P. SHANMUGHASUNDARAM
G. JAYABALAJI
and
R. KALAISELVI

Statistical analysis on exhaust emission of a CI engine operated with aphanizomenon flos biodiesel – TiO_2 nano-fluid blend

In this work, titanium dioxide (TiO_2) nano-fluid was blended with aphanizomenon Flos (AF) biodiesel blend in order to investigate the emission behaviour of compression ignition engine. Three different percentages of titanium dioxide (TiO_2) nano-fluid was blended with aphanizomenon Flos (AF) biodiesel (20%) – diesel (80%) blend. Taguchi method was used to find the optimum level of titanium dioxide nano-fluid. ANOVA was used to find the contribution of factors on the exhaust emission. As TiO_2 content increases in AFD - TiO_2 blend, NO emission of the engine increases. Correlation among the significant factors on the response was done using multiple linear regression equation.

Keywords: *Compression ignition engine; aphanizomenon flos biodiesel; titanium dioxide; nanofluid; taguchi; ANOVA.*

1.0 Introduction

The need of non-edible biodiesel has significantly increased in developing countries in substitute to mineral diesel. When the true potential, and the clean emission of the non-edible feedstock based biodiesel derived liquid fuel was realized the battle against feedstock scarcity has also come to a rest as researchers from various corners deliberates the use of biodiesel prepared from various indigenous feedstocks in diesel engines to reduce the pressure on a specific feedstock such as Jatropha and Karanjae specially in India. In this regard, research on biodiesel from algae is a potential choice.

Though, there are various algae species available for the production of biofuel, aphanizomenon flos (AF) is considered to be a potential species as it has more amount of lipid and the highest growth rate. This AF species can sustain extreme salinity condition and pH to survive. Algae based biofuels, considered greener, help in waste management and do not have a negative impact on the food supply as they are derived from sources, which are not used by human. The incorporation of nano-particles in the biodiesel-diesel blend can decline the delay in ignition, and enhance the evaporation of the fuel. Praveen et al [1] investigated the performance and emission characteristics of a diesel engine using calophyllum inophyllum biodiesel blends with titanium dioxide (TiO_2) nano-additives and EGR. They reported that CO and HC emissions were reduced with the addition of TiO_2 nano-particles to the B20 fuel.

Prabu [2] analyzed the performance of the engine operated with biodiesel with nano-particles. It was reported that the higher surface area/volume ratio, mixing and chemical reactivity are improved during the combustion which enhances the performance of the CI engine. Prabu and Anand studied the effect of oxygenates blended with Jatropha biodiesel in a single cylinder direct injection diesel engine. Minimal improvement was observed in the performance of the engine and drop in carbon monoxide (CO) and smoke opacity was observed [3]. TayfunÖzgür [4] investigated the effect of nano-particle to biodiesel for improvement of the performance and exhaust emissions in a CI engine. It was reported that exhaust emission values NO_x and CO were decreased while performance slightly increased with the addition of nano-particle additives. In this work aluminium oxide nano-particles were added to mahua methyl ester.

Syed Aalamand Saravanan [5] investigated the impact of nano metal oxide blended mahua biodiesel on CRDI CI engine. A significant improvement in the brake thermal efficiency and a minimal reduction in the CO, HC and smoke pollutants were observed for the nano-particles blended biodiesel. Sadhik Basha and Anand [6] studied the combustion characteristics of a diesel engine using carbon nanotubes blended jatropha methyl ester. Investigation was made in a single cylinder constant speed CI engine to establish the effects of carbon nano-tubes with the jatropha methyl esters emulsion fuel. It was reported that the level of pollutants such as NO_x and smoke was drastically reduced when compared to that of neat jatropha methyl ester [6]. Metal based additive ferric chloride ($FeCl_3$) was used as a

Blind peer reviews carried out

Messrs. P. Shanmughasundaram, G.Jayabalaji, Department of Automobile Engineering, Karpagam Academy of Higher Education and R. Kalaiselvi, Department of Information Science and Engineering, Kumaraguru College of Technology, Coimbatore 641049, Tamilnadu, India. Email: sunramlec@rediffmail.com / kalaiselvi.r.cse@kct.ac.in

fuel borne catalyst (FBC) for waste cooking palm biodiesel. Slight improvement in BSFC, BSEC and brake thermal efficiency was observed with FBC added biodiesel. Reduction in CO, UHC and smoke emission was observed whereas slight increase in NO and CO_2 was observed with FBC added biodiesel compared to biodiesel [7].

Shaafi et al [8] reviewed the effect of dispersion of various nano-additives on the performance and emission characteristics of a CI engine fuelled with diesel, biodiesel and blends. Addition of nano particles with fuel is one of the techniques which can be used to enhance the performance as well as reduction in pollutants. Incorporation of nano-particles as fuel additives in diesel improves the thermo physical properties. Dinesh [9] studied the effect of compression ratio and injection pressure on the vehicle exhaust emission and reported that the BSFC, BTE and EGT of Ricardo engine were found to be a function of biodiesel blend, load, compression ratio and injection timing. Naushad Ahamad Ansari et al and Yashvir Singh et al analyzed the exhaust emission of a diesel engine by employing Taguchi method [10, 11].

In this work the fuels and additives used in the analysis are diesel, aphanizomenon flos (AF) biodiesel, and titanium dioxide (TiO_2) nano-particles. The AF biodiesel and TiO_2 nano-particles were purchased from the local chemical trader and mixed in the author's laboratory, and prepared the blends. In the present investigation, three different percentages of titanium dioxide (TiO_2) nano-fluid such as 5%, 10% and 15% by volume was blended with aphanizomenon flos (AF) biodiesel (20%)-diesel (80%) blend in order to compute the influence of the additive TiO_2 on the engine exhaust emission of the engine. In this study Taguchi and ANOVA methods were employed to analyze the effect of TiO_2 nano-fluidon the CO, HC, NO and smoke emission of the engine.

2. Materials and methodology

2.1 Fuel preparation

The fuels used in the analysis are diesel and aphanizomenon flos (AF) biodiesel. Titanium dioxide (TiO_2) nano-particles were used as additive. The AF biodiesel and TiO_2nano-particles were purchased and prepared the blends. Our earlier work results infer that the addition of TiO_2 nano particles exceeds 10% with AF-D blends, CO and HC emission tends to increase. Hence AFD-10TiO_2 blend was found to be optimum value in obtaining lower emission. In this work 10TiO_2 was chosen. The physico-chemical properties of standard diesel, AF biodiesel, and AFD-10TiO_2 blend are given in Table 1. The properties of TiO_2 are given in Table 2.

Table 1: Properties of diesel, and AFD-10TiO_2

Properties	Test method, ASTM	Diesel	AF biodiesel	AFD-10TiO_2
Density, kg/m^3	-	831	835	831.4
LHV, MJ/kg	D 4809	43.6	39.8	42.7
Ignition temperature, °C	E 659	212-348	170-320	198-336
Cetane number	D 613	51	48	50.7
C, wt.%	-	85.3	65.74	76.47
H, wt.%	-	13.19	10.04	10.4
N, wt.%	-	1.21	1.01	0.40
S, wt.%	-	0.3	0.001	0.21
O, wt.%	-	-	23.1	12.52

Table 2: Properties of TiO_2

Parameter	Property
Particle size, nm	20
Molecular weight, g/mol	82
Color	White
Type	Powder

Table 3: Specifications of the engine

Make	Kirloskar, VCR
Type	1cyl., 4S, CI
Injection	Direct
Power, kW	3.7
Speed, rpm	1500
Cooling medium	Water
Volume, cm^3	551
Standard injection pressure, bar	180
Injection timing , ºCAbTDC	23
Compression ratio	17.5

2.2 Engine set up

The schematic of the CI engine set up is shown in Fig.1. The specifications of the engine are given in Table 3.

Experimental set up is shown in Fig.1. A single cylinder, compression ignition engine was employed for this study.

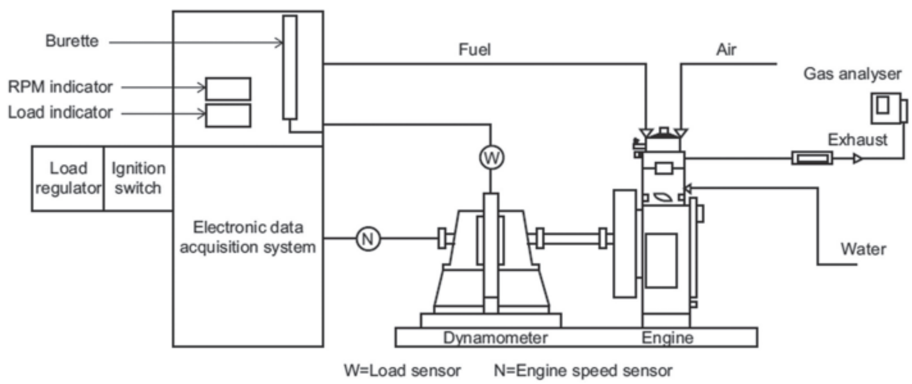

Fig.1. Experimental setup

The dynamometer which is coupled with the engine measures the load. AVL 444 gas analyzer was used to measure the exhaust emissions. K-type temperature measurement thermocouples which are installed in various locations are used to record the temperature of inlet water, outlet water, exhaust gas temperature and suction air temperature. The ambient condition of temperature and pressure during the experiment was about 30°C and, 1 bar respectively.

2.3. Methodology

2.3.1 Taguchi method

Genichi Taguchi has proposed a systematic and capable method in finding the optimum level of process parameters that have an effect on the performance of the process. It can be performed with only a small number of tests in order to select the optimum level of parameters which have an impact on quality of the process and product. Hence this method minimizes experimental runs, time and the cost.

Orthogonal arrays are used to study a large number of variables with a minimum number of configurations. In this study, "smaller is better" S/N ratio was considered to find the optimum level of parameters because a lower exhaust emission was desirable. Mathematical equation of the S/N ratio for "smaller is better" is represented in the equation (1).

$$\frac{S}{N} = -10\log[\frac{1}{n}\sum y2] \quad \text{... (1)}$$

where, y is the observed data and n is the number of observations.

In the present investigation, engine exhaust emissions such as CO, HC, NO and smoke were measured as per the L9 orthogonal array. Accordingly, 9 tests were carried out and each test was repeated twice in order to reduce the errors. The factors and the corresponding levels which are considered are presented in Table 4. In addition, the obtained results were analyzed using analysis of variance (ANOVA) to study the contribution of the factors on exhaust emission.

Table 4: Factors and levels

Level	A-load	B-fuel
I	0%	AFD blend 5 TiO_2
II	50%	AFD blend 10 TiO_2
III	100%	AFD blend 15 TiO_2

2.3.2 Results of S/N ratio

Ranking of factors was carried out using signal to noise ratios and given in the Tables 6 to 9 for the CO emission, HC emission, NO emission and smoke emission respectively. Load was the dominant factor followed by fuel for the CO, HC, NO and smoke emission of the engine. It may be due to the fact that the wide range of load (0% to 100%) was chosen for this study compared to the fuel TiO_2 content (5TiO_2 to 15TiO_2).

Measured values and S/N ratios for exhaust emission are given in the Table 5. The maximum S/N ratio values are

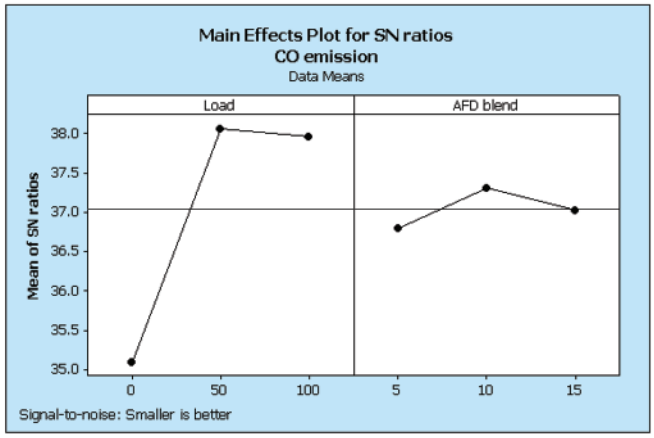

Fig.2 Response diagram of S/N ratio for CO emission

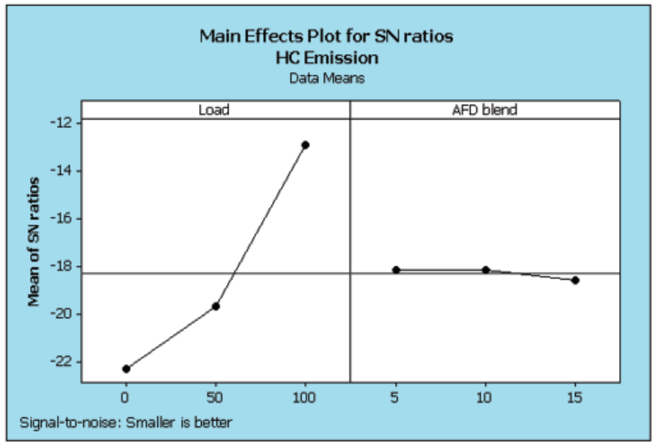

Fig.3 Response diagram of S/N ratio for HC emission

selected for all the factors representing the optimum condition which gives the preferred quality with the least variance. It can be seen from the response diagram for CO emission (Fig.2), that the optimum parameters were load (50%), and fuel (10 TiO_2). As load on the engine increases CO emission tends to decline. 10% of titanium dioxide (TiO_2) nano-fluid can be blended with aphanizomenon flos (AF) biodiesel (20%)-diesel (80%) blend in order to reduce the CO emission. TiO_2 nano particles provide the supplementary oxygen molecules which enhance the combustion and reduces the CO and HC emission. Moreover addition of TiO_2 nano-fluid exceeds 10%. CO emission tends to increase. Response diagram of S/N ratio for HC emission is portrayed in Fig.3. 10% of Titanium dioxide (TiO_2) nano-fluid can be blended with aphanizomenon flos (AF) biodiesel (20%)-diesel (80%) blend in order to reduce the HC emission.

It can be noted from the response diagram for NO emission (Fig.4), that the optimum level of parameters were loaded (0%), and fuel (5 TiO_2). As load on the engine increases NO emission tends to increase. 5% of titanium dioxide (TiO_2) nano-fluid was found to be optimal value in reducing the NO emission of the engine. It can be seen from the response diagram for smoke emission (Fig.5), that the

Table 5: Measured values and S/N ratios for exhaust emission

Exp no	A-load	B-fuel	Measured values				Signal to noise ratio			
			CO (% Vol.)	HC (ppm Vol.)	NO (ppm vol.)	Smoke (% vol)	CO	HC	NO	Smoke
1	0%	AFD blend 5 TiO_2	0.0180	13.03	95	14.2	34.89455	-22.2989	-39.5545	-23.0458
2	0%	AFD blend 10 TiO_2	0.0170	12.82	102	12.2	35.39102	-22.1578	-40.172	-21.7272
3	0%	AFD blend 15 TiO_2	0.0177	13.14	115	9.4	35.04053	-22.3719	-41.214	-19.4626
4	50%	AFD blend 5 TiO_2	0.0130	9.81	205	22.5	37.72113	-19.8334	-46.2351	-27.0437
5	50%	AFD blend 10 TiO_2	0.0120	9.31	215	21.3	38.41638	-19.379	-46.6488	-26.5676
6	50%	AFD blend 15 TiO_2	0.0125	9.73	235	19.9	38.0618	-19.7623	-47.4214	-25.9771
7	100%	AFD blend 5 TiO_2	0.0129	4.09	320	40.6	37.78821	-12.2345	-50.103	-32.1705
8	100%	AFD blend 10 TiO_2	0.0124	4.41	340	39.2	38.13157	-12.8888	-50.6296	-31.8657
9	100%	AFD blend 15 TiO_2	0.0126	4.72	375	38.3	37.99259	-13.4788	-51.4806	-31.664

Table 6: Response table for signal to noise ratios - smaller is better (CO emission)

Level	A-load	B-fuel
1	35.11	36.80
2	38.07	37.31
3	37.97	37.03
Delta	2.96	0.51
Rank	1	2

Table 7: Response table for signal to noise ratios - smaller is better (HC emission)

Level	A-load	B-fuel
1	-22.28	-18.12
2	-19.66	-18.14
3	-12.87	-18.54
Delta	9.41	0.42
Rank	1	2

Table 8: Response table for signal to noise ratios - smaller is better (NO emission)

Level	A-load	B-fuel
1	-40.31	-45.30
2	-46.77	-46.71
3	-50.74	-46.71
Delta	10.42	1.41
Rank	1	2

Table 9: Response table for signal to noise ratios - smaller is better (smoke emission)

Level	A-load	B-fuel
1	-21.41	-27.42
2	-26.53	-26.72
3	-31.90	-25.70
Delta	10.49	1.72
Rank	1	2

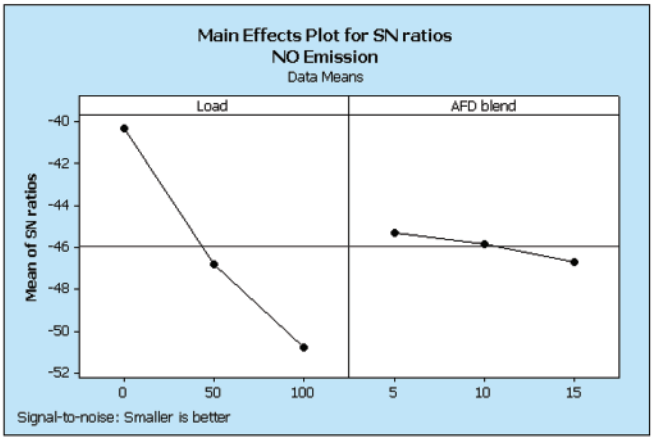

Fig.4 Response diagram of S/N ratio for NO emission

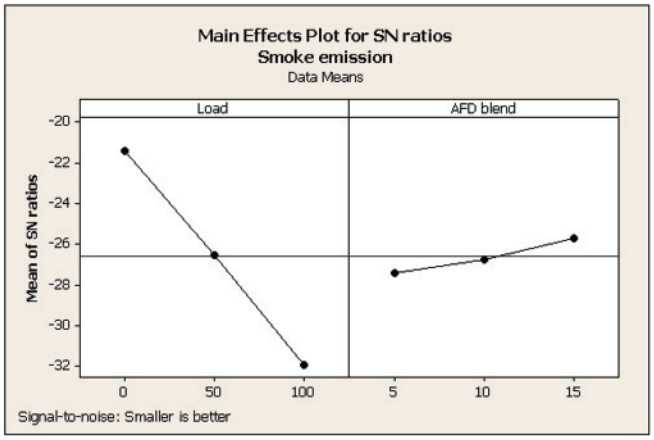

Fig.5 Response diagram of S/N ratio for smoke emission

optimum level of parameters were load (0 %), and fuel (15 TiO_2). As load on the engine increases smoke emission tends to increase. On the other hand 15% of titanium dioxide (TiO_2) nano-fluid was found to be optimal value in reducing the smoke emission of the engine.

2.3.3 Results of ANOVA

ANOVA was performed for determining the contribution of the factors in terms of percentage using the software package MINITAB. It was done for a level of significance of 5%. In the ANOVA table, P-value is given for each parameter. If the P-value is below 0.05, the parameter is to be considered as statistically important.

Table 10 demonstrates the outcomes of the ANOVA at the 95% confidence level. Since factors such as the engine load and fuel (TiO_2) have P-values lower than the 0.05, the two factors are considered as statistically highly important for CO emission of the engine. It was found from the Tables 11, 12 and 13 that the both engine load and fuel (TiO_2) are highly significant factors for HC, NO and smoke emission of the engine.

DoF- degrees of freedom; Seq. SS-sequential sums of squares; Adj.MS- Adjusted sums of squares, Pc-percentage of contribution

It can be noted from the ANOVA analysis (Table 10) that the engine load (97.65%) was the major contributing factor followed by fuel (1.953%) influencing the CO emission of the engine. The similar trend was observed for all the other emissions such HC emission (Table 11).

It can be noted from the ANOVA analysis (Table 12) that the engine load (98.50%) was the major contributing factor

Table 10: ANOVA analysis for CO emission

Factor	DoF	SS	F-value	P-value	Pc
A- Load	2	0.0000500	938	0.000	97.65
B- Fuel	2	0.0000010	19.63	0.009	1.953
Error	4	0.0000001			0.195
Total	8	0.0000512			100.00

Table 11: ANOVA analysis for HC emission

Factor	DoF	SS	F-value	P-value	Pc
A- Load	2	112.357	1081.39	0.000	99.64
B- Fuel	2	0.188	1.81	0.276	0.16
Error	4	0.208			0.184
Total	8	112.752			100

Table 12: ANOVA analysis for NOx emission

Factor	DoF	SS	F-value	P-value	Pc
A- Load	2	87198	525.64	0.000	97.51
B- Fuel	2	1891	11.40	0.022	2.11
Error	4	332			0.371
Total	8	89420			100.00

Table 13: ANOVA analysis for smoke emission

Factor	DoF	SS	F-value	P-value	Pc
A- Load	2	1167.90	1165.31	0.000	98.50
B- Fuel	2	15.70	15.66	0.013	1.324
Error	4	2.00			0.168
Total	8	1185.60			100.00

followed by fuel (1.324%) influencing the NO emission of the engine. The similar trend was observed for smoke emission of the engine (Table 13).

The percentage contribution of the fuel TiO_2 content seems to be very low compared to the engine load. It may be due to the fact that the wide range of load (0% to 100%) was selected compared to the range of fuel TiO_2 content (5TiO_2 to 15TiO_2). However both the engine load and fuel (TiO_2) are highly significant factors for CO, NO and smoke emission of the engine as they have P-values lower than the 0.05 according to the outcome of the ANOVA (Tables 10, 12-13).

Variation of CO emission with respect to engine load and AFD - TiO_2 blend is shown in Fig.6. Generally CO emission is formed due to the incomplete burning of fuel in the combustion chamber [12]. CO tends to drop for AF-D blend due to the existence of oxygen in the fuel. It was observed that the CO emission decreases linearly with increasing engine load as a result of the increase in combustion temperature associated with load. The higher combustion temperature enhances the thermal efficiency of the engine which reduces the CO emission. The drop in CO emission could be attributed to the addition of TiO_2 nano fluid. Moreover the incorporation of TiO_2 nano particles with AF-D blends considerably decreases the CO emission. Catalytic activity of TiO_2 enhances the combustion efficiency [13].

Variation of HC emission with respect to engine load and AFD - TiO_2 blend is shown in Fig.7. HC decreases with increase of engine load. This is due to high temperature combustion at high loads [14]. It may be due to the presence of oxygen in AF biodiesel. Moreover TiO_2 nano particles which provide the supplementary oxygen molecules enhance the combustion. HC emission of the engine fuelled with AFD-10TiO_2 blends was found to be lower compared to engine fuelled with AFD -15TiO_2[15].

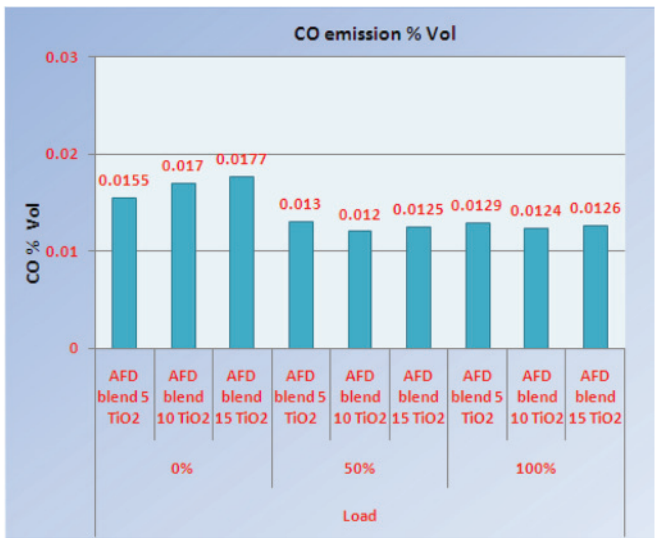

Fig.6: Variation of CO emission with respect to engine load and AFD - TiO_2 blend

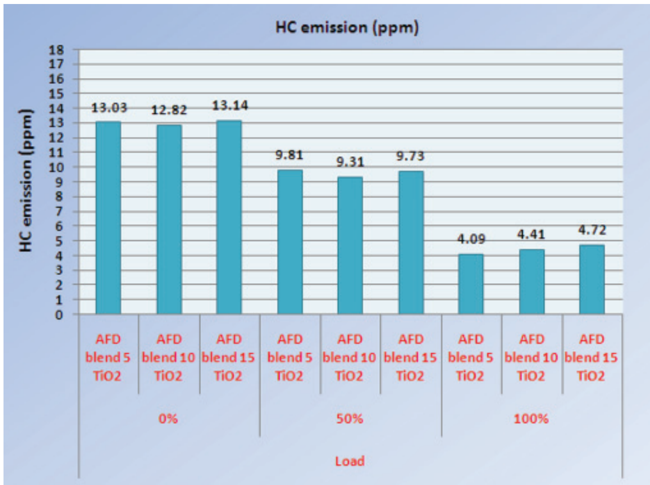

Fig.7: Variation of HC emission with respect to engine load and AFD - TiO_2 blend

The NO emission is found to have an increasing pattern throughout the load spectrum, and TiO_2 content in AFD - TiO_2 blend irrespective of fuels tested. As TiO_2 content increases in AFD - TiO_2 blend, NO emission of the engine increases proportionately owing to presence of oxygen in TiO_2. The increase in NO emission may be due to the rapid burning of fuel in the pre-mixed combustion phase, because of good atomization and dissolve oxygen in the fuel blend [16, 17, 18].

It was found that the smoke emission tends to increase with load. The smoke emission for AFD-TiO_2 blends decreases, throughout the test load. This may be caused by the formation of free radicals due to the action of TiO_2, and formation of short bonds between carbon and hydrogen molecules [19]. Another possible reason for low smoke is improved mixture formation and formation of multiple ignition centers inside the combustion chamber [20,21].

3.0 Multiple linear regression model

Correlation among the significant factors on the response was done using multiple linear regression equation. It can be seen in the Fig.6 that the value of regression coefficient, R^2 is very closer to the adjusted R^2 for exhaust emissions such as CO, HC, NO and smoke emission. Since both R^2 and adjusted R^2 coefficient values are close to unity, the obtained model equations ensures the existence of direct relationship between the factors and the output.

The regression equation developed for CO emission is

$$= 0.0173 - 0.000051\ A\text{- Load} - 0.000053\ B\text{- }TiO_2 \qquad (2)$$

The regression equation developed for HC emission is

$$= 13.1 - 0.0859\ A\text{- Load} + 0.0220\ B\text{- }TiO_2 \qquad (3)$$

The regression equation developed for NO emission is

$$= 66.9 + 2.41\ A\text{- Load} + 3.50B\text{- }TiO_2 \qquad (4)$$

The regression equation developed for smoke emission is

$$= 13.7 + 0.274\ A\text{- Load} - 0.323\ B\text{- }TiO_2 \qquad (5)$$

From the Eqns. (2-4), it is observed that the engine load plays a major role on exhaust emission followed by the fuel (B).

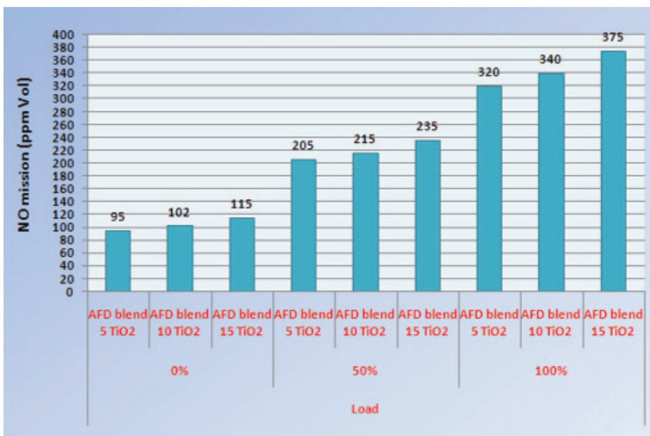

Fig.8: Variation of NO emissions with respect to engine load and AFD - TiO_2 blend

Fig.9 Variation of smoke emission with respect to engine load and AFD - TiO_2 blend

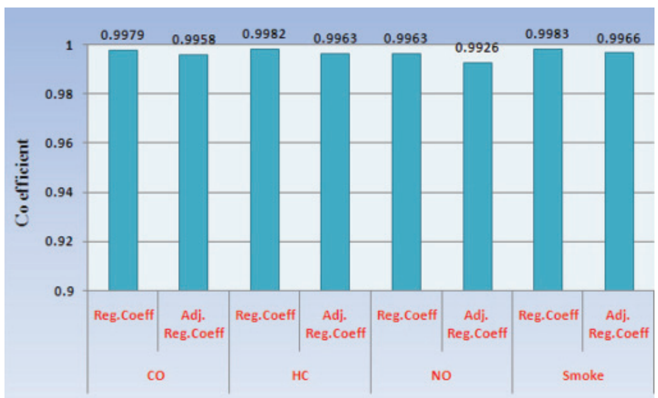

Fig.10: Comparison between regression coefficient and adjusted regression coefficient for exhaust emission

It can be observed from the Eq.2 that the coefficient associated with load and fuel is negative. It indicates that the CO emission decreases with increasing the engine load and fuel TiO_2 content. It can be observed from the Eq.4 that the coefficient associated with load and TiO_2 content is positive. It infers that the NO emission increases with increasing the engine load and TiO_2 content. On the other hand smoke emission increases with load while decreases with TiO_2 content in blend.

4.0 Conclusions

The incorporation of TiO_2 nano-particles up to 10% with aphanizomenon flos (AF) biodiesel (20%)-diesel (80%) blend reduces the CO and HC emission of the engine drastically. On the other hand the addition of TiO_2 nano-particles beyond 10%, CO and HC emission tend to increase.

It can be noted that the engine load (97.65%) was the major contributing factor followed by fuel (1.953%) influencing the CO emission of the engine. The similar trend was observed for all the other emissions. The percentage contribution of the fuel TiO_2 content was found to be very low compared to the engine load due to the load range (0% to 100%) and the range of fuel TiO_2 content ($5TiO_2$ to $15TiO_2$). However both the engine load and Fuel (TiO_2) are highly significant factors for CO, NO and smoke emission of the engine as they have P–values lower than the 0.05 according to the outcome of the ANOVA. NO emission increases with increasing the engine load and TiO_2 content. On the other hand smoke emission increases with load while decreases with TiO_2 content in blend.

Nomenclature

AF	Aphanizomenonflos
AF-D	Aphanizomenonflos-diesel
AFD-$5TiO_2$	Aphanizomenonflos-diesel blend with 5% of titanium dioxide
AFD-$10TiO_2$	Aphanizomenonflos-diesel blend with 10% of titanium dioxide
AFD-$15TiO_2$	Aphanizomenonflos-diesel blend with 15% of titanium dioxide
ASTM	American society for testing and materials
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
C	Carbon
CI	Compression ignition
CNG	Compressed natural gas
CO	Carbon monoxide
CR	Compression ratio
EGT	Exhaust gas temperature
H	Hydrogen
HC	Hydrocarbon
IEA	International energy agency
IP	Injection pressure
IT	Injection timing
LHV	Lower heating value
N	Nitrogen
NO	Nitrous oxide
O	Oxygen
S	Sulphur
TiO_2	Titanium dioxide
VCR	Variable compression ratio
DoF	Degrees of freedom
Seq.SS	Sequential sums of squares
Adj.MS	Adjusted sums of squares
Pc	Percentage of contribution
Eq	Equation

References

[1]. Praveen A., G. Lakshmi Narayana Rao and Balakrishna B., (2018): Performance and emission characteristics of a diesel engine using Calophyllum Inophyllum biodiesel blends with TiO_2 nanoadditives and EGR, *Egyptian Journal of Petroleum* Vol.27, Issue 4, December, P.731-738

[2]. Prabu (2018): nano-particles as additive in biodiesel on the working characteristics of a DI diesel engine, *Ain Shams Engineering Journal* 9, 2343–2349.

[3]. Prabu and Anand R.B. (2014): "Working Characteristics of a C.I. Engine Fuelled with Oxygenates as Additives in Jatropha Biodiesel", *Applied Mechanics and Materials*, Vol. 592-594, pp. 1842-1846.

[4]. TayfunÖzgür, Mustafa Özcanli and Kadir Aydin (2015): Investigation of nano-particle Additives to Biodiesel for Improvement of the Performance and Exhaust Emissions in a Compression Ignition Engine, International Journal of Green Energy, 12:1, 51-56.

[5]. Aalam Syed, Saravanan C. G., (2017): Effects of nano metal oxide blended Mahua biodiesel on CRDI diesel engine, *Ain Shams Engineering Journal*, Vol.8, Issue 4, December, P.689-696.

[6]. Sadhik Basha J., Anand R.B. (2014): Performance, emission and combustion characteristics of a diesel engine using Carbon Nanotubes blended Jatropha Methyl Ester Emulsions, *Alexandria Engineering Journal*, Vol.53, Issue 2, June, P.259-273

[7]. Kannan G.R., Karvembu R., Anand R. (2011): Effect of metal based additive on performance emission and combustion characteristics of diesel engine fuelled with biodiesel, *Applied Energy*, Vol.88, Issue 11, November, P.3694-3703.

[8]. Shaafi, K. Sairam, Gopinath A., Kumaresan G. and Velraj R. (2015): Effect of dispersion of various nanoadditives on the performance and emission characteristics of a CI engine fuelled with diesel, biodiesel and blends – A review, *Renewable and Sustainable Energy Reviews* Volume 49, September, Pages 563-573.

[9]. Dinesh, S., and K. Ö. K. Metin. (2018): "A review on different parameters affecting the vehicle emission gases of different fuel mode operations." *Research Journal of Science and Engineering Systems,* Vol.3, no.4: 146-164.

[10]. Ansari Naushad Ahamad, Sharma Abhishek, Singh Yashvir (2018): "Performance and emission analysis of a diesel engine implementing polanga biodiesel and optimization using Taguchi method", *Process Safety and Environmental Protection*,Vol.120, Pp.146-154.

[11]. Singh Yashvir, Sharma Abhishek, Tiwari Sumit and Singla

Amneesh (2019): Optimization of diesel engine performance and emission parameters employing cassia tora methyl esters-response surface methodology approach, Energy, Vol. 168, pp. 909-918.

[12]. Barik Debabrata, Kumar Asit, Murugan S. (2018): Effect of Compression Ratio on Combustion Performance and Emission Characteristic of a Direct Injection Diesel Engine Fueled with Upgraded Biogas–Karanja Methyl Ester–Diethyl Ether Port Injection *Energy and Fuels*, Vol (32) Issue 4 5081-5089

[13]. Raheman. H and Ghadge. S. V. (2008): Performance of diesel engine with biodiesel at varying compression ratio and ignition timing. Fuel, 87(12), 2659–2666.

[14]. Barik Debabrata, Murugan S. (2014): Investigation on combustion performance and emission characteristics of a DI (direct injection) diesel engine fueled with biogas–diesel in dual fuel mode Energy Vol.72, 1 August, Pages 760-771.

[15]. Hirkude, J., Belokar, V., and Randhir, J. (2018): Effect of Compression Ratio, Injection Pressure and Injection Timing on Performance and Smoke Emissions of CI engine Fuelled with Waste Fried Oil Methyl Esters - Diesel Blend. Materials Today: Proceedings, 5(1), 1563–1570.

[16]. Shanmughasundaram P. (2017): Experimental investigation on the emission characteristics of a variable compression ratio multi-fuel engine using palm biodiesel, *International Journal of Ambient Energy,* 38:6, 576-581.

[17]. Lapuerta M, Armas O, Fernàndez JR. (2008): Effect of biodiesel fuels on diesel engine emissions. *Prog Energy Combust Sci*; Vol.34 pp.198-223.

[18]. Shanmughasundaram P., (2019): Performance and Emission Characteristics of A Ci Engine Fuelled With Diethyl Ether Blended Pongamia Bio Fuel, *U.P.B. Sci.* Bull., Series D, Vol. 81, Iss.3

[19]. Balaji, S., Natesan Kapilan, and Saravanan R. (2016): "Influence of propyl gallate antioxidant on performance and emissions of a ci fuelled with neem oil biodiesel." *J Biofuels* 7, no.2 (2016): 62.

[20]. Gumus M, Sayin C, Canakci M. (2012): The impact of fuel injection pressure on the exhaust emissions of a direct injection diesel engine fueled with biodiesel diesel fuel blends. *Fuel*; 95:486–94

[21]. Kuti OA, Zhu J, Nishida K, Wang X, Huang Z. (2012): Characterization of spray and combustion processes of biodiesel fuel injected by diesel engine common rail system. *Fuel* 2012;11.

A STUDY OF SUBSIDENCE OVER A LONGWALL PANEL –PREDICTION AND CALIBRATION

(Continued from page 63)

(d) The horizontal strain values predicted around 2 mm/m - 4mm/m which are well within MOEF and CC permissible limits while extracting both panels.

Acknowledgement

The authors would like to thank the management of SCCL for allowing to visit the mine and collecting the data.

References

1. A. Nuric, et. al, (2012): "Numerical Modelling and Computer Simulation of Ground Movement Above Underground Mine", *International Journal of Geological and Environmental Engineering*, Vol:6, No:9, pp 579-587.
2. Brauner, G. (1973): "Subsidence due to underground mining. I. Theory and practices in predicting surface deformation," (in two parts), USDI Bur. of Mines. IC8571
3. Chrzanowski, A.S., and Forrester, D. J., (1998): "100 years of ground subsidence studies" proceedings (CDROM) of the 100th CIM Annual General Meeting Montreal, Canada, May.
4. Deb D. Finite element method: concepts and applications in geomechanics. PHI publications, New Delhi. 2006.
5. Handbook of Forest Conservation Act, 1980 and Forest Conservation Rules 2003, (Guidelines and clarifications), Ministry of Environment, Forest and Climate Change, Government of India, 2019, PP 55, 77
6. John Loui Porathur, B Veera Reddy, K Sridhar, Chadrani P Verma, S Chandra Sekhar, SVSS Ramalingeswarudu, (2016): "Subsidence Behaviour at Adriyala Longwall Project" workshop on Successful introduction of high capacity Longwall at Adriyala, Hyderabad, PP 142-151
7. Manohar Rao A, SVSS Ramalingswarudu, G Venkateswarulu, (2015): "Planning of ventilation requirements for deep mechanised long wall faces - A Case Study of Adriyala Longwall Project of The Singareni Collieries Company Limited (Sccl). *Procedia Earth And Planetary Science*; Vol.11: 548 – 55.
8. National Coal Board. "Subsidence Engineering Handbooks", London 1st edition. 1966
9. Peng, S.S. and Chiang, H., (1984): "Longwall Mining," John Wiley & Sons, Inc. New York.
10. Sheorey P R (2000): "Ground subsidence observations and a modified influence function method for complete subsidence prediction" *International Journal of Rock Mechanics and Mining Sciences*, Vol.37, 801-818
11. Sreenivasa Rao Islavath, Deb D and Hemant Kumar., (2016): Numerical analysis of a longwall mining cycle and development of a composite longwall index, Int J Rock Mech Min Sci, 89, 43-54.