RESEARCH ARTICLE OPEN ACCESS

Application of Exergy and Taguchi Methodology for a Power Plant under Varying Operating Conditions

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Abstract
In this study, exergy efficiencies of a thermal power plant under different operating conditions have been investigated. Taguchi method is applied using three factors, namely, ambient temperature, condenser pressure and steam temperature with three levels of each. The operating conditions are planned and are set following orthogonal array of L_9 and regression analysis is carried out in order to determine the effects of process parameters on exergy efficiency for the power plant. The correlation between exergy efficiencies and operating parameters are obtained by a 2nd order polynomial regression analysis and compared with the actual results and found to be quite correct having average error is about 1% only.

***Keywords**:* Exergy, Thermal power plant, Ambient temperature, Condenser pressure, Steam temperature, Taguchi, Orthogonal array, Regression analysis

I. INTRODUCTION

Improvement of the energy efficiency in any energy consuming process is a key aim of economy considering energy conservation, energy security, pollution potentials and cost involvement aspects. This trend will continue to increase in future. Considering this exergy analysis has become a very important tool to effectively analyze energy related systems such as thermal power plants [1-8]. Exergy is defined as the maximum useful work that can be obtained from a system. The exergy analysis method is based on the second law of thermodynamics. It deals with the performance of supplied energy and various losses associated during process operation both qualitatively and quantitatively. Therefore the exergy analysis gives more insight into the problem and help design and analysis of energy systems more effectively. We can get the location, type and true magnitude of exergy loss or 'quality destruction of energy' in a system performance. On the other hand, energy analysis, based on the first law, deals only with quantitative assessment of the various losses occurring in any process operation like in a thermal power plant.

Thermal power plants are responsible for the production of most electric power in the world, and even small increases in efficiency can mean large savings of fuel requirement and help mitigate atmospheric pollution in a large extent. Therefore, every effort is made to improve the efficiency of the cycle on which thermal power plants operate. Basically efficiency of a power plant depends on many factors like final steam temperature and pressure, ambient temperature, final flue gas temperature, condenser vacuum etc. The main purposes of present investigation is to study a 160 MW coal-fired steam power plant , all operating data for which are taken from [6,7], and determination of exergy efficiency for various relevant values of ambient temperature, condenser pressure and steam temperature to find out the individual effects of these parameters on the plant exergy efficiency. To study the individual and combined effects of these important parameters on exergy efficiency, a 2nd order polynomial equation has been developed following Taguchi orthogonal methodology and regression analysis. Some investigators like [7] followed Taguchi analysis, but the development of 2nd order polynomial equation following L_9 orthogonal array is uncommon.

II. SYSTEM DESCRIPTION

In this present study a 160 MW coal based steam power plant and its relevant data are considered for analysis as mentioned earlier. Fig. 1 depicts the line diagram of the considered plant. Temperature and pressure for different locations are given in Table 1 corresponding to Fig. 1.

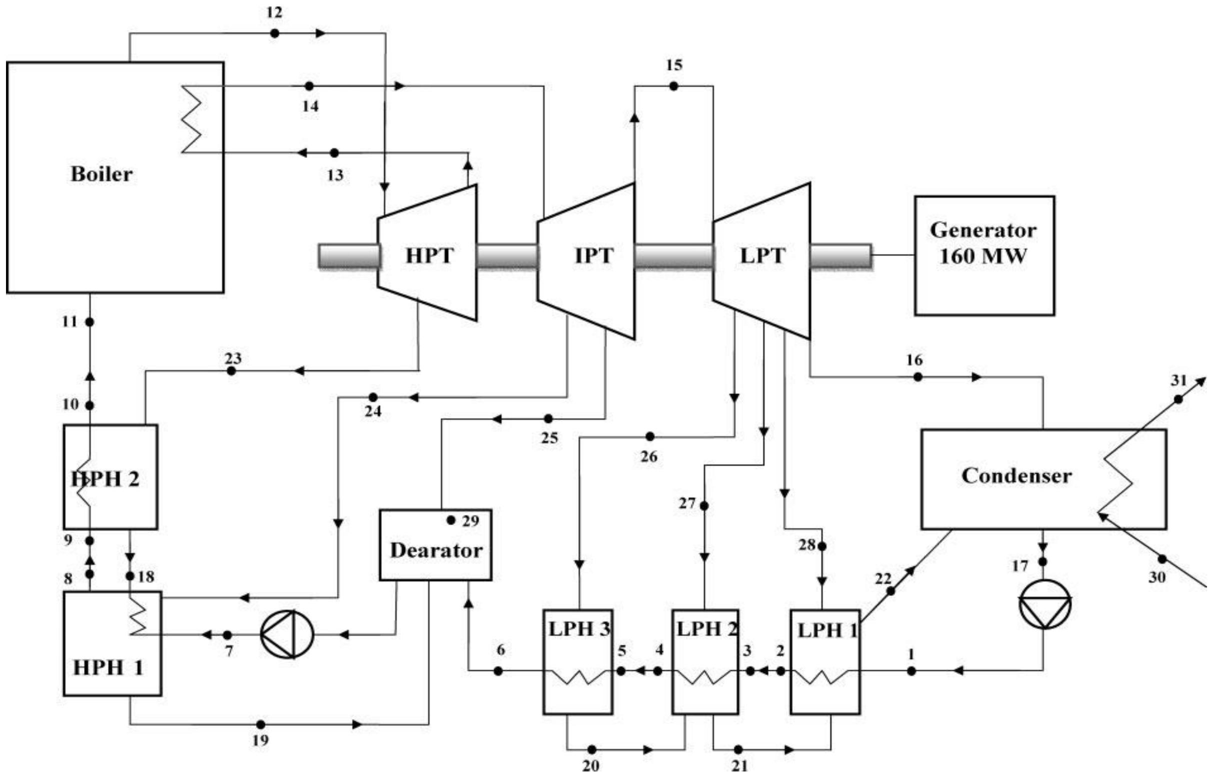

Fig. 1: Schematic diagram of power plant

The plant uses coal with an average calories of ~13 000 kJ kg^{-1} as fuel. The main components of the system are boiler, high pressure turbine (HPT), intermediate pressure turbine (IPT), low pressure turbine (LPT), three low pressure feed water heaters (LPH), two high pressure feed water heaters (HPH), condenser, pumps and a dearator. The energy released by combustion of coal is transferred to the water in the boiler. Normal steam temperature of the plant is 538^0C and pressure is 13.7 MPa, The total mass flow rate of the steam is 477 003 kg h^{-1} at the inlet of the HPT. The mass flow rate of coal to boiler is 3000 ton/day. The volumetric flow rate of air to boiler and the combustion products from boiler are 400 000 m^3 h^{-1} and 600 000 m^3 h^{-1} respectively. The power plant is described in more detail in [6, 7] and not described here. The important process data for the unit is summarized in Table 1.

III. ENERGY AND EXERGY ANALYSIS

In this present investigation Energy and Exergy analyses are carried out first. Exergy is a combined property and depends both on the state of the system and the environment. A system that is in complete equilibrium with its surroundings has zero exergy and is said to be at the dead state. The temperature and pressure of the environment i.e. at the dead state are denoted by T_0 and P_0. In this study, normal dead (reference) state values used for T_0 and P_0 are considered as 298.15 K and 101.325 kPa respectively.

General balance equations for a control volume at steady state process are given below:

The mass balance equation

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (1)$$

where $\dot{m}$ is the mass flow rate.

The energy balance equation

$$\sum_{in} \dot{E}_{in} + \dot{Q} = \sum_{out} \dot{E}_{out} + \dot{W} \quad (2)$$

The entropy balance equation

$$\sum_{in} \dot{S} + \sum_{in} \frac{\dot{Q}}{T} + \dot{S}_{gen} = \sum_{out} \dot{S} + \sum_{out} \frac{\dot{Q}}{T} \quad (3)$$

The exergy balance equation of the control volume in a general form can be defined by

$$\sum_{in} \dot{Ex}_{in} + \sum \dot{Ex}_{Q} = \sum_{out} \dot{Ex}_{out} + \dot{W} + \dot{Ex}_{d} \quad (4)$$

where $\dot{Ex}_Q$ and $\dot{Ex}_d$ are exergy transfer with $\dot{Q}$ and exergy destruction (irreversibility $\dot{I} = \dot{Ex}_d = T_0\dot{S}_{gen}$) respectively.

The exergy by heat

$$\dot{Ex}_Q = \sum (1 - \frac{T_0}{T})\dot{Q} \quad (5)$$

where T_0 is the dead (reference) state temperature varying between 5^0C and 30^0C, and $\dot{Q}$ is the output heat transfer rate in the system. The potential and kinetic energies in the system are neglected in our calculations.

Total exergy flow rate $\dot{Ex}$ in the exergy balance equation of the control volume is written as

$$\dot{Ex} = \dot{m}(ex) \tag{6}$$

The energy flow rate equation is given by

$$\dot{E} = \dot{m} \times h \tag{7}$$

where *ex* is the specific exergy. The specific exergy is given by

$$ex = (h - h_0) - T_0(s - s_0) \tag{8}$$

where h and s present the specific enthalpy and entropy respectively.

The thermal efficiency (energy efficiency) of the power plants can be calculated as follows

$$\eta_I = \frac{\dot{W}_{net}}{\dot{E}_{fuel}} \tag{9}$$

where $\dot{W}_{net}$ and $\dot{E}_{fuel}$ are the net work output and exergy input rate (LHV$\dot{m}_{fuel}$) from and to the power plant respectively.

The exergy efficiency of the power plants can be computed as

$$\eta_{II} = \frac{\dot{W}_{net}}{\dot{Ex}_{fuel}} \tag{10}$$

The exergy input rate can be described by

$$\dot{Ex}_{fuel} = LHV\dot{m}_{fuel}\,\dot{\varepsilon}_{fuel} \tag{11}$$

where $\dot{m}_{fuel}$ is the mass rate of fuel consumption, and $\dot{\varepsilon}_{fuel}$ is the exergy factor based on the LHV. $\dot{\varepsilon}_{fuel}$ is given as 1.06 [1,8].

IV. RESULT OF ENERGY AND EXERGY ANALYSIS

In this study, the energy and exergy analysis of the coal fired steam power plant, whose schematic diagram is given in Fig. 1, is performed. Table 1 shows thermodynamic properties of the cycle at different nodes given in Fig. 1. The energy and exergy analysis of different components can be obtained using these data. Enthalpy and entropy values are taken from [9]. The T_0 and P_0 values for the reference environment considered in the analysis are taken as 25^{0}C and 101.325 kPa respectively. The energy and exergy flow rates and specific exergy values for different nodes are also given side-by-side of the property values in Table 1.

Table 1: Energy and exergy analysis of power plant when T_0 = 298.15 K and P_0 = 101.325 kPa

Point	Temperature T/^{0}C	Pressure P/MPa	Mass flow rate m/ton h^{-1}	Enthalpy h/kJ kg^{-1}	Entropy s/kJ kg^{-1} K^{-1}	Specific exergy ex/ kJ kg^{-1}	Energy flow rate $\dot{E}$/kW	Exergy flow rate $\dot{Ex}$/kW
1	41.6	1.4	395.099	174.250	0.594	1.799	19123.89	197.46
2	72.3	1.4	395.099	302.600	0.983	14.169	33210.27	1555.03
3	72.8	1.4	395.099	304.700	0.989	14.480	33440.74	1589.18
4	100.1	1.4	395.099	419.460	1.308	34.130	46035.62	3745.77
5	100.1	1.4	395.099	419.460	1.308	34.130	46035.62	3745.77
6	134.5	1.4	395.099	565.240	1.682	68.402	62034.93	7507.10
7	167	18.300	477.003	710.100	1.992	120.835	94088.84	16010.81
8	194	18.300	477.003	825.510	2.274	152.167	109380.76	20162.28
9	190	18.300	477.003	807.620	2.236	145.607	107010.32	19293.04
10	234	18.300	477.003	1008.900	2.647	224.347	133680.09	29726.20
11	230	16.900	477.003	990.200	2.610	216.679	131202.33	28710.12
12	538	13.720	477.003	3428.430	6.535	1484.670	454269.83	196720.02
13	363	3.870	433.246	3128.230	6.652	1149.586	376470.32	138348.27
14	538	3.700	433.246	3535.350	7.236	1382.587	425465.62	166388.96
15	306	0.720	395.099	3071.110	7.310	896.284	337053.47	98366.90
16	41.6	0.06	335.023	2373.200	7.707	80.008	220854.61	7445.73
17	39	0.039	395.099	163.380	0.559	1.364	17930.91	149.75
18	208	4.707	43.757	890.400	2.410	176.509	10822.56	2145.42
19	172.3	1.863	62.727	729.320	2.065	118.291	12707.79	2061.12
20	105.1	0.343	23.336	440.560	1.364	38.534	2855.81	249.78
21	77.8	0.149	41.122	325.650	1.049	17.541	3719.83	200.37
22	45	0.06	60.076	188.450	0.634	4.073	3144.81	67.97
23	380	4.707	43.757	3150.390	6.601	1186.952	38292.12	14427.07
24	440	1.863	18.970	3337.550	7.284	1170.476	17587.03	6167.76
25	310	0.640	19.174	3081.440	7.379	886.042	16412.09	4719.16
26	245	0.343	23.336	2955.860	7.437	733.169	19160.54	4817.39
27	155	0.149	17.786	2782.700	7.472	559.574	13748.08	2764.60
28	100	0.039	18.954	2683.880	7.902	332.549	14130.63	1750.87
29	163	0.666	…..	687.420	1.983	100.840	…..	…..
30	22	0.200	10000	92.320	0.325	0.072	256444.44	198.78
31	34	0.200	10000	142.500	0.492	0.461	395833.33	1279.19

V. APPLICATION OF TAGUCHI METHOD

Taguchi methods [10-12] of experimental design provide a simple, efficient and systematic approach to test the sensitivity or, relative influence of a set of response variables by a set of control factors/parameters or, independent factors by considering experiments in 'Orthogonal Array' with an aim to attain the optimum setting of the control parameters. Taguchi design method, extensively used in engineering analyses, is a powerful tool to design system parameters. In line with Taguchi method, the steps followed in this present paper are:

1) Identification of the 'Objective or, Response Variable' (here, in our case Exergy efficiency) for the analysis
2) Identification of the 'Process factors or, Control Factors' (here, in our case ambient temperature, condenser pressure and steam temperature) that may influence the 'Objective or, Response Variable'.
3) Determination of Control Factor's 'Levels' (i.e., nature of variations or, different values) and their possible interactions with 'Response Variable'.
4) Selection of appropriate orthogonal array (OA) and assign the factors at their levels to the OA
5) Conduct the test described in the trials of the OA.
6) Development of 2nd order polynomial regression equation in terms of response variable (exergy efficiency) and process or control factors.
7) Verification of the developed equation with actual results.

The control factors and each parameter level used in the present investigation are given as shown in Table 2. Three factors are selected as the main operation condition parameters and it is considered as ambient temperatures, condenser pressures and steam temperatures. The design layout for the operation condition parameters using L_9 orthogonal array is shown in Table 3.

Table 2: Assignment of the levels to the factors

Symbol	Parameters	Levels		
		1	2	3
AT	Ambient Temperature (^{0}C)	10	20	30
CP	Condenser Pressure (MPa)	0.05	0.10	0.20
ST	Steam Temperature (^{0}C)	520	540	560

Table 3: Control factors for L_9 orthogonal array

Trial No.	AT	CP	ST
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

VI. REGRESSION ANALYSIS

By means of regression analysis, the relationship between exergy efficiency and operation conditions in evaluating the performance of power plant is obtained. For regression analysis, we need to develop some models which are known as regression models. Regression models are the mathematical estimation equations with response variable as a function of process parameters. These models are developed statistically by utilizing the information of the measured response variable and the corresponding design matrix. Considering the 'n' number of independent process parameters, a generalized regression model can be represented as

$$y = \beta_0 + \sum_{j=1}^{n} \beta_j x_j + \sum_{j=1}^{n} \beta_{jj} \left(x_j\right)^2 + \sum_{i=1}^{n}\sum_{j=1}^{n} \beta_{ij} x_i x_j + \varepsilon \qquad (12)$$

where y is a response variable, x_i and x_j refer to independent variables, β refer to the regression coefficients and ε is the error term.

The estimated second order response surface model is represented as

$$y = \beta_0 + \sum_{j=1}^{n} \beta_j x_j + \sum_{j=1}^{n} \beta_{jj} \left(x_j\right)^2 + \sum_{i=1}^{n}\sum_{j=1}^{n} \beta_{ij} x_i x_j \qquad (13)$$

Or,

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 \quad (14)$$

Replacing by the real problem variables in the above equation, the final regression equation becomes

$$\eta_{II} = \beta_0 + \beta_1(AT) + \beta_2(CP) + \beta_3(ST) + \beta_{11}(AT) \times (AT) + \beta_{22}(CP) \times (CP) + \beta_{33}(ST) \times (ST) + \beta_{12}(AT) \times (CP) + \beta_{13}(AT) \times (ST) + \beta_{23}(CP) \times (ST) \quad (15)$$

In this problem there are 3 independent variables and each variable has 3 levels and hence from the Taguchi Orthogonal Array (OA) table L_9 OA is best selected.

Experiments have been carried out using Taguchi's L_9 Orthogonal array experimental design which consists of 9 combinations of Ambient Temperature (AT), Condenser Pressure (CP) and Steam Temperature (ST). It considers three process parameters to be varied at three discrete levels. The experimental design has been shown in above table. Using the values of three variables in the polynomial regression equation (15) we get the following equations according to the Taguchi L_9 orthogonal array table.

$$\eta_{II} = \beta_0 + 10\beta_1 + 0.05\beta_2 + 520\beta_3 + 100\beta_{11} + 0.0025\beta_{22} + 270400\beta_{33} + 0.5\beta_{12} + 5200\beta_{13} + 26\beta_{23}$$
$$\eta_{II} = \beta_0 + 10\beta_1 + 0.1\beta_2 + 540\beta_3 + 100\beta_{11} + 0.01\beta_{22} + 291600\beta_{33} + 1\beta_{12} + 5400\beta_{13} + 52\beta_{23}$$
$$\eta_{II} = \beta_0 + 10\beta_1 + 0.2\beta_2 + 560\beta_3 + 100\beta_{11} + 0.04\beta_{22} + 313600\beta_{33} + 2\beta_{12} + 5600\beta_{13} + 112\beta_{23}$$
$$\eta_{II} = \beta_0 + 20\beta_1 + 0.05\beta_2 + 540\beta_3 + 400\beta_{11} + 0.0025\beta_{22} + 291600\beta_{33} + 1\beta_{12} + 10800\beta_{13} + 27\beta_{23}$$
$$\eta_{II} = \beta_0 + 20\beta_1 + 0.1\beta_2 + 560\beta_3 + 400\beta_{11} + 0.01\beta_{22} + 313600\beta_{33} + 2\beta_{12} + 11200\beta_{13} + 56\beta_{23}$$
$$\eta_{II} = \beta_0 + 20\beta_1 + 0.2\beta_2 + 520\beta_3 + 400\beta_{11} + 0.04\beta_{22} + 270400\beta_{33} + 4\beta_{12} + 10400\beta_{13} + 104\beta_{23}$$
$$\eta_{II} = \beta_0 + 30\beta_1 + 0.05\beta_2 + 560\beta_3 + 900\beta_{11} + 0.0025\beta_{22} + 313600\beta_{33} + 1.5\beta_{12} + 16800\beta_{13} + 28\beta_{23}$$
$$\eta_{II} = \beta_0 + 30\beta_1 + 0.1\beta_2 + 520\beta_3 + 900\beta_{11} + 0.01\beta_{22} + 270400\beta_{33} + 3\beta_{12} + 15600\beta_{13} + 52\beta_{23}$$
$$\eta_{II} = \beta_0 + 30\beta_1 + 0.2\beta_2 + 540\beta_3 + 900\beta_{11} + 0.04\beta_{22} + 291600\beta_{33} + 6\beta_{12} + 16200\beta_{13} + 108\beta_{23}$$

By solving the above equations we can get the values of the coefficients i.e. β and then we can develop the required 2nd order polynomial regression equation or, the Predicted Equation with those values.

VII. RESULT AND DISCUSSIONS OF REGRESSION ANALYSIS

Values of Coefficients for the Predicted Equation are determined by solving above equations by MATLAB and are as follows:

$\beta_0 = -12.5441$, $\beta_1 = -0.5682$, $\beta_2 = -58.1056$, $\beta_3 = 0.2464$, $\beta_{11} = -0.0013$, $\beta_{22} = -37.0077$, $\beta_{33} = -0.0003$, $\beta_{12} = -0.2772$, $\beta_{13} = 0.0013$, $\beta_{23} = 0.1384$

Now, Predicted equation from regression analysis for exergy efficiency becomes:

$$\eta_{II} = -12.5441 - 0.5682(AT) - 58.1056(CP) + 0.2464(ST) - 0.0013(AT)^2 - 37.0077(CP)^2 - 0.0003(ST)^2 - 0.2772(AT)\times(CP) + 0.0013(AT)\times(ST) + 0.1384(CP)\times(ST) \quad (16)$$

The results obtained by the Predicted equation are given in Table 4 side-by-side with actual values.

Table 4: Results showing the Actual and Predicted exergy efficiency (η_{II})

Trial No.	AT	CP	ST	η_{II}, %	
				Actual	Predicted
1	10	0.05	520	36.1708	35.8739
2	10	0.1	540	35.5749	35.2557
3	10	0.2	560	35.0163	34.6729
4	20	0.05	540	36.0189	35.6497
5	20	0.1	560	35.4458	35.0513
6	20	0.2	520	36.6319	36.2833
7	30	0.05	560	35.8858	35.4455
8	30	0.1	520	37.1015	36.7125
9	30	0.2	540	36.4754	36.0585

where AT is Ambient Temperature (^{0}C), CP is Condenser Pressure (MPa) and ST is Steam Temperature (^{0}C).

VIII. GRAPHICAL REPRESENTATION

The individual effect of ambient temperature and steam temperature on exergy efficiency are depicted in Fig. 2(a) and Fig. 2(b). In Fig. 2(a) steam temperature and condenser pressure are kept constant at 540^{0}C and 0.1 MPa. In Fig. 2(b) ambient temperature and condenser pressure are kept constant at 20^{0}C and 0.1 MPa.

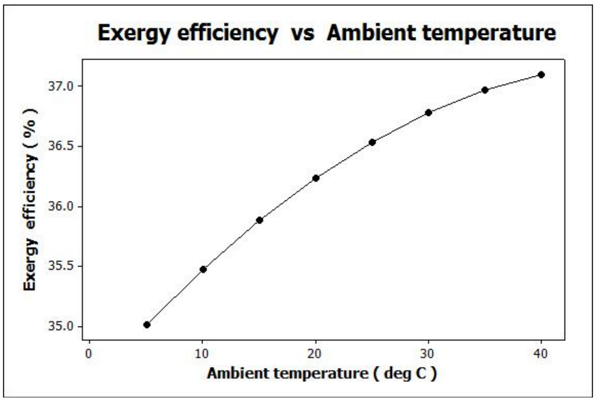

Fig. 2(a): Influence of Exergy efficiency on Ambient temperature

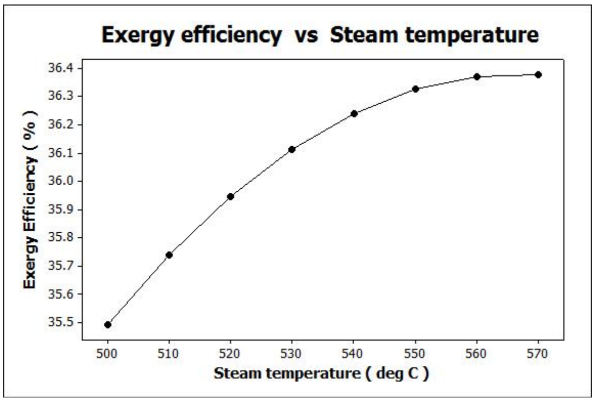

Fig. 2(b): Influence of Exergy efficiency on Steam temperature

IX. CONFIRMATION TEST

The actual exergy efficiency values are compared with the predicted values by the regression Eqn. (16) developed in the present study and given in Table 5. The % errors are noted for different conditions and it is observed that the average error is about 1 % only.

Table 5: Operation conditions and comparative results for confirmation test

Trial No.	Ambient Temperature (^{0}C)	Condenser Pressure (MPa)	Steam Temperature (^{0}C)	Actual result	Result as per developed model	Error %
1	10	0.05	520	36.1708	35.8739	0.8208
2	10	0.1	540	35.5749	35.2557	0.8973
3	10	0.2	560	35.0163	34.6729	0.9807
4	20	0.05	540	36.0189	35.6497	1.0250
5	20	0.1	560	35.4458	35.0513	1.1129
6	20	0.2	520	36.6319	36.2833	0.9516
7	30	0.05	560	35.8858	35.4455	1.2269
8	30	0.1	520	37.1015	36.7125	1.0485
9	30	0.2	540	36.4754	36.0585	1.1429
Average % error						1.0229

X. CONCLUSION

In this present study:

- The effects of some important parameters, viz. ambient temperature, condenser pressure and steam temperature, on exergy efficiency of a thermal power plant are investigated by applying L_9 Orthogonal Array of Taguchi methodology.
- A 2nd order polynomial equation is developed for predicting the exergy efficiency under different operating and this type of equation for prediction of exergy efficiency is really uncommon in the literature.
- The predicted equation is compared with the actual results and found to be quite correct having average error is about 1 % only.

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