Original Article

Statistical And Experimental Investigation of Engine Parameters for Performance and Emission in RCCI Mode Using Diesel/Gasoline

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Abstract

Internal combustion (IC) engines are likely to continue to rule the transportation industry for another couple of decades. This is despite the fact that research and government schemes today concentrate on alternative power generation units and technology like fuel-cells and hybrid cars. It has been demonstrated that using the right fuels and implementing new combustion modes would accelerate the development of IC engines. This experimental & statistical study is carried out on a single-cylinder engine which is operated in the RCCI mode using the diesel as the primary fuel and the gasoline as the secondary fuel. The parameters chosen for the study are Premixed Ratio (PR), Fuel Injection Pressure (IP), Start of main Injection (SOI), Start of Pilot Injection (SOPI) and Mass of Pilot Injection (MOPI). The objective of the study is to find the effects of these input parameters on BSFC & NOx and to examine the interactions between various parameters using a statistical approach. The results of Response Surface Method of analysis shows that PR, IP, and SOMI significantly impacted BSFC and NOx, while SOPI and MOPI had the least significant impact.

Keywords: RCCI, DOE, Premixed ratio, Diesel Injection

INTRODUCTION

The CI engine meets high power requirements while consuming less fuel [1]. CI engines range in power from a few watts to the high energy needed applications like railway and marine industries [2]. CI engines are limited because of their high levels of emissions, primarily NOx and soot. NOx is nothing more than nitrogen oxides primarily NO and NO_2 [3]. Understanding the mechanism or kinetics of NOx formation is complicated by the fact that combustion in diesel engines is extremely heterogeneous and transient. NOx is made up of nitric oxide (NO) and nitrogen dioxide (NO_2). These are formed during the post-flame combustion process by the oxidation of presence of nitrogen in the air (supplied as a charger). While both gases are considered toxic, there are several distinctions between them. NO is an odourless and colourless gas, whereas NO_2 is reddish-brown and has a strong odour. Although NO_2 is produced primarily by NO oxidation, controlling NO before and after combustion is difficult [4].

New emission standards, such as BS-VI, will became mandatory across the country from April of 2020. This has pushed the automotive industry and researchers now face the challenge of developing technology that will fulfil reducing emissions technology at a cost that is comparable to other technologies. A popular method for reducing emissions is the electronic control management (ECM) of fuel, fuel-air ratio, diesel particulate filter (DPF), enhanced catalytic converters like air/add-blue injection, and two staged catalytic converters have emerged. These ECM applications have become of interest to researchers working in more recent technology such as HCCI, PCCI, and RCCI.

Advanced combustion technology known as Homogeneous Charge Compression Ignition (HCCI) has the potential to cut NOx and Particulate Matter (PM) emissions while maintaining a level of efficiency comparable to diesel engines. Combustion in the engine takes place because of spontaneous auto-ignition at numerous points distributed throughout the charge volume in HCCI. These distinctive qualities of HCCI make it possible to burn a very lean and dilute mixture, which leads to relatively lower bulk temperatures and temperatures localised to the combustion process. This, in turn, results in a significant reduction in the amount of NOx emissions produced by the engine. Homogeneous combustions are possible with HCCI engines, in contrast to the heterogeneous mixture that is produced by CI engines. The HCCI engine does not have any fuel-rich zones, which significantly cuts down on the formation of PM [5].

In Premixed Charge Compression Ignition (PCCI), a proper Air to Fuel ratio before combustion can help to reduce PM, and an increased EGR rate and a lean mixture of Air to Fuel can help reduce NOx. Both factors are important. During the pre-premixed charge in CI engines, events such as ignition power, the formation of a homogeneous mixture, excess wall impingement, and many others take place. Due to its higher combustibility and lower diesel volatility, there are just a few more challenges that need to be overcome [6].

These problems are currently being addressed by a novel approach called the Reactivity Controlled Compression Ignition (RCCI) combustion strategy, which was recently been in vogue. The RCCI is a dual fuel method that supports various reactivity fuels to enhance the combustion process and minimize emissions from a diesel engine. This strategy is known as the RCCI. In this, both High Reactive Fuel (HRF) i.e. high cetane number and Low Reactive Fuel (LRF) i.e. high octane number can be used in a compression ignition engine while it is operating in RCCI mode [7].

When compared to traditional diesel engines, this combustion mode offers several advantages, including reduced NOx and particulate matter emissions. The mass of the diesel fuel is an important factor in determining the fuel's reactivity and adjusting the reactivity of the RCCI combustion gives one control over the phasing of the combustion. The fuel stratification and the regional equivalence ratios can be controlled in a variety of ways such as including timing of injection, multiple injection, and so on [8].

According to the findings of a Chinese research group [9], the ratio of LRF to HRF in the mixture has a significant impact on the overall reactivity of the mixture when it is used in RCCI engines. The effects of increasing the mass fraction of methanol as a low reactive fuel on a methanol/diesel RCCI engine were investigated, and it was discovered that increasing the mass fraction of methanol as a low reactive fuel causes an increase in ignition delay time while simultaneously reducing NOx emission. When it comes to RCCI engines, the ratio of the low reactive fuel to the total fuel mixture can be increased all the way up to 90 percent. In other research, it was found that increasing the total amount of LRF causes the combustion process to proceed more slowly, which leads to an increase in the amount of energy that can be utilized efficiently [10, 11].

Researchers, by conducting a design of experiment (DOE) analysis, [12] were able to investigate the effects of six different characteristics of diesel injection on an RCCI engine. They conclude that increasing the injection duration while simultaneously delaying the timing of the second injection will result in a reduction in NOx emissions. The DOE method used for research conducted on a light-duty diesel engine in order to investigate the most significant injection parameters. In fact, for each of the three different engine operating conditions that were investigated, a total of 16 tests were conducted (four parameters, two levels). According to the findings, the quantity of pilot injection is the most important parameter that influences UHC and reducing UHC emissions using single parameters is more effective than using combinations of parameters [13]. In order to investigate the effects that relative bowl diameter parameters have on the combustion of diesel engines, researchers demonstrated that by utilizing the DOE method, it is possible to observe the engine's response to a number of factors without making use of test results for each and every possible combination [14].

The Response Surface Method, also known as RSM, has been utilised by to optimize the functioning parameters of a heavy-duty direct injection diesel engine that makes use of multiple injections and EGR. They demonstrated that RSM optimization is an efficient method for maximizing the potential of the engine's operating parameters [15]. The DOE method was utilised in an investigation of a light-duty diesel engine's performance. They concluded that the torque and the amount of diesel fuel used are both compensated by individual variables such as the start of injection and the injection mass [16]. The following is a more in-depth look at some of the research that has been done on the topic of investigating significant injection factors on conventional CI engines using DOE techniques. However, it is abundantly clear that RCCI engines do not have access to a comprehensive DOE method. In other words, DOE has not been used in a significant amount of research on RCCI engines, and most of the research studies that have been conducted have utilised the one factor at a time (OFAT) approach. This method can consider only one factor while keeping the others constant. In diesel engines, many previous DOE studies were used to investigate the interaction of different parameters, but RCCI combustion still needs more investigation to evaluate the effects of different parameters at the same time. As a result, diesel engines have been the focus of many of these investigations. In addition, the previous DOE studies only considered a limited number of input factors, even though a number of factors can influence the combustion and emission characteristics of RCCI engines.

In this investigation, the full factorial design method, which is one of the DOE methods, was used to investigate the efficacy of various single input parameters as well as the interaction of parameters at the same time on the exhaust emissions and performance characteristics of the vehicle engine. The novel contribution of this paper is that it considers a few significant factors that have an effect on the combustion of an RCCI engine. In addition, the effects of a variety of factors, as well as the interaction between those factors, have been investigated in terms of the RCCI engine's NOx emissions. The parameters, which are studied in this work include the Premixed Ratio (PR), Fuel Injection Pressure (IP), Start of Main Injection (SOI), Start of Pilot Injection (SOPI) and Mass of Pilot Injection (MOPI). The following are the articles main contributions: First, the study have been done on the effects of a number of input parameters. Second, to examine the findings of interactions between various parameters.

Experimental Setup and Engine Specifications

A single-cylinder, four-stroke, water-cooled Diesel engine was employed for the study. The test rig consists of an externally mounted dynamometer and a CRDi engine that has been modified to operate in RCCI mode of combustion. The specifications of the engine and the dynamometer are shown in Table 1. With the aid of an AVL 415S gas analyser bench, the emissions were recorded. Figure 1 (a) and (b) shows the block diagram and engine test setup respectively.

Table 1. Specifications of the engine and the dynamometer

Description	Specifications
Engine	
Make	Mahindra and Mahindra
Engine Capacity (cc)	625
Type	Automotive (Multi-speed)
Compression Ratio	18:1
Power	9 HP @ 3000 rpm
Torque	30 NM @ 1800 rpm
Dynamometer	
Maker	Technomech
Type	Eddy current
Max. Power (in BHP)	10
Load measurement method	Strain Gauge
Cooling	Water

Fig. 1. Engine test setup

METHODOLOGY

The engine variables that are chosen for study is as follows,
Premixed Ratio (PR) is the ratio of energy release by burning the secondary fuel to the energy from both fuels combined. Its unit is percentage (%). PR is calculated using eq 1.

$$\mathrm{PR} = \frac{\mathrm{m_{sec}\ X\ LHV_{sec}}}{\mathrm{m_{sec}\ X\ LHV_{sec} + m_{pri}\ X\ LHV_{pri}}}\ \mathrm{X}\ 100 \qquad (1)$$

where, m_{sec} and m_{pri} are mass of secondary and primary fuel respectively
LHV_{sec} and LHV_{pri} are lower heating values of secondary and primary fuel respectively

The pressure at which primary fuel is injected into the combustion chamber is known as the injection pressure. It is expressed in bar. The starting point of the primary fuel injection into the combustion chamber is known as the injection timing or SOPI. It is typically stated as degrees of the crank angle (CAD) with respect to the top dead centre (TDC) of the compression stroke. The start of pilot injection marks the beginning of primary fuel main injection into the combustion chamber. It is typically expressed as the degrees of the crank angle (CAD) to the top dead centre (TDC) of the compression stroke. The mass of primary fuel that will be injected during the pilot injection is known as mass of pilot injection. It is stated as a percentage of the primary injection (%).

The Central Composite Design (CCD) is a statistical method used to study the effect of the engine parameters on BSFC and NOx emissions. The input parameters need to be arranged in five levels (-∝, −1, 0, +1, +∝) as per the CCD approach. The extreme negative (-∝) and extreme positive (+∝) values of the engine variables are chosen in consideration of the possibility of knocking and misfiring during combustion. Equations (2), (3), and (4) are used to find the variable and their levels which is shown in Table 2.

$$\text{Zero value} = \frac{(+\alpha\ \text{value}) + (-\alpha\ \text{value})}{2} \qquad (2)$$

$$+1\ \text{value} = (0\ \text{value}) + \frac{(+\alpha\ \text{value}) - (0\ \text{value})}{(\alpha)} \qquad (3)$$

$$-1 \text{ value} = (0 \text{ value}) - \frac{(+\alpha \text{ value}) - (0 \text{ value})}{(\alpha)} \qquad (4)$$

Table 2. Optimization parameters and their levels

Input parameters	*Unit*	*- ∝*	*-1*	*0*	*+1*	*+ ∝*
Premixed ratio (PR)	%	10	27	40	53	70
Fuel injection pressure (IP)	bar	300	387	450	513	600
Start of main injection (SOI)	CAD bTDC	15	17	18	19	21
Start of pilot injection (SOPI)	CAD	8	9	10	11	12
Mass of pilot injection (MOPI)	%	10	13	15	17	20

To analyze these five parameters with five levels, 52 experiments has been carried out. Out of 52 test combinations, 32 experimental runs establish 25 factorial designs with added center point repeated for 10 times. The distance of star points of 2.38 indicates extreme levels of each parameter. All five levels are denoted by -2.38, -1, 0, +1 and +2.38.

The experiments were carried on RCCI engine with diesel as primary fuel and gasoline as secondary fuel for all the test combinations. RCCI engine was maintained a constant speed and load of 1600 rpm and 15 Nm respectively. The BSFC, and NOx responses were calculated based on the output obtained. Gasoline was used as the secondary (low-reactivity) fuel and diesel as the primary (high-reactivity) fuel. The Properties of gasoline and diesel are shown in Table 3.

Table 3. Properties of gasoline and diesel [17]

FUEL PROPERTIES	*UNITS*	*DIESEL*	*GASOLINE*
Cetane number	-	51[a]	-
Lower heating value	kJ/kg	42,920	43,900
Density @ 15 ^{O}C	kg/m^3	815 - 845[a]	720 - 775[a]
Kinematic viscosity @ 40 ^{O}C	cSt	2 - 4.5[a]	-
Flash point (abel)	^{O}C	35[a]	-45 to -38
Auto-ignition temperature	^{O}C	246	425
Research octane number (RON)	-	-	91[a]

[a] as per Indian Oil Corporation Ltd

RESULTS AND DISCUSSIONS

Analysis of Variance (ANOVA) and its Significant Effects

The ANOVA computations have been carried out using MINITAB statistical analysis software. ANOVA is used to check the difference in mean square of each experimental group of input parameters in factorial experiments. By this method significance of input parameter has been segregated into main factor, square of main factor, interaction between the factor sand residual.

The ANOVA Technique, helpful in estimating the input parameters and experimental errors. Fisher exact test is a statistical tool, broadly known as F-Test to verify the significance of the input parameter on response. Here, P value approach has been widely adopted for analysis. The P value with preselected level of significance or level of confidence is used to find the effect of parameter on response statistically. This level of significance is designated as α. If P value is less than or equal α, it can be concluded that parameter is significant else insignificant.

It can be seen from Table 4, that there is a significant effect on BSFC by both the PR and IP which have linear variations. Also, the BSFC with premixed ratio (PR*PR) has a quadratic variation and a two-way interaction with IP and the SOMI. The two-way interaction of BSFC with IP and SOMI signifies that the effect of one depends on the level of another and both IP and SOMI combined affects.

Table 4. The ANOVA analysis for developed models

Source	*BSFC*		*NOx*		*Source*	*BSFC*		*NOx*	
	F-Value	**P-Value**	**F-Value**	**P-Value**		**F-Value**	**P-Value**	**F-Value**	**P-Value**
Model	5.45	0	1.36	0.214	PR*IP	0.58	0.454	0.61	0.441
PR	74.68	**0**	0.45	0.506	PR*SOMI	1.09	0.304	0.1	0.753
IP	4.7	**0.038**	9.12	**0.005**	PR*SOPI	0.11	0.743	0.46	0.505
SOMI	0	0.948	2.44	0.129	PR*MOPI	1.71	0.201	0	0.958
SOPI	0.46	0.5	0.05	0.83	IP*SOMI	10.12	**0.003**	0.09	0.763
MOPI	0.99	0.329	2.46	0.127	IP*SOPI	0.31	0.583	2.78	0.106
*PR*PR*	7	**0.013**	4.63	**0.039**	IP*MOPI	0.5	0.484	0.04	0.844
*IP*IP*	0.04	0.843	2.15	0.152	SOMI*SOPI	3.48	0.072	0.49	0.488
*SOMI*SOMI*	1.47	0.234	0.38	0.542	SOMI*MOPI	0.57	0.456	0.18	0.675
*SOPI*SOPI*	0.04	0.84	0.03	0.866	SOPI*MOPI	0.1	0.752	0.02	0.885
*MOPI*MOPI*	0	0.949	0.05	0.827					

The ANOVA results of the NOx emissions are also shown in Table 4 which confirms that the IP has a linear variation with NOx. The quadratic terms in ANOVA infers that as PR increased, NOx will reduce steeply initially but further increase in PR will results in less reduction in NOx which shows the non-linear distribution.

Normal Probability Plot for Effects

The normal effects plot is used to compare the relative magnitude and the statistical significance of both main and interaction effects. The effects that are negligible are normally distributed, with mean zero and variance and will tend to fall along a straight line whereas significant effects will have non-zero means and will not lie along the straight line. In addition, the plot indicates the direction of the effect. The factors which lie to the right of the line have positive effects and those which reside to the left of the line will have negative effects.

Fig. 2. Normal Probability Plot of BSFC

It can be seen in figure 2 that, the square PR*PR and the interaction IP*SOI have positive effects which means when the level of the factor is changed from low to high, the BSFC increases. The factor PR and IP residue have a negative effect, meaning when the level of the factor is changed from the low to high, the BSFC decreases

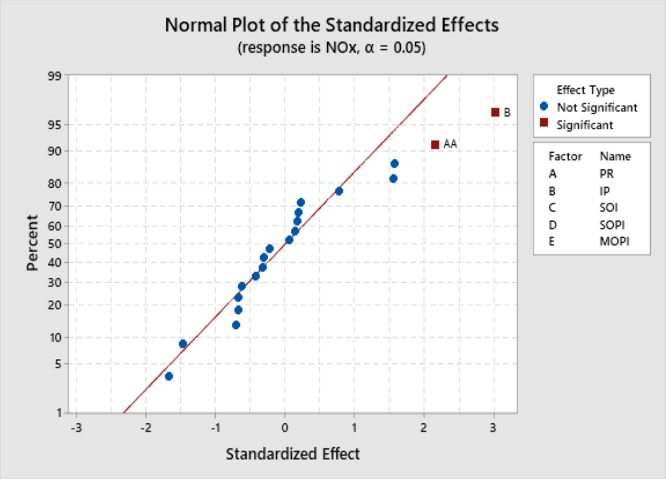


Fig. 3. Normal Probability Plot of NOx

Both factors, IP and PR*PR, have positive effects which means when the level of the factor is changed from low level to the high level, the NOx increases which is shown in figure 3. As IP increases, the fuel atomization is better which leads to better combustion which leads to high combustion temperature and thus higher NOx.

Main Effects and Interactions

Further, analysis can be performed with the assistance of main effects and interactions plots. The main effects plot displays the means values within a variable. A line connects the points for each variable. The line can determine whether a main effect is present for a variable or not. When the line is horizontal, there is no main effect present. The response mean is the same across all factor levels. When the line is not horizontal, there is a main effect present. The response mean is not the same across all factor levels. Although this plot can display the effects, performing the ANOVA test and evaluate the statistical significance of the effects is essential. If the interaction effects are significant, it is also important to interpret the interaction effects. The easiest way to identified interaction is to plot the results in an interaction graph which is an ISO-Plot of the responses variable for one of the parameters over the changes of other factor. If the ISO plots of parameter are parallel, then there is no interaction between the parameters considered.

Figures 4 & 5 show the main effects plots for BSFC and NOx respectively. It is seen in figure 4 that, as the SOPI and MOPI increase, the mean BSFC increases. The rate contribution of the MOPI is more than that of the SOPI.

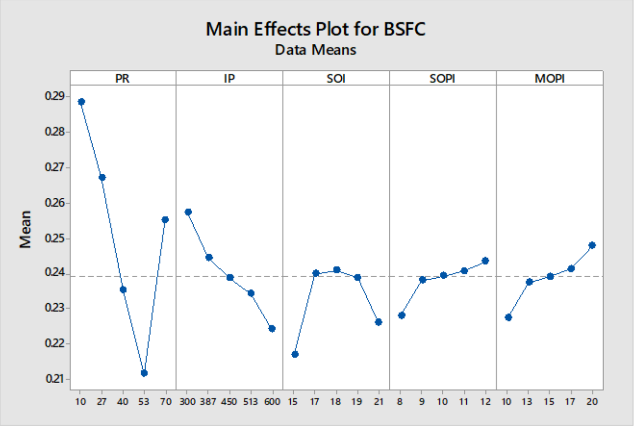


Fig. 4. Main effects plot for BSFC

The contribution of the SOPI to responses is negligible. Additionally, as the IP increases, the mean BSFC decreases. It is also very important to note that with the increase in PR, the mean BSFC tends to decrease up to PR of 53% i.e., +1 level. Further increase in the PR, increases steeply. As the SOI advances, the mean BSFC increases up to SOI of 18 CAD i.e., zero level and then decreases with further advancement of the SOI.

The main effects plot for NOx is shown in figure 5. It is clear that, the increase in PR leads to decrease in the mean NOx up to PR value of 53% i.e. +1 level. Further increase in PR increases steeply. The increase in Injection Pressure (IP) increases NOx due to better atomization leading to higher combustion temperature. Advancing SOI leads to lower of NOx, while the contribution of SOPI and MOPI is negligible.

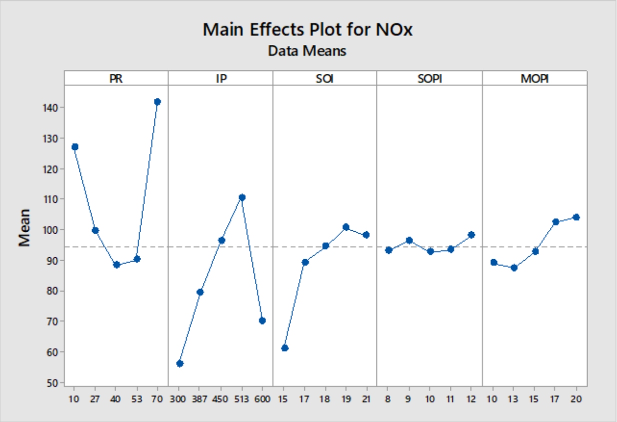


Fig. 5. Main effects plot for NOx

It is evident, from interaction plot given in the figure 6 that there are interaction effects between input parameters over the mean of response value. From the interaction plots, some lines are parallel, it clear that there is no interaction between the levels of the parameters such as PR*SOPI, IP*SOPI and SOPI*MOPI. Some lines are non-parallel which shows interaction between the levels of the parameters such as PR*IP, PR*SOI, PR*MOPI, IP*SOI, IP*MOPI, SOI*SOPI and SOI*MOPI.

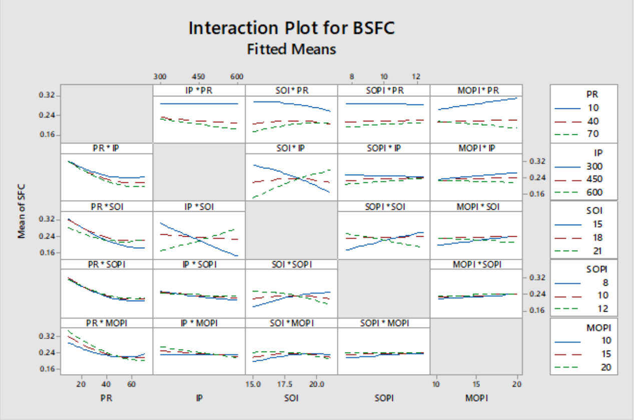


Fig. 6. Interaction Plot for BSFC

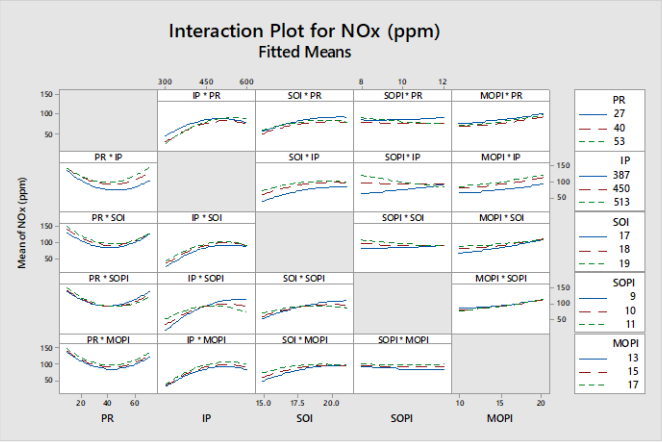


Fig. 7. Interaction Plot for NOx

It is clear From the interaction plots shown in figure 7 that some lines are parallel, that there is no interaction between the levels of the parameters such as SOI*PR, SOI*IP, PR*MOPI and IP*MOPI, Other lines are non-parallel which shows interaction between the levels of the parameters.

Mathematical Model

Mathematical models are developed using the experimental results to predict the response. The mathematical model includes the main & its square terms and two-way interactions effects of the parameters on response. General regression significance test analysis of variance has been carried out to develop mathematical model. The magnitude of regression co-efficient is a good indication of significance of parameter. Assuming linearity in parameter affects a simple linear model comprising main and its square term and it would be prudent to look into the possibility of that second order model which includes two-way interactions of parameters may be appropriate.

Using the least-squares approach, the second-order polynomial equations are obtained by the model for the individual response and are shown in the equations 5 and 6 [15].

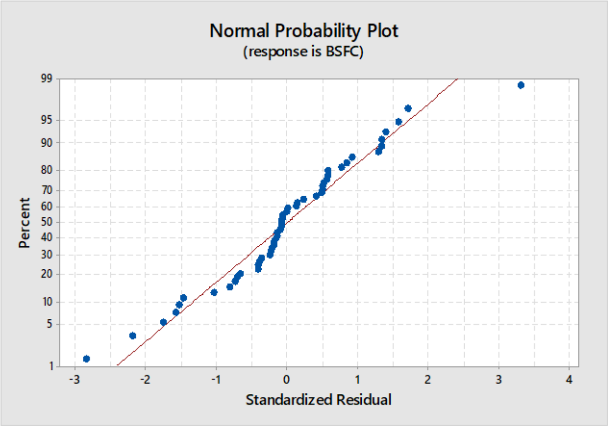
$$\text{BSFC (kg/kWh)} = -0.32 - 0.00629\,\text{PR} - 0.00283\,\text{IP} + 0.0585\,\text{SOI} + 0.1041\,\text{SOPI} + 0.0413\,\text{MOPI} + 0.000037\,\text{PR*PR} + 0.000000\,\text{IP*IP} - 0.00176\,\text{SOI*SOI} - 0.00046\,\text{SOPI*SOPI} - 0.000036\,\text{MOPI*MOPI} - 0.000003\,\text{PR*IP} + 0.000242\,\text{PR*SOI} + 0.000077\,\text{PR*SOPI} - 0.000151\,\text{PR*MOPI} + 0.000152\,\text{IP*SOI} + 0.000027\,\text{IP*SOPI} - 0.000017\,\text{IP*MOPI} - 0.00561\,\text{SOI*SOPI} - 0.00114\,\text{SOI*MOPI} - 0.00048\,\text{SOPI*MOPI} \qquad (5)$$

$$\text{NOx (PPM)} = -2262 - 1.61\,\text{PR} + 2.73\,\text{IP} + 120\,\text{SOI} + 104\,\text{SOPI} + 8.8\,\text{MOPI} + 0.0469\,\text{PR*PR} - 0.001299\,\text{IP*IP} - 1.41\,\text{SOI*SOI} + 0.80\,\text{SOPI*SOPI} + 0.171\,\text{MOPI*MOPI} + 0.00450\,\text{PR*IP} - 0.115\,\text{PR*SOI} - 0.245\,\text{PR*SOPI} + 0.010\,\text{PR*MOPI} - 0.0228\,\text{IP*SOI} - 0.1250\,\text{IP*SOPI} + 0.0074\,\text{IP*MOPI} - 3.31\,\text{SOI*SOPI} - 1.00\,\text{SOI*MOPI} + 0.34\,\text{SOPI*MOPI} (6)$$

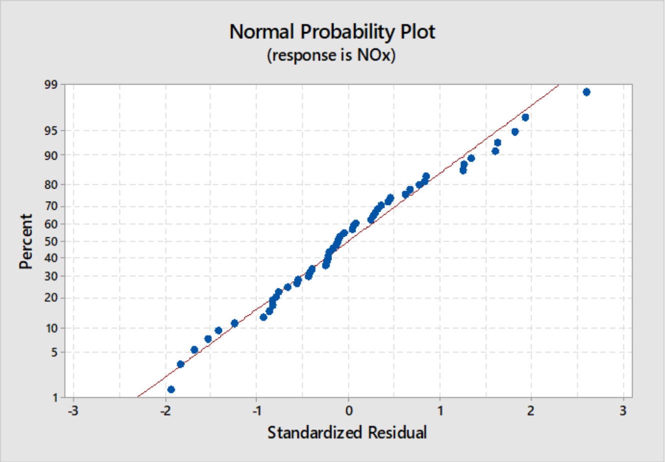
In order to predict the BSFC and NOx of RCCI engine, the actual values of the parameters have to be substituted in the equation 5 and 6 respectively.

Model Adequacy

The probability residual graphs and plot of fitted value versus residual are used to check the residual distribution among the data points and model adequacy. If the model is adequate, the points on the normal probability plots of the residuals should form a straight line.



(a)

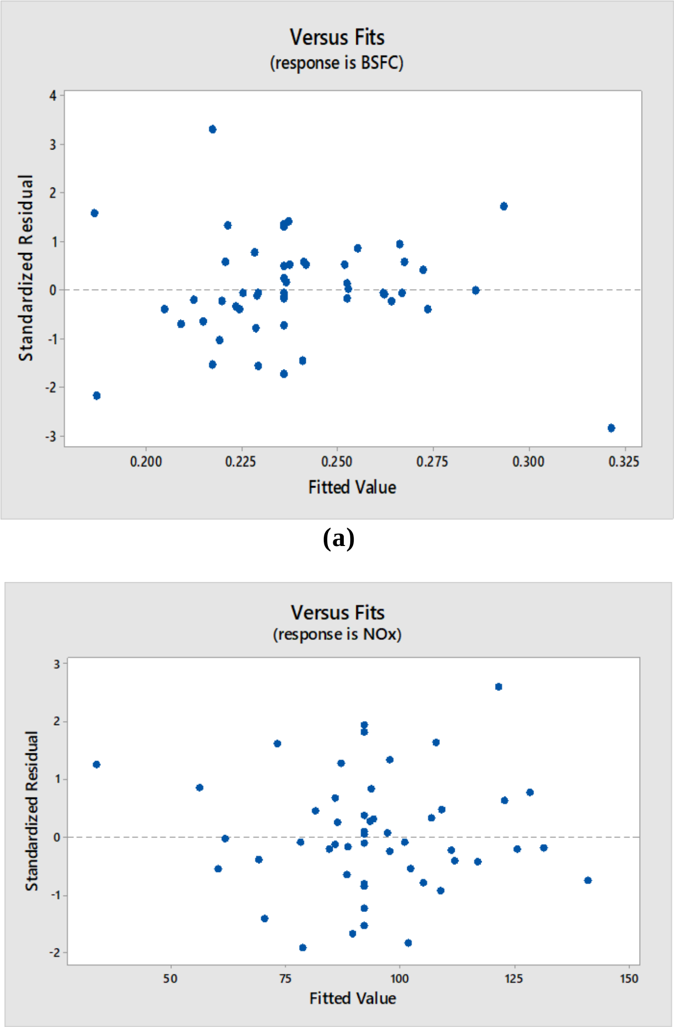


(b)

Fig. 8. Normal probability plots for (a) BSFC (b) NOx

The normal probability graphs of the BSFC and NOx are shown in figure 8. It is clear from figure 8 that no evidence of the violation is observed in any plots which suggest that the errors are normally distributed. It is also seen that the points on the normal probability plot of the residuals lie reasonably close to a straight line

Figure 9 shows the variation of the fitted values against the residual plots of the BSFC and NOx. It is known that the plots of the residuals versus the fitted response values should be structure less i.e., they should not contain any obvious patterns [18]. Hence, the model developed is more than adequate, as the measured points are scattered.



(a)

(b)

Fig. 9. Fitted values versus residual plots for (a) BSFC (b) NOx

CONCLUSION

The present work focuses on the variation of fuel injection parameters for a compression ignition engine working on RCCI mode when operating at constant speed and load using DOE. Based on the analysis of the results, the following conclusions are listed out.

The quadratic models using response surface methodology at 95% confidence levels were found to be the most important to analyse the injection parameters.

- The response surface methodology helps to find optimum factors for lower BSFC and NOx for variable injection parameters.
- Based on the multi-objective optimization technique from the contour plots, it is concluded that at IP as 600 bar and SOMI as 15 CAD, minimum BSFC can be achieved.
- The RSM results shown that performance parameters and exhaust emissions were most significantly affected by PR, IP and SOMI while SOPI and MOPI were least significantly affected.

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ABBREVIATIONS

ANOVA	Analysis of variance
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CAD	Degrees of Crank Angle
CDC	Conventional Diesel Combustion
CI	Compression ignition
DI	Direct Injection
DOE	Design of Experiment
EGR	Exhaust Gas Recirculation
EGT	Exhaust gas temperature
HCCI	Homogeneous Charge Compression Ignition
HRR	Heat release rate
ITE	Indicated thermal efficiency
IC	Internal combustion
LTC	Low Temperature Combustion
MOPI	Mass of Pilot Injection
NOx	Oxides of nitrogen
PCCI	Premixed Charge Compression Ignition

PM	Particulate matter
PFI	Port Fuel Injector
PR	Premixed ratio
PRR	pressure rise rate
RCCI	Reactivity Controlled Compression Ignition
SI	Spark Ignition
SOI	Start of Main Injection
SOPI	Start of Pilot Injection
TDC	Top dead center