COMBINED EFFECT OF VARIOUS OPERATING LOADS, NUMBER OF FEED WATER HEATERS AND MAKEUP WATER QUANTITIES ON THE PERFORMANCE OF COAL FIRED THERMAL POWER PLANT: A CASE STUDY

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Abstract: In this case study, combined effect of various operating parameters on the performance of thermal power plant is analyzed. For the analysis following operating parameters are selected: different operating loads, different number of feed water heaters and different mass flow rates of makeup water. To analyze the performance of the power plant: flow function, mass flow rates of steam at each stage, power output, heat rate, correction factors for power and heat rate are evaluated. And then performance characteristic curves are prepared. Finally those operating conditions are found at which power output is as high as possible but heat rate is as low as possible. This case study can be concluded as maximum power (121.21 MW) and minimum heat rate (2,393.05 kJ/MW s) both can be achieved at full operating load condition, with five feed water heaters and no makeup water addition in de-aerator. But minimum power (71.43 MW) and maximum heat rate (2,430.94 kJ/MW s) are found at low load, with large number of feed water heaters and more amount of makeup water addition.

1. Introduction
In the previous years, many researchers have done lot of work on thermal power plant. Various case studies and research work have been done by Geete (2016), Geete and Khandawala (2013, 2014, 2016).

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PUBLIC INTEREST STATEMENT
This research work is done on 120 MW coal fired thermal power plant. All power plants are designed on the basis of ideal conditions. But in actual, power plants are not working on ideal/designed conditions due to site situation, environmental conditions, leakages etc. It means, outputs from the plant will be different (less) then designed outputs. It will be matter of disputes between supplier/manufacturer and customer. To protect our design of the plant, correction curves are generated at various operating conditions. These curves are submitted as the time of installation of the plant to customer. With the help of these correction curves, plant design can be justified as if plant operating conditions are changed then plant outputs will be changed.

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2015, 2016) with different operating parameters at different conditions like different inlet pressures, different inlet temperatures, different condenser pressures and different extraction line pressure drops. Vosough et al. (2011) have suggested that maximum efficiency and maximum power output can be achieved at minimum condenser pressure. Mateen and Roa (2011) have also observed some important considerations that are required for perfect design of a condenser. Rafiee, Siadatan, Afiei, and Abadi (2012) have concluded that about 3.3% of thermal energy can be increased by using of thermo-electric generator in the condensation cycle. Dutta, Das, and Chakrabarti (2013) have introduced a new term called Loss Factor. They have noted that the efficiency is maximum when the Loss Factor equals to one. Zhonghua, Jizhen, and Guangjian (2013) have developed a model which is used to analyze condenser, condenser back pressure and cooling tower of the thermal power plant. A coal fired thermal power plant is opted for this case study. Major components of thermal power plant are – high pressure feed water pump, boiler, high pressure steam turbine, intermediate pressure steam turbine, low pressure steam turbine, condenser, cooling tower, high pressure feed water heaters, low pressure feed water heaters, deaerator and low pressure feed water pump. Schematic diagram of the power plant is shown in Figure 1 (Geete, 2016; Geete & Khandwawala, 2013, 2014, 2015, 2016; Steam Turbine Engineering (STE) Department, 2010). In this case study, various operating parameters are selected and effects of these parameters on the performance of power plant are determined. Selected operating parameters are: (a) operating load conditions (like 100% load, 80% load and 60% load), (b) number of feed water heaters (like five heaters, six heaters and seven heaters) and (c) mass flow rates of water addition in deaerator (like 0, 1 and 2% of total mass flow rate of steam generated in boiler). In actual power plant, operating loads are varied according to requirement of power. Numbers of feed water heaters are varied according to the temperature of feed water required in the boiler. And mass flow rates of makeup water addition in deaerator are varied according to leakages from power plant. To evaluate performance of the power plant, power output and heat rate are calculated at different conditions. For calculations one new term is used which is flow function. This term shows relation between mass flow rate of steam, steam pressure, steam temperature and volume of steam generated in boiler. Some leakages are presumed during calculations; leakages are: (1) leakage L₁ some amount of steam is taken from main pipeline and entered at last stage of HP turbine. This steam is used to reduce pressure difference between first and last stage of HP turbine. (2) Before entering steam in HP turbine, some amount of steam is leaked from

![Figure 1. Layout of 120 MW thermal power plant.](image-url)
pipeline, leakages are $L_1$, $L_2$, and $L_3$. (3) After expanding steam in HP turbine, $L_4$ and $L_5$ amount of steam are leaked. (4) $L_6$ and $L_7$ are leakages before entering steam in IP turbine. And (5) $L_8$ is a leakage before entering steam in LP turbine. All extraction quantities ($E_x$) are also taken into account during calculations, extraction quantities are: (1) $E_{x1}$ is first extraction quantity of steam after expansion in high pressure turbine, (2) $E_{x2}$ and $E_{x3}$ are extraction quantities of steam from intermediate pressure turbine at different stages respectively, (3) $E_{x4}$, $E_{x5}$ and $E_{x6}$ are extraction quantities of steam from low pressure turbine at different stages respectively. Mechanical losses and generator efficiency are also considered to calculate net output to improve accuracy of the results. Here heat rate is calculated and it can be defined as the ratio of total heat addition in the boiler and net amount of power output from the plant. Designed/ideal conditions of power plant are—mass flow rate of steam is 363,313.0 kg/h, steam pressure is 125.1 bar, steam temperature is 537.78°C, specific volume is 0.0186 m³/kg and flow function is 4,430.051 kg²/bar m³h. In this work, case studies are performed on coal fired thermal power plant. For case studies, power output and heat rate are evaluated for selected operating parameters at various conditions. After that performance characteristic curves are made. From these characteristic curves those operating conditions are found at which power output is maximum but heat rate is minimum.

2. Methodology
Here designed value of the flow function is calculated with the designed values of mass flow rate of steam, steam pressure and steam volume. Then with the help of calculated flow function, mass flow rates of steam are calculated at various operating conditions by relationship between flow function, mass flow rate, pressure and specific volume. Mathematic relation is given below (Cotton, 1993; Geete, 2016; Geete & Khandwawala, 2013, 2014, 2015, 2016; Steam Turbine Engineering (STE) Department, 2010):

$$FF = \frac{W}{\sqrt{P/V}}$$  \hspace{1cm} (1)

Here FF is flow function, $W$ is mass flow rate of working fluid in kg/s, $P$ is steam pressure in bar and $V$ is specific volume in m³/kg. By considering extraction quantities and leakages, different mass flow rates are calculated for high pressure turbine, intermediate pressure turbine and low pressure turbine (Cotton, 1993; Geete, 2016; Geete & Khandwawala, 2013, 2014, 2015, 2016; Steam Turbine Engineering (STE) Department, 2010). Calculations of mass flow rates of steam at various stages are done as follows. Mass flow rate of steam for high pressure steam turbine ($W_1$) is calculated by subtracting leakages $L_1$, $L_2$, $L_3$ and $L_4$ from steam which is generated in boiler. Mass flow rate of steam for intermediate pressure turbine after 1st extraction of steam for high pressure feed water heater ($W_2$) is calculated by adding $L_1$ and then subtracting leakages $L_5$, $L_6$ and extraction quantity $E_{x1}$ from mass flow rate of steam for high pressure steam turbine. Mass flow rate of steam ($W_3$) after 2nd extraction of steam for high pressure feed water heater is calculated by subtracting extraction quantity $E_{x2}$, leakages $L_7$ and $L_8$ from flow rate of steam after 1st extraction. Mass flow rate of steam ($W_4$) after 3rd extraction of steam for deaerator is calculate by subtracting extraction quantity $E_{x3}$ from flow rate of steam after 2nd extraction. Mass flow rate of steam ($W_5$) for low pressure turbine after 4th extraction of steam for low pressure feed water heater is calculated by subtracting extraction quantity $E_{x4}$ from flow rate of steam after 3rd extraction. Mass flow rate of steam ($W_6$) after 5th extraction of steam for low pressure feed water heater is calculated by subtracting extraction quantity $E_{x5}$ and leakage $L_9$ from flow rate of steam for low pressure turbine after 4th extraction. And finally mass flow rate of steam ($W_7$) after 6th extraction of steam for low pressure feed water heater is calculated by subtracting extraction quantity $E_{x6}$ from flow rate of steam after 5th extraction of steam. Where $E_{x1}$, $E_{x2}$, $E_{x3}$, $E_{x4}$, $E_{x5}$ and $E_{x6}$ are different extraction quantities which are extracted from high pressure, intermediate pressure and low pressure steam turbines. After finding mass flow rates at various stages of steam turbines, power and heat rate are calculated. Power is calculated with the relationship between mass flow rate and enthalpy drop in the turbine and net power is calculated by considering mechanical losses and generator efficiency. Heat rate is calculated with relationship between total heat addition and net power.
output. Power, net power and heat rate are calculated by Equations (3–5) (Geete, 2016; Geete & Khandwawala, 2013, 2014, 2015, 2016; Steam Turbine Engineering (STE) Department, 2010):

\[
P = \left[ W_1 (h_1 - h_2) \right] + \left[ W_2 (h_3 - h_4) \right] + \left[ W_3 (h_5 - h_6) \right] + \left[ W_4 (h_7 - h_8) \right] + \left[ W_5 (h_9 - h_{10}) \right] + \left[ W_6 (h_11 - h_{12}) \right] + \left[ W_7 (h_{13} - h_{14}) \right] + \left[ W_8 (h_{15} - h_{16}) \right] + \left[ W_9 (h_{17} - h_{18}) \right]
\]

\[
P_n = (P - L_{\text{mech}}) \eta_g
\]

(2)

Here \( P \) is power in MW, \( P_n \) is net power output from the plant in MW, \( L_{\text{mech}} \) is mechanical losses in generator in MW and \( \eta_g \) is generator efficiency.

\[
HR = \frac{Q}{P_n} = \left( \frac{Q_1 + Q_2}{P_n} \right)
\]

(4)

Here \( Q \) is summation of heat addition in boiler and superheater (\( Q_1 \) is amount of heat transfer in boiler and \( Q_2 \) is amount of heat transfer in superheater) in kJ/s and \( HR \) is heat rate in kJ/MW sec. After calculations of net power outlet and heat rate, correction factors are calculated. These correction factors are required to prepare performance characteristic curves for coal fired thermal power plant.

\[
CF_p = \left( \frac{P_d}{P_n} \right)
\]

(5)

\[
CF_h = \left( \frac{HR_d}{HR} \right)
\]

(6)

Here \( CF_p \) is correction factor for power output and \( CF_h \) is correction factor for heat rate. \( P_d \) is designed power output from the power plant at ideal operating conditions in MW and \( HR_d \) is designed heat rate from the plant in kJ/MW sec. In this case study, some quantities like leakages and extractions for designed conditions are collected from BHEL plant. Different leakages are—\( L_1 \): 1.263 kg/s; \( L_2 \): 0.042 kg/s; \( L_3 \): 0.311 kg/s; \( L_4 \): 0.108 kg/s; \( L_5 \): 0.233 kg/s; \( L_6 \): 0.083 kg/s; \( L_7 \): 0.366 kg/s; \( L_8 \): 0.101 kg/s; \( L_9 \): 0.041 kg/s. And different extraction quantities are—\( Ex_1 \): 6.397 kg/s; \( Ex_2 \): 4.116 kg/s; \( Ex_3 \): 5.522 kg/s; \( Ex_4 \): 2.092 kg/s; \( Ex_5 \): 3.811 kg/s and \( Ex_6 \): 3.383 kg/s (Steam Turbine Engineering (STE) Department, 2010).

3. Results

It has been observed that (a) when power plant is running at full load condition then it gives maximum performance, (b) when number of feed water heater increases then power output decreases because extraction quantity increases but heat rate improves whereas when number of feed water heater decreases then power output increases but heat rate decreases and (c) when makeup water quantity increases it means leakages from the plant increase and finally performance of the plant decreases because power output decreases. For the work, 120 MW coal fired thermal power plant is opted. And different operating loads, various number of feed water heaters and different mass flow rates of makeup water are selected as operating parameters for this case study. All the results are tabulated in Tables 1 and 2. Then by using correction factors, power plant’s characteristic curves are prepared as shown in Figures 2 and 3. These characteristic curves are important to improve the performance of the power plant. By these curves optimum operating conditions are also identified at which power output from the plant is highest but heat rate is lowest.

With the help of these results following characteristic curves are formed one is based on power outputs and other one is based on heat rates. In these figures, x-axis shows various case studies (which are combine effects of various operating loads, different number of feed water heaters and different mass flow rates addition in deaerator) and y-axis shows correction factors.

From these case studies, it is also found that when operating load decreases, number of feed water heater increases and percentage of makeup water addition in deaerator increases then power output from the plant decreases but correction factor increases whereas for the same conditions heat rate increases but correction factor decreases.
### Table 1. Power outputs with correction factors due to combined effect of various operating parameters

| Case study | Operating parameters | Power outputs (in MW) | Correction factors |
|------------|----------------------|-----------------------|--------------------|
|            | Operating loads (in %) | Numbers of feed water heaters | Mass flow rates of makeup water add in deaerator (in %) | |
| 1          | 100                  | 5                     | 0                  | 121.21 | 0.99 |
| 2          | 80                   | 6                     | 1                  | 97.56  | 1.23 |
| 3          | 60                   | 7                     | 2                  | 71.43  | 1.68 |
| 4          | 100                  | 7                     | 1                  | 116.50 | 1.03 |
| 5          | 80                   | 5                     | 2                  | 97.56  | 1.23 |
| 6          | 60                   | 6                     | 0                  | 73.62  | 1.63 |
| 7          | 100                  | 6                     | 2                  | 119.40 | 1.005 |
| 8          | 80                   | 7                     | 0                  | 94.49  | 1.27 |
| 9          | 60                   | 5                     | 1                  | 74.53  | 1.61 |

### Table 2. Heat rates with correction factors due to combined effect of various operating parameters

| Case study | Operating parameters | Heat rates (in kJ/MW s) | Correction factors |
|------------|----------------------|-------------------------|--------------------|
|            | Operating loads (in %) | Numbers of feed water heaters | Mass flow rates of makeup water add in deaerator (in kg/s) | |
| 1          | 100                  | 5                     | 0                  | 2,393.05 | 1.008 |
| 2          | 80                   | 6                     | 1                  | 2,428.49 | 0.994 |
| 3          | 60                   | 7                     | 2                  | 2,430.94 | 0.993 |
| 4          | 100                  | 7                     | 1                  | 2,418.76 | 0.998 |
| 5          | 80                   | 5                     | 2                  | 2,413.92 | 1.00 |
| 6          | 60                   | 6                     | 0                  | 2,421.18 | 0.997 |
| 7          | 100                  | 6                     | 2                  | 2,426.05 | 0.995 |
| 8          | 80                   | 7                     | 0                  | 2,416.34 | 0.999 |
| 9          | 60                   | 5                     | 1                  | 2,413.92 | 1.00 |

Figure 2. Characteristic curve for power at combined effect of various operating conditions.
4. Conclusion
In this paper, different case studies are performed by selecting various operating parameters like operating loads, number of feed water heaters and makeup water addition in deaerator. Then performance operating correction curves are formed. These curves are used to identify those operating conditions at which optimum outputs can be achieved from power plant. Case studies are done on plant to find out maximum power output/minimum heat rate from the power plant. And work can be concluded as maximum power output can be achieved at 100% operating load, five feed water heaters and zero percent of makeup water addition in deaerator but minimum power output is found at 60% operating load, seven feed water heaters and two percent makeup water addition in deaerator. Similar case studies are done to evaluate minimum heat rate from the plant. And work can also be concluded as – maximum heat rate can be achieved with seven feed water heaters, two percent makeup water addition in deaerator and at 60% operating load but minimum heat rate is found with five feed water heaters, zero percent makeup water addition in deaerator and at 100% operating load. From these case studies, optimum conditions (100% operating load, 5 feed water heaters and no makeup water addition) are identified at which power output is maximum (121.21 MW) and heat rate is minimum (2,393.05 kJ/MW s).

List of symbols, abbreviation and nomenclature
- \( E_x \) extraction quantity from HP, IP and LP Turbines at different stages (kg/s)
- \( h_i \) enthalpy of steam at different stages (kJ/kg)
- \( L_i \) leakage from pipeline (kg/s)
- \( W_i \) mass flow rate of steam at different stages (kg/s)

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