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[Research]

Modeling the effects of biodiesel-diesel fuel blends on CO_2 emission of a diesel engine by response surface methodology

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ABSTRACT

Nowadays biodiesel is receiving more attention as a most important renewable energy for using in diesel engines. Inthis research, the application of Response Surface Methodology (RSM) was highlighted to investigate the effects of biodiesel-diesel blends (B0, B20, B50 and B100), engine operating parameters (engine load and speed) on CO_2 emission of a diesel engine. The experiments were conducted on a four cylinder direct-injection diesel engine based on three-factor five-level central composite rotatable design. The developed mathematical models were helpful to predict the response parameters and further to identify the significant interactions between the input factors and the responses. The use of biodiesel resulted in higher emission of CO_2. The results also showed that an increase in engine speed leads to an increase in the emission of CO_2.On the other hand,CO_2 emission is higher at low engine loads,while is lower at high engine loads.

Key words: Biodiesel, CO_2 Emission, RSM , Diesel Engine.

INTRODUCTION

Biomass sources mostly biofuels for diesel engines are becoming increasingly important due to the growing energy needs as a consequence of spiraling demand and diminishing supply and also the environmental consequences of exhaust gases from petroleum fuelled engines(Shirneshan *et al.* 2014; Shirneshan *et al.* 2016). Besides, the requests for energy have grown very quickly due to the rapid development of certain growing economies, especially in Asia and the Middle East(Shirneshan *et al.* 2016). Indeed, the petroleum crisis exploded in the late 1970s and early 1980s, hence, its products became very scarce and expensive. These issues have triggered various research studies to replace the petroleum - based diesel fuel with the vegetable oils or their derivations (Canakci *et al.* 2009a). Biofuels such as alcohols and biodiesel have been proposed as alternatives for diesel engines (Agarwal *et al.* 2006; Demirbas 2007; Ribeiro *et al.* 2007). Biodiesel can be produced from various vegetable oils, waste cooking oils and animal fats. The fuel properties of biodiesel may be changed when different feedstocks are used. As compared to the properties of petroleum diesel fuels, biodiesel has a higher viscosity, density, pour point, flash point and cetane number, near-zero aromatic compound, and no sulfur link (Canakci *et al.* 2009b, Shirneshan *et al.* 2014). In particular, biodiesel has received wide attention as a replacement for diesel fuel because it is biodegradable, nontoxic and can significantly reduce toxic emissions and overall life cycle emission of CO_2

from the engine when burned as a fuel. Biodiesel can form blends with petroleum diesel fuel at any ratio and thus have thepotential to partially, or even totally, replace diesel fuel in diesel engines(Shirneshan *et al.* 2014).

Biodiesel fuel has many effects on diesel engine emissions. There has been a lot of research on emission characteristics of diesel engines with biodiesel/diesel blends (Shirneshan *et al.* 2012; Canakci *et al.* 2009a). The contribution rate of traffic on CO_2 emission is as high as 23%, some authors studied CO_2 emission of biodiesel. In the literatures (Ozsezen *et al.* 2009; Utlu & Koçak, 2008; Lin & Lin 2007; Sahoo *et al.* 2007), it was reported that, biodiesel resulted in fewer CO_2 emission than diesel after complete combustion due to the lower carbon to hydrogen ratio. The literature (Lin &Lin 2007) compared the CO_2 emission between three kinds of biodiesels (from vegetable oils, animal fats and used cooking oils) and ASTM No. 2D diesel using CO_2 emission index, which is defined as the CO_2 emission (%) divided by the corresponding fuel consumption rate (in unit of $g.h^{-1}$). Three kinds of biodiesels had lower CO_2 emission indices than ASTM No. 2D diesel. This is attributed to the fact that biodiesel is a low - carbon fuel and has a lower elemental - carbon – to - hydrogen ratio than diesel fuel. But it was reported in some studies (Ulusoy *et al.* 2009; Ramadhas *et al.* 2005; Fontaras *et al.* 2009; Canakci 2005; Labeckas & Slavinskas 2006) that CO_2 emission rise or keep similar (Song & Zhang 2008; Usta 2005),which is due to more efficient combustion. It was of course pointed out in the literatures(Labeckas & Slavinskas 2006; Sahoo *et al.* 2007) that in the case of biodiesel, the higher carbon dioxide emission should cause less concern because of nature recovery by raising biodiesel crops. The literatures (Carraretto *et al.* 2004; Lapuerta *et al.* 2008) evaluated the effect of biodiesel on global greenhouse gas emissions through the life cycle of CO_2 emission and pointed out that biodiesel will cause 50–80% reduction in CO_2 emission compared to petroleum diesel. The objective of this study is to investigate the effects of various biodiesel-diesel blends (B0, B20, B50 and B100) and engine operating parameters on changes in emission characteristics of a diesel engine. Response Surface Methodology (RSM) is employed to develop mathematical relationships between independent variables and CO_2 exhaust emission as the response. In addition, using response surface plots, the interaction effects of process parameters on the responses are also analyzed and discussed.

MATERIALS AND METHODS

Biodiesel preparation and fuel properties

Since biodiesel from frying cooking oil is a more economical source of the fuel(Di *et al.* 2009), in the present study, biodiesel was produced from this feedstock. The source of frying cooking oil included sunflower oil and soybean oil. In the present research, biodiesel was produced by a transesterification process which was catalyzed by KOH (as Alkali catalyst) and methanol (as alcohol) in Biofuels Laboratories atTarbiat Modares University, Tehran, Iran. Then, the fuel was analyzed according to ASTM D6751 standard. The important properties of frying vegetable cooking oil and No. 2 diesel are shown in Table 1.

Test engine experimental setup and procedure

The engine tests were carried out on a 4-cylinder, four-stroke, turbocharged, water cooled and DI diesel engine (OM 314). The major specifications of the engine under the test are shown in Table 2. The diesel engine was fuelled with blends of frying vegetable cooking oil and No. 2 diesel fuel (B0, B20, B50and B100). The fuel blends were used at the different engine speeds and engine loads. In each speed test run, the maximum engine torque was reached for each fuel. The engine speed was measured by a digital tachometer with a resolution of 1 rpm. The engine was coupled to a hydraulic dynamometer to provide brake load and an AVL gas analyzer model Di Com 4000 (made by AVL Company, Austria) was used to measure CO_2 emission. The engine was allowed to run for a few times until the exhaust gas temperature, the cooling water temperature, the lubricating oil temperature, as well as the CO_2 gas concentration attained the steady-state values and then the data were recorded.

Experimental design and statistical analysis

The standard RSM design using Central Composite Design (CCD) was employed to examine the relationship between the response variables and set of quantitative experimental factors. The advantage of using Design of Experiments is that it provides an opportunity to study not only the individual effect of each parameter with reducing the time but also their interactions with the minimum number of experiments for achieving the optimum conditions. Hence, RSM adopts both the mathematical andstatistical techniques to describe the influence of interactions of parameters on the response when they are varied simultaneously(Montgomery 2008). The independent variables were percentage of biodiesel in fuel mixture (x_1), engine speed (x_2) and engine load (x_3). Each independent variable had coded levels of -1, 0 and 1.The experimental designs of the coded (x) and actual (X) levels of variables are shown in Table 3. The response (Y) was CO_2 exhaust emission. The response function (Y) were related to the coded variables (xi, i = 1, 2, 3) by following second-order polynomial equation (Montgomery 2008).

The coefficients of the polynomial were represented by b_0 (constant term); b_1, $b_2$and b_3 (linear effects); b_{11}, $b_{22}$and b_{33} (quadratic effects); and b_{12}, $b_{13}$and b_{23} (interactioneffects):

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3$$

Table 1.Properties of diesel and biodiesel fuels used for present investigation.

Property	Method	Units	Biodiesel	Diesel
Flash point	ASTM-D92	°C	176	61
Pour point	ASTM-D97	°C	-4	0
Cloud point	ASTM-D2500	°C	-1	2
Kinematical viscosity, 40°C	ASTM-D445	$mm^2.s^{-1}$	4.15	4.03
Copper strip corrosion	ASTM-D130	--------	1a	1a
Lower heating value	---------	$MJ.kg^{-1}$	37.7	42.9
Cetane number	ASTM-D613	--------	55.1	50.33
Total sulfur	ASTM-D5453	wt. %	0.0018	0.0500

Table 2. Specifications of the test engine.

Engine type	Diesel OM314
Cylinder number	4
Stroke(mm)	128
Bore(mm)	97
Compression ratio	16:1
Power (hp/rpm)	110/2800
Torque (Nm/rpm)	340/1800
Cooling system	Water cooled

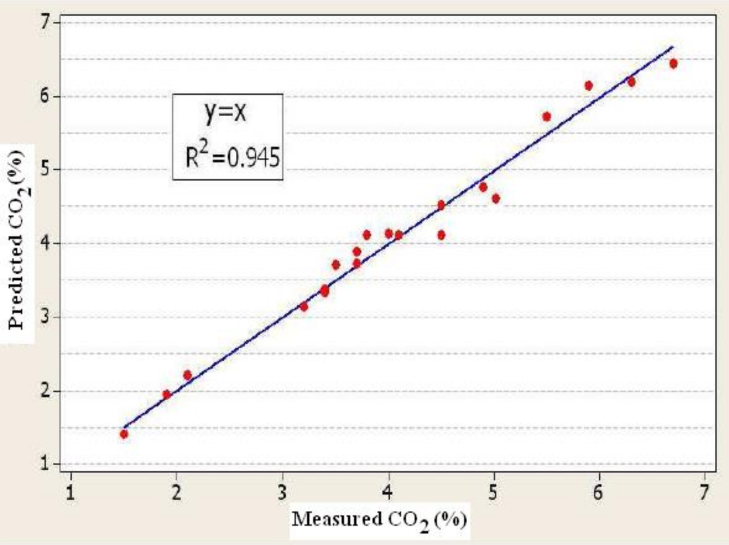

Fig. 1. The experimental and predicted data for CO_2 emission.

Minitab software version 15.0 (Montgomery 2008) was used to develop the mathematical model and to evaluate the subsequent regression analyses and analyses of variance (ANOVA). Fig. 1shows the experimental and predicted data for CO_2 emission.The developed mathematical models were effectively used to predict the range of parameters used in the study.

Based on these models, the main and interaction effects of the process parameters on the exhaust emissions characteristics were computed and plotted in contour and surface plots as shown in Figs.2 -5.

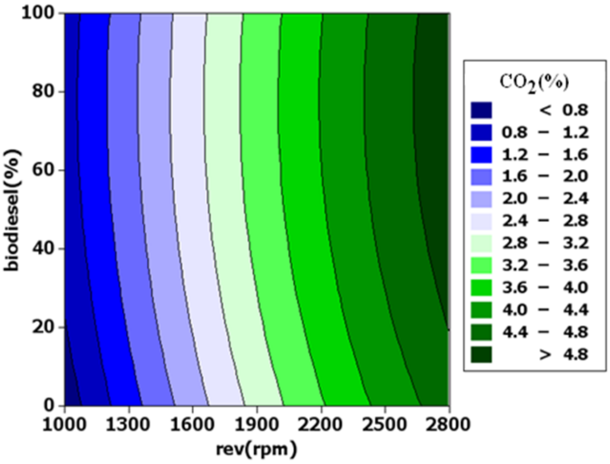

Fig. 2(a). Contour plot of Effect of biodiesel percentage and engine speed on CO_2 emission at 25% load.

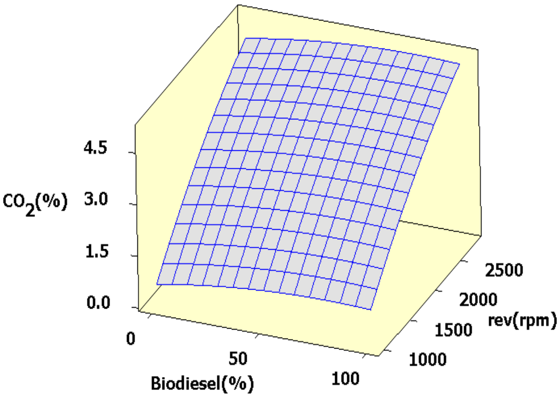

Fig. 2(b). Surface plot of Effect of biodiesel percentage and engine speed on CO_2 emission at 25% load.

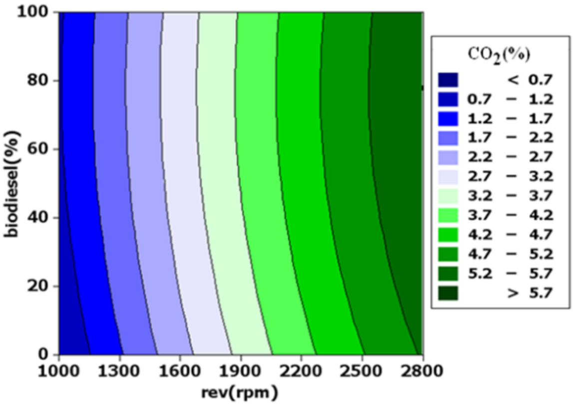

Fig. 3(a). Contour plot of Effect of biodiesel percentage and engine speed on CO_2 emission at 50% load.

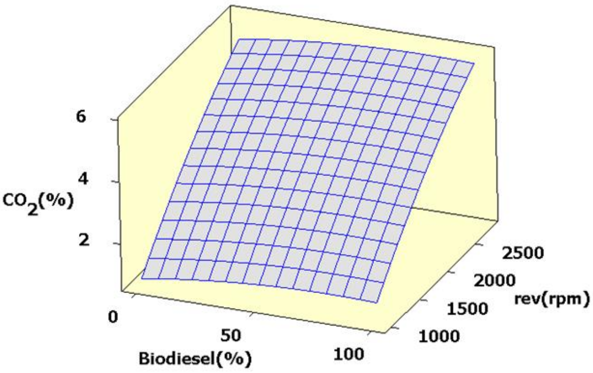

Fig. 3(b). Surface plot of Effect of biodiesel percentage and engine speed on CO_2 emission at 50% load.

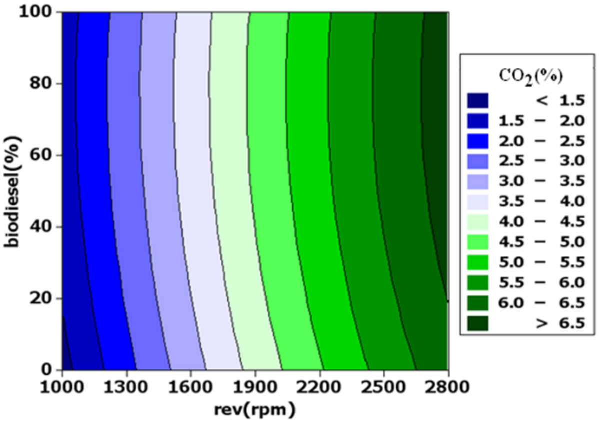

Fig. 4(a). Contour plot of Effect of biodiesel percentage and engine speed on CO_2 emission at 75% load.

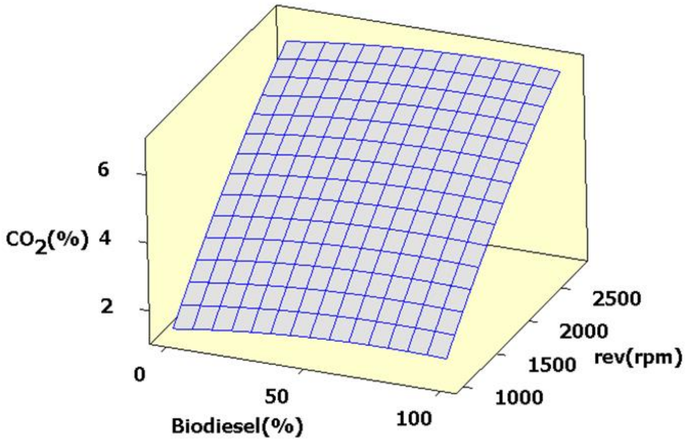

Fig. 4(b). Surface plot of Effect of biodiesel percentage and engine speed on CO_2 emission at 75% load.

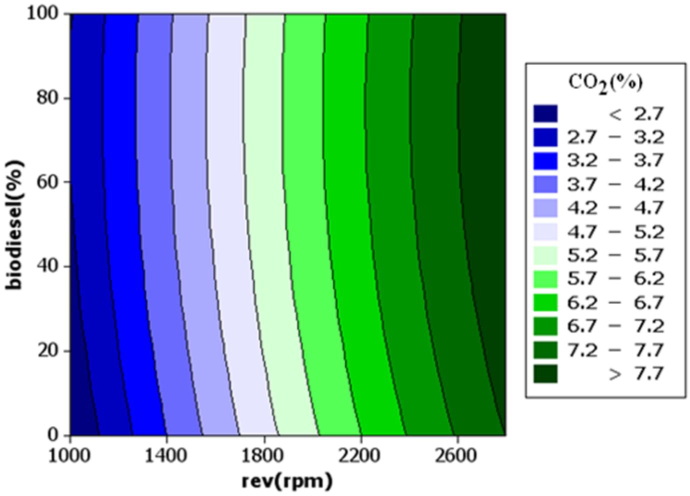

Fig. 5(a). Contour plot of effect of biodiesel percentage and engine speed on CO_2 emission at full load.

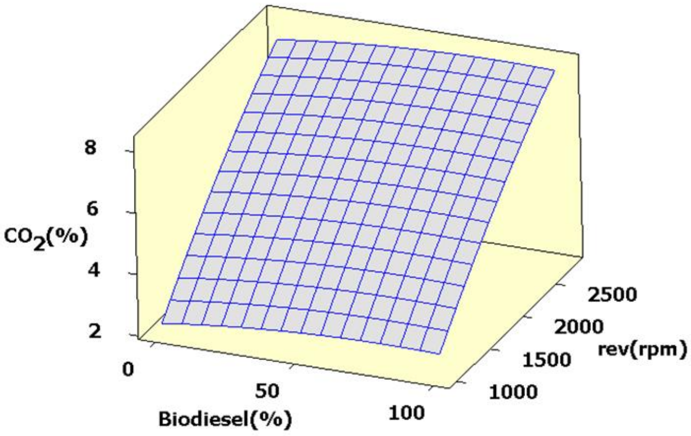

Fig. 5(b). Surface plot of effect of biodiesel percentage and engine speed on CO_2 emission at full load.

RESULTS AND DISCUSSION

Statistical analysis

The experiments were performed according to design matrix (Table 3) and the experimental data for the response (CO_2 exhaust emission of the diesel engine) are shown in Table 4.Table 5 summarizes the results of the dependent variable with its coefficient of determination (R^2).

The statistical analysis indicates that the proposed model was adequate, possessing no significant lack of fit and with very satisfactory values of the R^2 for the response. The R^2 value for CO_2 emission model was 0.945 with standard error 0.41. The closer the value of R^2 to unity, the better the empirical models fits the actual data. On the other hand, the smaller the value of R^2, the less relevance the dependent variables in the model have in explaining the behavior of variations (Little & Hills 1978). The probability (p) values of the regression model were significant at 0.001, with no lack-of fit. The mathematical model was also inspected for its validity by comparing the experimental data and the predicted data given by the models. It can be seen in Table 4 and Fig. 2.The predicted data proved that the model provided an accurate description of the experimental data, indicating the connection between the variable and output data. This data can be also observed using visual inspection by plotting the experimental data versus the predicted data corresponding to the respective responses in the DOE software. The results demonstrated that there are tendencies in the linear regression fit, and the model explains the experimental range studied adequately. The fitted regression equation showed good fit of the models and was successful in capturing the correlation between the three preparation variables.

The results of the analysis in Table 5 showed an overall curvilinear effect on CO_2 emission. As shown in Table 5, CO_2 emission were linearly related to the percentage of biodiesel in fuel mixture ($p < 0.05$), engine load and engine speed ($p < 0.001$). Also the analysis showed the negative quadratic effects of percentage of biodiesel in fuel mixture and engine speed ($p < 0.05$) and the positive quadratic effects of engine load ($p < 0.05$). The interaction effect between percentage of biodiesel in fuel mixture and engine speed ($p < 0.05$), and the interaction effect between engine speed and engine load ($p < 0.05$) were significant. Other factors that contribute to the CO_2 emission included the interaction effect of percentage of biodiesel in fuel mixture and engine speed and effect of percentage of biodiesel in fuel mixture and engine load were found to be not significant.

The relation between power with biodiesel percentage (x_1), engine speed (x_2) and load (x_3) is mentioned in the following Eq. .

$$CO_2(\%) = -2.39 + (0.0117)x_1 + (0.0036)x_2 + (-0.025)x_3 + (-7.51\times10^{-5})x_1^2$$

$$+(-4.17\times10^{-7})x_2^2 + (0.00029)x_3^2 + (1.047\times10^{-5})x_2x_3$$

Figs.2 - 5show the interactions between the engine speed and responses in contour plot and surface form. The graphical form plots were obtained by holding the value of engine load at 25%, 50%, 75% and 100% constant level in each related mathematical model. The X and Y-axis values of these figures are the real values.

CO_2 emission

The predicted amounts of CO_2 emission for different fuel blends and engine speeds are also shown in Figs. 3 - 6. According to the figures, the maximum amount of CO_2 emission (8.2%) occurs in the rage of 2700 to 2800 rpm of engine speed at full engine load and for fuel mixture included more that 40% biodiesel. The minimum amount of CO_2 emission is also less than 0.8% which found at 1000 rpm engine speed, while 25% engine load for fuel mixture included less than20% biodiesel. For the fuel blends, it is observed that the CO_2 emission increase with an increase in engine speed. This increase may be due to better combustion conditions and higher atomization ratio which increase at higher engine speeds. Poor atomization and uneven distribution of small portions of fuel across the combustion chamber, along with a low gas temperature, may cause local oxygen deficiency and incomplete combustion at lower engine speeds (Fazal *et al.* 2011). The CO_2 emission is found to increase for all fuels with increase in biodiesel percentage in fuel mixture, because of the oxygen inherently present in the biodiesel, which makes it easier to be burnt at higher temperature in the cylinder and provides a more complete combustion. Almost similar results can be found in other studies (Fazal *et al.* 2011;Xue *et al.* 2011).

Table 3. The central composite experimental design matrix.

Experiment number	Percentage of biodiesel in fuel mixture (%)	Engine speed(rpm)	Engine load (%)
	X_1 (x_1)	X_2 (x_2)	X_3 (x_3)
1	20(-1)	1365(-1)	40(-1)
2	80(1)	1365(-1)	40(-1)
3	20(-1)	2435(1)	40(-1)
4	80(1)	2435(1)	40(-1)
5	20(-1)	1365(-1)	80(1)
6	80(1)	1365(-1)	80(1)
7	20(-1)	2435(1)	80(1)
8	80(1)	2435(1)	80(1)
9	0(-1.682)	1900(0)	62.5(0)
10	100(1.682)	1900(0)	62.5(0)
11	50(0)	1000(-1.682)	62.5(0)
12	50(0)	2800(1.682)	62.5(0)
13	50(0)	1900(0)	25(-1.682)
14	50(0)	1900(0)	100(1.682)
15	50(0)	1900(0)	62.5(0)
16	50(0)	1900(0)	62.5(0)
17	50(0)	1900(0)	62.5(0)
18	50(0)	1900(0)	62.5(0)
19	50(0)	1900(0)	62.5(0)
20	50(0)	1900(0)	62.5(0)

Table 4. The experimental and predicted data for the response.

Experiment number	Experimental data	Predicted data
	CO_2 (%)	CO_2 (%)
	Y	Y
1	1.9	1.95
2	2.1	2.2
3	4.5	4.51
4	4.9	4.76
5	3.2	3.13
6	3.4	3.37
7	6.3	6.19
8	6.7	6.44
9	3.7	3.71
10	4	4.13
11	1.5	1.41
12	5.9	6.1
13	3.4	3.32
14	5.5	5.5
15	4.1	4.11
16	5.1	4.11
17	4.5	4.11
18	3.5	4.11
19	3.8	4.11
20	3.7	4.11

The CO_2 emission continuously increases with increasing engine load. CO_2 emission is primarily controlled by the local fuel-air equivalence ratio. In general, low local cylinder temperatures and lean fuel-air mixture regions at low engine loads may cause the combustion reactions to be unstable, so that CO can not continuously react into CO_2 ,or a temperature is reached at which the carbon monoxide concentration appears to freeze, leading to CO formation instead of CO_2 formation (Mani *et al.* 2009). Under high engine loads, the molecular oxygen in biodiesel fuel improves the combustion for local rich mixtures, and the high cetane number of biodiesel fuel leads to less fuel-rich zone formation; consequently, CO reacts into CO_2 and the CO_2 emission increases (Tan *et al.* 2012). On the other hand, the exhaust gas temperature which increases with an increase in load provides more complete combustion and more CO_2 formation (Cheung *et al.* 2009; Tan *et al.* 2012; Nascimento *et al.* 2008;Tat *et al.* 2007).

Table 5. Regression coefficients, R^2 and p-values of the model for CO_2 Emission of the Diesel Engine.

Regression coefficient	**CO_2 (%)**
b_0 *(intercept)*	-2.092
b_1	0.0057^{*}
b_2	0.0034^{***}
b_3	-0.024^{***}
b_{11}	$-7.51\times10^{-05*}$
b_{22}	$-4.17\times10^{-07*}$
b_{33}	$3\times10^{-04*}$
b_{12}	$3.14\times10^{-06*}$
b_{13}	1.86×10^{-20}
b_{23}	$1.047\times10^{-05*}$
R^2	94.5%
Standard Error	0.41
p-value	0.000^{***}

Subscripts: 1 = Percentage of biodiesel in fuel mixture, 2 = Engine speed, 3=Engine load

*Significant at 0.05 level, **Significant at 0.01 level, ***Significant at 0.001 level.

CONCLUSION

In this study, the mathematical models was developed using Response Surface Methodology to estimate the CO_2 exhaust emission of the diesel engine. It was concluded that:

1- The Design of Experiments was highly helpful to design the experiment and the statistical analysis helped to identify the significant parameters which are most influencing on the CO_2 emission.

2- The statistical models as fitted can be effectively used to predict the CO_2 emission characteristics. Also the effect of biodiesel produced from frying cooking oil blends and diesel No.2 fuel on engine CO_2 emission was investigated.

3- Results showed that with the increase of biodiesel in the blends, the CO_2emissionincrease due to the higher oxygen content of biodiesel that provided more complete combustion in combustion region.

4- An increase in engine speed appeared to cause an increase in the emission of CO_2.

5- In general, CO_2 emission is higher at high engine loads, and lower at low engine loads.These results are similar to those found in the literature and support that frying cooking oil methyl esters have similar properties with diesel fuel. Noteworthy, higher CO_2 formation occurred in biodiesel employing. Therefore, research is needed to propose CO_2 reduction strategies for biodiesel combustion especially in high engine loads and engine speeds. Since CO_2 formation is affected by the carbon–hydrogen ratio in the fuel, one way could be reducing the fuel carbon content per unit energy to reduce CO_2 emission.

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مدل‌سازی تاثیر مخلوط‌های سوخت بیودیزل-دیزل بر انتشار CO_2 یک موتور دیزل بوسیله روش سطح پاسخ

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چکیده

امروزه بیودیزل به عنوان یک انرژی تجدیدپذیر برای استفاده در موتورهای دیزل مورد توجه بیشتری قرار گرفته است. در این تحقیق کاربرد روش سطح پاسخ برای مطالعه تاثیر مخلوط های مختلف سوخت دیزل- بیودیزل (B0، B20، B50 و B100) و پارامترهای عملکردی موتور (بار و سرعت دورانی موتور) بر انتشار CO_2 در یک موتور دیزل در نظر گرفته شده است. آزمون های تحقیق بر روی یک موتور دیزل چهار سیلندر پاشش مستقیم و بر اساس طرح CCD سه فاکتوره پنج سطحی انجام شد. مدل های به دست آمده در این تحقیق برای پیش‌بینی پارامترهای پاسخ و مشخص کردن اثرات معنی‌دار متقابل بین فاکتورهای ورودی و پاسخ ها کاملا مفید بودند. نتایج تحقیق نشان داد که استفاده از بیودیزل سبب انتشار بیشتر CO_2 می‌شود. همچنین نتایج نشان داد که با افزایش سرعت دورانی موتور انتشار CO_2 نیز بیشتر می‌شود. از طرف دیگر مقدار CO_2 در بارهای کم موتور بیشتر و در بارهای زیاد موتور کمتر است.

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