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ORIGINAL ARTICLE

Optimization of combustion parameters for CRDI small single cylinder diesel engine by using response surface method

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ABSTRACT – Limited fossil fuel's reservoir capacity and pollution caused by them are the big problem today in the world. The small diesel engine, working with a conventional fuel injection system was the major contributor to this. The current study represented a statistical investigation of such a small diesel engine. A mechanical fuel injection system of the small diesel engine was retofitted with a simple version of the electronic common rail diesel injection (CRDI) system in the present study. The effect of combustion parameters such as compression ratio (CR), injection pressure (IP) and start of injection timing (IT) was considered in the study. The study was performed to optimize these parameters with respect to performance and emission aspects. The reduction in parameters such as carbon monoxide (CO), nitrogen oxides (NOx), smoke and hydrocarbon (HC) from engine exhaust gases were considered in the emission aspect. Improve brake thermal efficiency (BTE) and fuel economy was considered in the performance aspect. The response surfaced method (RSM) was used to optimise these combustion parameters. The regression equations were obtained for measurable performance and emission parameters using the RSM model. The surface plots derived from the regression equations were used to analyse the effect of considered combustion parameters. Diesel injected at a pressure 600 bar, with retarded injection timing 15° crank angle (CA) before top dead center (bTDC) and compression ratio set at 15 was found to be optimum for this CRDI small diesel engine. The further validation of optimum parameters was done by conducting a confirmatory test on the engine. The maximum error in prediction was found to be 2.7%, which shows the validation of the RSM model.

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KEYWORDS
CRDI small diesel engine; performance parameters; emission parameters; response surface method

INTRODUCTION

Today, the world is facing a major problem of pollution. The small diesel engines were primarily getting used in many stationery as well as mobile applications. Most of such small diesel engines still use a mechanical fuel injection system for delivering the required quantity of fuel at the end of the compression stroke. A conventional injection system does not have precise control over the fuel injecting process parameters. Hence, small diesel engines have become one of the leading causes of pollution in most of the cities in developing countries [1]. To curb pollution, the government has implemented stringent emission norms. Electronic fuel injection systems were adequate for large diesel engines due to their flexible injection strategy and process multiple injection capabilities. Also, in an electronic injection system, combustion parameters such as injection pressure (IP), fuel injection rate and the start of injection (SOI) can be modified to obtain a more complete combustion under different engine operating conditions [2]. However, such types of measures are still not implemented for small diesel engines, which cause fuel wastage and higher emissions from small diesel engines.

In the past, a lot of experimental work has been done on small diesel engines in order to improve efficiency and reduce emissions. The researchers have considered the combustion parameters such as fuel, injection pressure, injection timing (IT), compression ratio (CR) and % exhaust gas recirculation (EGR) during their study. Out of all these parameters IP, IT and CR are the most considered parameters for the study by the researchers due to possible effective control over the combustion by these parameters. Narsinga et al. [3] have performed experimental work on single-cylinder diesel engine operated with a conventional injection system. A trial was conducted at different IP, rangeing from 200 bar to 240 bar and IT was considered as 19, 23 and 27° crank angle (CA) before top dead center (bTDC). The performance and emission characteristics were observed and it was noted that 240 bar IP and 19° bTDC IT gives better performance with lower emission. The effect of IP on the performance of a conventional diesel engine was also studied by Srivastva et al. [4] and Theja et al. [5] . The results show improvement in performance attributes with an increase in IP. Despite all of the above work, the problem of pollution remained unsolved. The main reason for the same was the limited range of variation in parameters like IP, IT and nozzle geometrical parameters through a conventional mechanical injection system. Also, maintaining precise control over injection parameters such as IP and IT was quite difficult and less accurate in a conventional injection system. From last decade to till today, researchers try to implement the common rail direct injection (CRDI) system for small diesel engines. For the same, many of them took a trial by replacing the conventional injection

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system with the existing CRDI injection system and analyse the effect of the same on the small diesel engines. Agrawal et al. [6-7] had replaced replace the conventional injection system with CRDI. Authors had not made any drastic modifications in the hardware system or electronic control unit recalibration of the existing CRDI system. A series of experiments carried out for a different combination of IP as well IT. A similar kind of work was also done by Carpenter et al. [8] for small industrial diesel engines. After taking a trial with modified fuel injection system, it was found that nitrogen oxides (NOx) and smoke opacity decreases, but other parameters like hydrocarbon (HC) and carbon monoxides (CO) were increases. Authors had suggested suggest that optimizing the parameter of an electronic fuel injection system will give better results. Jain et al. [9] analysed from their experimental work that fuel-injected at a higher pressure and injection timing set nearer to the top dead center (TDC) improved combustion characteristics. It is also observed that too high fuel injection pressure (say beyond 1000 bar) shows inferior combustion behaviour. Pai et al. [10] analysed the effect of injection system parameters such as IP and IT on the performance and emission of a modified (CRDI) single-cylinder diesel engine. The analysis shows that 800 bar IP and IT set at 18° CA bTDC, gives the best results. Authors concluded that increasing fuel IP and proper injection timing results in quality combustion. Raeie et al. [11] were simulated the spray and combustion process of diesel for early and late injection timing related to TDC. The range of IP considered was from 275 to 1000 bar. It was observed that early injection timing shows lower soot and higher NOx emission than late injection. Hwang et al. [12] conduct an experiment on a single-cylinder engine attach with a high-pressure CRDI system. The result analysis shows that the increase in IP gives higher cylinder pressure and mean pressure acting on the piston with lower CO and HC formation. From the past study, it was found that CR significantly affects the performance and emission attributes of diesel engines. Hence, still today researchers give importance to CR parameter. An increase in CR improves the performance characteristics but degrades the emission characteristics and vice-versa [13]. Dev et al. [14] conducted a trial on the single-cylinder multi-fuel engine, which was operated with acetylene combined with diesel. The trial was conducted for different CR such as 18, 18.5,19 and 19.5. The result shows that cylinder pressure as well as heat release rate increases with CR. 19.5 CR shows higher break thermal efficiency (BTE) with a simultaneous reduction in NOx and CO emission. Goel et al. [15] summarised the individual and combined effect of IP, IT and CR on small diesel engines, which uses conventional injection system. Recently, low-temperature combustion was the new technique invented by researchers in order to decrease the NOx and soot emission without degrading the performance of small diesel engines. The lowering the CR of the engine has been found an effective way to get low temperature combustion [16-17].

However, a very scanty study was found on combining the benefit of CRDI injection system parameters with the compression ratio. Only a few tried to optimise the CRDI injection system parameters using a suitable optimisation technique. Hence in the present study, we have taken IP and IT along with CR as parameters for research and analysed the individual and interactive effect of the same on small diesel engines performance and emission attributes. The RSM method was used to obtain optimise value of combustion parameters. Experimental trials were performed to validate the obtained optimised parameters. The performed study and obtained optimum parameters are critical in designing an injection system for a small diesel engine.

METHODS AND MATERIALS

The design of experiments (DOE) strategy is applied to correlate the effect of combustion parameters on the selected responses. The effective and feasible ranges of parameters (IP, IT and CR) are finalised based on trial experiments. These ranges are used further for the preparation of DOE as per response surface methodology (RSM). With the help of DOE and RSM, the experiments were carried out on a variable compression ratio (VCR), 4-stroke water-cooled direct injection, diesel engine. Table 1 shows the specification of the engine used for performing experiments. An eddy current type dynamometer was connected inline to the engine for loading. A piezoelectric transducer was used to measure pressure variation inside the cylinder, which was flush-mounted in the cylinder head. The fuel flow rate was calculated using a fuel flow meter, while the intake air flow rate was calculated through the air transmitter. The conventional fuel injection system was retrofitted with an electronic CRDI system, which has a high-pressure fuel pump, high-pressure rail, an electronic diesel fuel injector and the engine control module (ECM). The parameters such as IP and IT was varied through ECM. The detailed specification of the same is mentioned in Table1. The pictorial view of the complete setup with retrofitted CRDI system and emission instruments was shown in Figure 1. The compression ratio of the engine was varied by using a method of tilting the cylinder block. The desired compression was achieved by referring to the scale provided on the CR indicator of the engine. Emissions such as CO, HC and NOx were measured by using an exhaust gas analyser, while smoke opacity value is obtained from the AVL smoke meter. The range, accuracy and percentage uncertainty of these instruments was as shown in Table 2. The trials were conducted for a different combination of a selected parameter, as shown in Table 3. Figure 2 shows the flowchart of the experimental procedure.

Table 1. Engine and retrofitted CRDI system specifications

Engine Specification		CRDI System Specification	
Engine type	Kirloskar	Common rail	Bosch
Number of cylinders	Single (01)	Injector	Solenoid
Bore	80 mm	No. of holes	7
Stroke	110 mm	Diameter of holes	215 mm
Compression Ratio	12 to 18	injector opening pressure	300-1400 bar
Rated Power	3.5 kW @1500 rpm	ECU control	Nira software

Table 2. Range, accuracy, resolution with measuring method of instruments used

Instrument Used	Exhaust Gas	Measurement Range	Resolution	Accuracy	Uncertainty
AVL 444N Five gas analyser	CO	0-15.0% vol	0.01% vol	± 0.06%	±0.2%
	HC	0-30,000 ppm	1 ppm vol	±12ppm	±0.2%
	NOx	0-5000 ppm	1 ppm vol	±50ppm	±1%
AVL 437C Smoke metre	Smoke Opacity	0-100%	1 ppm vol	±1%	±1%

Table 3. Parameters with their selected values for experimentation

Factors	Level		
	1	2	3
CR	14	16	18
IP in bar	400	500	600
IT °CA (bTDC)	15	20	25

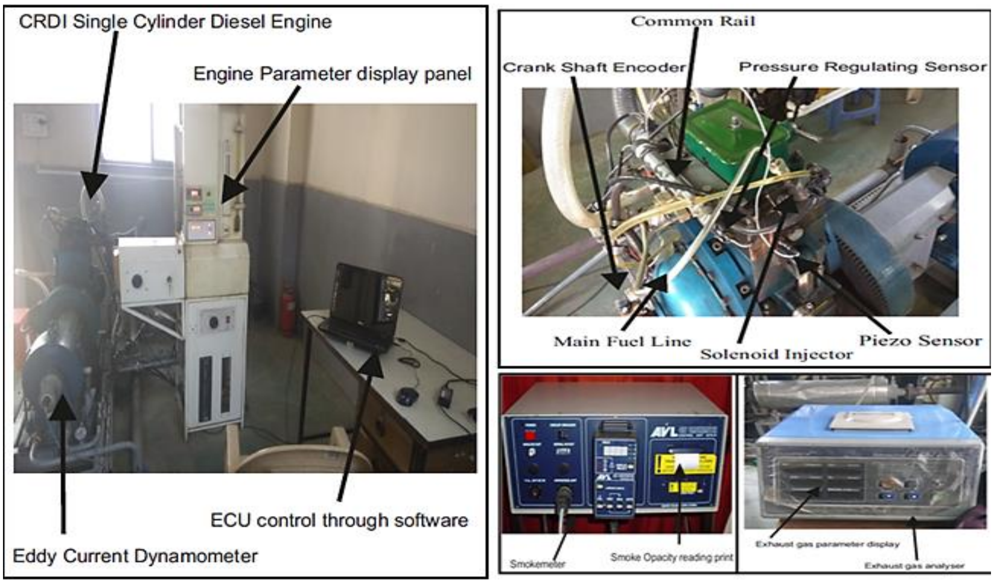


Figure 1. Pictorial view of experimental setup with modified CRDI system

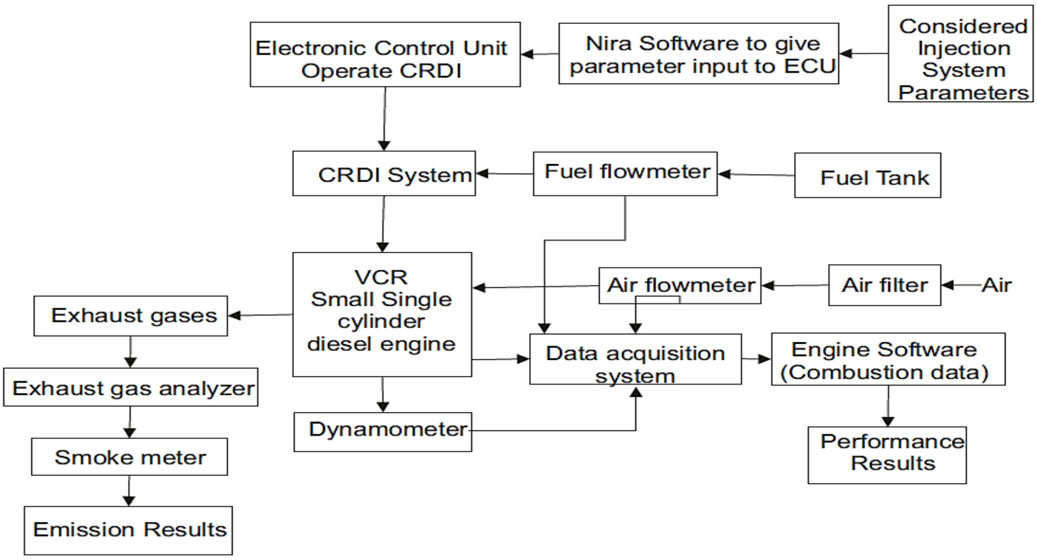


Figure 2. Flow chart for experimental methodology

RESULTS AND DISCUSSION

Experimental trials were conducted on different combinations parameters of Table 3 and from that engine performance and emission characteristics were obtained. Experiments were repeated and average values were considered for further calculations. For the entire set of experiments, the speed of the engine was maintained constant at 1500 rpm, keeping the load on the engine at 12 kg. The mineral diesel was used as the test fuel. RSM method was used to obtain regression equations of performance and emission parameters. Table 4 shows the summary of performance and emission parameters evaluation by RSM. All obtained values of the goodness of fit show that the model very well fits the data. Further, the regression equations were used to draw a surface plot in MATLAB. The combined effect of considered injection system parameters such as injection pressure (IP), injection timing (IT) and compression ratio (CR) on small diesel engine was analysed from the surface plot. The optimum solution for the best performance of the engine was obtained through the desirability approach.

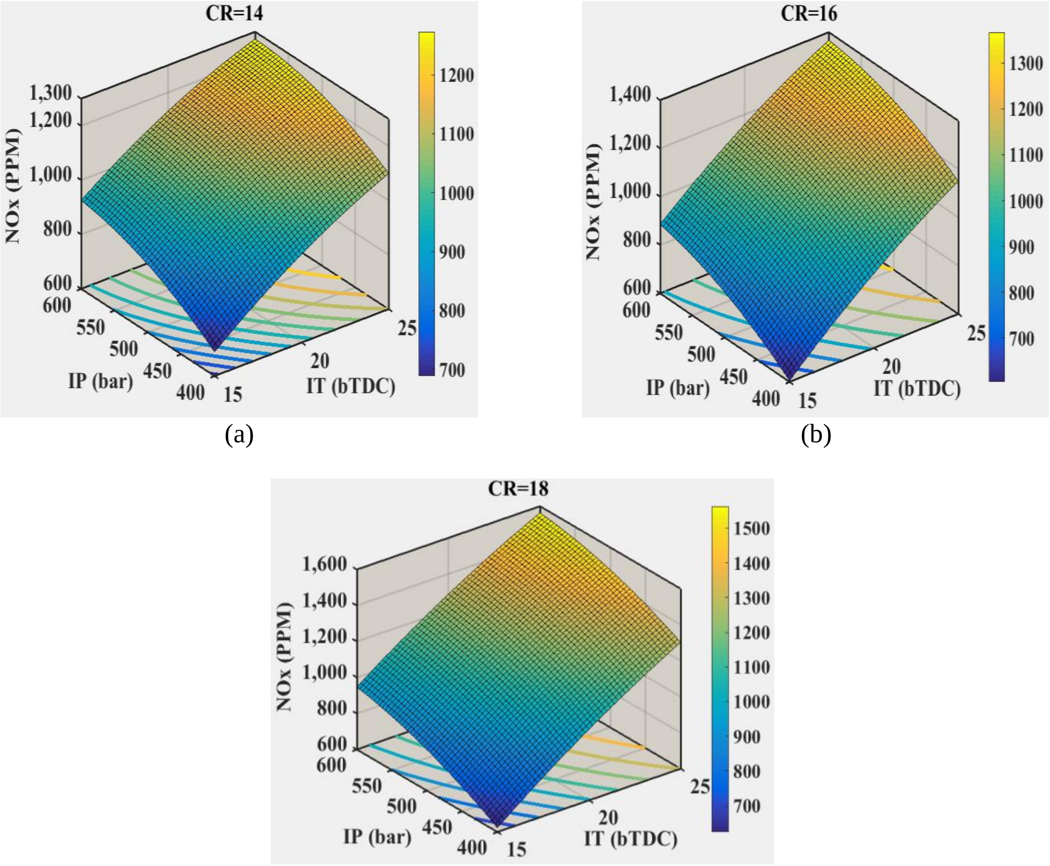
Table 4. Summary of response surface model evaluation

Model	BTE	BSFC	CO	HC	NOx	Smoke Opacity
Mean	24.81	0.3473	0.287	19.34	1063.3	8.759
Standard Deviation	0.9058	0.0128	0.069	5.788	217.5	3.114
R^2 (goodness of fit)	99.75%	99.73%	98.29%	98.72%	99.86%	99.10%
Adjusted R^2 (goodness of adjusted)	99.52%	99.49%	96.75%	97.56%	99.73%	98.29%
Predicted R^2 (goodness of prediction)	97.05%	97.52%	86.25%	91.48%	98.67%	90.95%

NOx Emission

The factor responsible for the formation of NOx emission was a rise in temperature inside the cylinder after combustion. The interactive effect of CR, IT for different IP on NOx emissions, as shown in Figure 3. It was observed that NOx emissions were low when IT shifts towards TDC with low IP (400 bar) for all CR. However, high IP with advanced IT shows relatively higher NOx emissions for all CR. This might be due to the longer ignition delay observed at advanced IT [18]. A more extended delay period results in fuel accumulation, due to this offered formation of high peak combustion pressures and temperatures inside engine cylinder [19]. Higher delay period also results in a higher heat release rate in the premixed combustion phase. Keeping low CR with retarded (shifting towards TDC) IT, limits the rise in combustion temperatures of fuel-air mixtures. This results in a reduction in NOx formation [20]. Figure 4 shows the individual effect of CR, IP and IT on the NOx emission, which shows that IT was the key parameter followed by IP and CR in order to control NOx emission. For low CR, pressure and temperature inside the cylinder at the time of fuel injection were less compared to a higher CR. Due to this, more time was required for vaporisation of the fuel-air mixture. Due to retarded injection timing, the actual combustion occurs near and after the top dead centre. The combined effect of these combustion parameters results in a lower rise in combustion temperature inside the cylinder [21]. However, the increase in IP caused an increase in NOx emission. This might be due to the breakdown of the fuel droplet at high IP, which was further appropriately mixed with air. This results in a more complete combustion, which produced high temperature after combustion [22]. Hence, the combination of high IP and appropriate retarded IT with moderate CR will reduce NOx emissions without decreasing the performance of the engine. Equation (1) as given below, was for the regression model developed for NOx emissions.

$$\begin{aligned} NOx = \; & 3407 - 571.4\,CR + 4.343\,IP + 10.4\,IT + 12.85\,CR{*}CR - 0.004209\,IP{*}IP - 1.264\,IT{*}IT \\ & + 0.1088\,CR{*}IP + 6.700\,CR{*}IT - 0.03150\,IP{*}IT \end{aligned} \tag{1}$$



(a) (b)

(c)

Figure 3. Interactive effect of IT and IP on NOx for: (a) CR = 14, (b) CR = 16 and (c) CR = 18

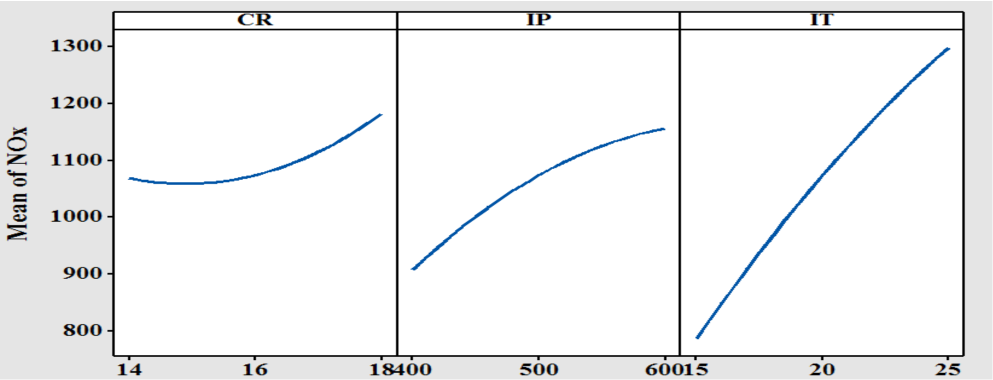
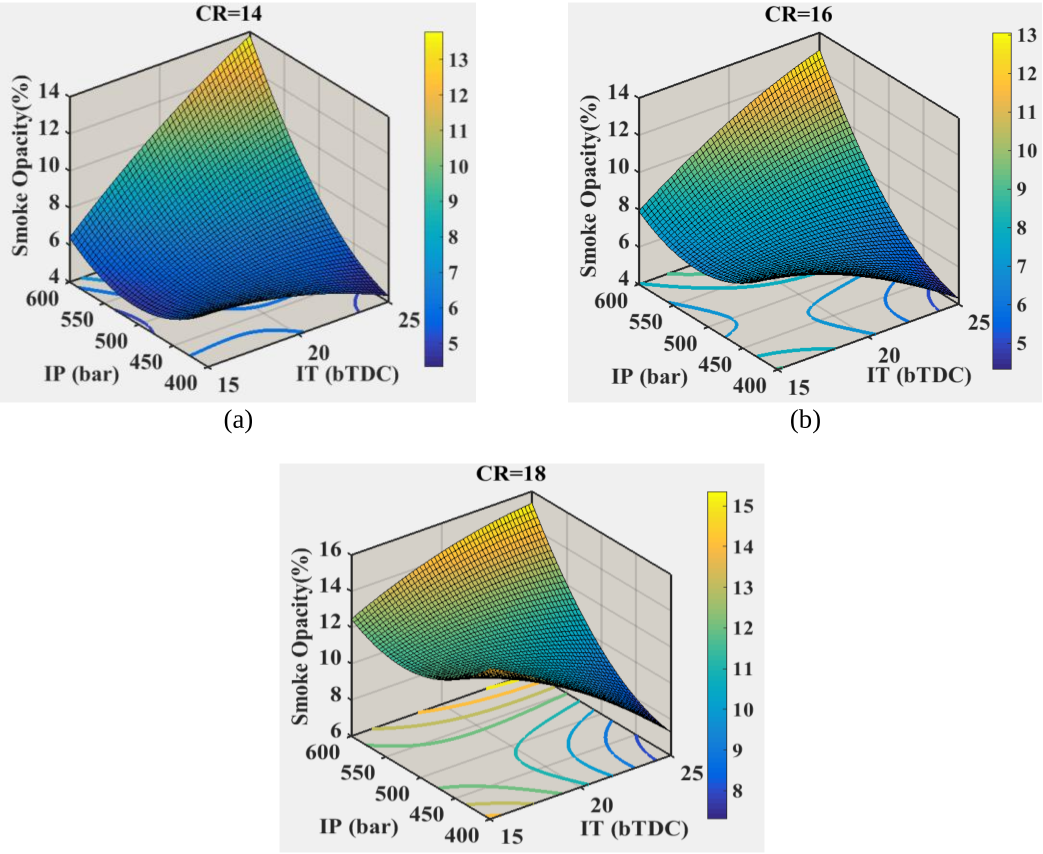


Figure 4. Individual effect of CR, IT and IP on NOx

Smoke Opacity

The solid or liquid carbon particles present in the engine exhaust gases are term as smoke. Improper mixing of fuel particles with the air causes the formation of smoke emissions. The interactive effect of CR and IT for different IP on smoke opacity is shown in Figure 5. It can be deduced that lower IP and at advance IT shows significantly less smoke emission for all CR. Low smoke emissions were also evident with an increase in IP with retarded IT. But at the same time, for advance IT, smoke emissions showed a steep rise with IP. A smoke emission mainly depends upon the oxygen content of the fuel. The rise in IP results in effective fuel spray atomisation, which gives improved fuel-air mixing, further decreasing the smoke emission. The same effect was observed by Jain et al. [23] in their research work. It was observed that lowering CR with advanced IT shows a decreas in smoke opacity. This might be due more extensive delay period, which gives more time for fuel to interlock with oxygen. The individual effect of considered combustion parameters CR, IT and IP was shown in Figure 6, which shows that CR and IP mainly affect smoke formation. The increased CR from 14-18 shows higher smoke emission for all combinations of IP and IT. As CR increases, the sufficient time required for fuel-air mixing was decreasing; hence there was a formation of a more heterogeneous fuel-air mixture inside the combustion cylinder. The regression equation between smoke opacity and all considered parameters were as given in Eq. (2),

$$\begin{aligned}\text{Smoke Opacity} = \quad & 111.1 - 7.79\ CR - 0.2270\ IP + 0.134\ IT + 0.3764\ CR{*}CR + 0.000175\ IP{*}IP \\ & - 0.01977\ IT{*}IT - 0.001750\ CR{*}IP - 0.1125\ CR{*}IT + 0.004950\ IP{*}IT\end{aligned} \tag{2}$$



(a)

(b)

(c)

Figure 5. Interactive effect of IT and IP on smoke opacity for: (a) CR = 14, (b) CR = 16 and (c) CR = 18

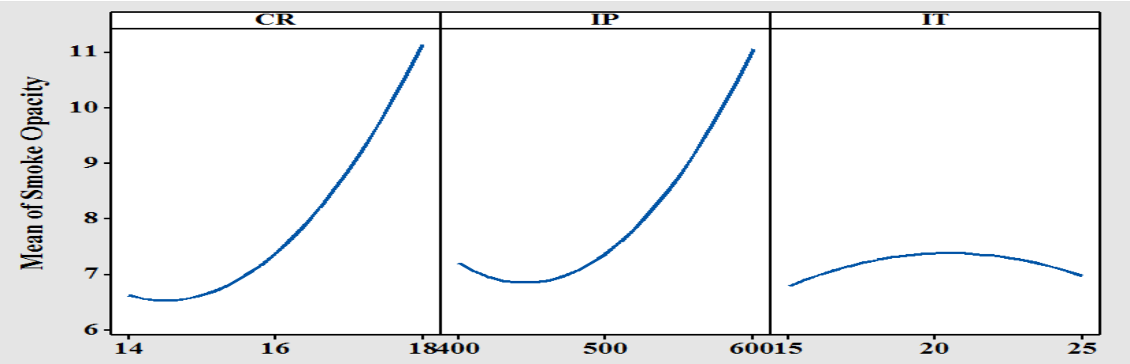
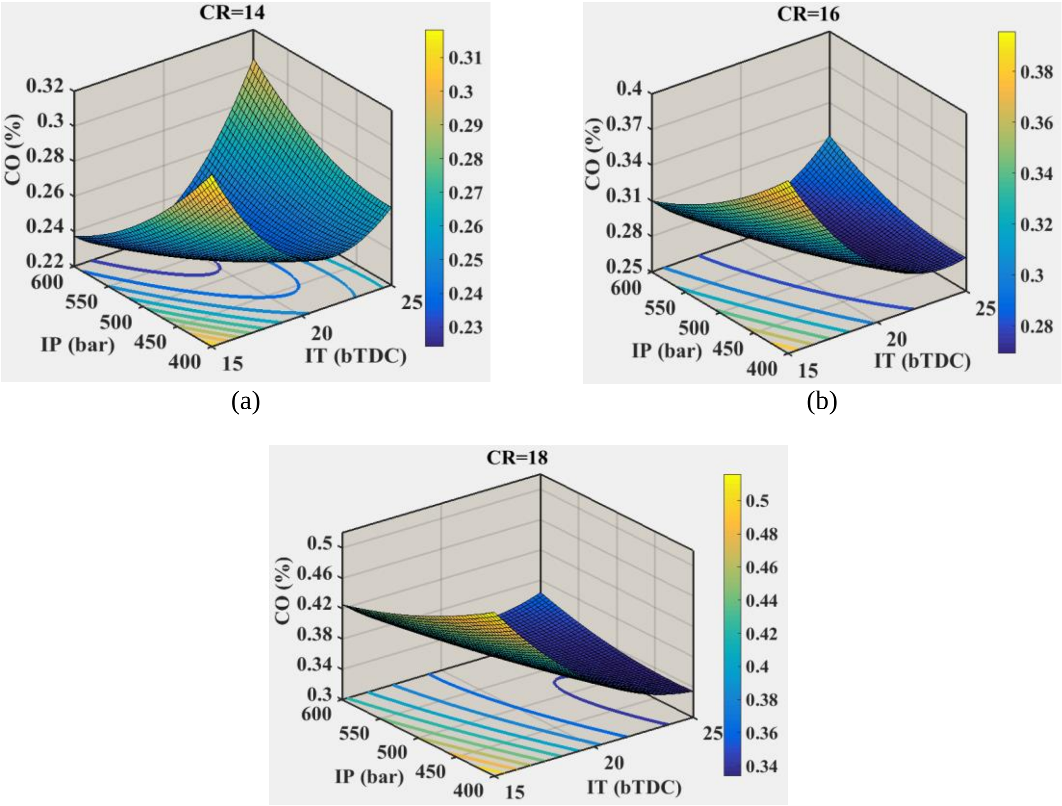


Figure 6. Individual effect of CR, IT and IP on smoke opacity

Carbon Monoxide (CO) Emissions

The incomplete oxidation of carbon particles or insufficient oxygen during combustion was the primary cause of CO emission. The interactive effect of CR and IT for different IP on CO emissions is shown in Figure 7. CO emissions were low at lower CR and retarded IT when IP set at 600 bar. It was observed that for retarded IT, CO emissions increases with increasing CR. A rise in CR increases the relative air-fuel ratio and hence more heterogeneous mixture formed inside the cylinder. This phenomenon results in higher CO emissions. Also, the retarded IT forced the major part of combustion after TDC i.e. into power stroke or during the expansion stroke. The combustion takes place after TDC having lower pressure and temperature. This causes the formation of CO [6]. The increase in injection pressure decreases CO emissions level at retarded IT. This was due to the quality spray penetration achieved because of high IP, resulting in nearly complete oxidation of carbon inside fuel [19]. Figure 8 shows the individual effect of CR, IT and IP on CO emissions, which indicates that CR mainly controls CO emissions, followed by IT and IP. Equation (3) shows regression equation developed for CO with the considered parameter, which given as below,

$$\begin{aligned}\mathrm{CO} = \quad & 1.675 - 0.0698\ \mathrm{CR} - 0.002137\ \mathrm{IP} - 0.0476\ \mathrm{IT} + 0.00537\ \mathrm{CR*CR} + 0.000001\ \mathrm{IP*IP} \\ & + 0.001571\ \mathrm{IT*IT} - 0.000012\ \mathrm{CR*IP} - 0.003188\ \mathrm{CR*IT} + 0.000060\ \mathrm{IP*IT}\end{aligned} \tag{3}$$



(a) (b)

(c)

Figure 7. Interactive effect of IT and IP on CO for: (a) CR = 14, (b) CR = 16, and (c) CR = 18

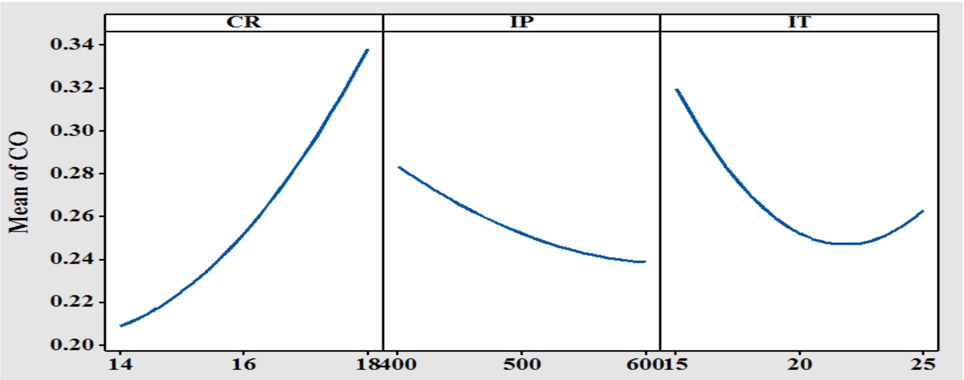
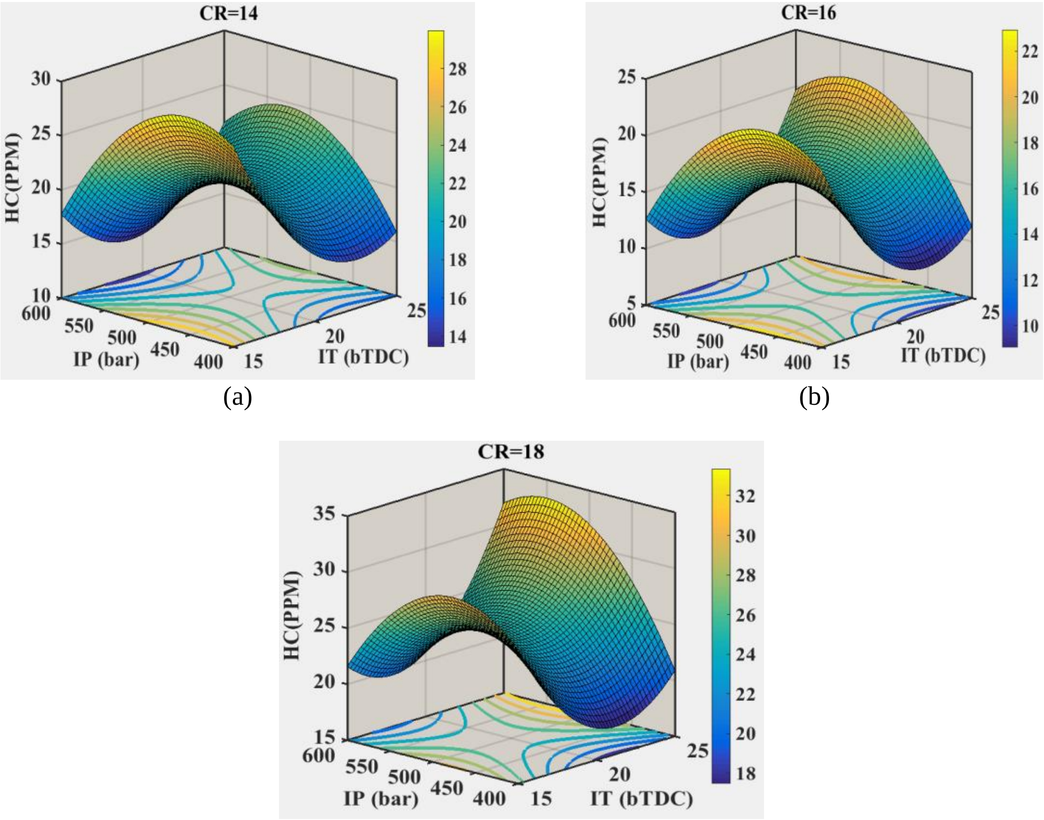


Figure 8. Individual effect of CR, IT and IP on CO

Hydrocarbon (HC) Emission

The incomplete combustion of fuel and less density of oxygen during combustion causes the formation of HC emission. The interactive effect of CR and IT for different injection pressures on HC emissions are shown in Figure 9. It was observed that there were fewer hydrocarbon emissions for the parameters IP set to 600 bar and IT at 20° bTDC at all CR. On the other hand, higher rate of HC emissions were observed on either side of moderate IT. At lower IP, hydrocarbon emission was found to decrease with advancing IT from 15° to 25° bTDC at all CR. But for higher IP and the advanced start of IT, showed a higher value of hydrocarbon emission and the same has been found to increases with an increase in CR from14 to18. 500 bar IP shows a higher value of HC emission at all CR. Figure 10 gives the individual effect of parameters IT, IP and CR on HC emission, which indicates that IP was the critical parameter in order to decrease the HC emission. The parameters such as the rate of fuel injection, penetration of fuel inside compressed air and mixing rate with air were accelerated with an increase in IP. An intermediate value of CR (CR16) shows lower HC emissions than the other two CR for a different combination of IP and IT. The reason for an increase in HC emission for retarded IT was piston wall impingement of the fuel sprays mention by kumar and Gakkhar [24] in his research work. This reason point towards the nozzle holes orientation and injector nozzle angle with respect to the combustion chamber. The regression equation developed between HC and all considered combustion parameter was given in Eq. (4) below,

$$\begin{aligned}HC = 597.4 - 61.96\,CR + 0.2851\,IP - 16.53\,IT + 1.762\,CR{*}CR - 0.000557\,IP{*}IP + 0.2420\,IT{*}IT + \\ 0.00678\,CR{*}IP + 0.1645\,CR{*}IT + 0.008210\,IP{*}IT\end{aligned} \tag{4}$$



(a) (b)

(c)

Figure 9. Interactive effect of IT and IP on HC for: (a) CR = 14, (b) CR = 16, and (c) CR = 18

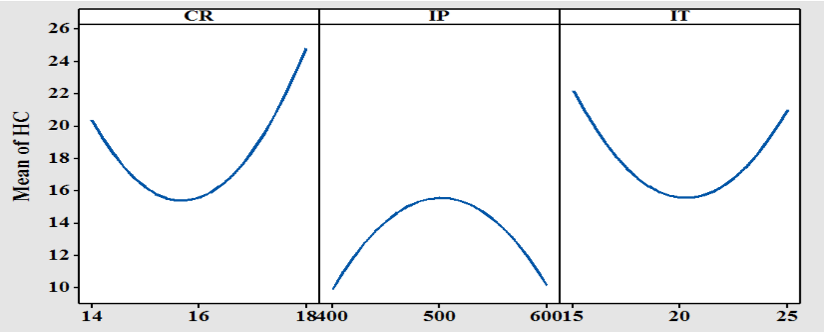
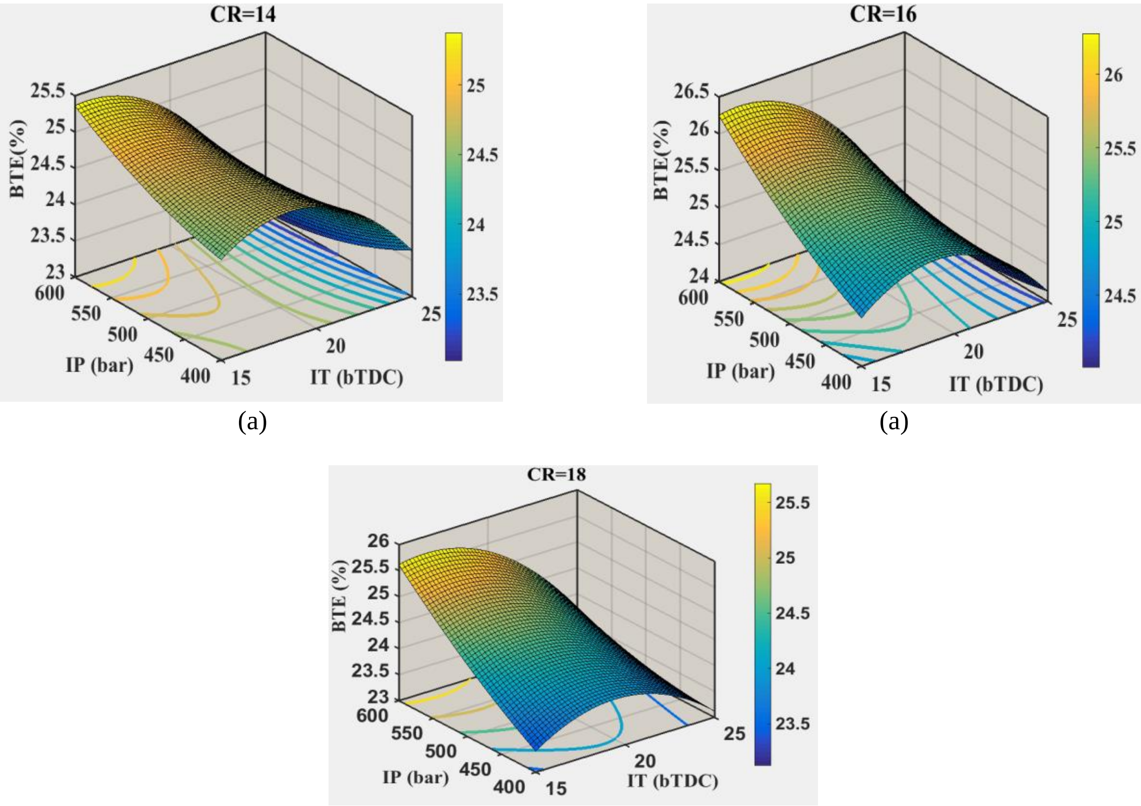


Figure 10. Individual effect of CR, IT and IP on HC

Brake Thermal Efficiency (BTE)

Effective conversion of chemical energy of the fuel to mechanical work is known as BTE. Figure 11 shows the interactive effect plot of IT, IP and CR. From the interaction plot, BTE was found to be high at CR16 and at retarded IT with high IP. IP shows a considerable effect on BTE. Advanced IT shows a decrease in thermal efficiency for this newly developed CRDI system. This might be due to negative work done on the piston due to the early combustion of fuel. High IP with retarded IT shows a high value of BTE at all CR. There was a decrease in injection interval timing due to high IP, which further affects the combustion parameters like cylinder pressure and heat release rate. The BTE was found to decreases with an increase in CR for retarded IT. For retarded injection, a large part of injection shifts towards TDC, which causes the combustion to continues into the expansion stroke. Due to the expansion of combustion gases, there will be a drop in cylinder peak pressure, temperature and heat loss from the cylinder. Subsequently, there was a reduction in the power output of the engine, which causes a lower performance of the engine [25]. Figure 12 shows the individual effect of considering combustion parameters on BTE, which shows that IP and IT was the key parameter followed by CR from the performance point of view. Equation (5) gives the regression model developed for BTE with considered combustion parameters,

$$\begin{aligned}\mathrm{BTE} = {} & -21.40 + 5.037\,\mathrm{CR} - 0.01776\,\mathrm{IP} + 1.1459\,\mathrm{IT} - 0.18984\,\mathrm{CR{*}CR} + 0.000013\,\mathrm{IP{*}IP} \\ & -0.02661\,\mathrm{IT{*}IT} + 0.001544\,\mathrm{CR{*}IP} + 0.01163\,\mathrm{CR{*}IT} - 0.000798\,\mathrm{IP{*}IT}\end{aligned} \tag{5}$$



(a)

(a)

(c)

Figure 11. Interactive effect of IT and IP on BTE for: (a) CR = 14, (b) CR = 16, and (c) CR = 18

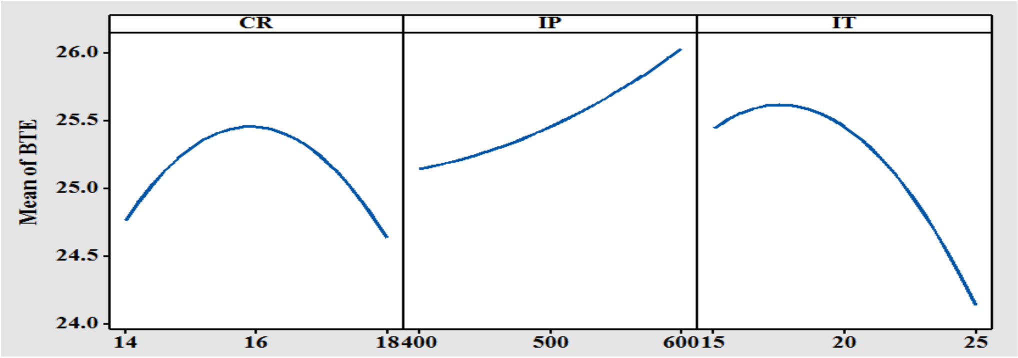
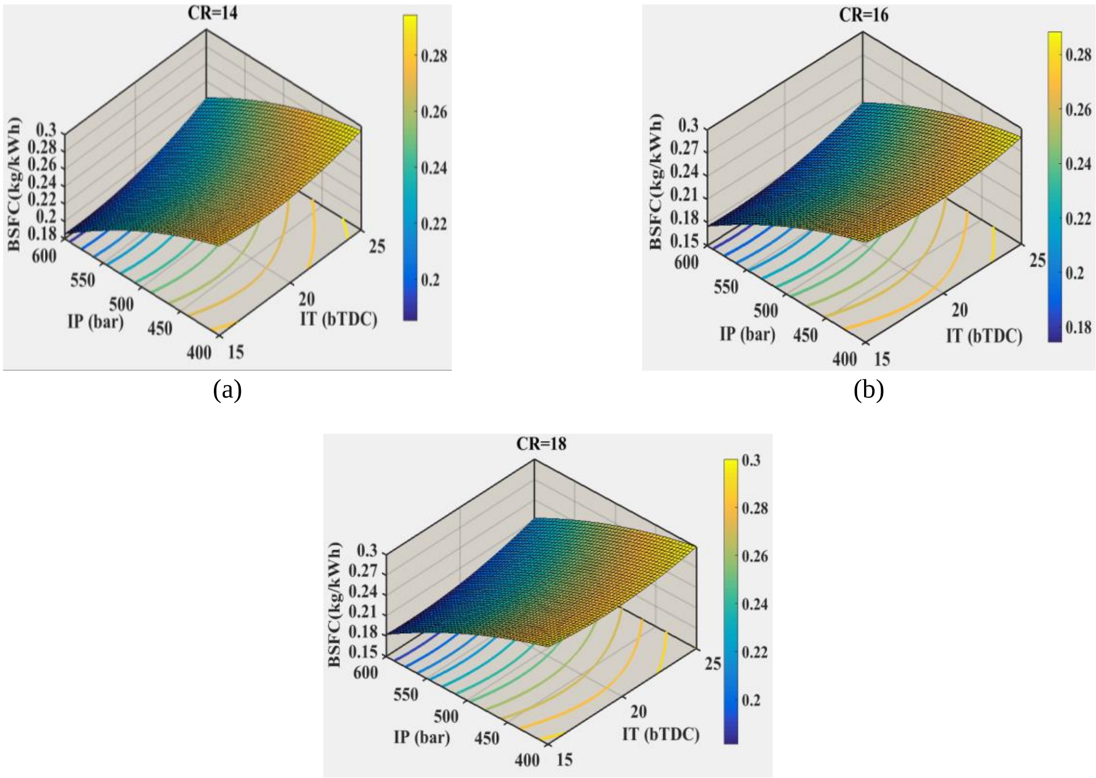


Figure 12. Individual effect of CR, IT and IP on BTE

Brake Specific Fuel Consumption (BSFC)

The BSFC value shows the economic performance of the engine. The interactive effect of CR and IT for different injection pressure on HC emissions were shown in Figure 13. From the interactive effect plot of BSFC, it could be seen that the retrofitted CRDI diesel setup presents the lower value of BSFC at the higher IP with retarded IT and low CR (bluish zones in the response surface). This was due to a breakdown of fuel droplets into finer because of high IP. Further, these droplets correctly mixed with the air due to an increase in the number of holes on the nozzle. Also, increase in penetration length due to high IP. All these factors helped to achieved nearly complete combustion of fuel. Hence, CRDI system offeres more effective utilisation of the chemical energy of fuel for small diesel engine by selecting appropriate IT and CR. The value of BSFC was decreasing with retarding IT for all CR. An increase in BSFC at advance IT, was observed because of the shifting of the combustion phase away from TDC [9]. Such a kind of combustion leads to a decrease in power output for the given fuel. When ignition occurs near or few degree CA before the TDC, the negative work acted on the piston gets minimized and the force exerted by combustion is delivered to the piston more effectively, resulting in the highest mean adequate pressure; thus the consumption of fuel was also getting decreased [19]. The individual effect of considered parameters CR, IP and IT on BSFC was shown in Figure 14, which shows that high IP with retarded IT gives economic fuel consumption of the engine. Equation (6) as given below, gives the regression model of BSFC with considered combustion parameter,

$$\begin{aligned} \text{BSFC} = {} & 0.8675 - 0.06061\ \text{CR} + 0.000569\ \text{IP} - 0.01957\ \text{IT} + 0.002245\ \text{CR*CR} - 0.000001\ \text{IP*IP} \\ & + 0.000439\ \text{IT*IT} - 0.000017\ \text{CR*IP} - 0.000120\ \text{CR*IT} + 0.000012\ \text{IP*IT} \end{aligned} \tag{6}$$



(a) (b)

(c)

Figure 13. Interactive effect of IT and IP on BSFC for: (a) CR = 14, (b) CR = 16, and (c) CR = 18

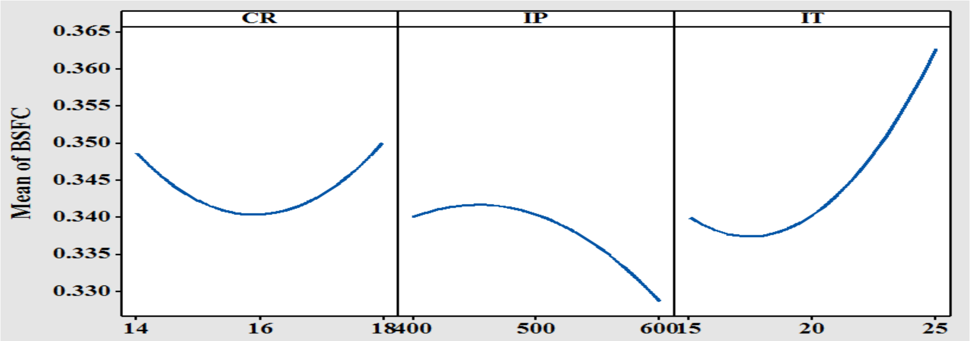


Figure 14. Individual effect of CR, IT and IP on BSFC

Optimization and Validation of Consider Combustion Parameters

There exist an essential trade-off relation between emission (NOx, smoke opacity, CO and HC) and performance (BSFC and BTE) attributes. Hence, to maximise the engine's performance, it was essential to optimize IP, IT and CR. The objective was considered to minimise NOx, smoke, HC and CO emissions along with higher BTE and lower BSFC values for optimisation. The criterion of optimization for the responses with their targeted values is mentioned in Table 5. MATLAB software was used to generate an appropriate optimum solution with high desirability over the set criterion. Table 6 gives the optimum value of the combustion parameters along with response variables for the set criteria of optimization.

Table 5. Optimization criteria with the desirability of responses

		Limit		
Response	Goal	Lower	Target	Upper
BSFC	Minimum	0.330	0.330	0.370
BTE	Maximum	23.170	25.980	25.980
NOx	Minimum	631.000	631.000	1569.000
CO	Minimum	0.196	0.196	0.510
HC	Minimum	10.770	10.770	32.000
Smoke Opacity	Minimum	4.700	4.700	15.700

Table 6. Solution obtain from desirability approach

Solution	CR	IP (bar)	IT (°CA bTDC)
1	15	600	15

BSFC FIT (Kg/Kwh)	BTE FIT (%)	NOx FIT (PPM)	CO FIT (%)	HC FIT (PPM)	Smoke Opacity FIT (%)	Desirability
0.3257	26.1216	894.222	0.230	13.755	6.780	0.9010

Results obtained through the desirability approach were validated by conducting an experiment on the engine with optimized parameters. Repeated the same experiment three times and average values were considered for further analysis. Table 7 shows the values obtained by this confirmatory experiment. The percentage error for response variables between the predicted and actual values was calculated. The maximum value of percentage error was found to be 2.70. The obtained less value of percentage error shows that the RSM model was adequate to describe the effect of considered combustion parameters on modified CRDI engine.

Table 7. Confirmatory trial test results.

Solution	CR	IP (bar)	IT (°CA bTDC)
Predicted	14.9697	600	15
Actual	15	600	15

	BSFC FIT (kg/kWh)	BTE FIT (%)	NOx FIT (PPM)	CO FIT (%)	HC FIT (%)	Smoke Opacity FIT (%)
Predicted	0.3257	26.121	894.222	0.230	13.755	6.780
Actual	0.3199	25.745	886.509	0.232	14.148	6.66
% Error	1.79	1.46	0.87	1.19	2.78	1.68

CONCLUSIONS

Present study investigated the interactive and individual effects of combustion parameters on the performance and emission characteristics of the CRDI small diesel engine. The response surface methodology was used to model, predict and optimize the measured response variables. The conclusions made from the analysis were as below:

- CR has a major influence on the emission parameter of the engine followed by the IP, while IP and IT have found a great impact on the performance characteristics of the engine.
- The moderate CR (set as 16) and retarded IT with high IP give a higher value of BTE and the best fuel economy.
- The retarded IT with lower CR shows less NOx emission, which increases further with an increase in CR and IP.

- The high IP and advanced IT at low CR give lower CO emission and smoke opacity value.
- The moderate IT (20° CA bTDC) and CR (set as 16) gives lower HC emission irrespective of IP.

From set optimization criteria and validation trial results on considered retrofitted CRDI system small diesel engine, following observations were made.

- Combustion parameters as 600 bar IP, 15° CA bTDC IT and CR set to 15 is found to be optimum for the engine.
- Confirmatory test results and obtain maximum error (less than 3%) show that the RSM models were adequate to describe the effect of the considered parameters on the engine.

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CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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