Open Journal of Optimization, **2012, 1, 25-33**
http://dx.doi.org/10.4236/ojop.2012.12005 Published Online December 2012 (http://www.SciRP.org/journal/ojop)

Application of Taguchi's Orthogonal Array in Multi Response Optimization of NO_x Emission of Crude Rice Bran Oil Methyl Ester Blend as a CI Engine Fuel

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Received September 17, 2012; revised October 18, 2012; accepted October 27, 2012

ABSTRACT

In this work an attempt was made to minimize the NO_x emission of a crude rice bran oil methyl ester (CRBME) blend with less sacrifice on smoke density and brake thermal efficiency. Three factors namely fuel injection timing, percentage EGR and fuel injection pressure were chosen as the influencing factors for the set objective. Experiments were designed by employing design of experiments method and Taguchi's L_9 orthogonal array was used to test the engine. MRSN ratio was calculated for the response variables and the optimum combination level of factors was obtained simultaneously using Taguchi's parametric design. ANOVA was employed to analyze the variance of MRSN and the most influencing factor for the set objective was taken from the ANOVA table. Obtained combination was confirmed experimentally and significant improvement was observed in the response variables.

Keywords: Diesel Engine; Emission; Crude Rice Bran Oil; Biodiesel; Taguchi's Orthogonal Array; MRSN; DOE

1. Introduction

Biodiesel, a clean burning renewable fuel derived from vegetable oil and animal fats is considered as the next generation fuel which reduces the dependency on fossil fuel and also the harmful pollutants. However biodiesel emits higher NO_x emission than petroleum diesel and the techniques of NO_x emission reduction of biodiesel are a dynamic research topic and big challenge for the young researchers [1-5]. In-cylinder control and exhaust gas treatment are the two important techniques for the control of NO_x emission [6]. In the former method combustion process was modified through retardation of fuel injection timing, EGR, fuel additives and water injection to prevent the formation of NO_x [7]. In the latter method exhaust gas was treated with the help of catalysts to remove the formed NO_x completely [8-12]. Reduction in NO_x emission through exhaust gas treatment can be considered only in those cases where the emission standards cannot be met by combustion process modification alone and the combustion process modification method is the most economical method for NO_x reduction [6] and this paper presents one of such modification processes to reduce the NO_x emission.

Earlier investigations on NO_x reduction were carried out by modifying the combustion process through retardation of fuel injection timing and recycling exhaust gases into the inlet manifold (EGR) [13-19]. In these methods, reduction in NO_x emission was achieved with an increase in smoke density and decrease in brake thermal efficiency. It was reported that retarding the fuel injection angle by 3˚ crank angle (CA) and more for biodiesel will increase the smoke density with decrease in brake thermal efficiency [14,18]. It was also reported that increasing the EGR by more than 15% will result in increase in smoke emission and fuel consumption for biodiesel and its blends [16,17,19]. These results indicate that to reduce the NO_x emissions without increasing the smoke emissions the retardation angle and amount of EGR should be optimized [7].

Hence in this work an attempt was made to reduce the NO_x emission of a biodiesel blend with minimum sacrifice on smoke density and brake thermal efficiency. Earlier research works on NO_x emission reduction have been carried out with retarded injection timing and EGR individually and the present work concentrates on the combined effect of these two methods. In addition to injection timing and percentage EGR, fuel injection pressure also varied since its role in I.C engine combustion is vital.

Biodiesel used in this investigation was derived from

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the high FFA crude rice bran oil (CRBO) which is a non-edible vegetable oil derived from the rice bran [20]. Rice bran is a by-product of rice milling process. As rice production is a renewable process, the availability of rice bran for oil extraction is also renewable in nature. Based on the rate of world wide rice production it was estimated that rice bran oil has the potential to replace nearly 0.9% of the world diesel consumption [21]. Crude rice bran oil (CRBO) with very low free fatty acid (FFA) content is subjected to further refining process to utilize it as a kind of edible oil which is consumed in some of the Asian countries like Japan, India. CRBO with higher FFA is restricted for use as a kind of edible oil. In the total production of CRBO, only a small portion (<10%) is processed into edible oil and the remaining high FFA CRBO is used in cosmetic and food industries. Hence CRBO with high FFA content can be utilized as a feedstock for biodiesel production and the obtained crude rice bran oil methyl ester (CRBME) can be utilized in CI engine as an alternate to diesel fuel [22].

Earlier research works on biodiesel indicated that B20 (20% of biodiesel mixed with 80% of diesel in volume basis) will be an optimum fuel blend for CI engine rather than neat biodiesel [23-25]. Blending biodiesel with diesel minimizes the property differences between diesel and biodiesel. B20 is popular because it represents a good balance of cost, emissions, cold weather performance, materials compatibility and solvency. B20 is also the minimum blend level that can be used for the Energy Policy Act (EPAct 1992) compliance for covered fleets [26]. Hence the present investigation is carried out using CRBME as a CI engine fuel in blended form (B20).

CRBME blend has comparable properties as those of diesel [27] and its combustion characteristics are similar with those of diesel [5]. CRBME blend was tested successfully in stationary [5] and automotive diesel engine [28]. From the earlier research works on CRBME [22,29] and CRBME blend [5,28] it was found that CRBME has a potential to replace diesel oil in its neat and blended form and their NO_x emission was higher than that of diesel. Hence a method to reduce NO_x emission of CRBME and its blend has to be investigated.

The main objective of this work is to find the best combination level of fuel injection timing, percentage EGR and fuel injection pressure in reducing the NO_x emission of CRBME blend with minimum increase in smoke density and minimum decrease in brake thermal efficiency.

2. Experimental Programme

2.1. Taguchi Design and Selection of Factor Levels

Before conducting tests on the engine, the experiment was designed by following design of experiments (DOE) method. For the formulated problem, fuel injection timing, percentage EGR and fuel injection pressure are considered as the factors influencing the objective.

The levels of the factors to be included for testing were chosen based on the conclusion of the earlier researchers during their research work with those factors individually. For fuel injection timing, in addition to the standard injection timing, one advanced and one retarded angle were chosen as other two levels of the factors. The retarded and advanced fuel injection angle was taken as 2.5˚ CA. Further increase in retardation and advancing angle will accelerate the increase in smoke emission and NO_x emission respectively [14]. To avoid the increase in smoke emission the maximum percentage EGR was fixed as 15 and within that 0 and 10 have been chosen as the other two levels. For fuel injection pressure 250 bar was fixed as the maximum pressure considering the smooth operation of the engine [30] and two more levels were chosen including the standard one. **Table 1** shows the three levels of the chosen factors.

Taguchi Orthogonal Array (OA)

In full factorial experiment for three factors with three levels, the number of experiments will be $3^3 = 27$. To reduce the number of experiments to be conducted, experiments were designed by using Taguchi orthogonal array (OA) technique. For more than two numbers of three level factors, the recommended OA is L_9 [31] which is given in **Table 2**. In **Table 2** column 1 indicates the levels of factor 1 (fuel inj[ection timing), column 2 the levels of factor 2 (percentage EGR) and column 3 the levels of factor 3 (fuel injection pressure).

2.2. Experimental Setup

Schematic diagram of the experimental set-up is shown in **Figure 1**. The technical specifications of the engine used in this investigation are given in **Table 3**. A swinging field electrical dynamometer was used to apply the load on the engine. This electrical dynamometer consisted of a 5-kVA AC alternator (220 V, 1500 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 rheo stat with an adjustable depth of immersion electrode was provided to dissipate the power generated. Injection timing was changed by changing the thickness of advance shim. Cooled EGR system was employed to study the effect of EGR.

2.2.1. EGR System

The schematic diagram of the EGR system is shown in

Table 1. Factors influencing the objective with chosen levels.

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

Table 2. L_9 orthogonal array (OA) [Rose 1988].

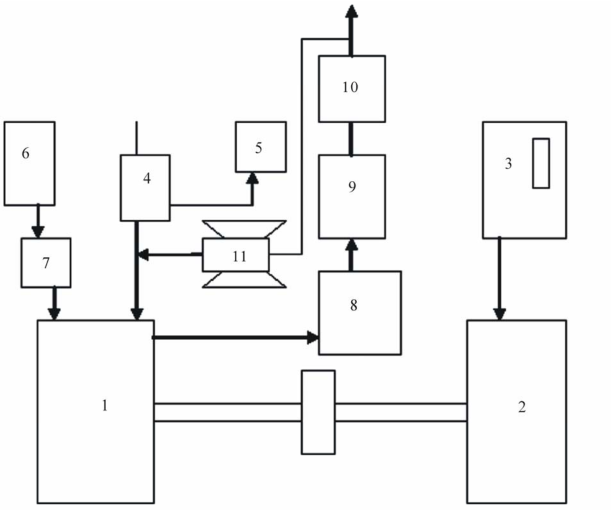
Trial No	Column 1	Column 2	Column 3
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 3. 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 lit
Rated power	4.4 KW
Rated speed	1500 rpm
Start of injection	23.4˚ bTDC
Injector operating pressure	200 - 205 bar

Figure 1. A piping arrangement was provided to tap the exhaust gases from the exhaust pipe and to connect it to the inlet air flow passage. To regulate the exhaust gases through this pipe, a control valve was provided in the pipe line. The exhaust gases were allowed to flow through the pipe after passing through 10 m of the exhaust pipe and a pulse reducer tank. Through the pipe the gases further travel 8 m which reduces the temperature of the exhaust gases approximately equal to that of the ambient air.

Percentage EGR was calculated by using Equation (1)



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

Figure 1. Experimental set up.

$$\text{Percentage EGR} = \frac{\text{Mass of air without EGR} - \text{Mass of air with EGR}}{\text{Mass of air without EGR}} \times 100 \quad (1)$$

2.2.2. Injection Timing and Injection Pressure

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.

2.3. Testing Procedure

Tests were conducted on the engine fuelled with CRBME blend with the selected factors at different levels to determine the effect of the factors on the objective. The engine was operated nine times with the combinations of the different levels of the influencing factors as given in **Table 2**. 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 1500 rpm in each trial, the engine was tested at various loads starting from no load to full load and at each load the responses (NO_x emission in ppm, smoke intensity in mg/m^3, time taken for fuel consumption in sec) were measured. NO_x emission was measured with MRU 1600 exhaust gas analyzer and the smoke intensity was measured with AVL smoke meter.

2.4. Error Analysis

The errors associated with various measurements and in calculations of performance parameters are computed in this section. The maximum possible errors in brake thermal efficiency (BTE) were estimated by using the method proposed by Moffat [32]. Errors were estimated from the minimum values of output and the accuracy of the instrument. This method is based on careful specification of the uncertainties in the various experimental measurements.

If an estimated quantity, S depends on independent variables like (x_1, x_2, $x_3 \cdots x_n$) then the error in the value of "S" was calculated by using Equation (2)

$$\frac{\partial S}{S}=\left\{\left(\frac{\partial x_1}{x_1}\right)^2+\left(\frac{\partial x_2}{x_2}\right)^2+\cdots+\left(\frac{\partial x_n}{x_n}\right)^2\right\}^{\frac{1}{2}} \quad (2)$$

where, $\left(\frac{\partial x_1}{x_1}\right)$, $\left(\frac{\partial x_2}{x_2}\right)$

etc. are the errors in the independent variables.

∂x_1 = Accuracy of the measuring instrument,

x_1 = Minimum Value of the output measured.

2.4.1. Errors in Measured Quantities

2.4.1.1. Brake Thermal Efficiency (BTE)

The brake specific fuel consumption is calculated from the fuel consumption and brake thermal efficiency. The maximum possible error in the calculation of BTE was determined by using Equation (3)

$$\left(\frac{\partial \text{BTE}}{\text{BFCE}}\right)=\left(\left(\frac{\partial \text{Torque}}{\text{Torque}}\right)^2+\left(\frac{\partial \text{rpm}}{\text{rpm}}\right)^2+\left(\frac{\partial \text{time}}{\text{time}}\right)^2\right)^{\frac{1}{2}} \quad (3)$$

$$\left(\frac{\partial \text{BTE}}{\text{BFCE}}\right)=\left(\left(\frac{0.021}{7.0}\right)^2+\left(\frac{0.15}{1500}\right)^2+\left(\frac{0.01163}{9.26}\right)^2\right)^{\frac{1}{2}}$$

$$\left(\frac{\partial \text{BTE}}{\text{BFCE}}\right)=\left((0.003)^2+(0.0001)^2+(0.001256)^2\right)^{\frac{1}{2}}$$

$$= 0.0033 = 0.33\% .$$

2.4.1.2. Exhaust Gas Emissions

The exhaust gas emissions were measured using an exhaust gas analyzer and a smoke meter. As per the specifications of the analyzer, the maximum possible error in the measurement of smoke concentration and NO_x emission is ±5%.

3. Analysis of Data

Obtained responses for each trial at different loading conditions were analyzed to get a result for the formulated problem.

3.1. Optimization

For the formulated problem, three variables have been chosen as the responses and multi response signal to noise ratio (MRSN) was used to get the optimum level of combination.

The procedure employed in the optimization process is explained.

3.1.1. Loss Function

As per the Taguchi categorization of response variables, smaller the better principle is considered to minimize the NO_x emission and smoke intensity. For the brake thermal efficiency, larger the better principle is considered to maximize it. For each of that case, the corresponding loss function can be expressed using Equations (4) and (5) [31].

For larger the better (Brake thermal efficiency)

$$L_{ij}=\frac{1}{n}\sum_{k=1}^{n}\frac{1}{y^2{}_{ijk}} \quad (4)$$

For smaller the better (NO_x emission and smoke intensity)

$$L_{ij}=\frac{1}{n}\sum_{k=1}^{n}y^2{}_{ijk} \quad (5)$$

where n is the number of repeated experiments, L_{ij} is the loss function of the i^{th} response variable in the j^{th} experiment and y_{ijk} is the experimental value of the i^{th} response variable in the j^{th} experiment at the k^{th} test.

3.1.2. Normalizing the Loss Function

Because of the different measured unit, the loss function was normalized in the range between zero and one. Normalization of loss function was done using Equations (6) and (7) [31].

$$S_{ij}=\frac{\min L_{ij}}{L_{ij}} \quad (6)$$

for smaller the better (NO_x emission and smoke intensity)

$$S_{ij}=\frac{L_{ij}}{\max L_{ij}} \quad (7)$$

for larger the better (Brake thermal efficiency) where S_{ij} is the normalized loss function for the response variable in j^{th} experiment, L_{ij} is the loss function for the i^{th} response variable in the j^{th} experiment and $\bar{L}_{ij}$ is the average loss function for the i^{th} response variable.

3.1.3. Assigning Weighting

To determine the importance of each normalized loss function, weighting method was employed. The total loss function can be expressed using Equation (8)

$$TL_i = \sum_{i=1}^{m} w_i s_{ij} \tag{8}$$

where w_i is the weighting factor for the i^{th} response variable and m is the number of response variables.

In multi response optimization, the relative importance of each response variable on the set objective with respect to others will be fixed by means of the weighting factor. 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 1. 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 combinations can be taken to get the optimum combination level of the influencing factors. For each combination of the weighting factor, the most influencing factor of achieving the objective is analysed through Analysis of Variance (ANOVA).

The main objective of the present work was to reduce the NO_x emission with minimum sacrifice on smoke emissions and 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.

3.1.4. MRSN

Multi response signal to noise ratio (MRSN) was calculated from the total loss function by using the Equation (9) [31].

$$\text{MRSN} = -10\log\left(TL_i\right) \tag{9}$$

Taguchi technique was employed to determine the optimal level of combinations for the obtained MRSN ratio corresponding to the assigned weighting factor. 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 with different combinations of weighting factors to predict the effect of weighting factor on the set objective. Finally the obtained combination was confirmed through an experiment.

3.2. Analysis of Variance

Analysis of variance (ANOVA) is a statistical method used to interpret experimental data and make the necessary decisions. The total variability of the MRSN ratio is measured by the sums of squares of MRSN ratio by using the Equation (10) [31].

$$SS_T = \left[\sum_{i=1}^{N} y_i^2\right] - \frac{T^2}{N} \tag{10}$$

where N is the total number of experiments, T is the sum of all experiments response variable and y_i is the i^{th} 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 the SS_f divided by the number of degree of freedom (DF) associated with the factors.

3.3. Verification

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.

4. Results and Discussion

4.1. MRSN Ratio

MRSN ratio for the experiments conducted was given in **Table 4** for the weighting factor 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 the experiment number 3 (1-3-3) is the best combination among the nine. MRSN ratio obtained with different combinations of weighting factors was further analysed through ANOVA.

4.2. ANOVA

Variance of the MRSN ratio was analysed through ANOVA. **Table 5** shows the results 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 factors on the set objective can be observed. It can be seen that the fuel injection timing is the most influencing factor on the set objective since its percentage contribution is much higher than the other two. As the fuel injection timing changes, the pressure and temperature of the air in the cylinder during fuel injection also change which changes the

Table 4. 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_i	MRSN ratio
	NO_x	Smoke	BTE								
1	572517.5	2987.92	0.000917	0.43	0.56	0.99	0.17	0.17	0.30	0.64	0.19
2	419385.9	4075.28	0.000856	0.59	0.41	0.92	0.24	0.12	0.28	0.64	0.2
3	365062.5	12653.12	0.000853	0.68	0.13	0.92	0.27	0.04	0.28	0.59	0.23
4	824196.9	1637.92	0.000879	0.30	1.03	0.95	0.12	0.31	0.28	0.71	0.15
5	625762	2567.12	0.00082	0.40	0.66	0.88	0.16	0.20	0.27	0.62	0.21
6	538792	1685	0.000853	0.46	1.00	0.92	0.18	0.30	0.28	0.76	0.12
7	425907.9	2920	0.000928	0.58	0.58	1.00	0.23	0.17	0.30	0.71	0.15
8	247740.3	6306.32	0.000817	1.00	0.27	0.88	0.40	0.08	0.26	0.74	0.13
9	275036.3	5745.68	0.00079	0.90	0.29	0.85	0.36	0.09	0.26	0.70	0.16

Table 5. 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)	0.006609	2	0.003305	0.56
Percentage EGR(SS_f)	0.000267	2	0.000133	0.02
Injection pressure(SS_f)	0.00372	2	0.00186	0.31
Error(SS_e)	0.001302	2	0.000651	0.11
Total (SS_T)	0.011898	8		

Table 6. Factor effects 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	0.21	0.16	0.14
Percentage EGR	0.16	0.45	0.17
Injection Pressure	0.15	0.17	0.2

burned gas temperature. This change in temperature will have an effect on both NO_x and smoke emission. At higher temperature 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.

Since change in fuel injection timing has a considerable effect on all the response variable, its influence on the set objective is more when compared with other two as obtained through ANOVA. Fuel injection pressure has considerable effect on the chosen objective since its contribution is significant as indicated in the ANOVA table. As the change in fuel injection pressure also causes a change in the fuel atomization which will affect the complete combustion process. Hence fuel injection pressure has a considerable effect on the set objective. It can also be observed that with this combination of weighting factors, EGR has minimum effect 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. However its effect on NO_x reduction of crude rice bran oil methyl ester is less when compared with injection timing as obtained through MRSN ratio and ANOVA

Table 6 shows the factor effects on measured response variables for the weighting factor of $w_1 = 0.4$, $w_2 = 0.3$ and $w_3 = 0.3$. The optimum level for each factor was the level which has the higher value when compared with other two levels. It was observed that first level of injection timing, second level of percentage EGR and third level of injection pressure has higher value when compared with other levels and hence that levels (1-2-3) were taken as the optimum level for the weighting factor of $w_1 = 0.4$, $w_2 = 0.3$ and $w_3 = 0.3$.

Table 7 shows the effect of weighting factor on the optimum combination level of factors and percentage contribution of all factors on the set objective. It was observed that weighting factor plays an important role in deciding the contribution of factors on the set objective. It was also observed that increase in weighting factor of w_1 results in increase in the percentage contribution of injection timing on the set objective. This ensures that fuel injection timing is the most influencing factor 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 contribution of

Table 7. 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	55.5	2.2	31.3
2	0.4	0.4	0.2	1	2	3	58.8	4.3	27.4
3	0.5	0.3	0.2	1	2	3	61.4	3.0	28.4
4	0.5	0.4	0.1	1	2	3	61.6	0.4	30.5
5	0.6	0.2	0.2	2	2	3	68.3	14.9	12.0
6	0.6	0.25	0.15	1	2	3	65.3	12.6	16.8
7	0.6	0.3	0.1	1	2	3	63.1	9.5	21.7
8	0.7	0.2	0.1	2	2	3	66.9	20.2	8.8
9	0.8	0.1	0.1	2	2	3	69.8	24.3	3.1

Table 8. Effect of optimization on response variables.

Normal operating conditions			Optimized conditions				% change		
NO_x (ppm)	Smoke (mg/m^3)	BTE (%)	Combination	NO_x (ppm)	Smoke (mg/m^3)	BTE (%)	NO_x (Decrease)	Smoke (Increase)	BTE (Increase)
756.6	54.6	16.51	1-2-3	650.6	60.8	17.1	14.01 (Decrease)	11.4 (Increase)	3.6 (Increase)
			2-2-3	791	50.6	17.5	4.55 (Increase)	7.3 (Decrease)	5.7578 (Increase)

EGR and injection timing decreases while for injection pressure it decreases. This trend was continued till the w_1 is 0.5 and above. If the w_1 is less than 0.5, the increase in the difference between w_2 and w_3 for the same w_1 results in the increase in the percentage contribution of EGR and injection timing and decrease in the percentage contribution of injection pressure. From the analysis it was inferred that fuel injection pressure and EGR are the influencing factors for smoke density when compared with injection timing. 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.

4.3. Confirmation Experiment

Optimum combination level obtained by Taguchi's parametric design was confirmed experimentally and the response variables of optimum combination have been compared with the response variables of the experiments conducted with the normal operating condition. **Table 8** shows the response variables at the two optimized condition and the same is compared with the variables at normal operating condition. It can be seen that brake thermal efficiency was increased as a result of this combined effect. This increase in brake thermal efficiency was due to the re-burning of unburnt hydrocarbons present in the EGR [17]. The combination 1-2-3 shows reduction in NO_x emission with increase in smoke density and brake thermal efficiency. The other optimum combination obtained by varying weighting factors was also shown in **Table 8**. It was observed that the combination 2-2-3 is the fifth trial in the L_9 orthogonal array. It was also observed that 2-2-3 combination 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. This combination reduces the NO_x by 14% with 11.4% increase in smoke density and 3.6% 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 formation. The increase in smoke emission as a result of this reduced temperature was reduced by increased fuel injection pressure.

5. Conclusions

In the present work the optimum combination of injection timing, percentage EGR and fuel injection pres sure in reducing the NO_x emission was arrived by calculating MRSN ratio. MRSN ratio was calculated by assigning different weighting factor to each response variable and the ratio was analysed by ANOVA method. From the results of the ANOVA and factor effects, the following conclusions are drawn.

1) Fuel injection timing has more percentage contribution in reducing NO_x emission of crude rice bran oil methyl ester with minimum increase in smoke density.

2) Percentage EGR has lesser effect on the set objective when compared with other two.

3) 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 less effect on smoke intensity and brake thermal efficiency.

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