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Research article

Modeling of specific fuel consumption and emission parameters of compression ignition engine using nanofluid combustion experimental data

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ABSTRACT

This paper investigated the use of mathematical models in predicting the brake specific fuel consumption, and exhaust emissions of a diesel engine in terms of parameters such as load and volume fractions of Fe_3O_4 magnetic nanoparticles. Regression analysis was performed using the experimental data. The experiments were carried out by dispersing the Fe_3O_4 nanoparticles in the diesel fuel with the nanoparticle concentrations of 0.4 and 0.8 vol.%. Moreover, the experiments were performed under variable load conditions, for which a direct-injection diesel engine was employed. The predicted values obtained by the regression equations were compared with the values obtained from the experimental measurements. Analysis of variance (ANOVA) of the results at 95% confidence level showed significance in the developed mathematical models. Furthermore, the regression fitted models were able to predict the brake specific fuel consumption and emission characteristics with a correlation coefficient (R^2) in the range of 94%–98% within the domain of experimental variables. In addition, the nanofluid fuel with the nanoparticle concentration of 0.4 vol.% had an optimal value. The results also revealed a dramatic decrease in NO_x and SO_2 emissions, while a significant increase was observed in the CO emission and smoke opacity by adding magnetic nanoparticles in diesel fuel.

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1. Introduction

Nowadays, design and improvement of diesel engines, fuel modification, exhaust gas treatment and alternative fuels are gaining much attention for better fuel economy, better performance and good toxic emissions control. Among these methods, the fuel modification is widely accepted by many researchers. The aim of the fuel modification is to improve the fuel consumption and emissions without requiring modifications to the engine, fuel injection or exhaust systems. The use of metal based additives for fuels was studied by majority of the researchers [1–11]. Hansen et al. [12] studied the combustion of ethanol-diesel fuel blend for engine performance, durability and emissions. They declared that ethanol-diesel blends were technically acceptable for diesel engines. Gürü et al. [13] reported a decline in the freezing point and the exhaust emission of the fuel by adding manganese to the diesel fuel. Metal based additives have many attractive features, however, they tend to easily sediment which is considered a restriction to the extensive application of these materials. The latest advances in nanoscience and nanotechnology have attempted to minimize such limitations by suspending nanometer-sized particles in fluids. There are a number of advantages in using nanoparticles as additives for fuels including less settling velocity of particles, low ignition delay time, as well as mechanical, thermophysical, optical, magnetic, and electrical properties. Tyagi et al. [14] reviewed the role of the Al and Al_2O_3 nanoparticle additives for the diesel fuel. The results obtained in their study indicated that the ignition possibility for the diesel nanoparticle mixture was higher than that of the pure diesel. Sadhik Basha and Anand worked at different dosing levels of alumina nano-additives 25, 50 and 100 ppm [15,16] and also they investigated CNT in the mass fractions of 25 and 50 ppm [17,18]. They found a significant improvement in the combustion efficiency with the reduction in the hazardous emissions. Fangsuwannarak and Triratanasirichai [19] investigated the combustion behavior of TiO_2 nanoparticles dispersed into palm biodiesel. They concluded that the most effective performance was obtained when the nano TiO_2 additive (0.1 by volume) was used. Moreover, the results indicated that the addition of the TiO_2 nanoparticle improved properties of the fuel such as increased cetane number, lower heating value, increased flash point and reduced kinematic viscosity. The use of cerium oxide nanoparticle with sizes of 10–20 nm at different dosing levels (20, 40, 60 and 80 ppm) to biodiesel [20] and with the size of 32 nm and dosing level of 25 ppm in neat diesel and diesel-biodiesel-ethanol blends [21] were reported. The performance and emission patterns of a four-stroke diesel engine were investigated by using the composition of ferrofluid and diesel fuel. The used ferrofluid contained the Fe_3O_4

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magnetic nanoparticles with the particle size of 10 nm and volume concentrations of 0, 0.4% and 0.8%. The results of this investigation showed that the combustion efficiency as well as the CO emissions were enhanced by adding nanoparticles to the fuel however, it decreased the NO_x emissions [22]. Kao et al. [23] investigated the performance of aqueous aluminum nanofluid in a diesel single-cylinder engine. The results showed that nanoparticles significantly increased the total combustion heat. Moreover, a significant reduction was also observed in the fuel consumption and emission concentration of NO_x and smoke. To present a comprehensive analysis on the performance characteristics of the engine, experimental studies must be conducted to determine the influence of input parameters on both the performance and exhaust emissions. In this regard, experimental measurements enhance money and time expenditure therefore, the application of simulations based on limited experimental data is very useful to predict performance characteristics of the engine in a wide range of conditions. Bamgboye and Hansen [24] used the linear regression analysis to create a regression relationship between the cetane number (CN) and fatty acid methyl ester (FAME) composition. In another study, a regression analysis was used to investigate the effect of biodiesel fuel on the brake power [25,26]. The response surface methodology was used successfully by Mumtaz et al. [27] to optimize biodiesel production using chemical and enzymatic transesterification of rice bran and sunflower oils. Mathematical modeling of performance and emission parameters of dual fuel diesel engine [28] and transesterification of *Jatropha curcas* seed oil was reported [29]. According to the literature, there is a few research on the application of the multi regression analysis in modeling the performance and emission parameters of the diesel engine with nanofluid fuels. Therefore, the aims of this research are: (1) regression modeling of performance and emission parameters in relation to volume fraction of nanoparticles and load. (2) Determining significant effect and contribution of each parameter of the model in the brake specific fuel consumption and exhaust emissions.

2. Materials and methods

2.1. Ferrofluid preparation

In the present study, two types of ferrofluid blends are prepared and their performances are then compared with the neat diesel. The ferrofluid presented by the Institute for Colorants, Paint and Coating which is composed of Fe_3O_4 nanoparticles with a mean diameter of 10 nm in diesel fuel base fluid in the original particle volume fraction of 5%, was used in this study. The synthesis approach of the aforesaid ferrofluid and its rheological properties have been found by Ghasemi et al. [30]. The viscosity and density of the nanofluid fuels were calculated based on an expression proposed by Aberoumand et al. [31–32]. Table 1 shows the properties of the employed fuels. In this study the treatments were: diesel fuel and nanofluid fuels (Fe_3O_4 magnetic nanoparticle in diesel fuel with concentration of 0.4 and 0.8% by volume, depicted as 0.4 vol.%NF and 0.8 vol.%NF).

2.2. Experimental measurements

The volume fractions of 0.4% and 0.8% of nanoparticles are prepared by mixing an original ferrofluid with the diesel fuel in a mechanical homogenizer. A single cylinder, naturally aspirated, four stroke, water-cooled, direct-injection diesel engine was employed for the experiment. The detailed specifications of this engine are given in Table 2. The engine was coupled to an electrical generator to apply the load. The fuel specific consumption and the exhaust emissions were measured at various engine loads at a constant engine speed of 2200 rpm. The engine was operated at four load levels as 0.8 kW, 1.6 kW, 3.2 kW and 4.2 kW load. The fuel consumption is measured using a burette and a stop watch. The brake specific fuel consumption was calculated by using the Eq. (1) and Eq. (2).

Table 1
Properties of the tested fuels.

Fuels	Viscosity ($mm^2\ s^{-1}$ at 40 °C)	Density (g/cm^3 at 15 °C)
Diesel	2.52	0.820
0.4 vol.%NF	2.90	0.835
0.8 vol.%NF	2.91	0. 851

Table 2
The specification of the engine.

Type of engine	ZS1125, single-cylinder, naturally aspirated, direct injection
Cycle	Four-stroke
Compression ratio	17.6:1
Cylinder bore	125 mm
Stroke	120 mm
Swept volume	1.473 L
Injection pressure	20 ± 0.49 MPa
Rated output	9 hp/2200 rpm
Cooling	Water cooled
Loading system	Electrical generator

$$M_f = Q_f \cdot p_f \tag{1}$$

$$SFC = M_f / p \tag{2}$$

where M_f is mass flow rate of fuel consumption (kg/h), Q_f is rate of fuel consumption (L/h), p_f is fuel density (kg/L), p is power (kW), and SFC is brake specific fuel consumption (kg/kW·h).

A K-type thermocouple is mounted on the exhaust pipe to measure the exhaust gas temperature. The exhaust emissions and smoke opacity were determined using a Testo 350 XL analyzer and a MDO2-LON smoke meter, respectively. A schematic of diesel engine test setup is shown in Fig. 1.

2.3. Multiple linear regressions

The regression models were used to predict the brake specific fuel consumption or emissions of ferofluied fuels given in Eqs. (3) to (6):

$$\text{Quadratic}: \quad y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \varepsilon \tag{3}$$

$$\text{Reduce Quadratic}: \quad y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \varepsilon \tag{4}$$

$$\text{Two Factor Interaction (2FI)}: \quad y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \varepsilon \tag{5}$$

$$\text{Linear}: \quad y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon \tag{6}$$

where y is the brake specific fuel consumption or emissions of ferofluied fuels, x_1 is the nanoparticle concentration in vol.%, x_2 is the load, β_0 is the

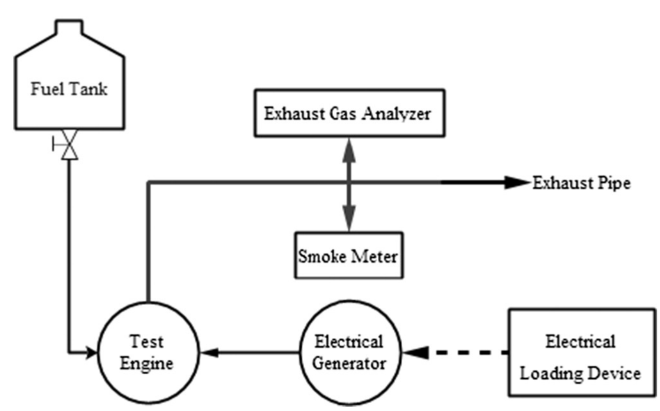

Fig. 1. Schematic layout of experimental set-up.

Table 3
Analysis of variance table for the regression model.

Source of variation	Degree of freedom	Sum of squares	Mean square	F statistic
Regression	$p-1$	$SS_R=\sum_{i=1}^{n}(\hat{y}_i-\overline{y})^2$	$MS_R=\frac{SS_R}{p-1}$	$F=\frac{MS_R}{MS_E}$
Residual	$n-p$	$SS_E=\sum_{i=1}^{n}(y_i-\hat{y}_i)^2$	$MS_E=\frac{SS_E}{n-p}$	
Total	$n-1$	$SS_T=\sum_{i=1}^{n}(y_i-\overline{y})^2$	–	

n: number of replicates; *p*: number of parameters in the model; *y*: the experimental value of response; *y*: the values predicted by the model.

constant coefficient of the model, and β_i, β_{ii} and β_{ij} are the linear, quadratic, and interaction coefficients of the regression model, respectively. Analysis of variance (ANOVA) for the multiple linear regression model is presented in Table 3. The total variance of the response model is divided into main elements including the sum of squares regression (SS_R) and the sum of squares residuals (SS_E). F-test was used to examine the significance of the regression model. Furthermore, the significance of coefficients of the fitted model was investigated using t-statistic.

2.4. Model performance evaluation criteria

The R^2, R^2_{adj}, CV, PRESS, RMSE and MAPE are used in this paper to evaluate the performance of the proposed regression models.

$$R^2=\frac{SS_R}{SS_T} \tag{7}$$

$$R^2_{adj}=1-\frac{n-1}{n-p}\times\frac{SS_E}{SS_T} \tag{8}$$

$$\text{PRESS}=\sum_{i=1}^{n}(y_i-\hat{y}_i)^2 \tag{9}$$

$$\text{CV}=\frac{\sqrt{\text{MSE}}}{\overline{y}}\times 100 \tag{10}$$

$$\text{RMSE}=\sqrt{\frac{\text{PRESS}}{n}} \tag{11}$$

$$\text{MAPE}=\frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_i-\hat{y}_i}{y_i}\right|\times 100 \tag{12}$$

In addition to the mentioned criteria for evaluating the performance regression models, the linear regression equation between the predicted values obtained from the regression model and the experimental value was calculated. All statistical analyses, graphs and calculations were performed using the MINITAB statistical program (Version 17).

3. Results and discussion

At first, each of the models 3 to 6 is evaluated based on the model performance evaluation criteria. Then, the significance of coefficients of the best fitted model was evaluated. Finally, the changes in each of the dependent parameters including the brake specific fuel consumption (BSFC), carbon monoxide (CO), nitrogen oxide (NOx), sulfur dioxide (SO_2) and smoke opacity were investigated using the extracted regression models.

3.1. Selection regression model of the BSFC and emissions

The experimental data was used to examine the adequacy regression models 3 to 6 to see whether the prediction performance of the models would give satisfactory results. The results of evaluation performance of the regression models are exhibited in Table 4. Based on the results in Table 4, the quadratic regression model was the most appropriate model for the BSFC, CO, NOx and SO_2. Moreover, the 2FI regression model was the best model for the smoke opacity. The selected models have the highest adjusted R^2 and also lowest coefficient variation (CV) as well as predicted error sum of squares (PRESS) among all the possible models.

3.2. ANOVA analysis

The ANOVA analysis was used for an accurate assessment of adequacy of the selected models. Table 5 shows the ANOVA analysis results of the proposed models for the brake specific fuel consumption and emissions. P-value was used to examine the impact of each of the sources of variations. The obtained P value had a significant impact if it was less than or equal to the threshold (0.01 or 0.05). The P-values for all developed models were <0.01, which indicates that the models are significant at 99% confidence level. Therefore, the regression models could be successfully used in prediction of BSFC and emissions. Furthermore, the coefficients of the regression model were evaluated by their corresponding p-values and the percentage contributions of the terms of the regression model were computed by dividing the sum of square of the terms by the total sum of square (Table 3). The ultimate models for prediction of BSFC and emissions could include terms that are significant or marginally significant at the 5% significance level or their percentage contributions are >5%. Based on the percentage contributions of the model variables, the linear terms had the highest level of contribution on the BSFC and emissions compared with the other terms. In addition, the percentage contributions of the quadratic terms were greater than the interaction terms. However, the interaction term in the carbon monoxide (CO) and the smoke opacity were only significant. Moreover, the percentage contribution of the model error to total variation was <6% in all cases.

Table 4
The values of performance criteria for each of the regression models.

Model		CV (%)	R^2	R^2_{adj}	PRESS		CV (%)	R^2	R^2_{adj}	PRESS
Linear	BSFC	15.93	73.49	67.60	0.015	CO	43.79	68.60	61.62	402,390
2FI		16.69	74.16	64.47	0.024		39.02	77.83	69.52	340,869
Quadratic		***6.80***	***96.78***	***94.09***	***0.003***		***23.49***	***93.97***	***89.00***	***197,988***
Red. quadratic		6.92	96.11	93.89	0.003		34.61	84.74	76.02	342,573
Linear	NOx	31.48	78.46	73.67	20,368	SO_2	13.60	88.31	85.71	599.85
2FI		31.57	80.74	73.52	21,232		14.02	88.95	84.80	736.77
Quadratic		***17.59***	***95.51***	***91.77***	***12,386***		***7.57***	***97.58***	***95.56***	***239.46***
Red. quadratic		20	93.27	89.36	10,686		7.89	96.94	95.19	244.89
Linear	Smoke opacity	42.69	84.81	81.44	8.59					
2FI		***24.26***	***95.64***	***94.0***	***2.45***					
Quadratic		26.66	96.05	92.76	4.17					
Red. quadratic		47.75	85.22	76.78	13.08					

Bold data indicates the best models.

Table 5
ANOVA of the regression models and percentage contributions of each source variations.

Source	DF	BSFC			CO			NOx		
		SS	P-value	PC (%)	SS	P-value	PC (%)	SS	P-value	PC (%)
Model	5	0.0318	0.000^{**}	96.78	633,442	0.001^{**}	93.97	51,566	0.001^{**}	95.51
x_1	1	0.0181	0.000^{**}	55.17	405,324	0.019^{*}	60.13	8068	0.006^{**}	14.94
x_2	1	0.0060	0.001^{**}	18.33	57,071	0.027^{*}	8.47	34,289	0.000^{*}	63.51
x_1x_2	1	0.0002	0.309^{ns}	0.66	62,252	0.023^{*}	9.24	1233	0.131^{ns}	2.28
x_1^2	1	0.0050	0.002^{**}	15.46	107,910	0.007^{**}	16.01	2368	0.052^{ns}	4.39
x_2^2	1	0.0023	0.011^{*}	7.16	885	0.730^{ns}	0.13	5607	0.010^{*}	10.39
Residual	6	0.0010		3.22	40,621		6.03	2424		4.49
Total	11	0.0328		100	674,062		100	53,989		100

Source	DF	SO_2			Source	DF	Smoke opacity		
		SS	P-value	PC (%)			SS	P-value	PC (%)
Model	5	2775.79	0.000^{**}	97.58	Model	3	26.337	0.000^{**}	95.64
x_1	1	2169.91	0.000^{**}	76.28	x_1	1	17.862	0.000^{**}	64.86
x_2	1	342.04	0.002^{**}	12.02	x_2	1	5.495	0.000^{**}	19.95
x_1x_2	1	18.24	0.254^{ns}	0.64	x_1x_2	1	2.981	0.002^{**}	10.83
x_1^2	1	213.43	0.005^{**}	7.50	Residual	8	1.088		4.36
x_2^2	1	32.18	0.145^{ns}	1.13	Total	11	27.538		100
Residual	6	68.82		2.42					
Total	11	2844.62		100					

**,* are significant at the 1% and 5% level, respectively.

The comparison of the predicted and experimental values is presented in Fig. 2. The results revealed that there was very good agreement between both data series (for all cases: $R^2 > 94\%$). The slope of the linear relationship between two data series was >0.94. Moreover, the intercept of the line was acceptable for all cases. By considering all the results obtained from Tables 4 & 5 as well as Fig. 2, the regression models can be satisfactorily used in predicting the response variables (BSFC and emissions).

3.3. Analysis of engine performance and emission characteristics

As discussed in the previous section, the validity of the regression models was confirmed. Therefore, the models can be used in the analysis of engine performance and emission characteristics.

3.3.1. Analysis of brake specific fuel consumption

The final form of the regression model for the brake specific fuel consumption was given in Eq. (13):

$$BSFC = 0.143 - 0.0430x_1 - 0.0234x_2 + 0.035x_1^2 + 0.0216x_2^2 \quad (13)$$

The impact of the interaction of the load and the nanoparticle percentage was not significant at the 95% confidence (Table 5). Moreover, the percentage contribution of it was equal to 0.66%. Therefore, the interaction term (x_1x_2) was removed from the model. Fig. 3(a) shows the estimated response surface for the brake specific fuel consumption in relation to the load and nanoparticle ratio. Generally, it is seen that the variations of BSFC with concentration of Fe_3O_4 nanoparticles from

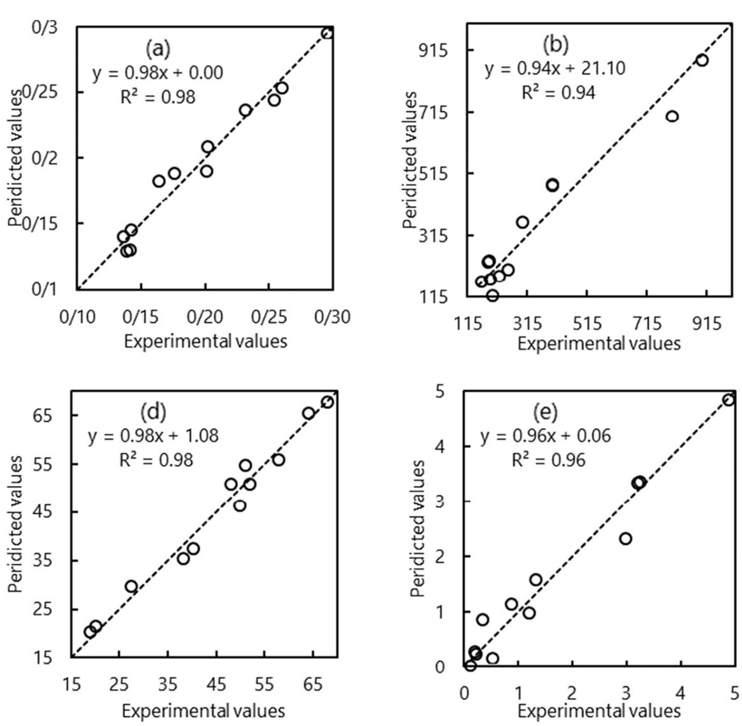

Fig. 2. Comparison of predicted and experimental (a) BSFC, (b) CO, (c) NOx, (d) SO_2 and (e) smoke opacity.

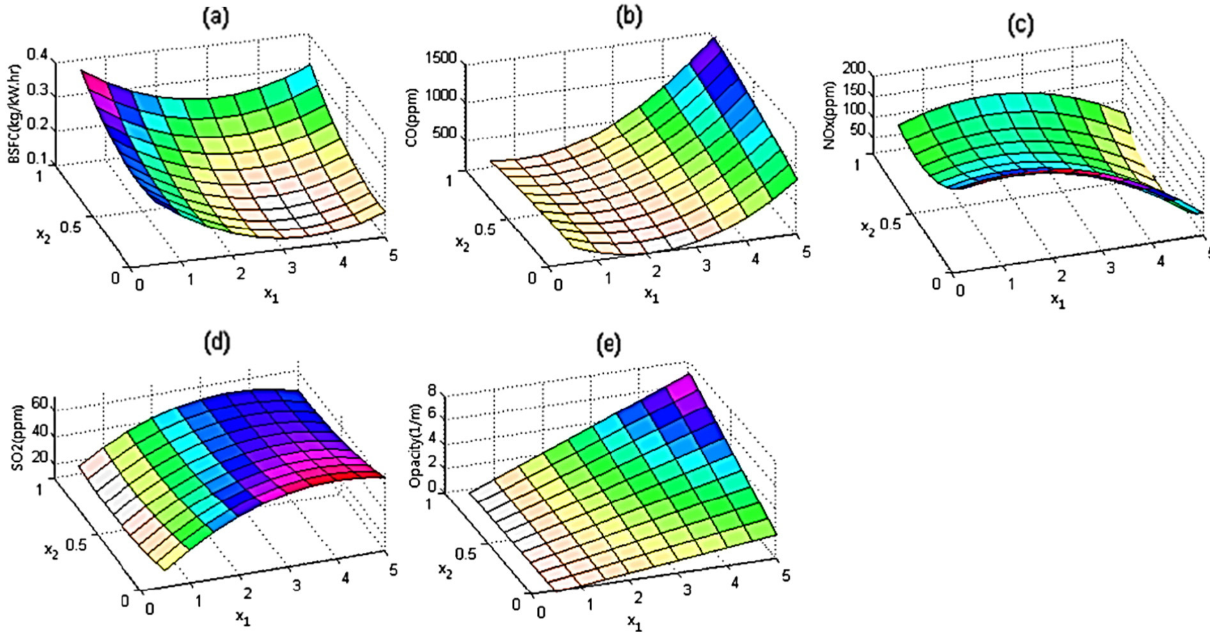

Fig. 3. Relationship of brake specific fuel consumption (a), CO emission (b), NOx emission (c), SO_2 emission (d) and opacity emission (e) with respect to load (x_1) and nanoparticle concentration (x_2).

0 to 0.4 vol.% and in range of the load from 2.5 to 4 kW are not remarkably. Moreover, the trend of variation of BSFC as a function of the concentration of Fe_3O_4 in the fuel was incremental. Also, based on the experimental results, it is observed that the 0.8 vol.%NF fuel shows a considerable BSFC value increasing of about 30% in comparison with other cases (see to Table 8). Therefore, the increase of viscosity and density of the fuel with the addition of Fe_3O_4 nanoparticles resulted in increase of fuel consumption [20,33]. The reason is that through the injection process, a fuel with higher viscosity value forms larger droplet, which can cause poor combustion characteristics and brake specific fuel consumption augmentation [22]. Furthermore, the slight reduction of the specific fuel consumption for lower concentrations of 0.4 is due to the high surface area and reactive surfaces of nanoparticles present in the fuel which increases the combustion efficiency. This result is in agreement with similar investigations by Saraee et al. [33] on silver nanoparticles. Their results showed that the fuel consumption decreases about 2% when the concentration of silver nanoparticles in diesel fuel was 10 and 20 ppm. Fangsuwannarak and Triratanasirichai [19] reported that the 0.1% nano-TiO_2 additive in biodiesel blended fuel could reduce the brake specific fuel consumption.

3.3.2. Analysis of CO

The results of the regression analysis (Table 4) show that the CO emission is expressed by Eq. (14).

$$CO = 213.4 + 180.8x_1 + 72.0x_2 + 78.6x_1x_2 + 162.4x_1^2 \quad (14)$$

Fig. 3(b) shows the variation of the CO emissions as a function of the load and nanoparticle percentage. It is observed that at high load condition and by further increasing the nanoparticle percentage, the CO emissions were increased due to the poor mixing of fuel and air, locally rich zone and incomplete combustion of fuel. Furthermore, the variation in CO emission is very small at low engine loads. According to the experimental results, the CO emission increase about 25% and 50% in the cases of 0.4 vol.%NF and 0.8 vol.%NF fuels, respectively (for details, please refer Table 8). Also, the experimental results indicated that the nanofluid fuel had no significant influence on the CO emission at low engine load. Moreover, it was observed that he higher viscosity and density of nanofluid fuel resulted in the poor mixing of fuel and air at the higher engine loads. As a result of this phenomenon, the augmentation of CO formation is formed. This result is in accordance with similar studies about nanoparticles in fuel composition [20,34].

3.3.3. Analysis of NOx

The final regression model for predicting NO_x emissions as a function of nanoparticle concentration and engine load was given in Eq. (15):

$$NOx = 105.7 - 25.43x_1 - 55.83x_2 - 24.068x_1^2 + 33.35x_2^2 \quad (15)$$

The equation is able to predict the NO_x emissions with a correlation coefficient of 0.96. Fig. 3(c) shows the variation of NO_X emissions with loads for various nanofluids. A significant reduction in the NOx emission was observed when diesel was blended with magnetic nanoparticle additives. This may be due to the fact that magnetic nanoparticles possess

Table 6
The results of k-fold cross validation.

Phase	Criteria	BSFC	CO	NOx	SO_2	Smoke opacity
Calibration	RMSE	0.008 ± 0.001	48.76 ± 10.85	12.44 ± 2.61	2.15 ± 0.22	0.262 ± 0.061
	MAPE	4.079 ± 0.741	15.22 ± 3.02	10.16 ± 2.09	4.66 ± 0.67	36.53 ± 9.508
	R^{2*}	0.972 ± 0.009	0.951 ± 0.022	0.965 ± 0.010	0.979 ± 0.006	0.963 ± 0.022
Validation	RMSE	0.0184 ± 0.005	138.81 ± 67.01	30.78 ± 14.75	4.90 ± 1.41	0.581 ± 0.272
	MAPE	9.746 ± 3.891	38.78 ± 20.11	32.82 ± 24.85	11.68 ± 5.25	81.19 ± 72.59
	R^2	0.999 ± 0.0001	0.934 ± 0.0341	0.999 ± 0.001	0.999 ± 0.0001	0.999 ± 0.0001
Total	RMSE	0.011 ± 0.001	75.51 ± 18.08	17.82 ± 3.24	2.85 ± 0.37	0.356 ± 0.041
	MAPE	5.024 ± 0.531	19.15 ± 3.69	13.94 ± 3.82	5.83 ± 0.80	43.97 ± 12.89
	R^2	0.957 ± 0.008	0.913 ± 0.027	0.940 ± 0.013	0.967 ± 0.008	0.948 ± 0.012

R^{2*} is the determination coefficient between the actual and predicted values.

high surface areas increasing their chemical reactivity which in turn reduces the ignition delay. Furthermore, the reduction of NOx could be caused by the absorbed oxygen using the iron oxide nanoparticles. As seen from experimental results, the NOx emission for 0.4 vol.%NF and 0.8 vol.%NF fuels were reduced by about 56% and 67%, respectively (for details, please refer Table 8). These results are in agreement with some findings in the literature [17,18,20,23,34–36].

3.3.4. Analysis of SO_2

Statistical analysis shows that the SO_2 emission is varied based on the quadratic model with respect to the load and nanoparticle percentage.

$$SO_2 = 49 + 14.54x_1 - 5.58x_2 + 11.06x_1x_2 - 7.22x_1^2 \quad (16)$$

The response surface for the SO_2 emission produced by variation of load and nanoparticle percentage is shown in Fig. 3(d). As can be seen from this figure, the SO_2 emission is reduced by means of adding iron oxide nanoparticles to the diesel fuel. Due to the significant influence of the nanoparticle percentage, the SO_2 emission is decreased for all levels of the load. Based on experimental observations, the SO_2 emission decreased by 14% and 20% for 0.4 vol.%NF and 0.8 vol.%NF fuels as compared to diesel fuel, respectively (for details, please refer Table 8).

3.3.5. Analysis of smoke opacity

The results of the regression analyses performed for the smoke opacity revealed that the two factor interaction (2FI) model was chosen as the best model form (Eq. (17)).

$$\text{Opacity} = 1.59 + 1.262x_1 + 0.707x_2 + 0.544x_1x_2 \quad (17)$$

Fig. 3(e) shows the estimated response surface of smoke opacity in relation to the nanoparticle and load. The figure shows that the smoke opacity increases with the increase of the engine load as expected. The higher smoke opacity of nanofluid fuels is caused by the high viscosity and poor atomization of the fuel blends. Moreover, the existence of black colored nanoparticles allows absorbing more amount of light and increases the smoke opacity.

3.4. Model generalization

Finally, k-fold cross validation was used to evaluate the model's generalization ability. The data were divided randomly in two sets, a calibration for finding the best coefficients of the regression model and a validation set for the evaluation. Five-fold cross-validation was 10 times. The average and standard deviation of RMSE, MAPE and R^2 values were computed (Table 6). The results showed that the performance of the models in the validation phase, with respect to the RMSE and MAPE, was much lower to the results from the calibration phase. However, the value of the determination coefficient between the actual and predicted values was indicated that the results of the validation phase were satisfactory. Therefore, the capability of generalization of regression model can be confirmed. Nevertheless, more experimental data are needed in order to achieve the higher generalization levels.

3.5. Comparison of blends with diesel fuel

Two-way analysis of variance (ANOVA) design and Tukey's honestly significant difference (HSD) test were used to compare the effect of blends on BSFC, NO_x, SO_2, CO and smoke opacity for different loads. The treatments were: diesel fuel and nanofluid fuels (0.4 vol.%NF and 0.8 vol.%NF). In two-way design, four different loads were considered as blocks (replications). Therefore, the treatments were arranged in randomized complete block design (RCBD) with four replications. Table 7 shows the results of ANOVA. The ANOVA table shows the degree of freedom (DF), mean of squares (MS) and significance of treatments (blends) and blocks (load). The null hypothesis is that the three blends have the same performance and the alternative hypothesis is that at least two blends have different performance. As seen in Table 7, the effect of treatments (fuels) on BSFC and exhaust emissions, except CO, is significant at the 0.01 and 0.05 level of significance. Also, the effect of loads (blocks) was significant.

Table 7
Two-way ANOVA results obtained.

Source of variation	DF	BSFC	NOx	SO_2	CO	Smoke opacity
Treat (fuels)	2	0.0084^{**}	$39{,}803^{**}$	374.22^{**}	57956^{ns}	5.562^{*}
Block (loads)	3	0.0241^{**}	$10{,}702^{*}$	2447.24^{**}	$520{,}794^{**}$	18.43^{**}
Error	6	0.0003	3296	23.16	95,312	3.53
Total	11	0.0328	53,801	2844.62	674,062	27.53

**,* are significant at the 1% and 5% level, respectively.

The results of ANOVA showed that the effect of fuel was significant. Therefore, the Tukey's HSD test was used to determine which of the three types of fuel differed significantly from which others. The results of HSD test are given in Table 8. According this result, we concluded that the BSFC values of neat diesel fuel and 0.4 vol.%NF fuel were not significant, while the BSFC approximately increased by 30% when 0.8 vol.%NF fuel was used. Also, we concluded that the nanofluid fuels are able to decrease exhaust emission (NOx and SO_2) except CO and smoke opacity. From statistical point of view, only the effect of fuels on CO emission was not significant. Moreover, smoke opacity was significantly increased with the increasing concentration adding magnetic nanoparticles in diesel fuel.

4. Conclusions

In fuel modification, it is important to know the percentage of additives to achieve better engine performance and emission characteristics. The statistical regression could be an important modeling method to study the effect of the components of fuel on engine performance and emission characteristics. In this work, by applying the regression analysis using the experimental data, the regression models for prediction of the brake specific fuel consumption, nitrogen oxide, carbon monoxide, sulfur dioxide and smoke opacity have been developed regarding the load and the nanoparticle ratio. The comparison of actual values with those predicted by the regression models revealed that a significant correlation between the various response variables (for all cases R^2 is >0.94). In addition, the results showed that the developed models can be used to predict the BSFC, CO, NOx, SO_2 and opacity for nanofluid fuels at different loads within the experimental domain. The results also indicated that the use of very low concentrations has a considerable influence on the diesel engine characteristics so that the specific fuel consumption is rising with increasing the volume fraction of nanoparticles. Moreover, there is a considerable reduction in the major exhaust emission components such as NOx and SO_2 with adding the Fe_3O_4 magnetic nanoparticles in diesel fuel while the CO emission and the smoke opacity are significantly increased. In this direction, it is evident that the selection of the proper concentration of nanoparticles should be considered.

Table 8
Tukey's HSD pairwise mean performance criteria comparison.

Treatments	BSFC (kW·h)	NOx (ppm)	SO_2 (ppm)	CO (ppm)	Smoke opacity (L/m)
Diesel fuel	0.1776^{a*}	195.00^{a}	52.38^{a}	259.65^{a}	0.715^{a}
0.4 vol.%NF	0.1753^{a}	83.75^{b}	42.37^{b}	362.32^{a}	1.702^{ab}
0.8 vol.%NF	0.2325^{b}	64.25^{b}	39.31^{b}	428.57^{a}	2.372^{b}

* Means with different letters are significantly different from each other (P < 0.05).

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