Enhancing energy efficiency of boiler feed pumps in thermal power plants through operational optimization and energy conservation

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This paper describes the various methods for enhancing the energy efficiency of Boiler Feed Pumps (BFP) in thermal power plants based on the energy audit study conducted in 28 numbers of 210 MW coal fired thermal power plants in India. The auxiliary power used by BFPs is about 2.4 to 3.2 % of the total gross energy generation. BFPs are the largest (in rating) motor in a thermal power plant. The detailed energy audit of auxiliary equipment in various thermal power stations, operational optimization and appropriate control system had shown ample scope for improving the energy efficiency of BFPs. The energy efficiency improvement of BFPs by reducing the re-circulation flow, pressure drop across feed water circuit elements, enhancing overall efficiency of BFPs, etc., are discussed with case studies. The implementation of energy conservation measures reduce the average auxiliary power used by BFPs for 210 MW plant from 2.97 % to 2.32 % of gross energy generation and release an additional power of about 480 MW that reduce the CO₂ emission by about 3.9 million tonne per year.

Keywords: Energy efficiency, boiler feed pumps, auxiliary power, pump efficiency, sec, energy conservation

INTRODUCTION

The total installed power generation capacity in India is about 223.344 GW, out of which the generation from coal fired power plant is about 56 %. The average auxiliary power used of coal fired thermal power plant is 8.44 % of gross energy generation at an average plant load factor (PLF) of 73.3 % (CEA, 2013). Among the auxiliary equipment BFPs are the major energy consuming equipment that forms 30 % of total auxiliary power used by thermal power plants (Siddhartha Bhatt M et al., 1999).
The estimated auxiliary power used BFPs of coal fired thermal power plants in India is about 4420 MW and average estimated CO₂ emission is about 36 million tonne per year on account of auxiliary power used by BFPs.

The thermal power plant availability and reliability depends largely upon the operational reliability of auxiliary equipment like BFPs and also the capability of the auxiliary system (Kiran Kumar et al., June 2013). The auxiliary power consumption is on higher side in Indian power plants as compared to other developed countries due to poor plant load factor, poor coal quality, excessive

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Boiler Feed Pumps (BFP) are the major energy consuming equipment which are essential to increase the feed water pressure in a coal fired thermal power plants. In a 210 MW power plant BFP is supplied along with Booster pump which is mounted on the same shaft. The Booster pump increases the feed water pressure from 0.5 – 0.66 MPa (Deaerator pressure) to intermediate pressure of about 1.2 – 1.4 MPa and BFP main pump increases the FW pressure from Booster pump discharge to about 17 – 18 MPa (Drum pressure). In a typical 210 MW power plant, three numbers of multistage pumps with hydraulic scoop coupling to control the feed water flow. Booster pumps are of centrifugal pumps.

Boiler feed pumps are axial split multistage, horizontal, barrel type, high capacity, high speed (about 5000 rpm), centrifugal pumps. There are three BFPs with HT induction motors of 6.6 kV and the motor rating will be of either 4.0 MW or 3.5 MW in a 210 MW power plants (Rajashekar P Mandi et al., 2010). Two pumps will be working continuously and third pump will be stand-by. The feed water flow will be regulated by scoop (fluid coupling) control and 3 element feed control valve station. There are two types of driving systems are used for Boiler Feed Pumps i.e., steam operated turbine drive or motor drive system. Generally in 500 MW above plant size, Turbine (steam operated) Driven BFP (TDBFP) are used because the motor size will be very big of the order of about two numbers of 10 MW size. Starting current of these motors will be very high and influence the voltage and other supply parameters in the network. The auxiliary steam at cold re-heat line will be used to run TDBFP. This steam is already taken part in producing partial output power in High Pressure Turbine (HPT). The overall efficiency of conversion from thermal energy (coal) to hydraulic output at BFP output is higher in case of TDBFP compared to motor driven BFP. The average conversion efficiency of coal to hydraulic power in TDBFP is about 62 % whereas at MDBFP is 26 %. But in 210 MW and lower size units adopt motor driven BFP due to lower operation and maintenance and also to optimize the space utilization.

Figure 1 is the energy used by different auxiliary equipment in a 210 MW power plant. The average specific auxiliary power used by BFP is 2.42 % of gross power generation at maximum continuation rating (MCR) and is high compared to design value of 2.28 % at MCR condition.

Boiler feed pumps have to overcome the hydrodynamic resistances offered by High Pressure Heater (HPH) (regenerative feed water heaters), feed regulating station (FRS), economizer, water walls, superheaters, reheaters, etc. (Figure 2) and provide the high pressure steam at boiler outlet and then to turbines.

**Performance Test of Boiler Feed Pumps**

The performance test of BFPs is carried out in 28 units of 210 MW units with similar design of BFPs in India to evaluate the energy losses in BFPs and to reduce these losses thereby reducing the environmental burden of CO₂ by enhancing the energy efficiency of BFPs through implementation of energy conservation measures and operational optimization. During this performance test, the plant load is maintained nearly constant (load variation < 3 %) for a period of 120 minutes continuously; coal from the same source is used; no change-over of auxiliary equipment; no intermittent bottom ashing; and no soot-blowing operation during the test.
Performance Evaluation of BFPS

The input power to pump-motor depends on the efficiency of pumps, motors, pressure gain (net head i.e., dynamic head and velocity head) across pump and flow (John S Hsu et al., 1998).

The feed water (FW) circuit consists of hydrodynamic resistive elements like HP heaters, Feed regulating station (FRS) where the FW pressure will be regulated to obtain final main steam pressure at turbine inlet, Economizer coils, Water Walls, Superheaters and Reheaters (Boiler circuit). BFPS have to overcome these pressure drop offered by all these hydrodynamic resistive elements. The pressure drop across all these elements influences the pressure gain across BFPS.

The above variables are directly dependent on the plant load factor (PLF). All these variables (array) are plotted with variation in plant load factor (array). The Pearson product moment correlation method is used for finding the correlation coefficient ($R^2$) between x-axis array (i.e., PLF independent variable) and y-axis array (i.e., $P_{in}$, $\Delta P_{R}$, $\Delta P_{HPH}$, $\Delta P_{FRS}$, $\Delta P_{ECO}$, $\Delta P_{Boiler}$, $m_{FW}$ and $\eta_{O}$ dependent variables)

Generally, coal fired thermal power stations are termed as base load power plants and are bound to operate at full load condition always. The predicted performance values for all the parameters of all auxiliary equipment are provided by manufacturers' for operating the plant at 100 % PLF (MCR condition) and 60 % PLF. The design values are extrapolated to 70 % of PLF because the plant operating below 70 % PLF with poor coal quality will be unstable and sometimes the plant may run even with oil support which is not economically advisable. Therefore, in this study the performance of BFPS is considered for the plant load variation between 70 % to 100 % PLF.

Pressure gain across pump

As the plant load on the unit increases, the discharge pressure at pump increases to provide the necessary steam pressure at turbine inlet (Becnel CL et al., 1987). Figure 3 is the pressure gain across pump with plant load. The correlation coefficient for the variation of pressure gain with plant load factor is 0.9539 and the noise level in data is less. At MCR condition, the average measured pressure gain is 16.85 MPa and is lower than the design value of 17.55 MPa at Maximum Continuous Rating (MCR) condition i.e., 210 MW plant load. The pressure gain at full load capacity of BFPS (max. efficiency point) is 20.07 MPa. The margin provided for operation of BFPS at MCR condition is about 13 % but the actual average measured operating point of BFPS is about 16 % of full load capacity of BFPSs. Operation of these pumps at non optimal operating point cause reduction in efficiency of pumps that increase the power loss. The power loss operating at pressure gain at MCR condition is 0.05 % of gross generation and the power loss compared at actual measured operating point at MCR condition is 0.27 %. The lower pressure gain at BFPSs is mainly because of higher margin is provided for BFPSs for higher operational reliability during single cycle operation. The measured average pressure gain at 70 % PLF is 16.30 MPa and is lower than the design value of 17.52 MPa. The deviation in pressure gain measured at different plant loading is computed using the MATLAB software average value got from the regression analysis with respect to operating the plant load at MCR condition and is:

$$\bar{P}_r = \left(1 - \frac{PR_T}{PR_{MCR}}\right) \times 100$$

Where $\bar{P}_r$ is the deviation in pressure gain (%), $PR_{MCR}$ is the pressure gain (MPa) at MCR condition (100 % PLF) and $PR_T$ is the pressure gain at tested plant load (MPa).

Pressure drop across hydrodynamic resistive elements

The pressure drop across each hydrodynamic resistive elements are also analyzed and the power loss due to these elements are computed. The pressure drop across HPH is varying in the range of 0.53 MPa at MCR and 0.50 MPa at 70 % PLF. The deviation between MCR to
70 % PLF is 5.9 %. The power loss in HP heaters is computed in the range of 108.2 kW at MCR and 82.3 kW at 70 % PLF. The power loss in HP heater forms about 1.87 % to 2.07 % of total BFP power input. The pressure drop across FRS is varying in the range of 0.60 MPa at MCR and 0.56 MPa at 70 % PLF. The deviation between MCR to 70 % PLF is 6.5 %. The power loss in FRS is computed in the range of 128.2 kW at MCR and 92.2 kW at 70 % PLF. The power loss in FRS forms about 2.09 % to 2.34 % of total BFP power input. The pressure drop across Economizer is varying in the range of 0.189 MPa at MCR and 0.178 MPa at 70 % PLF. The deviation between MCR to 70 % PLF is 5.8 %. The power loss in Economizer is computed in the range of 38.41 kW at MCR and 29.23 kW at 70 % PLF. The pressure drop across Boiler is varying in the range of 1.42 MPa at MCR and 1.34 MPa at 70 % PLF. The deviation between MCR to 70 % PLF is 5.8 %. The power loss in Boiler is computed in the range of 289.26 kW at MCR and 220.0 kW at 70 % PLF. The power loss in Boiler forms about 4.99 % to 5.55 % of total BFP power input.

Feed water flow

Similarly, the feed water flow for both BFPs is plotted with PLF (Figure 5) and the correlation coefficient for the variation between feed water flow with PLF is 0.9726. The variation of flow is more sensitive to change in plant load and the noise level in data is very less. At MCR condition the average measured FW flow is 732 m³/h and is on par with the design value of 708.3 m³/h at MCR condition. The FW flow at full load capacity of BFP (max. efficiency point) is 715.6 m³/h (357.8 m³/h per pump). The margin provided for operation of BFPs at MCR condition is about 1 % but the actual average measured FW flow is higher than the design value and operating point of BFPs is about –2.3 % of full load capacity of BFPs. The higher FW flow may be due to operating BFPs at lower pressure, increased specific steam consumption of turbines, higher DM make up water, use of higher auxiliary steam for tracing lines, soot blowers, etc. The measured average FW flow at 70 % PLF is 591.5 m³/h and is higher than the design value of 444.2 m³/h. The deviation in FW flow measured at different plant loading is computed with respect to operating the plant load at MCR condition and the deviation (%) is computed as:

\[
\delta m = \left(1 - \frac{m_T}{m_{MCR}}\right) \times 100
\]

Where \(\delta m\) is the deviation (%) in FW flow, \(m_{MCR}\) is the FW flow (m³/h) at MCR condition (100 % PLF) and \(m_T\) is the FW flow (m³/h) at tested plant load.
The deviation in feed water flow for operating the plant at 70 % of MCR is 19.2 %.

**Efficiency**

Similarly, the combined motor and pump (i.e., overall efficiency) is also plotted with PLF (Figure 6). The correlation coefficient of second order polynomial curve fit for the overall efficiency with PLF is 0.9551 and the noise level in data is less compared to flow and is on par with pressure gain. At MCR condition the average overall efficiency is 66.78 % and is lower than the design value of 72.1 % at MCR condition. The overall efficiency at full load capacity of BFP (max. efficiency point) is 73.3 %. The power loss for operating the plant at design MCR condition is 0.05 % of gross generation and the power loss compared at actual measured operating point at MCR condition is 0.27 %. The overall efficiency is low because of lower discharge pressure, higher FW flow, passing in re-circulation flow through RC valve, problem in pump like higher clearance between impeller and casing, pitting and erosion of pump impeller, etc., (El-Wakil MM, 1984). The deviation in overall efficiency at different plant loading is computed with respect to operating the plant load at MCR condition and the deviation (%) is computed as:

$$\hat{\eta}_O = \left(1 - \frac{\eta_{OT}}{\eta_{OMCR}}\right) \times 100$$

(3)

Where $\hat{\eta}_O$ is the deviation in overall efficiency (%), $\eta_{OMCR}$ is the overall efficiency at MCR condition (%) and $\eta_{OT}$ is the overall efficiency at tested plant load (%).

The deviation in overall efficiency for operating the plant at 70 % of MCR is 7.9 %.

**Power input**

The variation of power input is plotted with the variation in plant load (Figure 7). It can be seen from the Figure 7 that as the plant load increases the auxiliary power of BFP increases. The correlation coefficient for the variation between measured power input with PLF is 0.9776. The correlation coefficient for power input is slightly better compared to pressure gain and FW flow and the noise level in data is less. At MCR condition the average measured power input is 5129.07 kW and is higher than the design value of 4788 kW at MCR condition. The power input at full load capacity of BFP (max. efficiency point) is 5894 kW. The actual measured power input is high compared to MCR condition because BFPs operating point is shifted thereby lower efficiency of pumps, higher FW flow and lower BFP discharge pressure. The average power input at 70 % PLF is 4352.66 kW and is higher than the design value of 3795.75 kW.

The deviation in power input (%) is computed by using average value through best curve fit of second order polynomial:

$$\hat{\eta}_P = \left(1 - \frac{P_T}{P_{MCR}}\right) \times 100$$

(4)

Where $\hat{\eta}_P$ is the deviation in power input (%), $P_{MCR}$ is the power input (kW) at MCR condition (100 % PLF) and $P_T$ is the power input (kW) at tested plant load

The deviation in power input for operating the plant at 70 % of MCR is 15.1 %.

**Specific auxiliary power**

In order to evaluate the auxiliary power used by BFPs, the specific auxiliary power is computed and is the ratio of Power input to plant load. The variation of specific auxiliary power for both pumps is plotted with variation in plant load (Figure 8). The specific auxiliary power (%) for BFP motors is computed as:
Where \( P \) is measured power input (kW), \( n \) is the number of equipment and \( PL \) is the plant load (MW) at generator output.

The correlation coefficient for the variation between specific auxiliary power with PLF is 0.9966 and the noise level in data is less. At MCR condition the average SAP is 2.44 % and is higher than the design value of 2.28 % at MCR condition because of higher losses in pumps, higher FW flow, etc. The average SAP at 70 % PLF is 2.96 % and is higher than the design value of 2.63 %. The correlation coefficient for specific auxiliary power is better than the power input. The deviation in specific auxiliary power (% of gross gen.) is computed by using average value through best curve fit of second order polynomial.

\[
\delta AP = \left(1 - \frac{AP_{MCR}}{AP_T}\right) \times 100
\]

Where \( \delta AP \) is the deviation in specific auxiliary power input (%), \( AP_{MCR} \) is the specific auxiliary power (% of gross gen.) at MCR condition and \( AP_T \) is the specific auxiliary power (% of gross gen.) at tested plant load.

The specific auxiliary power at MCR condition is 2.44 % whereas at 70 % PLF the specific auxiliary power is 2.96 %. The deviation in specific auxiliary power for operating the plant at 70 % of MCR is 21.3 %.

**SIMULATION STUDIES**

The mechanical power output of pump is directly related with pressure gain and feed water flow. The electrical power input to BFP motor terminals is also directly related with mechanical power output along with motor and pump efficiency (i.e., overall efficiency). But all these parameters will not have the similar kind of variation trend for different plant load conditions. The simulation of variation of auxiliary power with plant load is carried out with respect to variation in pressure gain, pressure drop across hydrodynamic resistive elements (HPH, FRS, ECO, Boiler), feed water flow and overall efficiency. The Artificial Neural Network (ANN) feed forward technique is adopted to simulate the variation of power input. In this technique, three layer model is adopted i.e., input layer, hidden layer and output layer.

ANNs are computational models which simulate the function of biological networks that composed of neurons (Anderson JA, 2003). The unique concept of ANN is the multi layered feed forward neural networks. Figure 9 is the ANN architecture. In this case three layer concept is adopted i.e., input layer, hidden layer and output layer. A node in one layer is connected to all nodes in the next layer i.e., feed forward architecture (Parisi DR et al., 2001). The input layer takes all the input parameters, the information is transmitted to hidden layer where they will be processed and output is computed in output layer (Singh KK et al., 2004). In this study, the input layers are chosen as plant load factor, pressure gain, feed water flow, overall efficiency, measured electrical power input and Pressure drop across HPH, FRS, ECO and Boiler (Mustafa Golcu et al., 2010). Back propagation training algorithm which is a gradient descent technique to minimize the sum of square errors is used (Engin T, 2007). The output layer is the simulated power input to BFP motor.

\[
E = \sum_{i=1}^{N} \sum_{j=1}^{Q} \left( P_{PR} - P_{BFP} \right)^2
\]
training a neural network involves tuning the values of the weights and biases of the network to optimize network performance. There are two different ways in which training can be implemented i.e., incremental mode (adapt command) or batch mode (train command). In incremental mode, the gradient is computed and the weights are updated after each input is applied to the network. In batch mode, all the inputs in the training set are applied to the network before the weights are updated. In this study we have adopted batch mode of training process. In this batch mode training process, after each cycle, the error between simulated value by the ANN and input value is propagated backward to adjust the weight in a manner mathematically to converge. Adjustments of weights are done using the following relation:

\[ \Delta W_i = -\alpha \frac{\partial E}{\partial W_i} + \beta \Delta W_i (A-1) \]  

(8)

Where \( \alpha \) is the learning rate, \( \beta \) is the momentum coefficient and \( A \) is the current step.

Batch training can be done using train which is the best option for training because it typically has access to more efficient training algorithms. For small and medium size networks where enough memory is available, Levenberg-Marquardt training algorithms are suitable. Therefore, in this case, Levenberg-Marquardt algorithm is used. In this multilayer architecture tan-sigmoid transfer function 'tansig' is used for hidden layer and linear transfer function 'purelin' is used for output layer.

An input data set of 422 for all input variables taken for simulating the output parameter. All these input data set are normalized in the range of 0.1 to 0.9 by using the following technique:

\[ D_n = \frac{(D_T - D_{T-min})^{0.8}}{(D_{T-max} - D_{T-min})} + 0.1 \]  

(9)

Where \( D_n \) is the normalized value, \( D_T \) is the measured data, \( D_{T-max} \) is the maximum value of measured data and \( D_{T-min} \) is the minimum value of measured data.

RESULTS AND DISCUSSIONS

The simulated power at 100 % PLF is 5070 kW and at 70 % PLF is 4246 kW % as compared to measured value of 5083 kW at 100 % PLF and 4241 at 70 % PLF. The simulated specific auxiliary power at 100 % PLF is 2.42 % and at 70 % PLF is 2.88 % as compared to measured value of 2.41 % at 100 % PLF and 2.89 % at 70 % PLF. The Pearson product moment correlation coefficient (\( R^2 \)) value for measured power input is 0.9776 and is for simulated power input is 0.9774. The error between actual measured value (% of measured input power) is varying between -7.65635 to 0.83244 %. The error is slightly negative as the plant load factor increases. The correlation coefficient between the measured input power and predicted power is plotted in Figure 10. The correlation coefficient computed (as per Pearson product moment correlation method) (\( R^2 \)) is 0.99995 and Root Means Square Error (RMSE) for the correlation between predicted power input to measured power input is 0.00019 (Verma AK et al., 2010). The error is negative for lower plant load and is slightly positive at higher PLF. At lower PLF operation of the plant will be less stable compared to plant operating above 80 % PLF. The noise level of data will be less at a PLF more than 80 %. At present Indian power plants average PLF of 210 MW power plants is about 82 % and is lower may be due to use of poor coal quality and ageing of the plants (Shanmugam KR et al., 2005 and CEA, 2012).

![Figure 10. Correlation coefficient between measured and simulated power.](image)

The MATLAB Simulink programming is done to evaluate the performance of BFPs. This Simulink program input the simulated and curve fit values from the ANN program.

The performance tests are conducted for 210 MW power plants at different plant load conditions. The measured data are compared with the simulated data. The variations in power due to variation of different parameters are discussed.

Table 1 gives the performance results of BFPs at Unit 1 at Raichur Super Thermal Power Station (RTPS), Raichur, Karnataka, India (CPRI, 2011).

<table>
<thead>
<tr>
<th>PLF</th>
<th>Simulated Power (kW)</th>
<th>Actual Measured Input Power (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>5070</td>
<td>5083</td>
</tr>
<tr>
<td>0.85</td>
<td>4720</td>
<td>4735</td>
</tr>
</tbody>
</table>

The performance test is conducted at an average plant load of 170 MW (PLF: 80.95 %). The observations from the study are as follows:

- The total power input for both BFPs is 5630.16 kW (3.31 % plant load) and is higher than the
Table 1. Performance Results of BFPS at RSTPS.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Particulars</th>
<th>Unit</th>
<th>Predicted value at 80.95 % PLF</th>
<th>BFP 1B</th>
<th>BFP 1C</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Plant load</td>
<td>MW</td>
<td></td>
<td>170.0</td>
<td></td>
</tr>
<tr>
<td>02</td>
<td>BFP Motor rating</td>
<td>MW</td>
<td>4.00</td>
<td>4.00</td>
<td>4.00</td>
</tr>
<tr>
<td>03</td>
<td>Booster pump suction pressure</td>
<td>MPa</td>
<td>-</td>
<td>0.56</td>
<td>0.56</td>
</tr>
<tr>
<td>04</td>
<td>BFP discharge pressure</td>
<td>MPa</td>
<td>-</td>
<td>14.20</td>
<td>15.84</td>
</tr>
<tr>
<td>05</td>
<td>Pressure gain</td>
<td>MPa</td>
<td>16.47</td>
<td>13.64</td>
<td>15.28</td>
</tr>
<tr>
<td>06</td>
<td>FW flow</td>
<td>m³/h</td>
<td>325.4</td>
<td>393.78</td>
<td>363.63</td>
</tr>
<tr>
<td>07</td>
<td>Electrical power</td>
<td>kW</td>
<td>2330</td>
<td>2775.92</td>
<td>2854.24</td>
</tr>
<tr>
<td>08</td>
<td>Load factor of motor</td>
<td>%</td>
<td>54.17</td>
<td>64.10</td>
<td>65.94</td>
</tr>
<tr>
<td>09</td>
<td>Motor efficiency</td>
<td>%</td>
<td>93.00</td>
<td>92.36</td>
<td>92.42</td>
</tr>
<tr>
<td>10</td>
<td>Electrical power input to pump</td>
<td>kW</td>
<td>2166.90</td>
<td>2563.84</td>
<td>2637.89</td>
</tr>
<tr>
<td>11</td>
<td>Mechanical power output</td>
<td>kW</td>
<td>1460.92</td>
<td>1464.10</td>
<td>1514.57</td>
</tr>
<tr>
<td>12</td>
<td>Main pump and Booster pump efficiency</td>
<td>%</td>
<td>67.42</td>
<td>57.09</td>
<td>57.40</td>
</tr>
<tr>
<td>13</td>
<td>Overall efficiency</td>
<td>%</td>
<td>62.70</td>
<td>52.73</td>
<td>53.05</td>
</tr>
<tr>
<td>14</td>
<td>Specific Energy Consumption</td>
<td>kWh/m³/h of FW flow</td>
<td>7.16</td>
<td>7.76</td>
<td>8.64</td>
</tr>
<tr>
<td>15</td>
<td>Specific Auxiliary Power</td>
<td>% of plant load</td>
<td>2.74</td>
<td>3.31</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Increased power due to increased FW flow</td>
<td>kW</td>
<td>-</td>
<td>481.95</td>
<td>309.28</td>
</tr>
<tr>
<td>17</td>
<td>Reduction in power due to reduced pressure gain</td>
<td>kW</td>
<td>-</td>
<td>-476.91</td>
<td>-190.22</td>
</tr>
<tr>
<td>18</td>
<td>Increased power due to poor overall (motor+pump) efficiency</td>
<td>kW</td>
<td>-</td>
<td>440.88</td>
<td>405.18</td>
</tr>
</tbody>
</table>

b) average predicted Power input i.e., 2.74 % at 80.95 % PLF. The power input is even above the economical operating band i.e., 2.71 – 2.74 %.

c) The main reason for increase of FW flow is mainly due to passing in re-circulation valve and higher specific steam consumption of turbines.

d) Since BFP is the multistage high pressure pump during start-up of the pump, the FW flow is bypassed to deaerator through re-circulation valve. During normal operation of the plant, the re-circulation valve will be closed. But due to passing in these valves, the FW flow is increased in BFP. The additional FW flow increases the power of BFP. The replacement of valve seat of re-circulation valve for both pumps reduced the power of BFP by 0.30 MU/month. The reduction in specific auxiliary power is 0.25 % of plant load.

e) The pump efficiencies are in the range of 57.09 to 57.40 % and are lower compared to predicted pump efficiency at 80.95 % PLF of 67.42 %. The pump efficiency is low due to more clearances inside the pump. The pump impeller set (cartridge set) is replaced in both pumps. The replacement of BFP cartridge had enhanced the pump efficiency by average of 7 % (Mukherjee S et al., 2008) and had reduced the power of BFP by 0.40 MU/month. The investment for replacing the pump cartridge is $ 75,000 and payback period is 5 months. The reduction in specific auxiliary power is 0.32 % of plant load.

The performance test is conducted at an average plant load of 210 MW (PLF: 100 %). The observations from the study are as follows:

a) The total power input for both BFPS is 6239.05 kW (2.97 % plant load) and is higher than the average predicted Power input i.e., 2.46 % at 100 % PLF. The power input is even above the economical operating band i.e., 2.43 – 2.49 %.

b) The increased power due to higher pressure drop across High Pressure (HP) Heaters is 10.45 kW, across Feed Regulating Station (FRS) is 87.11 kW, across Economizer is 3.48 kW and across Water walls and super-heaters (SH) is 20.91 kW. The power change due to higher pressure available at Boiler outlet is 59.23 kW. The net power increased due to change in pressure drop.

Table 2 gives the performance results of BFPS at Unit 3 at Guru Gobind Singh Super Thermal Power Station (RGGSTPS), Rupnagar, Punjab, India (CPRI, 2011).
Table 2. Performance Results of BFPS at RGGSTPS.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Particulars</th>
<th>Unit</th>
<th>Predicted value at 100% PLF</th>
<th>BFP 3A</th>
<th>BFP 3B</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Plant load</td>
<td>MW</td>
<td>-</td>
<td>210.0</td>
<td></td>
</tr>
<tr>
<td>02</td>
<td>BFP Motor rating</td>
<td>MW</td>
<td>4.00</td>
<td>4.00</td>
<td>4.00</td>
</tr>
<tr>
<td>02</td>
<td>BFP Pump (Booster) suction pressure</td>
<td>MPa</td>
<td>-</td>
<td>0.56</td>
<td>0.56</td>
</tr>
<tr>
<td>03</td>
<td>BFP discharge Pressure</td>
<td>MPa</td>
<td>-</td>
<td>17.90</td>
<td>18.60</td>
</tr>
<tr>
<td>04</td>
<td>Pressure gain</td>
<td>MPa</td>
<td>17.16</td>
<td>17.34</td>
<td>18.04</td>
</tr>
<tr>
<td>05</td>
<td>Pressure drop across HP heaters</td>
<td>MPa</td>
<td>0.25</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>06</td>
<td>Pressure drop across FRS</td>
<td>MPa</td>
<td>0.10</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>07</td>
<td>Pressure drop across Economizer</td>
<td>MPa</td>
<td>0.15</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>08</td>
<td>Pressure drop across water wall and SH</td>
<td>MPa</td>
<td>1.25</td>
<td>1.31</td>
<td>1.31</td>
</tr>
<tr>
<td>09</td>
<td>Pump discharge FW flow</td>
<td>m³/h</td>
<td>391.03</td>
<td>394.56</td>
<td>390.63</td>
</tr>
<tr>
<td>10</td>
<td>Re-circulation flow</td>
<td>m³/h</td>
<td>-</td>
<td>1.29</td>
<td>38.18</td>
</tr>
<tr>
<td>11</td>
<td>Total FW flow in pump</td>
<td>m³/h</td>
<td>391.03</td>
<td>395.85</td>
<td>428.81</td>
</tr>
<tr>
<td>12</td>
<td>Electrical power</td>
<td>kW</td>
<td>2578.45</td>
<td>3022.19</td>
<td>3216.86</td>
</tr>
<tr>
<td>13</td>
<td>Load factor of motor</td>
<td>%</td>
<td>59.95</td>
<td>70.05</td>
<td>65.94</td>
</tr>
<tr>
<td>14</td>
<td>Motor efficiency</td>
<td>%</td>
<td>93.00</td>
<td>92.72</td>
<td>92.91</td>
</tr>
<tr>
<td>15</td>
<td>Electrical power input to pump</td>
<td>kW</td>
<td>2397.96</td>
<td>2802.17</td>
<td>2988.78</td>
</tr>
<tr>
<td>16</td>
<td>Mechanical power output</td>
<td>kW</td>
<td>1828.50</td>
<td>1464.10</td>
<td>2107.99</td>
</tr>
<tr>
<td>17</td>
<td>Main pump and Booster pump efficiency</td>
<td>%</td>
<td>76.25</td>
<td>66.75</td>
<td>70.93</td>
</tr>
<tr>
<td>18</td>
<td>Overall efficiency</td>
<td>%</td>
<td>70.91</td>
<td>61.89</td>
<td>65.53</td>
</tr>
<tr>
<td>19</td>
<td>Specific Energy Consumption</td>
<td>kWh/m³/h of FW flow</td>
<td>6.59</td>
<td>7.63</td>
<td>7.50</td>
</tr>
<tr>
<td>20</td>
<td>Specific Auxiliary Power</td>
<td>% of plant load</td>
<td>2.46</td>
<td>2.97</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Increased power due to higher Pr. Drop across HP heaters</td>
<td>kW</td>
<td>-</td>
<td>4.56</td>
<td>5.89</td>
</tr>
<tr>
<td>22</td>
<td>Increased power due to higher Pr. Drop across FRS</td>
<td>kW</td>
<td>-</td>
<td>38.01</td>
<td>49.10</td>
</tr>
<tr>
<td>23</td>
<td>Increased power due to higher Pr. Drop across Economizer</td>
<td>kW</td>
<td>-</td>
<td>1.52</td>
<td>1.96</td>
</tr>
<tr>
<td>24</td>
<td>Increased power due to higher Pr. Drop across Water walls and SH</td>
<td>kW</td>
<td>-</td>
<td>9.13</td>
<td>11.78</td>
</tr>
<tr>
<td>25</td>
<td>Reduction in power due to reduced net pressure gain at boiler outlet</td>
<td>kW</td>
<td>-</td>
<td>-25.85</td>
<td>-33.38</td>
</tr>
<tr>
<td>26</td>
<td>Increased power due to passing in re-circulation valve</td>
<td>kW</td>
<td>-</td>
<td>8.59</td>
<td>315.47</td>
</tr>
<tr>
<td>27</td>
<td>Increased power due to increase in FW flow (higher SSC)</td>
<td>kW</td>
<td>-</td>
<td>23.51</td>
<td>-3.30</td>
</tr>
<tr>
<td>28</td>
<td>Increased power due to poor overall (motor+pump) efficiency</td>
<td>kW</td>
<td>-</td>
<td>384.27</td>
<td>290.89</td>
</tr>
<tr>
<td>29</td>
<td>Net increase in power</td>
<td>kW</td>
<td>-</td>
<td>443.74</td>
<td>638.41</td>
</tr>
</tbody>
</table>

c) across feed water circuit elements is 62.72 kW that forms 0.03% of plant load.

d) Reducing the pressure drop across HP heaters by acid cleaning of HP heater tubes reduced the pressure drop from average value of 0.28 MPa to 0.24 MPa. This had reduced the auxiliary power of BFP by 6.5 MWh/month. The investment is $3,500 and the payback period is 11 months.

e) Reducing the pressure drop across FRS from an average value of 0.35 MPa to 0.10 MPa by operational optimization i.e., reducing the pressure drop across feed control valve, will reduce the auxiliary power of BFP by 50.2 MWh/month.

f) The replacement of valve seat of re-circulation valve for BFP 3B reduced the power of BFP 3B by 0.18 MU/month. The investment for replacing the valve seat of re-circulation valve is $3,000 and payback period is 4 months. The reduction in specific auxiliary power is 0.12% of plant load.

g) The pump efficiencies are in the range of 66.75 to
70.53 % and are lower compared to predicted pump efficiency at 100 % PLF of 76.25 %. The pump efficiency is low at BPF 3A due to more clearances inside the pump. The pump impeller set (cartridge set) is replaced for BFP 3A. The replacement of BFP cartridge had enhanced the pump efficiency by average of 7 % and had reduced the power of BFP by 0.14 MU/month. The investment for replacing the pump cartridge is $37,500 and payback period is 6 months. The reduction in specific auxiliary power is 0.12 % of plant load.

CONCLUSIONS

The specific auxiliary power of BFP at 100 % PLF is about 2.46 % of gross energy generation and is increased for operating the plant at reduced PLF of 70 % which is 2.87 % of gross energy generation. Reducing the passing in re-circulation valve will reduce the auxiliary power of BFP in the range of 10 – 15 % of BFP power and 0.2 – 0.4 % of gross energy generation (CO₂ reduction of about 3,400 – 7,200 t/year for one 210 MW plant). Improvement of pump efficiency by changing the impeller will enhance the BFP efficiency by about 7 – 10 % that will reduce the auxiliary power of BFP by 0.40 MU/month for one 210 MW plant. Operational optimization of BFPs and implementation of energy conservation measures for BFPs will reduce the auxiliary power of BFPs in Indian Thermal Power Generating Sector by about 480 MW and equivalent reduction of CO₂ emission is 3.9 million tonne per year.

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Abbreviation

| A          | Current step used in ANN |
| ANN       | Artificial Neural Network |
| AP        | Specific Auxiliary Power |
| BFP       | Boiler feed pump |
| D         | Data |
| E         | Error |
| ECO       | Economizer |
| FRS       | Feed Regulating Station |
| FW        | Feed Water |
| HP        | High Pressure |
| HPH       | High Pressure Heater |
| HPT       | High Pressure Turbine |
| HT        | High Tension |
| MCR       | Maximum Continuous Rating |
| MDBFP     | Motor Driven Boiler Feed Pump |

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Enhancing energy efficiency of boiler feed pumps in thermal power plants through operational optimization and energy conservation


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