical tests beyond just differences in means. The small sample size, with only 1-3 data points per group, restricts the analysis. Follow-up work should leverage larger sample sizes and additional techniques like distribution comparisons, correlation analysis, and error metrics. Overall, the ANOVA highlights deficiencies in the model's predictive capability for SFC, underscoring the need for comprehensive validation to characterise strengths, weaknesses, and uncertainties. Targeted model refinements may improve fidelity, but iterative validation is essential even after improvements.

Carbon Monoxide Model

The CO model constants were determined using the empirical equation 9 in section 2, and the experimental result for the brake thermal efficiency (for blends in levels of 0.1, 0.15, 0.2, 0.25 and 0.3, brake power levels at speed 1500rpm and loads varying from 3, 6, 9 and 12 kg) in appendix 3, fuel property results in table 3. The developed equation for CO is given below;

$$CO = 0.03B^{-0.12}\left(\frac{Bp}{\rho\vartheta^{2}{C_{v}}^{1/2}}\right)^{-0.35} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Where:

CO is the carbon monoxide emission, B is the blend percentage of biodiesel

Bp is the equivalent brake power

ϑ is the kinematic viscosity of the biodiesel

ρ is the density of the biodiesel

The accuracy of the developed CO model was validated by statistically comparing the model-predicted results against experiment CO values. The validation used engine test data from 9 different operating conditions. An ANOVA statistical test was applied to compare the means of the CO PRE and CO EXP groups. The ANOVA results demonstrated that the means of both groups were statistically similar at a 99 per cent confidence level for most operating conditions tested. This signified that the model accurately predicted the CO emissions and could be validated against the experimental engine test data.

Nitrogen Oxide Emission Model

Regression analysis was applied on the empirical equation 8 in section 2, and the experimental result for the brake thermal efficiency (for blends in levels of 0.1, 0.15, 0.2, 0.25 and 0.3, brake power levels at speed 1500 rpm and loads varying from 3, 6, 9 and 12 kg) in appendix 4 and fuel property results in table 3 to develop a mathematical model for predicting NOx emissions. The developed equation for NOx was;

$$NOx = 24000B^{0.16}\left(\frac{Bp}{\rho\vartheta^{2}{C_{v}}^{1/2}}\right)^{1.3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

Where:

NOx is the nitrogen monoxide emissions, B is the blend percentage of biodiesel

Bp is the equivalent brake power ϑ is the kinematic viscosity of the biodiesel

ρ is the density of the biodiesel, Cv is the lower heat value

The accuracy of the developed NOx model was validated by statistically comparing the model-predicted NOx values versus experimentally measured values from engine testing. The validation used engine test data collected at 9 different operating conditions. An ANOVA statistical test was adopted to compare the means of the Predicted NOx and Experimental NOx groups. The ANOVA results showed that the means of both groups were statistically similar at a 99 per cent confidence level for most operating conditions tested. This indicated that the model was able to predict the NOx emissions accurately and was validated against the experimental engine test data, as shown in Table 4.

CONCLUSION AND RECOMMENDATIONS

Conclusions: The study found that biodiesel-diesel blends have the potential to replace diesel for compression ignition engines, contributing to air pollution control and reducing dependence on fossil fuel resources without compromising engine performance. A mathematical model predicting brake thermal efficiency, specific fuel consumption, nitrogen oxides, and carbon monoxide emissions for CI engines fueled by biodiesel blends was successfully developed

Recommendations: Whereas the model offers a starting point for simulating biodiesel blend combustion in compression ignition (CI) engines, there is a need to expand the model inputs to cover a wider range of the biodiesel fuel properties, the different engine types and real-world operating conditions. Essentially, this shall leverage the model's applicability and improve its computational efficiency to ensure its reliability while providing increased insight into the application of biodiesel in engines.

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