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Multi Response Optimization of NO_x Emission of a Stationary Diesel Engine Fuelled with Crude Rice Bran Oil Methyl Ester

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Résumé — Optimisation à réponses multiples de l'émission de NO_x d'un moteur Diesel stationnaire alimenté par de l'ester méthylique d'huile de riz brut — Dans la présente étude, il a été tenté de réduire les émissions de NO_x de l'ester méthylique d'huile de riz brut sans accroissement considérable de la densité de fumée lorsqu'il est utilisé comme carburant dans un moteur stationnaire à allumage par compression. Trois facteurs, à savoir le calage d'injection de carburant, le pourcentage de recirculation des gaz d'échappement (EGR ; Exhaust Gas Recirculation) et la pression d'injection de carburant ont été choisis, et leur effet combiné a été examiné en matière de maîtrise des émissions de NO_x d'un moteur Diesel stationnaire alimenté avec de l'ester méthylique d'huile de riz brut. Trois niveaux ont été choisis pour chaque facteur et les émissions de NO_x, la densité de fumée ainsi que le rendement thermique au frein ont été retenus en tant que variables de réponse. Les expériences ont été conçues en employant la méthode des plans d'expériences et la table orthogonale L_9 de Taguchi a été utilisée pour conduire les essais moteurs selon différents niveaux des facteurs choisis. Le Rapport Signal-Bruit de Réponses Multiples (RSBRM) a été calculé pour les variables de réponse et le niveau de combinaison optimum des facteurs a été obtenu en utilisant simultanément la conception paramétrique de Taguchi. Une expérience de confirmation a été menée pour le niveau de combinaison optimum des facteurs, puis les résultats ont été comparés avec les conditions de fonctionnement normal et une amélioration significative des variables de réponse a été observée.

Abstract — Multi Response Optimization of NO_x Emission of a Stationary Diesel Engine Fuelled with Crude Rice Bran Oil Methyl Ester — *In the present work, an attempt was made to reduce the NO_x emission of crude rice bran oil methyl ester without any considerable increase in smoke density, when used as a fuel in a stationary CI engine. Three factors namely, fuel injection timing, Exhaust Gas Recirculation (EGR) and fuel injection pressure were chosen and their combined effect in controlling the NO_x emission of a stationary Diesel engine fuelled with crude rice bran oil methyl ester was investigated. Three levels were chosen in each factor and NO_x emission, smoke density and brake thermal efficiency were taken as the response variables. Experiments were designed by employing design of experiments method and Taguchi's L_9 orthogonal array was used to conduct the engine tests with different levels of the chosen factors. Multi Response Signal-to-Noise ratio (MRSN) was calculated for the response variables and the optimum combination level of factors was obtained simultaneously using Taguchi's parametric design. Confirmation experiment was conducted for the obtained optimum combination level of factors and the results were compared with normal operating conditions and significant improvement was observed in the response variables.*

INTRODUCTION

Significant work have been carried out to use bioDiesel as an alternate fuel in Diesel engine in the last two decades [1-8]. However, higher NO_x emission of bioDiesel compared to Diesel presents a significant barrier [9] and considerable work has been done in this direction [10-13]. NO_x emission in a Diesel engine can be controlled either by modification of the combustion process or by the treatment of exhaust gases [14]. In the former method retardation of fuel injection timing, Exhaust Gas Recirculation (EGR), fuel additives and water injection techniques are employed to prevent the NO_x formation [15] while the latter method was carried out with the help of different catalysts to remove NO_x emission completely [16-20]. Of the two methods the combustion process modification is comparatively cheaper [14] and the same has been discussed in this work.

Several attempts were made to reduce the NO_x emission of Diesel engines fuelled with bioDiesel by employing fuel injection retardation and EGR [21-27]. However, these methods result in decrease in brake thermal efficiency and increase in smoke density. Monyem and Van Gerpen [9] reported that for retardation of 3° crank angle (CA) NO_x emission of bioDiesel was reduced significantly but with drastic increase in smoke emission. For the same retardation angle, Tsolakis *et al*. [27] reported 16% reduction in NO_x with 20% increase in smoke emission for rapeseed methyl ester. Cooled Exhaust Gas Recirculation (EGR) has been proved to be a very effective NO_x reduction technique [14]. This reduces the peak flame temperature and oxygen partial pressure in the initial part of the flame and results in decrease in the NO_x formation [28]. Earlier research work on bioDiesel with 15% EGR achieved a NO_x reduction of 74% with 20% increase in smoke [9]. It was also reported that increasing the EGR beyond 15% results in increase in smoke emission and fuel consumption [24]. These results indicate that to reduce NO_x emissions without considerable increase in smoke emission, the retardation angle and percentage EGR should be optimized.

The present work was focused on controlling the NO_x emission of stationary engine fuelled with bioDiesel without any considerable effect on smoke density and thermal efficiency. BioDiesel used in this investigation is Crude Rice Bran oil Methyl Ester (CRBME) derived from high Free Fatty Acid (FFA) Crude Rice Bran Oil (CRBO) which is a non-edible vegetable oil derived from rice bran [29, 30]. CRBO with high FFA content is a non-edible vegetable oil [31] which can be utilized as a feedstock for bioDiesel production and the CRBME obtained can be used in CI engines as an alternate to Diesel fuel [29, 30].

Table 1 shows the properties of CRBME and Diesel together with the range preferred by ASTM for use in Diesel engines. It can be seen that CRBME possesses properties in the desirable range for use in Diesel engines. CRBME was tested successfully in stationary Diesel engine [29, 30] and it was found that it can be used in its neat form [32]. However, its NO_x emission was higher compared to Diesel. The main objective of this work was to reduce NO_x emission while using neat CRBME in Diesel engines.

TABLE 1

Properties of CRBME compared with Diesel

Fuel property	Diesel	CRBME	ASTM D 6751-07b
Viscosity at 40°C (mm^2/s)	3.522	4.03	1.9-6
Flash point (°C)	70	169	130 min.
Calorific value (kJ/kg)	43 356	38 853	~38 912.7
Distillation temperature T90 (°C)	335	345	360 max
Specific gravity	0.8	0.89	0.88

1 MATERIALS AND METHODS

Taguchi based Design of Experiments (DOE) method was employed to design the experiments to be conducted and Figure 1 shows the steps involved.

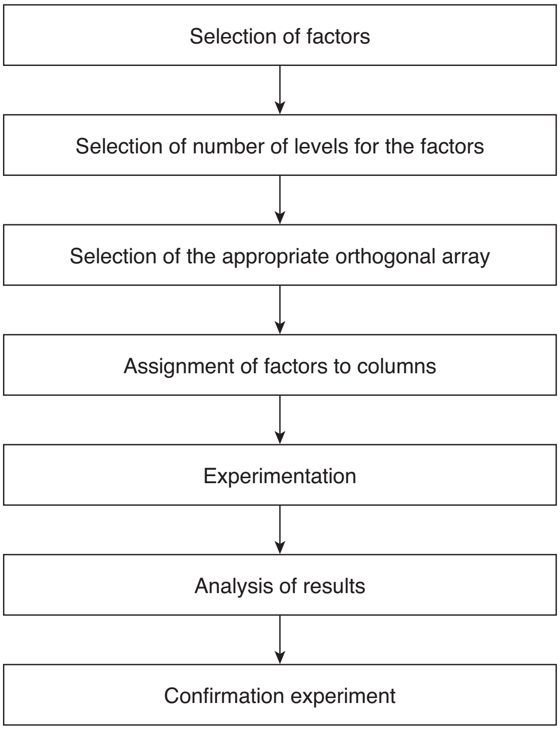


Figure 1

Flowchart of the experimentation procedure.

1.1 Selection of Factors

Combustion temperature and availability of oxygen during combustion are the two important factors affecting formation of NO_x, smoke and thermal efficiency of the engine. Variation in fuel injection timing and fuel injection pressure has a considerable effect on combustion temperature while it is well known that EGR influences oxygen availability. Hence fuel injection timing, EGR and fuel injection pressure are selected as factors for the present investigation. Figure 2 shows the components of the experimental design which shows the selected factors and the responses.

1.2 Selection of Levels of Factors

Factors chosen for the present investigation are not discrete and can be measured on a scale. To find the effects of fuel injection timing, percentage EGR and fuel injection pressure on NO_x, smoke density and thermal efficiency, their levels have to be chosen from a minimum value to a maximum value. For the present work, standard value or zero was chosen as a minimum value for the chosen factors. The maximum value for the factors were chosen based on the earlier research work conducted with those factors individually. Any value in between the minimum and maximum can be assumed to increase the levels of factors. For the present work, three levels were chosen for each factor to critically examine the effects of selected factors on the chosen objective. Precision and accuracy of the measuring instruments were also considered while selection of factors levels.

For fuel injection timing, the maximum value of retarded and advanced fuel injection angle was taken as 2.5° CA. Further change in injection timing was found to increase the smoke emission and NO_x emission for retarded and advanced angle respectively [22]. Hence for the fuel injection timing, standard injection timing, advance and retarded angle of 2.5° CA are the three levels of factors. For EGR, the conditions without EGR (0%) is taken as minimum level and from the earlier research work it is found that beyond 15% EGR, smoke emission increases significantly. Hence 15% EGR is chosen as the maximum value for EGR. Three levels, 0%, 10% and 15% were selected for EGR. Earlier research work on stationary Diesel engine with various injection pressures suggested that till 250 bar injection pressure the performance of the engine operation was smooth [33]. Hence maximum fuel injection pressure was fixed as 250 bar and 210 bar (standard pressure), 230 bar and 250 bar pressure were chosen as three levels for injection pressure. It was inferred that the magnitude variation of NO_x and smoke density between the chosen factor levels will be more than 5% [21-27]. Since the precision of NO_x and smoke density measurement is less than 5%, the chosen factor levels should have the ability to show their effect on NO_x and smoke density. The three levels of the chosen factors are given in Table 2.

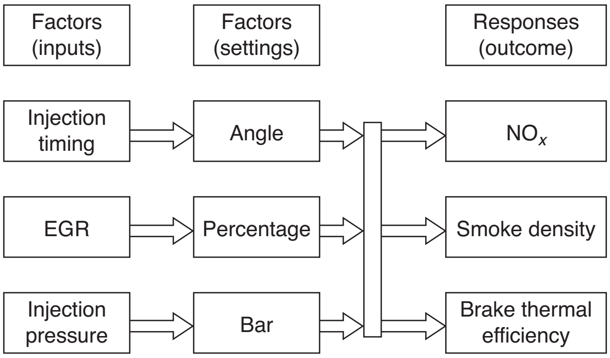


Figure 2

Components of Experimental Design.

TABLE 2

Factors influencing the objective with chosen levels

Factor No.	Factors influencing the objective	Level of factors		
		1	2	3
1	Injection timing	Standard timing (23.4° CA bTDC)	Advanced timing (by 2.5° CA)	Retarded timing (by 2.5° CA)
2	Percentage of EGR	0	10	15
3	Injector nozzle opening pressure	Normal pressure (200-210) bar	(220-230) bar	(240-250) bar

1.3 Selection of Orthogonal Array (OA)

In full factorial experiment for three factors with three levels the number of experiments to be conducted will be $3^3 = 27$. In order to reduce the number of experiments to be conducted, experiments were designed by using Taguchi Orthogonal Array (OA) technique. The selection of OA depends upon the number of factors and the number of levels of chosen factors. For more than two numbers of three level factors the recommended OA is L9 [34] which is given in Table 3. Selected OA for an experiment must satisfy the following inequality.

Total degrees of freedom available in an OA ≥ Degree of freedom required for factor.

In the present investigation, degree of freedom for the factors with three levels is 8 (2 × 2 × 2) and the degrees of freedom for L_9 OA are 8 (number of trials –1) and hence the inequality is satisfied.

TABLE 3

L_9 Orthogonal Array (OA) [34]

Trial No.	Column 1	Column 2	Column 3
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

1.4 Assignment of Factors to Columns

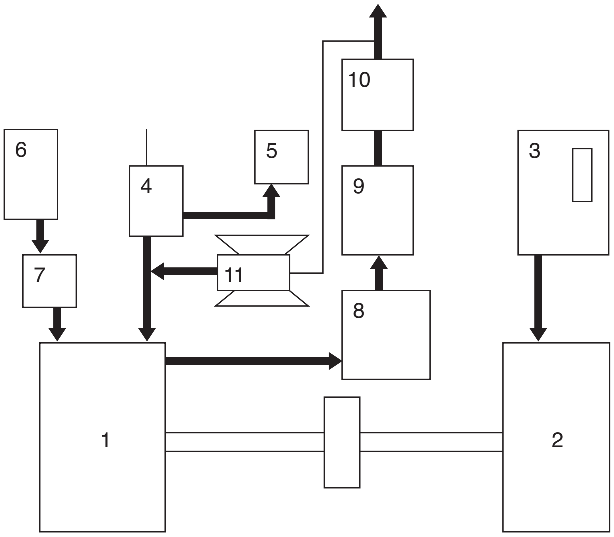
In Table 3 column 1 indicates the levels of factor 1 (fuel injection timing), column 2 the levels of factor 2 (percentage EGR) and column 3 the levels of factor 3 (fuel injection pressure).

1.5 Engine Testing

The schematic diagram of the experimental set-up is shown in Figure 3. The technical specifications of the engine used in the investigation are given in Table 4. A swinging field electrical dynamometer was used to apply the load on the engine. The electrical dynamometer consisted of a 5-kVA AC alternator (220 V, 1 500 rpm) mounted on bearings and on a rigid frame for the swinging field type loading. The output power was obtained by accurately measuring the reaction torque by a strain gauge type load cell. A water rheostat with an adjustable depth of immersion electrode was provided to dissipate the power generated.

Figure 3 also shows the schematic diagram of the cooled EGR system. A piping arrangement connects the exhaust pipe and inlet air flow passage. The length of the piping arrangement was 8 m and the starting point of the arrangement in the exhaust pipe was 10 m away from the engine. This reduces the temperature of the exhaust gases approximately equal to that of the ambient air without any additional cooling arrangement. The flow rate of the exhaust gases through the pipe was controlled by a control valve which regulates the quantity of exhaust gases. The temperature of the mixture was measured by using a *K* type thermocouple. Percentage EGR was calculated by using the expression:

$$\text{Percentage EGR} = \frac{\text{Mass of air without EGR} - \text{Mass of air with EGR}}{\text{Mass of air without EGR}} \times 100$$



1) Diesel engine - 2) Electrical dynamometer - 3) Dynamometer controls - 4) Air box - 5) U Tube Manometer - 6) Fuel tank - 7) Fuel measurement - 8) Exhaust gas analyzer - 9) AVL smoke meter - 10) Pulse reducer - 11) EGR control valve.

Figure 3

Layout of experimental setup.

TABLE 4

Specifications of engine

Make	Kirloskar
Model	TAF 1
Type	Direct injection, air cooled
Bore × Stroke	87.5 × 110 mm
Compression ratio	17.5:1
Cubic capacity	0.661 L
Rated power	4.4 kW
Rated speed	1500 rpm
Start of injection	23.4° bTDC
Injector nozzle opening pressure	200-205 bar

Injection timing was changed by changing the thickness of advance shim. The spring tension of the injector needle with setting screw was varied to get the different fuel injection pressure.

Tests were conducted on the engine fuelled with CRBME with the selected factors at different levels to determine the effect on NO_x emissions. Nine trials were conducted with the combination of different levels of influencing factors as given in Table 3. Two replicates were conducted for each trial and the order of the trial was selected randomly. The tests were conducted at a constant speed of 1 500 rpm. In each trial, the engine was tested at various loads as per the test matrix shown in Table 5. At each load the responses (NO_x emission in ppm, smoke concentration in mg/m^3, mass flow rate of fuel in kg/s) were measured. NO_x emission was measured with MRU 1600 exhaust gas analyzer and the smoke concentration was measured with AVL smoke meter. The technical specifications of the exhaust gas analyzer are given in Table 6.

TABLE 5

Test matrix

S. No.	Load (% of rated load)	Torque (N-m)	Speed (rpm)
1	0	0	1 500
2	25	7	
3	50	14	
4	75	21	
5	100	28	

TABLE 6

Specifications of exhaust gas analyser

	Exhaust gases			
	Oxygen (O_2)	Carbon monoxide (CO)	Nitrogen oxide (NO_x)	Hydrocarbon (HC)
Measuring ranges	0-25.0% vol	0-20.0%	0-2 000 ppm	0-20 000 ppm *n*-hexane
Precision	± 3%	± 5% of measured value		
Resolution	0.01%	0.01%	1 ppm	
Make	MRU Delta 1 600 L			
Response time T95	15 s			

The maximum possible errors associated with various measurements and in the calculation of performance parameters were estimated by using the method proposed by Moffat [35]. From the minimum values of measured output (speed in rpm, time taken for fuel consumption in s and torque in N-m) and the accuracy of the instruments, the maximum possible error in the calculation of brake thermal efficiency was estimated to be 0.33%. The maximum possible errors in the measurement of smoke concentration and NO_x emission are ± 5% as determined from the specifications of the analyzers.

1.6 Analysis of Data

Three variables (NO_x emission, smoke density and brake thermal efficiency) were chosen as the responses of the problem. The responses obtained for each trial at different loading conditions were analyzed to get a result for the formulated problem. In the analysis, average values of the responses measured at different loading conditions were considered as the responses for that trial. To optimize the combination of the level of factors for the formulated problem, Multi Response Signal to Noise ratio (MRSN) was calculated.

The procedure employed in the optimization process is explained below.

1.6.1 Loss Function

Loss function is used to calculate the deviation between the experimental value and the desired value. For each response variable, the corresponding loss function can be expressed as given below [34]. As per the Taguchi's categorization of response variables, smaller the better principle is considered to minimize the NO_x emission and smoke intensity. For brake thermal efficiency, larger the better principle is considered to maximize it.

For larger the better (Brake thermal efficiency):

$$L_{ij} = \frac{1}{n}\sum_{k=1}^{n}\frac{1}{y_{ijk}^{2}}$$

For smaller the better (NO_x emission and smoke density):

$$L_{ij} = \frac{1}{n}\sum_{k=1}^{n} y_{ijk}^{2}$$

where n is the number of repeated experiments, L_{ij} is the loss function of the ith response variable in the jth experiment and y_{ijk} is the experimental value of the ith response variable in the jth experiment at the kth test.

1.6.2 Normalising the Loss Function

Since the measured units of the response variables were different, the loss function was normalized in the range between zero and one. Normalization of loss function was done as follows [34]:

– for smaller the better (NO_x emission and smoke density):

$$S_{ij} = \frac{min\, L_{ij}}{L_{ij}}$$

– for larger the better (Brake thermal efficiency):

$$S_{ij} = \frac{L_{ij}}{max\, L_{ij}}$$

where S_{ij} is the normalized loss function for the response variable in jth experiment, L_{ij} is the loss function for the ith response variable in the jth experiment and L_i is the average loss function for the ith response variable.

1.6.3 Assigning Weighting Factor

In multi response optimization, the relative importance of each response variable on the set objective with respect to others will be fixed by assigning proper weighting factor for each of the normalized quality loss function. By including the weighting factor the total loss function (TL_j) can be expressed as:

$$TL_j = \sum_{i=1}^{m} w_i s_{ij}$$

where w_i is the weighting factor for the ith response variable and m is the number of response variables.

Weighting factors for the response variables are to be decided based on the priorities among the various responses. If equal importance is given to all the response variables, the weighting factors will have equal value such that the sum of weighting factors is always unity. In an optimization process with three response variables, for the combination 0.4, 0.3 and 0.3, the importance on first response variable is more when compared to the other two. In this way different combination as per the chosen objective can be taken to get the optimum combination level of the influencing factors. The most influencing factor in achieving the objective for each combination of the weighting factor was analysed through ANalysis Of VAriance (ANOVA).

The main objective of the present work was to reduce the NO_x emission with minimum smoke emissions and maximum brake thermal efficiency. Hence higher weightage was assigned to NO_x emission when compared to the other two. Initially 0.4(w_1), 0.3(w_2) and 0.3(w_3) were assigned as weighting factors for the response variables NO_x, smoke density and brake thermal efficiency respectively. Further it was varied to study the effect of weighting factor on the set objective.

1.6.4 MRSN

In multi response optimization of Taguchi loss function, Multi Response Signal to Noise ratio (MRSN) has to be maximized by using the formula given below [34].

$$\text{MRSN} = -10 \log (TL_j)$$

Optimal level of combinations for the obtained MRSN ratio with the assigned weighting factor was determined by following Taguchi parametric design. Variance of the MRSN ratio was analyzed through ANalysis Of VAriance (ANOVA) and the level of importance of each factor on the response variables for the assigned weighting factor was identified from the ANOVA table. This procedure was repeated for different combinations of weighting factors to predict the effect of weighting factor on the set objective.

1.6.5 Analysis of Variance (ANOVA)

ANOVA is a statistical method used to interpret experimental data and make necessary decisions and it establishes the relative significance of factors in terms of their percentage contribution to the response. Since three factors are involved in the present investigation it is necessary to evaluate the significant and percentage contribution of each factor on the reduction of NO_x emission with less sacrifice on smoke density and thermal efficiency. This analysis is performed on signal to noise ratios to find the contribution of the factors.

The total variability of the MRSN ratio is measured by the sums of squares of MRSN ratio by using the formula given below [34]:

$$SS_T = \left[\sum_{i=1}^{N} y_i^2\right] - \frac{T^2}{N}$$

where N is the total number of experiments, T is the sum of all experiments response variable and y_i is the ith response variable. The total sum of squares includes the sum of squares due to each factor (SS_f) and the sum of squares of errors (SS_e). The ratio of SS_f to SS_T is the percentage contribution (P) by the factor. MSF is equal to SS_f divided by the number of Degree of Freedom (DF) associated with the factors. The F-ratio provides a statistical value that can be compared to a probability distribution table for a given confidence level to identify the significant effect of each influencing factor on the responses. There are infinite number of F-distributions based upon confidence levels, degrees of freedom for factors, and degrees of freedom for error. F-ratio (F_{cal}) is compared to a value (F_{tab}) from the F-distribution table [34] for 95% confidence level. The larger the F_{cal} than the F_{tab}, the greater is the effect on the response due to the change in that factor.

1.7 Confirmation Experiment

Optimum combination of factor levels obtained through MRSN ratio and Taguchi parametric design was confirmed through experiment. After conducting the confirmation experiment with the optimum combination, the improvement in the response variable was verified by comparing it with the normal operating conditions (Responses measured at standard injection timing and injection pressure without EGR).

2 RESULTS AND DISCUSSION

2.1 MRSN Ratio

Table 7 shows the MRSN ratio for the experiments conducted for the weighting factors of $w_1 = 0.4$, $w_2 = 0.3$ and $w_3 = 0.3$. From the table, the combination which has the maximum MRSN ratio will be taken as the best combination among the nine in achieving the objective. It can be observed that experiment number 5 (2-2-3) is the best combination among the nine. ANOVA was employed to analyse the MRSN ratio obtained with different combinations of weighting factors.

TABLE 7

MRSN ratio for $w_1 = 0.4$, $w_2 = 0.3$ and $w_3 = 0.3$

Exp. No.	Loss function (L_{ij})			Normalization (S_{ij})			Weighting (w_iS_{ij})			TL_j	MRSN ratio
	NO_x	Smoke	BTE								
1	537 375.5	11 015.5	0.000917	0.44	0.47	0.99	0.18	0.14	0.30	0.61	0.212
2	397 108	17 346.98	0.000856	0.60	0.30	0.92	0.24	0.09	0.28	0.60	0.218
3	348 619.4	61 757.32	0.000853	0.68	0.08	0.92	0.27	0.03	0.28	0.57	0.242
4	715 816	5 200	0.000879	0.33	1.00	0.95	0.13	0.30	0.28	0.72	0.145
5	582 936.6	11 339.16	0.00082	0.41	0.46	0.88	0.16	0.14	0.27	0.56	0.248
6	502 976.4	5 334.23	0.000853	0.47	0.97	0.92	0.19	0.29	0.28	0.76	0.121
7	403 719.2	12 349.56	0.000928	0.59	0.42	1.00	0.23	0.13	0.30	0.66	0.18
8	236 391	29 882.88	0.000817	1.00	0.17	0.88	0.40	0.05	0.26	0.72	0.145
9	262 212.4	26 431.27	0.00079	0.90	0.20	0.85	0.36	0.06	0.26	0.68	0.171

Table 8 shows the effects of factors on measured response variables for the weighting factor of $w_1 = 0.4$, $w_2 = 0.3$ and $w_3 = 0.3$. The level which has the higher value when compared with other two levels is the optimum level for each factor. It is observed that the first level of injection timing, second level of percentage EGR and third level of injection pressure have higher value when compared with other levels and hence the levels (1-2-3) are taken as the optimum for the assigned weighting factors of $w_1 = 0.4$, $w_2 = 0.3$ and $w_3 = 0.3$.

TABLE 8

Effects of factor on response variables for $w_1 = 0.4$, $w_2 = 0.3$ and $w_3 = 0.3$

Factors	Level 1	Level 2	Level 3
Injection timing	0.22	0.186	0.17
Percentage EGR	0.18	0.51	0.18
Injection pressure	0.16	0.18	0.22

Table 9 shows the effect of weighting factor on the optimum combination level of factors and percentage contribution of influencing factors on the set objective. It is observed that the weighting factor plays an important role in deciding the contribution of factors on the set objective. As the weighting factor w_1 increases, the percentage contribution of injection timing on the set objective also increases which ensures the influence of fuel injection timing in NO_x reduction. For the assigned w_1 the percentage contribution of injection timing, EGR and injection pressure depends upon the difference between the weighting factors w_2 and w_3. As the difference between w_2 and w_3 for the same w_1 increases, the percentage

TABLE 9

Effect of weighting factor

Combination No.	Weighting factor			Optimum level of factors			Percentage contribution of factors from the ANOVA table		
	w_1	w_2	w_3	Injection timing	Percentage EGR	Injection pressure	Injection timing	Percentage EGR	Injection pressure
1	0.4	0.3	0.3	1	2	3	38.04	7.7	39.4
2	0.4	0.4	0.2	1	2	3	43.9	8.8	36.02
3	0.5	0.3	0.2	1	2	3	43.2	6.5	37.2
4	0.5	0.4	0.1	1	2	3	43.7	5.4	39.7
5	0.6	0.2	0.2	2	2	3	58.2	14.1	18.2
6	0.6	0.25	0.15	1	2	3	52.1	12.3	24.8
7	0.6	0.3	0.1	1	2	3	47.4	10.3	30.8
8	0.7	0.2	0.1	2	2	3	59.4	18.8	13.8
9	0.8	0.1	0.1	2	2	3	67.6	23.2	4.6

contribution of EGR and injection timing increases while for injection pressure it decreases till w_1 is 0.4. If w_1 is more than 0.4, the increase in difference between w_2 and w_3 for the same w_1 results in increase in the percentage contribution of injection timing and injection pressure and decrease in percentage contribution of EGR. From the analysis it is inferred that fuel injection timing is the most influencing factor for NO_x emission since change in w_1 increases the P value irrespective of w_2 and w_3. It is also inferred that increase in the value of w_2 also increases the P value of injection pressure which shows that fuel injection pressure is the most influencing factor for smoke density. It can be seen that the change in the weighting factor shows an effect in the optimum combination if the difference between w_1 and w_2 is 0.4 and more. At this combination of weighting factors, importance on the NO_x emission increases which changes the level of injection timing alone and ensures the influence of injection timing on NO_x emission.

2.2 ANOVA

Table 10 shows the results of ANOVA for the weighting factor of $w_1 = 0.4$, $w_2 = 0.3$ and $w_3 = 0.3$. From the table, the percentage contribution (P) of all the factors on the set objective can be observed. It can be observed that fuel injection pressure is the most influencing factor on the set objective since its percentage contribution is higher than the other two. It is observed from Table 1 that the viscosity of CRBME is higher than that of petroleum Diesel which needs higher pressure for better fuel atomization. This results in smaller droplets, increased rate of fuel vaporization and complete combustion. As a result of this brake thermal efficiency will increase and smoke density will decrease. Complete combustion also increases the NO_x emission. This ensures that any change in fuel injection pressure will have an effect on all the response variables and hence it is the most influencing factor in achieving the objective. Fuel injection timing has a considerable effect on the chosen objective since its contribution is significant and the difference in percentage contribution (P) between fuel injection pressure and fuel injection timing is marginal as indicated in the ANOVA table. Injection of fuel in the cylinder at a required pressure and temperature of air depends upon the fuel injection timing which has an effect on the temperature after combustion. This temperature will have an effect on both NO_x and smoke emission. At higher temperatures, NO_x emission is more with reduced smoke and *vice versa*. Reduction in peak combustion temperature will reduce the availability of heat for conversion into useful work which will have an effect on brake thermal efficiency. When compared with fuel injection pressure, fuel injection timing also has a considerable effect on all the response variables and its influence on the set objective is vital as obtained through ANOVA. It can also be observed that with this combination of weighting factors EGR has minimum effect on the objective since its percentage contribution is very low when compared with the other two. It is well known that EGR is an effective method in NO_x reduction for bioDiesel. However its effect on the objective (NO_x reduction of crude rice bran oil methyl ester with less effect on smoke emission and brake thermal efficiency) is less when compared with injection timing and injection pressure as obtained through MRSN ratio and ANOVA. This is due to the fact that recycling a portion of exhaust gases will result in reduction in the peak combustion temperature and also leads to smoke formation.

TABLE 10

Results of ANOVA for $w_1 = 0.4$, $w_2 = 0.3$ and $w_3 = 0.3$

Factor	*SS*	*DF*	*MSF*	*P*
Injection timing (SS_f)	0.006	2	0.003	0.38
Percentage EGR (SS_f)	0.001	2	0.0006	0.077
Injection pressure (SS_f)	0.007	2	0.003	0.39
Error (SS_e)	0.002	2	0.001	0.15
Total (SS_T)	0.0165	8		

2.3 Response Variables at Optimized Condition

Confirmation experiment was conducted for the obtained optimum combination level and the response variables of optimum combination have been compared with the response variables of the experiments conducted with the normal operating condition.

Table 11 shows the response variables at the two optimized conditions and the same is compared with the variables at normal operating condition. It can be observed that brake thermal efficiency is increased as a result of this combined effect. This increase in brake thermal efficiency is due to the re-burning of unburnt hydrocarbons present in the EGR [25]. One of the optimum combinations 1-2-3 obtained by varying weighting factors shows reduction in NO_x emission with increase in smoke density and brake thermal efficiency. The other optimum combination 2-2-3 is the fifth trial in the L_9 orthogonal array which shows an increase in NO_x emission with reduction in smoke density. Since the main objective of the work was to reduce the NO_x emission, this combination can be eliminated. Hence first level of injection timing, second level of percentage EGR and third level of injection pressure was the optimum combination for lower NO_x emission with lower smoke intensity and higher brake thermal efficiency for CRBME. This combination reduces NO_x by 14% with 2.4% increase in smoke density and 3.3% increase in brake thermal efficiency when compared with normal operating condition. Recycling a portion of exhaust gases reduces the maximum gas temperature attained in the cylinder and it decreases the NO_x

TABLE 11

Effect of optimization on response variables

Fuel	Normal operating condition			Optimized condition				% change		
	NO_x (ppm)	Smoke (mg/m^3)	BTE (%)	Combination	NO_x (ppm)	Smoke (mg/m^3)	BTE (%)	NO_x	Smoke	BTE
CRBME	733.0	28.48	16.39	1-2-3	633.2	29.17	16.94	13.6 (Decrease)	2.4 (Increase)	3.3 (Increase)
				2-2-3	763.4	26.17	17.30	4.15 (Increase)	8.13 (Decrease)	5.6 (Increase)
Diesel	671.2	71.8	16.77							

formation. The increase in smoke emission as a result of this reduced temperature was reduced by increased fuel injection pressure. Due to small diameter particles with higher injection pressure, smoke level is reduced for CRBME. The percentage decrease in NO_x emission of CRBME obtained in the present investigation is comparable with that of earlier results obtained with retarded fuel injection alone and the percentage increase in smoke density of CRBME is very much lower than the earlier results obtained with retarded fuel injection and EGR individually [9, 27].

2.4 Combustion Parameters at Optimized Condition

Combustion characteristics of CRBME at the optimized condition (CRBME-optimized) are presented by comparing it with normal operating conditions of the engine when fuelled with CRBME (CRBME-normal) and Diesel (Diesel-Normal).

The ignition delay of CRBME at optimized condition at different loads is compared with ignition delay of CRBME and Diesel at normal condition and is shown in Figure 4. It is observed that for all the fuels ignition delay decreases with increase in load. This is due to higher combustion chamber wall temperature and reduced exhaust gas dilution at higher loads. It is also observed that the ignition delay of CRBME is shorter than that of Diesel at all loads both under normal and optimized conditions. CRBME has higher cetane number compared to Diesel. Since the delay period of a liquid fuel is inversely proportional to its cetane number CRBME has a lower delay period than that of Diesel under normal operating conditions. Under optimum conditions the fuel injection pressure is higher (250 bar compared to 200 bar of normal conditions) and EGR is 10%. This results in shorter delay period at all loads. At higher injection pressure, atomization and vaporization of fuel are better which results in smaller droplets, shorter breakup length, higher dispersion which leads to a shorter delay period. It is also observed that the decrease in delay period under optimized conditions compared to normal conditions is higher at higher loads. This is due to the fact that the dilution of the mixture with EGR is less and the combustion chamber wall temperature is higher at higher loads.

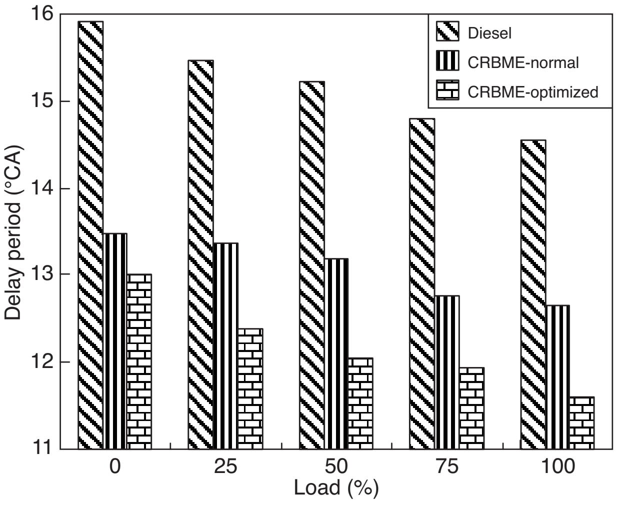


Figure 4

Ignition delay of CRBME at optimized condition.

The peak pressure of CRBME at optimized condition at different loads is compared with peak pressure of CRBME and Diesel at normal condition and is shown in Figure 5. It is observed that the peak pressure increases with load for all of the fuels and the variation between the fuels is marginal. It is also observed that the peak pressure of CRBME at optimized condition is marginally higher at all loads. As a result of shorter delay period, the duration of the compression after start of combustion is longer at optimized condition. This causes compression of combustion products which increase the peak pressure attained in the cylinder.

The Maximum Heat Release Rate (MHRR) of CRBME at optimized condition at different loads is compared with MHRR of CRBME and Diesel at normal condition and is shown in Figure 6. The MHRR is higher for Diesel at all loads due to its higher calorific value. For CRBME the MHRR is higher at normal conditions at lower loads (up to 25%) and

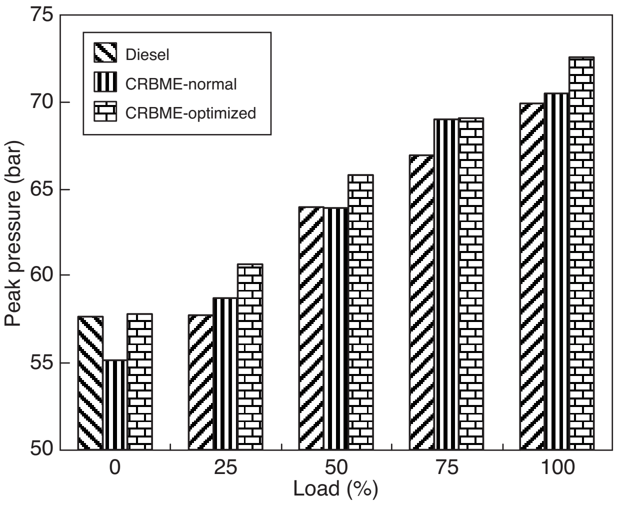


Figure 5

Peak pressure of CRBME at optimized condition.

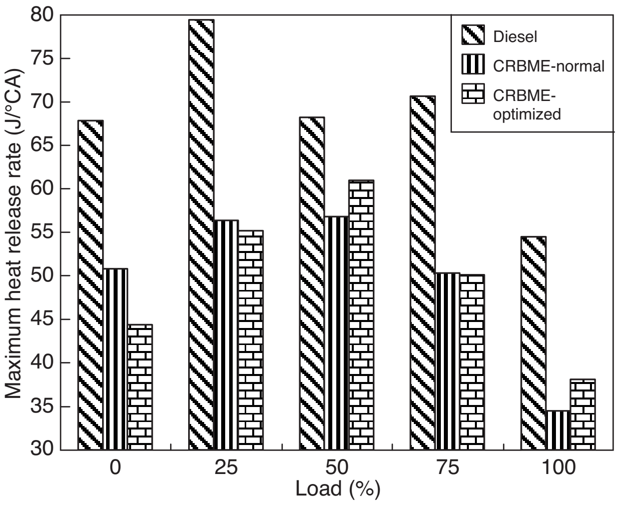


Figure 6

Maximum heat release rate of CRBME at optimized condition.

beyond that the MHRR for optimized condition is higher. At higher loads the mixture formation will be good as a result of higher temperature existing in the combustion chamber which improves the combustion process to produce higher heat release rate. As a result of better combustion resulting from higher injection pressure the energy absorbed by recycled exhaust gases is compensated.

CONCLUSION

This work explores the possibility of utilizing DOE and Taguchi orthogonal array in engine testing and attempts to investigate the combined effect of three factors on the three variables with minimum number of experimental work. Experimental results were analyzed through statistical tools and the findings of the analysis were used to make necessary decisions. Since more than one factor (injection timing, EGR and injection pressure) were chosen in this experiment to control three response variables (NO_x, smoke density and thermal efficiency), the most influencing factor for the chosen objective was found out by using the Taguchi method. The relative importance of each response variable was varied by fixing different weighting factors for the response variables and the combination of factor levels was obtained for each combination of weighting factors. In the present work, the optimum combination of injection timing, percentage EGR and fuel injection pressure in reducing the NO_x emission was arrived by calculating MRSN ratio. Different weighting factors were assigned to each response variable to calculate the MRSN ratio and the obtained ratio was analyzed through ANOVA method. From the results of ANOVA and factor effects, the following conclusions are drawn:

- fuel injection pressure appears to be the most influencing factor in reducing NO_x emission of crude rice bran oil methyl ester next to fuel injection timing with minimum increase in smoke density;
- percentage EGR has least effect on the set objective when compared with other two;
- standard injection timing with 10% EGR with 240-250 bar injection pressure will be the optimum combination for the reduction of NO_x emission with least effect on smoke intensity and brake thermal efficiency.

The conclusions are drawn with minimum number of experiments which saved time and cost because of the application of Taguchi based DOE. The optimum combination of factors was arrived after critical analysis of response variables with different possible combination of weighting factors. Without Taguchi method considerable experimental work has to carried out to study the effect of factors on the response variables.

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