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Original Research Article

Mathematical Model for Fuel Flow Performance of Diesel Engine

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Abstract

In this paper, response surface method (RSM) was proposed to determine fuel flow performance of an internal combustion diesel engine by using different specific conditions (injection pressure, engine speed and throttle position). Injection pressure of the diesel engine was chosen as 150 bars for turbocharger and pre-combustion chamber. Experiments were realized at four pressures corresponding to 100, 150, 200 and 250 bars each with throttle positions of 50, 75 and 100%. A mathematical model was used to predict fuel flow performance of engine according to pressures and throttle positions. The optimum performance conditions, for a required fuel flow, were obtained by using response surface method with 3D graphics. The developed prediction equations showed that the linear effect of engine speeds was the most important factor that influenced the fuel flow. Moreover, whether the proposed mathematical model of fuel flow is within the limits of the performance parameters has been considered.

Keywords: Diesel engine performance, fuel flow, mathematical modeling, response surface method.

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1. Introduction

Many experimental investigations about biodiesel production and its combustion emission have been realized. Aktaş et al [1] investigated biodiesel production from olive pulp in their research and also Behçet R. [2] researched biodiesel production from waste fish oils and its harmful effects on the environment and human health. Aktaş A. examined that mixture of melon seed oil and methyl esters with diesel fuel and its effects on engine performance and emissions [3]. As such, many researchers produced different biodiesel fuel and investigated the effects of these fuels on engine performance [4-9].

Analytical methods, numerical methods or experimental measurement methods have been used to solve internal combustion engine problems. Formerly, the limitations of computer speed and storage made analytical methods more favorable to examine many problems. However, experimental measurement methods have been preferred when analytical methods were impossible in some situations Çelikten et al [10].Therefore especially after

1990s, researchers developed numerical methods for accurate and efficient solutions. Recently, there is a trend toward optimization techniques that is done realized by using the results of experimental studies. The optimization techniques as simplex method, response surface method, artificial neural network (ANN) have been used for engine analysis [11-13]. Neşeli et al. [14] investigated influence of tool geometry on the surface finish obtained in turning of AISI 1040 steel. In order to find out the effect of tool geometry parameters on the surface roughness during turning, response surface methodology (RSM) has been used and a prediction model has been developed related to average surface roughness (Ra) using experimental data. Many similar studies about machinery manufacturing techniques were realized by experimentally and the results of experiments were used for RSM modeling. However, in our knowledge, there are no studies in literature related with RSM modeling of internal combustion diesel engine. Some researchers used experimental data to create RSM for mathematical model and they defined engine performance parameters such as power output, brake specific fuel consumption, fuel conversion efficiency, fuel injection timing, engine load, simulate altitude and oxygen volume fraction [15-16].

In this study, the fluid flow performance values for a diesel engine using response surface method (RMS) have been investigated. For this aim, experiments have been performed for both full and partial loads on a turbocharger diesel-engine with four-cylinder, four-stroke, indirect injection by changing the injection pressures from 100 to 250 bar with intervals of 50 bar and for throttle positions of 50, 75 and 100%. The developed prediction equations showed that the linear effect of engine speeds was the most important factor that influenced the fuel flow.

2. Experimental Set up and Measurements

Nowadays, fuel injection systems and injection pressure can be successfully adjusted in high pressure. This process increases the efficiency of diesel engine. Injection characteristics of diesel engine with direct injection have been studied in several researches. For instance in Ref Yang et al. [17] parameters have been calculated according to rotation and injection pressure. Employing some mathematical models to estimate engine emissions is another approach. But high accuracy of these approaches may not be ensured Massie [18]. An alternative to mathematical models can be experiment-based approaches. However, although reliable results can be obtained, experimental studies conducted to measure emission and performance of diesel engines are complicated, time consuming and expensive.

Specifications of the test engine are given in Table 1 [19-20]. Here, the specification of our test environment (i.e. the diesel engine) and the accuracy of the equipment used to collect the necessary data are summarized. In this study, an electrical dynamometer assembled on 4-cylinder and 4-stroke indirect injection diesel engine was used. As shown in Fig. 1, there are different thermocouples and electrical units on the dynamometer and the engine.

Table 1. Specifications of the test engine.

Item	**Specifications**
Make and model	Ford- XLD 418T, 1998
Motor type	Turbocharged, diesel, pre-combustion chamber, four-stroke
Number of cylinders and volume	Four-cylinders and 1.8 l
Engine power and torque	44 kW at 4800 rpm, 110 Nm at 2500 rpm
Fuel system and injectors	Lucas DPC type fuel-injection pump, single-point fuel injectors

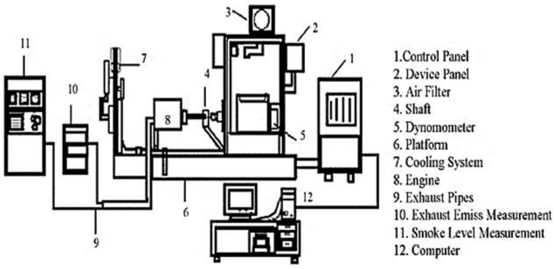

Fig. 1. Schematic picture of engine test bed.

Circuits in all units have been connected to each other, and they have also been controlled by a computer. In addition, there are two exhaust emission measurement equipment worked separately. One of the equipment was used for fuel flow measurements, and the other for other engine performance level. After nozzles that are changed pressure adjustment are assembled, they are investigated according to engine performance and emission for different throttle positions. Experiments have been conducted on a diesel engine connected with an electrical dynamometer. Before starting the engine, the nozzles were taken off and adjusted to 150 bars. For the adjustment, washer(s) has been used to change the nozzles pressures. After that, the nozzles adjusted have been fitted to the engine. Then, air in the nozzles has been transferred to the atmosphere and the engine was run. The computer controlled diesel engine which is connected to the electrical dynamometer was loaded in throttle position of 50%. Engine was tested in range of 1500 rpm to 4500 rpm with the interval of 500 rpm. In the throttle position, maximum torque level of 4500 rpm was reached. In the experiments, torque, power and fuel flow rate were recorded by computer. Similarly, these measurements were repeated in throttle positions of 75% and 100%. Fuel–air equivalence ratios are measured in the experiments, as well.

3. Material and Methods

Response Surface Methodology or (RSM) is a collection of mathematical and statistical techniques useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response Montgomery [21]. For example, operation of a diesel internal combustion engine is effected by rpm and amount of the fuel flow. Engine work condition can be any combination of x_1 and x_2. Therefore, x_1 and x_2 can vary continuously. When treatments are from a continuous range of values, then an RSM is useful for developing, improving, and optimizing the response variable. In this case, y is the response variable, and it is a function of rpm and Ip. It can be expressed as follows:

$$y = f(x_1, x_2) + \varepsilon \qquad (1)$$

The variables x_1 and x_2 are independent variables where the response y depends on them. The dependent variable y is a function of x_1, x_2, and the experimental error term, denoted as ε. The error term ε represents any measurement error on the response, as well as other type of variations not counted in f. It is a statistical error that is assumed to distribute normally with zero mean and variance s_2. In most RSM problems, the true response function f is unknown. In order to develop a proper approximation for f, the experimenter usually starts with a low-order polynomial in some small region. If the response can be defined by a linear function of independent variables, then the approximating function is a first-order model. A first-order model with 2 independent variables can be expressed as:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon \qquad (2)$$

If there is a curvature in the response surface, then a higher degree polynomial should be used. The approximating function with 2 variables is called a second-order model:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x^2_{11} + \beta_{22} x^2_{22} + \beta_{12} x_1 x_2 + \varepsilon \quad (3)$$

In general, all RSM problems use either one or the mixture of the both of these models. In each model, the levels of each factor are independent of the levels of other factors. In order to get the most efficient result in the approximation of polynomials the proper experimental design must be used to collect data. Once the data are collected, the Method of Least Square is used to estimate the parameters in the polynomials. The response surface analysis is performed by using the fitted surface. The response surface designs are types of designs for fitting response surface. Therefore, the objective of studying RSM can be accomplish by (1) understanding the topography of the response surface (local maximum, local minimum, ridge lines), and (2) finding the region where the optimal response occurs. The goal is to move rapidly and efficiently along a path to get to a maximum or a minimum response so that the response is optimized. The *RSM* is important in designing, formulating, developing, and analyzing new scientific studying and products. It is also efficient in the improvement of existing studies and products. The most common applications of *RSM* are in Industrial, Biological and Clinical Science, Social Science, Food Science, and Physical and Engineering Sciences. Since *RSM* has an extensive application in the real-world, it is also important to know how and where *Response Surface Methodology* started in the history. According to Hill and Hunter, *RSM* method was introduced by G.E. P. Box and K.B. Wilson in 1951 (Wikipedia 2006). Box and Wilson suggested to use a first-degree polynomial model to approximate the response variable. They acknowledged that this model is only an approximation, not accurate, but such a model is easy to estimate and apply, even when little is known about the process (Wikipedia 2006). Moreover, Mead and Pike stated origin of RSM starts 1930s with use of *Response Curves* (Myers, Khuri, and Carter 1989).According to research conducted (Myers, Khuri, and Carter 1989), the *orthogonal design* was motivated by Box and Wilson (1951) in the case of the first-order model. For the second-order models, many subject- matter scientists and engineers have a working knowledge of the *central composite designs* (CCDs) and *three-level designs* by Box and Behnken (1960). Also, the same research states that another important contribution came from Hartley (1959), who made an effort to create a more economical or *small composite design*. There exist many papers in the literatures about the response surface models. In contrast, 3-level fractional design has limited works. Thus, 3-level fractional design is an open research subject. *Fractional Factorial Experiment Design for Factor at 3-Levels* (Connor and Zelen 1959) is a helpful resource conducting this kind of design. Many three- level fractional factorial designs and more importantly their alias tables can be found in their study. According to (Myers, Khuri, and Carter 1989), the important development of optimal design theory in the field of experimental design emerged following Word World II. Elfving (1952, 1955, 1959), Chernoff (1953), Kiefer (1958, 1959, 1960, 1962), and Kiefer and Wolfowitz were some of the various authors who published their work on optimality. One of the important facts is whether the system contains a maximum or a minimum or a saddle point, which has a wide interest in industry. Therefore, RSM is being increasingly used in the industry. Also, in recent years more emphasis has been placed by the chemical and processing field for finding regions where there is an improvement in response instead of finding the optimum response (Myers, Khuri, and Carter 1989). As a result, application and development of RSM will continue to be used in many areas in the future Bradley [22].

4. Response Equation for Fluid Flow

RSM's Box-Behnken design consisting of 84 experiments was conducted for developing the mathematical model for fuel flow attained by the experimental set up. The input parameters and their levels chosen for this work are given in Table 1. The fluid flow results for the 17 experiments are given in Table 2.

Table 2. Input parameters and their levels.

SN	Parameter	Low Level	High Level
1	Throttle position (%)	50	95
2	Injection pressure (Bar)	100	250
3	Engine speed(rpm)	1500	4500
4	Fuel flow (kg/hr)	4.7	15.9

5. Result and Discussions

The analysis of variance (ANOVA) was applied to study the effect of the input parameters on the fuel flow. Table 3 gives the model summary statistics. It reveals that quadratic model is the best suggested model. So, for further analysis this model was used.

Table 3. Model summary statistics.

Source	R^2	Adj R^2
Linear	0.72	0.72
Square	0.86	0.84
Interaction	0.93	0.93

The value of "Prob. > *F*" in Table 4 for model is less than 0.05 which indicates that the model is significant, which is desirable as it indicates that the terms in the model have a significant effect on the response. In the same manner, the two-level interaction of injection pressure-engine speed (Ip x rpm) and injection pressure-throttle position are not significant model terms. Other model terms can be said to be significant. These insignificant model terms (not counting those required to support hierarchy) can be removed and may result in an improved model.

Estimated regression coefficients for surface roughness using data are shown in Table 5. The co-efficient of determination R^2 is used to decide whether a regression model is appropriate. The co-efficient of determination R^2 provides an exact match if it is 1. So, the quadratic model of response equation in terms of actual factors for fuel flow (Ff) is;

$$Ff=-13.2390+0.0463Ip-0.0001Ip^2+0.0001rpm-0.0000rpm^2+0.3972\,Tp-90034\,Tp^2+0.0000\,Ip\,rpm-0.0002Ip\,Tp+0.0001rpm\,Tp \quad (4)$$

Table 4. ANOVA table for response surface model.

	SS	df	MS	F	Prob.>F	PC(%)	R^2(%)
Ip	30.004	1	30.0037	32.7248	0.000000	2.59	
Ip^2	10.497	1	10.4967	11.4487	0.001147	1.02	
rpm	493.834	1	493.8338	538.6207	0.000000	48.17	
rpm^2	14.545	1	14.5453	15.8644	0.000158	1.41	
Tp	174.512	1	174.5118	190.3386	0.000000	17.02	
Tp^2	55.108	1	55.1083	60.1061	0.000000	5.37	93.38
IpxRPM	0.433	1	0.4335	0.4728	0.493850	0.00	
IpxTp	2.194	1	2.1935	2.3925	0.126188	0.00	
rxTp	136.877	1	136.8768	149.2905	0.000000	13.35	
Error	67.847	74	0.9168				
Total SS	1025.059	83					

The empirical Eq. (4) shows greater agreement than 93% in the fit values. The R^2 value in this case is high and close to 1, which is desirable. Hence, these equations can be used for determining the fuel flow in diesel engine. The normal probability plot of the observed versus the predicted response for surface roughness is shown in Fig. 2. A check on the plot in Fig. 2 revealed that the observed generally fall on a straight line implying that the errors are distributed normally. This implies that the models proposed are adequate and there is no reason to suspect any violation of the independence or constant variance assumption. The effect of throttle position (Tp), engine speed (rpm) and injection pressure (Ip) on fuel flow is shown in Fig. 3 via 3D surface graphs. Fig. 3a clearly displays that the value of fuel flow (Ff) increases with increase in the effect of throttle position (Tp) and engine speed (rpm). This result is compatible with the general expectation. Increasing rpm and decreasing Ip (Fig. 3b) have caused an increase in Ff. Like the situation in (Fig 3b), increasing Tp and decreasing Ip (Fig. 3c) have caused to reach to maximum values of Ff.

Table 5. Estimated regression coefficients for Ff.

	Regression	Std. Err.	t	p	R^2 (%)
Mean/Interc.	-13.2390	3.393137	-3.90169	0.000209	
Ip	0.0463	0.017444	2.65522	0.009700	
Ip^2	-0.0001	0.000042	-3.38359	0.001147	
rpm	0.0001	0.000903	0.06418	0.948999	
rpm^2	-0.0000	0.000000	-3.98302	0.000158	93.38
Tp	0.3972	0.068838	5.77028	0.000000	
Tp^2	-0.0034	0.000444	-7.75282	0.000000	
Ipxrpm	0.0000	0.000002	0.68761	0.493850	
IpxTp	-0.0002	0.000102	-1.54676	0.126188	
rpm xTp	0.0001	0.000006	12.21845	0.000000	

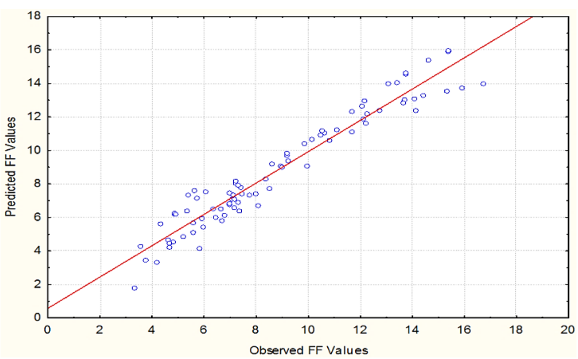

Fig. 2. Plot of observed vs. predicted response for Ff.

6. Conclusions

The aim of this paper is to show the possibility of using the RSM for fuel flow performance prediction of a diesel engine employing the experimental data. The experimental results of an internal combustion diesel engine are used to estimate the fuel flow performance by using RSM modeling. Relations between the parameters such as the fuel flow, the engine speed, the injection pressure and the throttle positions are found using RSM. The RSM approach based modeling analysis has been carried out for optimizing the performance of diesel engine. It is found that the most important parameter affecting the fuel flow is engine speed. The results of RSM of four-stroke IC diesel engine are observed to be very close with the experimental results. It is obtained that the R^2 value is 93.38. This study was also conducted to fill a gap in the literature in this subject.

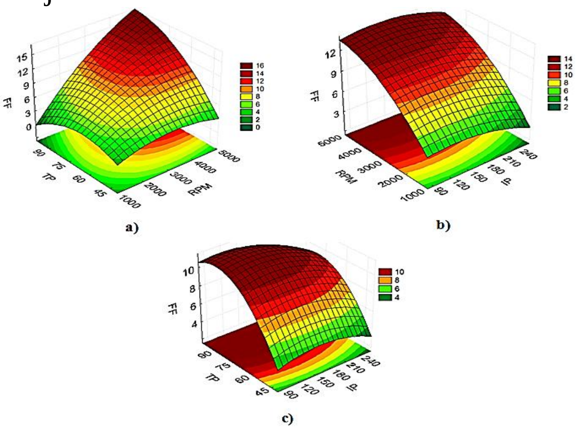

Fig. 3. 3D response surface graphs for the fuel flow vs. throttle position, injection pressure and engine speed.

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