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ORIGINAL ARTICLE

Relative Testing of Neat Jatropha Methyl Ester by Preheating to Viscosity Saturation in IDI Engine - An Optimisation Approach

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ABSTRACT – This paper investigates the effect of preheated Jatropha Methyl Ester (PJME) on the performance and emission characteristics of an indirect injection (IDI) diesel engine using combined Taguchi and Grey optimisation technique. For this purpose, PJME with different temperatures (50 °C to 100 °C), engine loads are considered as input factors and fuel consumption, thermal efficiency and exhaust emissions are output factors. Based on Taguchi orthogonal array design matrix, L_{18} experiments were conducted. The obtained results were analysed in Grey analysis and found that optimum performance and emissions for PJME at 60 °C with 50% load. From the analysis of variance (ANOVA) PJME influence factor is observed as 71.57% and a confirmation test is performed to validate the optimum parameters and observed both statistical and experimental are in good agreement. Finally, a full range of experiments was conducted for PJME at 60 °C and compared the results with diesel fuel. From the results, an appreciable reduction in exhaust emissions like CO, HC, and NO were observed for comparison, smoke and CO_2 have also decreased to a marginal extent indicating that PJME can be taken as a replacement to diesel fuel.

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INTRODUCTION

To combat environmental pollution, energy crises and to reduce the reliance on imports, research on alternative sources is gaining more importance. In India, 20% of the land is covered with forest where a wide variety of oil crops like Jatropha, Mahua, Neem, Palm, Pongamia, etc. can grow, and approximately 30 to 40% of oil can be extracted from these plants [1]. Approximately 467,000 hectors of wastelands are reorganised by the Government of India, and these lands can be utilised for biodiesel plantation. To promote biodiesel production and its utilisation, Indian Oil Corporation (IOCL) conjunction with Indian railways proposed to cultivate non-edible oil crops in one million square kilometres.

Production of biodiesel from these oils can reduce the dependency on imports, and at the same time, it promotes employment and environmentally sustainable development [2]. Among the available oil plants, Jatropha has a significant role; it is a draught resistance tree, can grow swiftly and produce seeds for 50 years with an oil content of 37% [3-4]. The physicochemical properties of Jatropha oils are closely matched with standard diesel fuels. High cetane number with low acid value, sulfur-free, and acts a self-lubricant are the palpable properties [5-6]. Apart from being renewable and alternative, it diminishes the production of HC (44-68%), CO (48-72%), CO_2 (52-78%), and Smoke (49-73%) [7-9]. It is also observed that NO_x emissions (6-26%) show an increasing trend. However, this can also be regulated with proper treatment of the fuel [10-11]. When non-edible oils are proposed to use as biodiesels, it is necessary to estimate the important combustion parameters. Combustion phenomenon in a diesel engine is known for its heterogeneity and several factors like fuel type, fuel properties, compression ratio, injection pressures, combustion chamber design, type of engine, speed, etc. will influence its overall performance [12-13].

In order to predict the contributing and influencing parameters in diesel engines optimisation technique (OT) is a preferred tool that can help in conducting the experiments in a well-planned manner to generate more significant information within stipulated experimental runs. OT finds the applications in multiple fields and internal combustion engines are not an exception for it. The commonly used optimisation techniques for diesel engine performance and emissions are Response Surface Method (RSM), Grey Relational Analysis (GRA), Non-linear regression, Genetic Algorithm (GA) and Taguchi method [14]. Taguchi techniques are popular and investigated by several researchers reveals that: Taguchi method is significant to find optimal operating parameters for fuel consumption, thermal efficiency, NO_x, and exhaust smoke as investigated by Horng-Wen Wu et al. [15]. Kalia Moorthy et al. [16] used the Taguchi method to optimise performance and emissions and reported that confirmation tests showed good agreement with predicted values of combustion parameters. Even though Taguchi techniques are popular in optimisation but unable to solve multi-objective problems [17] and this limitation can be overcome by Grey relation and Taguchi collectively. Taguchi method conjunction with grey relational analysis can be used successfully for investigation of multiple-performance variables in diesel engines [18]. Therefore, the present investigation utilises the Taguchi and Grey optimisation techniques collectively to predict the influence of preheated jatropha methyl ester (PJME) on diesel engine combustion and emission characteristics.

Studies on preheating of fuel reveal that: by preheating crude jatropha oil to 80 °C there is an increase in thermal efficiency and lower HC, CO, and smoke emissions as investigated by Chauhan et al. [19]. The preheating results in kinematic viscosity reduction, thereby improving the injection propensity. Anh Tuan Hoang and Anh Tuan Le [20] investigated the influence of neat diesel fuel, neat jatropha oil at 30 °C, and neat jatropha oil preheated to 90 °C on fuel spray characteristics, fuel injector deposit, and emission characteristics of a four-stroke high-speed diesel engine. Results reveal that after 300 hours of the continuous test, the number of deposits formed in the injector hole with jatropha oil at 30 °C was higher compared to the preheated at 90 °C. From the literature, it is evident that viscosity reduction by preheating the neat oils improve the combustion with regulated emissions in diesel engines [21-23]. However, preheated neat oils are recommended for short term applications and may not yield fruitful results in long term applications [20].

In this experimental investigation, the objective is to use neat biodiesel in a diesel engine. For this purpose, a non-edible and low-cost feedstock of jatropha oil is transesterified to reduce its viscosity. This high viscosity is further reduced by preheating to different temperatures using an online electronically controlled electrical heating system. Taguchi optimisation technique is used to choose the design of experiments; Grey and ANOVA analysis were used to find the optimum combination of input parameters and influencing factor. Finally, experiments were conducted to validate the statistical results and compared the results with diesel fuel operation.

METHODS AND MATERIALS

Transesterification of Jatropha oil

Raw Jatropha oil was purchased from the local market in Aaraku valley, Visakhapatnam district, Andhra Pradesh, India. The high viscous raw oil is pretreated to remove the suspended impurities and other traces. To reduce the high viscosity of Jatropha oil, a widely used process called transesterification [23] is employed. Methanol (CH_3OH) and sodium hydroxide (NaOH) are used as alcohol and catalyst for the transesterification process, and they were purchased from Merck chemicals Ltd India. During the transesterification process triglycerides (Jatropha Oil) reacts with the alcohol (CH_3OH) in the presence of a catalyst (NaOH) which results in the formation of glycerol (waste) and ester (Biodiesel) as shown in Figure 1.

Figure 1. Jatropha biodiesel and glycerin separation.

The obtained methyl esters from the transesterification process are tested for different physicochemical properties by following international standards. Table 1 represents the properties of Jatropha methyl ester (JME) in comparison with standard diesel fuel and Table 2 represents the viscosity index for preheated jatropha methyl ester. From Table 2, it is evident that the kinematic viscosity of PJME plummets down from 4.5 cSt to 2.47 cSt. This minimum viscosity happens at 60 °C and is being regarded as a critical temperature after which there is no change in viscosity observed.

Table 1. Properties of Jatropha methyl ester (JME).

S. No	Property	Diesel fuel	JME	ASTM
1	Density at 18 °C (kg/m^3)	822	895	D6751
2	Flash point (°C)	67	165	D93
3	Lower heating value (Mj/Kg)	42.6	38.48	D240
4	Sulphur (wt%)	0.28	Nil	D4294
5	Cetane number	48	52	D613
6	Viscosity cSt (30°C)	2.43	4.5	D445

Table 2. Viscosity index of preheated Jatropha methyl ester (PJME).

PJME (°C)	30	40	50	60	70	80	90	100
Viscosity (cSt)	4.5	3.5	3.03	2.47	2.47	2.47	2.47	2.47

Design of Experiment

To improve the performance with regulated exhaust emission from the IDI diesel engine, an optimum preheated Jatropha methyl ester (PJME) is chosen on the basis of the design matrix of the orthogonal array (OA) originally developed by R.A. Fisher and later added by Taguchi [24]. The reason for choosing this technique is; if there were more input and output variables, a large number of experimental tests have to be conducted which consumes more time, and accuracy is being challenged. To mitigate this challenge, a well-planned combo of predicted and designed experiments could make a more realistic approach. Therefore, OA is chosen on the basics of the number of input parameters and their levels. For this purpose, standard statistical software like Minitab®18 [17] is used in this endeavour to perform the data analysis.

In this study, a mixed design orthogonal array (L_{18}) is considered which is having 18 rows corresponding to the total number of tests (18 degrees of freedom) with two input columns of six levels suggested by the design of experiments (DOE) as shown in Table 3. The two input parameters, namely PJME to different temperatures of 50 °C to 100 °C with an increment of 10 °C and engine load (30%, 50%, and 100%) are considered as main design factors. Part load efficiency of the diesel engine is better and, however, the engine should not be run at lower loads because this may lead to engine overheating [25-27]. In this investigation, higher part loads have been taken into account. Seven output parameters were analysed; in which two of them were performance parameters of brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) the other five belong to exhaust emissions like unburnt hydrocarbon emissions (UHC), carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxide (NO) and exhaust smoke.

Table 3. Experimental input levels.

No	Input factor	L-I	L-II	L-III	L-IV	L-V	L-VI
1	Load (%)	50	75	100	-	-	-
2	PJME (°C)	50	60	70	80	90	100

Experimentation based on Design Matrix

Based on the design matrix (L_{18}) experimental investigation is carried out on a naturally aspirated, single-cylinder, four-stroke, three-wheeler auto, indirect injection (IDI) diesel engine. The technical specifications of the engine are presented in Table 4. Combustion pressure data is measure at every degree of the crank angle, and Eddy current dynamometer is used for loading the engine. Exhaust emissions and Smoke were measured by DELTA 1600-L and Diesel Tune 114 without affecting the back pressure from the exhaust pipeline. Jatropha biodiesel is preheated from 50^0C to 100^0C with an increment of 10^0C by the electronically controlled electrical preheating unit. This unit heats up the fuel from the pump line to the injector almost instantly and sends it into the injector at a predefined temperature. The consistency of the temperature defined is maintained by the electronic system with some thermal stabilisation time. The temperature of the fuel is measured by a thermocouple junction and displays digitally. The sensitivity of the thermocouple is also defined to estimate the time within which can obtain stable results keeping in view the thermocouple hysteresis period with respect to the flow rate of fuel. Air manometer and fuel U-tube are used to the respective quantities.

Experimentation starts with an engine warmup for 20 minutes with neat diesel fuel and then fuel change to neat JME which is preheated with an online electronically controlled electrical heating device as described earlier. The engine is subjected to 50%, 75%, and 100% maximum loads, and all the performance and emissions were measured at a constant rpm of 1500. The schematic arrangement of the experimental setup is presented in Figure 2.

Table 4. Technical specifications of the engine**.**

S.No	Description	Specification
1	Engine make and model	Baja RE-Diesel
2	No of cylinders × stroke	One × four-stroke
3	Bore × stroke	86 mm × 77mm
4	Engine displacement	447 cc
5	Maximum power output at a speed of 3000 rpm	5.04 kW
6	Compression ratio	24±1:1
7	Combustion chamber type	Indirect injection type
8	Injection pressure	142 to 148 bar
9	Manufacturers recommended injection timing	8.5° to 9.5° BTDC
10	Method of cooling	Oil cooled
11	Rated speed	1500 constant

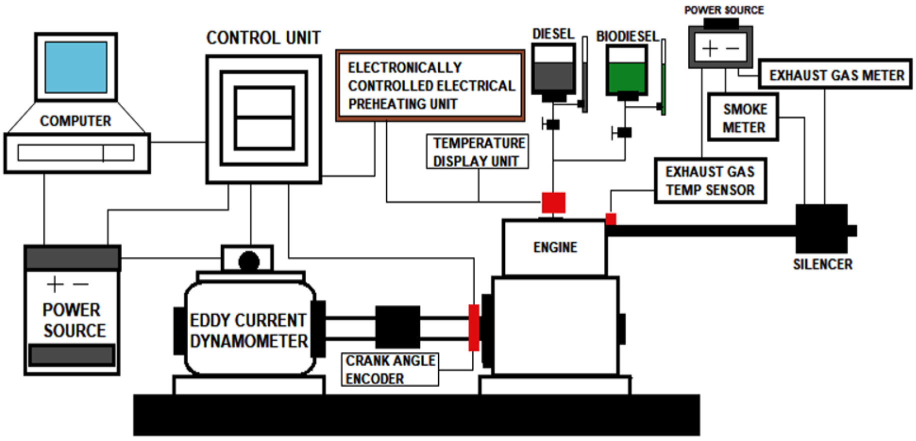


Figure 2. Schematic view of the experimental test rig.

Grey Analysis

Taguchi techniques are well known for solving single objective function effectively, for multiple objective functions with conflicting goals Grey analysis [17-18] is a widely accepted method which can effectively generate a single response from multiple responses. In this investigation, Grey analysis is also used. Experiments were conducted based on the OA design cannot be compared as they have different units; therefore; it is necessary to convert them into normalised dimensionless values which can be in comparable order. The data is normalised using the two criteria; one is larger the better and smaller the better [24]. If the desired objective is to maximise then, larger the better criteria are followed on the other hand if the desired objective is to minimise then smaller the better is followed which are presented in Eq.(1) and (2). In the present investigation, the larger, the better is used for thermal efficiency, and the smaller, the better is used for fuel consumption and exhaust emissions.

$$x_i(k) = \frac{y_i(k) - min\ y_i(k)}{max\ y_i(k) - min\ y_i(k)} \tag{1}$$

$$x_i(k) = \frac{\max\ y_i(k) - y_i(k)}{max\ y_i(k) - min\ y_i(k)} \tag{2}$$

Where $y_i\,(k)$ represents the original sequence, $x_i\,(k)$ represents the comparable sequence $i = 1,2,3,4, \ldots, m$ and $k = 1,2,3,4,.. n$ respectively. m represents the number of experiments to conduct and n represents the number of observations
The Grey Relational Coefficient (GRC) is used to approximate the degree of correlation between the original and comparable sequence and is given as:

$$£_i(k) = \frac{\Delta_{min} + \Psi \Delta_{max}}{\Delta_i(k) + \Psi \Delta_{max}} \tag{3}$$

Where $\Delta_i = |\,x_0(k) - x_i(k)|$ is the difference of the absolute value between $x_o\,(k)$ and $x_i\,(k)$ and Δ_{max}, Δ_{min} represents the maximum and minimum values of absolute differences (Δ_i) of comparing sequence. In the present analysis distinguishing coefficient, Ψ is taken as 0.5. Then, the overall grey relation grade is the average of grade relation coefficient corresponding to the given response. It can be calculated as follows.

$$\xi = \frac{1}{n}\sum_{k=1}^{n} £_i \beta_k \tag{4}$$

Where $\sum_{k=1}^{n} \beta_k = 1$. The ξ is the grey relation grade for the kth experiment, β_k is the weight factor for all the response variables should be unity. The weight factors for each response are assigned based on the relative significance.

RESULTS AND DISCUSSION

Experimental Results based on Orthogonal Array Design

Keeping in view the orthogonal design matrix of L_{18}, experiments are conducted and the results obtained are tabulated in Table 5 for two input parameters i.e. engine load and PJME, seven output responses like BTE, BSFC, HC, CO, CO_2, NO, and Smoke are measured. It is observed that with the change in biodiesel temperature, the combustion and emissions show a significant variation on the overall performance of the engine. This may be acclaimed to change in the kinematic viscosity index of the JME and other parameters like bulk modulus etc. To estimate the optimum combination of PJME temperature and engine load for better combustion with regulated exhaust emissions Taguchi-Grey analysis is elicited in this prediction.

Table 5. Experimental results based on L_{18} design matrix.

Run order	OA		Response output						
			Performance		Emissions				
	PJME (°C)	Load (%)	BTE (%)	BSFC (kg/kW-hr)	HC (PPM)	CO (%)	CO_2 (%)	NO (PPM)	Smoke (HSU)
1	50	50	27.45	0.3408	3	0.01	5.4	228	54
2	50	75	30.78	0.3039	1	0.02	8	242	58
3	50	100	29.93	0.3125	1	0.03	10.2	257	58
4	60	50	29.63	0.3379	2	0.01	5.7	224	52
5	60	75	30.28	0.309	1	0.01	8.2	244	56
6	60	100	30.11	0.3107	1	0.01	10.5	250	61
7	70	50	27.5	0.3354	2	0.05	5.8	224	48
8	70	75	29.9	0.3124	1	0.05	8.5	238	50
9	70	100	28	0.3333	0	0.06	10.1	247	54
10	80	50	26.38	0.3547	2	0.02	5.6	270	40
11	80	75	29.69	0.3151	1	0.03	8.3	257	58
12	80	100	28.38	0.3297	1	0.03	9.9	249	52
13	90	50	26.76	0.3497	3	0.05	5.9	283	52
14	90	75	28.68	0.3262	4	0.06	8.4	271	50
15	90	100	27.89	0.3355	1	0.07	10.6	262	54
16	100	50	27.69	0.3488	2	0.01	5.8	297	45
17	100	75	30.28	0.3232	1	0.02	8.5	281	43
18	100	100	30.11	0.323	2	0.03	10.4	277	45

Grey Taguchi Correlation

The output response from the experimental investigation like performance and emissions listed in Table 5 cannot be compared due to the fact that they have different units. Therefore, it is necessary to convert them into normalised dimensionless values which can be converted to a compared sequence and hence the usage of Grey relation. Experimental results are normalised by two criteria, one is by maximising the thermal efficiency, and another is by minimising the fuel consumption and exhaust emissions by using Eq. (1) and (2). The larger the value of a normalised result reflects the better performance of the engine, therefore, Table 6 represents the linear normalisation of the output parameters in terms of grey relation generation, which distributes the data uniformly and is being subjected to further analysis.

Table 6. Grey Relation (GR) generation.

Run order	Larger the better	Smaller the better					
	BTE	BSFC	HC	CO	CO_2	NO	Smoke
1	0.243182	0.94672	0.25	1	1	0.945205	0.333333
2	1	1.008545	0.75	0.833333	0.5	0.753425	0.142857
3	0.806818	0.994136	0.75	0.666667	0.076923	0.547945	0.142857
4	0.738636	0.951579	0.5	1	0.942308	1	0.428571
5	0.886364	1	0.75	1	0.461538	0.726027	0.238095
6	0.847727	0.997152	0.75	1	0.019231	0.643836	0
7	0.254545	0.955768	0.5	0.333333	0.923077	1	0.619048
8	0.8	0.994303	0.75	0.333333	0.403846	0.808219	0.52381
9	0.368182	0.959286	1	0.166667	0.096154	0.684932	0.333333
10	0	0.923431	0.5	0.833333	0.961538	0.369863	1
11	0.752273	0.98978	0.75	0.666667	0.442308	0.547945	0.142857
12	0.454545	0.965318	0.75	0.666667	0.134615	0.657534	0.428571
13	0.086364	0.931809	0.25	0.333333	0.903846	0.191781	0.428571
14	0.522727	0.971182	0	0.166667	0.423077	0.356164	0.52381
15	0.343182	0.9556	0.75	0	0	0.479452	0.333333
16	0.297727	0.933317	0.5	1	0.923077	0	0.761905
17	0.886364	0.976208	0.75	0.833333	0.403846	0.219178	0.857143
18	0.847727	0.976544	0.5	0.666667	0.038462	0.273973	0.761905

Evaluation of Grey Relation Coefficient (GRC) and Grey Relation Grade (GRG)

Based on the normalised data from Table 6, GRC is calculated by using the Eq.(3), which has the potential to develop a correlation between the desired test data and the actual data. In the next stage, GRG is calculated by using the Eq (4). The combination of optimal process parameters is evaluated based on the highest GRG are shown in Table 7. The maximum value in GRG represents the strong level of correlation between the referral and given sequence. The maximum GRG is obtained at the 4th run order, which reveals that the experiment sequence at this level is closer to the desired optimum value.

Table 7. GRC and GRG generation.

S.No	Grey relation coefficient (Ψ=0.5)							GRG	Rank
	BTE	BSFC	HC	CO	CO_2	NO	Smoke		
1	0.39783	0.903702	0.4	1	1	0.901235	0.428571	0.718763	2
2	1	1.017387	0.666	0.75	0.5	0.669725	0.368421	0.710314	4
3	0.721311	0.988408	0.666	0.6	0.351351	0.52518	0.368421	0.603048	13
4	0.656716	0.911709	0.5	1	0.896552	1	0.466667	0.775949	1
5	0.814815	1	0.666	1	0.481481	0.646018	0.396226	0.71503	3
6	0.766551	0.994336	0.666	1	0.337662	0.584	0.333333	0.668936	8
7	0.40146	0.918725	0.5	0.428	0.866667	1	0.567568	0.668999	7
8	0.714286	0.988735	0.666	0.428	0.45614	0.722772	0.512195	0.641338	10
9	0.441767	0.924704	1	0.375	0.356164	0.613445	0.428571	0.591379	14
10	0.333333	0.867199	0.5	0.75	0.928571	0.442424	1	0.68879	5
11	0.668693	0.979969	0.666	0.6	0.472727	0.52518	0.368421	0.611665	11
12	0.478261	0.935135	0.666	0.6	0.366197	0.593496	0.466667	0.586632	15
13	0.353698	0.879985	0.4	0.428	0.83871	0.382199	0.466667	0.53569	16
14	0.511628	0.945505	0.333	0.375	0.464286	0.437126	0.512195	0.511296	18
15	0.43222	0.918443	0.666	0.333	0.333333	0.489933	0.428571	0.514643	17
16	0.415879	0.882327	0.5	1	0.866667	0.333333	0.677419	0.667946	9
17	0.814815	0.954578	0.666	0.75	0.45614	0.390374	0.777778	0.687193	6
18	0.766551	0.955189	0.5	0.6	0.342105	0.407821	0.677419	0.607012	12

Analysis of Variance (ANOVA)

In order to identify the influencing and contributing parameter on the output results, the ANOVA test has been carried out. Based on the ANOVA results, fuel (PJME) is considered as an influencing factor with a contribution of 71.57 % followed by engine load 21.29% as shown in Table 8.

Table 8. ANOVA for output response.

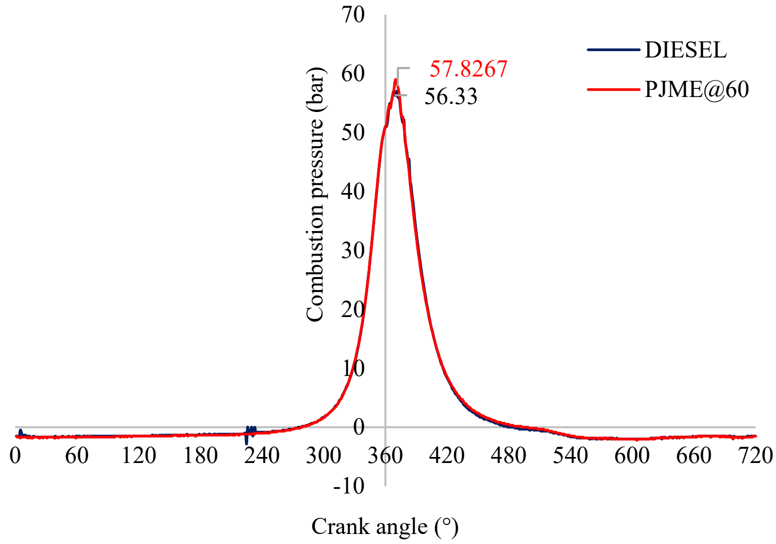
Factors	DOF	Adj (SS)	Adj (MS)	F-Value	P-Value	Contribution (%)
PJME	5	0.067239	0.013448	20.06	0.000	71.57
Load	2	0.020001	0.010000	14.92	0.001	21.29
Error	10	0.006704	0.000670	-	-	-
Total	17	0.093943	-	-	-	-
R^2 = 92.86% , R^2 (Adj) = 87.87%, R^2 (Pred) = 76.88%						

Confirmation Test with Experimental Validation

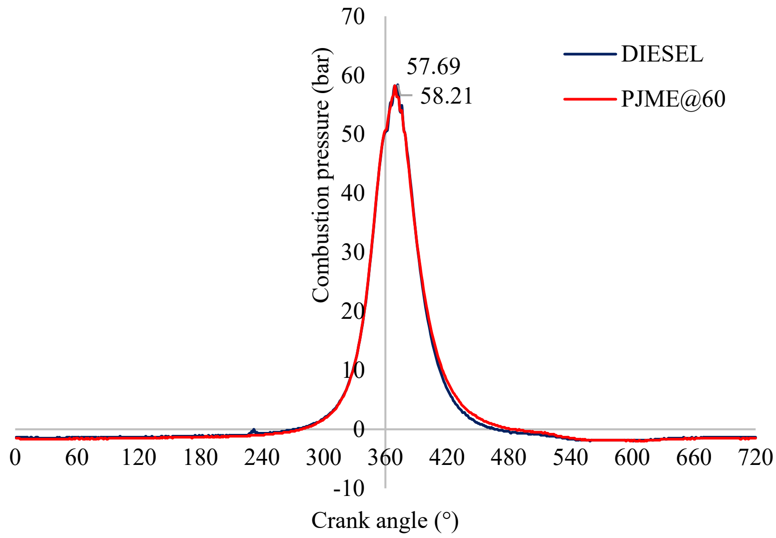
After achieving the optimum temperature of the PJME and engine load from Taguchi-Grey analysis, confirmation tests are carried out and observed that both experimental and statistical results are in good agreement. Now, the final step is to verify the optimum design parameters with diesel fuel by conducting a full range of experiments. The combustion pressures which are not involved in the optimisation process are also verified for better estimation of combustion propensity.

Combustion Pressure Analysis

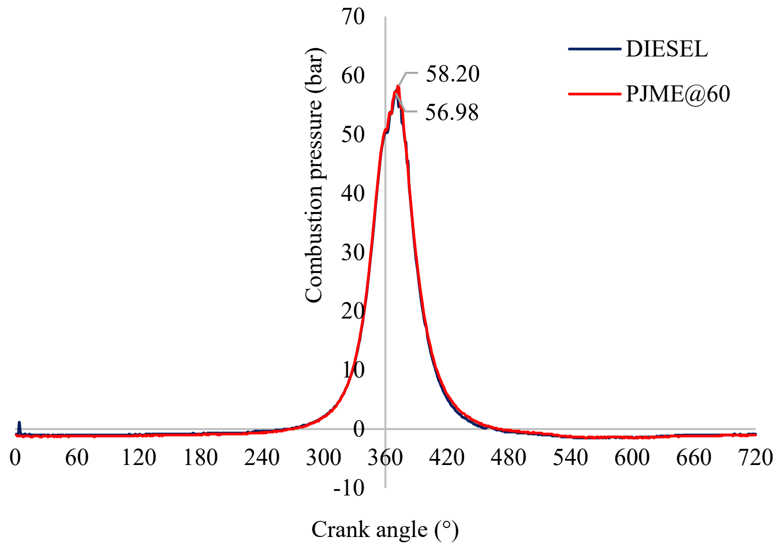
In this experimental investigation, combustion pressure is measured from 0 to 720° of the crank revolution with a least count of one degree. Figures 3(a) to 3(c) represent the maximum combustion pressure variations with a crank angle for PJME@60 °C and diesel fuel at various loads. It is observed from Figure 3(a) and 3(c), maximum peak pressures are attained with PJME@60 °C and this may be due to better fuel atomisation and evaporation. Figure 3(a) and 3(c) reportedly showing a 1.49 bar and 1.22 bar maximum pressure increment for PJME@60 °C compared to diesel fuel.



(a) 100% engine load



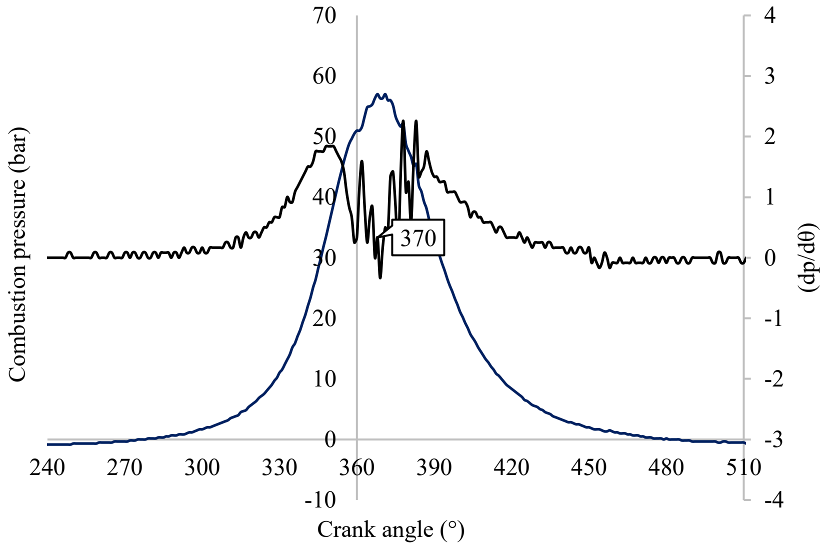
(b) 75% engine load



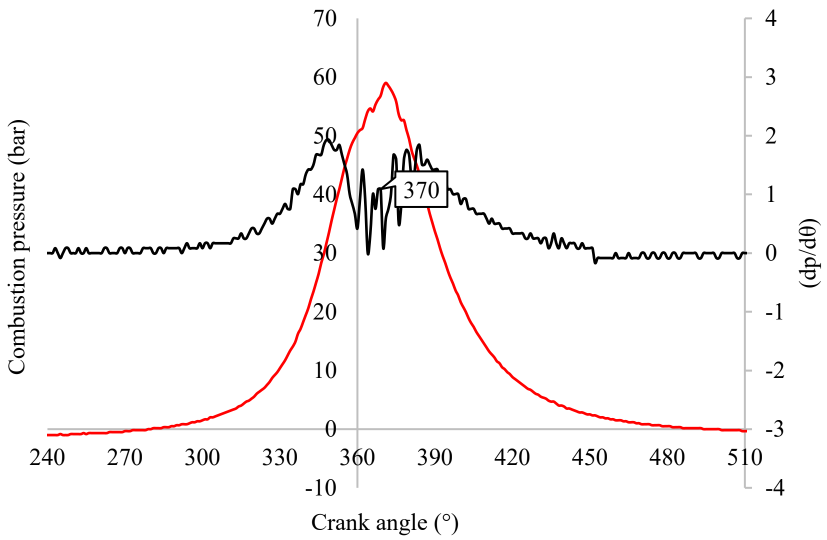
(c) 50% engine load

Figure 3. Combustion pressure at different engine loads.

Cylinder pressure with respect to crank angle plots may not reveal significant information about combustion phenomena whereas, their differential plots can predict the combustion duration and smoothness of the combustion to a micro extent. Plotting of pressure differential to explore the combustion trend in both the rising pressures and drooping pressures after reaching maximum is shown in Figure 4 to 6. In these figures, the arithmetic differential in the pressure dropping zone has been shown to emphasise the combustion differential on par with the rising trend of the pressures. This gives a comprehensive trend of the combustion in the expansion stroke eliminating negative pressure differentials. The demarcation point is 370° of the crank for almost every graph depicted for the loads defined. The differential graphs in the case of diesel fuel indicate sharp peaks and in the case of PJME@60 °C the peaks are rounded up indicating smoother combustion. The differential pressures are higher in the case of diesel fuel vis-a-vis more calorific value.

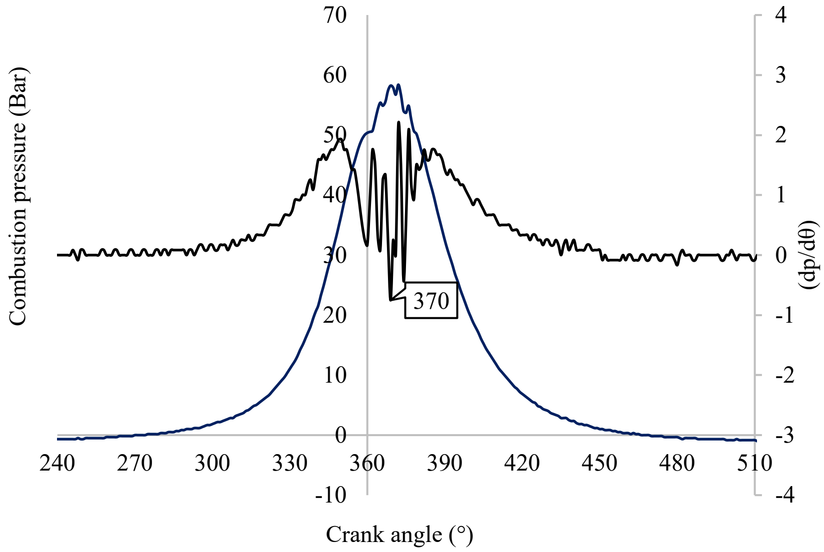


(a)



(b)

Figure 4. (a) Diesel and (b) PJME combustion pressure derivative at 100% engine load



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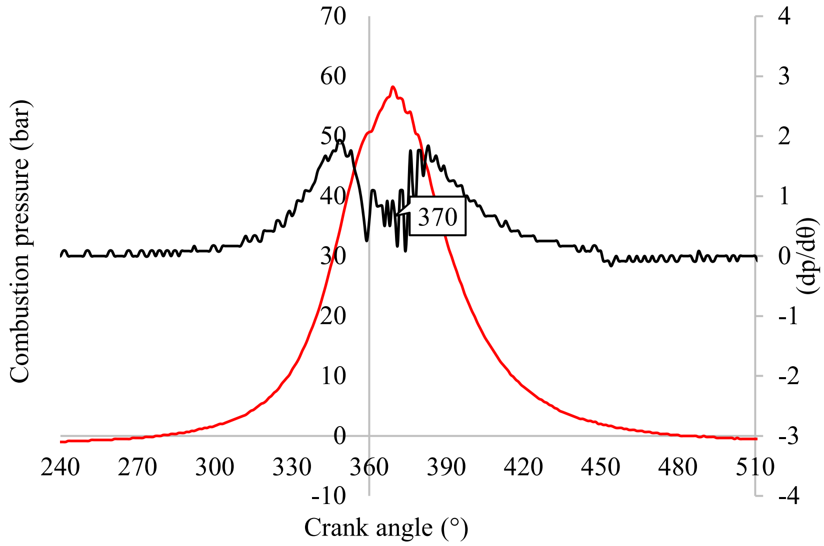
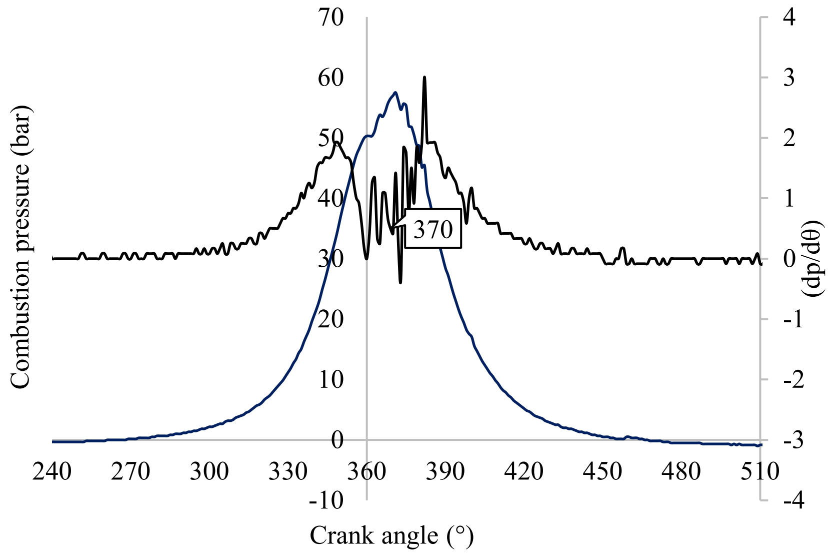
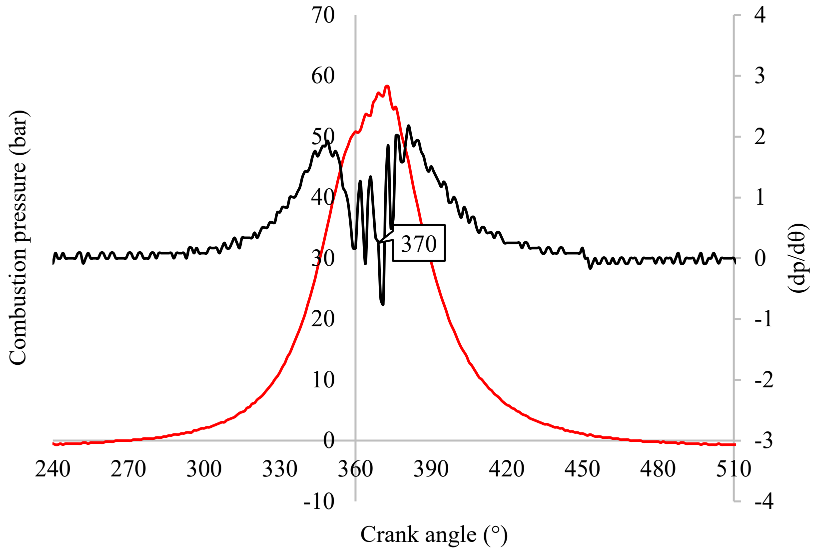


(b)

Figure 5. (a) Diesel and (b) PJME combustion pressure derivative at 75% engine load.



(a)



(b)

Figure 6. (a) Diesel and (b) PJME combustion pressure derivative at 50% engine load.

Performance Parameters

Brake thermal efficiency (BTE) and Brake specific fuel consumption (BSFC) plots for PJME@60 °C and diesel fuel are shown in Figure 7 and 8. Thermal efficiency change at part loads is marginally higher for the PJME@60 °C is observed. The BSFC is higher at all loads for the PJME@60 °C. The change in maximum increase in the fuel consumption from no load to full load is approximately 0.02 kg/kW-hr. and percentage wise it is approximately 15% hike in the PJME@60 °C consumption at every load on average as shown in Figure 8. The low calorific value of preheated methyl ester than that of diesel fuel is the reason for high fuel consumption.

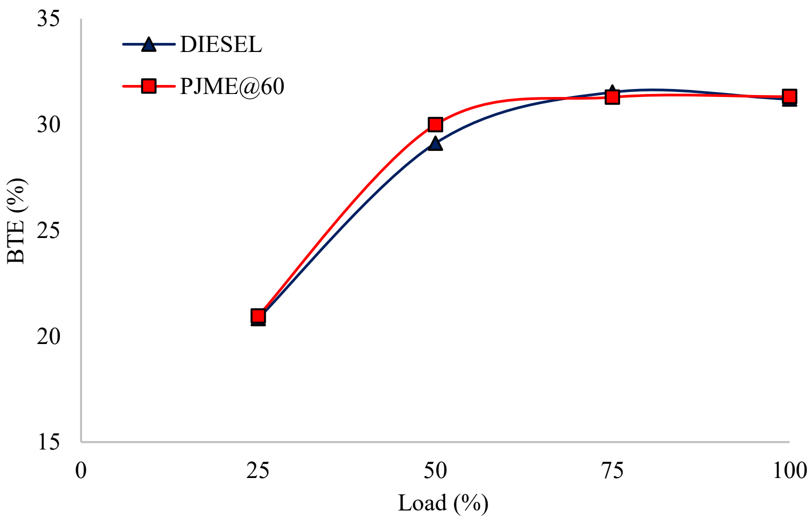


Figure 7. Brake thermal efficiency vs. engine load.

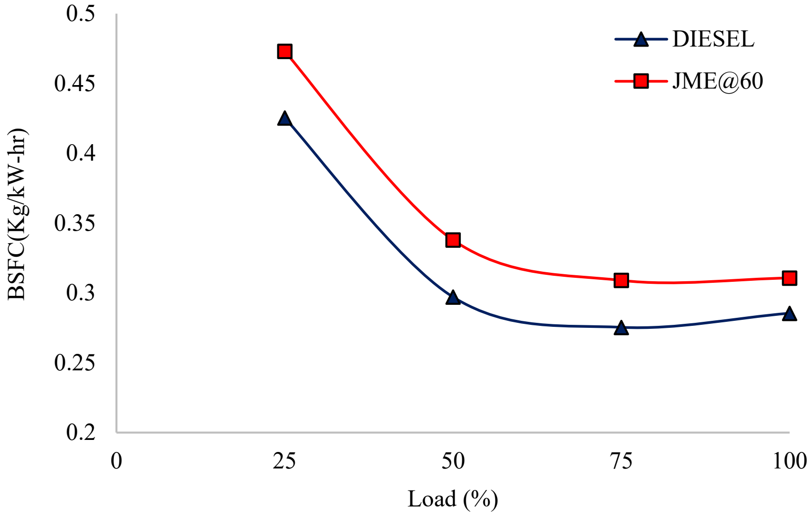


Figure 8. BSFC vs. engine load.

Exhaust Emission

Figure 9 represents the unburnt Hydro Carbon (HC) emissions for PJME@60 °C and diesel fuel at varying loads. It is observed that for neat diesel fuel operation the HC emissions are higher compared to PJME@60 °C and this may be due to relatively cold combustion. In the case of biodiesel, properties like higher cetane number, excess molecular oxygen content, and longer throw rate distance due to higher density results in low HC emissions than diesel fuel. From Figure 9 for PJME@60 °C at maximum and 3/4th maximum loads, the HC emissions are reduced by 66% and 50% compared to diesel fuel.

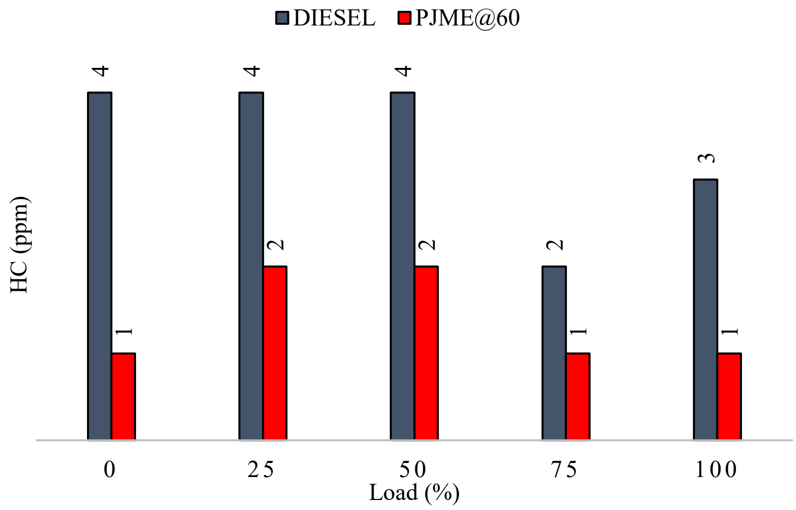


Figure 9. HC vs. engine load.

Figure 10 represents the carbon monoxide emissions using preheated jatropha methyl ester (PJME@ 60 °C) in comparison with diesel fuel at varying loads. From the figure, it is evident that there is a maximum reduction of CO emission at all the loads for PJME@ 60 °C. This may be acclaimed to improvised combustion owing to the preheating of methyl ester. Usually, the reason for CO formation is due to low cylinder temperature and an inadequate supply of oxygen [26-28]. The temperature of preheated methyl ester improves the overall combustion temperature and presence of excess molecular oxygen (11%) refine the combustion propensity by lowering the CO formation. For diesel fuel, due to inadequacy of oxygen and low combustion temperatures at lower loads result in higher CO formation, as observed from the data presented in Figure 10. Results of CO emissions show that 85% and 80% reduction is observed at maximum and 3/4th maximum loads compared to diesel fuel.

The complete combustion of fuel in the combustion chamber results in the oxidation of CO to CO_2 formation [26]. From Figure 11 shows the variation of CO_2 for PJME@60 °C and diesel fuel at varying loads. It is evident that 5.4% and 2.3% reduction of CO_2 is observed at maximum and 3/4th maximum loads when compared to diesel fuel and the formation of H_2O is complementary to the CO_2 formation.

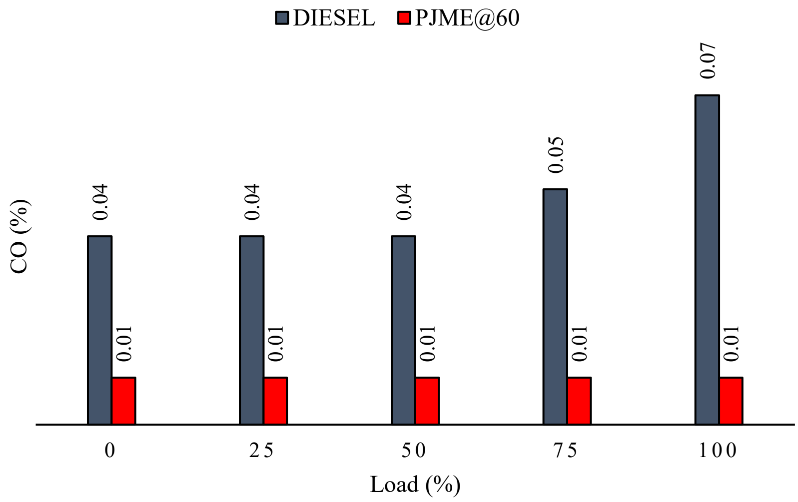


Figure 10. CO vs engine load.

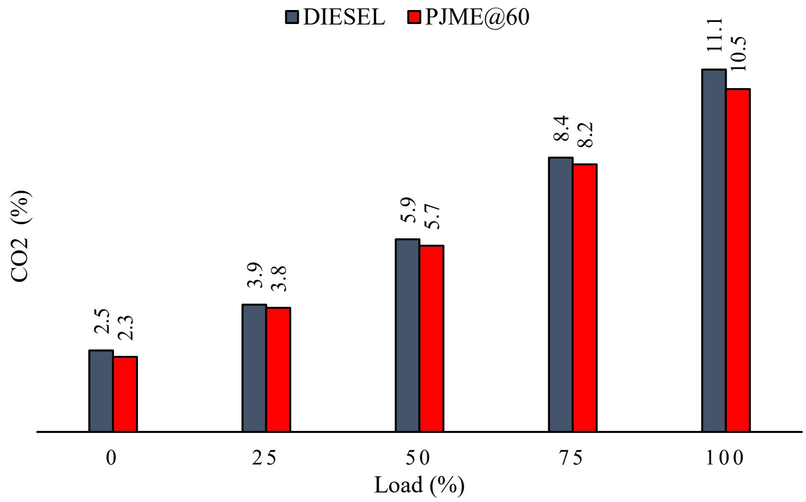


Figure 11. CO_2 vs engine load.

Figure 12 represents the variation of NO emissions for diesel and preheated jatropha methyl ester (PJME@60 °C) at varying loads. It is observed that for PJME@60 °C NO emission is marginally lower than diesel fuel and this may be due to the combustion of fuel in pre and main combustion chambers vowing to low temperature combustion. At combustion temperatures of more than 1200 °C, the atmospheric nitrogen reacts with available oxygen resulting in the formation of NO emissions [11, 28]. Results of NO emissions reveal that 15% and 14% reduction is observed for PJME@60 °C at maximum and 3/4th maximum loads compared to diesel fuel.

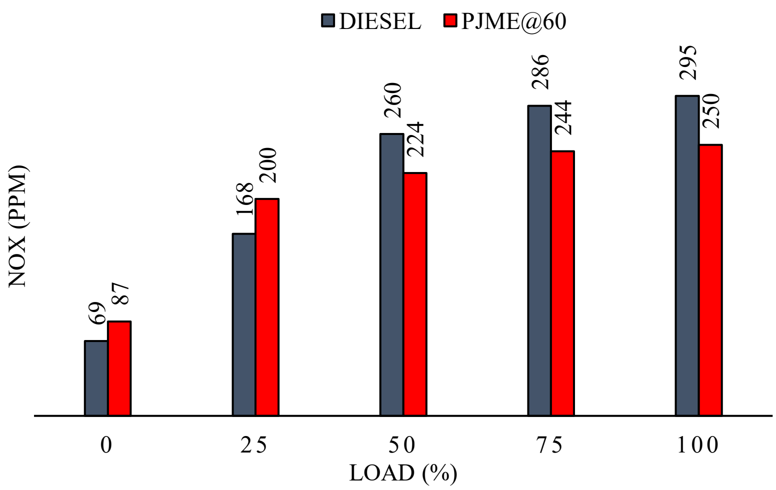


Figure 12. NO vs engine load.

From Figure 13 it is found that PJME@60 °C exhibits low smoke emissions at all the tested loads when compared to diesel fuel. At maximum and 3/4th maximum loads, 3.17% of low smoke emissions are recorded when compared to diesel fuel. This may be acclaimed to high molecular oxygen in the biodiesel [28]. The smoke emissions also depend on poor combustion behavior, adverse fuel properties, collision rate of gas molecules, the concentration of carbon content in fuel, equivalency ratios, high cylinder gas temperatures, and lack of available oxygen during combustion are the palpable reasons.

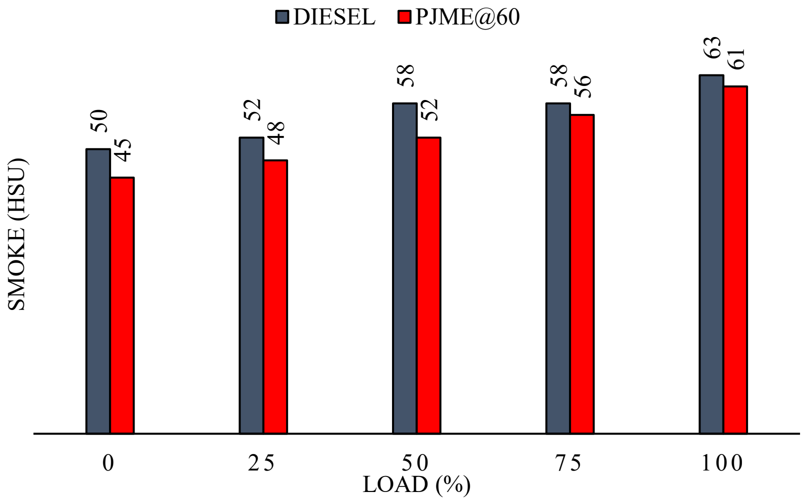


Figure 13. Smoke vs. engine load.

Experimental Uncertainty Measures

In the present investigation, different instruments are used for measuring various emission and performance parameters each one has a certain uncertainty level, which affects the certainty of the final result. Hence, error analysis is carried out to fix the uncertainty level of the obtained results. Table 9 represents the instruments used and their uncertainties.

Table 9. Uncertainties and their ranges.

S. No	Instruments	Range	Accuracy	% of uncertainties
1	Exhaust gas analyzer	CO; 0% -10%	±0.01%	±0.2
		CO_2; 0%-20%	±0.1%	±0.15
		NO; 0-2000ppm	±1 ppm	±0.2
		HC; 0-20000ppm	±1 ppm	±0.2
2	Smoke meter	Opacity (0% -100%)	±0.1	±0.1
3	Combustion Pressure pickup	0-110 bar	±0.1 kg	±0.1
4	Crank angle encoder	0-720 degree	±1 degree	±0.2
5	Engine rpm unit	0-10000 r/min	±10 r/min	±0.1
6	Eddy current dynamometer	0-50kg	±0.3%	±0.1
7	Least count of the thermocouple	± 2 °C, with 2minute thermal stabilisation to reach at the defined temperature at various flow rates of the fuel.		

CONCLUSION

The combination of Taguchi and Gray relation optimisation technique appears to be effective in investigating the effect of preheated jatropha methyl ester in IDI diesel engine combustion and emission characteristics. To minimise the experimental efforts, L_{18} experiments were conducted based on Taguchi design as suggested by Minitab®18 statistical software. Further, Gray relation analysis is used to solve multi-response to a single response, and the contributing parameter is identified by ANOVA analysis followed by experimental validation. The following are the key statistical findings appended and realised to be in good agreement with the experimentation.

i. Preheated jatropha methyl ester at 60 °C with 50% engine load is considered as optimum input conditions with output parameters of BTE (29.63%), BSFC (0.3379 kg/kW-hr), HC (2 PPM), CO (0.01%), CO_2 (5.7%), NO (224 PPM) and Exhaust Smoke (52 HSU).
ii. From the ANOVA analysis, preheated jatropha methyl ester at 60 °C is considered as an influencing parameter with a contribution of 71.57% followed by engine load with 21.29% contribution.
iii. The confirmation test reveals that both statistical and experimental results are in good agreement.

iv. The viscosity of biodiesel can be decreased by heating the oil to a level close on parity with the diesel oil's viscosity at 60 °C and above this temperature, the oil became critical indicating no more successful reduction in the viscosity.
v. Maximum combustion pressure change (increase) is noticeable in the case of PJME@60 °C while the rest of the curve in one cycle is unchanged.
vi. The combustion pressure derivatives in two parts, one when the pressure is rising and, in another part, when the pressure is plummeting down in a positive numeric situation indicates smoother combustion in the case of PJME@60 °C with flat rounding up peaks in the differential curve.
vii. Efficiency and fuel consumption follow suit of the calorific value of the heated fuel. Even though there is a sustenance of only marginal difference in thermal efficiency at the loads selected, it is evident that there is an obvious increase in fuel consumption observed with PJME@60 °C.
viii. Relatively lower emissions like HC and CO are observed in the case of PJME@60 °C. But in the case of CO_2, NO, and exhaust smoke the change is insignificantly lesser because of lesser delay period in the case of preheated jatropha methyl ester and more available oxygen.

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