Performance Analysis of Thermal Power Plant Under Various Operating Conditions: A Case Study

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Abstract **– This research work has been done for a coal fired thermal power plant. For evaluation of performance of the power plant, power outputs and heat rates have been calculated. These evaluations have been performed on selected operating parameters. Then combined effects of operating parameters on the performance of the power plant have been analyzed. Power outputs and heat rates have been found for all possible conditions. After analyses, optimum conditions have been identified at with power output is highest or heat rate is lowest. These case studies can be concluded as, for selected operating parameters, maximum power output is 121334.6 kW and minimum heat rate is 2.309. These outputs have been achieved with five feed water heaters, no makeup water addition, lowest back pressure and less pressure drop in extraction line.**

Keywords – Power output, heat rate, power plant, flow function, correction factor.

I. INTRODUCTION

These case studies have been performed on coal fired thermal power plant. And for these studies, various operating parameters have been chosen from power plant. Parameters are steam pressures, steam temperatures, back pressures of steam, extraction line pressure drops for high pressure feed water heater (heater number 6), makeup water addition in deaerator and number of feed water heaters. A power plant works on all these parameters and these parameters can be varied according to the conditions. For example if coal quality/quantity varies then generated steam pressure and temperature can also vary. Back pressure of steam can also vary due to leakages in condenser. If friction factor is considered then extracted steam pressure decreases in pipeline. From the joints, small amount of steam or water leaks from the plant so that leakage amount must be added in the deaerator as makeup water which is an open type heat exchanger. And as per the requirement or maintenance work, feed water heater bypasses thus number of feed water heaters can also be varied. Power output and heat rate have been calculated in this work so both are explained as; power output can also be called as generated electrical power from power plant. This power output has been evaluated by considering mechanical losses between turbine shaft/generator shaft and generator efficiency [1]. And heat rate can be defined as the ratio of heat addition in boiler to the power output from the plant [1]. Schematic diagram of thermal power plant is as shown in figure 1 [2]. Brief description of working of power plant is as – inlet water comes from high pressure feed water heater after feed water heating process. This feed water enters into the high pressure boiler with the help of feed pump where water is converted into high pressure and temperature steam. This is done by constant pressure heat addition process in the boiler and then steam enters into the high pressure, intermediate pressure and then low pressure steam turbines respectively. Steam expands in steam turbines and then low pressure/low temperature steam enters into condenser where that steam is converted into saturated water by constant pressure heat rejection process. To exchange heat or to change phase of steam, cooling water is circulated in the condenser. This cooling water comes from cooling tower and a pump is used to circulate cooling water. Some amount of steam is extracted from high pressure, intermediate pressure and low pressure steam turbines for feed water heating process. After exchanging heat in feed water heater, extracted steam enters into the previous feed water heaters as shown in figure 1. Thus more heat energy of the extracted steam is utilized to increase temperature of feed water. These heat transfer processes are completed in high pressure, intermediate pressure and low pressure feed water heaters. And finally heated water is pumped into the boiler. Due to some leakages, makeup water is added in the deaerator from river/pond [3-8].

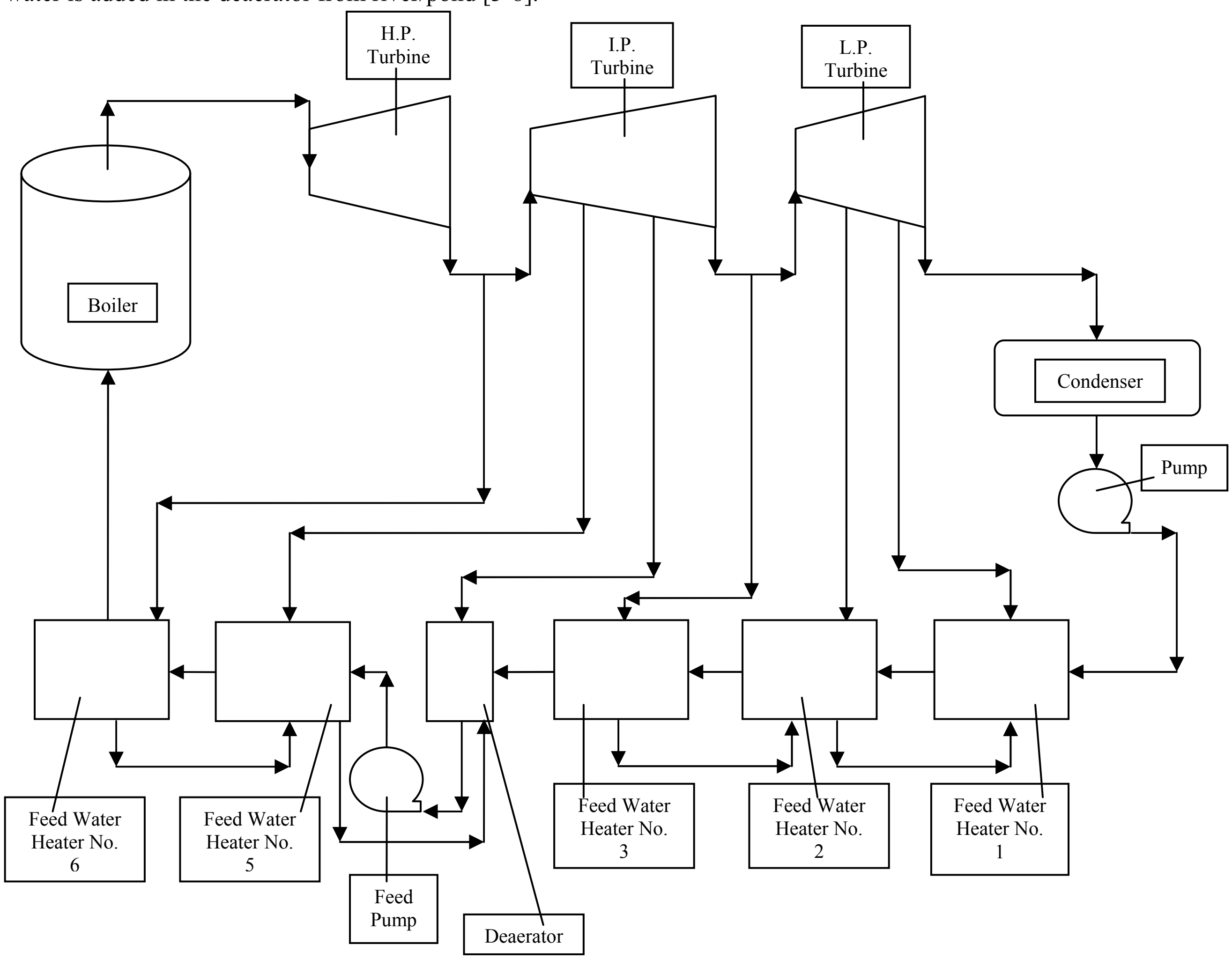

Figure 1 – Coal fired thermal power plant

In the previous years, several research works were done by me on 120MW coal fired thermal power plant. For each case study, different operating parameters were taken for analyses. First study was done with constant inlet pressure (124.61 bar) and different inlet temperatures conditions. After thermodynamic analysis, work was concluded as best performance of the power plant can be achieved at 124.61 bar pressure and 507.78°C temperature. At these operating conditions, plant gives maximum power output [3]. For second study, fix inlet pressure (127.06 bar) and different condenser back pressures were taken as operating parameters. After analysis, case study was concluded as maximum power is achieved at 127.06 bar pressure and 0.068 condenser pressure [4]. In third study, correction curves were generated for extraction line pressure drop for power and heat rate. These curves can be used to optimize thermal power plant [5]. In the next work, computer software was developed to generate correction factor curves at various inlet temperature conditions [6]. Thermodynamic analysis was done for power plant at various conditions of extraction line pressure drops for feed water heater 5. Power outputs and heat rates were calculated at different conditions with software. This work was concluded as highest power is found at lowest extraction line pressure drop [7]. Then finally, combined effect of different extraction line pressure drops (from six feed water heaters) on the performance of coal fired thermal power plant was analysed. This analysis was concluded as maximum power and minimum heat rate are achieved at 2%, 3%, 4%, 5%, 6% and 7% pressure drops from heater 1, 2, 3, 4, 5 and 6 respectively [8]. In this research paper following operating parameters are taken for analysis – (a) steam pressure, (b) steam temperature, (c) back pressure of steam, (d) extraction line pressure drops for high pressure feed water heater, (e) makeup water addition in deaerator and (f) number of feed water heaters. Combined effects of all these parameters on power output and heat rate are evaluated.

II. METHODOLOGY

In these case studies following mathematical equations have been used. Equation 1 shows relationship between flow function, mass flow rate of steam generated in boiler, steam pressure and specific volume. This equation has been used to find value of flow function for designed condition. And then with the help of flow function, mass flow rates of steam have been calculated at various operating conditions [2].

$$FF = W/\sqrt{(P/V)} \tag{1}$$

Here FF is flow function, W is mass flow rate of steam in kg/sec, P is steam pressure in bar and V is specific volume of steam in m^3/kg. By equation 2, actual mass flow rate of steam for high pressure turbine has been calculated. In this calculation, leakages have also been considered.

$$W_1 = (W' - L_1 - L_2 - L_3 - L_4) \tag{2}$$

Here W_1 is mass flow rate of steam which enters into high pressure steam turbine in kg/sec, L_1, L_2, L_3 and L_4 are leakage quantities. All these quantities have been taken from power plant [2-8].

$$W_2 = (W_1 + L_1 - L_5 - L_6 - Ex_1) \tag{3}$$

Equation 3 has been used to calculate mass flow rate of steam which enters into intermediate pressure turbine. Here W_2 is mass flow rate of steam enters into intermediate pressure turbine in kg/sec, Ex_1 is steam extraction quantity after expansion in high pressure steam turbine in kg/sec and leakage quantities have been taken from power plant; leakages quantities are – L_5 and L_6. Similarly equation 4 and equation 5 have been used to evaluate mass flow rates of steam for intermediate pressure turbine. Here W_3 and W_4 are flow rates of steam after extraction from IP turbine in kg/sec, Ex_2 and Ex_3 are steam extraction quantities from IP turbine in kg/sec [2-8].

$$W_3 = (W_2 - Ex_2 - L_7 - L_8) \tag{4}$$

$$W_4 = (W_3 - Ex_3) \tag{5}$$

Then finally equation 6, equation 7 and equation 8 have been used to evaluate mass flow rates of steam for low pressure turbine at different stages. Here W_5, W_6 and W_7 are mass flow rates of steam at different stages in LP turbine in kg/sec, Ex_4, Ex_5 and Ex_6 are steam extraction quantities of steam from LP turbine for feed water heating process in kg/sec [2-8].

$$W_5 = (W_4 - Ex_4) \tag{6}$$

$$W_6 = (W_5 - Ex_5 - L_9) \tag{7}$$

$$W_7 = (W_6 - Ex_6) \tag{8}$$

Equation 9 and equation 10 have been used to calculate power output from power plant. Equation 9 shows relation between mass flow rates of steam at various stages of steam turbines and enthalpy drops. By considering losses and efficiency, power output has been calculated with equation 10. Enthalpy drop in high pressure turbine has been calculated with h_1 and h_2, enthalpy drops in intermediate pressure turbine have been calculated with h_3, h_4, h_5, and h_6, and enthalpy drops have been calculated with h_6, h_7, h_8 and h_9. So power is,

$$\mho = \{W_1 (h_1 - h_2)\} + \{[W_2 (h_3 - h_4)] + [W_3 (h_4 - h_5)] + [W_4 (h_5 - h_6)]\} + \{[W_5 (h_6 - h_7)] + [W_6 (h_7 - h_8)] + [W_7 (h_8 - h_9)]\} \tag{9}$$

$$\mho_{net} = (\mho - £)\, \eta \tag{10}$$

Here h_1 and h_2 are enthalpies of steam at inlet and outlet from high pressure steam turbine in kJ/kg, h_3, h_4, h_5 and h_6 are enthalpies of steam at inlet, at 2nd extraction, at 3rd extraction and at outlet from intermediate pressure steam turbine respectively in kJ/kg, h_7, h_8 and h_9 are enthalpies of steam at 5th extraction, at 6th extraction and at outlet from low pressure steam turbine respectively in kJ/kg. £ is mechanical losses in kW, η is generator efficiency in % and $\mho_{net}$ is net power output from power plant.

$$\epsilon_{net} = (Q_1 + Q_2)/ \mho_{net} \tag{11}$$

From equation 11 heat rate of the plant has been calculated. Here Q_1 and Q_2 are amounts of heat transfer in boiler in kJ/sec and ϵ_{net} is heat rate which is unit less quantity. Finally from equations 12 and 13, correction factors for power and heat rate have been calculated respectively. Here CFP and CFHR are correction factors for power and heat rate, correction factor is also a unit less quantity.

$$CFP = \mho_{designed} / \mho_{net} \tag{12}$$

$$CFHR = \epsilon_{designed} / \epsilon_{net} \tag{13}$$

These case studies have been completed with different steam pressure conditions, different steam temperature conditions, different back pressures of steam for condenser, different percentages of pressure drops in extraction line, different amounts of makeup water addition in deaerator and various number of feed water heaters. Following steam pressure conditions have been selected; conditions are 122.16, 123.14, 124.12, 125.10, 126.08, 127.06 and 128.04 in bar. Following steam temperature conditions have been selected; conditions are 780.78, 790.78, 800.78, 810.78, 820.78, 830.78 and 840.78 in Kelvin. Following back pressures have been selected; conditions are 0.068, 0.088, 0.1015, 0.107, 0.127 and 0.142 in bar. Following percentages of pressure drop conditions have been selected; conditions are 2, 3, 4, 5, 6, 7 and 8 in percentage. Following percentages of makeup water addition have been selected; conditions are 0, 1, 2, 3 and 4 in percentage. And five, six and seven feed water heaters have been selected [3-8].

With all these conditions, calculated outputs are as follows. For different pressure conditions, 117231kW, 117977kW, 119017kW, 120000kW, 120825kW, 121585kW and 122671kW power outputs have been found respectively and 2.41 heat rate have been found for all conditions. For different temperature conditions, 120822kW, 120580kW, 120355kW, 120000kW, 119505kW, 119276kW and 119042kW power outputs have been calculated respectively and 2.376, 2.390, 2.404, 2.413, 2.433, 2.446 and 2.460 heat rates have been calculated respectively. For different back pressures, 122752kW, 120913kW, 120000kW, 119273kW, 117881kW and 116652kW power outputs have been found respectively and 2.359, 2.395, 2.413, 2.428, 2.457 and 2.483 heat rates have been found respectively. For different extraction line pressure drops (high pressure feed water heater; heater number 6), 119422kW, 119538kW, 119.657kW, 120000kW, 120010kW, 120016kW and 120138kW power outputs have been found respectively and 2.424, 2.422, 2.420, 2.413, 2.416, 2.414 and 2.412 heat rates have been found respectively. For different percentages of makeup water addition in deaerator, 120000kW, 119579kW, 119361kW, 119192kW and 118996kW power outputs have been found respectively and 2.413, 2.422, 2.426, 2.429 and 2.433 heat rates have been found respectively. For various numbers of feed water heaters, 121047kW, 120000kW and 116598kW power outputs have been found respectively and 2.393, 2.413 and 2.407 heat rates have been found respectively. And with the help of individual outputs (power/heat rate), combined effects on the power plant have been analyzed.

III. RESULTS

In this research work, the performance of power plant has been evaluated with all selected operating parameters. To analyze the performance of the plant, power outputs have been calculated at various operating conditions and then heat rates have also been calculated at same operating conditions. Results have been tabulated in table 1 and in table 2.

TABLE 1 – POWER OUTPUTS AND CORRECTION FACTORS WITH VARIOUS OPERATING PARAMETERS

Sr. No.		**Operating Conditions**	**1**	**2**	**3**	**4**	**5**	**6**
1	**Operating Conditions**	**Steam Pressure (bar)**	122.16	126.08	123.14	127.06	124.12	128.04
2		**Steam Temperature (K)**	780.78	820.78	790.78	830.78	800.78	840.78
3		**Back Pressure (bar)**	0.068	0.107	0.088	0.127	0.1015	0.142
4		**Extraction Line Pressure Drop (%)**	2	6	3	7	4	8
5		**Makeup Water Addition (%)**	0	3	1	4	2	4

6		**Number of Feed Water Heaters**	5	5	6	6	7	7
Power Output (kW)			121334.6	119880.1	118460.0	117762.5	115052.7	114176.9
Correction Factor			0.989	1.001	1.013	1.019	1.043	1.051

TABLE 2 – HEAT RATES AND CORRECTION FACTORS WITH VARIOUS OPERATING PARAMETERS

Sr. No.		**Operating Conditions**	**1**	**2**	**3**	**4**	**5**	**6**
1	**Operating Conditions**	**Steam Pressure (bar)**	122.16	124.12	123.14	126.08	127.06	128.04
2		**Steam Temperature (K)**	780.78	800.78	790.78	820.78	830.78	840.78
3		**Back Pressure (bar)**	0.068	0.1015	0.088	0.107	0.127	0.142
4		**Extraction Line Pressure Drop (%)**	2	4	3	6	7	8
5		**Makeup Water Addition (%)**	0	2	1	3	4	4
6		**Number of Feed Water Heaters**	5	7	6	5	6	7
Heat Rate			2.309	2.322	2.347	2.457	2.516	2.548
Correction Factor			1.045	1.039	1.028	0.982	0.959	0.947

Now after findings of correction factors for power outputs and heat rates, correction curves have been generated. Figure 2 shows power outputs at various operating conditions of power plant. In this figure x-axis shows various operating conditions and y-axis shows power outputs in kW. And figure 3 shows correction curve for power output. In this figure x-axis shows various operating conditions and y-axis shows correction factors for power. Similarly Figure 4 shows heat rates at various operating conditions of plant. In this figure x-axis shows various operating conditions and y-axis shows heat rates at that conditions. And figure 5 shows correction curve for heat rate. In this figure x-axis shows various operating conditions and y-axis shows correction factors for heat rate. From these curves plant optimum conditions have been found.

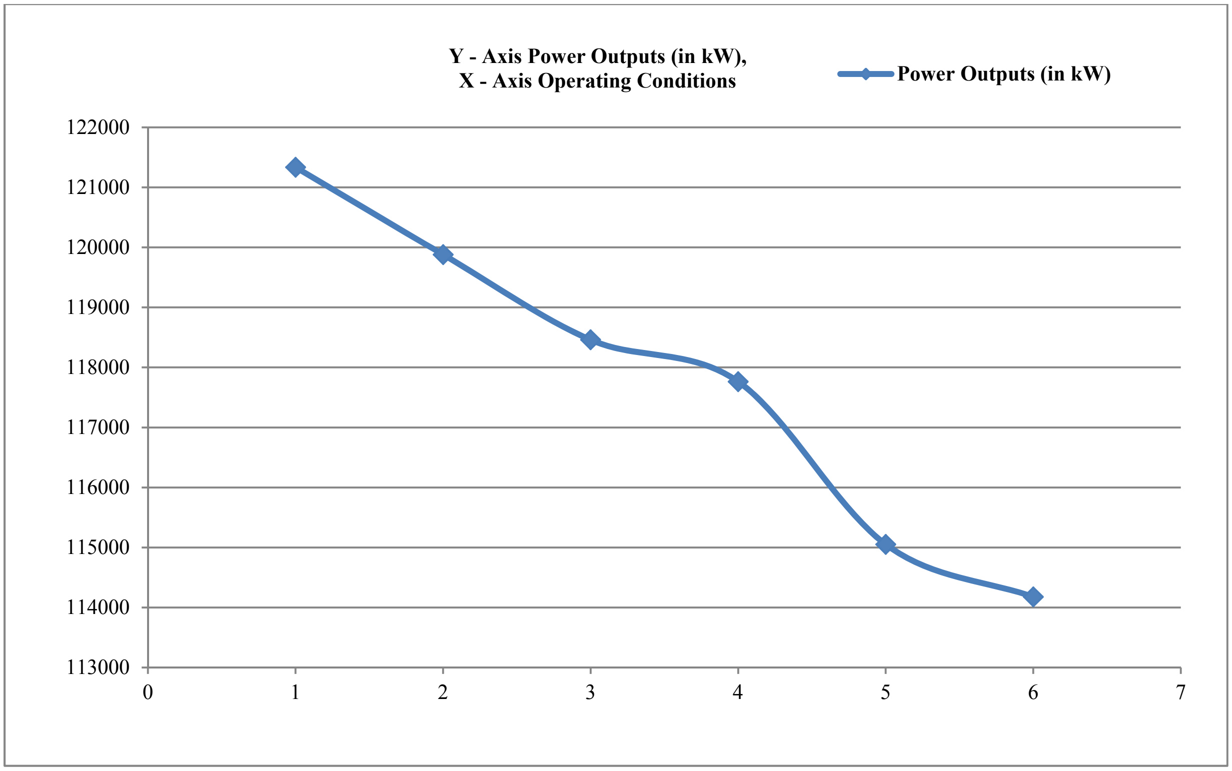

Figure 2 – Power outputs at various operating conditions

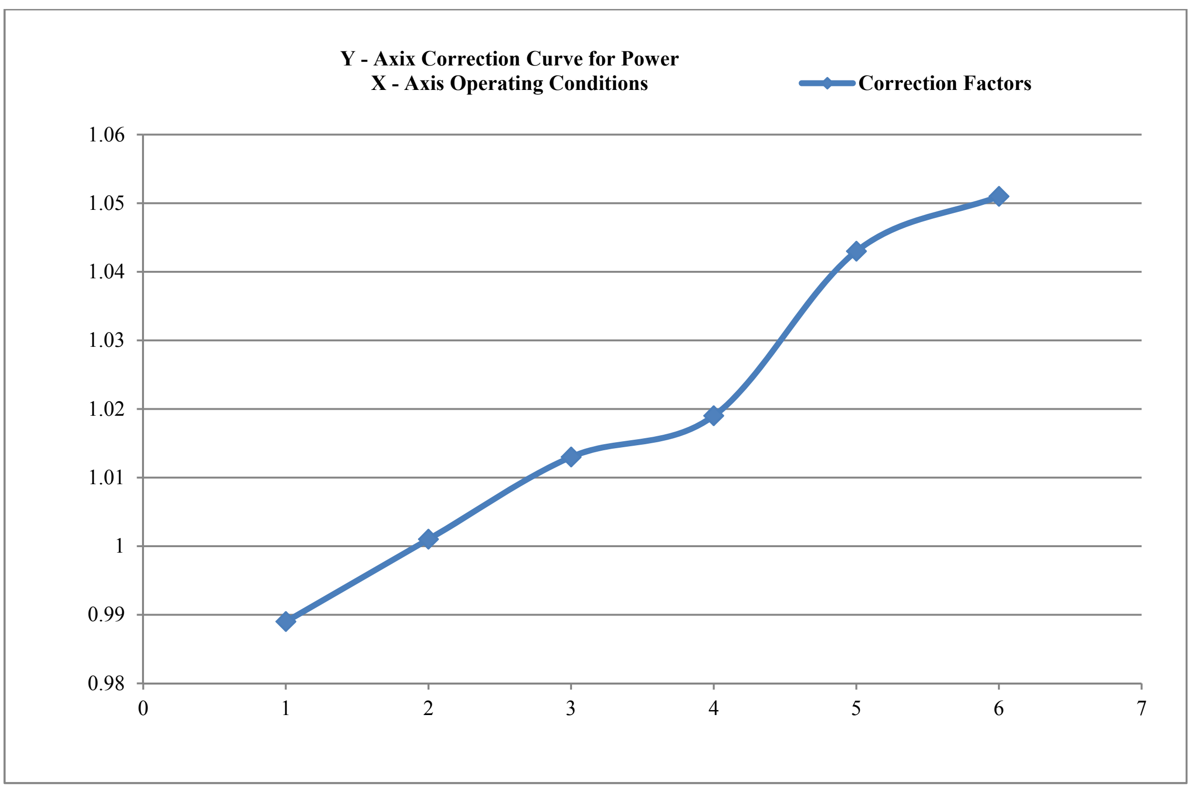

Figure 3 – Correction curve for power output

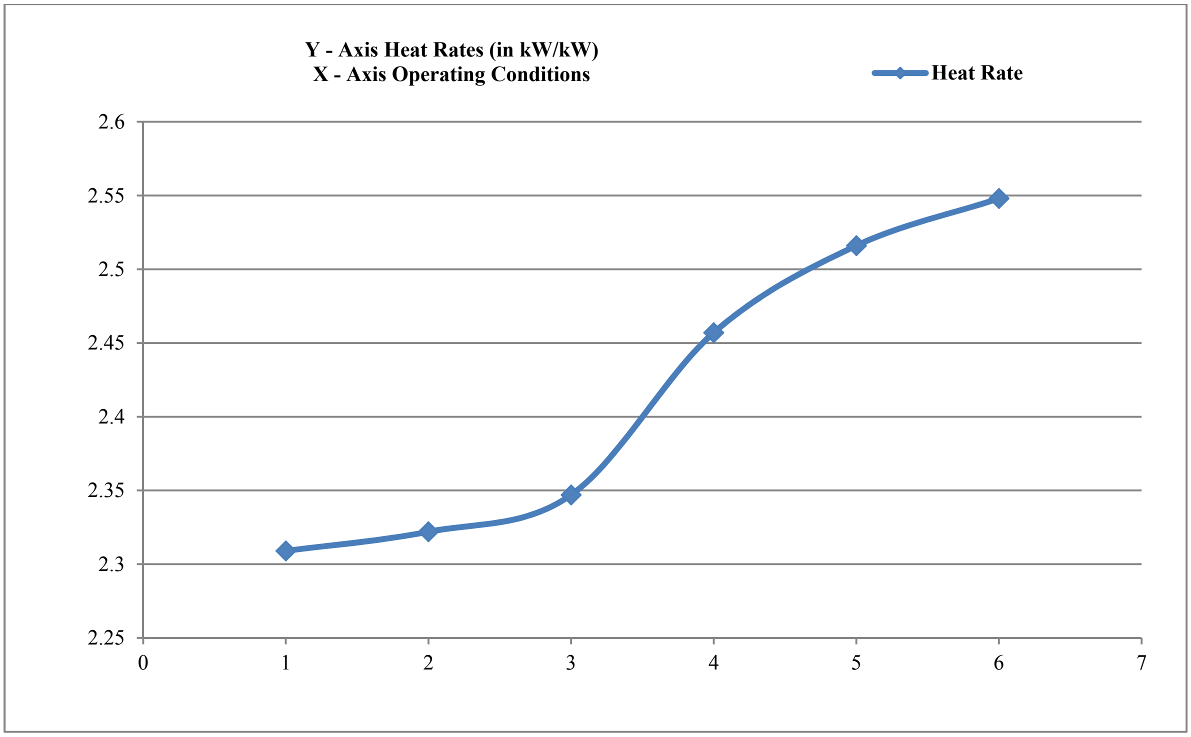

Figure 4 – Heat rates at various operating conditions

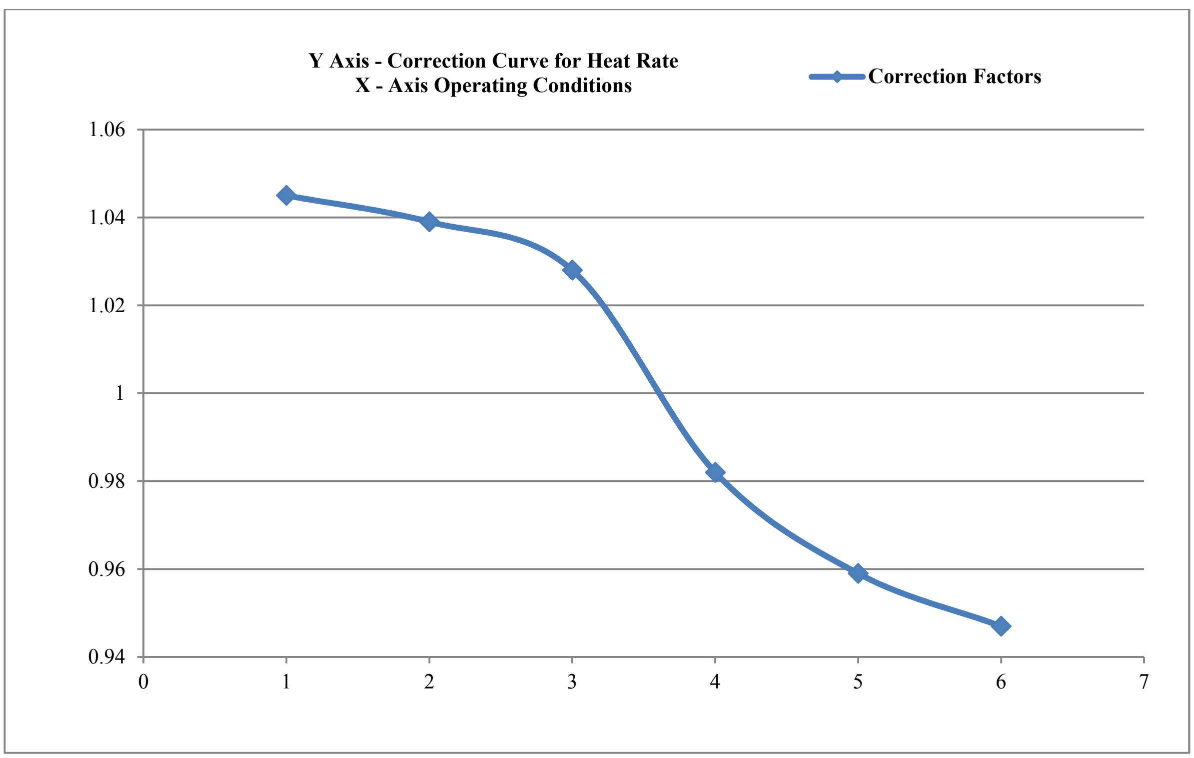

Figure 5 – Correction curve for heat rate

IV. CONCLUSIONS

From these case studies, optimum operating conditions have been found. Conditions at which power output from power plant will be highest or heat rate will be lowest. Maximum values of the power output from power plant and minimum value of the heat rate have been found which are 121334.6 kW power and 2.309 heat rate. Highest power and lowest heat rate have been achieved at following operating conditions; steam pressure 122.16 bar, steam temperature 780.78 K, back pressure 0.068 bar, extraction line pressure drop for high pressure feed water heater 2% (heater number 6), no makeup water addition in deaerator and with five numbers of feed water heaters. But lowest value of power output and highest value of heat rate have been obtained at following operating conditions; back pressure 0.142 bar, extraction line pressure drop 8%, makeup water addition in deaerator 4% and with seven feed water heaters. The lowest value of power output is 114176.9 kW and highest value of heat rate is 2.548 which are undesirable. So from these case studies, those operating conditions can be selected at which coal fired thermal power plant performance is best.

LIST OF ABBREVIATIONS, NOMENCLATURE AND SYMBOLS

Ex = Extraction quantities from steam turbines; kg/sec.

FF = Flow function

h = Enthalpy of steam at various stages; kJ/kg.

€$_{net}$ = Heat rate for power plant

Ʊ$_{net}$ = Power output from power plant; kW

W = Mass flow rate of steam at various stages; kg/sec.

REFERENCES

[1] Cotton K. C., "Evaluating and improving steam turbine performance", 1st ed., Rexford, NY12148 USA : Cotton Fact, Inc; 254–262.

[2] Documents from steam turbine engineering (STE) department BHEL, Bhopal.

[3] Geete A., Khandwawala A. I., "Thermodynamic analysis of 120 MW thermal power plant with combined effect of constant inlet pressure (124.61 bar) and different inlet temperatures", *Case Studies in Mechanical Engineering*, 1;1, 17-25, 2013.

[4] Geete A., Khandwawala A. I., "Thermodynamic analysis of 120 MW thermal power plant with combined effect of constant inlet pressure (127.06 bar) and different condenser back pressures", *The IUP Journal of Mechanical Engineering*, 7;1, 25-46, 2014.

[5] Geete A., Khandwawala A. I., "Generate correction curves for 120 mw thermal power plant for extraction line pressure drop (heater no. 6) with the help of designed computer aided software", *International Journal of Mechanical Engineering Applications Research,* 4;1, 229-233, 2013.

[6] Geete A., Khandwawala A. I., "Thermodynamic analysis of 120 MW thermal power plant by designed computer aided software for different inlet temperature conditions and generate correction curves", *International Journal of Thermal Technologies,* 3;1, 20-22, 2013.

[7] Geete A., Khandwawala A. I., "Thermodynamic analysis of 120 MW thermal power plant and generate correction curves for extraction line pressure drop (heater no. 5) with the help of designed computer aided software", *International Journal of Mechanical Engineering*,57, 14301-14304, 2013.

[8] Geete A., Khandwawala A.I., "To analyse the combined effect of different extraction line pressure drops on the performance of coal fired thermal power plant", *International Journal of Ambient Energy,* DOI: 10.1080/01430750.2015.1121919, 2016.