Generation of correction curves for power and heat rate by thermodynamic analysis of combined effect of inlet pressure (123.14 bar) and different inlet temperatures on thermal power plant

Ankur Geete¹* and A. I. Khandwawala²

¹Mechanical Department, S. D. Bansal College of Technology, Indore, Madhya Pradesh, India.
²Mechanical Department, SGSITS, Indore Madhya Pradesh, India.

ABSTRACT

The thermal power plants are used to generate power. The thermal power plants are designed based on required conditions, but actually inlet conditions are not as per the designed conditions. Variations in the power outputs from power plant are always a matter of disputes. So correction curves for power and heat rate are generated. In this paper, the thermodynamic analysis of 120MW thermal power plant has been done at a different inlet pressure (123.14 bar) and at different inlet temperatures (507.78°C, 517.78°C, 527.78°C, 537.78°C, 547.78°C, 557.78°C, 567.78°C). The correction curves for power and heat rate have been generated for the combined effect of inlet pressure and different inlet temperatures. These curves indicate that if inlet conditions vary then power output and heat rate also vary.

© 2013 Elixir All rights reserved

List of Symbols, Abbreviation and Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex₃</td>
<td>Extraction Quantity after Expansion in HP Turbine for Heater No. 6 (kg/sec).</td>
</tr>
<tr>
<td>Ex₂</td>
<td>1st Extraction Quantity from IP Turbine for Heater No. 5 (kg/sec).</td>
</tr>
<tr>
<td>Ex₃</td>
<td>2nd Extraction Quantity from IP Turbine for Deaerator (kg/sec).</td>
</tr>
<tr>
<td>Ex₄</td>
<td>Extraction Quantity after Expansion in IP Turbine for Heater No. 3 (kg/sec).</td>
</tr>
<tr>
<td>Ex₅</td>
<td>1st Extraction Quantity from LP Turbine for Heater No. 2 (kg/sec).</td>
</tr>
<tr>
<td>Ex₆</td>
<td>2nd Extraction Quantity from LP Turbine for Heater No. 1 (kg/sec).</td>
</tr>
<tr>
<td>FF</td>
<td>Flow Function</td>
</tr>
<tr>
<td>h</td>
<td>Enthalpy of Feed Water at Inlet of Boiler (kJ/kg).</td>
</tr>
<tr>
<td>hₙ</td>
<td>Enthalpy of Steam Before Entering Super heater (kJ/kg).</td>
</tr>
<tr>
<td>hₙ</td>
<td>Enthalpy of Steam at Inlet of HP Turbine (kJ/kg).</td>
</tr>
<tr>
<td>hₙ</td>
<td>Enthalpy of Steam at Outlet from HP Turbine (kJ/kg).</td>
</tr>
<tr>
<td>hₙ</td>
<td>Enthalpy of Steam at Inlet to IP Turbine or Outlet from Super heater (kJ/kg).</td>
</tr>
<tr>
<td>hₙ</td>
<td>Enthalpy of Steam after 1st Extraction from IP Turbine (kJ/kg).</td>
</tr>
<tr>
<td>hₙ</td>
<td>Enthalpy of Steam after 2nd Extraction from IP Turbine (kJ/kg).</td>
</tr>
<tr>
<td>hₙ</td>
<td>Enthalpy of Steam at Outlet from IP Turbine (kJ/kg).</td>
</tr>
<tr>
<td>hₙ</td>
<td>Enthalpy of Steam after 1st Extraction from LP Turbine (kJ/kg).</td>
</tr>
<tr>
<td>hₙ</td>
<td>Enthalpy of Steam after 2nd Extraction from LP Turbine (kJ/kg).</td>
</tr>
<tr>
<td>L</td>
<td>Steam Used for Reducing Pressure Difference b/w 1st &amp; Last Stage of HP Turbine (kg/sec).</td>
</tr>
<tr>
<td>Lₖ</td>
<td>Leakage before Entering Steam in HP Turbine (kg/sec).</td>
</tr>
<tr>
<td>Lₖ</td>
<td>Leakage before Entering Steam in IP Turbine (kg/sec).</td>
</tr>
<tr>
<td>Lₖ</td>
<td>Leakage Before Entering Steam in HP Turbine (kg/sec).</td>
</tr>
<tr>
<td>Lₖ</td>
<td>Leakage after Steam Expand in HP Turbine (kg/sec).</td>
</tr>
<tr>
<td>Lₖ</td>
<td>Leakage after Steam Expand in IP Turbine (kg/sec).</td>
</tr>
<tr>
<td>Lₖ</td>
<td>Leakage before Entering Steam in IP Turbine (kg/sec).</td>
</tr>
<tr>
<td>Lₖ</td>
<td>Leakage before Entering Steam in LP Turbine (kg/sec).</td>
</tr>
<tr>
<td>P</td>
<td>Pressure of Steam for 120MW Power Plant (design condition) (N/m²).</td>
</tr>
<tr>
<td>Qₙ</td>
<td>Heat addition in Boiler (kJ/kg).</td>
</tr>
<tr>
<td>Qₙ</td>
<td>Heat addition in Super heater (kJ/kg).</td>
</tr>
<tr>
<td>V</td>
<td>Specific Volume of Steam for 120MW Power Plant (design condition) (m³/kg).</td>
</tr>
<tr>
<td>W</td>
<td>Mass Flow Rate of Steam for 120MW Power Plant (design condition) (kg/sec).</td>
</tr>
<tr>
<td>W</td>
<td>Mass Flow Rate Generated in Boiler at Different Conditions (kg/sec).</td>
</tr>
<tr>
<td>W₂</td>
<td>Mass Flow Rate at Inlet of HP Turbine (kg/sec).</td>
</tr>
<tr>
<td>W₂</td>
<td>Mass Flow Rate at Inlet of IP Turbine (kg/sec).</td>
</tr>
<tr>
<td>W₃</td>
<td>Mass Flow Rate after 1st Extraction of Steam from IP Turbine (kg/sec).</td>
</tr>
<tr>
<td>W₃</td>
<td>Mass Flow Rate after 2nd Extraction of Steam from IP Turbine (kg/sec).</td>
</tr>
<tr>
<td>W₃</td>
<td>Mass Flow Rate at Inlet of LP Turbine (kg/sec).</td>
</tr>
<tr>
<td>W₄</td>
<td>Mass Flow Rate after 1st Extraction of Steam from LP Turbine (kg/sec).</td>
</tr>
<tr>
<td>W₄</td>
<td>Mass Flow Rate after 2nd Extraction of Steam from LP Turbine (kg/sec).</td>
</tr>
</tbody>
</table>
Introduction

This paper is based on 120 MW thermal power plant, so a brief description of 120 MW thermal power plant is given as under –

Thermal power plant consists of five major components – (1) Boiler, (2) Steam Turbines – High pressure turbine, Intermediate pressure turbine and Low pressure turbine, (3) Condenser, (4) Feed Water Pump – Pump after condenser and pump after deaerator and (5) Feed Water Heater – one feed water heater for high pressure turbine, two feed water heater for intermediate pressure turbine and three feed water heater for low pressure turbine.

In the boiler, water converts into high pressure and temperature steam by the constant pressure heating process. Then high pressure and temperature steam enters into a high pressure steam turbine, in which steam expands and some amount of steam extract for feed water heating process. Then steam enters into an intermediate pressure steam turbine, in which steam expands and some amount of steam again extract for feed water heating process. And finally steam enters into a low pressure steam turbine, in which steam expands and some amount of steam again extract for feed water heating process. After passing through the low pressure turbine steam is converted into saturated water. Then water enters into the boiler with the help of a pump [1]. Bekdemir Sukrii, Ozturk Reccep and Yumurtac Zehra [2] have been worked on condenser optimization in steam power plant. Sharda G. G. and Batra K. R. [3] have been worked on super thermal power station to improve the performance of the plant by distribution control system technology. Bednorz Richard and Henken Fritz [4] have been worked on modernization of turbine and condenser for improving the performance of power plant. Kaushik Prabhakar and Khanduja Dinesh [5] have been applied six sigma DMAIC methodologies for condenser optimization in steam power plants. Amir Vosough, Alireza Falahat, Sadegh Vosough, Hasan Nasr Esfahani, Azam Behjat and Roya Naseri Rad [6] have been worked on condenser to improve the efficiency of condenser by finite element analysis. Carvalho L.M. and Cristiani P. [8] have been analyzed the corrosion in condenser tubes. Humbert F. Claude [9] has been worked on step-by-step approach to the evaluation and life extension of condenser tubes. Linda Riley, Carroll Williss and Claude Humbert [10] have been worked on a feed water heater. Schaarschmidt Andreas, Jenikejew Eduard and Nach Greg [11] have been worked on power plant to improve the performance by an elaborate design process. Schimon Rene, Simic Dragan, Haumer Anton, Kral Christian and Plainer Markus [12] have been worked on a simulation of the components of a thermal power plant. Dr. Quinkertz Rainer, Ulma Andreas, Gobrecht Edwin and Wechsung Michael [13] have been worked on retrofit design and operation for large steam turbine. Lahoda Jaroslav, Arndt Olaf and Hanstein Walter [21] have been worked on the reheat concept by biomass fuel to increase efficiency of the plant. Mateen Abdul Sk. and Roa Nageswara Amar N. [22] have been done structural and thermal analysis of the condenser by finite element analysis. Vora Yogesh, Patel B. M. and Tewari C. P. [23] have been worked on performance evaluation of the turbo generator system of a thermal plant by the use of probabilistic approach. Sharma Meeta and Singh Onkar [24] have been worked on the thermodynamic evaluation of waste heat recovery boiler for its optimum performance. This work deals with the generation of correction curves for different inlet pressure and inlet temperature conditions. These curves help as a reference or as a document to prove the design of thermal power plant. A layout of 120MW thermal power plant.

Figure 1 – Layout of 120 MW thermal power plant

Methodology

Flow Function Calculation

First of all flow function has been calculated with the relationship between mass flow rate, pressure and specific volume [25].

\[ FF = \frac{W}{\sqrt{P/V}} \]  
Eq. (1)

Where:

- \( FF \) is flow function
- \( W \) is mass flow rate (kg/hr)
- \( P \) is pressure (bar)
- \( V \) is specific volume (m³/kg)

Then different mass flow rates have been calculated at different stages for HP, IP and LP Turbines.

Mass Flow Rate Calculation

Then mass flow rate (W) has been calculated for given condition [25].

\[ FF = \frac{W}{\sqrt{P/V}} \]  
Eq. (2)

4430.051 = \( W \) / \( \sqrt{P/V} \), here P and V given as per given condition.

Mass Flow Rate Calculation for Different Stages of HP, IP and LP Turbines

Then different mass flow rates have been calculated at different stages for HP, IP and LP Turbines for given condition [26].

1. \( W_1 = (W_2 - L_1 - L_2 - L_3 - L_4) \) kg/sec  
Eq.(2)
2. \( W_2 = (W_1 + L_1 - L_2 - L_3 - L_4 + L_5) \) kg/sec  
Eq.(3)
3. \( W_3 = (W_2 - L_5 - L_6 - L_7 - L_8) \) kg/sec  
Eq.(4)
4. \( W_4 = (W_3 - Ex_3) \) kg/sec 
   \[ \text{Eq.(5)} \]
5. \( W_5 = (W_4 - Ex_4) \) kg/sec 
   \[ \text{Eq.(6)} \]
6. \( W_6 = (W_5 - Ex_5 - L_0) \) kg/sec 
   \[ \text{Eq.(7)} \]
7. \( W_7 = (W_6 - Ex_6) \) kg/sec 
   \[ \text{Eq.(8)} \]

**Total Power Calculation**

Then power has been calculated with the relationship between mass flow rate and enthalpy drop in the turbine for given condition [26].

\[
\text{Power} = (\text{Mass flow rate} \times \text{Enthalpy drop in the turbine})
\]

\[ \text{Eq. (9)} \]

\[
P = \text{HP Turbine} \{W_1 (h_1 - h_2) \} + \text{IP Turbine} \{W_2 (h_2 - h_3)\} + \text{LP Turbine} \{W_3 (h_3 - h_4)\} + \text{IP Turbine} \{W_6 (h_6 - h_5)\} + \text{LP Turbine} \{W_7 (h_7 - h_6)\} \text{ kW}
\]

\[ \text{Eq. (10)} \]

**Net Power Calculation**

Then net power has been calculated for given condition [26].

\[
P_{\text{net}} = (\text{Power} - \text{Mechanical Losses}) \times \text{Generator Efficiency}
\]

\[ \text{Eq. (11)} \]

**Heat Rate Calculation**

And then heat rate has been calculated with the relationship between total heat addition in boiler and net power output from the power plant for given condition [26].

Heat rate = (Total heat addition in boiler) / (Net power)

\[ \text{Eq. (12)} \]

\[
HR = \frac{Q}{P_{\text{net}}} \text{kJ/MW-sec}
\]

\[ \text{Eq. (13)} \]

\[
HR = \frac{Q_1 + Q_2}{P_{\text{net}}} \text{kJ/MW-sec}
\]

\[ \text{Eq. (15)} \]

**Case Study-2 - Inlet Temperature**

**Inlet Temperature - 547.78°C**

**Flow Function Calculation**

Flow Function = \( \sqrt{\frac{W}{P}} \) (PV)

\[ \text{Eq. (14)} \]

**Power Calculation**

\[
W_1 = (W' - L_1 - L_2 - L_3 - L_4) = 99.33 - 1.263 - 0.042 - 0.311 - 0.108 = 97.606 \text{ kg/sec}
\]

\[ \text{Eq. (5)} \]

\[
W_2 = (W_1 + L_1 - L_4 - Ex_1) = 97.606 + 1.263 - 0.233 - 0.083 - 6.466 = 92.087 \text{ kg/sec}
\]

\[ \text{Eq. (15)} \]

\[
W_3 = (W_2 - Ex_2 - L_2 - L_3) = 92.087 - 4.187 - 0.366 - 0.101 = 87.480 \text{ kg/sec}
\]

\[ \text{Eq. (16)} \]

**Case Study-1 - Inlet Pressure**

**Inlet Pressure - 123.14 bar**

**Flow Function Calculation**

\[ FF = \frac{W}{P} \text{(PV)} \]

\[ \text{Eq. (17)} \]

\[ FF = 363313/ \sqrt{(125.1/0.0186)} = 4430.051 \text{ kg²/bar m³ hr} \]

\[ W = 363313 \text{ kg/hr, } P = 125.1 \text{ bar and } V = 0.0186 \text{ m}^3/\text{kg} \]

**Power Calculation**

\[
W_1 = (W' - L_1 - L_2 - L_3 - L_4) = 100.382 - 1.263 - 0.042 - 0.311 - 0.108 = 98.658 \text{ kg/sec}
\]

\[ \text{Eq. (5)} \]

\[
W_2 = (W_1 + L_1 - L_2 - L_3 - Ex_1) = 98.658 + 1.263 - 0.233 - 0.083 - 6.494 = 93.111 \text{ kg/sec}
\]

\[ \text{Eq. (15)} \]

**Total Power Calculation**

Then net power has been calculated for given condition [26].

\[
P_{\text{net}} = (\text{Power} - \text{Mechanical Losses}) \times \text{Generator Efficiency}
\]

\[ \text{Eq. (11)} \]

**Heat Rate Calculation**

\[
HR = \frac{Q}{P_{\text{net}}} \text{kJ/MW-sec}
\]

\[ \text{Eq. (13)} \]

\[
HR = \frac{Q_1 + Q_2}{P_{\text{net}}} \text{kJ/MW-sec}
\]

\[ \text{Eq. (15)} \]

**Case Study-2 - Inlet Temperature**

**Inlet Temperature - 547.78°C**

**Flow Function Calculation**

Flow Function = \( W/\sqrt{P} \) (PV)

\[ \text{Eq. (14)} \]

**Power Calculation**

\[
W_1 = (W' - L_1 - L_2 - L_3 - L_4) = 100.382 - 1.263 - 0.042 - 0.311 - 0.108 = 98.658 \text{ kg/sec}
\]

\[ \text{Eq. (5)} \]

\[
W_2 = (W_1 + L_1 - L_2 - L_3 - Ex_1) = 98.658 + 1.263 - 0.233 - 0.083 - 6.494 = 93.111 \text{ kg/sec}
\]

\[ \text{Eq. (15)} \]
### Table for Power

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>507.78</td>
<td>102.840</td>
<td></td>
<td>120.775</td>
<td>0.9935</td>
</tr>
<tr>
<td>2</td>
<td>517.78</td>
<td>102.304</td>
<td></td>
<td>120.580</td>
<td>0.9951</td>
</tr>
<tr>
<td>3</td>
<td>527.78</td>
<td>101.744</td>
<td></td>
<td>120.355</td>
<td>0.9970</td>
</tr>
<tr>
<td>4</td>
<td>537.78</td>
<td>100.920</td>
<td></td>
<td>120.000</td>
<td>1.0000</td>
</tr>
<tr>
<td>5</td>
<td>547.78</td>
<td>100.382</td>
<td></td>
<td>119.505</td>
<td>1.0041</td>
</tr>
<tr>
<td>6</td>
<td>557.78</td>
<td>99.852</td>
<td></td>
<td>119.276</td>
<td>1.0060</td>
</tr>
<tr>
<td>7</td>
<td>567.78</td>
<td>99.330</td>
<td></td>
<td>119.042</td>
<td>1.0080</td>
</tr>
</tbody>
</table>

### Table for Heat Rate

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Temperature (in °C)</th>
<th>Total Input (in kcal/hr)</th>
<th>Heat Rate (in kJ/MW-sec)</th>
<th>Correction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>507.78</td>
<td>287054.517</td>
<td>2376.770</td>
<td>1.0156</td>
</tr>
<tr>
<td>2</td>
<td>517.78</td>
<td>288258.218</td>
<td>2390.597</td>
<td>1.0097</td>
</tr>
<tr>
<td>3</td>
<td>527.78</td>
<td>289363.759</td>
<td>2404.252</td>
<td>1.0040</td>
</tr>
<tr>
<td>4</td>
<td>537.78</td>
<td>289671.178</td>
<td>2413.926</td>
<td>1.0000</td>
</tr>
<tr>
<td>5</td>
<td>547.78</td>
<td>290769.145</td>
<td>2433.112</td>
<td>0.9921</td>
</tr>
<tr>
<td>6</td>
<td>557.78</td>
<td>291862.434</td>
<td>2446.930</td>
<td>0.9865</td>
</tr>
<tr>
<td>7</td>
<td>567.78</td>
<td>292948.537</td>
<td>2460.883</td>
<td>0.9809</td>
</tr>
</tbody>
</table>

### Result

#### Table for Power with Combined Effect of Inlet Pressure and Inlet Temperature

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Temperature (in °C)</th>
<th>Pressure (in bar)</th>
<th>Power (in MW)</th>
<th>Correction Factor (120/Power)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>507.78</td>
<td>123.14</td>
<td>118.776</td>
<td>1.0103</td>
</tr>
<tr>
<td>2</td>
<td>517.78</td>
<td>123.14</td>
<td>118.577</td>
<td>1.0120</td>
</tr>
<tr>
<td>3</td>
<td>527.78</td>
<td>123.14</td>
<td>118.354</td>
<td>1.0139</td>
</tr>
<tr>
<td>4</td>
<td>537.78</td>
<td>123.14</td>
<td>117.979</td>
<td>1.017</td>
</tr>
<tr>
<td>5</td>
<td>547.78</td>
<td>123.14</td>
<td>117.520</td>
<td>1.0211</td>
</tr>
<tr>
<td>6</td>
<td>557.78</td>
<td>123.14</td>
<td>117.290</td>
<td>1.0231</td>
</tr>
<tr>
<td>7</td>
<td>567.78</td>
<td>123.14</td>
<td>117.061</td>
<td>1.0251</td>
</tr>
</tbody>
</table>

#### Table for Heat Rate with Combined Effect of Inlet Pressure and Inlet Temperature

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Temperature (in °C)</th>
<th>Pressure (in bar)</th>
<th>Heat Rate (in kJ/MW-sec)</th>
<th>Correction Factor (2413.926/HR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>507.78</td>
<td>123.14</td>
<td>2381.772</td>
<td>1.0135</td>
</tr>
<tr>
<td>2</td>
<td>517.78</td>
<td>123.14</td>
<td>2395.718</td>
<td>1.0076</td>
</tr>
<tr>
<td>3</td>
<td>527.78</td>
<td>123.14</td>
<td>2409.348</td>
<td>1.0019</td>
</tr>
<tr>
<td>4</td>
<td>537.78</td>
<td>123.14</td>
<td>2418.525</td>
<td>0.998</td>
</tr>
<tr>
<td>5</td>
<td>547.78</td>
<td>123.14</td>
<td>2438.062</td>
<td>0.9901</td>
</tr>
<tr>
<td>6</td>
<td>557.78</td>
<td>123.14</td>
<td>2451.930</td>
<td>0.9845</td>
</tr>
<tr>
<td>7</td>
<td>567.78</td>
<td>123.14</td>
<td>2465.957</td>
<td>0.9789</td>
</tr>
</tbody>
</table>

### Correction Curve for Heat Rate

X axis – Different Inlet Temperature Conditions, Y axis – Correction Factor

**Figure 3** – Correction curve for combined effect of inlet pressure and temperature for heat rate

### Conclusion

Power, heat rate and correction factor have been calculated by the thermodynamic analysis of 120MW thermal power plant. And with the help of calculated correction factors, correction curves have been generated. From this work following conclusion has been found –

1. If inlet pressure is 123.14 bar and inlet temperature is 547.78°C then power output from the power plant is 117.520 MW and correction factor is 1.0211. For the same conditions, heat rate is 2438.062 kJ/MW-sec and correction factor is 0.9901.
2. Similarly, if inlet pressure is 123.14 bar and inlet temperature is 517.78°C then power output from the power plant is 118.577 MW and correction factor is 1.0120. For the same conditions, heat rate is 2395.718 kJ/MW-sec and correction factor is 1.0076.

### References

References:


[26] Documents from Steam turbine engineering (STE) department BHEL Bhopal.