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Modeling and Optimization of Process Parameters of Bagasse-based Co-generation Power Plant to improve its Performance at Akluj Sugar Factory

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Abstract

In this research to optimize the various operating parameters for improving the overall plant efficiency (η_{plant}) and reducing the overall plant hate rate (q_{plant}) of the bagasse-based co-generation power plant by using Taguchi method. The operating parameters considered are the pressure of steam at boiler outlet (P_g) and the percentage of moisture in bagasse (w). As these variables have a major impact on the overall performance characteristics of the bagasse-based co-generation power plant, the test is conducted to study their influence and interactions on the overall performance characteristics. The experiments run as per Taguchi L9 orthogonal array and the results of overall performance for each run have been optimized in Taguchi method using MINITAB 18 computer software. To obtain the optimum process parameters optimization are performed by the Signal to Noise (S/N) ratio analysis of the Taguchi method using L9 Orthogonal Array. An analysis of variance (ANOVA) is used to provide the impact of process parameters. The results obtained by the Taguchi method and ANOVA method, those results are compared and they match closely with each other. The regression equation is formulated for calculating the predicted values of overall plant efficiency and overall plant heat rate. The results show that the selected parameters in this research have a vital impact on the selected responses and the validation results show vital improvement in the overall performance of the bagasse-based cogeneration power plant.

Keywords: Bagasse based cogeneration, Performance optimization, Taguchi Method, S/N ratio, ANOVA, Regression analysis.

I. INTRODUCTION

The most obvious problem nowadays is the reduction of non-renewable energy sources. Consequently, energy security is the main concern of today's world. Improving the performance of energy systems is an important option for the security of future energy. Every power plant losses their performance because of its continuous operation, age and several other reasons. Everything grows older as time passes. After years of operation, a plant won't be operating at best practice levels. This reduction in performance causes an increase in CO_2 emission [1]. The optimizations of co-generation systems are probably the most important subjects in the energy engineering field. The co-generation power plant of Sahakar Maharshi Shankarrao Mohite Patil Sahakari Sakhar Karkhana Limited (SMSMPSSKL) sugar factory in Akluj in Maharashtra has improved the overall performance by optimizing various parameters.

The optimization procedure was done by using Taguchi method with two parameters and three levels instead of full factorial which examines all factors [2]. Taguchi method gives the benefit into the short running experiments because of its robust orthogonal array pattern with the intention to reduce the number of the experiment and time [3]. Taguchi methods have been widely used with the aim of obtaining information about the behavior of a given process. Parameter design was determined the factors affecting performance characteristics in the cogeneration process. By selecting the correct orthogonal array (OA) based on the parameter design, the optimum condition of a process was determined [4].

II. METHODOLOGY

2.1. Selection of optimization method:

Taguchi's method is a powerful technique for the parameters optimization of a cogeneration power plant. The method involves minimizing the variation in an activity through robust design of experiments. The experimental design suggested by Taguchi method using an orthogonal array to organize the parameters affecting procedure and the levels at which they should be varied. It permits for the collection of the required data to determine which factors most affect performance with a minimum level of experimentation, thus saving time.

(A) Design of Experiment:

***1) Step 1- Selection of process parameters*:** The parameters are identified for this test such as steam pressure and percentage of moisture in bagasse which is reported to be the main parameters in the process of the bagasse-based cogeneration plant.

2) Step 2- Selection of orthogonal array**:** Based on the calculation carried out for total degrees of freedom (DOF) in case of two factors at three levels each without interaction, the best suitable orthogonal array L9 has been selected for performing experiments.

3) Step 3- Recording of responses**:** Nine experimental runs were carried out according to the Taguchi's L9 orthogonal array. The corresponding responses are collected and will be used for the analyses.

4) Step 4- Signal-to-noise ratio (S/N ratio) analysis**:** In the Taguchi's method, the signal-to-noise ratio is used to measure the quality characteristics and also to evaluate the influence of each selected factor on the responses. Taguchi method is an easy and effective solution for parameter design and experimental planning [4]. S/N ratio approach measures the performance characteristic deviating from the required value. S/N ratio is used as a target function for optimizing parameters. Control factors are simply adjustable. These factors are most significant in determining performance characteristics. Noise factors are difficult or impossible to control. The S/N ratio is the ratios of the mean (signal) to the standard deviation (noise). There are three types of S/N ratio the smaller is the better, the larger is the better, and the nominal is the better [5].

The S/N ratio with a smaller is the better characteristic that can be expressed as:

$$\text{Type 1: S/N ratio} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right] \quad (1)$$

The S/N ratio with a larger is the better characteristic can be expressed as:

$$\text{Type 2: S/N ratio} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} \frac{1}{Y_i^2}\right] \quad (2)$$

Where Y_i is the response for i^{th} treatment condition and n is the total number of tests.

5) Step 5- ANOVA analysis**:** The ANOVA is used to discuss the relative importance of all controlling factors and also to elect which controlling factor has the most significant effect. ANOVA is to investigate the input parameters and to indicate which parameters are significantly affecting the output parameters. In the analysis, the sum of squares and variance are calculated. An F-ratio value at 95 % confidence level is used to choose the vital factors affecting the process. Larger F-ratio shows that the difference of process parameters makes a big change on the overall performance [6] [7].

6) Step 6- Regression analysis**:** The regression analysis generates an equation to explain the statistical relationship between a number of predictor variables and the response variable [8].

2.2. Running of the experiments and data collection:

The Experiments was conducted as per L9 orthogonal array, assigning various values of the levels to the process parameters or control parameters (see Table.1).

Response parameters considered in this research are as follows:

- Overall plant efficiency (η_{plant}), in %
- Overall plant heat rate (q_{plant}), in kJ/kWh

The overall plant efficiency and overall plant heat rate were calculated by using the mathematical model (see Eq.15 and Eq.16) and final results are given in Table 5.

Table 1. Control parameters with their respective levels

	Control parameters	Unit	Level 1	Level 2	Level 3
A	Pressure of steam at boiler outlet (P_g)	bar	85 (A1)	108 (A2)	122 (A3)
B	Percentage of moisture in bagasse (w)	%	50 (B1)	45 (B2)	40 (B3)

Table 2. Taguchi L9 Orthogonal array for the experiment

Experiment number	Parameters Combination	
	Pressure of steam at boiler outlet (P_g)	Percentage of moisture in bagasse (w)
1	85	50
2	85	45
3	85	40
4	108	50
5	108	45
6	108	40
7	122	50
8	122	45
9	122	40

Table 3. Data collection of the cogeneration power plant while conducted nine experiments

	Experiment number									
	Unit	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Carbon in bagasse (C)	%	22.95	25.24	27.54	22.95	25.24	27.54	22.95	25.24	27.54
Hydrogen in bagasse (H_2)	%	2.84	3.12	3.41	2.84	3.12	3.41	2.84	3.12	3.41
Oxygen in bagasse (O_2)	%	21.46	23.6	25.75	21.46	23.6	25.75	21.46	23.6	25.75
Moisture in bagasse (w)	%	50	45	40	50	45	40	50	45	40
Gross calorific value of bagasse (GCV)	kJ/kg	9120	10030	10940	9120	10030	10940	9120	10030	10940
Oxygen in exhaust gas (O_2)	%	6.25	6.40	6.46	6.25	6.40	6.46	6.25	6.40	6.46
Mass flow rate of the steam (ms)	kg/s	38.89	38.89	38.89	38.89	38.89	38.89	38.89	38.89	38.89
Pressure of steam at boiler outlet (P_g)	bar	85	85	85	108	108	108	122	122	122
Temperature of steam at boiler outlet (T_g)	°C	515	515	515	540	540	540	550	550	550
Pressure of feed water (P_f)	bar	87	87	87	111	111	111	125	125	125
Temperature of feed water (T_f)	°C	170	170	170	210	210	210	240	240	240
Pressure of steam at turbine inlet (P_1)	bar	82	82	82	103	103	103	117	117	117
Temperature of steam at turbine inlet (T_1)	°C	510	510	510	535	535	535	545	545	545
Pressure of steam at turbine outlet (P_2)	bar	3	3	3	3	3	3	3	3	3
Temperature of steam at turbine outlet (T_2)	°C	135	135	135	135	135	135	135	135	135

2.3. Formalizing mathematical model of bagasse based co-generation power plant:

(A) Thermal efficiency or efficiency of the boiler by indirect method (η_{th}):

The indirect method is also known as a heat loss method. A detailed process of determining thermal efficiency or boiler efficiency through indirect method is provided below [9].

- Theoretical Air Requirement (TAR):

$$TAR = \frac{\left[(11.6\times C)+34.8\times\left(H_2-\frac{O_2}{8}\right)\right]}{100} \text{ (kg/kg of bagasse)} \quad (3)$$

Where,

C = Percentage of Carbon in bagasse [10]

H_2 = Percentage of Hydrogen in bagasse [10]

O_2 = Percentage of Oxygen in bagasse [10]

- Excess air Supplied (EA):

$$EA = \frac{O_2}{21-O_2}\times 100 \text{ (\%)} \quad (4)$$

Where,

O_2 = Percentage of Oxygen in the exhaust gas [10]

- Mass of actual air supplied (AAS):

$$AAS = \left[1+\frac{EA}{100}\right]\times TAR \text{ (kg of air/kg of bagasse)} \quad (5)$$

- Total mass of exhaust gas (m):

$$m = AAS + 1\text{kg of bagasse (kg/kg of bagasse)} \quad (6)$$

- Estimation of all losses:

(1) Heat loss in dry flue gas (L_1):

$$L_1 = \frac{m \times C_P \times (T_{exhaust\ gas} - T_a)}{GCV} \times 100 \ (\%) \quad (7)$$

Where,

m = Total mass of exhaust gas, in kg/kg of bagasse

C_P = Specific Heat of exhaust gas (0.23 kcal/kg °C) [9]

$T_{exhaust\ gas}$ = exhaust gas temperature (150°C) [11]

T_a = Ambient temperature, (31°C)

GCV = Gross Calorific Value of bagasse, in kcal/kg

(2) Heat loss due to the formation of water from H_2 in bagasse (L_2):

$$L_2 = \frac{9 \times (H_2/100) \times (584 + C_P(T_{exhaust\ gas} - T_a))}{GCV} \times 100 \ (\%) \quad (8)$$

Where,

H_2 = Percentage of Hydrogen in bagasse

C_P = Specific Heat of Superheated steam (0.45 kcal/kg °C) [9]

(3) Heat loss due to moisture in bagasse (L_3):

$$L_3 = \frac{(w/100) \times (584 + C_P(T_{exhaust\ gas} - T_a))}{GCV} \times 100 \ (\%) \quad (9)$$

Where,

w = Percentage of moisture in bagasse

C_P = Specific Heat of Superheated steam (0.45 kcal/kg °C) [9]

(4) Heat loss due to moisture in the air (L_4):

$$L_4 = \frac{AAS \times Humidity \times C_P \times (T_{exhaust\ gas} - T_a)}{GCV} \times 100 \ (\%) \quad (10)$$

Where,

AAS = mass of actual air supplied, in kg of air/kg of bagasse

Humidity = humidity of air (0.0204 kg/kg of dry air) [9]

C_P = Specific Heat of Superheated steam (0.45 kcal/kg °C) [9]

(5) Heat Loss due to radiation from the boiler to surroundings (L_5):

Radiation Loss is because of hot boiler casing losing heat to the surroundings. ABMA chart provides approx. 1% radiation losses for bagasse fired boilers. Therefore, L_5 = 1%. [12]

(6) Unburnt fuel Loss (L_6):

This is based on experience entirely. Unburnt fuel loss depends upon the type of boiler and type of fuel. Unburnt loss is generally about 2% for bagasse. Therefore, L_6 = 2%. [12]

(7) Unaccounted Losses or Manufacturer's Margin (L7):

This is for most unaccounted losses as well as for margin. Unaccounted losses are due to incomplete burning carbon to CO, heat loss in ash .etc. Unaccounted loss is generally about 1% for bagasse fired boilers. Therefore, L_7 = 1%. [12]

- Thermal efficiency or efficiency of the boiler (η_{th}): (%)

$$\eta_{th} = [100 - (L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7)] \quad (11)$$

(B) Specific fuel consumption (m_f):[9]

$$m_f = \frac{m_s \times (h_g - h_f)}{(\eta_{th}/100) \times GCV} \times 3600 \ \ (kg/hr) \quad (12)$$

Where,

m_s = mass flow rate of the steam, in kg/s

h_g = specific enthalpy of steam at boiler outlet, in kJ/kg (From steam table)

h_f = specific enthalpy of feed water, in kJ/kg (From steam table)

η_{th} = thermal efficiency or efficiency of the boiler, in %

GCV = gross calorific value of the bagasse, in kJ/kg

(C) Power output (P): [13]

$$P = [m_s \times (h_1 - h_2)] \times (\eta_{mech}/100) \times (\eta_g/100) \quad (13)$$

Where,

P = Power output, in kW

h_1 = specific enthalpy of steam at turbine inlet, in kJ/kg (From steam table)

h_2 = specific enthalpy of steam at turbine outlet, in kJ/kg (From steam table)

η_{mech} = mechanical efficiency (98%) [13]

η_g = generator efficiency (97%) [13]

(D) Electrical efficiency (η_e): [14]

$$\eta_e = \frac{P \times 3600}{m_f \times GCV} \times 100 \ (\%) \quad (14)$$

(E) Overall plant efficiency (η_{plant}): [14, 15]

$$\eta_{plant} = \eta_{th} + \eta_e$$

$$\text{Or} \quad = \frac{[(P \times 860 \times 4.19) + (m_s \times (h_g - h_f) \times 3600)]}{m_f \times GCV} \times 100 \ (\%) \quad (15)$$

(F) Overall plant heat rate (q_{plant}): [14]

$$q_{plant} = \frac{860 \times 4.19 \times 100}{\eta_{plant}} \ (kJ/kWh) \quad (16)$$

Table 4. Experimental Results for L9 Orthogonal Array

Experiment number	Pressure of steam at boiler outlet (P_g) bar	Percentage of moisture in bagasse (w) %	Overall plant efficiency (η_{plant}) %	Overall plant heat rate (q_{plant}) kJ/kWh
1	85	50	84.17	4280
2	85	45	87.44	4120
3	85	40	90.25	3992
4	108	50	86.07	4186
5	108	45	89.42	4029
6	108	40	92.29	3904
7	122	50	87.28	4128
8	122	45	90.67	3973
9	122	40	93.59	3850

III. TAGUCHI OPTIMIZATION RESULTS AND DISCUSSIONS

3.1. S/N ratio analysis:

After the collection of experimental data, the S/N ratio value for overall plant efficiency (η_{plant}) and overall plant heat rate (q_{plant}) from the original response values were obtained treatment condition wise based on performance characteristics of "larger the better" for overall plant efficiency (η_{plant}) and "smaller the better" for overall plant heat rate (q_{plant}) as shown in the Table 5. Subsequent analyses were carried out on the basis of these S/N ratio values and it is shown in Table 6.and Table 7.

From Table 5 - It is clear that the S/N ratio is higher for experiment no.9, hence the optimum value levels of control factors for higher overall plant efficiency (η_{plant}) are a pressure of steam at boiler outlet (122bar) and percentage of moisture in bagasse (40%) as well as the S/N ratio lower for experiment no.9, hence the optimum value levels of control factors for lower overall plant heat rate (q_{plant}), are a pressure of steam at boiler outlet (122bar) and percentage of moisture in bagasse (40%).

Table 5. Signal-to-Noise ratios

Experiment number	η_{plant}	q_{plant}	S/N ratio η_{plant}	S/N ratio q_{plant}
1	84.17	4280	38.5031	-72.6289
2	87.44	4120	38.8342	-72.2979
3	90.25	3992	39.1089	-72.0238
4	86.07	4186	38.6970	-72.4360
5	89.42	4029	39.0287	-72.1039
6	92.29	3904	39.3031	-71.8302
7	87.28	4128	38.8183	-72.3148
8	90.67	3973	39.1493	-71.9824
9	93.59	3850	39.4246	-71.7092

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From Table 6, it is clear that larger the 'delta' value, greater the significance of the control factor. It means for higher overall plant efficiency (η_{plant}), the most significant factor is the percentage of moisture in bagasse, followed by the pressure of steam at boiler outlet. Figure 1 shows the trend for overall plant efficiency of nine experiments.

Table 6. Average S/N ratio for overall plant efficiency

Level	Pressure of steam at boiler outlet (P_g)	Percentage of moisture in bagasse (w)
1	38.82	39.28
2	39.01	39.00
3	39.13	38.67
Delta	0.32	0.61
Rank	2	1

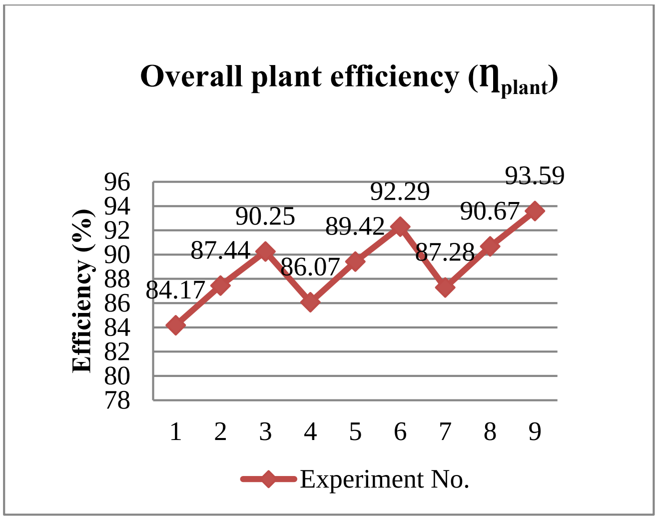

Figure 1. Overall plant efficiency of nine experiments

From Table 7, it is clear that larger the 'delta' value, greater the significance of the control factor. It means for lower overall plant heat rate (q_{plant}), the most significant factor is the percentage of moisture in bagasse, followed by the pressure of steam at boiler outlet. Figure 2 shows the trend for overall plant heat rate of nine experiments.

Table 7. Average S/N ratio for overall plant heat rate

Level	Pressure of steam at boiler outlet (P_g)	Percentage of moisture in bagasse (w)
1	-72.32	-71.85
2	-72.12	-72.13
3	-72.00	-72.46
Delta	0.31	0.61
Rank	2	1

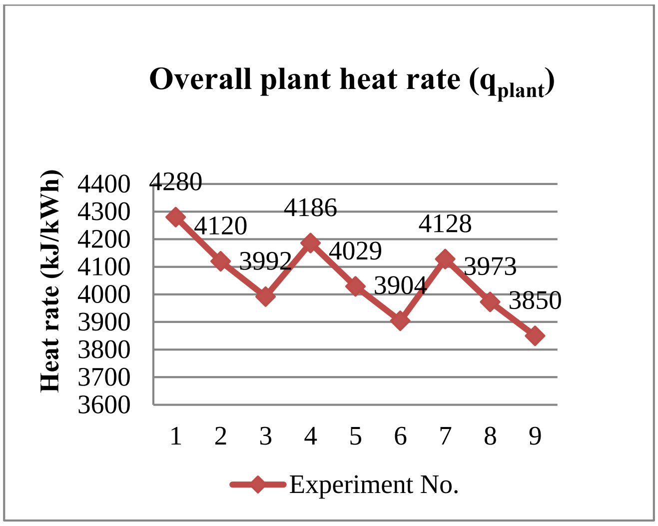

Figure 2. Overall plant heat rate of nine experiments

3.2. ANOVA analysis:

- ANOVA for Overall plant efficiency (η_{plant}):

Analysis of variance (ANOVA) is performed to obtain the percentage contribution of the factors and their significances. From the ANOVA studied for the effect of factors on overall plant efficiency (η_{plant}) as indicated in Table 8, it was observed that the percentage of moisture in bagasse (F-ratio=8588.98) and pressure of steam at boiler outlet (F-ratio=2357.86) in this order, are the most significant control factors affecting the overall plant efficiency (η_{plant}). It means, the percentage of moisture in bagasse is the most significant factor and the pressure of steam at boiler outlet has less influence on the overall plant efficiency.

Table 8. ANOVA for overall plant efficiency

Source	Sum of square	DOF	Mean square	F-ratio	Contribution (%)	Rank
Pressure of steam at boiler outlet	15.8763	2	7.9381	2357.86	21.54%	2
Percentage of moisture in bagasse	57.8325	2	28.9162	8588.98	78.45%	1
Error	0.0135	4	0.0034		0.02%	
Total	73.7222	8			100.00%	

- ANOVA for Overall plant heat rate (q_{plant}):

From the ANOVA studied for the effect of factors on overall plant heat rate (q_{plant}) as indicated in Table 9, it was observed that the percentage of moisture in bagasse (F-ratio=9502.32) and pressure of steam at boiler outlet (F-ratio=2607.32) in this order, are the most significant control factors affecting the overall plant heat rate (q_{plant}). It means, the percentage of moisture in bagasse is the most significant factor and the pressure of steam at boiler outlet has less influence on the overall plant heat rate.

Table 9. ANOVA for overall plant heat rate

Source	Sum of square	DOF	Mean square	F-ratio	Contribution (%)	Rank
Pressure of steam at boiler outlet	33026	2	16513.0	2607.32	21.53%	2
Percentage of moisture in bagasse	120363	2	60181.3	9502.32	78.46%	1
Error	25	4	6.3		0.02%	
Total	153414	8			100.00%	

3.3. Regression analysis:

Regression analysis is used for explaining the relationship between the response or output variable and input or independent variables. The mathematical model for process parameters such as the pressure of steam at boiler outlet (P_g) and percentage of moisture in bagasse (w) is obtained from regression analysis using MINITAB 18 statistical software to predict the overall plant efficiency (η_{plant}) and overall plant heat rate (q_{plant}). Table 10 shows the regression analysis model of overall plant efficiency (η_{plant}) and Table 11 shows the regression analysis model of overall plant heat rate (q_{plant}).

- Regression analysis for overall plant efficiency (η_{plant}):

Table 10. Regression analysis model for overall plant efficiency

Predictor	Coef	SE Coef	T-Value	P-Value
Constant	107.793	0.630	171.22	0.000
Pressure of steam at boiler outlet	0.08707	0.00317	27.50	0.000
Percentage of moisture in bagasse	-0.6203	0.0118	-52.43	0.000

The regression equation for overall plant efficiency (η_{plant}):

$$Y = 107.793 + 0.08707 \times A - 0.6203 \times B \qquad (17)$$

Where,

Y = Response i.e. Overall plant efficiency (η_{plant}), in %

A = Pressure of steam at boiler outlet, in bar

B = Percentage of moisture in bagasse

If we put optimum parameters (A3B3) which are drawn by S/N ratio, in equation (17), it will give the optimum value of performance characteristic which will be the maximum overall plant efficiency (η_{plant}).

$$Y_{opt} = 107.793 + 0.08707 \times A - 0.6203 \times B$$

$$Y_{opt} = 107.793 + 0.08707 \times 122 - 0.6203 \times 40$$

Y_{opt} = 93.60 % (η_{plant} predicted by regression equation)

- Regression analysis for overall plant heat rate (q_{plant}):

Table 11. Regression analysis model for overall plant heat rate

Predictor	Coef	SE Coef	T-Value	P-Value
Constant	3196.3	41.1	77.72	0.000
Pressure of steam at boiler outlet	-3.971	0.207	-19.20	0.000
Percentage of moisture in bagasse	28.267	0.773	36.57	0.000

The regression equation for the overall plant heat rate (q_{plant}):

$$Y = 3196.3 - 3.971 \times A + 28.267 \times B \qquad (18)$$

Where,

Y = Response i.e. overall plant heat rate (q_{plant}), in kJ/kWh

A = Pressure of steam at boiler outlet, in bar

B = Percentage of moisture in bagasse

If we put optimum parameters (A3B3) which are drawn by S/N ratio, in equation (18), it will give the optimum value of performance characteristic which will be the minimum overall plant heat rate (q_{plant}).

$$Y_{opt} = 3196.3 - 3.971 \times A + 28.267 \times B$$

$$Y_{opt} = 3196.3 - 3.971 \times 122 + 28.267 \times 40$$

Y_{opt} = 3843 kJ/kWh (q_{plant} predicted by regression equation)

CONCLUSION

- The overall plant efficiency (η_{plant}) increased by 9.42% with an increase 37bar pressure of steam at boiler outlet and a decrease 10% of moisture in bagasse.
- The overall plant heat rate (q_{plant}) decreased by 430kJ/kWh with an increase 37bar pressure of steam at boiler outlet and a decrease 10% of moisture in bagasse.
- The optimum condition for overall plant efficiency (η_{plant}) and overall plant heat rate (q_{plant}) was obtained as A3B3 i.e., the pressure of steam at boiler outlet at 122bar and percentage of moisture in bagasse at 40%.
- The optimum overall plant efficiency (η_{plant}) and overall plant heat rate (q_{plant}) value calculated by Regression equation closely matches with the actual overall plant efficiency (η_{plant}) and overall plant heat rate (q_{plant}) value obtained by Trial No. 9 of Taguchi method.

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