

Investigation into the effects of fuel composition on the emission characteristics of a low-speed direct injection engine

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Abstract

This paper presents the results of an investigation into the effect of fuel composition on the emission characteristics of a four stroke, single cylinder, Viking super direct injection diesel engine run at different operating conditions using diesel fuel and soybean biodiesel blends (B15, B20 and B25). A PerkinElmer 2400 series CHNS/O elemental analyser was used in determining the fuel composition. Exhaust emission testing was conducted using Crowcon gas sensors to quantify the concentration of Nitrogen dioxide (NO₂), carbon monoxide (CO) and sulphur dioxide (SO₂) from the exhaust gases. The relationships between the exhaust emissions, engine speed, torque, throttle position and elemental fuel composition have been reported. The predictive model equations were developed using multiple regression analysis to predict exhaust emissions. The results show that the engine that is run on B15 gives the lowest levels of Nitrogen dioxide (NO₂) emissions of 2.58 ppm, carbon monoxide (CO) emissions of 0.153 ppm and sulphur dioxide (SO₂) emissions of 6.5 ppm when compared to other fuel blends. This outcome signals the possibility of using B15 as an alternative fuel to diesel for a healthier environment.

Keywords: fuel composition, soya biodiesel, emissions, environmental pollution.

1 Introduction

The idea of using vegetable oils instead of diesel fuel is not new and goes back to at least 1928 [1]. Since then, the concept was dropped due to the cheap supply of petroleum-based fuels. The environmental concern and depletion of



conventional sources have prompted research world-wide into alternative energy sources for internal combustion (IC) engines. Biofuels appear to be a potential alternative energy resource to fossil fuels because it is renewable and available throughout the world. The sulphur content is negligibly small thus the issue of acid rain is ameliorated. The problem of using neat vegetable oils in diesel engines relates to their high viscosity. Today, diesel engines are a major and widely used power source for in-sea and on-land transportation vehicles due to their simple mechanism, excellent performance, easy maintenance, low fuel oil cost, low fuel consumption rate, low breakdown rate, high compression ratio, high power/weight ratio, high fuel oil density, high thermal efficiency and durability. However, diesel engines are also considered a major source of air pollution in port and urban areas because of their black smoke, HC, NO_x, particulate matter (PM), CO, CO₂, SO_x emissions. The disgusting odor and noise from these engines may impair human health and the natural environment, such as ozone layer destruction, greenhouse effect enhancement and acid rain production [2–4]). While diesel engines are still the most common energy production equipment for ships, the air pollution threat caused by them cannot be neglected.

Studies show that the composition of diesel exhaust gas varies considerably, depending on the engine type, operating conditions, fuel, lubricating oil, and whether an emission control system is present. Reduction of exhaust emissions is extremely important for diesel engine development in view of increasing concern regarding environmental protection and stringent exhaust gas regulations. Controlling diesel exhaust emissions through fuel modification seems to be promising because it would affect both the new and old engines. The modification of diesel fuel to reduce exhaust emissions can be performed by increasing the cetane number, reducing fuel sulphur, reducing aromatic content, increasing fuel volatility and decreasing the fuel density. However, the potential of conventional diesel fuel for emissions reduction has already been, to a large extent, exploited and the most important fuel parameters mentioned above can nowadays be changed within only a narrow range.

2 Materials and methods

2.1 Experimental set-up for the determination of fuel composition

The instrumentation used in this study includes a PerkinElmer 2400 Series II CHNS/O Analyzer and a PerkinElmer AD6 microbalance. Both the analyzer and the microbalance were connected to a Windows based PC running Perkin Elmer's proprietary software.

2.2 Engine set-up

A single cylinder Viking Super diesel engine was used as the test engine. It is an air-cooled direct injection, four-stroke, horizontal type engine. The engine specifications are given in Table 1.



Table 1: Test engine specifications.

S/No.	Description	Specification
1.	Engine Model	165F
2.	Type	Horizontal Single Cylinder four stroke, air cooled
3.	Bore/Stroke	65/70 mm
4.	Compression Ratio	20.5–22
5.	Max. Torque	8.9 Nm
6.	Max. Brake Power	2.43 kW
7.	Rated Speed	2600 rpm
8.	Fuel Injection Pressure	14 MPa
9.	Injection opening angle	20°–24° before T.D.C

The engine was mounted on a test bench and then connected to a hydraulic dynamometer and control panel, which has accessories for monitoring speed, torque and temperature. The fuel sample was fed from fuel tank mounted on the instrumentation unit and was being gravity fed to the engine, which was below the level of the tank. The engine tests were conducted at three different throttle positions (I – fully opened, II – three-quarter opened and III – half opened). Under each of the positions, the engine speed was kept constant while the load was varied and the corresponding exhaust gases recorded. The procedure was repeated with the load kept constant and engine speed varied for diesel fuel and blends. All readings were taken after stable operating conditions were experimentally achieved. Figure 1 shows the experimental set up.



Figure 1: Engine set up with control panel.

The parameters recorded at each operating condition include: engine speed (rpm); torque (Nm); exhaust temperature (°C); NO₂ emission (ppm); CO emission (ppm) and SO₂ emission (ppm). The compositions of the exhaust toxic gases were measured using the Crowcon gas sensor obtained from the Pollution Control Laboratory, Ministry of Environment, Kano, Nigeria.

The data obtained were further analysed using statistical method of regression analysis. It is imperative to note that, the exhaust gas emission of NO₂, CO and SO₂ are functions of the engine speed, torque, throttle position and blend ratio as shown in the following equations:

$$\begin{Bmatrix} NO_2 \\ CO \\ SO_2 \end{Bmatrix} = F(n, T, Z, R) \quad (1)$$

where: n is the engine speed in rpm, T is the torque in Nm, Z is the throttle position and R is the blend ratio.

Similarly, the exhaust gas emissions of NO₂, CO and SO₂ may be expressed as functions of the elemental fuel composition as shown in the equation below:

$$\begin{Bmatrix} NO_2 \\ CO \\ SO_2 \end{Bmatrix} = F(C, H, O, S) \quad (2)$$

where: C is the carbon, H is the hydrogen, O is the oxygen and S is the sulphur compositions in the fuel.

For this study, it was assumed that the relation between the emissions and the other independent variable is linear and could be studied using linear regression techniques. However, it should be noted that the word “linear” in linear regression does not mean that the function is a straight line, but that the partial derivatives with respect to each coefficient are not functions of other coefficients [5]. Therefore, equations 1 and 2 may be transformed to the model equations 3 and 4 respectively in the form:

$$\begin{Bmatrix} NO_2 \\ CO \\ SO_2 \end{Bmatrix} = A + Bn + CT + DZ + ER \quad (3)$$

$$\begin{Bmatrix} NO_2 \\ CO \\ SO_2 \end{Bmatrix} = a + bC + cH + dO + eS \quad (4)$$

where: $A, B, C, D, E, a, b, c, d$ and e are constants obtained from the regression analysis.

In reality, engine emission may be influenced by both operating settings and fuel composition. Therefore, equations 3 and 4 may be represented in the form:

$$\begin{Bmatrix} NO_2 \\ CO \\ SO_2 \end{Bmatrix} = F(C, H, O, S, n, T, Z, R) \quad (5)$$

It can be noted that when $n, T, Z, R = \text{constant}$ (fixed) equation 5 becomes equation 2; while as $C, H, O, S = \text{Constant}$, equation 5 becomes equation 1. Thus, emission of any of the gases may then be expressed in matrix form as:

$$\begin{bmatrix} NO_2 \\ CO \\ SO_2 \end{bmatrix} = a + bC + cH + \delta O + eS + fn + gT + hZ + iR \quad (6)$$

Three generalized model equations were determined from the regression analysis of the exhaust gas emissions taking cognizance of engine speed, torque, throttle position and elemental compositions of the fuel. The regression analysis indicates that the generalized equations show better correlation with respect to the parameters considered in that, the value of any emission can be predicted in as much as the other independent variables are known.

3 Results and discussion

The test analyzer used in the elemental analysis is usually employed for the determination of carbon and hydrogen content of liquid fuels including gasoline, diesel, biodiesel blends, and gasoline-ethanol blends. When the only elements present in significant quantities are carbon and hydrogen, the oxygen content can be determined by difference. Tables 2 and 3 show the elemental composition and properties respectively of fuel blends used for the study.

Table 2: Elemental composition in fraction of fuel used.

Elements	Fuel Blends				
	B ₀	B ₁₅	B ₂₀	B ₂₅	B ₁₀₀
C	0.8520	0.8490	0.8412	0.8310	0.7607
H	0.1240	0.1230	0.1220	0.1210	0.1181
O	0.0040	0.0269	0.0355	0.0465	0.1162
S	0.0200	0.0011	0.0013	0.0015	0.0050

Table 3: Properties of diesel and biodiesel produced from soybeans oil.

Property	Diesel	B ₁₅	B ₂₀	B ₂₅	B ₁₀₀
Density at 15°C (kg/m ³)	830	836	842	849	878
Flash Point (°C)	66	78	84	86	97
Viscosity at 40°C (cSt)	6.5	7.1	7.6	8.0	10.2
Calorific Value (MJ/kg)	44	43.9	43.95	43.85	43.6
Cetane Number	47	47.42	47.79	48.21	50.4



Experimental results show that the NO₂ emission for diesel and all the blends followed an increasing trend with respect to load for all throttle positions (position I – fully opened, position II – three-quarter opened and position III – half opened) as shown in Tables 4, 5 and 6. In a similar way, the emissions of the test engine, run on B25 biodiesel were investigated (not shown). For the blends, an increase in the emission was found at all loads when compared to diesel (Tables 5 and 6). While from the variation of nitrogen dioxide with engine speed (speed characteristics), it was observed that, the NO₂ emission for diesel is much lower than that of the blends at all speeds. Also the NO₂ emission for diesel and all the blends followed a decreasing trend with respect to increase in speed at all the levels of the throttle positions. Similar observations for carbon

Table 4: Exhaust gas emissions for engine run on Diesel (B0).

A) At throttle position I (fully opened).

S/No	SPEED (rpm)	TORQUE (Nm)	EXHAUST TEMP. °C	COMPOSITION OF EXHAUST TOXIC GASES (ppm)		
				CO	NO ₂	SO ₂
1	2600	0.8	132	10	1.3	24
2	2600	1.8	153	9.4	1.4	23
3	2600	2.7	171	8.7	1.5	22
4	2600	3.6	198	7.2	2.1	15
5	2600	4.8	219	7.0	2.3	11

B) At Throttle position II (three-quarter opened).

S/No	SPEED (rpm)	TORQUE (Nm)	EXHAUST TEMP. °C	COMPOSITION OF EXHAUST TOXIC GASES (ppm)		
				CO	NO ₂	SO ₂
1	1900	0.8	120	6.8	1.4	23.5
2	1900	1.0	128	6.2	1.6	23.1
3	1900	2.0	142	4.2	2.2	22.5
4	1900	2.5	165	3.0	2.7	22.3
5	1900	3.2	190	2.3	3.1	22.0

C) At throttle position III (Half opened).

S/No	SPEED (rpm)	TORQUE (Nm)	EXHAUST TEMP. °C	COMPOSITION OF EXHAUST TOXIC GASES (ppm)		
				CO	NO ₂	SO ₂
1	1200	0.8	110	5.1	2.0	23.1
2	1200	1.2	121	4.8	2.4	22.8
3	1200	1.8	133	4.2	2.8	22.4
4	1200	2.4	156	3.8	3.2	22.1
5	1200	3.0	171	2.0	3.6	21.8



monoxide and oxides of sulphur revealed that the engine emits more CO for diesel when compared to the blends. However, as the proportion of soybean oil in the blend increases the percentage of CO emission decreases. Also the SO₂ emission for diesel and all the blends followed a decreasing trend with respect to load in all the levels.

Table 5: Exhaust gas emissions for engine run on biodiesel B15.

A) At throttle position I.

S/No	SPEED (rpm)	TORQUE (Nm)	EXHAUST TEMP. °C	COMPOSITION OF EXHAUST TOXIC GASES (ppm)		
				CO	NO ₂	SO ₂
1	2600	1.0	112	4	5.2	9.5
2	2600	1.8	131	3	6.0	8.5
3	2600	3.7	159	2.5	6.8	8.0
4	2600	5.5	182	2.0	8.0	7.9
5	2600	5.8	201	1.4	9.1	6.5

B) At throttle position II.

S/No	SPEED (rpm)	TORQUE (Nm)	EXHAUST TEMP. °C	COMPOSITION OF EXHAUST TOXIC GASES (ppm)		
				CO	NO ₂	SO ₂
1	1900	0.9	104	2.5	4.8	10.4
2	1900	1.1	111	2.1	5.2	9.0
3	1900	2.0	130	1.8	5.9	9.2
4	1900	3.4	143	1.3	6.3	8.3
5	1900	3.8	159	1.0	6.8	7.0

C) At throttle position III.

S/No	SPEED (rpm)	TORQUE (Nm)	EXHAUST TEMP. °C	COMPOSITION OF EXHAUST TOXIC GASES (ppm)		
				CO	NO ₂	SO ₂
1	1200	0.7	90	1.7	3.4	9.1
2	1200	1.5	109	1.4	3.8	7.1
3	1200	1.9	123	1.1	4.1	6.3
4	1200	2.3	130	0.9	4.4	6.5
5	1200	2.6	139	0.8	5.6	5.8



Table 6: Exhaust gas emissions for engine run on biodiesel B20.

A) At throttle position I.

S/No	SPEED (rpm)	TORQUE (Nm)	EXHAUST TEMP. °C	COMPOSITION OF EXHAUST TOXIC GASES (ppm)		
				CO	NO ₂	SO ₂
1	2600	2.3	141	1.0	9.1	8.2
2	2300	2.3	134	1.0	11.8	7.2
3	1900	2.3	128	0.8	14.2	6.2
4	1500	2.3	126	0.7	16	5.8
5	1200	2.3	124	0.7	18.0	5.0

B) At throttle position II.

S/No	SPEED (rpm)	TORQUE (Nm)	EXHAUST TEMP. °C	COMPOSITION OF EXHAUST TOXIC GASES (ppm)		
				CO	NO ₂	SO ₂
1	2600	1.8	130	2.0	12.8	8.2
2	2300	1.8	126	1.6	13.1	7.1
3	1900	1.8	120	1.2	13.5	6.8
4	1500	1.8	116	1.0	15	6.1
5	1200	1.8	114	1.0	17.0	5.9

C) At throttle position III.

S/No	SPEED (rpm)	TORQUE (Nm)	EXHAUST TEMP. °C	COMPOSITION OF EXHAUST TOXIC GASES (ppm)		
				CO	NO ₂	SO ₂
1	2600	0.8	107	3.2	10.6	9.3
2	2300	0.8	102	3.0	10.9	9.1
3	1900	0.8	94	2.9	11.3	8.8
4	1500	1.8	91	2.9	13	8.4
5	1200	0.8	88	3.1	16.6	7.9

Table 7: Sample regression analysis of experimental results.

<i>Regression Statistics</i>						
Multiple R	0.804328					
R Square	0.646944					
Adjusted R Square	0.619348					
Standard Error	1.310807					
Observations	120					
ANOVA						
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>	
Regression	7	355.7777	50.82539	34.51042	3.3E-25	
Residual	113	194.1582	1.718214			
Total	120	549.9359				
	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>
Intercept	1428.649	2128.358	0.671244	0.503435	-2788.01	5645.31
SPEED	0.001571	0.00026	6.041589	2E-08	0.001056	0.002087
TORQUE	-0.24845	0.115643	-2.14841	0.033816	-0.47756	-0.01934
THTR	-2.46701	0.770803	-3.20057	0.001781	-3.99411	-0.93991
C	-1634.59	2434.425	-0.67145	0.503306	-6457.62	3188.446
H	0	0	65535	#NUM!	0	0
O	-1419.82	2190.505	-0.64817	0.51819	-5759.6	2919.966
S	-1258.72	2273.634	-0.55362	0.580935	-5763.2	3245.758

The exhaust emission of sulphur dioxide from biodiesel blends is observed to be about 40% lower than the sulphur dioxide emission from diesel. Statistical analysis of the results shows that correlation coefficients (R-square) of about 93% and 96% which signifies that there is a good relationship between the observed and predicted NO₂ and SO₂ emissions respectively. The low value of about 65% correlation for CO emission might be due to experimental errors (Table 7). The key findings are the predictive model equations for the emission of NO₂, CO and SO₂ respectively with respect to engine speed (n), torque (T), throttle position (Z) and the elemental compositions (C, O and S) for the liquid fuel blends used in the study:

- $\text{NO}_2 = -32968 - 0.00264 (n) + 0.922251 (T) - 0.07623 (Z) + 37706.34 (C) + 34385.27 (O) + 35505.95 (S)$
- $\text{CO} = 1428.649 + 0.001571 (n) - 0.24845 (T) - 2.46701 (Z) - 1634.59 (C) - 1419.82 (O) - 1258.72 (S)$
- $\text{SO}_2 = 2215.24 + 0.000947 (n) - 0.98184 (T) + 0.26994 (Z) - 2523.74 (C) - 2335.35 (O) - 1699.91 (S)$

4 Conclusion

This study has investigated the effects of fuel composition and operating regime of a low speed direct injection engine on its emission characteristics. The key findings are the predictive model equations for the emission of NO_2 , CO and SO_2 respectively as functions of the engine speed (n), torque (T), throttle position (Z) and the elemental compositions (C, O and S) for the liquid fuel blends used in the study.

The concentration of hydrogen in the fuel does not have any effect on the predictive equations because when included in the regression analysis, the coefficient is always zero. From the environmental point of view, the B15 fuel was established to be a good alternative to diesel fuel because the study revealed that there were low NO_2 , CO and SO_2 emissions for this blend as compared to other fuel blends used in the study. The results show that engine run on B15 gives lowest Nitrogen dioxide (NO_2) emission of 2.58 ppm, carbon monoxide (CO) emission of 0.153 ppm and sulphur dioxide (SO_2) emission of 6.5 ppm when compared to other fuel blends. The observed increase in NO_2 emissions of the all the biodiesel blends as compared to B0 (petro diesel) is in agreement with Canakci [6].

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