Enhancement of combustion characteristics of VCR diesel engine by optimizing engine parameters

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Abstract

In recent years, engine emissions have been one of the important problems which are of great concern. Hence, there is a growing need to develop engines with reduced emission. In the present study, Variable Compression Ratio diesel engine model has been validated by comparing the simulation results with the experimental. The study is aimed at analyzing the effect of compression ratio, exhaust gas recirculation, fuel injection pressure and start of injection on engine performance and emission characteristics. Using composite desirability technique, the engine parameters have been optimized to achieve lower NO_x, soot and ISFC. The optimum combination has been observed at Compression ratio 17.52, Start of injection -30.1° aTDC, Fuel injection pressure 736.06 bar and Exhaust gas recirculation 28.29%. ISFC, NO_x and soot are reduced by 2.37%, 29.11% and 83.81% respectively. Higher Target Fuel Distribution Index indicates the improved mixture homogeneity for the optimized parameters.

Keywords Compression ratio · Exhaust gas recirculation · Fuel injection pressure · Start of injection

1 Introduction

Emission control has been a major challenge faced by the modern world. IC engine being a major source of emission have to be optimized in order to improve combustion and reduce emission. In addition, diesel engines have proved to be a great threat to the environment compared to SI engines in consideration to their high NO_x and soot emission. Hence, diesel engines must be designed in order to improve their performance. These days the use of catalytic converters has come into existence. However, these are expensive. Designing an engine without incorporating any such components would be a cost effective approach [5, 16–18, 23, 26, 31].

Experimental work carried out by [1] explains the effect of EGR on performance, emission and carbon deposits in a

diesel engine. It explains how the EGR displace oxygen in the intake air and reduces the oxygen content in the combustion chamber. The specific heat of the intake air mixture increases which reduces the flame temperature. This also reduces the specific fuel consumption. In a nutshell, EGR is an effective method that can be applied to a diesel engine to reduce NO_x emission without sacrificing its fuel economy and efficiency. Min et al. [20] studied the effect of EGR by changing the N₂ mass fraction results show that the indicated specific NO_x emissions were decreased with increased EGR fractions while increases soot emissions. The simultaneous reduction of NO_x and soot was done by optimizing the engine parameters.

Jayashankara and Ganesan [14] worked on diesel engine to study the effect of fuel injection timing and injection pressure on its performance. Advanced injection

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timing resulted in an increase in in-cylinder temperature, pressure, heat release rate and NOx emissions. Advancing the injection timing increased the soot while retarding the injection timing reduced the soot emission. But at high fuel injection pressures (1.7–2 bar) advancing the injection timing reduced the soot emission. According to the work of [28] the increase in fuel injection pressure reduced the specific fuel consumption and specific energy consumption whereas decrease in injection pressure increased fuel consumption per power output.

Song et al. [30] investigated on the effect of compression ratio on combustion characteristics for homogeneous charged compression ignition engine. It was observed that compression temperature and pressure in the cylinder vary significantly with compression ratio. The study concluded almost zero NOx emission at compression ratios 10.7 and 14. Prasad et al. [24] investigated that increasing compression ratio helps in improving efficiency and reduces soot where as NOx emissions increased. The effect of FIP (Fuel Injection Pressure) on the combustion and emission characteristics was not monotonic and there exists an optimum value of fuel injection pressure. Various studies have also been reported by using preheated alternative fuels blend with various oxide nano particles in the works of Elumalai [9, 11]). It was found that inherent oxygen content improved its combustion characteristics.

From the literature it can be ascertained that improvement in the mixture homogeneity can be achieved by improvising the air–fuel mixing rate. The parameters such as EGR, compression ratio, SOI, injection pressure, etc. have shown a significant effect on air–fuel mixing rate. This can be done by optimizing the engine parameters such as

Fig. 1 Computational domain of variable compression ratio (VCR) engine model

2 Computational domain and methodology

CONVERGE™ [27] has been used for modeling the axis-symmetric engine sector and for simulation purpose. The computational domain of the VCR engine is shown in Fig. 1. The fluid flow properties are governed by the following equations:

Conservation of mass

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = S_i \quad (1)$$

Conservation of momentum

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial \sigma_{ij}}{\partial x_j} + S_i \quad (2)$$

Conservation of energy

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = -\rho \frac{\partial u_j}{\partial x_j} + \sigma_{ij} \frac{\partial x_i}{\partial x_j} + \frac{\partial}{\partial x_j} \left(K \left(\frac{\partial T}{\partial x_j} \right) \right) + \frac{\partial}{\partial x_j} \left(\rho D \sum_m h_m \frac{\partial Y_m}{\partial x_j} \right) + S_i \quad (3)$$

fuel injection pressure, compression ratio, injection timing, EGR, etc.[4].

The primary objective of this work is to improve the mixture homogeneity and analyze the effects of various parameters and their interactions on the ISFC, NOx, and soot. The simulations were performed based on design of experiments (DOE) using response surface methodology. The work also aims to find the optimal combination of compression ratio, exhaust gas recirculation, fuel injection pressure, and start of injection, which would result in better performance with reduced NOx, soot emissions.

Equation of state presented below is used to couple density, temperature and pressure

$$\frac{P}{\rho} = Z \left[\frac{R}{W} \right] \quad (4)$$

Optimization of engine parameters has been done using Design of Experiments (DOE) method. This method is effective in optimizing the engine parameters by evaluating the combined effect of input factors on output responses. The DOE technique considered in the present study is Response Surface Methodology (RSM). RSM is an efficient way of reducing the computational time with reasonable accuracy. The main aim of RSM is optimizing an output response which is effected by various input factors [6, 22].

The following 2nd order polynomial equation represents a simple approximating function

$$y = \beta_0 + \sum_{i=1}^n \beta_i x_i + \sum_{i=1}^n \beta_{ii} x_i^2 + \sum_{1 \leq i < j}^n \beta_{ij} x_i x_j + \epsilon \quad (5)$$

where, 'n' denotes the number of variables, β_0 denotes the constant term, β_i denotes the coefficient of linear terms, β_{ij} denotes the coefficient of interaction terms and ϵ denotes the error.

3 Validation of VCR engine model (Diesel)

The simulation and experimental results are compared to validate numerical results obtained for VCR diesel case from CFD code CONVERGE™. The VCR engine specifications are given in Table 1. Validation of the predicted numerical results with that of the experimental data was carried out by comparing the pressure variation with crank angle. Figure 2 shows the variation of pressure with crank angle for experimental and simulation results. The trends of simulation are similar to that of experiment. However, a slight difference of around 1.2% in peak pressure is observed. Experimental pressure shows lesser as compared to simulation. This may be due the fact that during the compression stroke the gases may escape from the crevice region and would end up with lower in-cylinder pressure. This shows that the present model is in good accordance with the experimental results of the VCR diesel engine.

Table 1 Specifications of VCR engine

Cylinder bore × stroke (mm)	87.5 × 110 mm
Connecting rod length (mm)	234 mm
Displacement volume (L)	0.66
Compression ratio	17.5
Number of nozzle orifice × diameter (mm)	3 × 0.255
Piston crown	Hemispherical
Intake valve closure (CA)	144.5°bTDC
Swirl ratio (nominal)	0.7
Inlet air temperature (K)	303
Inlet air pressure (kPa)	111
Engine speed (rpm)	1500 rpm
Fuel	Diesel/PB20
Type of fuel injection	Direct Injection
Injection pressure (MPa)	28
Fuel injected (kg/cycle)	2.57778e−05
Overall equivalence ratio	0.55
Injection duration	21 crank angle degrees
Start of injection	23°bTDC (baseline case)

Fig. 2 Validation of pressure versus Crank Angle for VCR diesel engine

Validation of emissions were also performed by comparing the experimental soot and NOx emissions with the simulation values and given in Table 2. It is observed that they are in good harmony.

4 Results and discussions

Box-Behnken method was applied for designing the numerical experiments. In this method each variable is maintained at 3 equal intervals. For example, if the CR range is from 12 to 18, it is assigned as 12, 15 and 18 and considered for numerical experiment design. Since there are 4 variables and 3 center points, it becomes a set of 27 experiments with each block having 2 variations (means two independent variables are varied per experiment). The design of experiments and their responses are given the Table 3.

4.1 Interaction effects of VCR Diesel engine

The interactive effect graphs are generated through mod-eFrontier [12] software. Figure 3 shows the interaction plots of EGR and CR at different levels of SOI and FIP VCR diesel engine. It can be observed from figure that in the interaction of EGR and CR, as the EGR is increased from 0

Table 2 Validation of emission analysis

Emissions	Experimental	Simulation
NOx (g/kWh)	4.98	5.29
Soot (g/kWh)	1.15	1.18

Table 3 Experimental design and their responses for VCR diesel engine

Run order	CR	SOI (°bTDC)	FIP (bar)	EGR (%)	ISFC (g/kWh)	Soot (g/kWh)	NO _x (g/kWh)
1	18	27.5	250	20	242.811	0.48552	4.15
2	18	27.5	625	0	195.396	0.04004	10.4732
3	15	40	625	0	182.571	0.78328	12.1134
4	15	27.5	625	20	226.281	0.61038	2.97377
5	18	27.5	1000	20	217.721	0.11951	5.03205
6	15	27.5	1000	0	208.337	0.64078	8.47935
7	18	40	625	20	195.497	0.10355	8.547
8	12	27.5	625	40	261.431	1.216	1.45875
9	15	27.5	250	0	237.53	0.74746	6.234
10	12	15	625	20	264.755	1.64901	0.5319
11	15	40	625	40	210.29	0.92654	3.897
12	12	27.5	250	20	277.856	1.22303	1.12884
13	15	27.5	1000	40	232.921	0.70414	1.48125
14	15	15	250	20	277.571	2.01875	0.9867
15	12	27.5	1000	20	256.956	0.5529	2.03835
16	12	40	625	20	218.643	0.9291	5.9634
17	15	15	1000	20	227.193	1.3965	1.5768
18	15	27.5	625	20	221.707	0.61038	2.8035
19	15	15	625	0	223.25	1.292	6.23505
20	15	40	1000	20	209.171	0.93376	7.1258
21	18	27.5	625	40	216.781	0.417	3.125
22	18	15	625	20	214.596	1.32316	3.20124
23	15	27.5	625	20	221.707	0.59442	2.73675
24	15	40	250	20	231.306	1.0526	5.3205
25	15	27.5	250	40	257.132	1.7005	0.67695
26	12	27.5	625	0	224.184	0.70167	5.125
27	15	15	625	40	237.747	2.11351	1.9125

to 40% ISFC increased from the level 195 to 265 g/kWh. It is observed from the figure that the ISFC is favorable in the mid to high range of FIP and SOI. The operating range of CR between high and mid (fig (a), (b) and (d)) seems to be quite favorable in reducing ISFC. Further, a detailed view can reveal that operating range was good enough in the case of high FIP and mid SOI.

Figure 4 represents the interaction of CR and FIP on NO_x emissions at different levels of EGR and SOI. It is observed from the figure that the NO_x emissions are favorable in mid to high range of EGR and low to mid-range of SOI. It can also be interpreted from the figure that the increase in the fuel injection pressure increases NO_x emissions [19]. Low EGR and high SOI combination is not fruitful at any stage of the interaction of CR and FIP. The effect of fuel injection pressure and compression ratio on NO_x emissions mainly depends on the state of the mixture and ignition delay [29]. As the EGR is increased, the NO_x decreases. This is due to the fact that EGR increases the specific heat of intake mixture, thus reduces the combustion temperature. It may also lower the amount of oxygen in the intake mixtures.

This combination of reduced combustion temperatures and reduced oxygen content lowers the NO_x emissions.

Figure 5 shows contour plots of soot for SOI and CR at different levels of FIP and EGR. It is seen from the figure that the interaction of CR and SOI is dominant in the region of high EGR and mid to high FIP. The variation of interaction is less aggressive in the low EGR range. The interaction causes more fruitful region when the other two parameters (EGR and FIP) are set at low and high levels respectively [2, 15].

It is observed from the Table 4 that the difference between predicted and adjusted R^2 values is less than 0.2 for all the three responses, which implies that the model was able to fit the data with reasonably good accuracy. Analysis of variance (ANOVA) is used to determine the significant and insignificant parameters and their interactions. ANOVA gives the p value for the different response parameters, such as ISFC, NO_x, and soot emissions, and are given in Table 5. All the individual parameters (CR, SOI, FIP, and EGR) are significant for ISFC, NO_x, and soot [13].

Fig. 3 Contour plots of ISFC for EGR and CR at different levels of SOI and FIP (VCR DIESEL)

4.2 Optimization of VCR diesel

The objective of any engine design is to minimize emissions and maximize the performance. It can be observed from the above discussions that the tradeoff is observed between the NO_x and soot emissions. So there is a need for optimization of the design parameters aimed to reduce both NO_x and soot without losing its performance. Optimization was performed using the desirability approach which is search based optimization technique [6, 7]. The whole approach is to modify all the responses (X_i) as a

separate desirability function (D_i) and then will be varied in the entire range.

$$0 \leq (D_i) \leq 1 \quad (6)$$

If the response is at its mark value or objective, then $(D_i) = 1$ on the other hand, if the mark value is in the infeasible region then the $(D_i) = 0$ [21]. Each of the desirability function is established depending upon the goal of optimization. Table 6 shows the criteria of optimization in the desirability approach.

Fig. 4 Contour plots of NOx for FIP and CR at different levels of SOI and EGR (VCR DIESEL)

$$D_i = \begin{cases} 1X_i < T_i \\ \left(\frac{U_i - X_i}{U_i - T_i}\right)T_i \leq X_i \leq U_i \\ 0X_i > U_i \end{cases} \quad (7)$$

where U_i is the upper limit of the responses (X_i), T_i is the target of the response.

The optimum combination of the VCR diesel case was found out to be the 17.52 CR, 30.1°bTDC SOI, FIP 736.06 bar and EGR 28.29% with a composite desirability of 0.95. The compression ratio did not alter much from the baseline case which is also beneficial in terms of the design aspect.

4.3 Comparison of optimized and baseline configuration of VCR (Diesel)

The optimized and baseline cases of the VCR diesel engine were compared for pressure, temperature, NOx,

soot, HC and CO vs crankangle and are shown in the Figs. 6, 7, 8, 9, 10 and 11 respectively. It was noticed from the Fig. 6 that the optimized case is superior in performance as the peak pressure of optimized is more as compared to the baseline case this is also manifested in Table 7 with reduced ISFC for optimized case. It is noticed from the Fig. 7 that the average temperature of the optimized case reduces during the combustion. This is because of the presence of EGR which could suppress the combustion temperature [8]. Figures 8 and 9 shows comparison of the NOx and soot formation for the optimised and baseline cases. It is evident that the both NOx and soot levels were decreased for the optimized case. It is also observed from Figs. 10 and 11 that the HC and CO emissions are decreased in the optimum case than the baseline. Table 7 gives the comparison of baseline and optimized cases of VCR diesel based on performance and emissions. It is noticed that the ISFC decreased by 2.37%

Fig. 5 Contour plots of soot for SOI and CR at different levels of FIP and EGR (VCR DIESEL)

Table 4 Model evaluation of RSM

	ISFC (g/kWh)	NOx (g/kWh)	Soot (g/kWh)
R-sq	99.93%	97.91%	99.14%
R-sq(adj)	99.85%	95.47%	98.14%
R-sq(pred)	99.61%	87.96%	95.06%

Table 5 *p* values for model terms of ANOVA analysis

Source	ISFC	NOx	Soot
CR	<0.0001	<0.0001	<0.0001
SOI	<0.0001	<0.0001	<0.0001
FIP	<0.0001	<0.0001	<0.0001
EGR	<0.0001	<0.0001	<0.0001
CR*SOI	<0.0001	0.477	0.006
CR*FIP	<0.0001	0.011	0.065
CR*EGR	0.021	0.006	0.039
SOI*FIP	<0.0001	0.020	0.006
SOI*EGR	0.121	<0.0001	0.001
FIP*EGR	<0.0001	0.039	0.000

Table 6 Criteria of optimization used for desirability method for VCR diesel case

Parameter/response	Limits		Criterion	Desirability
	Lower	Upper		
Compression ratio	12	18	In range	1
Fuel injection pressure (bar)	250	1000	In range	1
Start of injection (°bTDC)	15	40	In range	1
Exhaust gas recirculation (%)	0	40	In range	1
ISFC (g/kWh)	182.57	277.87	Minimize	0.98
NOx (g/kWh)	0.5	12.17	Minimize	0.84
Soot (g/kWh)	0.04	2.11	Minimize	0.99
Combined				0.95

Fig. 6 Comparison of Pressure versus Crank Angle for optimized and baseline (VCR diesel)

Fig. 8 Comparison of NOx versus Crank Angle for optimized and baseline (VCR diesel)

Fig. 7 Comparison of Temperature versus Crank Angle for baseline and optimized (VCR diesel)

Fig. 9 Comparison of Soot versus Crank Angle for optimized and baseline (VCR diesel)

Fig. 10 Comparison of HC versus Crank Angle for baseline and optimized (VCR diesel)

Fig. 11 Comparison of CO versus Crank Angle for baseline and optimized (VCR diesel)

Table 7 Comparison of baseline and optimized cases of VCR diesel engine

	ISFC (g/kWh)	NOx (g/kWh)	Soot (g/kWh)
Baseline case of VCR diesel	210.25	5.29	1.18
Optimized case of VCR diesel	205.48	3.75	0.191
Change w.r.t baseline	2.37% ↓	29.11% ↓	83.81% ↓

and NOx decreased by 29.11% and soot decreased by 83.81% with respect to the baseline case. The decreased soot is because of the advanced injection and higher injection pressure. The reduced temperature due to presence of EGR favours the NOx reduction.

4.4 Mixture homogeneity comparison of the baseline and optimized cases

TFDI (Target Fuel Distribution Index) determines the homogeneity of the mixture [25] and is compared for the baseline and optimized cases at different crank angle instances during the combustion as shown in Fig. 12. The target range of the equivalence ratio for the practical diesel engine applications is from 0.3 to 1.2 [3]. It is observed that the optimized case has more TFDI than the baseline case in all the instances. This is a clear indication of the better homogeneous mixture formation in the optimized case than the baseline case. Better homogeneity was attained due to advanced injection, higher fuel injection pressure and presence of EGR in the optimized case. Better homogeneity favors the lesser soot formation in optimized case. Figure 13 shows the temperature distribution plotted in the target region. It is also observed that the target region has lesser in-cylinder temperatures for optimum configuration than the baseline case which is responsible for lesser NOx.

Fig. 12 Equivalence ratio distribution of baseline and optimized cases at different crank angles

Fig. 13 Temperature distribution of baseline and optimized cases at different crank angles (VCR diesel)

5 Conclusions

The VCR diesel engine was analyzed using DOE based study and optimization has also been done using desirability technique. Start of Injection is the second most influential parameter in view of ISFC. This implies that the CR and SOI are two potential parameters in deciding the engine performance. However, there is a limit in advancing SOI due to the possibility of negative work. Overall the individual effects play a major role in deciding the ISFC. This means the linear relation with respect to the individual parameters are dominant over the squared and interaction effects. The optimum combination of the VCR diesel was found out to be CR 17.52, SOI -30.1° aTDC, FIP 736.06 bar and EGR 28.29% with a composite desirability of 0.95. Optimized set of combination was capable of reduced NO_x, soot, HC and CO emissions as compared to the baseline VCR diesel. ISFC, NO_x and soot are reduced by 2.37%, 29.11% and 83.81% respectively. It was likewise mentioned that the optimized case got higher target fuel distribution index (TFDI) which proves that better homogeneous mixture was achieved.

It is crucial to mention that the optimal solutions are only for a particular load and speed other load and speed shall have different optimum conditions. Hence, in future numerical experiments can be carried out to obtain optimal conditions for various loads and speeds. The parametric study may be analyzed further and can be optimized using Genetic Algorithm based optimization techniques such as NSGA II, ARMOGA etc. to obtain Pareto optimal solutions.

Author contributions Prabhakara Rao Ganji: Collected the data from the literature survey, Conceived and design the analysis, Graphical work. Rajesh Khana Raju Vysaraju: Supervisor 1, Contributed data analysis, Numerical analysis, Optimization. Srinivasa Rao Surapaneni: Supervisor 2, Reference work, Performed the result analysis, Wrote the paper. B Karuna Kumar: Reference work, Performed the result analysis, Proof read the paper.

Declarations

Conflict of interest The authors declare that they have no conflict of interests.

Ethical approval The authors confirm that the final version of the manuscript has been reviewed, approved, and consented for publication by all author.

Ethical Standards This study was as per the ethical standards approved by the Animal Use Ethics Committee of the University of Oeste Paulista (UNOESTE), Presidente Prudente, São Paulo, Brazil, by Protocol Number 4396.

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