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Optimization of Piston Grooves, Bridges on Cylinder Head, and Inlet Valve Masking of Home-Fueled Diesel Engine by Response Surface Methodology

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Abstract: Naturally replenished biodiesel fuels are more precise in place of diesel engine applications as they have complying thermal properties, which are extensively used by various researchers. However, there is necessity to optimize their utility to meet stringent emission norms as per Bharat Stage VI (BS VI) and Euro 6. From the exhaustive survey on the studies, number of piston grooves (NG), number of grooves-n-bridges on cylinder head (Gr-Br), and inlet valve masking (IVM) using the response surface methodologies (RSM) technique have not been reported on the competence, emissions, and combustion attributes of diesel engines running on Honge oil methyl ester (HOME), hence this is an identified gap in literature. The present simulation work is for optimizing the performance and lessening exhaust emitted from the diesel prime mover tested on non-conventional and petro fuels. Experimentation was carried out to inquest the competence, combustion, and emittance of a vertical cylinder, overhead valve, water cooling, open or induction swirl diesel engine running on HOME as the injecting fuel. The object of the present effort is to optimize competence of diesel engines via a statistics inquest called designs of experiments (DoE). To curtail the diverse variations to be experimented on, full factorial designs (FFDs) array was employed. The response surface methodologies (RSM)-based nonlinear or quadratic predictors establish the relation between the input parameters and proposed attributes. The RSM-based mathematical predictors are established to prognosticate the distinguished engine output attributes at 95% confidence interval. The response surface assay discovered that a combination of 2B 3G, 'IVM' of 90°, and 'NG' of six grooves yields highest brake thermal efficiency (BTE), lessening smoke, carbon monoxide (CO), and hydrocarbon (HC), but nitrogenous oxides (NO_x) emissions increased slightly. Additionally, combustion attributes, such as Ignition delay (ID) and combustion duration (CD), were lessened, but peak pressure (PP) and heat release rate (HRR) had a higher contrast to performance of HOME biodiesel in a conventional CI engine.

Keywords: Honge oil methyl ester; piston grooves; number of grooves-n-bridges on cylinder head; inlet valve masking; optimization; full factorials designs; response surface methodologies; regression; validity by international relevance

1. Introduction

Diesel powered CI engines have high part load thermo efficacy and hence are amply applied for power plant and automobile utilities. However, every country is becoming more and more aware of pollution caused due to their malodourous exhaust, vibration

levels, noise, particulate matter, and smoke. Already stringent legislations are further updated regularly to control pollution and to avoid affecting the delicate ecosystem balance. NO_x emission is especially weighed as a “strongest” greenhouse gas, having a deleterious effect on the ozone layer of the atmosphere. Hence, it is time to implement new optimization techniques that ameliorate the efficacy of diesel engines using its proven substitute biodiesel and in turn tackle environmental problems and ameliorate socio-economic tie ups. Agarwal et al. [1] showed that straight linseed oil posed operational and durability problems in the CI engine. These hindrances attribute to the polyunsaturated character of vegetable oils, i.e., they are less volatile and highly viscous. However, such problems were not encountered for in linseed oil methyl ester (LOME) biodiesel due to the transesterification process, which reduces its viscosity and thus rules out operating and longevity hurdles. Economic assay was also done in this inquest, and it was found that use of veggie oil and its BDF as an option for diesel costs almost the same as that of fossil diesel. Goldemberg and Coelhobn [2] proved that naturally replenished biofuels can be super temporal and are eco-friendly. Abuhabaya et al. [3] adopted response surface methodology (RSM), and a centralized complex rotating design (CCRD) matrix showed that the molarity ratio of methanol to raw sunflower oil and catalyst concentration had the most leveraging inputs in comparison to reaction time and reaction temperature, affecting the percentage conversion of fuel into biodiesel, which was validated by experimental testing. The model was fit and accordable to be put forth the actual linkages among vital variables, and the output with an acceptable determination fraction ($R^2 = 0.8142$), which directed that 81.42% of the variation in the outcome could be described by the second-order polynomial prediction, as revealed by assay of variance (ASOVA). Yashvir Singh et al. [4] optimized competence and emissions of cassia tora biodiesel, having five coded levels based on centralized complex rotatory design (CCRD) matrices. The best compound of input variants was recorded at 15° bTDC fuel injecting time, 221 bar IOP of fuel, 40.1% mixture of cassia tora and diesel, and 47.3% engine loading, which emitted an outcome of highest BTE and lowest UBHC and NO_x. Ganapathy, et al. [5] simulated the jatropha biodiesel performance using the Taguchi method and linear graph theory. The test trials layout of the engine was determined by a L16 orthogonal array. To maximize the competence, the signal noise ratio (SNR), related to higher-then-better (HTB) quality attributes, was utilized. The model correctly prognosticated Wiebe’s heat releasing constants, the compression ratio, and duration of burning zone as the vital variables that influence the competence contrasted with other variables. Raheman and Phadatare [6] showed that, by blending Karanja esterified oil (B20 and B40) with diesel output responses, torque, brake power, and BTE increased and exhaust emissions decreased, thus controlling air pollution. Win et al. (2005) carried out a RSM fit statistics analysis for the input variables engine speed, static injection timing, and load as per the full factorial design array of $4 \times 4 \times 3$. They showed that two outputs, NO_x and noise, have applicable good fittings, showing R^2 values of 0.963 and 0.971, respectively, by ANOVA. Sufficiently better fitting was obtained for BSFC and smoke, with R^2 valued as 0.82 and 0.807. The fitting of HC illustrates a poor fitting due to a very low value of R^2 0.669. Hirkude et al. [7] considered ratio of compression, blend, and load as input variables and predicted output variables by DoE based on RSM to optimize the competence of the diesel power unit with wasted fried oils methyl esters (WFOME) blending with fossil diesel. The developed models represent experimental data and are vital as values of p , which were less than 0.05. The rightness of fit (R^2) and the rightness of prognostication (Adjusting R^2) regression statistics are represented for all the outcomes. The predictors are accounted by value of Adjusted R^2 , and the model suits the data very well. The experimental validation of optimized inputs shows that measured responses were in good agreement with RSM values. The effect of speed, load, and blend ratio on the competence of a multi cylinder indirect injecting diesel power unit was investigated by Adam et al. (2015), using statistical tool, Box-Behnken design (BBD) based on RSM to predict and assess their net effects on the responses, such as torque, power, BSFC, and BTE. Blends of 5–20% volume of BDF (prepared from a mixture of palm and rubber seed oils) to diesel fuel were prepared. The

load was found to be the most effective input, both individually and in combination, contrasted to variables blend and speed. A strong influence of speed over the outcomes was observed, except for torque, whereas its combined effect was not vital, except for BSFC and BTE. No paramount contribution was noticed for the blend over the outcomes, except for torque. However, the models established fitted the experimental results of all the outcomes investigated. Prasada Rao and Appa Rao [8] investigated indirect injection engine fueling with Mahua oil Methyl Ester (MOME), diesel, and methanol added blends, with predictor variables load and fuel, for nine output responses, such as EGT, BSFC, BTE, and emanations such as UBHC, CO, CO₂, Oxygen O₂, NO_x, and smoke. To find optimized responses, the set of experimental works were carried out using the DoE, as advised by Taguchi for lessening cost and time. The optimized set of the fuel and load were found by Grey Relational Analysis (GRA), applying to the experimental data by transacting the multi outcome hurdle into the single outcome hurdle using Grey Relating Grades (GRG). The optimal combinations, 20 kg of loading and MOME + 3% Methanol, were found by calculating signal noise ratio for GRG. After GRA, the results were validated with the RSM, expediency approach was used, and the optimal combinations were found. The validation outcomes almost coincided with experimental outcomes. They concluded that, when MOME was blended with methanol, CO and HC emissions decreased because of the methanol's inherent oxygen content and hence reduced viscosity. GRA and expediency approach of the RSM was found to be the most effective and simple optimizing tool, and experiment outcomes almost coincided with the validated outcomes. For optimized engine variants of fuel blend, MOME + 3% Methanol, and loading of 20 kg, high desirability was obtained, where the values of the EGT, BSFC, BTE, UBHC, CO, CO₂, O₂, NO_x, and smoke intensity were found as 163.9 °C, 0.3617 kg/kW-h, 26.341%, 3.82 ppm, 0.0181%, 5.271%, 20.983%, 230 ppm, and 36.555 HSU, respectively. Contrasting the validation result, there was an error of 0.0970 for the experimented result of loading. Berber [9] proposed RSM to find the performance of fuel flow in a DI diesel power unit by using diverse unique conditions (IOP, N, and throttle position). IOP was chosen as 150 bar for a turbo-charged and pre-combustion vestibule. A math model was used to prognosticate fuel flow competence, according to IOPs 100, 150, 200, and 250 bars and throttle positioning 50, 75, and 100%. The optimized competence conditions for a needed fuel flow were obtained by using the response to surface methodologies with 3D graphing. The obtained polynomial predictions proved that the linear variation of engine speeds were most vital and affected the flow. A biodiesel fueled engine resulted in lessened competence, increased fuel consumption, and UBHC and CO emitted with lessened NO_x levels [10]. The blend ratio and operating parameters were optimized using FFD for modelling and studying the experiments' data. Nayyar et al. [11] validated experimental data with forecasted values and discovered that models put forth were very easily used for adequacy checking. Combustion features were analyzed by many investigators using statistical tools. Hence, the use of RSM quadratic models has developed and explored the competence of double fuel engines, as shown in References [12–14], which analyzed the influence of EGR and IT on the competence and emanations of a diesel prime mover running on diesel blends. Using RSM, optimization was enacted through the expediency approach to lessen the smoke and NO_x emanations levels with lessened BSFC. The model building was done using the DoE-RSM combination, and an assay of multi linear regression math models were used to prognosticate the competence and emanations of diesel and H₂-fueled engines at diverse loads. It was shown that outcomes obtained were at a 95% assurance level and hence were eloquent [15,16]. Further, the effect of injector variables and nozzle tip protuberance on the combustion attributes of two cylinders of natural aspiration diesel prime mover was explored using RSM statistic techniques. These variables got higher BTE and NO_x with lesser BSFC, UBHC, and CO at optimum IT of 21°bTDC (before Top Dead Centre), IOP of 225 bar, and nozzle tip protuberance of 2.5 mm [17]. According to Reşitoğlu et al. [18], it is not possible to achieve emission norms by engine modifications only. Similarly, the numerical simulation results shows that the higher-pressure gasoline direct injecting improved smaller-scale turbulent

intensity and evaporation of fuel, both at the same time. These duo effects were considered as the prime factors to enhance the flame propagation velocity, indicating new combustion ideas that were different from conventional SI combustion controlled by in-cylinder bulk flow, as reported by Kaminaga. et al. [19]. A set of laminar burning speeds with pressure, temperature, and equivalence ratio dependences were combined into a 3D-CFD calculation to compare the predicted displacements of flame front in an SI engine with that of the experiments. It was found that the reaction mechanism was very well validated in 1D–3D combustion calculations, as per the research by Ratnak. et al. [20].

Present Work

From the above literature survey, it is observed that research on the utility of biodiesels with design changes, NG, BG, and IVM, in diesel engines is rarely studied. Hence, these design changes need to be applied for detailed studies. Further RSM techniques have not been reported on the competence, emanations, or combustion attributes of diesel prime movers fueled with HOME with simultaneous design changes of NG, BG, and IVM in diesel engines. This work is an effort towards enhancing competence and curtailing exhaust emanations from diesel engines powered with renewable fuels. In addition, a statistical approach must be employed for modelling and optimization of engine variables and to ratify the valuable outcomes by the experiments inquest.

2. Experimentation Particulars

2.1. Thermal Characters of Fuels Utilised

Renewable Honge oil methyl esters (HOME) were derived from Honge vegetable oil through already improved and demonstrated technologies, called the simple alkali transesterification process, in which the Viscosity of HOME biodiesel obtained was 5.6 c. St at 40 °C, which is within the range of acceptance as diesel engine fuel, according to ASTM standards (1.9 to 6 c. St at 40 °C). Fuel properties in this inquest are tabulated in Table 1.

Table 1. Thermal characters of diesel, Honge oil, and its ester, HOME.

Sl. NoN	Properties	Diesel	Honge Oil	HOME	ASTM Standards
1	Viscosity (c. St at 40 °C)	4.59	56	5.6	ASTMD445
2	Flash point (°C)	56	270	163	ASTM D93
3	Calorific Value (kJ/kg)	45,000	35,800	36,100	ASTM D5865
4	Mass Density (kg/m ³ at 15 °C)	830	930	890	ASTM D4052
5	Cetane Number	45–55	40	40–42	ASTM D613
6	Cloud Point (°C)	15	13		ASTM D2500
7	Pour Point (°C)	1	−2 to −5		
8	Carbon Residue (%)	0.1	0.66		ASTM D4530
9	Type of oil	Fossil fuel	Non edible	Non edible	

2.2. Experimentation Methodologies

The experiments were carried out on existing single cylinder four stroke CI prime movers to operate on HOME. Set up was interfaced with a data acquiring system with Engine soft as the software. Figure 1 shows the line diagram of the test unit and modification to run on selected fuel, and its specific features are given in Table 2. The prime mover was always run at a rated RPM of 1500. A piezoelectrical transducer for pressure (made by PCB Piezotronics, Model: HSM 111A22, with Resolution: 0.145 mV/KPa) was fixed on the cylinder's head surface to record the cylinder gas pressure for a combustion inquest. Figure 2 shows IVM with a masking angle varying from 30°, 60°, and 90°. The mask acts as a turbine blade and hence the inlet valve rotates along with its spring as inlet air flows into the cylinder. Thus, araldite was applied to the spring to fix it and avoid rotation of its inlet valve. Figure 3 shows altered cylinder heads with a diverse number of bridges-n-grooves. Figure 4 shows triangular-shaped grooves on the piston, and the number of grooves varies from 3 to 9 in steps of 3. A five holes injector, with holes at a

diameter of 0.3 mm, was used, which was optimized in our previous work. The number of grooves made on the piston and cylinder head kept the same compression ratio and intensified the air swirl. An optimized IOP of 240 bar and injecting time fixed at 27°bTDC resulted in overall meliorated competence, while the compression ratio was kept constant at 17.5. The Hartridge smoke opacity meter was used to record the exhaust smoke intensity, which was a light extinction type working on the principle of a contrastive basis. The emitted levels of UBHC, CO, and NO_x were measured by a DELTA 1600 S exhaust gas assayer. The exhaust gas assayer and smoke recorder, which were periodically calibrated, were switched on, and before measurements, they were allowed to attain a steady state. To assure high accuracy, readings were noted five times and were plotted after finding their average graphs.

2.3. Uncertainties Estimated

The experiment's inquest and data obtained may be uncertain and thus could creep into various processes and hinder the proper outcomes of the research. Errors, due to the use of many instruments and sensors, are bound to occur randomly from the changes, resulting from diverse trials and measurements. Systematic errors may be made constant by calibrating the instruments periodically. To minimize measuring error, five readings were taken, and the average values were considered for their results assay. Accuracy or correctness of recorded loading, engine speed, temperature, and fuel consumptions were 0.11, 1.1, 1.0, and 0.12, respectively. Uncertainties determined for BTE%, EGT °C, and BSFC kg/kWh were ± 1.2 , ± 3.1 , and ± 1.1 , respectively. Similarly, uncertainties of outputs smoke HSU, UBHC ppm, CO%, and NO_x ppm were ± 5.25 , ± 2.35 , ± 2.6 , and ± 2.35 , respectively.

Figure 1. T1, T3 = Water inlet temperature, T2 = Engine water jacket outlet temperature, T4 = Calorimeter outlet temperature, T5 = Exhaust gas temperature (EGT) before calorimeter, T6 = EGT after calorimeter, F1= Fuel flow DP(differential pressure) unit, PT = Pressure transducer, N = RPM encoder, EGA = Exhaust gas analyzer, SM = Smoke meter.

Table 2. Diesel engine specifications.

Sl. No.	Parameters	Specifications
1	Engine type	TV1 (Kirloskar make)
2	Software interfaced	Engine soft
3	Injector opening pressure	200 to 225 bar
4	Static injecting time	23°bTDC
5	Governor type	Centrifugal type Mechanical
6	Number of cylinders	Single cylinder
7	Number of strokes	4 strokes
8	Fuel oil	Diesel
9	Rated power	5.2 kW at 1500 rpm
10	Cylinder diameter (Bore)	0.0875 m
11	Stroke length	0.11 m
12	Ratio of compression	17.5: 1

Figure 2. Masking inlet valve with different mask angles °. (a) 30°; (b) 60°; (c) 90°.

Figure 3. Cylinder heads modified with diverse numbers of bridges-n-grooves, all having the same compression ratio.

(a)

(b)

(c)

Figure 4. Piston grooves: (a) 3 grooves (b) 6 grooves, and (c) 9 grooves.

2.4. Design of Experiments and Experimentation

The designs of experiments (DoE) gave us the outcomes of several possible variations that coincidentally had fewer numbers of experimental inquests to be conducted within the minimum time frame and lessened material consumptions.

The entire process of sampling was well extracted based on the earlier iterations on the experimental work. Further care was taken to arrive at the data points after several cases of dry runs. The exhaustive study used predicted the results near to the accuracy study, with a 90–95% confidence level.

Based on many facts and their levels, an appropriate DoE was selected [3,21–23]. In this work, three input variants, namely number of piston grooves, inlet valve masking, and number of grooves-n-bridges on cylinder heads, were considered as predictor variables or regressors, selecting their range based on previous works. Such input variants chosen for the inquest with levels are shown in Table 3, and the designs of the experimentation plan is presented in Table 4. The readings were recorded, and competence, emanations, and combustion attributes, i.e., BTE, smoke, UBHC, CO, NO_x, PP, ID, CD, and HRR, were determined. Additionally, emissions attributes were obtained using calibration of devices and are presented in Table 5.

Table 3. Notified engine predictor variables and levels.

Variables	Notation and Units	Levels		
Number of grooves on piston	G or A, Nr	3	6	9
Inlet valve masking	M or B, Degrees	30	60	90
Grooves and Bridges on Cylinder head	Br-Gr or C, Nr	3	5	7

Table 4. Matrix of experimental design plan and measured values of responses.

Trial No.	Settings of Parameters			Responses Characteristics (80% Load)								
	No. of Grove	Masking (Degree)	BR-GR	BTE (%)	Smoke (HSU)	HC (ppm)	CO (%)	NO _x (ppm)	Pmax (Bar)	ID (°CA)	CD (°CA)	HRR (J/°CA)
1	3	30	1B2G	23.5	67	60	0.35	730	55	20	33	60
2	3	30	2B3G	25.5	58	49	0.31	750	60	18	31	63
3	3	30	3B4G	24.5	62	57	0.33	740	58	19	32	62
4	3	60	1B2G	24.15	65	58	0.33	740	57	19	32	62
5	3	60	2B3G	26.25	54	47	0.29	760	62	17	30	65
6	3	60	3B4G	25.20	60	55	0.31	750	60	18	31	64
7	3	90	1B2G	24.85	63	56	0.31	760	60	17	31	64
8	3	90	2B3G	27.95	52	45	0.27	780	65	15	29	67
9	3	90	3B4G	25.75	58	53	0.29	770	63	16	30	66
10	6	30	1B2G	25.45	61	54	0.3	790	61	16	30	65
11	6	30	2B3G	28.53	50	43	0.26	810	66	14	28	69
12	6	30	3B4G	26.25	56	51	0.27	800	64	15	29	67
13	6	60	1B2G	26.05	59	52	0.28	810	63	15	28	67
14	6	60	2B3G	29.15	49	41	0.24	830	68	13	26	71
15	6	60	3B4G	27.15	57	49	0.25	820	66	14	27	69
16	6	90	1B2G	28.55	57	50	0.26	840	65	14	26	69
17	6	90	2B3G	31.55	47	39	0.22	860	70	12	24	73
18	6	90	3B4G	28.15	55	47	0.24	850	68	13	25	71
19	9	30	1B2G	24.47	64	57	0.33	760	58	18	31	62
20	9	30	2B3G	26.52	54	46	0.29	780	63	16	29	66
21	9	30	3B4G	25.37	59	54	0.30	770	61	17	30	64
22	9	60	1B2G	25.10	62	55	0.31	775	60	17	30	65
23	9	60	2B3G	27.20	52	44	0.27	795	65	15	28	68
24	9	60	3B4G	26.17	59	52	0.28	785	63	16	29	66
25	9	90	1B2G	25.70	60	53	0.29	800	62	15	28	67
26	9	90	2B3G	30.25	50	50	0.25	820	68	13	26	70
27	9	90	3B4G	27.95	57	51	0.27	810	66	14	27	69

Table 5. RSM fitted values of the competence, combustion, and emanation attributes.

Trial No.	Parameter Settings			Fitted Responses (80% Load)								
	No. of Grove	Masking (Degree)	BR-GR	BTE (%)	Smoke (HSU)	HC (ppm)	CO (%)	NOx (ppm)	Pmax (Bar)	ID (°CA)	CD (°CA)	HRR (J/°CA)
1	3	30	1B-2G	23.5215	67.3796	60.2500	0.351574	717.5	55.1574	19.8889	33.1944	59.8611
2	3	30	2B-3G	25.5694	56.4074	49.9722	0.311574	747.5	60.1019	17.8889	33.1944	63.3889
3	3	30	3B-4G	24.3757	61.9907	57.0278	0.327130	737.5	57.9352	18.8889	33.1944	61.9167
4	3	60	1B-2G	24.1174	65.0741	57.4167	0.329074	740.0	57.1574	18.8889	32.1111	61.8056
5	3	60	2B-3G	26.2528	54.5185	47.2222	0.290741	760.0	62.1852	16.8889	30.1111	65.3333
6	3	60	3B-4G	25.1465	60.5185	54.3611	0.307963	750.0	60.1019	17.8889	31.1111	63.8611
7	3	90	1B-2G	24.7465	62.3241	55.5833	0.308796	762.5	59.7130	17.2222	30.6944	63.7500
8	3	90	2B-3G	27.9694	52.1852	45.4722	0.272130	782.5	64.8241	15.2222	28.6944	67.2778
9	3	90	3B-4G	25.9507	58.6019	52.6944	0.291019	772.5	62.8241	16.2222	29.6944	65.8056
10	6	30	1B-2G	25.4458	61.3796	53.4167	0.300185	795.0	60.8241	16.2222	29.4444	65.1111
11	6	30	2B-3G	28.3167	50.7407	43.2222	0.258519	815.0	65.8519	14.2222	27.4444	68.5556
12	6	30	3B-4G	26.3458	56.6574	50.3611	0.272407	805.0	63.7685	15.2222	28.4444	67.0000
13	6	60	1B-2G	26.0667	59.4074	51.3333	0.278519	810.0	62.7407	15.2222	28.1111	67.2222
14	6	60	2B-3G	28.8250	49.1852	41.2222	0.238519	830.0	67.8519	13.2222	26.1111	70.6667
15	6	60	3B-4G	27.1417	55.5185	48.4444	0.254074	820.0	65.8519	14.2222	27.1111	69.1111
16	6	90	1B-2G	28.7208	56.9907	50.2500	0.259074	835.0	65.2130	13.5556	26.4444	69.3333
17	6	90	2B-3G	31.3679	47.1852	40.2222	0.220741	855.0	71.4074	11.5556	24.4444	72.7778
18	6	90	3B-4G	27.9708	53.9352	47.5278	0.237963	845.0	68.4907	12.5556	25.4444	71.2222
19	9	30	1B-2G	24.4118	63.6019	56.5833	0.331019	757.5	58.0463	17.8889	31.3611	62.3611
20	9	30	2B-3G	26.5056	53.2963	46.4722	0.287685	777.5	63.1574	15.8889	29.3611	65.7222
21	9	30	3B-4G	25.3576	59.5463	53.6944	0.299907	767.5	61.1574	16.8889	30.3611	64.0833
22	9	60	1B-2G	25.0576	61.9630	55.2500	0.310185	775.0	59.8796	16.8889	29.7778	64.6389
23	9	60	2B-3G	27.2389	52.0741	45.2222	0.268519	795.0	65.0741	14.8889	27.7778	68.0000
24	9	60	3B-4G	26.1785	58.7407	52.5278	0.282407	785.0	63.1574	15.8889	28.7778	66.3611
25	9	90	1B-2G	25.7368	59.8796	54.9167	0.291574	802.5	62.2685	15.2222	27.8611	66.9167
26	9	90	2B-3G	30.1056	50.4074	44.9722	0.251574	822.5	67.5463	13.2222	25.8611	70.2778
27	9	90	3B-4G	27.0326	57.4907	52.3611	0.267130	812.5	65.7130	14	26.8611	68.6389

2.5. Response Surface Modelling and Assay

RSM is extensively applied to problems in which numerous inputs with different levels potentially influence the competence of responses or the quality attributes of the process. The results are shown in the form of a surface of responses between input parameters. Hence, every point is a predicted and optimized useful result, maximizing or minimizing a response. Thus, any desirable point can be selected, its operating conditions are fixed accordingly, and an experiment can be conducted. The mathematic modeling for outcomes is fixed with correlation among input predictors. The quadratic polynomial predictor based on RSM is given by [24].

$$Z = C_0 + \sum_{i=1}^k C_i X_i + \sum c_{ii} X_i^2 + \sum_{i < j=2} c_{ij} X_i X_j \quad (1)$$

Equation (1) is the response surface Z that accounts linearity, interactions, and curvy-linear terms, where

c_0 = constant coefficient,

c_i' s = coefficients for all linearity terms,

c_{ii}' s = coefficients for quadratic terms,

c_{ij}' s = coefficients for interactions terms.

The regression predictors and regressing coefficients are obtained according to the literature given in Reference [19]:

$$c = (X^T X)^{-1} X^T Z \quad (2)$$

where C = matrix for input variant estimations;

X = calculations matrix, which includes linear, interaction, and quadratic terms;

X^T = transposing of matrix X and Z is the matrix of the outcome attribute.

The current work can reach for higher order polynomials, at least mathematically; however, the interpretation of higher order modelling is complex. There is always a higher risk of introducing over-fitting of the model, which might result in bad predictions. On the other hand, more terms could result in multi-collinearity and ill-conditioning of ($X'X$), which can become an issue as the second-degree terms are the square or product of the first-degree terms and so forth.

The established predicting models are obtained through multiple regressing assays using the Design-Expert11 software program. The regression equations in terms of uncoded variables are:

$$\text{BTE} = 9.11701 + 2.10081 \times A + 0.01299 \times B + 4.21042 \times C - 0.16435 \times A^2 + 0.00002 \times B^2 - 0.40521 \times C^2 + 0.00028 \times A \times B + 0.00382 \times A \times C + 0.006764444 \times B \times C \quad (3)$$

The linear influences were due to changes in number of grooves on piston, G or A , angle of masking, M or B , and bridge–groove configuration, $Br-Gr$ or C , and the quadratics effect C^2 and the interactions effect $M \times Br-Gr$ ($B \times C$) were prime finding factors for the BTE as their coefficients were the largest. Additionally, the linear effect angle of masking M or B and quadratic effect C^2 were secondary evaluating factors, and other terms did not affect significantly. The positive coefficients increased the response.

$$\text{SMOKE} = 132.42 - 6.389 \times A - 0.087 \times B - 22.417 \times C + 0.457 \times A^2 - 2.069 \times C^2 + 0.004 \times A \times B + 0.056 \times A \times C + 0.007 \times B \times C \quad (4)$$

Smoke considerably decreased due to the linear and quadratic effect of the C configuration due to a large negative co-efficient. Similarly, the linear and quadratic effect of A influences smoke formation. Piston grooves and grooves-n-bridges on cylinder heads enhance the rate of swirl and hence the rate of combustion, resulting in less smoke. Similarly, the linear effect of masking B and the interactive effect of B and C have less effect on smoke formation and others have negligible effect.

$$\text{HC} = 129.833 - 7.569 \times A - 0.177 \times B - 22.556 \times C + 0.556 \times A^2 + 0.001 \times B^2 + 2.167 \times C^2 + 0.0008 \times A \times B + 0.014 \times A \times C + 0.001 \times B \times C \quad (5)$$

HC considerably decreases due to the linear and quadratic effect of C configuration due to a large negative co-efficient. Similarly, the linear and quadratic effect of A influences smoke formation. Piston grooves and grooves-n-bridges on cylinder heads enhance the rate of swirl and hence the rate of combustion, resulting in less HC. Similarly, the linear effect of masking B has a considerable effect because it meliorates swirl, decreasing HC formation and offsetting its associated effect of decrease in volumetric efficiency.

$$\text{CO} = 0.674907 - 0.057685 \times A - 0.000972 \times B - 0.075556 \times C - 0.04568 \times A^2 + 0.000001 \times B^2 + 0.006944 \times C^2 + 0.000009 \times A \times B - 0.000278 \times A \times C + 0.000028 \times B \times C \quad (6)$$

For CO quadratic effects, A^2 and C^2 and linear effects of A and C are significant. Other terms have a negligible effect.

$$\text{NOx} = 468.750 + 74.167 \times A - 0.167 \times B + 40.0008 \times C - 5.833 \times A^2 + 0.006 \times B^2 - 3.750 \times C^2 + 0.0028 \times A \times B \quad (7)$$

Piston grooves and grooves-bridges on cylinder heads enhance the rate of swirl and hence the rate of burning, resulting in higher peak temperatures and pressures, thus increasing NOx formation. The largest coefficients of A and C prove which can be considered as primary significant factors. However, their quadratic effect tends to decrease NOx formation, and while it is a secondary determining factor, the interactive effect is negligible.

$$\text{Pmax} = 19.0185 + 6.0972 \times A + 0.0375 \times B + 9.500 \times C - 0.4691 \times A^2 + 0.0003 \times B^2 - 0.8889 \times C^2 - 0.0009 \times A \times B + 0.0139 \times A \times C + 0.0014 \times B \times C \quad (8)$$

For all linear coefficients significantly increasing the response, their quadratic effect tends to decrease the response with a negligible interactive effect.

$$ID = 37.8472 - 3.8889 \times A + 4.00 \times C + 0.0963 \times A^2 - 0.0004 \times B^2 + 0.3750 \times C^2 \quad (9)$$

Linear coefficients and quadratic coefficients increase this response.

$$CD = 51.7361 - 4.00 \times A - 0.0111 \times B - 4.0000 \times C + 0.3148 \times A^2 - 0.0002 \times B^2 - 0.3750 \times C^2 - 0.0028 \times A \times B \quad (10)$$

Linear coefficient of A decreases this response, but its quadratic coefficient increases the response. Quadratic coefficient of C decreases the response and has a considerable interactive effect on A and B.

$$HRR = 30.0417 + 5.7361 \times A + 0.0593 \times B + 6.8056 \times C - 0.4444 \times A^2 - 0.6250 \times C^2 + 0.0019 \times B \times C \quad (11)$$

For HRR, all linear coefficients significantly increase the response, while quadratic coefficients of A and C decrease the response and have negligible interactive effects. NOTE: It is to be observed that interactions were particularly important for BTE and CD. They indirectly decreased emissions where BTE was in %, smoke in HSU, HC in ppm, CO in %, NOx in ppm, ID in °CA, CD in °CA, Pmax in bar, and HRR in J/°CA.

The paramount parameter tests were: (1) Z-tests; (2) *t*-tests; (*3) χ^2 -tests, and (4) F-tests, which were based on the normality assumption, i.e., the source for data taken had normal distribution. The Fisher (F)-test [24] was used to check the sufficiency of the RSM fittings-based modellings and was found to be adequately applicable at 95% assurance level.

The contrasted prognosticated and experimented values of competence attributes can be shown by graphs which were drawn taking two variables at a time, while keeping the third variable at the central level.

The response surface model accuracy was given by calculating the error of prognostication, i.e.:

$$\Delta = \frac{100}{n} \sum_{i=1}^n \left| \frac{y_{i,exp} - y_{i,pred}}{y_{i,pred}} \right| \quad (12)$$

where, y_i , except design of experiments (DoE) value of competence, attributes correspond to the i th trial. y_i , predicted: RSM predicted value of competence attribute, corresponding to i th trial n : number of trials in FFD.

Equations (3)–(11) are used to test the accuracy of the predictors, taking the experimented data set in FFDs. The percentages predicting errors were found to be 0.58, −0.392, −3.038, −0.3356, 0.5847, −1.97, 3.845, −1.818, and 0.3053 for the BTE, smoke, HC, CO, NOx, Pmax, ID, CD, and HRR model, respectively. As the percentage of predicting errors are small, the RSM predicted values may be considered for implementation by corresponding design change and anticipating better results. However, it can be noted that percentage errors are more for HC and ID, as reported in literature by [4,6,23]. Yashvir Singh et al. [4] gave percentage errors for BTE, HC, and NOx as 3.97, 4.65, and 2.67, respectively.

Therefore, Equations (3)–(11) are used to prognosticate the required attribute by substitution of the values of piston grooves, inlet valve masking, and number of grooves-bridges on cylinder heads within the ranges of the variants notified. The impact of notified input variables on competence, emissions, and combustion attributes are shown in Figures 5–13. These contours were obtained, taking two variables at a time while keeping the third variable at the central level.

Figure 5. Effect of the 'TVM' and 'NG' on BTE.

Figure 6. Effect of the 'TVM' and 'NG' on smoke emission.

Figure 7. Effect of the 'TVM' and 'NG' on HC emission.

Figure 8. Effect of the 'TVM' and 'NG' on CO emission.

Figure 9. Effect of the 'IVM' and 'NG' on NOx emission.

Figure 10. Effect of the 'IVM' and 'NG' on Pmax.

Figure 11. Effect of the 'IVM' and 'NG' on ignition delay.

Figure 12. Effect of the 'IVM' and 'NG' on combustion duration.

Figure 13. Effect of the 'IVM' and 'NG' on heat release rate.

The significance testing using ANOVA was carried out to validate the models after establishing the use of the RSM. If p -values were less than 0.05, as given in Table 6, the model terms were assumed to be significant and hence were able to describe 95% of the variability of the response, as reported in literature [3,4,7,8]. Table 7 shows the significant model terms for BTE, smoke, HC, CO, NO_x, Pmax, ID, CD, and HRR predictor models. The p -values greater than 0.05 showed unimportant models, which are indicated by the terms in bold. Usually, the p values for interactions are much more than 0.05, which shows lack of fit, as also reported by [25,26]. This is because the interactions between predictor variables used in our works were arbitrarily taken, and it was quite possible that the particular combination may not be the best and hence usually ended up with p values of more than 0.05. Hence, there are endless design variabilities possible for interactions and we are supposed to use the best combination to maximize responses, which may have p values less than 0.05. It is usually very difficult to test different combinations in our works. Additionally, linear and quadratic models show lack of fit for input variable masking. The regressing statistics for rightness of fit (R^2) and the rightness of prognostication (Adjusting R^2) are provided in Table 7 for all the outcomes. The value of R^2 indicates the percentage variation of the outcome after the paramount factors were considered. The adjusting R^2 value gives an idea about the number of predictor inputs in the model. Both these values indicate that the models fit the experimental data sufficiently. The data fitting quality was expressed as a coefficient of multiple determination (R^2) and rightness of prediction (Adj- R^2), but as the number of affecting variables increased, the R^2 value increased. Hence, adj- R^2 was a better parameter, which is recommended to use as it decreases if unimportant terms are included, as reported by K. Ibrahim et al. [26]. Therefore, the regressing R^2 value

can be preferably put forth as the percent of information utilized by the models from the data. For instance, R^2 equal to 0.94 informs us that the models account for over 94% of the changeability in the experimented data. The prima facie evidence from the R^2 values in Table 8 shows that all outcomes in the assay had very good fittings. The HC emissions show lack of fit with the R^2 value of 0.9478 and predicted R^2 value of 0.8666. HC is usually much less predictable as it is not smoothly related to other quantities, as reported by many researchers, H. Raheman et al., 2004 [6] and Z. Win et al., 2005 [23], with a R^2 value of 0.669. Along with ANOVA, the precise indexing values, such as R^2 , 'adjusting R^2 ', and 'predicting R^2 ', were also found to be adequate as they were nearer to the experimented values. The precise indexing values of the diverse predictor models are shown in Table 7. The press residuals, the predicting errors sum of squares (press) supposed by Allen (years 1971 and 1974), present a meaningful residual scale. Press can be utilized to evaluate a probable R^2 value for predictions, such as R^2 predictions = $1 - (\text{Press}/\text{SST})$.

Table 6. ANOVA evaluation for the responses indicating p -values.

Response	BTE	Smoke	HC	CO	NOx	Pmax	ID	CD	HRR
Regression	0.001	0.002	0.002	0.001	0.005	0.000	0.000	0.000	0.001
Linear	0.000	0.002	0.000	0.000	0.000	0.003	0.000	0.001	0.000
Number of Grooves	0.000	0.000	0.005	0.000	0.006	0.001	0.000	0.000	0.000
Masking	0.077	0.094	0.086	0.000	0.477	0.052	1.000	0.657	0.010
Grooves	0.002	0.002	0.003	0.000	0.003	0.001	0.000	0.002	0.000
Square	0.006	0.055	0.005	0.000	0.002	0.002	0.001	0.000	0.000
Number of Grooves * No of Grooves	0.010	0.020	0.000	0.030	0.003	0.057	0.002	0.000	0.045
Masking * Masking	0.714	0.492	0.429	0.248	0.004	0.029	0.010	0.310	1.000
Grooves * Grooves	0.003	0.040	0.003	0.000	0.010	0.022	0.000	0.000	0.010
Interaction	0.063	0.083	0.413	0.013	0.170	0.406	1.000	0.216	0.304
Number of Grooves * Masking	0.440	0.155	0.104	0.222	0.029	0.325	1.000	0.040	0.094
Number of Grooves * Grooves	0.479	0.155	0.851	0.021	1.000	0.325	1.000	1.000	0.388
Masking * Grooves	0.013	0.080	0.851	0.021	1.000	0.325	1.000	1.000	1.000

Table 7. RSM model evaluation.

Response	BTE	Smoke	HC	CO	NOx	Pmax	ID	CD	HRR
Mean	26.5139	59.7005	50.6666	0.27495	788.3333	62.8889	15.7777	29.1851	66.3333
Range	7.8464	20.1944	20.0278	0.130833	137.5	16.25	8.3333	8.75	12.9167
Variance	3.5902	33.026	26.3673	0.0009456	1158.333	13.8556	4.1234	5.6855	9.7109
Standard Deviation	1.894	5.7468	5.1349	0.03075	34.0343	3.7223	2.0306	2.3844	3.1162
Model Degree	Linear, Quadratic and Interactive	Linear and Quadratic	Linear and Quadratic	Linear and Quadratic	Linear and Quadratic	Linear and Quadratic	Linear and Quadratic	Linear Quadratic and Interactive	Linear and Quadratic
R2	99.58	98.50	94.78	99.67	99.29	99.62	98.82	98.08	99.32
PRESS	0.598056	25.1137	99.2654	0.000236424	587.972	3.62095	3.33283	6.71292	4.65460
Predicted R2	98.76	96.30	86.66	99.10	98.13	98.99	97.04	95.02	98.24
Adjusted R2	99.35	97.70	92.01	99.49	98.91	99.41	98.19	97.07	98.95

Table 8. ANOVA and R² values for the fitted predictor models.

	Sum of Squares		Degrees of Freedom		Mean Square		F-Ratio	R ²
	Regression, SST	Residual	Regression	Residual	Regression	Residual		
BTE	48.0350	0.2042	9	17	5.3372	0.0120	444.37	0.9958
Smoke	669.417	10.213	9	17	74.38	0.601	123.81	0.9850
HC	705.139	38.861	9	17	78.349	2.286	34.27	0.9478
CO	0.026186	0.000088	9	17	0.002910	0.000005	562.31	0.9967
NOx	31275.0	225.0	9	17	3475.0	13.2	262.56	0.9929
Pmax	358.028	1.38	9	17	39.781	0.081	490.19	0.9962
ID	111.333	1.333	9	17	12.3704	0.0784	157.72	0.9882
CD	132.083	2.583	9	17	14.6759	0.1520	98.58	0.9808
HRR	262.194	1.806	9	17	29.1327	0.1062	274.3	0.9932

The Fisher (F)-test was used to check the sufficiency of the RSM fittings-based modellings and was found to be adequately applicable at 95% assurance level. ANOVA summations are provided in Table 8, clearly notifying that the fitted model was satisfactory. The determination coefficient (R²) [24] was also evaluated (Table 8), showing good linkages among the experimented and prognosticated values for every outcome.

Looking at the values of range and standard deviation, it can be stated that there is considerable variation in values of responses and hence it justifies 3³ trials for DoE.

3. Results and Discussions

3.1. RSM Analysis

The response surface profiles and contours of the optimized characteristics are shown in Figures 5–13. For a combination of the 2B 3G cylinder head, IVM of 90°, and ‘NG’ of six grooves on piston RSM, analysis of the experimental results optimizes outcome responses as: BTE, 31.3679%; smoke, 47.1852 HSU; HC emission, 40.2222 ppm; CO, 0.220741%; NOx, 855.0 ppm; peak pressure, 70.4074 bar; ignition delay, 11.5556 °CA; combustion duration, 24.4444 °CA, and heat release rate of 72.7778 J/°CA. This optimized condition was validated with an actual experiment. It is to be noted that, for the above combination, BTE was 31.3679% for HOME in the CMFIS operation, which was equal to the BTE of diesel in the conventional engine. The above result had the highest NOx emissions of 855.0 ppm due to the improved rate of combustion, which was much less than conventional diesel engine and, due to improved swirl and enhanced heat transfer to cylinder walls, was the main concept of this work. The highest NOx emissions may be due to an increased rate of swirling and proper fuel air mixture formation, resulting in maximum peak temperature attained in the cylinder, which enhanced formation of NOx. Hence, to reduce NOx emissions and its harmful effects on the formation of photochemical smog, we can look for other combinations. A combination of the 3B 4G cylinder head, IVM of 90°, and NG of three grooves on the piston optimized a low NOx of 772.5 ppm with BTE 26.0%, a compromise of 5.3679% in BTE compared to the above combination.

3.2. Performance Attributes

Brake Thermal Efficiency

The outturns of Inlet Valve Masking (IVM) and Number of Grooves (NG) on BTE for a given bridge-groove configuration (BGC) at 80% loading are presented in Figure 5. It is clear that the BTE enhances with increased IVM up to 90°, principally for enhanced swirl, resulting in improved air-fuel mixture formation, whereas, reduced IVM showed a decreasing trend of BTE. For a fixed bridge-groove configuration at 80% load, higher BTE was observed with and increased NG up to six, and beyond, this BTE decreased. Additionally, it is clear that the ID decreased to NG of six grooves, then exhibited increasing trends for the other value of ‘BGC’. However, for given IVM and NG combinations, ‘BGC’ with the 2B 3G model showed the highest BTE. The reasons could be due to an increase in swirl, bridges, and grooves induced in a tumbling flow. Therefore, it can be inferred

that lower ID at NG of six and IVM of 90° facilitated higher combusting efficacy and lessened heat escape in the cylinder due to escalated flaming temperatures and HRR. Similar inquests are written in literature by Ganapathy et al., [5] and Khoobakht et al., [13]. The highest BTE achieved for NG of six and IVM of 90° was 31.3679%, which was 3.3679% higher and 10.73% more compared to the neat HOME operation in CI mode, which was 28%. In their RSM studies, Hirkude et al., [7] reported an increase in BTE by 5.41% for B70 waste fried oil methyl ester (WFOME).

3.3. Emission Attributes

3.3.1. Smoke Emissions

Figure 6 depicts the variant smoke intensity with the 'IVM' for diverse 'NG' at 80% loading. For a given BGC at 80% loading, the smoke emitted decreased up to an 'IVM' of 90° then showed an increasing tendency at other values of 'NG'. The rationale for this tendency may be due to better intermixing of fluids air and fuel and perfect combustion at 'IVM' of 90° and 'NG' of six, resulting in high BTE. However, for a given IVM and NG, combinations of 'BGC' with the 2B 3G model showed the lowest smoke. The lower smoke emitted level attained was 47.1852 HSU in the CMFIS, working at an 'IVM' of 90° and 'NG' of six, which was 44.11% lesser than the neat HOME utilized CI mode of engine working, which was 68 HSU. A similar reduction of smoke by 20% for B100 was reported by Raheman et al. [6] and Win et al. [20].

In addition, for only 2B 3G, operation of HSU reduced to 54 HSU, which was around 66 HSU for an 'IVM' of only 90° or 'NG' of only six in CMFIS operation taken from our previous work. Now, their combination reduced smoke emissions to 47.1852 HSU.

3.3.2. HC Emissions

HC emittance tendency with the 'IVM' and 'NG' is presented in Figure 7 for the BDF injected, i.e., HOME in the CMFIS mode. For a given BGC at 80% loading, the HC emission decreased up to an 'IVM' of 90° then tended to increase at any other value of 'NG'. The rationale for this trend may be due to an idealized combustion of fuel injecting, resulting in high BTE at an 'IVM' of 90° and 'NG' of six. However, a given IVM and NG combinations 'BGC' with the 2B 3G model showed the lowest HC emissions. The lesser HC emissions level attained was 40.2222 ppm in the CMFIS, working at an 'IVM' of 90° and an 'NG' of six, which was 38.12% lower when contrasted to the neat HOME fueled CI mode of working, which was 65 ppm. Additionally, for the opposite trend of increased HC emissions with other bridge-groove combinations, the possible reason might be due to an insufficient swirl developed for a 1B2G cylinder head and too much turbulence induced for the 2B3G cylinder head, not allowing proper air-fuel mixture formation. A similar work is reported by Najafi [10], using biodiesel in a diesel prime mover, resulting in lessened competence, increased fuel intake, and UBHC and carbon CO, emitted with curtailed NOx gas formation.

3.3.3. CO Emissions

Figure 8 portrays the nature of CO emitted for HOME fueled CMFIS, working at 80% loading. Large heat unleashing in the pre-mixed uncontrolled burning phases rather than the diffusing or controlled burning phases is always amenable for lowered CO emission. CO emitted strongly depends on the air fuel (A/F) ratios linked to stoichiometric proportions. Richer combustion inevitably ends in more CO emissions and increases linearly with the air fuel (A/F) ratios other than the stoichiometric A/F ratio. For a given BGC, at 80% load-increased 'IVM' up to 90° showed lowered CO emissions similar to HC emissions at any given value of 'NG'. At 'IVM' of 90° and 'NG' of six, the lowest CO emanations were seen. The rationale may increase in local temperatures and improve CO oxidation to CO₂, as reported in the literature [3,7,16], which is similar with our findings. However, for a given IVM and NG, combinations 'BGC' with the 2B 3G model showed the lowest CO emissions. The least CO emanations level attained was 0.220741% in the CMFIS, work-

ing at 'IVM' of 90° and 'NG' of 6, which was considerably less compared with the neat HOME utilized CI mode of engine working, which was 0.35%, thus reduced by 58.55%. This satisfies emission standards BS 6 and Euro 6. Additionally, for the opposite trend of increased CO emissions with other bridge-groove combinations, the possible rationale might be an unsuitable swirl and lesser time available for the perfect combustion, similar to the work of Najafi [10], which used biodiesel in a diesel prime mover and resulted in inferior competence, increased fuel intake, and UBHC and CO emitted with lessened NOx formation.

3.3.4. NOx Emissions

The NOx emissions measured for CMFIS mode at 80% loading are indicated in Figure 9. The NOx gas emitted is meliorated by enhanced cylinder pressures and charge temperatures. Elated NOx emitted for BDF HOME might be due to the presence of a large oxygen content of the oil chemical structure itself. A notified BGC at 80% load that increased IVM up to 90° showed increased NOx concentration at first and then a decreasing tendency for any given value of 'NG' under CMFIS operation. A suitable description for this could be due to the enhanced temperatures registered inside the cylinder for the uncontrolled combustion stage at IVM of 90° and NG of 6, which ended in larger NOx. Similarly, Pandel et al. [16] reported elated BTE and NOx with lesser BSFC, HC, and CO at optimal IT of 21° bTDC, IOP of 225 bar, and nozzle tip protuberance of 2.5 mm.

However, a given IVM and NG combinations of BGC with the 2B 3G model showed the highest NOx emissions of 855 ppm, which were 18.01% less contrasted with the neat HOME utilized CI mode of working, which was 1009 and 900 ppm, respectively, with and without bridge-groove configuration. Lowered NOx emitted with other combinations may be linked to low combusting temperatures. Similar inquests are written in literature [14,22,27]. Use of biodiesel resulted in lessened BTE and enhanced BSFC, CO, and HC emittance with lowered NOx formed, as reported by Najafi [10]. It is to be noted that, for diesel engine simulation, fueled with HOME, when implementing a combination of 1B 2G cylinder heads, an IVM of 30° , and NG of 3 grooves on the piston optimizes a low NOx of 717.5 ppm, BTE decreased slightly from 31.3679% to 23.5215%. This was much less than that for neat HOME in a conventional engine, i.e., 1009 ppm. Hence, the percentage reduction of NOx was about 40.62%. This suffices, to some extent, emission standards BS 6 and Euro 6, which are planning to reduce NOx by a staggering 70% compared to BS 4 and Euro 5. Thus, by making further design changes in the above combination, NOx may be decreased towards 70%.

3.4. Combustion Attributes

3.4.1. Peak Pressure (Pmax, PP)

The variant PP for HOME fueled CMFIS working at diverse IVM and NG is put forth in Figure 10. The PP is influenced by contained energy and the dynamic viscous nature of the injecting fuel. At an IVM of 90° and NG of 6, cylinder gas pressure was the highest. The lessened ID and CD could be the reason for these set conditions making combusting reactions, faster ending at enhanced PP. However, a given a IVM and NG combinations of BGC with the 2B 3G model showed the highest peak pressure of 71.4074 bar. However, the PP in a neat HOME utilized CI engine working with and without bride-groove configuration was 70 and 50 bar, respectively. Therefore, comparing PP in neat HOME injected CI engine operation without bride-groove configuration, it was 30% lower than the optimized value.

3.4.2. Ignition Delay (ID)

The behavior of ID with IVM and NG for different BGC is shown in Figure 11. The charge in temperatures during compression, heat energy unleashed in premixed combustion, heat conveyed to the surrounding materials, and the residue gas quantity appears to be the prime factors amenable for changes in ID crank angles. The ID value was evaluated based on the static injection timing, considering pressure crank angles data for 100 power

cycles. For the IVM of 90° and NG of 6, shorter ID was noted because of the highest charge temperatures. However, the ignition delay duration increased for either increasing or decreasing IVM and NG from the optimized values due to lessened temperatures prevailing. However, a given IVM and NG combinations of BGC with the 2B 3G model showed lower ID of 11.5556°CA , which was 55.76% (without BGC) lower than the ID in neat HOME fueled CI engine operation with and without bridge-groove configuration, i.e., 13 and 18 degrees, respectively. Though ID decrease, it marginally results in PP nearer to TDC position, which acts through larger lengths of strokes, leading to more displacement work done and higher BTE.

3.4.3. Combustion Duration (CD)

The variant CD, as in Figure 12, has been calculated as the duration between the SOC and 90% net heat unleashed. In addition, total CD is the time length of the net fuel oxidation processes and is the summation of the flames establishment period. For a given BGC at 80% load, an IVM of 90° and NG of 6 lower CD was noticed due to higher cylinder temperatures prevailing inside the engine cylinder. Similar inquests are written in literature [16]. The high BTE due to rapid-fire and more combusting intensity with the shortest ID in both stages of the HRR demonstrates the noticed results.

However, a given IVM and NG combinations of BGC with the 2B 3G model showed higher CD of 24.4444°Ca , which was 43.18% lower than the CD in neat HOME fueled CI engine operation with and without bridge-groove configuration, which was 32 and 35°CA , respectively. Reduced CD resulted in decreased burning time loss, enhancing competence. Additionally, though CD decreased marginally, it resulted in a shifting of PP towards the TDC position, which acted through larger stroke lengths, resulting in more work done and higher BTE.

3.4.4. Heat Release Rate (HRR)

Figure 13 portrays the variant HRR for CMFIS mode of prime mover, running at diverse IVM and NG for a given BGC. For the given NG, the HRR varies first with increasing tendency up to 90° , as presented in Figure 11. At IVM of 90° and NG of 6, maximized HRR was realized, which might be because of more heat unleashed in the uncontrolled combusting phase. Meliorated air fuel mixture forming, and consequently swift combusting, could have rendered for higher HRR. However, a given IVM and NG combinations of BGC with the 2B 3G model showed higher HRR of $72.7778\text{ J}/^\circ\text{CA}$, which was 17.55% higher than the HRR in neat HOME fueled CI engine operation with and without bridge-groove configuration, i.e., 70, $60\text{ J}/^\circ\text{CA}$, respectively. Faster HRR meliorates competence, and thus we can design high speed engines.

4. Validation of Test Results

4.1. Validation of Test Results for Optimized Conditions

The experimental work conducted thrice at the predictor variables of the piston with six numbers of grooves (NG), 90° inlet valve masking (IVM), and five numbers combinations of bridges-n-grooves on cylinder heads (Br-Gr) for validating the predicted results. An optimum IOP of 240 bar and injecting time of 27°bTDC resulted in overall better performance at 80% load and for a five-hole injector with a 0.3 mm hole size. For the actual value of outputs, the mean of three experimental results was considered. The summary of the theoretical RSM values, the mean of the measured values, and the percent error between them is given in Table 9. This validates that the models generated were accurate as the percent error in predictions agreed well with actual values.

Table 9. Validation of test results.

Response	BTE %	Smoke HSU	HC ppm	CO %	NOx ppm	Pmax Bar	ID (°CA)	CD (°CA)	HRR (J/°CA)
Predicted	31.3679	47.1852	40.2222	0.220741	855.0	71.4074	11.5556	24.4444	72.7778
Actual	29.94	55	46	0.24	820	66	14	32	67
Error%	−4.5521	16.56	14.36	8.72	−4.09	−7.572	21.15	30.91	−7.938

4.2. Emission Norms Set by Worldwide Councils and Validation of Engine Test

In BS 6 and Euro 6, the mass of pollutants emitted are computed by the equation in g/kwh.

$$M = \frac{(m_f + m_a) \times 1000 \times 3600}{28} \times \frac{(\text{NOx in ppm})}{1,000,000} \times \frac{30}{BP} \quad (13)$$

$$M = \frac{(0.00019531 + 0.007982) \times 1000 \times 3600}{28} \times \frac{(220)}{1,000,000} \times \frac{30}{1.04} \quad (14)$$

$$M = 6.641 \text{ g/kWh} \quad (15)$$

In which $m_f + m_a$ = mass of fuel and air in kg/s. and BP = brake power output of the engine.

Additionally, in BS 6 and Euro 6, the mass of pollutants emitted are computed by the equation in g/km:

$$Mi = \left[\frac{Qi \times Ci \times KH \times V_{mix} \times 10^{-6}}{d} \right] \quad (16)$$

In which Mi = Emission of the pollutant in g/km

V_{mix} = Exhaust gases volume diluted expressed in m^3 for the test and then corrected to normal pressure and temperatures 101.33 kPa. and 293 K.

Qi = Pollutant i density in kg/m^3 at 101.33 kPa and 293 K, standard conditions.

kH = Correction factor for humidity used for calculating the mass emission of nitrogen oxides. Such correction is not needed for CO and HC.

Ci = Pollutant i concentration in ppm of the dilute exhaust gases and correction made by the quantity of the pollutant i present in the diluting air.

d = Distance travelled in km.

The Central Pollution Control Board (CPCB), along with the Ministry of Forests and Environment in India, laid down emission regulations for diesel gensets (Figure 14), its logo. Permissible limits of emissions and other CPCB regulations that diesel genset manufacturers and users should be aware of are set. According to CPCB, the emission of NOx and HC in a diesel generator up to 19 kW output power should not exceed 7.5 g/kW-h. The emissions of CO should not be more than 3.5 g/kW-h, while that of particulate matter not exceed 0.3 g/kW-h. An expert committee estimated that only cars released approximately 48.678 tons of NOx in the year 2016 in the national capital of New Delhi, causing serious health problems. This November 2019, the Air Quality Index (AQI) of Delhi is 613 and extremely hazardous to health, and we can contrast it with the safe and good AQI range of 0–50.

Figure 14. Logo of Central Pollution Control Board.

The Conseil International Des Machines A Combustion (CIMAC), Frankfurt/Main (Website www.cimac.com) Germany (Figure 15), guide to diesel exhaust emissions control of NO_x , SO_x , particulates, smoke, and CO_2 —seagoing ships, big and small stationary diesel power plants, and units gives some background information on diesel exhaust gas components and their environmental impact, along with a short overview of the most important existing and upcoming regulations and various existing and future potential emission abatement technologies. CIMAC was founded in Paris in 1951, which is The International Council on Combustion Engines.

Figure 15. Logo of Conseil International Des Machines a Combustion.

The European Union and USA both set up the International Maritime Organization (IMO) for NO_x regulations. Accordingly, inland waterways and engines with a per cylinder displacement of less than 30 L/cylinder have a maximum permitted value for NO_x emissions at 7.2 to 11 g/kWh, depending on engine size.

The following Tables 10 and 11 show load tests carried out on the engine, with optimized conditions and emissions calculated in g/kWh. It can be seen that all values of HC emissions are less than 7.5 g/kW-h, which is the maximum permitted value as per CPCB India and is also less than 11 g/kW-h, which is the maximum permitted value as per CIMAC and USA. Additionally, only the first value of NO_x emissions is less than 7.5 g/kW-h, but others are more as per CPCB. However, two values of NO_x emissions are less than 11 g/kW-h, but others are more as per CIMAC and USA. Furthermore, all the values of CO emissions are more than 3.5 g/kW-h, which is the maximum permitted value as per CPCB India. Therefore, as the emissions are less than or very close to the norms, it can be stated that inlet valve masking (IVM), number of piston grooves (NG), and cylinder head bridge-groove configuration (BGC) can be implemented for any diesel engines.

Table 10. Observations of load test on diesel engine at optimised conditions.

S.No	N (rpm)	Time for 20 cc Fuel Consumption (s)	Air Consumption (m ³ /h)	EGT (°C)	NO _x (ppm)	HC (ppm)	CO (%vol)/ppm
1	1500	84.99	28.1	170	220	20	0.05/500
2	1500	69.78	30.46	216	380	25	0.08/800
3	1500	53.53	30.89	250	520	30	0.10/1000
4	1500	34.50	28.57	325	710	45	0.15/1500
5	1500	31.63	29.29	340	850	70	0.28/2800

Table 11. Validation of test emission results as per CPCB India, the European Union, and USA.

Brake Power (kW)	Mass of Fuel (kg/s)	BSFC (g/kWh)	Mass of Air (kg/s)	A/F Ratio	BMEP (Bar)	BTE (%)	Volumetric Efficiency (%)	NO _x (g/kWh)	CO (g/kWh)	HC (g/kWh)
1.04	0.00019531	417.63	0.007982	40.86	1.27	16.98	88.61	6.641	15.16	1.78
2.08	0.00023789	287.93	0.008293	34.86	2.54	24.22	86.89	10.81	12.65	2.22
3.12	0.00031010	236.33	0.008411	27.12	3.81	27.87	86.67	16.17	10.78	2.67
4.16	0.00048110	226.48	0.007778	16.17	5.08	29.94	84.52	22.08	11.48	4.00
5.20	0.00052475	211.53	0.007974	15.19	6.35	27.45	80.65	26.43	17.65	6.23

The emissions of CO for non-road diesel engines should not be more than 3.5 g/kW-h as per CPCB, BS VI norms. Diesel is proven to be a good fuel for diesel engines but, for diesel, these norms are not satisfied as all the values of CO emissions are more than 3.5 g/kW-h. Thus, for any blends of diesel with biodiesels, CO emissions are more than that of diesel due to incomplete combustion. For 100% HOME biodiesel, in conventional engines, these norms were not satisfied as all the values of CO emissions were more than 3.5 g/kW-h and considerably more than diesel due to poor combustion. However, for 100% HOME biodiesel with optimized combination of inlet valve masking (IVM) of 90° and number of piston grooves (NG) of 6 grooves on piston crown and cylinder head bridge-groove configuration (BGC) of 2B 3G, CO emissions are considerably reduced from 46.0 g/kW-h to 17.65 g/kW-h, if we take the last readings for a full load of 5.2 kW, as given in Table 12. Thus, we can conclude that, for CO, BS VI norms cannot be satisfied only from engine research, as reported by Resitoglu et al. [18], and may be satisfied by on board equipment, such as a (diesel oxidation catalyst (DOC). According to RSM studies, at 80% load, the lowest percentage of CO emissions is 0.220741% or 2207.41 ppm. at the same above optimum combinations, for which CO emissions are 16.90 g/kW-h, which is more than the corresponding value of the validation experiment, i.e., 11.48 g/kW-h, as given in Table 11.

Table 12. Comparison of CO emissions for diesel and HOME in conventional diesel engine and for validation test.

S.No	Brake Power (kW)	For Diesel		For HOME		For Validation Test	
		CO (%vol)/ppm	CO (g/kWh)	CO (%vol)/ppm	CO (g/kWh)	CO (%vol)/ppm	CO (g/kWh)
1	1.04	0.03/300	9.906	0.08/800	24.25	0.05/500	15.16
2	2.08	0.04/400	6.320	0.09/900	14.23	0.08/800	12.65
3	3.12	0.06/600	6.46	0.12/1200	12.93	0.10/1000	10.78
4	4.16	0.1/1000	10.78	0.25/2500	19.13	0.15/1500	11.48
5	5.20	0.35/3500	22.06	0.73/7300	46.01	0.28/2800	17.65

4.3. Theoretical Calculations of Approximate Emission of Greenhouse Gases CO₂ and NO₂ Based on Diesel Consumption by Vehicles in g/km

In total, 1 L of diesel weighs 835 g if specific gravity is 0.835. Diesel consists of about 86.2% of carbon or 720 g of carbon per liter. We know that 12 g of carbon needs 32 g of oxygen and burns to form 44 g of CO₂. Hence, for the complete combustion of 720 g of this carbon to CO₂, carbon needs $(720 \times 32)/12 = 1920$ g of oxygen. The sum is then

$720 + 1920 = 2640$ g of CO_2 /liter diesel. An average diesel consumption of 5 L/100 km by a vehicle then corresponds to 5×2640 g/liter/100 km = 132 g CO_2 /km. If 1920 g of oxygen is used, then $2.33 \times 1920 = 4480$ g of nitrogen is used, then, $(4480 \times 32)/14 = 10,240$ g of oxygen is needed for the formation of NO_2 if it is completely oxidized. This oxygen is taken from large amount of air available in the engine cylinder. The sum is then $4480 + 10,240 = 14,720$ g of NO_2 . Therefore, an average diesel consumption of 5 L/100 km by a vehicle then corresponds to $5 \times 14,720$ g/liter/100 km = 736 g NO_2 /km. However, if about 75% of the nitrogen exhaust is N_2 , then the remaining 25% burns to form NO_2 . Hence, the quantity of NO_2 formed is $0.25 \times 736 = 184$ g NO_2 /km. The carbon content of biodiesel is 76.5% or less, hence the above values shall reduce proportionately.

5. Conclusions

1. RSM is a powerful optimization tool for diesel engines fueled with HOME. Significant outcomes on the competence and emission attributes were assayed. A second-degree model was prosperously established to narrate the linkages among input parameter grooves on piston, inlet valve masking, and bridges and grooves on cylinder heads on output responses.
2. Optimal input variables for maximizing performance and minimizing emissions, except NO_x , are 2B 3G cylinder head, 'IVM' of 90° , and 'NG' of 6 grooves on the piston. RSM analysis of the experimental results optimizes outcome responses, as given below in Table 13.

Table 13. RSM analysis with optimized outcome responses.

Trial No.	Parameter Settings			Fitted Responses (80% Load)								
	No. of Grove	Masking (Degree)	BR-GR	BTE (%)	Smoke (HSU)	HC (ppm)	CO (%)	NOx (ppm)	Pmax (Bar)	ID °CA	CD °CA	HR R J/°CA
1	3	30	1B-2G	23.5215	67.3796	60.2500	0.351574	717.5	55.1574	19.8889	33.1944	59.8611
17	6	90	2B-3G	31.3679	47.1852	40.2222	0.220741	855.0	71.4074	11.5556	24.4444	72.7778

Although trial no 17 maximizes BTE, NO_x is also maximum. However, for trial no 1, NO_x is the minimum, but BTE decreases considerably as shown in Table 13.

3. Provision of bridges and grooves on the cylinder head proves to be very effective as they reduce emissions considerably. Additionally, a slight change in configuration of bridges and grooves can change flow directions and patterns and vary the way gases react, thus may reduce emissions further.
4. In RSM assay, BTE achieved for 'NG' of 6 and 'IVM' of 90° and 2B 3G cylinder head for HOME is 31.3679%, which is equal to BTE of diesel in a conventional engine. It is 3.3679% higher and 10.73% more compared to neat HOME operation in CI mode, which is 28%. In addition, BTE for the validity test was 29.94% less than the RSM value. Similarly, for the above combinations, smoke, HC, CO, and NO_x were reduced by 28.5% (66 to 47.1852 HSU), 38.12% (65 to 40.2222 ppm), 36.93% (0.35 to 0.220741%), and by 15.26% (1009 to 855 ppm) compared to neat HOME operation in CI mode.
5. The assay of variances (ASOVA) revealed that this model could put forth the actual linkages among the outcomes and eloquent variables, with an acceptable overall or average determining coefficient $R^2 = 0.9862$ of all responses, which directs that 98.62% of the adaptability for the responses could be described by the second-order polynomial predictors.
6. This optimized condition was validated by conducting an experiment and found similar results.

7. The other experimental design values of FFD and RSM values can also be considered in actual implementation in engine applications, keeping in view the response to be optimized.
8. Response surface assay-based quadratic predictors can be used with ease to create the linkages among the independent parameters and dependent characteristics.
9. The validation of predicted outputs shows that the quadratic predictors are accurate enough and in good agreement.
10. The effect of provision of bridges and grooves on cylinder heads proves to be an important parameter to improve competence and curtail emissions, but some other variables, such as injection pressure, injection timing, compression ratio, nozzle geometry, and speed, etc., should be tested and assayed alongside them.
11. According to the validation of test emission results as per CPCB India, the European Union, and the USA, the emissions are less than or very close to the norms and are in general around 10 g/kW-h, thus it can be stated that inlet valve masking (IVM) and number of piston grooves (NG) and cylinder head bridge-groove configuration (BGC) can be implemented for any diesel engines.
12. The major difference between the existing BS-IV and forthcoming BS-VI norms is the presence of diverse Sulphur compounds in the fuel. While the BS-IV fuel contains 50 parts per million (ppm) or mg/kg Sulphur, the BS-VI grade fuel only has 10 ppm or mg/kg Sulphur content. The different compounds of Sulphur form SO_2 , and 10% of SO_3 formed combines with water to form H_2SO_4 aerosols, combining with soot and dust to form particulate matter. Additionally, the harmful NO_x (nitrogen oxides) from diesel cars has to be brought down by nearly 70%. In the petrol cars, they can be reduced by 25%. However, when we discuss air pollution, particulate matter, such as PM 2.5 (particles smaller than 2.5 microns) and PM 10 (particles smaller than 10 microns), are the most harmful components, and the BS VI will bring down the cancer-causing particulate matter in diesel cars by a phenomenal 80%. As there is no Sulphur in BDF, there is no PM problem.
13. An IVM of 90° , a 'NG' on piston 6, and 'BGC' with 2B 3G model showed the highest NO_x emissions of 855 ppm, which was 15.26% less contrasted with neat HOME utilized CI mode of working, which was 1009 and 900 ppm, respectively, with and without bridge-groove configuration. Lowered NO_x emitted with other combinations may be linked to low combusting temperatures. It is to be noted that, for diesel engine simulation fueled with HOME, if we implement a combination of 1B 2G cylinder head, 'IVM' of 30° and 'NG' of 3 grooves on the piston optimizes a low NO_x of 717.5 ppm (BTE decreases slightly from 31.3679% to 23.5215%). It is much less than that for neat HOME in a conventional engine, i.e., 1009 ppm. Hence, the percentage reduction of NO_x is about 40.62%. This suffices, to some extent, emission standards BS 6 and Euro 6 (to be implemented from April 2020), which are planning to reduce NO_x by a staggering 70% compared to BS 4 and Euro 5. For the time being, this large reduction has not been made possible by engine research only, as reported by İbrahim Aslan Reşitoğlu et al. [18]. Thus, by using further On Board Equipment (OBE) and Real Driving Emissions (RDE) on all vehicles, enabling real-time tracking of emissions, diesel vehicles will include a Diesel Particulate Filter (DPF) and Selective Catalytic Reduction (SCR) technologies. With these design changes, NO_x may be decreased towards 70%. Additionally, by 2023, catalytic converters and misfire detectors are to be incorporated as per the (Automotive Research Association of India (ARAI), which is the leading automotive R&D organization of the country, set up by the Automotive Industry with the Government of India.
14. For 100% HOME biodiesel with a combination of inlet valve masking (IVM) of 90° , number of piston grooves (NG) of 6 grooves on piston crown, and cylinder head bridge-groove configuration (BGC) of 2B 3G, CO emissions are considerably reduced from 46.0 g/kW-h to 17.65 g/kW-h if we take the last readings for a full load of 5.2 kW, as given in Table 6. Thus, we can conclude that, for CO, BS VI norms cannot be satis-

fied only from engine research, as also reported by İbrahim Aslan Reşitoğlu et al. [18], and may be satisfied by on board equipment such as a DOC (diesel oxidation catalyst).

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Nomenclature

DOE	Designs of experiments
FFD	Full factorial designs
RSM	Response surface methodologies
ASTM	American Society for Testing and Materials
BTE	Brake thermal efficiency
BGC	Bridge-groove configuration
IVM	Inlet valve masking
CR	Compression ratio
SOC	Start of combustion
BDF	Biodiesel fuel
DICI	Direct injection compression ignition
IT	Injection timing
IOP	Injector opening pressure
EGR	Exhaust gas recirculation
TDC	Top dead center
bTDC	Before top dead center
a TDC	After top dead center
BSFC	Brake specific fuel consumption
ID	Ignition delay
CD	Combustion duration
NO _x	Oxides of nitrogen
HC	Hydrocarbon
UBHC	Unburnt hydrocarbon
CO	Carbon monoxide
PM	Particulate matter
SI	Spark ignition
CA	Crank angle
PP	Peak pressure
HRR	Heat release rate
BTL	Burning time loss
EGT	Exhaust gas temperature

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