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Thermodynamic Modeling and Optimization of a Coal Fired Thermal Power Plant using Cycle Tempo, Taguchi and ANOVA

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Abstract

In the present study, exergy efficiency of a 250MW coal fired thermal power plant under various operating conditions have been evaluated by using Cycle Tempo 5. Taguchi design method is applied to optimize the operating conditions for maximization of exergy efficiency by using three factors namely main steam pressure, condenser pressure and reheat temperature. The operating conditions are planned with three levels of each of selected three factors as the orthogonal array of L9. Signal-to-noise (S/N) ratio analysis and analysis of variance (ANOVA) are carried out to investigate the effects of individual parameters.

Findings of the study indicates that condenser pressure is having most dominant effect on plant exergy efficiency with a contribution of 78.81% followed by main steam pressure with 13.05%. Finally the correctness of analysis is tested and verified.

Keywords: Exergy efficiency, signal-to-noise(S/N) ratio, orthogonal array, Taguchi, Analysis of Variance (ANOVA).

1.Introduction

In India, power generation capacity has grown from 42584.72MW at the end of 6th plan to 329204.53MW at the end of 12th plan. Coal has been the major fossil fuel used in power plants, with annual consumption of 530.4MT for power generation during the year 2014-15 [1]. A slight improvement in efficiency of coal-fired boiler will just not conserve the huge quantiy of coal but also help to control CO_2 emission. In an attempt to quantify the losses and identify its different sources in the plant, authors have carried out the research work earlier [2-5] and concluded that the quantity wise energy loss in boiler may not be the matter of great concern but, it is when quality degradation is considered as the boiler energy efficiency was found to be around 87% and exergy efficiency just around 46% only. Further, the loss through flue gases was identified as the biggest source of energy losses by quantity while heat exchanger section as the major exergy destruction area. Thermal power

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plant technology has been evolved over years and has now reached the stage where marginal improvement in its efficiency is a difficult task.

Exergy analysis is an effective tool in the design and analysis of energy systems as it is useful for quantifying and locating the amount of energy losses and quality degradation both [6-8]. Concept of energy and exergy analysis has been used by the several authors [9-11] for performance assessment of energy conversion systems like boiler and power plants. A. Acir et al. [12] investigated the effects of variation of dead state temperatures on the energy and exergy efficienccies in a thermal power plant. S. Mitra and S. Sarkar [13] determined the individual influence of ambient temperature, condenser pressure and steam temperature on exergy efficiency of a thermal power plant by using Taguchi S/N ratio and ANOVA. They found steam temperature as the most dominant factor and next to it was ambient temperature. E. Baysal et al. [14], and S. Mitra and S. Sarkar [15] investigated the exergy efficiencies of a thermal power plant under various operating conditions. Three factors namely ambient temperature, condenser pressure and steam temperature with 3 levels of each are considered for planning operating conditions. S/N ratio analysis and analysis of variance (ANOVA) and regression analysis were carried out to determine the effects of individual parameters. Ambient temperature was having the most dominant effect. Finally, confirmation tests verified that the Taguchi design is successful in optimizing operating conditions. M. Jamil et al. [16] used the Taguchi method to obtain the optimal level of the parameters involved in the cost function. Meng-Hui Wang et al. [17] applies an Extension Taguchi method on the optimized allocation of equipment capacity for power generation with several sources. M. Gupta and Raj Kumar [18] using second law of thermodynamics analyze the effect of inlet steam temperature on thermo economic and exergetic performance, and unit product cost of turbine and optimizes the value of inlet steam temperature. Many authors [19-22] used the Taguchi method to optimize the process parameters of turning and facing operations. S. Xiao et al. [23] applies computational fluid dynamics (CFD), Taguchi and ANOVA technique to optimize combustion and emissions in a diesel engine.

This study is carried out with the main objective of optimization of exergy efficiency of a coal fired 250MW thermal power plant at Korba, Chhattisgarh, India. Effects of main steam pressure, condenser pressure and reheat temperature are considered in the analysis. Various operating conditions are planned and investigated by using the Taguchi design method. Signal-to-noise ratio analysis is used for the investigation of optimum operating conditions, and percent contributions of different factors are determined by analysis of variance (ANOVA). Finally the confirmation tests are also performed. Shrinivas T. [24] optimized the combined cycle system at a gas inlet temperature of 1400°C with the modern gas turbine blade cooling system. After validation of simulated model of the present double pressure reheat heat recovery steam generator model they compared the exergetic losses in combined cycle system with the plant and published data. Arunkumar et al. [25] use Taguchi method for optimizing the parameters of 210MW steam turbine operation and found the maximum turbine efficiency as 41.7%.

2. Plant Description and Exergy Analysis

Plant details in form of its schematic layout and thermodynamic properties at various points are already described in author's earlier research paper [2]. Schematic layout of boiler and its operating parameters are given in author's other papers [3-4].and not repeated here.

The concept, use and method of exergy analysis had also been discussed in author's earlier papers [4-5].

3. Methodology

The various steps involved in this work are as follows:

A. Application of Taguchi method: Taguchi method is a statistical method of experimental design developed by Prof. G. Taguchi. This method provides a simple, efficient and systematic approach for experimental design optimization of process parameters. A powerful tool of designing system parameters in engineering analysis involves the following steps [26-29]:

(1) Identification of objective or response variable or output quality characeteristics to be optimized (in the present case exergy efficiency of the thermal power plant).
(2) Identification of the process parameters or control factors (in the present case main steam pressure, condenser pressure and reheat temperature) that may influence the objective or response variable.
(3) Identification of levels of control factors of their possible interactions.
(4) Selection of appropriate orthogonal array (OA) and assigning the factors at their levels to the OA.
(5) Conducting the test as described in the trials of the OA.
(6) Analyzing the experimental results using the signal-to-noise ratio (S/N) and statistical analysis of variance (ANOVA)
(7) Determine the set of optimal design parameters.
(8) Verify the results i.e. the optimal design parameters.

The control factors and each parameters level used in the investigation are given in Table 1. The design layout for the operating parameters using L_9 orthogonal array is shown in Table 2.

Table 1: Assignment of the levels to the factors

Symbol	Parameters	Levels		
		1	2	3
MSP	Main Steam Pressure(bar)	135	145	155
CP	Condenser Pressure (bar)	0.08	0.10	0.12
RHT	Reheat Temperature (^{0}C)	520	540	560

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Table 2: Control factors experimental set-up for L_9 orthogonal array

Trial No.	MSP	CP	RHT
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

B. Signal-to-Noise ratio (S/N) Analysis: The signal-to-noise (S/N) are the log functions of desired output and represents the amount of variation present in the quality characteristic. Taguchi method, unlike the commonly used standard methods, considers both the standard deviation and mean of trial results to determine the effect and subsequently optimum condition. Generally, there are three forms of S/N ratios i.e. the lower-the better (LB), the higher-the- better (HB) and the nominal-the-better (NB). In the present investigation to obtain the optimal operational condition, the maximum exergy efficiency in power plant is desired. Therefore, the HB quality characteristics of exergy efficiency are selected which means the optimal level of the process parameter is the level with the highest S/N ratio [26-27].

The HB quality characteristics can be expressed as: $\eta(S/N) = -10\log_{10}\left(\frac{1}{n}\times\frac{1}{y_i^2}\right)$

where $\eta(S/N)$ is the S/N ratio (dB) for higher-the-better case and y_i represents the actual exergy efficiency (η_{II}) determined from cycle tempo simulation model with different sets of parameters as designed under the Taguchi experiment and n is the number of repetitions in a trial [26-27]. The calculation results of exergy efficiencies [30] and corresponding S/N ratios are given in Table 3.

Table 3: Exergy results and S/N ratios for various operating conditions in power plant

Trial	MSP	CP	RHT	η_{II} (%)	S/N ratio(dB)
1	135	0.08	520	36.239	31.184
2	135	0.10	540	35.859	31.092
3	135	0.12	560	35.423	30.986
4	145	0.08	540	36.710	31.296
5	145	0.10	560	36.308	31.200

6	145	0.12	520	35.301	30.956
7	155	0.08	560	37.144	31.398
8	155	0.10	520	36.159	31.164
9	155	0.12	540	35.707	31.055

C. Analysis of Variance (ANOVA): The Taguchi method alone cannot determine the effect of individual parameters on performance of entire system, but it is possible with ANOVA. The ANOVA is a statistical method [31], which is used to know the extent of influence of different control factors on the response variable and it is employed to investigate that which design parameters significantly affect the quality characteristics [26-27]. This analysis is carried out with 5% confidence level.
MINITAB software is used to carry out the ANOVA calculation and the results are shown in Table 4. The result shows that the condenser pressure is the most dominating factor with the percent contribution of 78.81% followed by main steam pressure with 13.05% contribution.

Table 4: Result of ANOVA for exergy efficiency

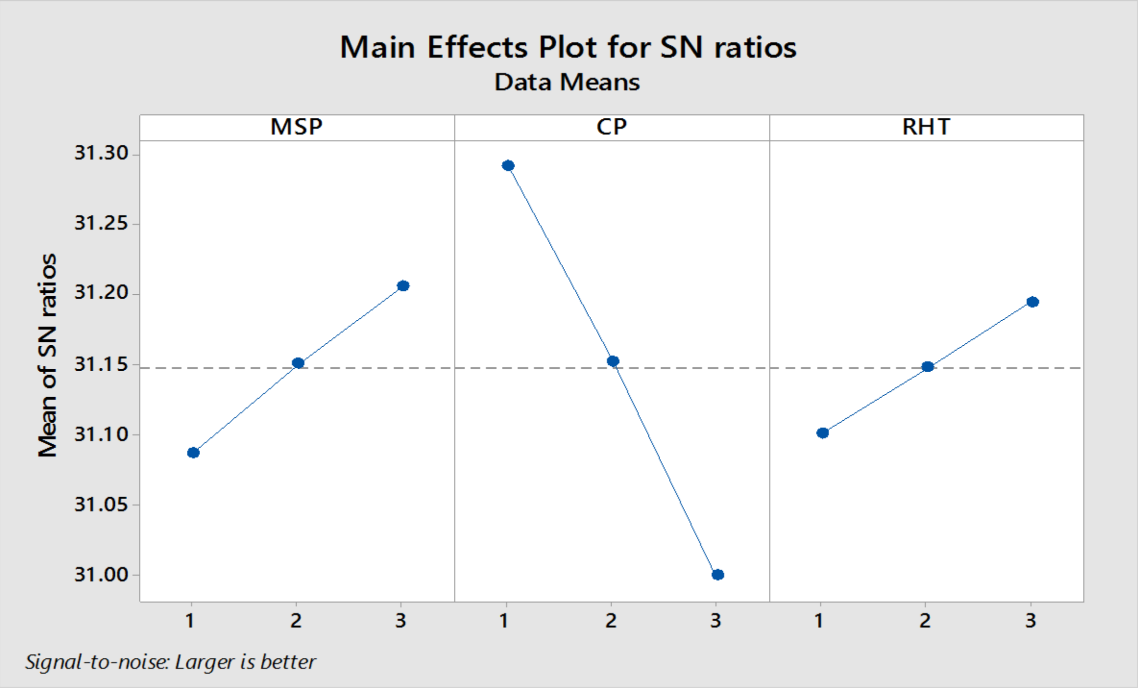
Source	DoF	Adj SS	Adj MS	F-Value	P-Value	% contribution
MSP	2	0.37016	0.18508	814.92	0.001	13.05%
CP	2	2.23595	1.11798	4922.59	0	78.81%
RHT	2	0.23052	0.11526	507.51	0.002	8.13%
Error	2	0.00045	0.00023			0.02%
Total	8	2.83708				

D. Determination of Optimal Factor Levels: The mean response and the mean S/N ratio for the MSP, CP and the RHT are as shown in Fig 1. The optimum condition corresponds to parameter levels are shown as the peak point in Fig 1. The values are given in Table 5 based on the S/N ratio. In addition, the optimal combination of levels for the criteria of the highest response and highest S/N ratio are determined as A3B1C3 for the exergy efficiencies as presented in Table 6. In other words, the optimum operation conditions for the best exergy efficiencies and system performance in power plant are main steam pressure at level 3, the condenser pressure at level 1 and the reheat steam temperature at level 3.

Table 5: Response Table for mean S/N ratio

Level	MSP	CP	RHT	Overall Mean S/N Ratio
1	31.090	31.290	31.100	31.147
2	31.150	31.150	31.150	
3	31.210	31.000	31.190	
Delta	0.120	0.290	0.090	
Rank	2	1	3	

Figure 1: Mean S/N ratio *vs* process parameter



E. Confirmation test: Once the optimum level of process parameters are decided, the final step is to predict and verify the improvement in performance in terms of the response variable by using the optimum level of process parameters. The predicted S/N ratio can be determined by [32]:

$$\eta_{predicted} = \eta_m + \sum_{i=1}^{o} (\eta_i - \eta_m)$$

Where η_m is the total mean of the S/N ratio, η_I is the mean S/N ratio at the optimum level, and o is the number of parameters considered. Improvement in the S/N ratio is as shown in Table 6.

Table 6: Result of confirmation test for exergy efficiency

Levels	**Starting process parameters**	**Optimal process parameters**	
		Prediction	**Actual**
	A1B2C2	A3B1C3	A3B1C3
Exergy efficiency, %	35.859	37.129	37.144
S/N ratio	31.092	31.394	31.398
Improvement of S/N ratio	0.306		
Prediction error	0.004		

F. Validity checking of the whole analysis: (a) From Table 6 it is clear that a higher F-value has larger effect (in terms of % contribution) on response variable i.e., exergy efficiency. Hence the analysis and thereby, contributing effect of control factors are justified by F-test.

(b) 'Hypothesis' tests:

Our Null Hypothesis (H_0): Control factors are not significant in respect of response factor i.e., exergy efficiency.

Alternative Hypothesis (H_A): Control factors are significant in respect to response factor. The decision rule for accepting the null hypothesis or rejecting is that:

At a α level of confidence, reject H_0 if $P > \alpha$, and do not reject H_0 if $P < \alpha$

Where, for a 95 % confidence level, $\alpha = 1 - 0.95 = 0.05$.

In the present work, from Table 4, it is observed that p-values of all three parameters are less than 0.05 i.e. these factors are realy very significant in respect of exergy efficiency but the degree of their influence is different.

Conclusion

In this present investigation:

- Using Taguchi S/N ratio and ANOVA the individual influence of control factors on response factor (here exergy efficiency) of a thermal power plant, is determined. It is found that the condenser pressure is having most dominant effect on plant exergy efficiency with a contribution of 78.81%, followed by main steam pressure with 13.05%.
- The optimum operating conditions in terms of specific levels of the control variables for the best exergy efficiency of a thermal power plant are identified. For example, in present analysis main steam pressure at level 3, the condenser pressure at level 1 and the reheat steam temperature at level 3
- The ANOVA calculations are carried out considering 95% confidence level and confirmation test varifies the optimum level of process factors selected and finally the validity of the whole analysis and results are verified by F-statistics values and 'hypothesis test'.

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