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Optimization Evaluation of Various Type Nanoparticles - Diesel Blended Fuels on Diesel Engine Combustion Characteristics, Performances and Exhaust Emissions

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Abstract—**The objective of this paper is to determine the optimal concentration of three types of nanoparticles (aluminium oxides, carbon nanotubes and silicone oxide) blended in diesel fuel. The fuel blends test was done with YANMAR TF120M single cylinder direct injection four stroke compression ignition engine. The experimental results of the brake specific fuel consumption (BSFC), exhaust gas temperature (EGT), carbon monoxides (CO), carbon dioxides (CO_2), hydrocarbons (HC) and nitrogen oxides (NO_x) were the analyzed by using Box-Behnken's response surface methodology (RSM). The RSM was implemented with four variables such as concentration of nanoparticles and engine loads. The model evaluates using ANOVA and the model was used for optimization with the objective of reducing the fuel consumption, NO_x and HC emissions. From this approach, Al_2O_3 of 45.82 ppm give the highest desirability of 0.9778 at 50% engine load.**

Index Terms—**nanoparticles, diesel combustion, engine performance, exhaust emissions, RSM optimization**

I. INTRODUCTION

Current global situation shows high energy demand to support mass transportation, heavy industry, agriculture and marine activities. Diesel engine becomes the right solution due to its efficient power machinery for automotive application. Another advantage of diesel engine is its better fuel economy compared to gasoline engine owing to its high compression ratio operation mechanism. However, among the downfall of the diesel engine operates at high compression ratio is that, it produces high nitrogen oxides (NO_x) emission. NO_x formed from high compression and temperature combustion that encourage nitrogen in air to bond with oxygen (O_2) [1]. NO_x represent mono-nitrogen oxides (NO) and nitrogen dioxide (NO_2). NO_x is categorized as a toxic gas to human as it causes respiratory problem and may also causes cardiovascular disease. Beside NO_x, combustion exhaust from diesel engine also associated with particulate matter (PM) emission which also cause major health problem. PM is responsible for the visible black smoke produce operation of diesel power engine. PM is made up of microscopic solid or liquid aerosol [2]. In addition, the diesel engine exhaust emission also produce carbon monoxide (CO) which is harmful to human due to its capability to displaces oxygen in the blood when breathed and deprives the heart, brain and other vital organs of oxygen [3].

Recent trend on energy demand also increase the pressure to find suitable renewable alternatives fuel for diesel fuel. The trend lead to introduction of biodiesel fuel which is made of mono-alkyl-ester mixture derived through transesterification process of natural oils. The biodiesel fuel could changes the emission characteristic of diesel engine [4]. Furthermore, biodiesel fuel can be used in diesel engine without any modification needed. Several studies on biodiesel fuel showed reduction of PM, dry soot and carbon monoxide (CO) [5]. However, biodiesel fuel combustion also shows slight increase in NO_x [6].

Another development show that the emission control technologies for diesel engine application is improving day by day [7]. Over the last few years, wide variety of different technologies such as high pressure common-rail fuel injector, complex exhaust gas recirculation (EGR) system, particle traps, selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR) and oxidation catalysts have been introduced by many researchers [8, 9]. Consequently, the focus shifts toward fuel related studies such as emulsified fuel (water blend with diesel or biodiesel fuel) and short chain or long chain alcohol based additives such as ethanol, methanol, butanol and hexanol. However, most of these blending diesel or biodiesel fuel with water or alcohol additives causes alteration in physicochemical properties of the blended fuel such as latent heat, cetane number, kinematic viscosity, calorific value and density [10,11]. Researchers reported that alcohol blended fuel shows high latent heat with help in reduce of NO_x emission [12]. In addition, alcohol blended fuel also carries additional oxygen content which help in reduce the PM emission [13]. However, the drawback of alcohol blended fuel is due to its low calorific value fuel resulted in higher fuel consumption which defeats the main purpose of diesel

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being able to produce more work for the same mass of fuel. Generally, the alteration in blended fuel properties overall are in favor of one properties while adverse other, affecting the fuel storage, fuel delivery and most important of all is the fuel combustion ability.

Nanoparticle additive is an alternative approach to improve the compression ignition engine which does not require any engine or exhaust system modification. Nevertheless, to overcome the disadvantages of emulsified fuel or alcohol fuel, the nanoparticles blended fuel need to have similar or better physicochemical properties characteristics compare to the diesel fuel or biodiesel fuel [14]. Advancement of nanoscience and nanotechnology in recent year enables to produce nano size particle which could uphold better opportunity improving diesel fuel or biodiesel fuel shortcoming [15, 16].

This study will focus on three types of nanoparticles of aluminium oxide (Al_2O_3), carbon nanotubes (CNT) and silicon oxide (SiO_2). The two of the nanoparticles Al_2O_3 and CNT are commonly researched nanoparticles but SiO_2 is less researched by researchers [17,18]. To the best of the author’s knowledge, no report yet on the optimization analysis of these nanoparticles-diesels blended fuels. The effects of nanoparticles addition on combustion characteristics, performance parameters and exhaust emissions of a single-cylinder diesel engine were investigated comprehensively at different engine loads (0%, 25%, 50%, 75% and 100%) at 1500 rpm constant engine speed.

II. EXPERIMENTAL SETUP

In this study, the concentration of Al_2O_3, CNT and SiO_2 were considered as the input factors which potentially affect output responses such as brake specific fuel consumption (BSFC), exhaust gas temperature (EGT) and emission parameters such as CO, unburned hydrocarbons (HC), carbon dioxides (CO_2) and NO_x. Box-Behnken designs of experiments (DOEs) with three variables (concentration of nanoparticles) in three level and one box (engine load) is used to evaluate the responses of considered factors and to determine the optimum combination of variables. The experiment design matrix consists of 85 runs, is generated using Design Expert software which commonly used to by researchers to optimizing their study. The experiments are carried out as per fuel. The model was analyzed by using analysis of variance (ANOVA). Optimization is carried out by using Design Expert software using desirability approach of response surface methodology (RSM), where the solution with highest desirability is considered as the optimum one. The corresponding factor combination for the optimum solution is considered to be the best parameter for the blends.

The engine in use for the experiment is YANMAR TF120M four stroke single cylinder with direct injection. The engine fuel injection occurs at 17^o CA bTDC. The specification of the diesel engine was listed in Table I. Fig. 1 shows the schematic diagram of the engine test with necessary equipment that connects to the dynamometer. The engine is attached to Focus Applied Technologies’ BD-15KW dynamometer as shown in Fig. 2. The dynamometer is a generator-type “eddy current” dynamometer which its rotor is rotated by the engine crank. The test is conducted at 1500 rpm engine speed with engine load of 0%, 25%, 50%, 75% and 100%. The dynamometer load is controlled by the current supplied from the dynamometer controller Focus Applied Technologies’ DC5 into rotor which control the magnetic field of rotor. Exhaust emission is measured with QRO-402 gas analyzer. Intake, exhaust and tailpipe K-type thermocouple is connected as in Fig. 1 then is link to a PicoLog TC-08(USB) thermocouple data logger.

TABLE I. ENGINE SPECIFICATIONS

YANMAR TF 120M Specifications	
Type	4 strokes, single cylinder
Bore x stroke	92 x 96 mm
Displacement	638 cc
Continuous output	10.5 HP @ 2400 rpm
Rated output	15 HP @ 2400 rpm
Cooling system	Water - radiator

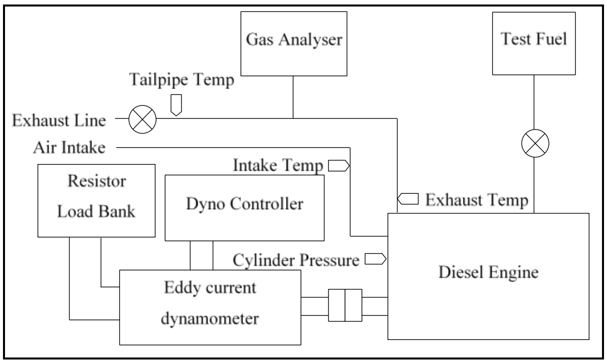

Figure 1. Experimental setup.

Figure 2. Engine and dynamometer assembly

TABLE II. INDEPENDENT VARIABLES USED FOR BOX-BEHNKEN

Variables	**Symbols**	**Levels**		
		-1	**0**	**1**
Al_2O_3 concentration	A	0	50	100
CNT concentration	B	0	50	100
SiO_2 concentration	C	0	50	100
Engine load	D	0	50	100

III. RESULTS AND DISCUSSION

A. Analysis of the Model

Analysis is based on analysis of variance (ANOVA) which provides the numerical information about p-value. P-value is defined as the alternative to rejection points to provide the smallest level of significance at which the null hypothesis would be rejected. The maximum value of p is considered to be 0.05 and the model terms for which p-value is more than 0.05 are insignificant. The models for various responses are found to be significant as the p-values are less than 0.05. The regression equations developed for different responses are shown below.

BSFC $=357.7995915 - 7.57A - 18.30B - 23.84C$
$+228.29D[20] + 113.94D[2] + 82.45D[3] - 117.87D[4]$

EGT $=255.09 + 3.39A + 2.33B + 8.61C$
$-111.99D[1] - 76.42D[2] - 20.70D[3] + 73.88D[4]$

1/(CO) $=40.00 + 8.58A + 0.31B + 2.85C$
$+ 4.00AB - 3.17AC - 0.79BC - 4.23A2$
$-1.44B2 - 2.77C2$
$+ 9.07D[1] + 7.30D[2] + 6.32D[3] - 10.34D[4]$
$+1.83AD[1] + 2.46AD[2] + 2.46AD[3] - 2.33AD[4]$

B. Evaluation of the Model-1

$-1.35BD[1] + 1.77BD[2] - 0.31BD[3] + 1.15BD[4]$
$-1.81CD[1] + 1.94CD[2] + 4.02CD[3] - 2.23CD[4]$

Ln(HC) $=2.63 - 0.67A - 0.26B - 0.67C$
$+ 0.59AB + 0.90AC + 0.44BC + 0.05A2$
$+0.12B2 + 0.69C2$
$+ 0.37D[1] + 0.20D[2] - 0.32D[3] - 0.36D[4]$
$+0.10AD[1] + 0.48AD[2] - 0.16AD[3] + 0.19AD[4]$
$0.01BD[1] - 0.38BD[2] + 0.28BD[3] + 0.25BD[4]$
$+0.08CD[1] + 0.12CD[2] + 0.43CD[3] - 0.27CD[4]$

CO_2 $=5.98 + 0.42A + 0.36B + 0.26C - 0.52AB$
$- 0.70AC - 0.62BC - 0.37A2 - 0.60B2 - 0.16C2$
$- 2.45D[1] - 2.04D[2] - 0.05D[3] + 2.07D[4]$
$+ 0.17AD[1] - 0.16AD[2] + 0.26AD[3] - 0.37AD[4]$
$-0.40BD[1] - 0.04BD[2] - 0.08BD[3] + 0.16BD[4]$
$-0.16CD[1] - 0.15CD[2] - 0.08CD[3] + 0.16CD[4]$

NO_x $=511.80 + 45.75A + 30.65B + 38.90C$
$-35.50AB - 106.00AC - 63.60BC - 34.25A2$
$-59.35B2 - 50.85C2$
$-214.00D[1] - 164.94D[2] + 26.41D[3] + 159.06D[4]$
$-1.62AD[1] - 25.00AD[2] + 23.88AD[3] - 12.50AD[4]$
$-30.78BD[1] - 10.15BD[2] - 1.28BD[3] + 22.10BD[4]$
$-31.90CD[1] - 18.65CD[2] - 8.40CD[3] + 24.35CD[4]$

where A: Al_2O_3, B: CNT, C: SiO_2 of concentration (ppm) and D[1]: 25% D[2]: 50% D[3]: 75% D[4]: 100% of engine load.

TABLE III. MODEL EVALUATION

Model	**BSFC**	**EGT**	**CO**	**HC**	**CO_2**	**NO_x**
	Linear	**Linear**	**Quadratic**	**Quadratic**	**Quadratic**	**Quadratic**
p-value	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001
Std. dev.	75.27	20.86	5.13	0.67	0.64	54.37
Mean	357.8	254.28	36.03	3.03	5.45	443.82
Transformation	Power	Power	Inverse	Natural log	None	None
R-Squared	0.8083	0.9580	0.8894	0.7822	0.9432	0.9460
Adj. R-Squared	0.7908	0.9532	0.8425	0.6900	0.9192	0.9231
Pred. R-Squared	0.7595	0.9393	0.7235	0.4531	0.8466	0.8540

The stability of the model is analyzed using ANOVA presented in Table III. From the table, the model is found to be stable with p-values less than 0.0001. Regression statistics such as the goodness of fit (R-Squared) and the goodness of predictions (adj. R-Squared) shown in the table are in good accordance with each other as the difference between them is less than 0.2. Here, R-Squared value indicates the total variability of the response after significant factors are considered and adj. R-Squared indicates a number of predictors in the model. From the values of R-Squared and adj. R-Squared it can be concluded that the model fits the data very well. Fig. 3 to 8 shows the graph between the predicted and actual values of each response. Each response shows good accordance between predicted and experimental data thereby validate the reliability of the modal developed for establishing a correlation between the nanoparticles concentration and the responses.

C. Evaluation of the Model-2

Table IV shows the criteria of optimization for the responses based on the objective stated above with their lower and upper limits, the weightages used and their importance. Weights range from 0.1 to 10. A weight greater than 1 gives more emphasis to the goal while a weight less than 1 gives less emphasis. The desirability value varies in a linear mode with weight equal to 1. All the parameters were given high and equal relative importance (r = 5) among each other.

Table V presents the top five solutions as per the set criteria of optimization (as described in Table IV) generated by the Design Expert software using desirability approach. Solutions with high desirability are close to the set criteria and are preferred. From this approach, Al_2O_3 of 45.82 ppm give the highest desirability of 0.9778 at 50% engine load.

TABLE IV. OPTIMIZATION CRITERIA OF EMISSION AND PERFORMANCE PARAMETERS

Model	**Target**	**Limit**		**Weight**		**Importance**
		Lower	**Upper**	**Lower**	**Upper**	
A: Al_2O_3	in range	0	100	1	1	5
B: CNT	in range	0	100	1	1	5
C: SiO_2	in range	0	100	1	1	5
D: LOAD	equal to 50	0	100	1	1	5
CO	none	0.02	0.08	1	1	5
HC	minimize	1.5	721.5	1	0.1	5
CO_2	none	1.5	9.2	1	1	5
NO_x	minimize	63	710	1	0.1	5
EGT	none	151.67	403.18	1	1	5
BSFC	minimize	208.44	882.09	1	0.1	5

TABLE V. SOLUTIONS OF FIVE HIGHEST DESIRABILITY BASED ON OPTIMIZATION CRITERIA

No.	**Al_2O_3 (ppm)**	**CNT (ppm)**	**SiO_2 (ppm)**	**LOAD (%)**	**CO (%)**	**HC (ppm)**	**CO_2 (%)**	**NO_x (ppm)**	**EGT (°C)**	**BSFC (g/kWh)**	**Desirebility**
1	45.82	0.00	0.00	50	0.03	51.9	3.93	286.6	240.6	317.2	0.9778
2	45.34	0.00	0.01	50	0.03	54.9	3.91	284.6	240.6	317.5	0.9778
3	47.09	0.00	0.02	50	0.03	44.8	3.98	292.2	240.5	316.3	0.9778
4	44.62	0.00	0.10	50	0.03	59.5	3.88	281.8	240.7	317.9	0.9778
5	45.95	0.00	0.86	50	0.03	47.8	3.95	290.7	240.6	316.5	0.9777

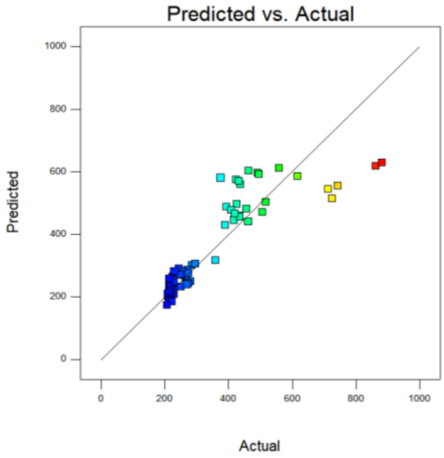

Figure 3. Predicted versus actual BSFC value

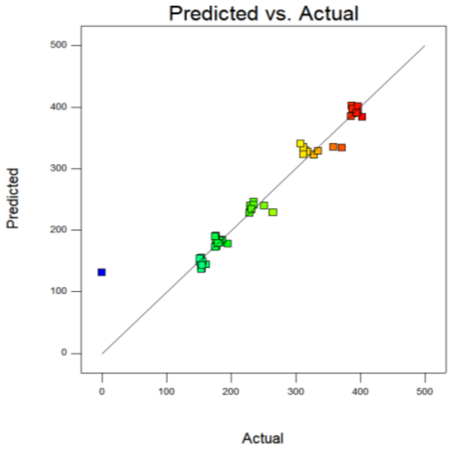

Figure 4. Predicted versus actual EGT value

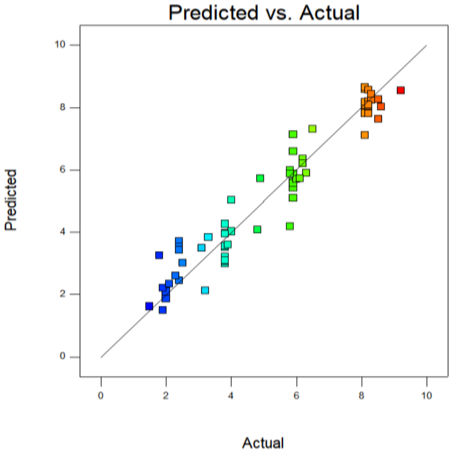

Figure 5. Predicted versus actual CO value

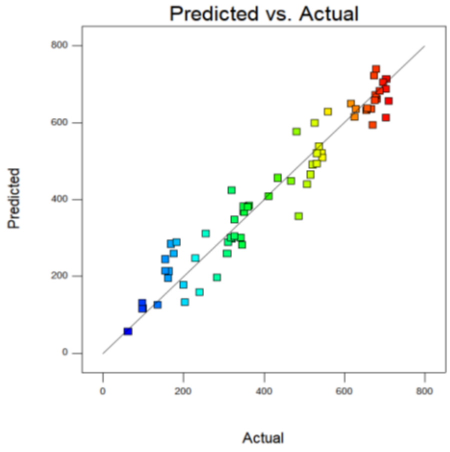

Figure 6. Predicted versus actual HC value

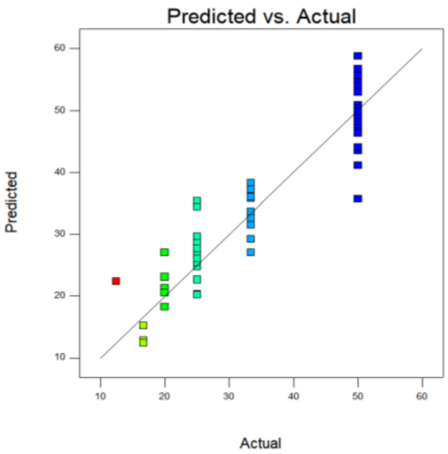

Figure 7. Predicted versus actual CO_2 value

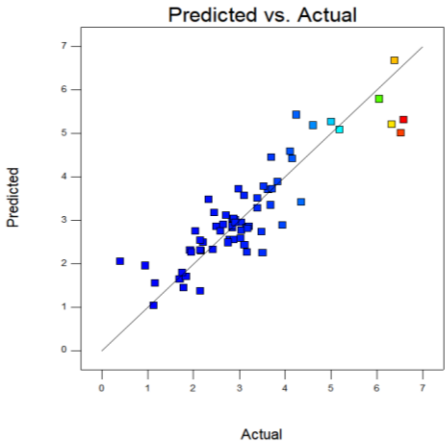

Figure 8. Predicted versus actual F value

IV. CONCLUSIONS

This present study was designed to determine the optimization evaluation of various type nanoparticles – diesel blended fuels on diesel engine combustion characteristics, performances and exhaust emissions. The results of the experiments are summarized as follows

i) The response model produce is found to be stable with p-values less than 0.0001.
ii) Regression statistics such as the goodness of fit (R-Squared) and the goodness of predictions (adj. R-Squared) are in good accordance with each other as the difference between them is less than 0.2.
iii) Optimization with the objective of reducing fuel consumption, NO_x and hydrocarbon emission resulted with nanoparticle blend of 45.82 ppm of Al_2O_3 give the highest desirability of 0.9778 at 50% engine load.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The manuscript was written through contributions of all authors in the experimental work, analyzed the data and manuscript preparation. All authors have given approval to the final version of the manuscript.

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