ISSN (e): 2250 – 3005 || Volume, 09 || Issue, 6 || June– 2019 ||
International Journal of Computational Engineering Research (IJCER)

Multi objective optimization of piston bowl geometry and fuel Injection pressure on CRDI assisted diesel engine using Grey Relation Analysis

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ABSTRACT*; The present study probes into the multi-objective optimization of Common Rail Direct Injection (CRDI) diesel engines performance parameters such as brake thermal efficiency, brake specific fuel consumption, and brake power. To understand the influence of performance parameters, different piston geometries, fuel injection pressures (FIP), and loads were selected as input parameters for an investigation. The criteria weighting method is the combination of the Analytical Hierarchy Process (AHP), and Entropy method is being used to find out the weight of engine performance parameters. In addition to that, Grey Relation method was implemented to convert multi-objective engine performance parameters into a single parameter. Furthermore, the contribution of input parameters on the engine performance parameters was also calculated by using Analysis of Variance method. After, conduction of sets of experiments, piston geometry, and fuel injection pressure contributes predominantly to the performance parameters. The confirmation tests were also carried out to check the accuracy of results on an optimized setting in a studied range.*

KEYWORDS:*CRDI diesel engine, Tangential piston, Analytical Hierarchy Process, Entropy method, Grey relation analysis*

Date of Submission: 30-05-2019 Date of acceptance:14-06-2019

Nomenclature	
CRDI Common Rail Direct Injection	PPM parts per millions
BTE Brake Thermal Efficiency	CCD Central Composite Design
BSFC brake specific fuel consumption	DOE Design of Experiment
BP Brake Power kW	AHP Analytical Hierarchy Process
FIP Fuel Injection Pressure , bar	ANOVA Analysis of Variance
EGR Exhaust Gas Recirculation	GA Genetic algorithm
NOx Nitrogen Oxides	ANN Artificial neural network
CO Carbon Monoxide	PID Proportional Integral Derivative
HC Hydrocarbon,ppm	SCC Shallow depth Combustion Chamber
UHC UnburntHydrocarbon,ppm	OCC Omega Combustion Chamber
PM particulate matter	SVM support Vector Machine
aTDC after top dead center	ECU Electronic Control Unit
bTDC before top dead center	MAP Manifold Air Pressure
RCCI Reactivity Controlled Compression Ignition	HP/LP High Pressure/ Low Pressure

I. INTRODUCTION

In the development of the automobile sector and transportation industry, the diesel and gasoline engines both played a vital role [1]. However, in comparison with the gasoline engine, the diesel engine offers more advantages, such as low fuel consumption, high durability, and high thermal efficiency [2]. The diesel-powered goods vehicle market shares are increasing drastically in the market. Unfortunately, in comparison with the conventional catalyst equipped gasoline engine, diesel engines being the primary source of soot and NOx emissions.

In this article literature review is based on fuel injection pressure (FIP) and different Piston bowl geometries. A.K Agrawal et al.[1] experimented with a single cylinder diesel engine with baseline fuel with three different fuel injection pressures i.e., 300,500 and 700 bars and four different injection timings. The results depict that as the load increases, the particulate size goes on an increasing while, it reduces with further increase in injection pressure. To understand the influence of injection timing, D.H Qi et.al.[2] adopted different injection strategies for diesel-tung oil and ethanol blended in CRDI diesel engine for reducing the engine emissions. At lower engine loads, a higher concentration of CO and low NOx emissions were observed, but the smoke emission reduces drastically with higher engine load. However, the same trend was not observed for HC emissions with an increase in percentages of tung oil and ethanol [2].

The essential parameters like fuel injection pressures (FIP) were reported by K. Nanthagopal et al. [3] with Calophylluminophyllum methyl ester as fuel and results were compared with conventional fuel and 100% biodiesel. They concluded from their experimentation that with the higher injection pressure, bsfc had been reduced meanwhile, NOx emissions increases. However, at 220 bar of fuel injection pressure fuelled with biodiesel, there was a significant reduction in UHC, CO, and particulate matters. Akash Deep et al. [4] reported in his experimental investigation that 20% blend of castor biodiesel in diesel can be used without any significant modification in the fuel injection system. A. Dhar and A.K. Agarwal [5] predicted the effect of FIP and injection timing of Karanja biodiesel blends on CRDI diesel engine. Although, the fuel injection duration was slightly decreased with an increasing percentage of biodiesel and significantly reduced with increasing fuel injection pressure. However, the repercussion of high FIP on the performance of CRDI diesel engine fuelled with (mahua methyl ester) MME20 has been reported by C.S. Aalam et al. [6]. To have the better exploitation of mahua methyl ester blend, FIP was increased from 22 MPa to 88 MPa, and better combustion characteristics were exhibited at 88 MPa of fuel injection pressure. M. Mikulski et al. [7] studies focus on phenomena of combustion of swine lard methyl esters–diesel mixture in a CRDI engine. They have confirmed the downgrade of fuel performance parameters with an increasing percentage of biodiesel. However, there were indicative curtailment in exhaust gas emissions (excluding NOx) and opacity in all operating conditions. At low engine load, advanced injection strategies were applied to fuel mixtures with high biodiesel contents, which results in excellent emission characteristics. Also, optimized results were obtained using Response Surface Methodology for the effect of FIP and injection timing on diesel engine with biodiesel obtained from waste cooking oil investigated by G.R. Kannan and R. Anand [8]. The combined effect of higher injection pressure of 280 bar and an advanced injection timing of 25.5º bTDC have an immediate improvement in the BTH, cylinder gas pressure, and heat release rate.

Further, experimentation reveals the impact of piston bowl geometry on RCCI performance and emissions in a heavy-duty engine.J. Benajes et al. [9] concluded that the three geometries under consideration enable lower NOx and soot emissions at low and medium load. The results obtained by A.H. Kakaeeet. al.[10]also shows that among the three different piston bowl geometries i.e., stock, bathtub and cylindrical under consideration, the bathtub design turns out to be the optimum from performance and emissions point of view at high speeds in case of a natural gas and diesel RCCI engine. They have also revealed that both piston bowl depth and chamfered ring-land can also perturb engine-out emissions. The numerical investigation was done by Abdul Gafoor C.P. and Rajesh Gupta [11] to get an insight into the effects of piston bowl geometry and swirl ratio on diesel engine performance and emissions. The variation in bowl geometry and initial swirls affects bowl to piston diameter ratio and emission characteristics more compelling with bowl volume, compression ratio, engine speed, and the mass of fuel injected being constant. With the advent of Genetic algorithm (GA) and artificial neural network (ANN) optimization techniques, KesginU[12] was able to anticipate the effects of design as well as the operational parameters on engine efficiency and emissions characteristics of a natural gas engine. The result also confirms that both, as well as the amount of NOx emissions, increase for stationary engines.

KIVA-3V code coupled with a CHEMKIN chemistry solver and a micro-genetic algorithm was used for piston bowl geometry and operating conditions of a gasoline-diesel dual fuel engine. S. Lee and S.Park [13] found that 9% improvement in BSFC with accompanying reduction in UHC, CO, NOx, and soot emissions. They have reported the re-entrant shape for the baseline case while the optimized case has to be a shallow shape and a narrower spray angle. D.K. Soni and Rajesh Gupta [14] considered AVL FIRE software to investigate the flow dynamics at different spray angles for different piston bowl designs. The re-entrant piston bowl with different spray angles was found to be best for significant reduction of NOx and soot mass fraction compared to the conventional piston. CHEMKIN II code was unified into the KIVA-4 code to analyze the effects of piston bowl geometry on combustion and emission characteristics of biodiesel fuelled diesel engines. The simulation results of J. Li et al. [15] indicates Shallow depth Combustion Chamber(SCC) is favorable at lower engine speed whereas, at higher engine speed, OCC is preferred which results in high NOx emissions. The potential of ANN on a CRDI diesel engine was explored by Sumit Roy et al. [16] to predict the BSFC, ŋbth, CO2, NOx and PM with load, fuel, FIP, EGR and fuel injected as input parameters under consideration. Furthermore, the developed ANN model was adequate of mapping the PM–NOx–BSFC trade-off potential of the CRDI operation under EGR for all cases with significant accuracy.

X. Niu et al. [17], predicted the performance and emissions characteristics of a CRDI-assisted marine diesel engine using ANN and SVM. Also, the Taguchi orthogonal array was employed for the determination of the operating point. S.V. Khandal et al. [18], considered the simultaneous effect of EGR, FIP, and IT on the performance of the CRDI engine powered with Honge Biodiesel (BHO). The response surface analysis indicates that 10º bTDC and 900 bar yields better performance, which in turn reduces the NOx emissions. Senatoreet. al.[19] have demonstrated a detailed analysis of diesel engine fuelled with biodiesel influences on engine parameters to obtain an optimized strategy of ECU parameters that could be applied to the modified diesel engine.

From the literature review under consideration, it was observed that the majority of the investigation done by the peer researchers are only by varying the performance parameters independently or in the combination of two. Hence the present study focuses on the combined effect of various parameters i.e., the effect of piston geometry, EGR rates, and injection pressure on the performance and emission characteristics of CRDI engine. Therefore, the present investigation emphasizes on the conversion of the multi-output of a CRDI diesel engine into single response output optimization. The engine performance characteristics such as ŋbth, bsfc, and B.P were taken as output criteria for optimization of piston geometries, fuel injection pressures, load and percentage of exhaust gas recirculation rates.

In the present study, the improvements were made in the piston geometry by making tangential and square grooves on the face of the piston by keeping the clearance volume constant. Basic, tangential, and square piston geometries are selected as an input factor. Furthermore, FIP and Load are selected as the input factor, which can be varied to study their influence on engine performance like BSFC, BTE, and BP. Each factor is distributed on three levels. A Full factorial design of the experiment is used for complete and thorough experimentation. Multi-output problems were catered by using grey relation method, which converts the multi-output response into a single grey relation grade. The weight of multi criteria's for grey relation analysis was calculated with the help of the Analytical Hierarchy Process (AHP) method and Entropy Method. Multi-objective optimization is carried out on grey relation grade with the help of S/N ratio. Analysis of Variance (ANOVA) was employed to check the model authenticity. Confirmation test was performed to check the optimal settings for CRDI diesel engine.

II. EXPERIMENTAL SET UP DETAILS AND MODIFICATIONS IN SINGLE CYLINDER ENGINE TO CRDI ENGINE

The experimental investigations carried out with a single cylinder four stroke diesel engine used for an agricultural application. As this investigation involves experimentation on CRDI engine, the conventional diesel engine with single cylinder and direct injection has been converted into a CRDI engine as per the testing requirement. The additional components such as Electronic Control Unit (ECU), fuel rail, wiring harness, HP/LP fuel pump, and different types of sensors have been included.

Furthermore, piston with tangential grooves and square bowl geometry has been selected for a modified engine. The ECU was programmed according to the testing methodology. The engine that was chosen for the conversion to CRDI engine is an agricultural based constant speed diesel engine as depicted in Fig. 1and its specifications are as shown in Table 1.

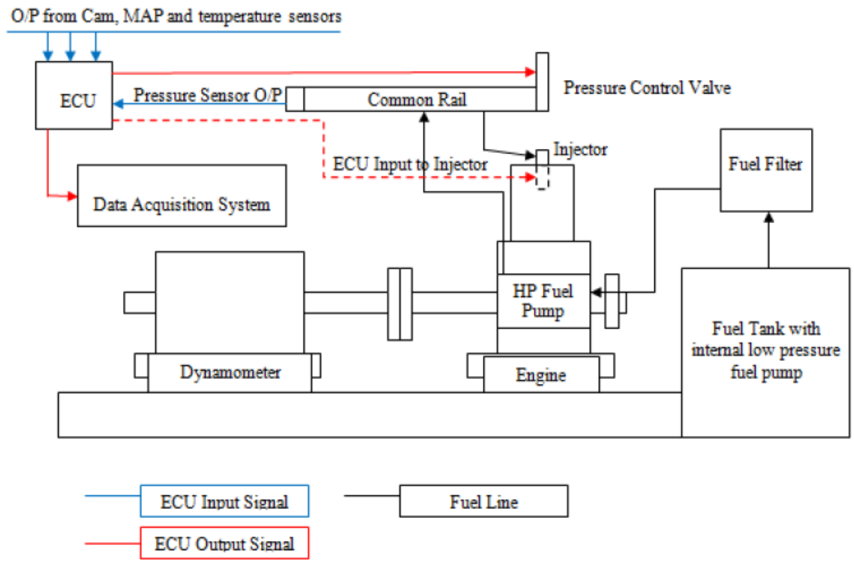

Figure 1: Schematic Diagram of CRDI Engine Setup

Table 1: Engine Specification

Make	Kirloskar
Type	4 Stroke, Direct Injection, Water Cooling
No. of Cylinders	1
Bore	87.5 mm
Stroke	110 mm
Compression Ratio	17.5:1
Capacity	3.75 kW(5HP)
Speed	1500 rpm
Injection Timing	23^o bTDC
Type of Loading	Electrical Resistance

The high-pressure plunger type pump was utilized and produced up to 1600 bar of pressure, in turn, giving a discharge of 1.2 LPH. Filter was fitted before the HP fuel pump so that all the contaminants and foreign particles from the fuel gets trapped. The fuel rail has an inlet line, return line, and two injector outputs along with the pressure sensor and a pressure control valve. The sensor gives a signal to the ECU about the pressure inside the rail, and if pressure is not desirable, the ECU actuates the pressure control valve to maintain the pressure. As the fuel rail was for the two cylinder engine, one of the outputs given by the rail was closed. The solenoid type injector consists of a solenoid (coiled wire with a needle placed inside) which is actuated as and when needed by the ECU. The conventional fuel injector has three, but six whole nozzles were adopted for better fuel atomization and mixing.

The rail pressure sensor gives an input signal to the ECU about the pressure inside the fuel rail. It consists of a piezo material which when deformed gives an electrical signal which can be easily interpreted by the ECU. The MAP (Manifold Air Pressure) sensor measures the manifold pressure corresponding to the atmospheric pressure and fitted on the intake manifold. The signal given by this sensor is processed by ECU to control the quantity of fuel to be injected during engine operations. The K type thermocouples were used to measure temperatures of the coolant water as well as exhaust gas for further analysis. Thermocouple used has its range from 0-1200 ºC giving an output voltage signal in the range from 4-20 mA which can be readily interpreted by ECU.

Cam position sensor gives a signal to the ECU about the speed of the engine and the piston position during the cycle. The inductive resistance type CAM sensor was used, which consists of a coil carrying current and thus produces a magnetic field. When the other part cuts this magnetic field, the eddy current is induced in it which is easily detected by this sensor, and this voltage signal is then fed to the ECU. The Eddy Current Dynamometer was utilized to change the load on the engine to following the speed changes.

The ECU Nirai7 made by NIRA was selected with full programmable capability that supports complete diesel engine operations. The ECU, as well as the connectors with the crimp pin, was used to connect the wires to the ECU. It provides the user to make changes in the micro-controller program using a Nira RK interface. The ECU consists of a micro-controller which gathers data from the sensors, process it and then delivers output as the per-user requirement. The ECU chosen was also compatible with both solenoids as well as the piezo fuel injectors. The ECU had a fuzzy logic control, which is the set of rules that processes the data from sensors and gives output accordingly.

As number parameters important in the study of engine performance are large in number, therefore it requires a large number of experiments to find the optimum operation setting of Diesel Engine, hence to reduce the design of the experiment of experiment with Taguchi design was implemented.[20,21]

After the conversion of conventional engine to CRDI engine, pistons with different bowl geometries such as tangentially grooved and square bowl pistons were manufactured for testing.

The conventional piston had a clearance volume of 34cc (valve cut volume not included) and 40cc (including all valve cuts and head clearance) with a swept volume of 661cc. Thus, to keep the compression ratio constant, the only possibilities left out was to make changes in the crown of the piston bowl. Therefore, the two types of piston crowns were selected, and the performance of these piston crowns was compared with the conventional hemispherical piston bowl of an engine.

The square bowl had volume same as that as of the original hemispherical bowl i.e., 34cc. The dimensions of the cube are 36.9x36.9x25 mm^3. There are four tangential grooves cut on the top of the piston. The dimension of the groove was 6.5x2 mm. The utmost care was taken that all the grooves were made in such a way that the clearance volume of the piston doesn't change. For this reason, the inner hemispherical bowl was made smaller by 1mm in diameter. The tangential bowl piston creates more turbulence than the ordinary hemispherical bowl piston due to strong squish motion into the bowl. Also, the rate of heat release reduces, which in turn increases the combustion phasing and complete combustion of the fuel-air mixture. Figure 2 (a,b,c) shows different piston bowl geometries.

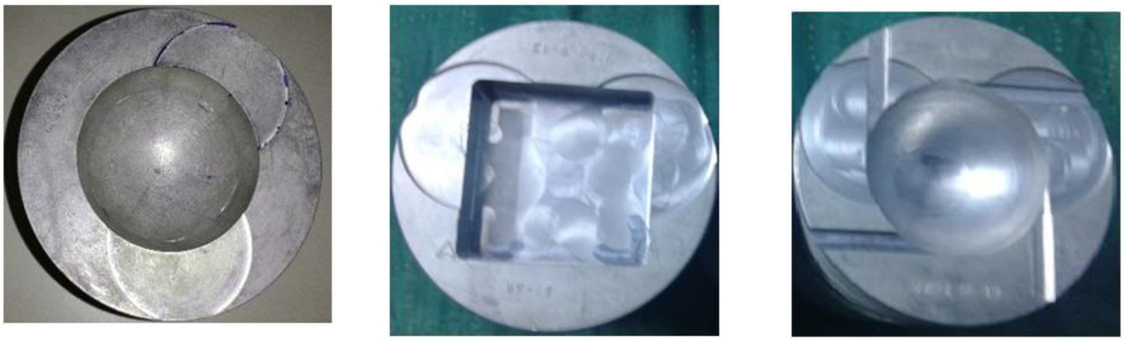

Figure 2a: Basic Piston b: Square Bowl Piston c:Tangentially Grooved Bowl Piston

III. EXPERIMENTAL RESULTS AND DISCUSSION

The experimentation was carried out on Single cylinder CRDI four stroke agricultural engine at 5% constant EGR.The injection pressure varied as 500kPa, 600kPa, and 700kPa. From the Fig. is observed that compared to basic and square bowl piston, the performance of tangential bowl piston is higher. As injection pressure increases from 500kPa to 700kPa BSFC decreases and brake thermal efficiency, brake power increases. At part load, the performance of all the geometries is higher compared to the minimum and maximum load. The performance of tangential piston is higher due to tangential swirl motion produced due to flow passages. This causes better air and fuel mixing, which results in higher performance. Square bowl piston performance is higher than base geometry but lower than a tangential piston. The reason may be due to the formation of eddies at the corner of the square piston.

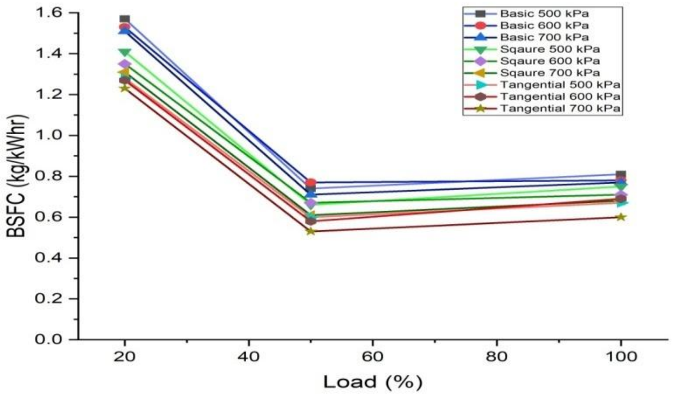

Figure 3 Variation of bsfc with laod

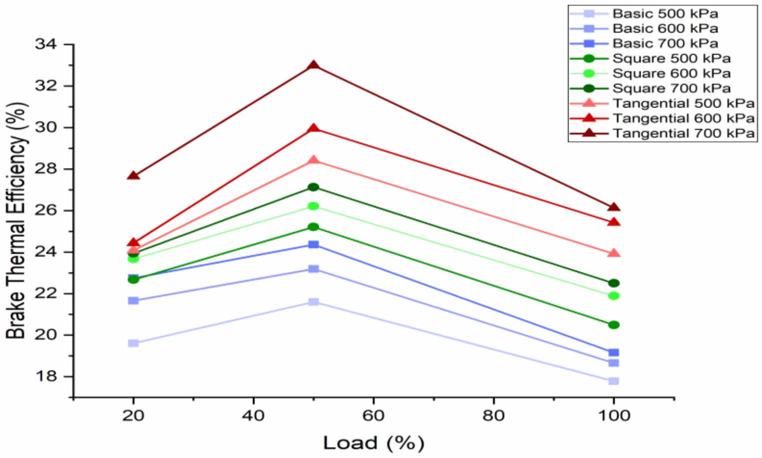

Figure 5 Variation of brake thermal efficiency with load

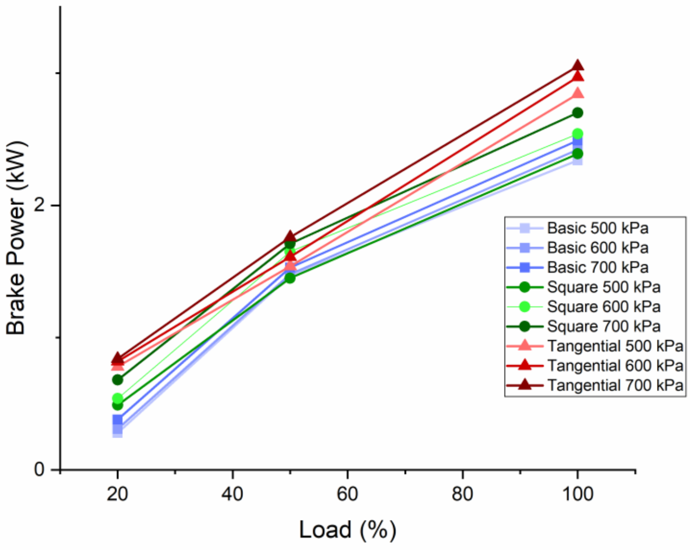

Figure 5 Variation of brake power with load

The experimental data obtained is used for multi-objective optimization analysis. The full factorial design of experiment methods is used for designing the experiment. The compromise weighing method is consisting of

Analytical Hierarchy and entropy method. Gray relation analysis is used to convert the multi-objective problem into a single objective problem.

IV. DESIGNS OF EXPERIMENTS USING FULL FACTORIAL METHOD

The experiments are designed with the help of the Full Factorial method with 27 experiments 3 factors namely piston shape, fuel injection pressure, and Load. Table 2 shows the level and factor selected for the design of experiments.

Table 2: Design factors and their levels

Factors	**Unit**	**Levels**		
		1	2	3
Piston Shape(A)		Basic	Tangential	Square
FIP (B)	kPa	500	600	700
Load (D)	Kg	20	50	100

V. MULTI OBJECTIVE OPTIMIZATION

5.1 Determination of Weightage

5.1.1 AHP method

The AHP method is invented by Saaty to solve the multi-response criteria problem or MADM based on the hierarchy of the system. AHP method works on three steps (i) structure of system ii) comparative analysis importance of each criteria over another by using relative importance grade as described in Table 4.(iii)determination of the weight of each criteria based on the Eigenvector method.[20,24]

5.1.2 Entropy method

AHP method is dependent on the pairwise comparison matrix aij, which is given by user, its credibility; authenticity depends on the user's experience and knowledge. Wherever Entropy method is dependent on the output responses of each alternative of their respective criteria. Therefore, Error assigning pair wise comparison matrix is reduced Entropy method uses probability theory which measures uncertainty in the output responses of each criteria. [25-26]

5.2. Grey relational analysis (GRA)

Multi-objective optimization technique which works on converting the multi-objective output into a single objective. The GRA is mostly used for conflicting objective outputs [27-31].

VI. RESULTS AND DISCUSSION OF MULTI OBJECTIVE OPTIMIZATION TECHNIQUES

The runs are performed on the CRDI diesel engine, as discussed in section 2. The BSFC, BTE, and BP are measured. These readings are also illustrated in Table 5 with respective experiment number

6.1. Determination of weight.

The criteria weighing method is a combination of AHP and Entropy Method. First Subjective weights of all criteria are obtained by using AHP method. The three-level hierarchy is prepared in the first level decision process, second level criteria, and third level material alternatives.

The engine Performance criteria's like BSFC and BTE are equally important because they are dependent on each other. Hence the relative importance of both these criteria's is taken as 1. In this study, we have considered the BP is less important criteria relative to BSFC and BTE.

The weights of the output responses for AHP, Entropy and Compromised Weighing are describe in Table 3. The weights "w" are considered for Grey relation analysis.

Table 3 Comparison of Weights

	BSFC	H	BP
α	0.428571	0.428571	0.142857
β	0.340521	0.373542	0.285937
w	0.420721	0.461519	0.11776

6.2 Grey relation analysis

Grey relation methods, experimental results were are given in Table 5 are normalized according to their goals. The difference in the absolute values of each criteria is calculated, and those values are given in Table 3.

Grey relation coefficients (ξ) were calculated for each response. Considering weighing factors obtained, the overall grey relation grade is calculated; thus, obtained is shown in Table 4.

Table 4 Grey relation Coefficient and Grade

Run. No	Δ_{01}	Δ_{02}	Δ_{03}	Grey relational coefficient ξ_1	ξ_2	ξ_3	Grade γ	Rank
1	1.0000	0.8797	1.0000	0.3333	0.3624	0.3333	0.3456	27
2	0.2019	0.7488	0.5704	0.7123	0.4004	0.4671	0.5685	14
3	0.2692	1.0000	0.2563	0.6500	0.3333	0.6611	0.5317	18
4	0.9615	0.7449	0.9892	0.3421	0.4016	0.3358	0.3828	26
5	0.2308	0.6443	0.5668	0.6842	0.4369	0.4687	0.5726	13
6	0.2404	0.9421	0.2274	0.6753	0.3467	0.6873	0.5526	16
7	0.9423	0.6732	0.9639	0.3467	0.4262	0.3416	0.3969	25
8	0.1731	0.5674	0.5487	0.7429	0.4684	0.4768	0.6152	10
9	0.2308	0.9093	0.2022	0.6842	0.3548	0.7121	0.5634	15
10	0.8462	0.6785	0.8339	0.3714	0.4243	0.3748	0.4114	24
11	0.1250	0.5115	0.8087	0.8000	0.4943	0.3821	0.6423	9
12	0.2115	0.8218	0.7004	0.7027	0.3783	0.4165	0.5479	17
13	0.7885	0.6128	0.8231	0.3881	0.4493	0.3779	0.4310	23
14	0.1346	0.4458	0.8195	0.7879	0.5287	0.3789	0.6522	8
15	0.1731	0.7298	0.7112	0.7429	0.4066	0.4128	0.5791	12
16	0.7500	0.5950	0.8448	0.4000	0.4566	0.3718	0.4391	22
17	0.0769	0.3853	0.8231	0.8667	0.5648	0.3779	0.7051	5
18	0.1442	0.6897	0.7148	0.7761	0.4203	0.4116	0.6006	11
19	0.7212	0.5858	0.8195	0.4094	0.4605	0.3789	0.4461	21
20	0.0673	0.3669	0.5451	0.8814	0.5768	0.4784	0.7293	4
21	0.1346	0.5963	0.0758	0.7879	0.4561	0.8683	0.6764	7
22	0.7115	0.5621	0.8051	0.4127	0.4708	0.3831	0.4528	20
23	0.0481	0.1999	0.5199	0.9123	0.7144	0.4903	0.8085	2
24	0.1538	0.4977	0.0289	0.7647	0.5012	0.9454	0.6955	6
25	0.6731	0.3511	0.7978	0.4262	0.5875	0.3853	0.5132	19
26	0.0000	0.0000	0.4657	1.0000	1.0000	0.5178	0.9840	1
27	0.0673	0.4510	0.0000	0.8814	0.5258	1.0000	0.7672	3

6.3 Analysis of Variance

Analysis of variance (ANOVA) is performed on the GRG to check the percentage contribution of each input parameter on to output, as shown in Table 5. The fitness of the GRG of output with respect input parameter is checked using R^2 and R^2 adjusted values. The percentage contribution of each parameter is calculated with the help of the adjusted sum of squares.

The ANOVA is performed on the 27 experiments for grey relation grade where A, B, C, and D are input parameters, respectively, as discussed in Table 2. The using R2 and R2 adjusted values are above-prescribed limit to verify the even distribution of data. The ANOVA results show that the Fuel Injection Pressure and Piston geometry are most significantly affect the GRG.

Table 5 Results of ANOVA

Source	Degree of Freedom	Adjusted Sum of Square	Adjusted Mean Value	F-Value	P-Value	Contribution (%)
PISTON	2	0.138731	0.069366	89.26	0.000	24.65338
FIP	2	0.352005	0.176002	226.49	0.000	62.55353
LOAD	2	0.027085	0.013542	17.43	0.001	4.813177
PISTON×Load	4	0.023341	0.005835	7.51	0.008	4.147845
PISTON×FIP	4	0.009817	0.002454	3.16	0.078	1.744544
FIP×Load	4	0.005530	0.001382	1.78	0.226	0.982716
Error	8	0.006217	0.000777			
Total	26	0.562726				
Model	Summary					
S	R^2	R^2(adjusted)	R^2(Pridicted)			
0.0278761	98.90%	96.41%	87.42%			

6.4 Confirmation test

Experimentation are performed on the predicted operating conditions given by grey relation grade methods and their SN ratio, grade of each are calculated again on the basis engine performance as shown Table 6

Table

Optimal settings	Grey Relation Grade Prediction	Experiment	Error
A3B3C2	0.9840	0.9558	2.87%

	BSFC =0.61 BTHE =31.67 BP =1.71

6 Confirmation Test

VII. CONCLUSIONS

1. The use of compromised criteria weighting method gives a refined weight factor for each output parameter. The BSFC (0.4207) and BTE (0.46152) is having higher Weightage factor than the Brake power(0.1177).
2. The BSFC (0.53 kg/kW hr) is minimum for tangential piston geometry, Fuel Injection Pressure 700 kPA, and Load 50% .BTE (32.99 %) is maximum at tangential piston geometry, Fuel Injection Pressure 700 kPA, and load 50%. The Brake Power (3.05 kW) is maximum at tangential piston geometry, Fuel Injection Pressure 700 kPA and load 100% A2B3C3D3
3. The ANOVA shows that the fitness of the model used for Grey relation Grade is reliable
4. The optimum setting for CRDI Diesel engine for multi-objective optimization is obtained at Tangential Grooved Piston Geometry, FIP700 kPa, Load 50%
5. Confirmation test shows that the results obtained at optimized settings are repeatable.

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Sndeep Kore" Multi objective optimization of piston bowl geometry and fuel Injection pressure on CRDI assisted diesel engine using Grey Relation Analysis" International Journal of Computational Engineering Research (IJCER), vol. 09, no. 6, 2019, pp 39-47