Available online www.jocpr.com

Journal of Chemical and Pharmaceutical Research, 2016, 8(2):726-732

Research Article

ISSN : 0975-7384
CODEN(USA) : JCPRC5

Multi response optimization of spray characteristics of biodiesel in constant volume chamber

P. Raghu[1], R. Parthiban*[1], K. Pitchandi[1] and N. Nallusamy[2]

[1]Department of Mechanical Engineering, Sri Venkateswara College of Engineering, Sriperumbudur, India
[2]Department of Mechanical Engineering, S S N College of Engineering, OMR, Kalavakkam, India

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ABSTRACT

The main purpose of this research was to discuss about the optimization of spray characteristics of biodiesel fuel in a spray chamber. Three factors fuel injection pressure, fuel temperature and fuel blends were chosen as the influencing factor for the set objective. Three levels were chosen in each factor and spray tip penetration (S), spray angle (θ) and Sauter mean diameter (SMD) were taken as the response variables. Experiments were designed by employing Design of experiment method and Taguchi full factorial array was used to conduct the 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.

Keywords: ANOVA, Spray characteristics, Design of experiments, MRSN

INTRODUCTION

The Taguchi method helped to understand the effect of control parameter and to optimize the experimental conditions from a limited number of experiments and contribution of each noise factor calculator by ANOVA [1].Design of experiment consists of a set of experiments which is the setting of several products or process parameters to be studied that are changed from one experiment to another. Design of experiments is also called matrix experiments. Parameters are also called factors and parameter settings are also called levels. ANOVA which is a statistical technique can be employed to identify to identify the significant parameters and to find the percentage contribution of parameters on the performance characteristic [2]. ANOVA was performed by employing MINITAB software for a level of significance of 5% to study the contribution of the parameters. In the ANOVA analyse there is a P-value which is computed from the F ratio for each independent parameter in the model. If P- value is have less than 0.05,the parameter can be considered as statistically highly significant. Each one contributes with variables percentages in the production of desired response. ANOVA also helps to know the variables that are most contributing and least contributing. A parameters called F- test shows significance and insignificance of involved control variables. The parameters that have F- test value lower than four is consider as insignificant parameters and effects over desired response is meagre. Similarly, the variable that has highest F- test value is considered as most significant variables and its effect over desired response is higher. The purpose of analysis of variance (ANOVA) is to investigate the percentage contribution parameter. Statically, there is a tool called an F- test named after Fisher to check the significance of variance on the output characteristic. Usually when F>4 means the change of the design parameter had a significant effect over the output characteristic [4].The Taguchi method was applied to find an optimal setting of the fuel delivery parameters process. The result from the Taguchi method chooses an optimal solution from combinations of factors of it gives optimized combined S/N ratio of targeted outputs [5, 6].

In spray study, the inertia force and air drag force are more important factors compared to the viscous force and surface tension force [10].Droplet size and its distribution follows the vibration and breakup process [11].The effects of spray flow rate, spray height, and inlet temperature on spray cooling were investigated, and the corresponding droplet axial velocity and Sauter mean diameter (SMD) were correlated with mean absolute error of 15% [12]. As the ratio of biodiesel in the blends increased, spray tip penetration increased, but the spray cone angle decreased [13]. A reduced fuel viscosity leads to a slim spray that is characterized by a reduced spray width and an increased spray penetration [15].Spray characteristics of the fuel mainly depend on fuel injection pressure, fuel density, fuel viscosity, ambient pressure and temperature [16].The penetrating speed during the initial stage is primarily controlled by the competition between the inertia and surface tension [17].Atomization and mixing of sprays are key parameters to successfully describe and predict combustion in direct-injection engines [14].

EXPERIMENTAL SECTION

Taguchi based Design of Experiments (DOE) method was employed to design the experiments to be conducted and the steps involved are Selection of factors, Selection of number of levels for the factors Multi response optimization, analysis of results, confirmation experiment.

2.1 Selection of Factors

The fuel temperature and fuel injection pressure are the two important factors affecting the spray characteristics such as spray tip penetration (S), spray angle (θ) and Sauter mean diameter (SMD).The fuel temperature and fuel injection pressure has greater influence on spray breakup and spray atomization process. Hence fuel, fuel temperature and fuel injection pressure are selected as the factors for the present investigation.

2.2 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, fuel temperature and fuel injection pressure on spray tip penetration (S), spray angle (θ) and Sauter mean diameter (SMD), 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. For the present work, three levels were chosen for each factor to critically examine the effects of selected factors on the chosen objective. The three levels of the chosen factors are given in Table 1.

TABLE 1 Factors with chosen levels

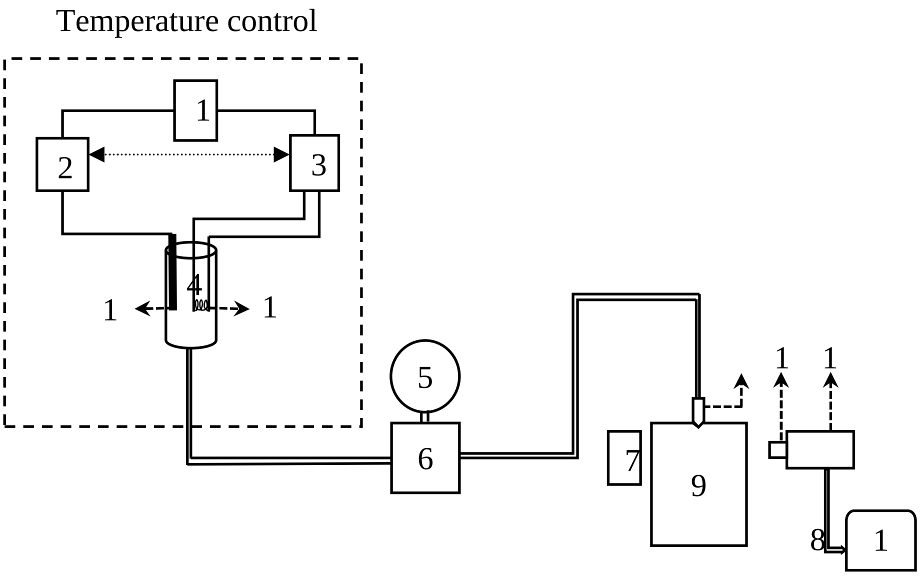
Factors	Level of factors		
	1	2	3
Fuel	KB20	KOME	COME
Fuel Injection Pressure (bar)	180	200	220
Fuel Temperature (^{o}C)	50	60	70

2.3 Design of experiment for the optimization

The Taguchi method is a structural approach for determining the best combination of inputs to produce which based on a Design of Experiments (DOE) methodology for determining parameter levels [7, 8]. In full factorial experiment for three factors with three levels the number of experiments to be conducted will be $3^3 = 27$.

2.4 Experimental setup

A schematic diagram of experimental setup shown if figure, the setup consists of a spray chamber, fuel injection system, high speed video camera and data acquisition system. In this experiment, the diesel spray was observed from a constant volume chamber along with fuel injection system and temperature control system. The fuel injection system having electric motor (0.25hp), fuel pump and fuel injector with delivery opening pressure set at 180, 200 and 220 bar. The temperature control system consist of microcontroller, relay coil, thermostat and heater. The fuel temperature is varied by the microcontroller. A high speed video camera, Fastec Motion to capture the image and it will be further processed and analysed by using (Proanalyst software). The high speed camera is fitted with boroscope to enlarge the image. The Mie scattering technique is applied with camera on one end and light source on other end. A 1000 W halogen lamp is used to illumine for clear and visible images. The region of spray has been illuminated by lamp and light scattered by fuel droplet has been collected by camera at frame rate of 250fps with resolution of (800x600) and the images are analysed by proanalyst software. The purpose of preheater setup is to maintain a pre-set temperature over an extended period of time. It consists of a microcontroller in which the required temperature is set. Microcontroller is an integrated closed circuit which receives the input from the thermostat placed in fuel tank and controls the relay coil based on the input signal. The thermostat senses the temperature of the fuel in the fuel tank and converts the temperature into an electrical signal which is fed to the microcontroller that in turn compares it with the reference temperature. If the fuel temperature is below the reference temperature, the relay coil closes the circuit and the heater remains in switched-on state. In case the fuel temperature equals or exceeds the reference temperature, the relay coil opens thereby disconnecting the heater from the preheating circuit. Thus the fuel is maintained at desired temperature for an extended period of time with the aid of this setup. The spring tension of the injector needle with setting screw was varied to get the different fuel injection pressure.



1-Power supply 2-Controller3-Heater 4-Fuel tank 5-Motor 6-Pump 7-Halogen lamp
8-Cable wire 9-Glass box 10-Camera 11-Laptop 12-Heating coil13-Thermosat14-Fuel injector15-Boroscope

Figure 1 Layout of experimental setup

2.5 Analysis of Data

Three variables (Spray tip penetration, Spray angle and Sauter mean diameter) were chosen as the responses of the problem. The responses obtained for each trial at different conditions were analysed to get a result for the formulated problem. In the analysis, average values of the responses measured at different 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 to get the desired objective is explained below.

2.5.1 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. As per the Taguchi's categorization of response variables, smaller the better principle [9] is considered to minimize the Spray tip penetration and Sauter mean diameter. For Spray angle, larger the better principle is considered to maximize it.
For larger the better [Spray angle (θ)]:

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

For smaller the better [Spray tip penetration (S)and Sauter mean diameter (SMD)]:

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

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.

2.5.2 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:

For smaller the better [Spray tip penetration (S) and Sauter mean diameter (SMD)]:

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

For larger the better [Spray angle (θ)]:

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

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

2.5.3 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 [9]. By including the weighting factor the total loss function (TL_i) can be expressedas:

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

where $w_i$is the weighting factor for the ith response variableand 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 0.6, 0.2and 0.2, the importance on second 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 increase the Spray angle with minimum Sauter mean diameter and Spray tip penetration. Hence higher weightage was assigned to the Spray angle 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 Sauter mean diameter, Spray angle and Spray tip penetration respectively. Further it was varied to study the effect of weighting factor on the set objective.

2.5.4 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.

$$MRSN = -10 \log(TL_i)$$

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.

2.6 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. 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:

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

where N is the total number of experiments, T is the sum of all experiments response variable and yi 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 SST 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 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.

RESULTS AND DISCUSSION

3.1 MRSN Ratio

Table 2 shows the MRSN ratio for the experiments conducted for the weighting factors of $w_1 = 0.6$, $w_2 = 0.2$ and $w_3 = 0.2$.From the table, the combination which has the maximum MRSN ratio will be taken as the best combination among all in achieving the objective. It can be observed that experiment number 21(3-1-3) is the best combination amongthe nine. ANOVA was employed to analyse the MRSN ratio obtained with different combinations of weighting factors.

TABLE 2 MRSN ratio for $w_1 = 0.6$, $w_2 = 0.2$ and $w_3 = 0.2$

Exp. No.	Loss function L_{ij}			NormalizationS_{ij}			Weighting$w_i s_{ij}$			TL_i	MRSN ratio
	θ	S	SMD								
1	0.0047	2352.25	132.67	0.77	0.93	0.72	0.46	0.19	0.14	0.79	1.005
2	0.0044	2284.84	123.26	0.72	0.96	0.77	0.43	0.19	0.15	0.78	1.090
3	0.0041	2196.80	116.67	0.67	1.00	0.82	0.40	0.20	0.16	0.77	1.145
4	0.0050	2489.01	119.34	0.82	0.88	0.80	0.49	0.18	0.16	0.83	0.806
5	0.0046	2327.10	110.87	0.76	0.94	0.86	0.46	0.19	0.17	0.82	0.882
6	0.0044	2274.34	104.95	0.71	0.97	0.91	0.43	0.19	0.18	0.80	0.956
7	0.0054	2609.17	108.44	0.87	0.84	0.88	0.52	0.17	0.18	0.87	0.611
8	0.0049	2489.01	100.75	0.81	0.88	0.95	0.48	0.18	0.19	0.85	0.710
9	0.0045	2330.96	95.36	0.74	0.94	1.00	0.44	0.19	0.20	0.83	0.807
10	0.0055	2724.84	155.55	0.89	0.81	0.61	0.53	0.16	0.12	0.82	0.870
11	0.0048	2601.00	143.65	0.79	0.84	0.66	0.48	0.17	0.13	0.78	1.096
12	0.0047	2518.03	135.70	0.77	0.87	0.70	0.46	0.17	0.14	0.77	1.112
13	0.0059	2833.43	139.92	0.96	0.78	0.68	0.57	0.16	0.14	0.87	0.630
14	0.0052	2745.76	129.22	0.85	0.80	0.74	0.51	0.16	0.15	0.82	0.866
15	0.0050	2620.42	122.06	0.81	0.84	0.78	0.49	0.17	0.16	0.81	0.912
16	0.0061	2988.81	127.14	1.00	0.74	0.75	0.60	0.15	0.15	0.90	0.472
17	0.0057	2899.82	117.42	0.93	0.76	0.81	0.56	0.15	0.16	0.87	0.603
18	0.0051	2748.90	110.92	0.84	0.80	0.86	0.50	0.16	0.17	0.83	0.785
19	0.0054	3156.19	151.20	0.88	0.70	0.63	0.53	0.14	0.13	0.79	1.017
20	0.0045	2994.28	138.44	0.73	0.73	0.69	0.44	0.15	0.14	0.72	1.416
21	0.0042	2784.67	128.26	0.68	0.79	0.74	0.41	0.16	0.15	0.72	1.451
22	0.0058	3278.71	136.00	0.95	0.67	0.70	0.57	0.13	0.14	0.84	0.748
23	0.0046	3132.64	124.53	0.76	0.70	0.77	0.45	0.14	0.15	0.75	1.260
24	0.0044	3005.23	115.37	0.72	0.73	0.83	0.43	0.15	0.17	0.74	1.280
25	0.0060	3470.39	123.58	0.98	0.63	0.77	0.59	0.13	0.15	0.87	0.597
26	0.0051	3223.97	113.15	0.84	0.68	0.84	0.50	0.14	0.17	0.81	0.935
27	0.0046	3038.21	104.84	0.75	0.72	0.91	0.45	0.14	0.18	0.78	1.099

Table3 shows the effects of factors on measured response variables for the weighting factor of $w_1 = 0.6$, $w_2 = 0.2$ and $w_3 = 0.2$. 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 third level of fuel, first level of fuel injection pressure and third level of fuel temperature have higher value when compared with other levels and hence the levels (3-1-3) are taken as the optimum for the assigned weighting factors of $w_1 = 0.6$, $w_2 = 0.2$ and $w_3 = 0.2$.

TABLE 3 Effects of factor on response variables for w_1 = 0.6, w_2 = 0.2 and w_3 = 0.2

Factors	Level 1	Level 2	Level 3
Fuel	0.89	0.82	1.09
Fuel pressure	1.13	0.93	0.74
Fuel temperature	0.75	0.98	1.06

Table 4shows 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_2 increases, the percentage contribution of fuel temperature on the set objective also increases which ensures the influence of fuel temperature in Spray angle enlargement.

For the assigned w_1 the percentage contribution of fuel temperature, fuel and fuel 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 (P) of fuel and fuel temperature increases while for fuel 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 fuel and fuel temperature and decrease in percentage contribution of fuel injection pressure. From the analysis it is inferred that fuel temperature is the most influencing factor for Spray angle 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_1 also increases the P value of fuel temperature which shows that fuel temperature is the most influencing factor for Spray angle. It can be seen that the change in the weighting factor shows an effect in the optimum combination if the difference between $w_2$and w_3 is 0.4 and more. For all the values $w_1$the P value of fuel temperature increases.

TABLE 4 Effect of weighting factor

Weighting factor			Optimum level of Factors			% contribution (P)		
w_1	w_2	w_3	Fuel	Fuel pressure	Fuel temperature	Fuel	Fuel pressure	Fuel temperature
0.4	0.3	0.3	3	1	2	55.52	38.52	1.72
0.4	0.4	0.2	3	1	2	77.09	15.69	2.49
0.5	0.3	0.2	3	1	2	46.29	32.53	13.79
0.5	0.4	0.1	3	1	2	65.35	11.15	15.72
0.6	0.2	0.2	3	1	3	21.39	42.55	28.03
0.6	0.25	0.15	3	1	3	28.85	31.51	30.91
0.6	0.3	0.1	3	1	3	36.66	21.13	32.99
0.7	0.2	0.1	3	1	3	21.27	26.54	43.71
0.8	0.1	0.1	3	1	3	17.64	27.9	47.4

3.2 ANOVA

Table 5 shows the results of ANOVA for the weighting factor of w_1 = 0.6, w_2= 0.2 and w_3 = 0.2. 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 and fuel temperature is the most influencing factor on the set objective since its percentage contribution is higher. It is observed that the viscosity of biodiesel is higher than that of petroleum Diesel which needs higher temperature for better fuel atomization. This results in smaller droplets, increased rate of fuel vaporization and complete combustion. As a result of this spray angle will increase and SMD and spray tip penetration will decrease.

The fuel temperature will have an effect on spray tip penetration, spray angle and Sauter mean diameter. At higher temperatures, spray angle is more with reduced spray tip penetration and Sauter mean diameter and vice versa. When compared with fuel injection pressure, fuel temperature 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.

TABLE 5 Results of ANOVA for w_1 = 0.6, w_2 = 0.2 and w_3 = 0.2.

Source	DF	SeqSS	Contribution	AdjMS	F-Value
Fuel	2	0.3588	21.39%	0.179408	26.61
Fuel pressure	2	0.7137	42.55%	0.356848	52.93
Fuel temperature	2	0.4701	28.03%	0.235063	34.87
Error	20	0.1348	8.04%	0.006742	
Total	26	1.6775	100.00%		

CONCLUSION

This work explores the prospect of developing DOE and Taguchi full factorial array and attempts to investigate the combined effect of three factors on the three variables with the experimental work. Experimental results were analysed through statistical tools and the findings of the analysis were used to make necessary decisions. Since more than one factor (fuel, fuel temperature and fuel injection pressure) were chosen in this experiment to control three response variables (spray tip penetration, spray angle and Sauter mean diameter), 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 fuel, fuel temperature and fuel injection pressure in increasing the spray angle 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 analysed through ANOVA method. From the results of ANOVA and factor effects, the following conclusions are drawn:

Fuel temperature appears to be the most influencing factor in increasing the spray angle of cotton oil methyl ester next to fuel injection pressure. Minimum fuel injection pressure and higher fuel temperature will be the optimum combination for increasing the spray angle and decreasing the spray tip penetration and Sauter mean diameter.

Acknowledgement
We thank the management of Sri Venkateswara College of Engineering and for providing us with the necessary experimental setup to perform this research work.

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