STEAM DRIVEN BOILER FEED PUMPS FOR LAKVIJAYA POWER STATION, SRI LANKA

By

B. H. Wanasinghe

2016
Abstract

Energy saving in coal power plants is a popular topic in present days with the global energy crisis. Internal electricity demand or auxiliary power consumption is an energy portion related with equipment supportive to the main equipment, which is unavoidable but with a proper investigation, some amount of this energy can be saved either by introducing thermally efficient auxiliary equipment or improving efficiencies of available equipment.

Out of the various auxiliary equipment, the driving motor of boiler feed pump is the largest power consumer of internal electricity demand in 3x300 MW sub-critical Lakvijaya Power Station in Sri Lanka. So it is obvious that prime movers of feed pumps could be contributed for a large percentage of the losses. So it was decided to find out how to minimize the losses related to Boiler Feed Pump (BFP) system using small steam turbine to drive the BFP.

The widely used alternatives for the BFP drivers are condensing type and back pressure type steam turbines. Eleven (11) different configurations of Condensing type, back pressure type and also extraction back pressure type turbines were considered and software programs for each configuration were implemented using Engineering Equation Solver (EES) software. The considered
configurations are different to each other by inlet steam thermodynamic parameters, steam flow rate, exhaust thermodynamic steam parameters and intermediate extraction parameters etc.

Thermodynamic analysis ended up with interesting solutions while all the configurations are giving improved efficiencies than existing electrical motor driven mode. But some of them had not improved their net output and hence there were no gain in net generator power output although the efficiencies are higher. Out of other configurations with improved net output and efficiency, the case with back pressure turbine arranged parallel to the HP turbine had the highest net output gain with better improvement in efficiency without changing the input power to the boiler. Considering the CO₂, SOx and NOx emissions, it was cleared that power plant with suggested BFP modes will give more clean energy than existing power plant.

Considering the partial loads behavior it was observed that power plant with Back pressure turbine, steam extracted from HP turbines inlet for prime movers of boiler feed pumps is more thermodynamically economical than existing power plant.

Annual financial saving with BFP configurations with positive net output gain and zero boiler input gain were calculated and it will be in between 0.46 and 2.72 UDS million / Year.
Declaration

The work submitted in this thesis is the result of my own investigation, except where otherwise stated.

It has not already been accepted for any other degree and is also not being concurrently submitted for any other degree.

B. H. Wanasinghe

Date

We/I endorse declaration by the candidate.

Prof. Andrew Martin,

Dr. N. S. Senanayake

Eng. Ruchira Abeyweera
Acknowledgement

It is pleasure to submit this thesis report of my master thesis and I would like to convey my heartiest thank to following people.

Initially I would like to convey my gratitude **Department of Energy Technology, Royal Institute of Technology (KTH), Sweden** for offering the DSEE program to Sri Lanka and exposing the world of Sustainable Energy Engineering and specially granting me this opportunity to do my master thesis. I really thank to all the staff members of KTH, who were involved to the DSEE program and contributed their valuable support for successful completion of this program.

Special thank should be done for Prof. Andrew Martin, Main KTH supervisor my thesis for giving necessary advice on time and helping me in all the way to be successive.

It is my great pleasure to mention about Dr. Nihal Senanayake and Mr. Ruchira Abeyweera, local supervisors of the thesis, for spending their valuable time for guiding me in correct path through my thesis and doing necessary corrections in the thesis report.

Then my heartfelt thanking goes to my wife Nisansala, for encouraging and giving me the freedom and utmost support to complete this successfully and loving daughter Sethunya for giving freedom to complete the task sacrificing the time to be spent with her.

I must be thankful to all the coworkers of Puttalam Coal Power Project and Lakvijaya Power Station who gave me a big support when collecting data of the power plant.

Finally I must convey my thanks to the academic staff of the Open University of Sri Lanka who were in the panel board of the thesis presentations for giving their valuable comments to do the necessary corrections of my works.
# Nomenclature

<table>
<thead>
<tr>
<th>Appellation</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enthalpy</td>
<td>h</td>
<td>(kJ/kg)</td>
</tr>
<tr>
<td>Entropy</td>
<td>s</td>
<td>(kJ/(kg.K))</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>(°C)</td>
</tr>
<tr>
<td>Mass flow rate</td>
<td>(\dot{m})</td>
<td>(kg/h)</td>
</tr>
<tr>
<td>Pressure</td>
<td>p</td>
<td>(kPa)</td>
</tr>
<tr>
<td>Power</td>
<td>P</td>
<td>(MW)</td>
</tr>
<tr>
<td>Heat Rate</td>
<td>HR</td>
<td>(kJ/kWh)</td>
</tr>
<tr>
<td>Efficiency</td>
<td>(\eta)</td>
<td>(%)</td>
</tr>
<tr>
<td>Heat</td>
<td>Q</td>
<td>(MW)</td>
</tr>
</tbody>
</table>

# List of abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>APH</td>
<td>Air Pre Heater</td>
</tr>
<tr>
<td>BFP</td>
<td>Boiler Feed Pump</td>
</tr>
<tr>
<td>BFPM</td>
<td>Boiler Feed Pump Motor</td>
</tr>
<tr>
<td>BFPT</td>
<td>Boiler Feed Pump Turbine</td>
</tr>
<tr>
<td>BOP</td>
<td>Balance Of Plant</td>
</tr>
<tr>
<td>BPT</td>
<td>Back Pressure Turbine</td>
</tr>
<tr>
<td>CCCW</td>
<td>Closed Cycle Cooling Water</td>
</tr>
<tr>
<td>CEP</td>
<td>Condensate Extraction Pump</td>
</tr>
<tr>
<td>COND</td>
<td>Condenser</td>
</tr>
<tr>
<td>CRH</td>
<td>Cold Re-heat</td>
</tr>
<tr>
<td>CT</td>
<td>Condensing Turbine</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>DRTR</td>
<td>De-aerator</td>
</tr>
<tr>
<td>EBPT</td>
<td>Extraction Back Pressure Turbine</td>
</tr>
<tr>
<td>EES</td>
<td>Engineering Equation Solver</td>
</tr>
<tr>
<td>EM</td>
<td>Electric Motor</td>
</tr>
<tr>
<td>ESP</td>
<td>Electrostatic Precipitator</td>
</tr>
<tr>
<td>FDF</td>
<td>Forced Draft Fan</td>
</tr>
<tr>
<td>FGD</td>
<td>Flue Gas De-Sulfurizer</td>
</tr>
<tr>
<td>HPH</td>
<td>High Pressure Heater</td>
</tr>
<tr>
<td>HPT</td>
<td>High Pressure Turbine</td>
</tr>
<tr>
<td>HR</td>
<td>Heat Rate</td>
</tr>
<tr>
<td>HRH</td>
<td>Hot Re-heat</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating Ventilation and Air Conditioning</td>
</tr>
<tr>
<td>IDF</td>
<td>Induced Draft Fan</td>
</tr>
<tr>
<td>IPP</td>
<td>Independent Power Producers</td>
</tr>
<tr>
<td>IPT</td>
<td>Intermediate Pressure Turbine</td>
</tr>
<tr>
<td>LPH</td>
<td>Low Pressure Heater</td>
</tr>
<tr>
<td>LPT</td>
<td>Low Pressure Turbine</td>
</tr>
<tr>
<td>LVPS</td>
<td>Lakvijaya Power Station</td>
</tr>
<tr>
<td>MCW</td>
<td>Main Cooling Water</td>
</tr>
<tr>
<td>NPSH</td>
<td>Net Positive Suction Head</td>
</tr>
<tr>
<td>OCCW</td>
<td>Open Cycle Cooling Water</td>
</tr>
<tr>
<td>PAF</td>
<td>Primary Air Fan</td>
</tr>
<tr>
<td>SAF</td>
<td>Seal Air Fan</td>
</tr>
<tr>
<td>TRL</td>
<td>Turbine Rated Load</td>
</tr>
</tbody>
</table>
Table of Contents

Abstract ..................................................................................................................................................................I

Declaration.......................................................................................................................................................... III

Acknowledgement ............................................................................................................................................IV

Nomenclature ...................................................................................................................................................... V

List of abbreviations ........................................................................................................................................... V

Table of Figures .................................................................................................................................................IX

List of Tables ......................................................................................................................................................XI

1. Introduction ................................................................................................................................................ 1
   1.1. Background ......................................................................................................................................... 1
   1.2. Problem statement ............................................................................................................................. 6
   1.3. Objectives ........................................................................................................................................... 8

2. Methodology ............................................................................................................................................... 9

3. Literature Review ..................................................................................................................................... 10

4. Methods ..................................................................................................................................................... 13
   4.1. Identifying the current system ............................................................................................................. 13
       4.1.1. General description ................................................................................................................ 13
       4.1.2. Booster pump .......................................................................................................................... 13
       4.1.3. Main Boiler Feed Pump ......................................................................................................... 14
       4.1.4. Gear Box and Turbo Coupling ............................................................................................ 14
       4.1.5. Electric motor ......................................................................................................................... 14
       4.1.6. Technical Data ........................................................................................................................ 14
4.2. Calculations ....................................................................................................................................... 16

4.2.1. Selection of BFP driver configurations ............................................................................... 16

4.2.2. Assumptions ............................................................................................................................ 23

4.2.3. Sample calculation .................................................................................................................. 23

5. Results and Analysis ................................................................................................................................ 29

5.1. Thermodynamic analysis ................................................................................................................ 29

5.2. Emission Analysis ............................................................................................................................ 34

5.3. Part load behavior ............................................................................................................................ 36

5.4. Selecting the no of feed water pumps .......................................................................................... 40

5.5. Selecting Pump and Turbine arrangement .................................................................................. 40

5.6. Financial Economic analysis of BFP drivers ............................................................................... 41

5.6.1. Financial saving with steam driven BFP ............................................................................. 41

5.6.2. Detailed financial analysis ..................................................................................................... 43

6. Conclusion ................................................................................................................................................ 44

7. Annexurs ................................................................................................................................................... 46

7.1. EES program for thermodynamic analysis of steam cycle with available EM driven BFP configuration............................................................................................................................................. 46

7.2. EES program for thermodynamic analysis of steam cycle with steam driven BFP configuration (CT-A)............................................................................................................................................................. 50

7.3. EES program for thermodynamic analysis of steam cycle with steam driven BFP configuration (BPT-A)................................................................................................................................................................. 55

7.4. EES program for thermodynamic analysis of steam cycle with steam driven BFP configuration (EBPT-B).............................................................................................................................................................. 60

7.5. EES program for thermodynamic analysis of steam cycle with steam driven BFP configuration-BPT-A for 75% of TRL ..................................................................................................................................................... 65
Table of Figures

Figure 1-1 Steam cycle of the power plant ................................................................................................................. 4

Figure 1-2 T-s Diagram of the Steam cycle ................................................................................................................... 5

Figure 1-3 h-s diagram of steam cycle ........................................................................................................................ 5

Figure 4-1 General arrangement and Flow diagram of BFP unit .................................................................................... 13

Figure 4-2 Selected points to feed steam to BFPT ........................................................................................................ 17

Figure 4-3 CT-A: Condensing Turbine as BFP drive, fed steam from HP turbine inlet .............................................. 17

Figure 4-4 CT-B: Condensing Turbine as BFP drive, fed steam from HP turbine outlet ............................................. 18

Figure 4-5 CT-C: Condensing Turbine as BFP drive, fed steam from IP turbine inlet ................................................. 18

Figure 4-6 BPT-A: Back Pressure Turbine as BFP drive, fed steam from HP turbine inlet and exhausted to HPT outlet .................................................................................................................................................. 19

Figure 4-7 CT-D: Condensing Turbine as BFP drive, fed steam from LP turbine inlet .............................................. 19

Figure 4-8 BPT-C1: Back Pressure Turbine as BFP drive, fed steam from IP turbine inlet and exhausted to IPT outlet .................................................................................................................................................. 20

Figure 4-9 BPT-C2: Back Pressure Turbine as BFP drive, fed steam from IP turbine inlet and exhausted to additional heater in between LPH 6 & 7 ........................................................................................................................................ 20

Figure 4-10 EBPT-B: Back Pressure Turbine as BFP drive, fed steam from HP turbine outlet and bleed to LPH 5 and remaining exhausted to LPH 6. Balance to LPH 6 is from LPT. No extraction to LPH5 from LPT ........................................................................................................................................ 21

Figure 4-11 EBPT-C1: Back Pressure Turbine as BFP drive, fed steam from IP turbine inlet and bleed to LPH 5 and remaining exhausted to LPH 6. Balance to LPH 6 is from LPT. No extraction to LPH5 from LPT ........................................................................................................................................ 21
Figure 4-12 EBPT-C2: Back Pressure Turbine as BFP drive, fed steam from IP turbine inlet and bleed to LPH 4 (De-aerator) and remaining exhausted to additional heater in between LPH 6 & 7. No extraction to LPH4 from IPT

Figure 4-13 EBPT-C3: Back Pressure Turbine as BFP drive, fed steam from IP turbine inlet and bleed to LPH 6 and remaining exhausted to additional heater in between LPH 6 & 7. No extraction to LPH5 from LPT

Figure 5-1 Variation of Plant efficiency with BFP driver configuration

Figure 5-3 Variation of Heat Gain in boiler with BFP driver configuration

Figure 5-2 Gross and Net heat rates of each BFP driver Configuration

Figure 5-4 Comparison of Power gain, Heat gain and Plant efficiency with BFP driver configuration

Figure 5-5 Comparison of Equivalent electrical power consumption of BFPTs

Figure 5-6 Variation of Net power output with BFP driver configuration

Figure 5-7 BFP Turbine and pump arrangement - Option 01

Figure 5-8 BFP Turbine and pump arrangement - Option 02
List of Tables

Table 1-1 List of Abbreviations used in figures .......................................................... 2

Table 1-2: Available grid capacities and Annual generation by source in Sri Lanka (Central Bank of Sri Lanka, 2010) .......................................................... 3

Table 1-3 Internal Electricity Demand distribution among auxiliaries in LVPS ............... 7

Table 1-4 Internal electricity demand distribution of pumps in LVPS .............................. 8

Table 4-1 Technical Data of electric motor (SPEM, 2009) ............................................. 14

Table 4-2 Technical Data of booster pump (SPEM, 2009) ............................................. 14

Table 4-3 Technical Data of Boiler feed pump (SPEM, 2009) ....................................... 15

Table 4-4 Technical Data of Turbo coupling (SPEM, 2009) ........................................... 15

Table 4-5 Selection of cases to be modeled ..................................................................... 16

Table 4-6 Data used for emission factors calculation ...................................................... 27

Table 4-7 Input data to the EES program (inlet conditions of extraction steam to heaters) (HTC, 2006) .......................................................... 27

Table 4-8 Input data to the EES Program (Thermodynamic parameters of the steam cycle) (HTC, 2006) .......................................................... 28

Table 4-9 Input data to the EES program (other important data) ..................................... 28

Table 5-1 Variation of some important parameters with BFP Configuration ................... 30

Table 5-2 Remarks on Each Case considered .................................................................. 34

Table 5-3 Input data to the EES program for Partial Loads (inlet conditions of extraction steam to heaters) (HTC, 2006) .......................................................... 37

Table 5-4 Input data to the EES Program for Partial Loads (HTC, 2006) ......................... 37

Table 5-5 Input data to the EES program (other important data) ..................................... 37

Table 5-6 Results obtained with Partial Loads ............................................................... 39
Table 5-7 Annual financial Saving of each BFP configuration ................................................................. 42

Table 5-8 Average Unit cost of Thermal Power Plant in Sri Lanka – 2014 (PUCSL, Generation Performance in Sri Lanka – 2014; 2014) ........................................................................................................................................ 42
1. Introduction

1.1. Background

Sri Lanka is a small island, having 65,610 km² of area and around 20,966,000 of population (by 2015) located in the Indian Ocean, within the geographical coordinates of 6.9167° N and 79.8333° E. Since there is no any proven fossil fuel, energy demand of the country is mainly dependent on hydropower and imported petroleum based thermal power.

World is facing an energy crisis since the global oil and gas reserves will not be last beyond the next 50 to 70 years, and extracting the remaining reserves will not be economical. But it is expected that the global coal reserves will be last for the next 500 years. By considering the electricity data of Sri Lanka in past few years (Table 1-2) it is clear that the thermal and hydro power play major roles in power generation in Sri Lanka.

Currently the hydropower potential of country is almost saturated and then thermal power production will be significant in near future. Since the power generation by using oil and gas is further not viable and economical, the only available thermal fuel option for base load power generation in Sri Lanka is coal.

To fulfill the increasing demand on electricity, the Sri Lankan government launched a large-scale coal power project in Puttalam called “Puttalam Coal Power project”. The Puttalam Coal Power project having 900MW capacity (three similar units, each one having capacity of 300MW) was started in May 2006 and it is the first and largest Coal Power plant in Sri Lanka named as “Lakvijaya Power Station”, (LVPS). Currently all the three units are connected to the national grid bear around 45% from total power generation.

One power plant unit (300MW) majorly consists of the following items

- A steam boiler with rated steam capacity of 1025 ton/h at the pressure of 17.5 MPa and the temperature of 541 °C
- Five coal pulverizers
- An Electrostatic precipitator (ESP) unit to remove fly ash
- A Flue Gas De-sulfurizer (FGD) unit to remove SO₂
- A high pressure turbine (HPT)
- An intermediate pressure turbine (IPT)
- A low pressure turbine (LPT)
- A condenser cooled by sea water
- An electricity generator
- Four low pressure heaters
- A de-aerator
- Three high pressure heaters
- A condensate polishing unit

1 Coordinates of Colombo - the Capital city of Sri Lanka
• Two condensate pumps and
• Three boiler feed pumps (BFP)

The said boiler has the following characteristics

• steel-frame suspension structured
• Sub-bituminous pulverized coal- fired
• Having a drum
• Sub-critical parameters
• Natural circulation
• Single furnace
• Primary intermediate reheat
• Balanced draft
• Corner firing (four corner arrangement with sway burners)
• Tangent burning
• Dry ash extraction

The said Turbine has the following characteristics

• Sub-critical
• Primary intermediate reheat
• Single-shaft
• Double cylinders
• Double exhausts
• Impulse and Reaction type
• Condensing steam turbine

A flow diagram of the power plant is shown in Figure 1-1 below. Consider the abbreviations listed in table below for figures of steam cycle of the power plant throughout the report.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRTR</td>
<td>High Pressure Turbine</td>
</tr>
<tr>
<td>IPT</td>
<td>Intermediate Pressure Turbine</td>
</tr>
<tr>
<td>LPT</td>
<td>Low Pressure Turbine</td>
</tr>
<tr>
<td>HPH</td>
<td>High Pressure Heater</td>
</tr>
<tr>
<td>LPH</td>
<td>Low Pressure Heater</td>
</tr>
<tr>
<td>DRTR</td>
<td>De-aerator</td>
</tr>
<tr>
<td>BFP</td>
<td>Boiler Feed Pump</td>
</tr>
<tr>
<td>BFPT</td>
<td>Boiler Feed Pump Turbine</td>
</tr>
<tr>
<td>COND</td>
<td>Condenser</td>
</tr>
</tbody>
</table>
Table 1-2: Available grid capacities and Annual generation by source in Sri Lanka (Central Bank of Sri Lanka, 2010)

<table>
<thead>
<tr>
<th>Year</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydro</td>
<td>1207</td>
<td>1207</td>
<td>1207</td>
<td>1207</td>
<td>1207</td>
<td>1357</td>
<td>1361</td>
<td>1361</td>
<td>1377</td>
<td>1377</td>
</tr>
<tr>
<td>Fuel Oil(^2)</td>
<td>548</td>
<td>548</td>
<td>548</td>
<td>548</td>
<td>554</td>
<td>554</td>
<td>564</td>
<td>544</td>
<td>604</td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>900</td>
<td>900</td>
</tr>
<tr>
<td>Other</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Private</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydro - Small</td>
<td>107</td>
<td>117</td>
<td>138</td>
<td>172</td>
<td>175</td>
<td>194</td>
<td>227</td>
<td>267</td>
<td>288</td>
<td>307</td>
</tr>
<tr>
<td>Fuel Oil(^3)</td>
<td>567</td>
<td>567</td>
<td>737</td>
<td>742</td>
<td>842</td>
<td>842</td>
<td>784</td>
<td>771</td>
<td>671</td>
<td>511</td>
</tr>
<tr>
<td>Other</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>12</td>
<td>42</td>
<td>48</td>
<td>87</td>
<td>96</td>
<td>150</td>
<td>149</td>
</tr>
<tr>
<td>Maximum Demand, MW</td>
<td>1893</td>
<td>1842</td>
<td>1922</td>
<td>1868</td>
<td>1955</td>
<td>2163</td>
<td>2146</td>
<td>2164</td>
<td>2152</td>
<td>2283</td>
</tr>
<tr>
<td>Units Generated, GWh</td>
<td>9389</td>
<td>9814</td>
<td>9901</td>
<td>9882</td>
<td>10714</td>
<td>11528</td>
<td>11801</td>
<td>11898</td>
<td>12357</td>
<td>13090</td>
</tr>
<tr>
<td>CEB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydro</td>
<td>4290</td>
<td>3603</td>
<td>3700</td>
<td>3356</td>
<td>4988</td>
<td>4018</td>
<td>2727</td>
<td>5990</td>
<td>3632</td>
<td>4904</td>
</tr>
<tr>
<td>Fuel Oil</td>
<td>1669</td>
<td>2336</td>
<td>2083</td>
<td>2091</td>
<td>1394</td>
<td>1494</td>
<td>2029</td>
<td>1283</td>
<td>1696</td>
<td>1501</td>
</tr>
<tr>
<td>Coal</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1038</td>
<td>1404</td>
<td>1469</td>
<td>3202</td>
<td>4443</td>
</tr>
<tr>
<td>Other</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Private</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydro - Small</td>
<td>345</td>
<td>344</td>
<td>428</td>
<td>525</td>
<td>646</td>
<td>601</td>
<td>565</td>
<td>916</td>
<td>902</td>
<td>1064</td>
</tr>
<tr>
<td>Fuel Oil</td>
<td>3082</td>
<td>3528</td>
<td>3680</td>
<td>3883</td>
<td>3601</td>
<td>4253</td>
<td>4906</td>
<td>1977</td>
<td>2610</td>
<td>1225</td>
</tr>
<tr>
<td>Other</td>
<td>-</td>
<td>-</td>
<td>6</td>
<td>23</td>
<td>83</td>
<td>121</td>
<td>168</td>
<td>260</td>
<td>313</td>
<td>401</td>
</tr>
</tbody>
</table>

\(^1\) Provisional
\(^2\) Data from 2011 had been split as fuel oil and coal power, as coal power generation commenced in 2011. Up to 2013, both fuel oil based power and coal based power were considered as thermal power
\(^3\) Inclusive of Independent Power Producers (IPP)
Consider the operation process of the power plant simply which runs according to the Regenerative, Reheat Rankine Cycle. Pulverized coal from coal pulverizers is sent to the boiler and superheated steam is generated in the boiler by means of heat of fired coal. Superheated steam is initially sent to the High pressure turbine and turbine exit steam is sent again to the boiler for the purpose of reheating. Reheated steam is sent to the intermediate pressure turbine and that exit steam is directly sent to the low pressure turbine.

All the three turbines are coaxially connected as a single shaft and the electricity generator is also connected to that shaft itself. The outlet of the LP turbine is directed to the condenser. Condensate from the condenser is pumped to the condensate polishing unit by using a condensate pump. Polished condensate from the polishers is sent to the LP heater no 8 and then to no 7, 6 and 5 respectively. Heated condensate from LP heaters is sent to the de-aerator and condensate from de-aerator is pumped to high pressure heater no 03, and then to no 02 and 01 HP heaters using two boiler feed pumps. (After the Feed pumps the condensate is named as feed water.)

In LP and HP heaters, condensate is indirectly heated using steam extracted from different levels of different turbines. De-aerator is a mixing type heat exchanger having both functions of heating of condensate and expelling dissolve oxygen from the condensate. Feed water from HP heater 01 is sent to the economizer in boiler and is heated using flue gas and then it is sent to boiler drum. Then the condensate is circulated from the boiler drum to down comers and then to water wall tubes and then again to boiler drum. Qualified dry saturated steam is separated from the boiler drum and then flown to super-heater panels. Superheated steam from super heater panels is sent to the HP turbine and the steam cycle is completed. A T-s diagram and a h-s diagram are shown in Error! Reference source not found. and Error! Reference source not found. below.
Figure 1-2 T-s Diagram of the Steam cycle

Figure 1-3 h-s diagram of steam cycle
1.2. Problem statement

The electric generator which has coaxially coupled to the steam turbine tandem produces the electric power and this power is defined as Gross Power output of the Power plant. For the various electric motor driven equipment and other electrical appliances, a significant fraction of that gross power output should be spent and that amount of that electricity is called as the house load or auxiliary power consumption or internal electricity demand of the power plant. In Lakvijaya Power station, about 30 MW out of 300MW of generator gross power output is consumed as the internal electricity demand. Then the net power output (difference between gross power output and internal electricity demand) will be nearly 270 MW.

Auxiliary power consumption of different sections of the power plant can be identified as follows. All the sub system of the power plant can be classified into four main systems as Turbine Plant, Boiler Section, Coal Handling system and Balance of Plant system (BOP).

Turbine section including Boiler Feed water Pumping system (BFP), the Condensate Extraction Pumping system (CEP), Main Cooling Cater system (MCW), Close Cycle Cooling Water system (CCCW), Open Cycle Cooling Water system (OCCW) and other related sub systems having several high capacity pumps such as CEP, Booster pumps and main BFP, MCW pumps, OCCW pumps, CCCW pumps etc consumes about 14.9 MW from the 30MW of internal electricity demand. Out of that power, BFP consumes about 9.6 MW to pump the feed water from de-aerator to boiler drum from suction pressure of 0.9 MPa to discharge pressure of 22 MPa. Other than that, Main cooling water system consumes about 3.2 MW for two-mixed flow vertical type MCW pumps having a flow capacity of 18m$^3$/s, for cooling the condenser.

Coal handling system having several unloading cranes, stacker-reclaimers, conveyer belts, coal crushers and pulverisers etc consumes about 1.1MW from internal electricity demand.

BOP section including water treatment system, Chlorination plant, Hydrogen generation plant, Chillers for HVAC, Air compressors and fire & service water pumps etc consumes about 3.6 MW from the auxiliary power consumption. Out of that power, water treatment system including Sea water pre-treatment plant, Sea water desalination plant, Boiler make up water treatment plant and consumes about 1.8 MW for the number of different types of pumps and other appliance which are involved with this system. About 1.75MW of auxiliary power goes to air compressor system chillers having a large number of compressors and chill water pumps, compressors etc.

Air and flue gas handling system of boiler, including various no of high capacity fans, pumps and other equipment such as, Forced Draft Fans (FDF), Induced Draft Fans (IDF), Primary Air Fans (PAF), Seal Air Fans, Air Pre-Heaters (APH), Absorber pumps, Booster fan and Aeration Fans for Flue Gas De-sulpurizer (FGD) etc consumes about 7.7 MW from the auxiliary power consumption.

Other than that various electrical equipment in the power plant including lifts, lights, small pumps and fans, tools and equipment used for maintenance works, office equipment etc also poses a significant amount of power from the internal electricity demand.
The said main auxiliary systems are essential to the power generation with correct functionality and coordination of boiler turbine and generator units and cannot be omitted. As described earlier auxiliary power consumption (~30 MW) of the power plant is 10% of gross power output (300 MW) of the plant. Even though 10% is shown as a small figure, its impotency can be identified when it is compared with the capacities of other power plants in Sri Lanka. Considering the capacities of power plants connected to the national grid this value can be equivalent to the full capacity of a hydro power plant or to the power capacity of 5 - 6 mini hydro plants or power capacity of a wind farm with 20 wind towers. Hence it is obvious that 1 MW saving from auxiliary power of a coal power plant is a huge saving for a country like Sri Lanka.

Since making zero, the internal electricity demand is impossible, reducing it by improving the efficiency or any other strategic way should be investigated via proper research. Instead of using internal electricity demand from generator output, if there is a way to operate the auxiliary equipment by using alternative power sources in a power plant it will cause to reduce the internal electricity demand and hence increase the net power output. This should be done while observing both technical and economic aspects of this problem.

Rather than considering all the auxiliary equipment, considering major component will be beneficial for this purpose. Consider the percentage composition of power consumption of each category as shown in Table 1-3.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Power Consumption (MW)</th>
<th>Percentage from internal electricity demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cranes</td>
<td>0.80</td>
<td>2.67%</td>
</tr>
<tr>
<td>Conveyor belts</td>
<td>1.05</td>
<td>3.50%</td>
</tr>
<tr>
<td>Coal crushers</td>
<td>1.00</td>
<td>3.33%</td>
</tr>
<tr>
<td>Pulverizers</td>
<td>1.35</td>
<td>4.50%</td>
</tr>
<tr>
<td>Pumps</td>
<td>18.50</td>
<td>61.66%</td>
</tr>
<tr>
<td>Fans</td>
<td>4.85</td>
<td>16.17%</td>
</tr>
<tr>
<td>Compressors</td>
<td>1.10</td>
<td>3.67%</td>
</tr>
</tbody>
</table>

The table emphasizes that power consumption of the motor driven pumps play a huge role in auxiliary power portion. Considering the Table 1-4, it is clear that out of the various types and amount of pumps in the power plant BFPs are the largest power consumer and responsible for about 30% of the auxiliary power consumption.

There are three boiler feed pumps (BFP) for one unit (300MW) which are used to pump the condensate water from the de-aerator to boiler drum through 3 high pressure heaters and the economizer. Out of these three pumps, two pumps are in operation while the other one is in standby condition (3X50%).
Table 1-4 Internal electricity demand distribution of pumps in LVPS

<table>
<thead>
<tr>
<th>Pump</th>
<th>Total power consumption, MW</th>
<th>As a percentage of load of pumps</th>
<th>As a percentage of internal electricity demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Makeup water transfer pump</td>
<td>0.10</td>
<td>0.57%</td>
<td>0.33%</td>
</tr>
<tr>
<td>Condensate water pumps</td>
<td>0.50</td>
<td>2.86%</td>
<td>1.67%</td>
</tr>
<tr>
<td>Booster pumps</td>
<td>0.85</td>
<td>4.86%</td>
<td>2.83%</td>
</tr>
<tr>
<td>Main boiler feed water pumps</td>
<td>9.60</td>
<td>54.86%</td>
<td>32.00%</td>
</tr>
<tr>
<td>Condenser cooling pumps</td>
<td>2.80</td>
<td>16.00%</td>
<td>9.33%</td>
</tr>
<tr>
<td>FGD absorber pumps</td>
<td>0.55</td>
<td>3.14%</td>
<td>1.83%</td>
</tr>
<tr>
<td>Pumps in pre-treatment plant</td>
<td>0.45</td>
<td>2.57%</td>
<td>1.50%</td>
</tr>
<tr>
<td>Pumps in desalination plant</td>
<td>0.75</td>
<td>4.29%</td>
<td>2.50%</td>
</tr>
<tr>
<td>Pumps in Boiler make up water treatment plant</td>
<td>0.41</td>
<td>2.34%</td>
<td>1.37%</td>
</tr>
<tr>
<td>Pumps in firefighting system</td>
<td>0.58</td>
<td>3.31%</td>
<td>1.93%</td>
</tr>
</tbody>
</table>

Each BFP consumes around 5MW at full load condition and this is the largest power consuming motor in the power plant. So to produce 300MW, around 10 MW should be supplied to the BFP since two pumps should be operated to achieve this load. As the total auxiliary power consumption of the plant is around 30MW, 33.3% of the auxiliary power or in other way, 3.33% of the generator power output is used for the BFPs.

The cost of one kWh of energy generated in power plant is around 8 LKR (1 LKR= 0.006914 USD as at 01/01/2016) (Exchange-rates.org, 2016), i.e. the cost for the operation of the BFP is around 10,000 kW X 8 LKR/kWh = 80,000 LKR/h (553.12 USD/h). If a steam driven boiler feed water pump is used, instead of a motor driven boiler feed water pump, this cost could be reduced by some amount, because the energy losses in the Main Turbine, Generator, Transformers, Pump motors, fluid couplings can be saved. But on the other hand the initial installation cost, material cost and the operation and maintenance cost may increase since steam turbines are expensive than electric motors and the complexity of the operation.

1.3. Objectives

- Determine technical and economic feasibility of using steam driven boiler feed pumps in place of present electric motor driven pumps in a sub critical 300 MW coal power plant
- Identify most suitable configuration of steam driven boiler feed pump
2. Methodology

In this research, main objectives were to investigate the technical and economic feasibility of using steam driven boiler feed pumps in place of present electric motor driven pumps in a sub critical 300 MW coal power plant and identify most suitable configuration of steam driven boiler feed pump.

Initially, a literature survey was carried out to study about steam driven and motor driven BFPs with their merits and demerits and theoretical background of the steam driven feed water pumps. It was found out that both methods are widely used and both methods have advantages and disadvantages and wanted to investigate how it can be applicable to selected Lakvijaya Power Station.

All the data needed for the calculation was gathered by referring relevant documents in Lakvijaya Power station and an EES software program was created to the steam cycle of the plant with existing motor driven BFP. Then 11 different configurations of steam driven BFPs with different inlet and outlet conditions (different extraction points) and different turbine types were selected and the EES program was modified to those configurations.

The results from EES programs was analyzed and configurations with increased efficiency of BFP system with reduced power consumption and hence increased efficiency of power plant with increased net output were separated out.

Then different arrangements of BFPs (no of BFPs and their capacity) with suggested steam turbine driver and finally economic feasibility of using steam driven feed water system were discussed.
3. Literature Review

Many factors are affected to the driving mode of the boiler feed pump, such as thermal economy, operational reliability and simplicity, the investment to equipment, complexity of the structure etc. Out of these factors, thermal economy is one of the most important factors when choosing the driving mode of the BFP. It is well known that there are two main driving types of BFP that are electric motor driven and steam turbine driven.

According to the presentation of *Pumps in Steam Power Plants* (Subbarao, 2010) by Professor P M V Subbarao, Mechanical Engineering Department, IIT, Delhi, the designers and owners of coal-fired power plants in Western European countries prefer motor-driven pumps system to feed water for boiler since the internal efficiency of small steam turbines which drive feed water pumps in their countries is almost equivalent to the product of the efficiency of power transmission and internal efficiency of low-pressure cylinder of main steam turbine. On this premise, an integrated investment of motor-driven feed water pump system is lower than that of steam-driven feed water pump. Other people such as American, Russian and Japanese consider that steam-driven mode is superior to motor-driven mode. The cause of this choice is that the internal efficiency of the small steam turbines produced by companies in their countries is much higher than the product of the efficiency of power transmission and internal efficiency of low-pressure cylinder of main steam turbine. In other word, the net output of generating unit which has steam-driven feed water pumps is more than that of the same generating unit which feed water system is driven by electromotor.

Prof. Subbarao emphasizes in his presentation that steam turbine driven BFPs are better in performance than motor driven BFP by comparing Heat consumption rate (HR) and Equivalent work Efficiency (EWE). Generally HR is the key indicator to determine thermal economy of the turbine generator unit. From different point of view, it has two expression forms, one known as the gross heat rate, and the other called the net heat rate. **Heat consumption rate is defined as the amount heat which generates 1kW electricity by generating unit.** For different thermodynamic cycle, the formula of heat rate has different expression forms. The gross heat consumption rate for an intermediate reheat unit when the boiler water is fed by motor-driven pump, can be expressed as

\[
HR_{Gross, M} = \frac{\dot{m}_{\text{mainsteam}}(h_{\text{sup}} - h_{\text{fw}}) + \dot{m}_{\text{rhsteam}}(h_{\text{hrh}} - h_{\text{crh}})}{P_{Gen}}
\]

Where,

- \( HR_{Gross} \) = Gross Heat Consumption Rate in kJ/kWh
- \( \dot{m}_{\text{mainsteam}} \) = Main steam mass flow rate in kg/hr
- \( \dot{m}_{\text{rhsteam}} \) = Reheated steam mass flow rate in kg/hr
- \( h_{\text{sup}} \) = Enthalpy of Superheated steam in kJ/kg
- \( h_{\text{fw}} \) = Enthalpy of feed water in kJ/kg
- \( h_{\text{hrh}} \) = Enthalpy of Hot reheat steam in kJ/kg
- \( h_{\text{crh}} \) = Enthalpy of Coal reheat steam in kJ/kg
- \( P_{Gen} \) = Generator Power output in kW
The Net Heat consumption Rate can be expressed as Formula

\[ HR_{Net,M} = \frac{m_{\text{mainsteam}}(h_{\text{sup}} - h_{\text{fw}}) + m_{\text{rheateam}}(h_{\text{hrh}} - h_{\text{crh}})}{P_{\text{Gen}} - P_{\text{bfp}}} \]

Where,

\[ P_{\text{bfp}} = \text{Power consumption of boiler feed pumps in kW} \]

The gross heat consumption rate for an intermediate reheat unit when the boiler water is fed by steam-driven pump, can be expressed as

\[ HR_{\text{Gross,T}} = \frac{m_{\text{mainsteam}}(h_{\text{sup}} - h_{\text{fw}}) + m_{\text{rheateam}}(h_{\text{hrh}} - h_{\text{crh}})}{P_{\text{Gen}} + P_{\text{bfp}}} \]

The Net Heat consumption Rate can be expressed as Formula

\[ HR_{\text{Net,T}} = \frac{m_{\text{mainsteam}}(h_{\text{sup}} - h_{\text{fw}}) + m_{\text{rheateam}}(h_{\text{hrh}} - h_{\text{crh}})}{P_{\text{Gen}}} \]

The **Relative equivalent work efficiency rate** is defined that the ratio of power consumption of motor-driven pumps and electricity which can be generated in steam turbine by the equivalent enthalpy drops of the steam flow from extraction point entering into small steam turbine (SST). This definition can reflect thermal economy of energy owned by steam and electricity. The calculation method by equivalent work efficiency is easy to understand and be performed, simultaneously avoiding the computational precision difficulty of small steam turbine exhaust enthalpy.

Mr. Jerry Diorio, Senior Service Engineer, Siemens Demag Delaval, Hamilton, New Jersey, describes about factors to be considered when designing a Steam turbine for feed water pump in his paper of **Tutorial on steam turbine drivers for fossil and nuclear feed pump application** (Diorio, 2008).

According to Mr. Jerry mainly there are three factors to be considered when designing a steam turbine for feed water pump application: steam source, operating point of pump and start-up requirements. BFP turbines accept two separate and unique source of steam. The most common sources used are low pressure steam from the main unit crossover line between the high pressure and intermediate pressure turbine and high pressure steam from the boiler. The steam characteristics are determined by the external steam source supplying the steam, while the required power and speed are determined by the requirements of the pump. When considering the startup condition, startup can be achieved by using either the LP or HP inlet. This is normally dependent on the pressure level of the desired steam source.

The presentation of **Key Specification Points for Turbine Driven Boiler Feed Water Pumps Used in Super Critical and Ultra Super Critical Coal Fired Power Plants** (PE) by Mr. Ed Simmons PE, Shaw Power Division, is described about key specification for BFP turbine used in super critical and ultra supercritical coal power plants. Although our power plant is a sub critical one same specification may be applicable.
The first specification described in above presentation is purchasing a steam turbine not as a package with generator turbine. Because while purchasing the “turbine package” may save capital equipment dollars, but it may end up spending those same dollars during the design development and review. The second key specification is the arrangement of pumps and turbine. Some typical arrangements are

- 1 X 100% or 2 X 50% booster and boiler feed water pump. Turbine is in between speed reducer/booster pump and main pump (common)
- 1 X 100% or 2 X 50% Single drive turbine. Turbine drives main pump which in turn drives booster pump. This arrangement requires an abnormally long coupled shaft to allow for the removal of the BFP cartridge. (less common)
4. Methods
4.1. Identifying the current system
4.1.1. General description

The manufacture of the BFP unit is “Shanghai power equipment manufacture co.ltd; (SPEM), Shanghai, China”. It was founded in 1956 and subordinated to the State Grid Corporation of China. SPEM is a specialized power equipment manufacturing enterprise which integrates the research, design, manufacture and service into a whole (www.spem.com.cn, 2012).

Each pump set consists of a booster pump, directly driven from one end of the shaft of an electric motor, and a boiler feed pump driven from the opposite end of the motor shaft through a gear box and a variable speed turbo coupling. The drive is transmitted in each case through a spacer type flexible coupling.

The bearing in the booster pump, boiler feed pump, turbo coupling and in the motor are lubricated from the lubricating oil system incorporated in the turbo coupling.

Each pump, motor and turbo coupling is mounted on its own base plate, the individual base plates being secured to a common concrete foundation block.

![Figure 4-1 General arrangement and Flow diagram of BFP unit](image)

4.1.2. Booster pump

The booster pump is used to boost the inlet pressure of main pump to avoid cavitations due to low NPSH. The booster pump is a single-stage, double-suction impeller and horizontal and axial-split casing type, having the suction and discharge branches on the bottom casing half, thus allowing the pump internals to be removed without disturbing the suction and discharge pipe work or the alignment between the pump and the driving motor. The pump is sealed at the drive and non-drive ends by mechanical seals.

The bearing arrangement consists of a double tilting pad thrust and sleeve journal bearing at the non-drive end and a sleeve journal bearing at the drive end, each bearing being lubricated from the lubricant oil system associated with turbo coupling.
4.1.3. Main Boiler Feed Pump

The BFP has an integrated cartridge with the 6 stage-impeller. The pump’s internals can be withdrawn as a whole without interrupting alignment between the pump and its inlet and outlet line.

The pump is sealed at the drive and non-drive ends by mechanical seals. The seals are flushed by water in a closed circuit. This flushing water is cooled by passing through heat exchanger one per each heat exchanger being circulated with cooling water from an external source.

The bearing arrangement consists of a double tilting pad for thrust and sleeve journal bearing at the non-drive end and a sleeve journal bearing at the drive end, each bearing being lubricated from the lubricating oil system associated with the turbo coupling.

4.1.4. Gear Box and Turbo Coupling

The pump and the motor have connected via a gear box and turbo coupling. Rotational speed is stepped up by the gear box and stepped down to required level by the turbo coupling to achieve required pump pressure. The drive from the turbo coupling to the pump is transmitted through a flexible membrane type coupling.

4.1.5. Electric motor

Electric motor is a three phase induction type motor.

4.1.6. Technical Data

Some important technical data of booster pump, turbo coupling, BFP and electric motor are given below.

Table 4-1 Technical Data of electric motor (SPEM, 2009)

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>kW</td>
<td>5400</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>kV</td>
<td>6</td>
</tr>
<tr>
<td>Rated speed</td>
<td>rpm</td>
<td>1490</td>
</tr>
<tr>
<td>Efficiency</td>
<td>%</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Table 4-2 Technical Data of booster pump (SPEM, 2009)

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of stages</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>179.18</td>
</tr>
<tr>
<td>Suction pressure</td>
<td>MPa</td>
<td>0.939</td>
</tr>
<tr>
<td>Flow rate</td>
<td>m³/h</td>
<td>606.7(683.2)</td>
</tr>
<tr>
<td>Head</td>
<td>m</td>
<td>100</td>
</tr>
<tr>
<td>NPSH</td>
<td>m</td>
<td>3.97</td>
</tr>
<tr>
<td>Efficiency</td>
<td>%</td>
<td>82.6</td>
</tr>
<tr>
<td>Power at duty</td>
<td>kW</td>
<td>201.13</td>
</tr>
<tr>
<td>Speed</td>
<td>rpm</td>
<td>1490</td>
</tr>
</tbody>
</table>
Table 4-3 Technical Data of Boiler feed pump (SPEM, 2009)

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of stages</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>179.18</td>
</tr>
<tr>
<td>Suction pressure</td>
<td>MPa</td>
<td>0.939</td>
</tr>
<tr>
<td>Suction Flow rate</td>
<td>m³/h</td>
<td>606.7(683.20)</td>
</tr>
<tr>
<td>Discharge Flow rate</td>
<td>m³/h</td>
<td>563.7(634.78)</td>
</tr>
<tr>
<td>Head</td>
<td>m</td>
<td>2193.51</td>
</tr>
<tr>
<td>NPSH</td>
<td>m</td>
<td>37.47</td>
</tr>
<tr>
<td>Flow rate (inter-stage tapping)</td>
<td>m³/h</td>
<td>43 (48.42)</td>
</tr>
<tr>
<td>Inter stage pressure at 3rd stage</td>
<td>MPa</td>
<td>7.9</td>
</tr>
<tr>
<td>Efficiency</td>
<td>%</td>
<td>81.63</td>
</tr>
<tr>
<td>Power at duty</td>
<td>kW</td>
<td>4221.57</td>
</tr>
<tr>
<td>Speed</td>
<td>rpm</td>
<td>5358</td>
</tr>
</tbody>
</table>

Table 4-4 Technical Data of Turbo coupling (SPEM, 2009)

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input speed</td>
<td>rpm</td>
<td>1490</td>
</tr>
<tr>
<td>Output speed</td>
<td>rpm</td>
<td>5358</td>
</tr>
<tr>
<td>Max output power</td>
<td>kW</td>
<td>4221.57</td>
</tr>
<tr>
<td>Variable speed range</td>
<td>%</td>
<td>25~100</td>
</tr>
<tr>
<td>Slip</td>
<td>%</td>
<td>≤ 3</td>
</tr>
<tr>
<td>Mechanical loss (full load)</td>
<td>kW</td>
<td>178 ± 27</td>
</tr>
<tr>
<td>Hydraulic loss (full load)</td>
<td>kW</td>
<td>76</td>
</tr>
<tr>
<td>Efficiency</td>
<td>%</td>
<td>94.1</td>
</tr>
</tbody>
</table>
4.2. Calculations
4.2.1. Selection of BFP driver configurations

The possible configurations of the driving turbine of the boiler feed pump can be in following three ways.

- As a condensing turbine (CT), (outlet steam is condensed in a separate condenser or can be condensed in the main condenser itself)
- As a backpressure turbine (BPT), (outlet steam is fed back to an appropriate location before the condenser).
- As an extraction backpressure turbine (EBPT), (outlet steam and steam bleeds are condensed in low-pressure regenerative heaters).

To feed steam to turbine of BFP, four points were selected by considering the practical feasibility of modifying the steam lines. (Figure 4-2)

(A) HP turbine inlet
(B) Re-heater inlet (Cold Re-heat)
(C) Re-heater outlet (Hot Re-heat)
(D) IP turbine outlet

Thermodynamic model for the existing thermal cycle with electric motor driven feed pump was created using the Engineering Equation Solver (EES) software and the model was modified to following eleven (11) selected cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Configuration</th>
<th>Feeding point</th>
<th>Exhaust arrangement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CT</td>
<td>A</td>
<td>Condenser</td>
</tr>
<tr>
<td>2</td>
<td>CT</td>
<td>B</td>
<td>Condenser</td>
</tr>
<tr>
<td>3</td>
<td>CT</td>
<td>C</td>
<td>Condenser</td>
</tr>
<tr>
<td>4</td>
<td>CT</td>
<td>D</td>
<td>Condenser</td>
</tr>
<tr>
<td>5</td>
<td>BPT</td>
<td>A</td>
<td>HPT outlet (CRH)</td>
</tr>
<tr>
<td>6</td>
<td>BPT-C1</td>
<td>C</td>
<td>IPT outlet</td>
</tr>
<tr>
<td>7</td>
<td>BPT-C2</td>
<td>C</td>
<td>Additional LPH in between heater 6 &amp; 7</td>
</tr>
<tr>
<td>8</td>
<td>EBPT</td>
<td>B</td>
<td>Bleed to LPH 5 (full requirement) and remaining to LPH 6. The balance to LPH 6 is from LPT.</td>
</tr>
<tr>
<td>9</td>
<td>EBPT-C1</td>
<td>C</td>
<td>Bleed to LPH 5 (full requirement) and remaining to LPH 6. The balance to LPH 6 is from LPT.</td>
</tr>
<tr>
<td>10</td>
<td>EBPT-C2</td>
<td>C</td>
<td>Bleed to de-aerator (full requirement) and remaining to additional heater in-between LPH 6 &amp; 7. No extraction to de-aerator from IPT</td>
</tr>
<tr>
<td>11</td>
<td>EBPT-C3</td>
<td>C</td>
<td>Bleed to LPH 6 (full requirement) and remaining to additional heater in-between LPH 6 &amp; 7. No extraction to HTR 6 from IPT</td>
</tr>
</tbody>
</table>
Driving configurations of selected cases are shown in following figures. Consider the following abbreviations for figures from Figure 4-2 to Figure 4-13.

Figure 4-2 Selected points to feed steam to BFPT

Figure 4-3 CT-A: Condensing Turbine as BFP drive, fed steam from HP turbine inlet
Figure 4-4 CT-B: Condensing Turbine as BFP drive, fed steam from HP turbine outlet

Figure 4-5 CT-C: Condensing Turbine as BFP drive, fed steam from IP turbine inlet
Figure 4-7 CT-D: Condensing Turbine as BFP drive, fed steam from LP turbine inlet

Figure 4-6 BPT-A: Back Pressure Turbine as BFP drive, fed steam from HP turbine inlet and exhausted to HPT outlet
Figure 4-8 BPT-C1: Back Pressure Turbine as BFP drive, fed steam from IP turbine inlet and exhausted to IPT outlet

Figure 4-9 BPT-C2: Back Pressure Turbine as BFP drive, fed steam from IP turbine inlet and exhausted to additional heater in between LPH 6 & 7
Figure 4-10 EBPT-B: Back Pressure Turbine as BFP drive, fed steam from HP turbine outlet and bleed to LPH 5 and remaining exhausted to LPH 6. Balance to LPH 6 is from LPT. No extraction to LPH5 from LPT.

Figure 4-11 EBPT-C1: Back Pressure Turbine as BFP drive, fed steam from IP turbine inlet and bleed to LPH 5 and remaining exhausted to LPH 6. Balance to LPH 6 is from LPT. No extraction to LPH5 from LPT.
Figure 4-12 EBPT-C2: Back Pressure Turbine as BFP drive, fed steam from IP turbine inlet and bleed to LPH 4 (De-aerator) and remaining exhausted to additional heater in between LPH 6 & 7. No extraction to LPH4 from IPT.

Figure 4-13 EBPT-C3: Back Pressure Turbine as BFP drive, fed steam from IP turbine inlet and bleed to LPH 6 and remaining exhausted to additional heater in between LPH 6 & 7. No extraction to LPH5 from LPT.
4.2.2. Assumptions

Thermodynamic calculations to analyze the steam cycle after adding steam driven BFP to the system for each cases mentioned earlier was considered. The flow in a turbine mainly depends on the inlet pressure. As an example, if the FW turbine extracts a few percent of the flow from the outlet of the HP turbine, then the inlet pressure and temperature of the HP turbine is constant and the flow and the power of the HP turbine are considered as constants. The flow in the downstream of extraction point is reduced by the extracted flow and the powers of turbines are reduced by some proportions. It is assumed that there is no pressure drop before or after in HP, IP or LP turbines due to reduced flow. Summarized assumptions are as follows.

- Inlet conditions to the turbine and the reheat temperature are kept constant by boiler control.
- No pressure drops in downstream of steam path due to extraction flow to BFP turbine.
- No change in inlets conditions of heaters due to extraction for BFP turbine.
- Mechanical efficiency of the selected BFPT is 90%.
- Isentropic efficiency of the selected BFPT is 90%.
- Efficiency of the boiler and the internal efficiency of turbines are not change with steam flow
- Since speed of booster pump is constant, it is considered as booster pump is driven by a separate electric motor and only the main BFP is running with BFPT.
- Two identical BFPs and their prime movers are considered as a single pump and single prime mover with doubled capacity for the simplicity.

4.2.3. Sample calculation

Consider the case 1 (CT-A), Condensing Turbine as BFP drive fed steam from HP turbine inlet. (Figure 4-3)

Calculations were done according to the following equations. The symbol \( m \) denotes for steam/water mass flow rate and \( h \) denotes for enthalpy of steam/water. Subscript notes are represented the corresponding point through the steam water path of relevant figure.

4.2.3.1. Power consumption of BFP driver

Total power added by Boiler Feed Pump (from both booster pump and main BFP) to the system in MW can be expressed as

\[
P_{\text{bfptotal}} = \frac{m_{12}}{3600} \left( h_{13} - h_{12} \right)
\]

Since the booster pump is considered as running with separate electric motor, power input to Boiler Feed Pump Turbine (in MW) can be expressed as
\[ P_{bfpt} = \frac{P_{bfpt, total} - (P_{bp} / \eta_{mech,bp})}{\eta_{mech,bfpt} \cdot \eta_{mech,bfp}} \]

Where,

\( P_{bp} \) = Power consumption of the booster pump in MW

\( \eta_{mech,bp} \) = Mechanical efficiency of booster pump

\( \eta_{mech,bfp} \) = Mechanical efficiency of BFPT

\( \eta_{mech,bfp} \) = Mechanical efficiency of Main BFP

And also it can be expressed as another way

\[ P_{bfpt} = \frac{\dot{m}_A}{3600} \left[ \frac{h_A - h_5}{1000} \right] \]

Power out puts of each turbine can be expressed as follows

4.2.3.2. **Power output of Turbines**

HP turbine power output

\[ P_{hpt} = \frac{\dot{m}_1 (h_1 - h_{htr1,in}) + (\dot{m}_1 - \dot{m}_{htr1,in})(h_{htr1,in} - h_2)}{3600 \times 1000} \]

IP turbine power output

\[ P_{ipt} = \frac{\dot{m}_3 (h_3 - h_{htr3,in}) + (\dot{m}_3 - \dot{m}_{htr3,in})(h_{htr3,in} - h_{htr4,in}) + (\dot{m}_3 - \dot{m}_{htr3,in} - \dot{m}_{htr4,in})(h_{htr4,in} - h_4)}{3600 \times 1000} \]

LP turbine power output

\[ P_{lpt} = \frac{\dot{m}_4 (h_4 - h_{htr5,in}) + A(h_{htr5,in} - h_{htr6,in}) + B(h_{htr6,in} - h_{htr7,in}) + C(h_{htr7,in} - h_{htr8,in}) + D(h_{htr8,in} - h_5)}{3600 \times 1000} \]

Where;

\( A = (\dot{m}_4 - \dot{m}_{htr5,in}) \)

\( B = (\dot{m}_4 - \dot{m}_{htr5,in} - \dot{m}_{htr6,in}) \)
\[ C = (\dot{m}_4 - \dot{m}_{htr\,5,in} - \dot{m}_{htr\,6,in} - \dot{m}_{htr\,7,in}) \]

\[ D = (\dot{m}_4 - \dot{m}_{htr\,5,in} - \dot{m}_{htr\,6,in} - \dot{m}_{htr\,7,in} - \dot{m}_{htr\,8,in}) \]

### 4.2.3.3. Power output of Generator

The Generator gross power output of the power plant can be expressed as

\[ P_{Gen,Gross} = (P_{hpt} + P_{ipt} + P_{ipt}) \eta_{mech,turb} \cdot \eta_{elec,gen} \]

Where;

- \( \eta_{mech,turb} \) = Overall mechanical efficiency of the all turbines (HPT, IPT, LPT)
- \( \eta_{elec,gen} \) = Electrical efficiency of the Generator

Net power output of the generator can be expressed as follows.

For EM mode;

\[ P_{Gen,Net,m} = P_{Gen,Gross} - P_{Aux} \]

For BFPT modes;

\[ P_{Gen,Net,t} = P_{Gen,Gross} - (P_{Aux} - P_{bfpm} + P_{bpm}) \]

Where;

- \( P_{Aux} \) = Total Auxiliary power consumption of the plant with EM configuration
- \( P_{bpm} \) = Power consumption of motor of booster pump

### 4.2.3.4. Gross heat rate and Net heat rate

When boiler water is fed by motor-driven pump;

Gross heat consumption rate can be expressed as

\[ HR_{gros,motor} = \frac{\dot{m}_{16}(h_1 - h_{16}) + \dot{m}_{3}(h_3 - h_2)}{P_{Gen,Gross}} \]

The net heat consumption rate can be expressed as

\[ HR_{net,motor} = \frac{\dot{m}_{16}(h_1 - h_{16}) + \dot{m}_{3}(h_3 - h_2)}{P_{Gen,Gross} - P_{bfpm}} \]
Where;

\[ P_{\text{bfpm}} = \text{Power consumption of the motor of BFP} \]

When boiler water is fed by steam-driven pump;

The gross heat consumption rate can be expressed as

\[ HR_{\text{net,turb}} = \frac{m_{16}(h_1 - h_{16}) + m_3(h_3 - h_2)}{P_{\text{Gen,Gross}} + P_{\text{bfpt}}} \]

The net heat consumption rate can be expressed as Formula

\[ HR_{\text{net,turb}} = \frac{m_{16}(h_1 - h_{16}) + m_3(h_3 - h_2)}{P_{\text{Gen,Gross}}} \]

### 4.2.3.5. Plant Efficiency

The Plant efficiency can be expressed as

\[ \eta_{\text{plant}} = \frac{P_{\text{Gen,Net}}}{Q_{\text{boiler input}}} = \frac{P_{\text{Gen,Net}}}{\{m_{16}(h_1 - h_{16}) + m_2(h_3 - h_2)\}/\eta_{\text{boiler}}} \]

Where;

\[ Q_{\text{boiler,input}} = \text{Total heat input to the boiler by its fuel} \]

### 4.2.3.6. Equivalent Electrical Power consumption of BFPT

One of the objectives of this master thesis research is to find out the best configuration of BFPT while reducing the power consumption of the BFP drive and hence improving the net output power and hence improving the plant efficiency by a considerable amount. To investigate that objective is achieved or not, it is needed to find out the BFP power consumption for each case.

Calculating the electrical power consumption of BFP motor is straightforward and it can be presented as equations mentioned in 4.2.3.1 section above. In that section power consumption of the BFPT was calculated from the enthalpy difference and steam mass flow rate through BFPT. That figure reflects how much of energy available in steam has used by the BFPT. But the value of the power consumption of BFP motor reflects a smaller portion from the energy of steam used to run the BFP motor. This is due to the efficiencies of turbines, generator, and transformer are not 100%, Since in case of turbine-driven BFP case, power losses through turbines, generator and transformer and driving motor is not available, power consumption may show a higher value than EM case. So, equivalent electric power consumption of the BFPT was calculated as follows.

\[ P_{\text{bfpt,equivalent}} = P_{\text{Gen,Gross,m}} - P_{\text{Gen,Gross,t}} \]
4.2.3.7. CO$_2$, SOx and NOx Emission Factors

To calculate the CO$_2$, SOx and NOx Emission Factors of each mode, following data of available EM mode was used.

Table 4-6 Data used for emission factors calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$ Emission Factor</td>
<td>g/MJ</td>
<td>94</td>
</tr>
<tr>
<td>SOx Emission Factor</td>
<td>g/MJ</td>
<td>0.0056</td>
</tr>
<tr>
<td>NOx Emission Factor</td>
<td>g/MJ</td>
<td>0.26</td>
</tr>
</tbody>
</table>

This emission factor is based on unit energy input to the boiler. Initially Emission factors of each configuration were calculated as per following equation. Consider CT-A configuration as an example

Emission Factor for CT – A mode

\[ \frac{\text{Boiler Energy Input in CT – A mode}}{\text{Boiler Energy Input in EM mode}} \times \text{Emission Factor for EM mode} \]

Then those emission factors were converted to a form based on unit energy generated using following equation.

\[ \text{Emission Factor, energy generated based \left[ \frac{g}{\text{kWh}} \right]} = \text{Emission Factor, energy input based \left[ \frac{g}{\text{MJ}} \right]} \times \frac{3.6 \left[ \frac{\text{MJ}}{\text{kWh}} \right]}{\text{Plant Efficiency}} \]

4.2.3.8. Other data used

The following data taken from the O&M manual of the Harbin turbine were used for the calculations.

Table 4-7 Input data to the EES program (inlet conditions of extraction steam to heaters) (HTC, 2006)

<table>
<thead>
<tr>
<th>Heater No</th>
<th>Inlet conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Steam flow</td>
</tr>
<tr>
<td></td>
<td>kg/h</td>
</tr>
<tr>
<td>1</td>
<td>73320</td>
</tr>
<tr>
<td>2</td>
<td>78400</td>
</tr>
<tr>
<td>3</td>
<td>32000</td>
</tr>
<tr>
<td>4</td>
<td>42580</td>
</tr>
<tr>
<td>5</td>
<td>42430</td>
</tr>
<tr>
<td>6</td>
<td>26180</td>
</tr>
<tr>
<td>7</td>
<td>29140</td>
</tr>
<tr>
<td>8</td>
<td>18910</td>
</tr>
</tbody>
</table>
Table 4-8 Input data to the EES Program (Thermodynamic parameters of the steam cycle) (HTC, 2006)

<table>
<thead>
<tr>
<th>Point</th>
<th>Steam flow kg/h</th>
<th>Enthalpy kJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>964000</td>
<td>3397.0</td>
</tr>
<tr>
<td>2</td>
<td>799380</td>
<td>3047.0</td>
</tr>
<tr>
<td>3</td>
<td>799380</td>
<td>3537.0</td>
</tr>
<tr>
<td>4</td>
<td>726850</td>
<td>3170.0</td>
</tr>
<tr>
<td>5</td>
<td>610560</td>
<td>2404.0</td>
</tr>
<tr>
<td>6</td>
<td>757730</td>
<td>189.3</td>
</tr>
<tr>
<td>7</td>
<td>757730</td>
<td>192.8</td>
</tr>
<tr>
<td>8</td>
<td>757730</td>
<td>258.5</td>
</tr>
<tr>
<td>9</td>
<td>757730</td>
<td>358.8</td>
</tr>
<tr>
<td>10</td>
<td>757730</td>
<td>446.6</td>
</tr>
<tr>
<td>11</td>
<td>757730</td>
<td>586.6</td>
</tr>
<tr>
<td>12</td>
<td>992920</td>
<td>747.4</td>
</tr>
<tr>
<td>13</td>
<td>992920</td>
<td>773.5</td>
</tr>
<tr>
<td>14</td>
<td>992920</td>
<td>884.6</td>
</tr>
<tr>
<td>15</td>
<td>992920</td>
<td>1068.0</td>
</tr>
<tr>
<td>16</td>
<td>992920</td>
<td>1221.0</td>
</tr>
</tbody>
</table>

Table 4-9 Input data to the EES program (other important data)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Efficiency of BFP Electric motor</td>
<td>$\eta_{\text{elec,motor}}$</td>
<td>98.00%</td>
</tr>
<tr>
<td>Mechanical Efficiency of BFP Main Pump</td>
<td>$\eta_{\text{mech,bfp,main}}$</td>
<td>81.63%</td>
</tr>
<tr>
<td>Mechanical Efficiency of BFP Booster Pump</td>
<td>$\eta_{\text{mech,bfp,bp}}$</td>
<td>82.60%</td>
</tr>
<tr>
<td>Mechanical Efficiency of Hydraulic coupler</td>
<td>$\eta_{\text{mech,hc}}$</td>
<td>94.00%</td>
</tr>
<tr>
<td>Isentropic Efficiency of BFPT (Assumed)</td>
<td>$\eta_{\text{isentropic,bfpt}}$</td>
<td>90.00%</td>
</tr>
<tr>
<td>Internal Efficiency of BFP Turbine (Assumed)</td>
<td>$\eta_{\text{internal,bfpt}}$</td>
<td>90.00%</td>
</tr>
<tr>
<td>Electrical Efficiency of Transformer</td>
<td>$\eta_{\text{elec,transformer}}$</td>
<td>99.00%</td>
</tr>
<tr>
<td>Overall Internal Efficiency of turbines (HPT, IPT and LPT)</td>
<td>$\eta_{\text{internal,turb}}$</td>
<td>93.60%</td>
</tr>
<tr>
<td>Electrical Efficiency of Generator</td>
<td>$\eta_{\text{elec,gen}}$</td>
<td>98.50%</td>
</tr>
<tr>
<td>Efficiency of boiler</td>
<td>$\eta_{\text{boiler}}$</td>
<td>89.00%</td>
</tr>
<tr>
<td>Auxiliary Power Consumption of Plant with EM-BFP</td>
<td>$P_{\text{Aux}}$</td>
<td>28.9 MW</td>
</tr>
<tr>
<td>Power consumption of Booster Pumps</td>
<td>$P_{\text{bp}}$</td>
<td>400 kW</td>
</tr>
</tbody>
</table>
5. Results and Analysis
5.1. Thermodynamic analysis

As same as the calculation shown above for Case I (CT-A), for other cases also same calculations were done using modified EES programs. (See Annexure 7.1, 7.1, 7.3 and 7.4. Only 4 EES programs were annexed (EM, CT-A, BPT-A, EBPT-C1)) The important results are presented in Table 5-1.

![Figure 5-1 Variation of Plant efficiency with BFP driver configuration](image)

Consider the Figure 5-1 above. According to the results obtained, it is clear that efficiencies of all the cases with steam driven feed water pumps are higher than the existing EM configuration. Out of those cases, BPT-C2 has the highest efficiency while EBPT-C2 and EBPT-C3 became the second and third highest efficiencies respectively with significant increase compared to current EM case. Although all other steam driven BFP configurations show higher efficiency than existing EM configuration, those increments are not significant. The common feature of configurations with highest efficiencies is newly added LP heater in between LPH 7 & 6. Due to that heater an energy quantity (latent heat), which was originally discharged to sea via condenser, was captured to feed water and hence final enthalpy of feed water at inlet of boiler became higher by a little amount than original one. Then the heat input from the boiler became lesser and hence the efficiency became higher. That observation is clearly shown in Figure 5-4 and heat gains in those three cases are shown the same pattern of efficiency curve.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>EM</th>
<th>CT-A</th>
<th>CT-B</th>
<th>CT-C</th>
<th>CT-D</th>
<th>BPT-A</th>
<th>BPT-C1</th>
<th>BPT-C2</th>
<th>EBPT-B</th>
<th>EBPT-C1</th>
<th>EBPT-C2</th>
<th>EBPT-C3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Efficiency</td>
<td>%</td>
<td>34.59</td>
<td>34.64</td>
<td>34.63</td>
<td>34.67</td>
<td>34.67</td>
<td>34.77</td>
<td>34.72</td>
<td>36.25</td>
<td>34.77</td>
<td>34.68</td>
<td>35.48</td>
<td>35.30</td>
</tr>
<tr>
<td>Gross Heat Rate</td>
<td>[kJ/kWh]</td>
<td>8369</td>
<td>8340</td>
<td>8342</td>
<td>8339</td>
<td>8338</td>
<td>8318</td>
<td>8327</td>
<td>7965</td>
<td>8306</td>
<td>8337</td>
<td>8143</td>
<td>8185</td>
</tr>
<tr>
<td>Net Heat Rate</td>
<td>[kJ/kWh]</td>
<td>8650</td>
<td>8622</td>
<td>8624</td>
<td>8620</td>
<td>8618</td>
<td>8597</td>
<td>8606</td>
<td>8236</td>
<td>8588</td>
<td>8617</td>
<td>8418</td>
<td>8461</td>
</tr>
<tr>
<td>Gross Power Output of Generator</td>
<td>[MW]</td>
<td>299.3</td>
<td>289</td>
<td>288.3</td>
<td>290.6</td>
<td>290.6</td>
<td>291.4</td>
<td>291</td>
<td>287.1</td>
<td>287.6</td>
<td>290.7</td>
<td>289</td>
<td>289.2</td>
</tr>
<tr>
<td>Net Power Output of Generator</td>
<td>[MW]</td>
<td>270.4</td>
<td>269.4</td>
<td>268.7</td>
<td>271</td>
<td>271.1</td>
<td>271.8</td>
<td>271.4</td>
<td>267.5</td>
<td>268.1</td>
<td>271.1</td>
<td>269.5</td>
<td>269.6</td>
</tr>
<tr>
<td>Power Output of HPT</td>
<td>[MW]</td>
<td>94.08</td>
<td>91.45</td>
<td>94.08</td>
<td>94.08</td>
<td>94.08</td>
<td>85.48</td>
<td>94.08</td>
<td>94.08</td>
<td>94.08</td>
<td>94.08</td>
<td>94.08</td>
<td>94.08</td>
</tr>
<tr>
<td>Power Output of IPT</td>
<td>[MW]</td>
<td>88.12</td>
<td>85.34</td>
<td>84.26</td>
<td>85.06</td>
<td>88.12</td>
<td>88.12</td>
<td>79.16</td>
<td>83.85</td>
<td>80.92</td>
<td>82.52</td>
<td>81.6</td>
<td>83.7</td>
</tr>
<tr>
<td>Power Output of LPT</td>
<td>[MW]</td>
<td>142.4</td>
<td>136.6</td>
<td>134.3</td>
<td>136</td>
<td>133</td>
<td>142.4</td>
<td>142.4</td>
<td>133.5</td>
<td>137</td>
<td>138.7</td>
<td>137.8</td>
<td>135.9</td>
</tr>
<tr>
<td>Total Turbine Power Output</td>
<td>[MW]</td>
<td>324.6</td>
<td>313.4</td>
<td>312.7</td>
<td>315.2</td>
<td>315.2</td>
<td>316</td>
<td>315.7</td>
<td>311.4</td>
<td>312</td>
<td>295.1</td>
<td>313.5</td>
<td>313.7</td>
</tr>
<tr>
<td>Heat Input To the Boiler</td>
<td>[MW]</td>
<td>781.7</td>
<td>777.6</td>
<td>776.0</td>
<td>781.7</td>
<td>781.7</td>
<td>781.7</td>
<td>781.7</td>
<td>738.0</td>
<td>771.0</td>
<td>781.7</td>
<td>759.3</td>
<td>763.8</td>
</tr>
<tr>
<td>Equivalent Electrical Power consumption of BFT</td>
<td>[MW]</td>
<td>9.74</td>
<td>10.30</td>
<td>11.00</td>
<td>8.70</td>
<td>8.70</td>
<td>7.90</td>
<td>8.30</td>
<td>12.20</td>
<td>11.70</td>
<td>8.60</td>
<td>10.30</td>
<td>10.10</td>
</tr>
<tr>
<td>Power output Gain</td>
<td>[MW]</td>
<td>0</td>
<td>-1</td>
<td>-1.7</td>
<td>0.6</td>
<td>0.7</td>
<td>1.4</td>
<td>1</td>
<td>-2.9</td>
<td>-2.3</td>
<td>0.7</td>
<td>-0.9</td>
<td>-0.8</td>
</tr>
<tr>
<td>Heat input Gain</td>
<td>[MW]</td>
<td>0.0</td>
<td>4.0</td>
<td>5.7</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>43.7</td>
<td>10.7</td>
<td>0.0</td>
<td>22.4</td>
<td>17.9</td>
</tr>
<tr>
<td>CO2 Emission Factor (Per Unit Energy Input)</td>
<td>[g/MJ]</td>
<td>94.60</td>
<td>94.11</td>
<td>93.91</td>
<td>94.60</td>
<td>94.60</td>
<td>94.60</td>
<td>94.60</td>
<td>89.31</td>
<td>93.31</td>
<td>94.60</td>
<td>91.89</td>
<td>92.44</td>
</tr>
<tr>
<td>CO2 Emission Factor (Per Unit Energy Output)</td>
<td>[g/kWh]</td>
<td>984.6</td>
<td>978.1</td>
<td>976.2</td>
<td>982.3</td>
<td>982.3</td>
<td>979.5</td>
<td>980.9</td>
<td>886.9</td>
<td>966.1</td>
<td>982.0</td>
<td>932.4</td>
<td>942.7</td>
</tr>
<tr>
<td>SOx Emission Factor (Per Unit Energy Input)</td>
<td>[g/MJ]</td>
<td>0.0056</td>
<td>0.0056</td>
<td>0.0056</td>
<td>0.0056</td>
<td>0.0056</td>
<td>0.0056</td>
<td>0.0056</td>
<td>0.0053</td>
<td>0.0055</td>
<td>0.0056</td>
<td>0.0054</td>
<td>0.0055</td>
</tr>
<tr>
<td>SOx Emission Factor (Per Unit Energy Output)</td>
<td>[g/kWh]</td>
<td>0.0583</td>
<td>0.0579</td>
<td>0.0578</td>
<td>0.0581</td>
<td>0.0581</td>
<td>0.0581</td>
<td>0.0581</td>
<td>0.0525</td>
<td>0.0572</td>
<td>0.0581</td>
<td>0.0552</td>
<td>0.0558</td>
</tr>
<tr>
<td>NOx Emission Factor (Per Unit Energy Input)</td>
<td>[g/MJ]</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.25</td>
<td>0.26</td>
<td>0.26</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>NOx Emission Factor (Per Unit Energy Output)</td>
<td>[g/kWh]</td>
<td>2.71</td>
<td>2.69</td>
<td>2.68</td>
<td>2.70</td>
<td>2.70</td>
<td>2.69</td>
<td>2.70</td>
<td>2.44</td>
<td>2.66</td>
<td>2.70</td>
<td>2.56</td>
<td>2.59</td>
</tr>
</tbody>
</table>
But the only factor influence to the plant efficiency is not the Heat gain in boiler. Power gain in generator also affects to plant efficiency. When heat gain is higher, if power gain is lower or vice versa, then how it affects to the plant efficiency? The answer is shown in Figure 5-4 below.
According to the Figure 5-4, it can be seen that, when the heat gain is higher (positive), the power gain has become lower (negative) and when the power gain is zero, heat gain has become positive. Since the value of heat gain is much higher than power gain value, most of the times, the efficiency curve reflects the pattern of the heat gain curve.

The major objective of this master thesis research is to find out the best configuration of BFPT while reducing the power consumption of the BFP drive and hence improving the net output power and hence improving the plant efficiency by a considerable amount. To investigate that objective is achieved or not, it is needed to compare the power consumption of BFP motor with the BFPT equivalent electrical power consumption.

From Figure 5-5 and Figure 5-6, it is clear that CT-C, CT-D, BPT-A, BPT-C1 and EBPT-C1 have higher net output lower BFPT power consumption than EM mode. Out of those configurations, BPT-A gives the highest net output and lowest BFPT power consumption. According to the Figure 5-4, it is clear that for all the above mentioned points the heat gain is zero and power gain is proportional to the net output of the power plant. By the aspect of thermal economy, BPT-A configuration is the best solution for BFPT. Value vise, it has saved 1.84 MW from BFP driver and 1.4 MW will be added to the national grid.
Figure 5-5 Comparison of Equivalent electrical power consumption of BFPTs

Figure 5-6 Variation of Net power output with BFP driver configuration

For Figure 5-5 and Figure 5-6 consider the following color references.

- Blue: Reference
- Dark Pink: Bad
- Red: Good
Remarks on each configuration are shown in Table below.

<table>
<thead>
<tr>
<th>Case</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM</td>
<td>Existing BFP driving configuration</td>
</tr>
<tr>
<td>CT-A</td>
<td>Net generator output is lower. Heat input has reduced. Since mass flow rate through Re-heater panels became reduced, heat input reduced and hence power output reduced.</td>
</tr>
<tr>
<td>CT-B</td>
<td>Net generator output is lower. Heat input has reduced. Since mass flow rate through Re-heater panels became reduced, heat input reduced and hence power output reduced.</td>
</tr>
<tr>
<td>CT-C</td>
<td>No change in mass flow rate through boiler. No heat gain. Since BFPT power is lesser, net output became slightly higher. Efficiency improved with a net output gain. Mass flow rate and hence the power output reduced only through LPT.</td>
</tr>
<tr>
<td>CT-D</td>
<td>No change in mass flow rate through boiler. No heat gain. Since BFPT power is lesser, net output became slightly higher. Efficiency improved with a net output gain. Mass flow rate and hence the power output reduced only through LPT. Nearly Same results as CT-C</td>
</tr>
<tr>
<td>BPT-A</td>
<td>No change in mass flow rate through boiler. No heat gain. Mass flow rate and hence the power output reduce only through HPT. Since BFPT power is lesser, net output became slightly higher. Efficiency improved with a net output gain.</td>
</tr>
<tr>
<td>BPT-C1</td>
<td>No change in mass flow rate through boiler. No heat gain. Mass flow rate and hence the power output reduce only through IPT. Since BFPT power is lesser, net output became slightly higher. Efficiency improved with a net output gain.</td>
</tr>
<tr>
<td>BPT-C2</td>
<td>Due to the additional heater added, huge amount of energy which was originally discharged to sea via condenser was saved. Hence heat input from the boiler became lesser. But due to reduced mass flow rate through both IPT and LPT, power output largely reduced. Since energy input reduced by a big amount efficiency improved largely.</td>
</tr>
<tr>
<td>EBPT-B</td>
<td>Net generator output is lower. Since mass flow rate through Re-heater panels became reduced, heat input reduced and hence power output reduced. Efficiency has improved due to that heat input gain.</td>
</tr>
<tr>
<td>EBPT-C1</td>
<td>No heat gain. Net output has reduced due to reduced mass flow rate through both IPT and LPT. Results are nearly same as CT-C.</td>
</tr>
<tr>
<td>EBPT-C2</td>
<td>Due to the additional heater heat gain is higher. Net output is slightly lower. Due to larger heat gain efficiency became higher.</td>
</tr>
<tr>
<td>EBPT-C3</td>
<td>Due to the additional heater heat gain is higher. Net output is slightly lower. Due to larger heat gain efficiency became higher.</td>
</tr>
</tbody>
</table>

5.2. Emission Analysis

Consider the Figure 5-7, Figure 5-8 and Figure 5-9 below. According to those figures it is clear that since there is no heat gain in selected cases from thermodynamic analysis (CT-C, CT-D, BPT-A, BPT-C1 and EBPT-C1), there is no any difference in CO2 or SOx or NOx emission factor based on input energy. But for the other cases, since boiler heat input is much lower, the emission factor have been reduced.

If it is considered the emission factor based on energy output of the power plant, it is clear that all the configurations with steam driven BFP have lower emission factors compared to existing motor driven BFP mode. So it is cleared that the quality of the energy generated has improved, empowering clean energy concept.
Figure 5-7 CO2 Emission Factor for each configuration

Figure 5-8 SOx Emission Factor for each configuration
To complete this analysis, the behavior of steam driven BFP in part loads also should be considered. So calculations were done with modified EES program for 75%, 50% and 30% of turbine rated load (TRL) for EM mode and BPT-A mode (which was selected from thermodynamic analysis). Data used for the calculation were shown in Table 5-3.

Table 5-4 below.

<table>
<thead>
<tr>
<th>Heater No</th>
<th>Inlet conditions of Heaters</th>
<th>75% TRL</th>
<th>50% TRL</th>
<th>30% TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Steam flow</td>
<td>Enthalpy</td>
<td>Steam flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>kg/h</td>
<td>kJ/kg</td>
<td>kg/h</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>42040</td>
<td>3112</td>
<td>26170</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>48290</td>
<td>3010</td>
<td>31270</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>16560</td>
<td>3353</td>
<td>12120</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>23140</td>
<td>3180</td>
<td>17860</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>27810</td>
<td>2979</td>
<td>19130</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>17240</td>
<td>2790</td>
<td>11910</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>19280</td>
<td>2657</td>
<td>13340</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>12350</td>
<td>2521</td>
<td>5060</td>
</tr>
</tbody>
</table>
Table 5-3 Input data to the EES program for Partial Loads (inlet conditions of extraction steam to heaters)

(HTC, 2006)

<table>
<thead>
<tr>
<th>Heater No</th>
<th>Inlet conditions of Heaters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>75% TRL</td>
</tr>
<tr>
<td></td>
<td>Steam flow</td>
</tr>
<tr>
<td></td>
<td>kg/h</td>
</tr>
<tr>
<td>1</td>
<td>42040</td>
</tr>
<tr>
<td>2</td>
<td>48290</td>
</tr>
<tr>
<td>3</td>
<td>16560</td>
</tr>
<tr>
<td>4</td>
<td>23140</td>
</tr>
<tr>
<td>5</td>
<td>27810</td>
</tr>
<tr>
<td>6</td>
<td>17240</td>
</tr>
<tr>
<td>7</td>
<td>19280</td>
</tr>
<tr>
<td>8</td>
<td>12350</td>
</tr>
</tbody>
</table>

Table 5-4 Input data to the EES Program for Partial Loads (HTC, 2006)

<table>
<thead>
<tr>
<th>Point</th>
<th>75% TRL</th>
<th>50% TRL</th>
<th>30% TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Steam flow</td>
<td>Enthalpy</td>
<td>Steam flow</td>
</tr>
<tr>
<td></td>
<td>kg/h</td>
<td>kJ/kg</td>
<td>kg/h</td>
</tr>
<tr>
<td>1</td>
<td>674800</td>
<td>3397.0</td>
<td>482000</td>
</tr>
<tr>
<td>2</td>
<td>574670</td>
<td>3010.0</td>
<td>417310</td>
</tr>
<tr>
<td>3</td>
<td>574670</td>
<td>3546.0</td>
<td>417310</td>
</tr>
<tr>
<td>4</td>
<td>530100</td>
<td>3180.0</td>
<td>388530</td>
</tr>
<tr>
<td>5</td>
<td>453800</td>
<td>2409.0</td>
<td>339470</td>
</tr>
<tr>
<td>6</td>
<td>531830</td>
<td>163.4</td>
<td>389860</td>
</tr>
<tr>
<td>7</td>
<td>531830</td>
<td>169.1</td>
<td>389860</td>
</tr>
<tr>
<td>8</td>
<td>531830</td>
<td>230.5</td>
<td>389860</td>
</tr>
<tr>
<td>9</td>
<td>531830</td>
<td>325.7</td>
<td>389860</td>
</tr>
<tr>
<td>10</td>
<td>531830</td>
<td>409.3</td>
<td>389860</td>
</tr>
<tr>
<td>11</td>
<td>531830</td>
<td>542.5</td>
<td>389860</td>
</tr>
<tr>
<td>12</td>
<td>674810</td>
<td>691.4</td>
<td>482010</td>
</tr>
<tr>
<td>13</td>
<td>674810</td>
<td>716.2</td>
<td>482010</td>
</tr>
<tr>
<td>14</td>
<td>674810</td>
<td>817.8</td>
<td>482010</td>
</tr>
<tr>
<td>15</td>
<td>674810</td>
<td>984.2</td>
<td>482010</td>
</tr>
<tr>
<td>16</td>
<td>674810</td>
<td>1115.0</td>
<td>482010</td>
</tr>
</tbody>
</table>

Efficiencies of each equipment assumed same as 100% TRL load as given in Table 4-9 and some other important data were shown in Table 5-5 below.

Table 5-5 Input data to the EES program (other important data)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>75% TRL</th>
<th>50% TRL</th>
<th>30% TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>75% TRL</td>
<td>50% TRL</td>
<td>30% TRL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>kg/h</td>
<td>kJ/kg</td>
<td>kg/h</td>
</tr>
<tr>
<td>1</td>
<td>42040</td>
<td>3112</td>
<td>26170</td>
<td>3074</td>
</tr>
<tr>
<td>2</td>
<td>48290</td>
<td>3010</td>
<td>31270</td>
<td>2978</td>
</tr>
<tr>
<td>3</td>
<td>16560</td>
<td>3353</td>
<td>12120</td>
<td>3324</td>
</tr>
<tr>
<td>4</td>
<td>23140</td>
<td>3180</td>
<td>17860</td>
<td>3156</td>
</tr>
<tr>
<td>5</td>
<td>27810</td>
<td>2979</td>
<td>19130</td>
<td>2960</td>
</tr>
<tr>
<td>6</td>
<td>17240</td>
<td>2790</td>
<td>11910</td>
<td>2774</td>
</tr>
<tr>
<td>7</td>
<td>19280</td>
<td>2657</td>
<td>13340</td>
<td>2645</td>
</tr>
<tr>
<td>8</td>
<td>12350</td>
<td>2521</td>
<td>5060</td>
<td>2512</td>
</tr>
</tbody>
</table>
With the aid of EES programs the results obtained are shown in Table 5-6. For the comparison purpose results obtained with 100% TRL condition for EM mode and BPT-A mode are also shown in the table.

According to the results obtained, it is clear that steam driven BFP is more thermally economical than electric motor driven BFP in partial load conditions too. 1.2 MW, 1.2 MW and 0.69 MW of power output gains and 0.20%, 0.28% and 0.23% improvement in net efficiency of the power plant can be achieved with 75%, 50% and 30% TRL conditions.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>100% TRL</th>
<th>75% TRL</th>
<th>50% TRL</th>
<th>30% TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Efficiency / %</td>
<td>%</td>
<td>EM</td>
<td>BPT-A</td>
<td>EM</td>
<td>BPT-A</td>
</tr>
<tr>
<td>Gross Heat Rate/ (kJ/kWh)</td>
<td>[kJ/kWh]</td>
<td>8369.00</td>
<td>8318.00</td>
<td>8411.00</td>
<td>8354.00</td>
</tr>
<tr>
<td>Net Heat Rate(kJ/kWh)</td>
<td>[kJ/kWh]</td>
<td>8650.00</td>
<td>8597.00</td>
<td>8659.00</td>
<td>8599.00</td>
</tr>
<tr>
<td>Gross Power Output of Generator /(MW)</td>
<td>[MW]</td>
<td>299.30</td>
<td>291.40</td>
<td>219.60</td>
<td>214.80</td>
</tr>
<tr>
<td>Net power Output of Generator /(MW)</td>
<td>[MW]</td>
<td>270.40</td>
<td>271.80</td>
<td>196.10</td>
<td>197.30</td>
</tr>
<tr>
<td>Power Output of HPT</td>
<td>[MW]</td>
<td>94.08</td>
<td>85.48</td>
<td>66.22</td>
<td>61.02</td>
</tr>
<tr>
<td>Power Output of IPT</td>
<td>[MW]</td>
<td>88.12</td>
<td>88.12</td>
<td>66.53</td>
<td>66.53</td>
</tr>
<tr>
<td>Power Output of LPT</td>
<td>[MW]</td>
<td>142.40</td>
<td>142.40</td>
<td>105.50</td>
<td>105.50</td>
</tr>
<tr>
<td>Total Turbine Power Output</td>
<td>[MW]</td>
<td>324.60</td>
<td>316.00</td>
<td>238.20</td>
<td>233.00</td>
</tr>
<tr>
<td>Heat Input To the Boiler</td>
<td>[MW]</td>
<td>781.70</td>
<td>781.70</td>
<td>513.10</td>
<td>513.10</td>
</tr>
<tr>
<td>Steam Rate</td>
<td>[kg/kWh]</td>
<td>3.57</td>
<td>3.55</td>
<td>3.44</td>
<td>3.42</td>
</tr>
<tr>
<td>Equivalent Electrical Power consumption of BFPT</td>
<td>[MW]</td>
<td>9.74</td>
<td>7.90</td>
<td>6.28</td>
<td>4.80</td>
</tr>
<tr>
<td>Power output Gain</td>
<td>[MW]</td>
<td>0.00</td>
<td>1.40</td>
<td>0.00</td>
<td>1.20</td>
</tr>
<tr>
<td>Heat input Gain</td>
<td>[MW]</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
5.4. Selecting the no of feed water pumps

FW pumps are key components for operation of the plant. Efficiency and reliability are required and also good performance at all operating conditions of the plant, including start up.

A single 100% pump gives usually high efficiency but can give problems at start up, especially if driven with steam turbine. If the single pump fails, the plant must be stopped. An additional smaller electric driven pump can solve this problem. High reliability of the pump is demanded in this case.

If two 100% pumps are used, it will give high reliability but at high cost. Two 50% pumps give lower efficiency and high reliability at 50% load but lower at 100% load. Three 50% pumps give high reliability at all loads and are often chosen. A thing that can influence the reliability is the number of components that are needed at the installation of the pumps, like valves. Installation of one single pump is less complicated than installation with three parallel pumps.

In currently available electric motor driven BFP set have three 50% pumps. But it is not possible to use three 50% steam driven BFPs, since in the startup there is no any steam source for the turbine. And if one of steam driven pump is failed, the plant needed to de-load approximately half load. But keeping the plant at full load using a motor driven BFP until failed steam driven BFP is rectified will be financially economic. So for the start up purpose and standby purpose, one 50% capacity electric motor driven feed pump should be used. So one 50% motor driven feed pump and two 50% steam driven feed pumps is suggested. Normally motor driven BFP can be used up to 65% of the rated load of the power plant. In between 40% to 65% of the rated load, motor driven feed pump should be interchanged to a steam driven feed pump and for loads beyond 65% both two steam driven feed water pumps should be used.

5.5. Selecting Pump and Turbine arrangement

The existing electric motor driven BFP arrangement is shown in figure 3-1. A turbo-coupler or speed regulator has placed in between motor and main pump because main pump maximum speed is 5358 rpm and motor speed is 1490 rpm. Booster pump also has the speed of 1490 rpm and directly coupled to the motor. But when it is used a steam turbine for the prime mover, the speed of steam turbine should be higher or equal to 5358 rpm. So the speed reducer should be used to reduce the speed to booster pump while direct coupling main pump to steam turbine. Then the booster pump, main pump, speed regulator (turbo-coupler) and turbine will be arranged as shown in figure below.

![Figure 5-10 BFP Turbine and pump arrangement - Option 01](image-url)
But the drawback of this arrangement is when the speed of the main BFP is needed to be changed the turbine speed should be changed and then according to the turbine speed, speed of the booster pump should be kept constant by regulated the speed through turbo coupler. But in existing arrangement speed of the booster pump has fixed with fixed motor speed and only the main BFP speed will be changed. In this option both BFP and booster pump RPM should be control using two complicated control systems.

Then another option as shown in Figure 5-11 was considered.

The booster pump is driven by a separate electric motor with small capacity (~ 0.2 MW) and not coupled to the steam turbine shaft. Only the main BFP is coupled to the steam turbine shaft and speed of the main BFP can be control by the speed of the turbine, independent from the booster pump. In this option the complexity of the operation is lesser and the energy consumption of total BFP system can be lesser as efficiency of electric motors are higher than efficiencies of turbo couplings.

5.6. **Financial Economic analysis of BFP drivers**

5.6.1. **Financial saving with steam driven BFP**

As stated in Table 5-1, five BFP configurations have positive net output gain with zero boiler input power gain. With existing BFP configuration (EM), that power is obtained from another thermal power plant with higher unit cost. If one of those configurations is implemented, the energy generated with higher costs can be reduced by some amount. According to the Table 5-8, it is clear that unit cost of thermal power plants in Sri Lanka varies from 24.83 LKR/kWh to 63.45 LKR/kWh. Based on those two values maximum annual financial saving and minimum annual financial saving were calculated using following equations.

\[
\text{Min Annual Financial saving in LKR Mn} = \frac{(\text{Net output gain in MW}) \times (1000 \text{ kW/MW}) \times (24.83 \text{ LKR/kWh}) \times (24 \text{ h/day}) \times (365.25 \text{ days/Year}) \times (\text{Plant Factor})}{1,000,000 \text{ LKR/LKR Mn}}
\]

\[\text{LVPS Plant factor} = 51.85\% \text{ (PUCSL, Generation Performance in Sri Lanka – 2014, 2014)}\]
Max Annual Financial saving in LKR Mn

\[
\frac{\text{Max Annual Financial saving in LKR Mn}}{1,000,000 \text{LKR/LKR Mn}} = (\text{Net output gain in MW}) \times (1000 \text{ kW/MW}) \times (63.45 \text{ LKR/kWh}) \times (24 \text{ h/day}) \times (365.25 \text{ days/Year}) \times (\text{Plant Factor})
\]

Annual Financial saving in USD Mn

\[
\frac{\text{Annual Financial saving in USD Mn}}{\text{USD Million}} = (\text{Annual Financial saving in LKR Mn}) \times 0.006914 \text{ USD/LKR}^1
\]

Table 5-7 Annual financial Saving of each BFP configuration

<table>
<thead>
<tr>
<th>BFP driver Configuration</th>
<th>Net output Gain / MW</th>
<th>Min Annual financial Saving</th>
<th>Max Annual financial Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LKR Million</td>
<td>USD Million</td>
<td>LKR Million</td>
</tr>
<tr>
<td>CT-C</td>
<td>0.6</td>
<td>67.71</td>
<td>0.46</td>
</tr>
<tr>
<td>CT-D</td>
<td>0.7</td>
<td>79.00</td>
<td>0.53</td>
</tr>
<tr>
<td>BPT-A</td>
<td>1.4</td>
<td>158.00</td>
<td>1.06</td>
</tr>
<tr>
<td>BPT-C1</td>
<td>1</td>
<td>112.86</td>
<td>0.76</td>
</tr>
<tr>
<td>EBPT-C1</td>
<td>0.7</td>
<td>79.00</td>
<td>0.53</td>
</tr>
</tbody>
</table>

According to the results in Table 5-7, it is clear that using one of above mentioned BFP configuration, it can be saved 0.46 USD million to 2.72 USD million annually. Compared to the total project cost of Puttalam coal power project (Average construction project cost of one unit of 300 MW = 477 USD Million (Ministry of Power and renewable energy, 2016)) this value is a significant value.


<table>
<thead>
<tr>
<th>Power Station</th>
<th>Average Unit cost (LKR/KWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asia Power</td>
<td>35.40</td>
</tr>
<tr>
<td>AES Kelanitissa</td>
<td>28.21</td>
</tr>
<tr>
<td>Colombo Power</td>
<td>26.53</td>
</tr>
<tr>
<td>Heladhanavi</td>
<td>24.83</td>
</tr>
<tr>
<td>ACE Embilipitiya</td>
<td>26.43</td>
</tr>
<tr>
<td>West Coast</td>
<td>40.96</td>
</tr>
<tr>
<td>Northern Power</td>
<td>35.45</td>
</tr>
<tr>
<td>Sapugaskanda A</td>
<td>29.63</td>
</tr>
<tr>
<td>Sapugaskanda B</td>
<td>25.35</td>
</tr>
<tr>
<td>Kelanitissa Small GTs</td>
<td>63.45</td>
</tr>
<tr>
<td>Kelanitissa PS GT7</td>
<td>47.85</td>
</tr>
<tr>
<td>Kelanitissa Combined</td>
<td>31.23</td>
</tr>
<tr>
<td>LVPS</td>
<td>8.07</td>
</tr>
<tr>
<td>Uthura Janani</td>
<td>27.00</td>
</tr>
</tbody>
</table>

\(^1\) 1 LKR = 0.006914 USD as at 01/01/2016: (exchange rates, 2016)
5.6.2. Detailed financial analysis

Both initial investment and operation and maintenance (O&M) Costs of steam turbines are normally much higher than electric motors in same power ratings. Many factors affects to the cost of a steam turbine. The initial investment cost is higher due to higher material cost, complexity due to higher no of components including piping, valves, governing system, insulation etc. The O&M cost of steam turbines is higher due to its complexity with higher number of moving parts. Since the no of moving parts are higher, the possibility to failure is higher and hence maintenance cost is higher and then operation reliability is lower. But the advantage of using steam turbines as BFP drivers is, as proven by thermal economic analysis above, power saving due to higher efficiency of the turbine arrangement. To find out the best option for BFP drive, it should be calculate the payback periods for each option. Although the both initial investment and O&M cost are higher for steam turbine option than EM option, due to increased net power output without spending additional input energy, the payback period of steam turbine option can be lower.

Cost of the equipment for each BFP driver configurations with steam turbine is different to each other. In back pressure turbines, exhaust pressure and energy content is high and that energy is used in equipment in downstream of the turbine. In this type of turbine, the exhaust must be maintained at a constant pressure by a PCV control system in downstream of the turbine exhaust to prevent changes in the exhaust pressure that would affect the turbine speed by changing the pressure drop across it. The governor would be fighting against these pressure fluctuations and speed control would be erratic (articles.compressionjobs.com, 2015). In condensing type steam turbines, exhaust has directed to the condenser and downstream pressure regulation is not necessary. But thermodynamic parameters of exhaust steam are in the mixed phase of saturated water and steam (with dryness fraction of 0.85), there is a tendency to form water droplets in last stage of steam turbine and hence precautions like surface hardening with special alloy coats, should be taken to prevent damages to turbine blades by water hammering due to water droplets.

To calculate the payback periods of each option, since the energy saving and its economic value is known, cost for the investment and O&M should be calculated. To investigate the investment cost, detailed design should be carried out including designing new pipe lines, new basements, new building etc. And hence the total project cost should be estimated including cost of equipment and materials, shipping and other transportation cost, installation cost including labor, consultancy and machinery costs etc.

To investigate O&M cost comparison exactly, a detailed research should be done with large no of data gathered from at least five different power plants at least over last ten years. The data should be gathered are, details about break downs of BFP motors or BFPTs and related cost including maintenance cost as same as lost of revenue due to unavailability of power plant if it was needed to de-load or shutdown due to BFP driver failure.
6. Conclusion

Energy saving of power plants is a popular topic in present days with the global energy crisis. The dominant solutions among different ways of energy saving are minimizing losses, optimization of the existing systems and introducing alternative solutions. Internal electricity demand is an energy portion related with equipment supportive to the main equipment, which is unavoidable but with a proper investigation, some amount of this energy can be saved either by introducing thermally efficient auxiliary equipment or improving efficiencies available equipment.

Out of various auxiliary equipment such as, pumps, fans, cranes and compressors which are majorly contributed to the plant internal electricity demand, the boiler feed water system responsible for a large share of the internal electricity demand. (In sub critical 3x300 MW Lakvijaya Coal Power Station Sri Lanka, the power share of BFP motors are about 3% of generator power output.) So it is obvious that prime movers of feed pumps could be contributed for a large percentage of the losses which associated with the power plant. So it was decided to find out how to minimize the losses related to BFP system.

Since the possibility to improve the existing BFP arrangement is less, introducing alternative efficient power source for BFP driver was considered. The widely used alternative for the BFP driver is small steam turbines. Condensing type and back pressure type BFPTs are commonly used. Eleven (11) different configurations of Condensing type, back pressure type and also extraction back pressure type turbines were considered and thermodynamic models for each configuration were implemented using Engineering Equation Solver (EES) software. The considered configurations are different to each other by inlet steam thermodynamic parameters, steam flow rate, exhaust thermodynamic steam parameters and intermediate extraction parameters etc.

Thermodynamic analysis ended up with interesting solutions while all the configurations giving improved efficiencies than existing EM mode. But some of them had not improved their net output and hence there were no gain in MW output although the efficiencies are higher. Out of other configurations with improved net output and efficiency, the case BPT-A (back pressure turbine arranged parallel to the HP turbine) had the highest net output gain with better improvement in efficiency without changing the input power to the boiler.

After that changes in CO2, Sox and NOx emissions with suggested BFP configurations were compared with existing EM driven BFP mode and it was observed that energy generated with new BFP modes are more clean than existing BFP mode.

Then two different arrangements of BFP system with introduced BFPT was discussed and decided to use a separate small motor for booster pump and run the main BFP along with steam turbine.

Calculations were done (only for BPT-A mode) to investigate the behavior of the power plant with partial loads (75%, 50% and 30% of TRL) and it was observed that BPT-A mode is more thermodynamically economical than existing EM mode in partial loads too.
Then annual financial saving with BFP configurations with positive net output gain and zero boiler input gain were calculated and the minimum and maximum possible saving can be achieved were 0.46 and 2.72 USD Millions/Year.

Finally, a discussion on financial economy of different BFPT configuration over existing EM method was done and to investigate most financially economic configuration a detailed analysis must be carried out.
7. Annexurs

7.1. EES program for thermodynamic analysis of steam cycle with available EM driven BFP configuration

"P : Pressure in MPa  T: Temperature in °C  G: Steam mass flow in kg/h  H: Enthalpy in kJ/kg"

\begin{align*}
G_1 &= 964000 \text{[kg/h]} \\
H_1 &= 3396.9 \text{[kJ/kg]} \\
G_2 &= 799380 \text{[kg/h]} \\
H_2 &= 3049.4 \text{[kJ/kg]} \\
G_3 &= 799380 \text{[kg/h]} \\
H_3 &= 3536.0 \text{[kJ/kg]} \\
G_4 &= 726850 \text{[kg/h]} \\
H_4 &= 3170.1 \text{[kJ/kg]} \\
G_5 &= 610560 \text{[kg/h]} \\
H_5 &= 2404.2 \text{[kJ/kg]} \\
G_6 &= G_7 \\
H_6 &= 189.3 \text{[kJ/kg]} \\
G_7 &= 757730 \text{[kg/h]} \\
H_7 &= 192.8 \text{[kJ/kg]} \\
G_8 &= G_7 \\
H_8 &= 258.5 \text{[kJ/kg]} \\
G_9 &= G_7 \\
H_9 &= 358.8 \text{[kJ/kg]} \\
G_{10} &= G_7 \\
H_{10} &= 446.6 \text{[kJ/kg]} \\
G_{11} &= G_7 \\
H_{11} &= 586.6 \text{[kJ/kg]} \\
\end{align*}
\[ G_{12} = G_{16} \]
\[ H_{12} = 747.4 \text{[kJ/kg]} \]
\[ G_{13} = G_{16} \]
\[ H_{13} = 773.5 \text{[kJ/kg]} \]
\[ G_{14} = G_{16} \]
\[ H_{14} = 884.6 \text{[kJ/kg]} \]
\[ G_{15} = G_{16} \]
\[ H_{15} = 1068.2 \text{[kJ/kg]} \]
\[ P_{16} = 20320 \text{[kPa]} \]
\[ G_{16} = 992920 \text{[kg/h]} \]
\[ H_{16} = 1220.9 \text{[kJ/kg]} \]

{Leaking steam From HPT to IPt}
\[ G_{\text{leak_HPT_out}} = 20720 \text{[kg/h]} \]
\[ H_{\text{leak_HPT_out}} = 3345.8 \text{[kJ/kg]} \]
\[ G_{\text{leak_IPT_in}} = 6990 \text{[kg/h]} \]
\[ H_{\text{leak_IPT_in}} = 3345.8 \text{[kJ/kg]} \]

{Boiler Blow Down}
\[ H_{\text{BD}} = \text{Enthalpy(steam, } P=P_{16}, \text{ X=0)} \]
\[ G_{\text{BD}} = G_{16} - G_1 \]

"--------------- Extraction Steam -HTR_in-----------------------------"
\[ G_{\text{htr8_in}} = 18910 \text{[kg/h]} \]
\[ H_{\text{htr8_in}} = 2514.7 \text{[kJ/kg]} \]
\[ G_{\text{htr7_in}} = 29140 \text{[kg/h]} \]
\[ H_{\text{htr7_in}} = 2651.4 \text{[kJ/kg]} \]
\[ G_{\text{htr6_in}} = 26180 \text{[kg/h]} \]
H_htr6_in=2781.8[kJ/kg]
G_htr5_in=42430[kg/h]
H_htr5_in=2967.6[kJ/kg]
G_htr4_in=42580[kg/h]
H_htr4_in=3170.1[kJ/kg]
G_htr3_in=28000[kg/h]
H_htr3_in=3342.8[kJ/kg]
G_htr2_in=64670[kg/h]
H_htr2_in=3049.4[kJ/kg]
G_htr1_in=73320[kg/h]
H_htr1_in=3160.9[kJ/kg]

"----------Calculations----------"

{BFP Power}

\[ P_{\text{bfp\_total}} = \frac{G_{12}}{3600}[\text{s/h}]*\frac{(H_{13}-H_{12})}{1000}[\text{kW/MW}] \]

\{Total Power added by BFPs (Main BFP + Booster pump)\}

eta\_motor=0.97
eta\_transformer=0.99
eta\_bp=0.826 \{Mechanical efficiency of booster pump\}
eta\_bfp=0.8163 \{Mechanical efficiency of main BFP \}
eta\_hc=0.94 \{Mechanical efficiency of Hydraulic coupling \}

P_bp= 0.4[MW] \{Power consumed by booster pump\}

P_{bfpm}=(P_{bp}+(P_{bfp\_total}-P_{bp}*eta\_bp)/(eta\_bfp*eta\_hc))/(eta\_motor*eta\_transformer) \{Power consumed by BFP Motor\}

P_{BFP\_Fuel}=P_{bfpm}/eta\_elec\_gen/eta\_internal\_turb \{Power to BFP from Fuel\}

"--------Turbine Power Out put--------"

{HP Turbine}
\[ P_{\text{hpt}} = \frac{(G_1 \cdot H_1) - (G_{\text{leak HPT out}} \cdot H_{\text{leak HPT out}}) - (G_{\text{htr1 in}} \cdot H_{\text{htr1 in}}) - (G_{\text{htr2 in}} \cdot H_{\text{htr2 in}}) - G_2 \cdot H_2}{3600 \text{[s/h]}}/1000 \text{[kW/MW]} \]

\{IP Turbine\}

\[ P_{\text{ipt}} = \frac{(G_3 \cdot H_3) + (G_{\text{leak IPT in}} \cdot H_{\text{leak IPT in}}) - (G_{\text{htr3 in}} \cdot H_{\text{htr3 in}}) - (G_{\text{htr4 in}} \cdot H_{\text{htr4 in}}) - (G_4 \cdot H_4)}{3600 \text{[s/h]}}/1000 \text{[kW/MW]} \]

\{LP Turbine\}

\[ P_{\text{lpt}} = \frac{(G_4 \cdot H_4) - (G_{\text{htr5 in}} \cdot H_{\text{htr5 in}}) - (G_{\text{htr6 in}} \cdot H_{\text{htr6 in}}) - (G_{\text{htr7 in}} \cdot H_{\text{htr7 in}}) - (G_{\text{htr8 in}} \cdot H_{\text{htr8 in}}) - G_5 \cdot H_5}{3600 \text{[s/h]}}/1000 \text{[kW/MW]} \]

\[ \text{eta}_{\text{internal turb}} = 0.936 \quad \{\text{Overall Internal Efficiency of HP, IP & LP Turbines}\} \]

\[ \text{eta}_{\text{elec gen}} = 0.985 \]

\[ \text{eta}_{\text{boiler}} = 0.89 \]

\[ P_{\text{aux}} = 28.9 \text{[MW]} \quad \{\text{Auxiliary Electric Power consumption of plant}\} \]

\[ P_{\text{Turb}} = (P_{\text{hpt}} + P_{\text{ipt}} + P_{\text{lpt}}) \]

\[ P_{\text{Gen Gross}} = (P_{\text{hpt}} + P_{\text{ipt}} + P_{\text{lpt}}) \cdot \text{eta}_{\text{internal turb}} \cdot \text{eta}_{\text{elec gen}} \]

\[ P_{\text{Gen Net}} = P_{\text{Gen Gross}} - P_{\text{aux}} \]

\[ Q_{\text{Boiler}} = \frac{(G_1 \cdot h_1 + G_{\text{BD}} \cdot H_{\text{BD}} - G_{16} \cdot h_{16}) + G_3 \cdot (h_3 - h_2)}{3600 \text{[s/h]}}/1000 \text{[kW/MW]} \quad \{\text{Heat added}\} \]

\[ \text{HR}_{\text{gross motor}} = \frac{Q_{\text{Boiler}}}{3600 \text{[s/h]}}/P_{\text{Gen Gross}} \]

\[ \text{HR}_{\text{net motor}} = \frac{Q_{\text{Boiler}}}{3600 \text{[s/h]}}/(P_{\text{Gen Gross}} - P_{\text{bfpm}}) \]

\[ \text{eta}_{\text{plant}} = \frac{P_{\text{Gen Net}}}{Q_{\text{Boiler}}/\text{eta}_{\text{boiler}}} \]

\[ SR = G_1/P_{\text{Gen Net}}/1000 \]

"-----------------isentropic Efficiency of Turbine-----------------

"------------------HPT-------------------------

{Considering expansion from 1 to 2}

\[ T_1 = 538 \text{[C]} \]
\[ T_2 = 331.2 \text{[C]} \]
\[ P_2 = \text{pressure(steam, H=H}_2, T=T_2) \]
\[ S_1 = \text{entropy(steam, H=H}_1, T=T_1) \]
\[ H_{2-2} = \text{enthalpy(steam, } P=P_2, S=S_1) \]

\[ \eta_{\text{isentropic HPT}} = \frac{H_1 - H_2}{H_1 - H_{2-2}} \]

"------------------IPT-------------------------"

{Considering expansion from 3 to 4}

\[ T_3 = 538[^\circ C] \]
\[ P_4 = 951[kPa] \]
\[ S_3 = \text{entropy(steam, } H=H_3, T=T_3) \]
\[ H_{4-2} = \text{enthalpy(steam, } P=P_4, S=S_3) \]

\[ \eta_{\text{isentropic IPT}} = \frac{H_3 - H_4}{H_3 - H_{4-2}} \]

"------------------LPT-------------------------"

{Considering expansion from 4 to 5}

\[ P_5 = 9.7[kPa] \]
\[ S_4 = \text{entropy(steam, } H=H_4, P=P_4) \]
\[ H_{5-2} = \text{enthalpy(steam, } P=P_5, S=S_4) \]

\[ \eta_{\text{isentropic LPT}} = \frac{H_4 - H_5}{H_4 - H_{5-2}} \]

7.2. EES program for thermodynamic analysis of steam cycle with steam driven BFP configuration (CT-A)

"P : Pressure in MPa  T: Temperature in °C  G: Steam mass flow in kg/h  H: Enthalpy in kJ/kg"

\[ G_1 = G_{1-0} - G_{1-1} \]
\[ H_1 = 3396.9[kJ/kg] \]

{SH outlet of boiler}

\[ G_{1-0} = 964000[kg/h] \]
\[ H_{1-0} = 3396.9[kJ/kg] \]

{BFPT inlet}

\[ H_{1-1} = 3396.9[kJ/kg] \]
\begin{align*}
G_2 &= 799380\text{[kg/h]} - G_{1,1} \\
H_2 &= 3049.4\text{[kJ/kg]} \\
G_3 &= G_2 \\
H_3 &= 3536.0\text{[kJ/kg]} \\
G_4 &= 726850\text{[kg/h]} - G_{1,1} \\
H_4 &= 3170.1\text{[kJ/kg]} \\
G_5 &= 610560\text{[kg/h]} - G_{1,1} \\
H_5 &= 2404.2\text{[kJ/kg]} \\
G_6 &= G_7 \\
H_6 &= 189.3\text{[kJ/kg]} \\
G_7 &= 757730\text{[kg/h]} \\
H_7 &= 192.8\text{[kJ/kg]} \\
G_8 &= G_7 \\
H_8 &= 258.5\text{[kJ/kg]} \\
G_9 &= G_7 \\
H_9 &= 358.8\text{[kJ/kg]} \\
G_{10} &= G_7 \\
H_{10} &= 446.6\text{[kJ/kg]} \\
G_{11} &= G_7 \\
H_{11} &= 586.6\text{[kJ/kg]} \\
G_{12} &= G_{16} \\
H_{12} &= 747.4\text{[kJ/kg]} \\
G_{13} &= G_{16} \\
H_{13} &= 773.5\text{[kJ/kg]} 
\end{align*}
\[ G_{14} = G_{16} \]
\[ H_{14} = 884.6 \text{[kJ/kg]} \]
\[ G_{15} = G_{16} \]
\[ H_{15} = 1068.2 \text{[kJ/kg]} \]
\[ P_{16} = 20320 \text{[kPa]} \]
\[ G_{16} = 992920 \text{[kg/h]} \]
\[ H_{16} = 1220.9 \text{[kJ/kg]} \]

{Leaking steam From HPT to IPT}
\[ G_{\text{leak_HPT_out}} = 20720 \text{[kg/h]} \]
\[ H_{\text{leak_HPT_out}} = 3345.8 \text{[kJ/kg]} \]
\[ G_{\text{leak_IPT_in}} = 6990 \text{[kg/h]} \]
\[ H_{\text{leak_IPT_in}} = 3345.8 \text{[kJ/kg]} \]

{Boiler Blow Down}
\[ H_{\text{BD}} = \text{Enthalpy(steam,} P=P_{16}, \text{X=0)} \]
\[ G_{\text{BD}} = G_{16} - G_{1_0} \]

"------------------- Extraction Steam -HTR_in-----------------------------"

\[ G_{\text{htr8_in}} = 18910 \text{[kg/h]} \]
\[ H_{\text{htr8_in}} = 2514.7 \text{[kJ/kg]} \]
\[ G_{\text{htr7_in}} = 29140 \text{[kg/h]} \]
\[ H_{\text{htr7_in}} = 2651.4 \text{[kJ/kg]} \]
\[ G_{\text{htr6_in}} = 26180 \text{[kg/h]} \]
\[ H_{\text{htr6_in}} = 2781.8 \text{[kJ/kg]} \]
\[ G_{\text{htr5_in}} = 42430 \text{[kg/h]} \]
\[ H_{\text{htr5_in}} = 2967.6 \text{[kJ/kg]} \]
G_htr4_in=42580[kg/h]
H_htr4_in=3170.1[kJ/kg]

G_htr3_in=28000[kg/h]
H_htr3_in=3342.8[kJ/kg]

G_htr2_in=64670[kg/h]
H_htr2_in=3049.4[kJ/kg]

G_htr1_in=73320[kg/h]
H_htr1_in=3160.9[kJ/kg]

"-------------------------------Calculations-------------------------------"}

{BFP Power}
eta_bp=0.826   {Mechanical efficiency of booster pump}
eta_bpmotor=0.97  {Electrical Efficiency of booster pump motor}
eta_bfp=0.8163  {Mechanical efficiency of main BFP }
eta_bfpt=0.90   {Internal efficiency of BFP Turbine}
eta_transformer=0.99

P_bp= 0.4[MW]  {Power consumed by booster pump motor}
eta_isentropic_BFPT=0.9    {Isentropic efficiency of BFPT}
eta_isentropic_BFPT=(H_1_1-H_bfpt_exh)/(H_1_1-H_bfpt_exh_2)
H_bfpt_exh_2=enthalpy(steam,P=P_5,S=S_1)

P_5=9.7[kPa]
S_1=entropy(steam,H=H_1,T=T_1)
T_1=538[C]

P_bfp_total=G_12/3600[s/h]*(H_13-H_12)/1000[kW/MW]  {Total Power added by BFPs (Main BFP + Booster pump)}
\[ P_{\text{bfpt}} = \frac{(P_{\text{bfpt\_total}} - P_{\text{bp}} \cdot \eta_{\text{bp}})}{\eta_{\text{bfpt}}} \]  \{Input power to BFPT\}

\[ P_{\text{bfpt}} = \frac{G_1}{3600\text{s/h}} \cdot \frac{(H_1 - H_{\text{bfpt\_exh}})}{1000\text{kW/MW}} \]  \{Input Power to BFPT\}

\[ P_{\text{BFP}} = \frac{P_{\text{bp}}}{\eta_{\text{bp\_motor}}} + P_{\text{bfpt}} \]

\[ P_{\text{BFP\_Fuel}} = \frac{P_{\text{bp}}}{\eta_{\text{bp\_motor}}} \cdot \eta_{\text{transformer}} \cdot \eta_{\text{electric\_generator}} \cdot \eta_{\text{internal\_turb}} + P_{\text{bfpt}} \]

{Power to BFP from Fuel}

"------------------------Turbine Gross Power Out put-------------------------------"

{Gross power output of HP Turbine}

\[ P_{\text{hpt}} = \frac{((G_1 \cdot H_1) - (G_{\text{leak\_HPT\_out}} \cdot H_{\text{leak\_HPT\_out}}) - (G_{\text{htr1\_in}} \cdot H_{\text{htr1\_in}}) - (G_{\text{htr2\_in}} \cdot H_{\text{htr2\_in}}) - G_2 \cdot H_2)}{3600\text{s/h}} \cdot \frac{1}{1000\text{kW/MW}} \]

{Gross Power output of IP Turbine}

\[ P_{\text{ipt}} = \frac{((G_3 \cdot H_3) + (G_{\text{leak\_IPT\_in}} \cdot H_{\text{leak\_IPT\_in}}) - (G_{\text{htr3\_in}} \cdot H_{\text{htr3\_in}}) - (G_{\text{htr4\_in}} \cdot H_{\text{htr4\_in}}) - (G_4 \cdot H_4))}{3600\text{s/h}} \cdot \frac{1}{1000\text{kW/MW}} \]

{Gross Power output of LP Turbine}

\[ P_{\text{lpt}} = \frac{((G_4 \cdot H_4) - (G_{\text{htr5\_in}} \cdot H_{\text{htr5\_in}}) - (G_{\text{htr6\_in}} \cdot H_{\text{htr6\_in}}) - (G_{\text{htr7\_in}} \cdot H_{\text{htr7\_in}}) - (G_{\text{htr8\_in}} \cdot H_{\text{htr8\_in}}) - (G_5 \cdot H_5))}{3600\text{s/h}} \cdot \frac{1}{1000\text{kW/MW}} \]

"------------------------ Other Calculations -----------------------------------"

\[ \eta_{\text{internal\_turb}} = 0.936 \]  \{Overall internal Efficiency of HP, IP and LP Turbines\}

\[ \eta_{\text{elec\_gen}} = 0.985 \]  \{Electrical Efficiency of Generator\}

\[ \eta_{\text{boiler}} = 0.89 \]  \{Net efficiency of the boiler\}

\[ P_{\text{aux}} = \frac{28.9\text{[MW]} - 9.738\text{[MW]} + 0.4\text{[MW]}}{\eta_{\text{bp\_motor}}} \]  \{Auxiliary Electric Power consumption of plant\}

\[ P_{\text{Turb}} = (P_{\text{hpt}} + P_{\text{ipt}} + P_{\text{lpt}}) \]

\[ P_{\text{Gen\_Gross}} = (P_{\text{hpt}} + P_{\text{ipt}} + P_{\text{lpt}}) \cdot \eta_{\text{internal\_turb}} \cdot \eta_{\text{elec\_gen}} \]

\[ P_{\text{Gen\_Net}} = P_{\text{Gen\_Gross}} - P_{\text{aux}} \]

\[ Q_{\text{Boiler}} = \frac{((G_1 \cdot h_1 - G_0 \cdot h_0) + (G_{\text{BD}} \cdot H_{\text{BD}}) - (G_16 \cdot h_16) + G_3 \cdot (h_3 - h_2))}{3600\text{s/h}} \cdot \frac{1}{1000\text{kW/MW}} \]  \{Heat added to system by boiler\}
HR_Gross_turb=Q_Boiler*3600[s/h]/(P_Gen_Gross+P_BFP)

HR_Net_turb=Q_Boiler*3600[s/h]/(P_Gen_Gross)

eta_plant=(P_Gen_Net)/(Q_Boiler/eta_boiler)

SR=G_1_0/P_Gen_Net/1000

7.3. EES program for thermodynamic analysis of steam cycle with steam driven BFP configuration (BPT-A)

"P : Pressure in MPa   T: Temperature in °C   G: Steam mass flow in kg/h   H: Enthalpy in kJ/kg"

G_1=G_1_0-G_1_1
H_1=3396.9[kJ/kg]

{SH outlet of boiler}

G_1_0=964000[kg/h]
H_1_0=3396.9[kJ/kg]

{BFP inlet}

H_1_1=3396.9[kJ/kg]

G_2_0=799380[kg/h]-G_1_1
H_2_0=H_2
G_2=799380[kg/h]
H_2=3049.4[kJ/kg]
G_3=G_2
H_3=3536.0[kJ/kg]
G_4=726850[kg/h]
H_4=3170.1[kJ/kg]
\( G_5 = 610560 \text{[kg/h]} \)
\( H_5 = 2404.2 \text{[kJ/kg]} \)

\( G_6 = G_7 \)
\( H_6 = 189.3 \text{[kJ/kg]} \)
\( G_7 = 757730 \text{[kg/h]} \)
\( H_7 = 192.8 \text{[kJ/kg]} \)

\( G_8 = G_7 \)
\( H_8 = 258.5 \text{[kJ/kg]} \)

\( G_9 = G_7 \)
\( H_9 = 358.8 \text{[kJ/kg]} \)

\( G_{10} = G_7 \)
\( H_{10} = 446.6 \text{[kJ/kg]} \)

\( G_{11} = G_7 \)
\( H_{11} = 586.6 \text{[kJ/kg]} \)

\( G_{12} = G_{16} \)
\( H_{12} = 747.4 \text{[kJ/kg]} \)

\( G_{13} = G_{16} \)
\( H_{13} = 773.5 \text{[kJ/kg]} \)

\( G_{14} = G_{16} \)
\( H_{14} = 884.6 \text{[kJ/kg]} \)

\( G_{15} = G_{16} \)
\( H_{15} = 1068.2 \text{[kJ/kg]} \)

\( P_{16} = 20320 \text{[kPa]} \)
\( G_{16} = 992920 \text{[kg/h]} \)
$H_{16} = 1220.9 \text{[kJ/kg]}$

{Leaking steam From HPT to IPt}

$G_{\text{leak HPT out}} = 20720 \text{[kg/h]}$

$H_{\text{leak HPT out}} = 3345.8 \text{[kJ/kg]}$

$G_{\text{leak IPT in}} = 6990 \text{[kg/h]}$

$H_{\text{leak IPT in}} = 3345.8 \text{[kJ/kg]}$

{Boiler Blow Down}

$H_{BD} = \text{Enthalpy(steam, P=P}_{16} \text{, X=0)}$

$G_{BD} = G_{16} - G_{1_0}$

"------------------------- Extraction Steam -HTR_in-------------------------------" 

$G_{\text{htr8 in}} = 18910 \text{[kg/h]}$

$H_{\text{htr8 in}} = 2514.7 \text{[kJ/kg]}$

$G_{\text{htr7 in}} = 29140 \text{[kg/h]}$

$H_{\text{htr7 in}} = 2651.4 \text{[kJ/kg]}$

$G_{\text{htr6 in}} = 26180 \text{[kg/h]}$

$H_{\text{htr6 in}} = 2781.8 \text{[kJ/kg]}$

$G_{\text{htr5 in}} = 42430 \text{[kg/h]}$

$H_{\text{htr5 in}} = 2967.6 \text{[kJ/kg]}$

$G_{\text{htr4 in}} = 42580 \text{[kg/h]}$

$H_{\text{htr4 in}} = 3170.1 \text{[kJ/kg]}$

$G_{\text{htr3 in}} = 28000 \text{[kg/h]}$

$H_{\text{htr3 in}} = 3342.8 \text{[kJ/kg]}$

$G_{\text{htr2 in}} = 64670 \text{[kg/h]}$

$H_{\text{htr2 in}} = 3049.4 \text{[kJ/kg]}
G_htr1_in=73320[kg/h]

H_htr1_in=3160.9[kJ/kg]

"-----------------------------Calculations---------------------------------------------"

{BFP Power}

\( \eta_{bp} = 0.826 \) \{Mechanical efficiency of booster pump\}

\( \eta_{bpmotor} = 0.97 \) \{Electrical Efficiency of booster pump motor\}

\( \eta_{bfp} = 0.8163 \) \{Mechanical efficiency of main BFP\}

\( \eta_{bfpt} = 0.90 \) \{Internal efficiency of BFP Turbine\}

\( \eta_{transformer} = 0.99 \)

\( P_{bp} = 0.4[MW] \) \{Power consumed by booster pump motor\}

\( \eta_{isentropic_BFPT} = 0.9 \) \{Isentropic efficiency of BFPT\}

\( \eta_{isentropic_BFPT} = \frac{(H_{1_1}-H_{bfpt\_exh})}{(H_{1_1}-H_{bfpt\_exh\_2})} \)

\( H_{bfpt\_exh\_2} = \text{enthalpy(steam}, P=P_{2}, S=S_{1}) \)

\( P_{2} = \text{pressure(steam}, H=H_{2}, T=T_{2}) \)

\( S_{1} = \text{entropy(steam}, H=H_{1}, T=T_{1}) \)

\( T_{1} = 538[C] \)

\( T_{2} = 331.2[C] \)

\( P_{bfp\_total} = G_{12}/3600[s/h]*(H_{13}-H_{12})/1000[kW/MW] \) \{Total Power added by BFPs (Main BFP + Booster pump)\}

\( P_{bfpt} = (P_{bfp\_total}-P_{bp}\_eta_{bp})/(\eta_{bfpt}\_\eta_{bfp}) \) \{Input power to BFPT\}

\( P_{bfpt} = G_{1_1}/3600[s/h]*(H_{1_1}-H_{bfpt\_exh})/1000[kW/MW] \) \{Input Power to BFPT\}

\( P_{BFP} = P_{bp}/\eta_{bpmotor}/\eta_{transformer}+P_{bfpt} \)

"--------------------------Turbine Gross Power Output----------------------------------"

{Gross power output of HP Turbine}
P_hpt=((G_1*H_1)-(G_leak_HPT_out*H_leak_HPT_out)-(G_htr1_in*H_htr1_in)-
(G_htr2_in*H_htr2_in)-G_2*0*H_2)/3600[s/h]/1000[kW/MW]

{Gross Power output of IP Turbine}

P_ipt=((G_3*H_3)+(G_leak_IPT_in*H_leak_IPT_in)-(G_htr3_in*H_htr3_in)-
(G_htr4_in*H_htr4_in)-(G_4*H_4))/3600[s/h]/1000[kW/MW]

{Gross Power output of LP Turbine}

P_lpt=((G_4*H_4)-(G_htr5_in*H_htr5_in)-(G_htr6_in*H_htr6_in)-(G_htr7_in*H_htr7_in)-
(G_htr8_in*H_htr8_in)-(G_5*H_5))/3600[s/h]/1000[kW/MW]

"-------------------- Other Calculations ---------------------------------"

eta_internal_turb=0.936   {Overall internal Efficiency of HP, IP and LP Turbines}
eta_elec_gen=0.985   {Electrical Efficiency of Generator}
eta_boiler=0.89    {Net efficiency of the boiler}

P_aux=28.9[MW]-9.738[MW]+0.4[MW]/eta_bpmotor/eta_transformer  {Auxiliary
Electric Power consumption of plant}

P_Turb=(P_hpt+P_ipt+P_lpt)

P_Gen_Gross=(P_hpt+P_ipt+P_lpt)*eta_internal_turb*eta_elec_gen

P_Gen_Net=P_Gen_Gross-P_aux

Q_Boiler=((G_1_0*h_1_0)+(G_BD*H_BD)-(G_16*h_16)+G_3*(h_3-
h_2))/3600[s/h]/1000[kW/MW]  {Heat added to system by boiler}

HR_Gross_turb=Q_Boiler*3600[s/h]/(P_Gen_Gross+P_BFP)

HR_Net_turb=Q_Boiler*3600[s/h]/(P_Gen_Gross)

eta_plant=( P_Gen_Net)/(Q_Boiler/eta_boiler)

SR=G_1_0/P_Gen_Net/1000
7.4. EES program for thermodynamic analysis of steam cycle with steam driven BFP configuration (EBPT-B)

{Feeding steam to bftp form point 2 and bleed to htr5 (full requirement) and remaining to htr 6. The balance to htr 6 is from LPT}

"P : Pressure in MPa  T: Temperature in °C  G: Steam mass flow in kg/h  H: Enthalpy in kJ/kg"

\[
\begin{align*}
G_1 &= 964000 \text{[kg/h]} \\
H_1 &= 3396.9 \text{[kJ/kg]} \\
G_2 &= 799380 \text{[kg/h]} - G_{2_1} \\
H_2 &= 3049.4 \text{[kJ/kg]} \\
G_{2_0} &= 799380 \text{[kg/h]} \\
H_{2_0} &= 3049.4 \text{[kJ/kg]} \\
H_{2_1} &= 3049.4 \text{[kJ/kg]} \\
G_3 &= G_2 \\
H_3 &= 3536.0 \text{[kJ/kg]} \\
G_4 &= 726850 \text{[kg/h]} - G_{2_1} \\
H_4 &= 3170.1 \text{[kJ/kg]} \\
G_5 &= 610560 \text{[kg/h]} \\
H_5 &= 2404.2 \text{[kJ/kg]} \\
G_6 &= G_7 \\
H_6 &= 189.3 \text{[kJ/kg]} \\
G_7 &= 757730 \text{[kg/h]} \\
H_7 &= 192.8 \text{[kJ/kg]} 
\end{align*}
\]
\[ G_8 = G_7 \]
\[ H_8 = 258.5 \text{[kJ/kg]} \]
\[ G_9 = G_7 \]
\[ H_9 = 358.8 \text{[kJ/kg]} \]
\[ G_{10} = G_7 \]
\[ H_{10} = 446.6 \text{[kJ/kg]} \]
\[ G_{11} = G_7 \]
\[ H_{11} = 586.6 \text{[kJ/kg]} \]
\[ G_{12} = G_{16} \]
\[ H_{12} = 747.4 \text{[kJ/kg]} \]
\[ G_{13} = G_{16} \]
\[ H_{13} = 773.5 \text{[kJ/kg]} \]
\[ G_{14} = G_{16} \]
\[ H_{14} = 884.6 \text{[kJ/kg]} \]
\[ G_{15} = G_{16} \]
\[ H_{15} = 1068.2 \text{[kJ/kg]} \]
\[ P_{16} = 20320 \text{[kPa]} \]
\[ G_{16} = 992920 \text{[kg/h]} - H\_\text{drop} \]
\[ H_{16} = 1220.9 \text{[kJ/kg]} \]

{Leaking steam From HPT to IPt}
\[ G\_\text{leak\_HPT\_out} = 20720 \text{[kg/h]} \]
H\_leak\_HPT\_out=3345.8[kJ/kg]

G\_leak\_IPT\_in=6990[kg/h]

H\_leak\_IPT\_in=3345.8[kJ/kg]

\{Boiler Blow Down\}

H\_BD=Enthalpy(steam, P=P\_16, X=0)

G\_BD=G\_16-G\_1

"------------Extraction Steam \-HTR\_in-----------------------------"

G\_htr8\_in=18910[kg/h]

H\_htr8\_in=2514.7[kJ/kg]

G\_htr7\_in=29140[kg/h]

H\_htr7\_in=2651.4[kJ/kg]

G\_htr6\_in=26180[kg/h]

H\_htr6\_in=2781.8[kJ/kg]

G\_htr5\_in=42430[kg/h]

H\_htr5\_in=2967.6[kJ/kg]

G\_htr4\_in=42580[kg/h]

H\_htr4\_in=3170.1[kJ/kg]

G\_htr3\_in=28000[kg/h]

H\_htr3\_in=3342.8[kJ/kg]

G\_htr2\_in=64670[kg/h]

H\_htr2\_in=3049.4[kJ/kg]
G\text{\_htr1\_in}=73320\text{[kg/h]}

H\text{\_htr1\_in}=3160.9\text{[kJ/kg]}

"--------------------Calculations----------------------------------"

{BFP Power}

\eta_{bp}=0.826 \quad \{\text{Mechanical efficiency of booster pump}\}

\eta_{bpmotor}=0.97 \quad \{\text{Electrical Efficiency of booster pump motor}\}

\eta_{bfp}=0.8163 \quad \{\text{Mechanical efficiency of main BFP}\}

\eta_{bfpt}=0.90 \quad \{\text{Internal efficiency of BFP Turbine}\}

\eta_{transformer}=0.99

P_{bp}=0.4\text{[MW]} \quad \{\text{Power consumed by booster pump motor}\}

\eta_{isentropic\_BFPT}=0.9 \quad \{\text{Isentropic efficiency of BFPT}\}

\eta_{isentropic\_BFPT}=(H_{2\_1}-H_{bfpt\_ext})/(H_{2\_1}-H_{bfpt\_ext\_2})

H_{bfpt\_ext\_2}=\text{enthalpy(steam,}P=P_{htr5},S=S_{2})

P_{htr5}=402\text{[kPa]}

S_{2}=\text{entropy(steam,}H=H_{2},T=T_{2})

T_{2}=331.2\text{[C]}

\eta_{isentropic\_BFPT}=(H_{bfpt\_ext}-H_{bfpt\_exh})/(H_{bfpt\_ext}-H_{bfpt\_exh\_2})

H_{bfpt\_exh\_2}=\text{enthalpy(steam,}P=P_{htr6},S=S_{bfpt\_ext})

P_{htr6}=146\text{[kPa]}

S_{bfpt\_ext}=\text{entropy(steam,}H=H_{bfpt\_ext},P=P_{htr5})
\[ H_{\text{drop}} = (G_{\text{htr5\_in}}(H_{\text{htr5\_in}}-H_{\text{bfpt\_ext}}) + (G_{2\_1}-G_{\text{htr5\_in}})(H_{\text{htr6\_in}}-H_{\text{bfpt\_exh}}))/G_6 \]

\[ P_{\text{bfpt\_total}} = G_{12}/3600\text{[s/h]}(H_{13}-H_{12})/1000\text{[kW/MW]} \quad \text{(Total Power added by BFPs (Main BFP + Booster pump))} \]

\[ P_{\text{bfpt}} = (P_{\text{bfpt\_total}} - P_{\text{bp}} \cdot \eta_{\text{bp}})/(\eta_{\text{bfpt}} \cdot \eta_{\text{bfpt}}) \quad \text{[Input power to BFPT]} \]

\[ P_{\text{bfpt}} = ((G_{2\_1}H_{2\_1}) - (G_{\text{htr5\_in}}H_{\text{bfpt\_ext}}) - (G_{2\_1} - G_{\text{htr5\_in}})H_{\text{bfpt\_exh}})/3600\text{[s/h]}/1000\text{[kW/MW]} \quad \text{(Input Power to BFPT)} \]

\[ P_{\text{BFP}} = P_{\text{bp}}/\eta_{\text{bmp\_motor}}/\eta_{\text{transformer}} + P_{\text{bfpt}} \]

"------------Turbine Gross Power Output--------------------------"

\{Gross power output of HP Turbine\}

\[ P_{\text{hpt}} = ((G_{1}H_{1}) - (G_{\text{leak\_HPT\_out}}H_{\text{leak\_HPT\_out}}) - (G_{\text{htr1\_in}}H_{\text{htr1\_in}}) - (G_{\text{htr2\_in}}H_{\text{htr2\_in}}) - G_{2\_0}H_{2})/3600\text{[s/h]}/1000\text{[kW/MW]} \]

\{Gross Power output of IP Turbine\}

\[ P_{\text{ipt}} = ((G_{3}H_{3}) + (G_{\text{leak\_IPT\_in}}H_{\text{leak\_IPT\_in}}) - (G_{\text{htr3\_in}}H_{\text{htr3\_in}}) - (G_{\text{htr4\_in}}H_{\text{htr4\_in}}) - (G_{4}H_{4}))/3600\text{[s/h]}/1000\text{[kW/MW]} \]

\{Gross Power output of LP Turbine\}

\[ P_{\text{lpt}} = ((G_{4}H_{4}) - (G_{\text{htr7\_in}}H_{\text{htr7\_in}}) - (G_{\text{htr8\_in}}H_{\text{htr8\_in}}) - (G_{\text{htr5\_in}}+G_{\text{htr6\_in}}-G_{2\_1})H_{\text{htr6\_in}}-G_{5}H_{5})/3600\text{[s/h]}/1000\text{[kW/MW]} \]

"------------ Other Calculations ------------------------"

\[ \eta_{\text{internal\_turb}} = 0.936 \quad \text{(Overall internal Efficiency of HP, IP and LP Turbines)} \]

\[ \eta_{\text{elec\_gen}} = 0.985 \quad \text{[Electrical Efficiency of Generator]} \]

\[ \eta_{\text{boiler}} = 0.89 \quad \text{[Net efficiency of the boiler]} \]

\[ P_{\text{aux}} = 28.9\text{[MW]} - 9.738\text{[MW]} + 0.4\text{[MW]}/\eta_{\text{bmp\_motor}}/\eta_{\text{transformer}} \quad \text{[Auxiliary Electric Power consumption of plant]} \]
\[ P_{\text{Turb}} = (P_{\text{hpt}} + P_{\text{ipt}} + P_{\text{lpt}}) \]

\[ P_{\text{Gen\_Gross}} = (P_{\text{hpt}} + P_{\text{ipt}} + P_{\text{lpt}}) \times \eta_{\text{internal\_turb}} \times \eta_{\text{elec\_gen}} \]

\[ P_{\text{Gen\_Net}} = P_{\text{Gen\_Gross}} - P_{\text{aux}} \]

\[ Q_{\text{Boiler}} = \frac{(G_1 \times H_1) + (G_{BD} \times H_{BD}) - (G_{16} \times H_{16}) + G_3 \times (H_3 - H_2)}{3600 \text{[s/h]} / 1000 \text{[kW/MW]}} \quad \text{\{Heat added to system by boiler\}} \]

\[ HR_{\text{Gross\_turb}} = \frac{Q_{\text{Boiler}} \times 3600 \text{[s/h]}}{(P_{\text{Gen\_Gross}} + P_{\text{BFP}})} \]

\[ HR_{\text{Net\_turb}} = \frac{Q_{\text{Boiler}} \times 3600 \text{[s/h]}}{(P_{\text{Gen\_Gross}})} \]

\[ \eta_{\text{plant}} = \frac{P_{\text{Gen\_Net}}}{Q_{\text{Boiler}} / \eta_{\text{boiler}}} \]

\[ SR = \frac{G_1}{P_{\text{Gen\_Net}}} / 1000 \]

### 7.5. EES program for thermodynamic analysis of steam cycle with steam driven BFP configuration-BPT-A for 75% of TRL

"P : Pressure in MPa   T: Temperature in °C   G: Steam mass flow in kg/h   H: Enthalpy in kJ/kg"

\[ G_1 = G_{1_0} - G_{1_1} \]

\[ H_1 = 3396.9 \text{[kJ/kg]} \]

\{SH outlet of boiler\}

\[ G_{1_0} = 674800 \text{[kg/h]} \]

\[ H_{1_0} = H_1 \]

\{BFPT inlet\}

\[ H_{1_1} = H_1 \]

\[ G_{2_0} = G_2 - G_{1_1} \]

\[ H_{2_0} = H_2 \]

\[ G_2 = 574670 \text{[kg/h]} \]

\[ H_2 = 3010.2 \text{[kJ/kg]} \]
$G_3 = G_2$

$H_3 = 3545.7 \text{[kJ/kg]}$

$G_4 = 530100 \text{[kg/h]}$

$H_4 = 3180.4 \text{[kJ/kg]}$

$G_5 = 453800 \text{[kg/h]}$

$H_5 = 2408.5 \text{[kJ/kg]}$

$G_6 = G_7$

$H_6 = 163.4 \text{[kJ/kg]}$

$G_7 = 531830 \text{[kg/h]}$

$H_7 = 169.1 \text{[kJ/kg]}$

$G_8 = G_7$

$H_8 = 230.5 \text{[kJ/kg]}$

$G_9 = G_7$

$H_9 = 325.7 \text{[kJ/kg]}$

$G_{10} = G_7$

$H_{10} = 409.3 \text{[kJ/kg]}$

$G_{11} = G_7$

$H_{11} = 542.5 \text{[kJ/kg]}$

$G_{12} = G_{16}$

$H_{12} = 691.4 \text{[kJ/kg]}$

$G_{13} = G_{16}$

$H_{13} = 716.2 \text{[kJ/kg]}$

$G_{14} = G_{16}$

$H_{14} = 817.8 \text{[kJ/kg]}$
\[ G_{15} = G_{16} \]

\[ H_{15} = 984.2 \text{[kJ/kg]} \]

\[ P_{16} = 18550 \text{[kPa]} \]

\[ G_{16} = 674810 \text{[kg/h]} \]

\[ H_{16} = 1115.4 \text{[kJ/kg]} \]

\{Leaking steam From HPT to IPT\}

\[ G_{\text{leak HPT out}} = 14540 \text{[kg/h]} \]

\[ H_{\text{leak HPT out}} = 3284.8 \text{[kJ/kg]} \]

\[ G_{\text{leak IPT in}} = 5160 \text{[kg/h]} \]

\[ H_{\text{leak IPT in}} = 3284.8 \text{[kJ/kg]} \]

\{Boiler Blow Down\}

\[ H_{\text{BD}} = \text{Enthalpy(steam, P=P\_16, X=0)} \]

\[ G_{\text{BD}} = G_{16} - G_{1_0} \]

"------------------------ Extraction Steam -HTR_in-----------------------------"

\[ G_{\text{htr8 in}} = 12350 \text{[kg/h]} \]

\[ H_{\text{htr8 in}} = 2521.0 \text{[kJ/kg]} \]

\[ G_{\text{htr7 in}} = 19280 \text{[kg/h]} \]

\[ H_{\text{htr7 in}} = 2657.4 \text{[kJ/kg]} \]

\[ G_{\text{htr6 in}} = 17240 \text{[kg/h]} \]

\[ H_{\text{htr6 in}} = 2789.8 \text{[kJ/kg]} \]

\[ G_{\text{htr5 in}} = 27810 \text{[kg/h]} \]

\[ H_{\text{htr5 in}} = 2978.8 \text{[kJ/kg]} \]

\[ G_{\text{htr4 in}} = 26730[\text{kg/h}] - 3590[\text{kg/h}] \]

\[ H_{\text{htr4 in}} = 3180.4 \text{[kJ/kg]} \]
G\_htr3\_in=19430\,[kg/h]-2870\,[kJ/kg]

H\_htr3\_in=3352.6\,[kJ/kg]

G\_htr2\_in=48290\,[kg/h]

H\_htr2\_in=3010.2\,[kJ/kg]

G\_htr1\_in=42040\,[kg/h]

H\_htr1\_in=3112.3\,[kJ/kg]

" -------------------------------Calculations-----------------------------" 

eta\_bp=0.826 \{Mechanical efficiency of booster pump\}

eta\_bpmotor=0.97 \{Electrical Efficiency of booster pump motor\}

eta\_bfp=0.8163 \{Mechanical efficiency of main BFP\}

eta\_bfpt=0.90 \{Internal efficiency of BFP Turbine\}

eta\_transformer=0.99

P\_bp= 0.31\,[MW] \{Power consumed by booster pump motor\}

eta\_isentropic\_BFPT=0.9 \{Isentropic efficiency of BFPT\}

eta\_isentropic\_BFPT=(H\_1\_1-H\_bfpt\_exh)/(H\_1\_1-H\_bfpt\_exh\_2)

H\_bfpt\_exh\_2=enthalpy(steam,P=P\_2,S=S\_1)

P\_2=pressure(steam,H=H\_2,T=T\_2)

S\_1=entropy(steam,H=H\_1,T=T\_1)

T\_1=538\,[C]

T\_2=303.9\,[C]

P\_bfp\_total=G\_12/3600\,[s/h]*(H\_13-H\_12)/1000\,[kW/MW] \{Total Power added by BFPs (Main BFP + Booster pump)\}

P\_bfpt=(P\_bfp\_total-P\_bp*eta\_bp)/(eta\_bfp*eta\_bfpt) \{Input power to BFPT\}

P\_bfpt=G\_1\_1/3600\,[s/h]*(H\_1\_1-H\_bfpt\_exh)/1000\,[kW/MW] \{Input Power to BFPT\}
\[ P_{BFP} = P_{bp} / \eta_{bpmotor} / \eta_{transformer} + P_{bfpt} \]

"************************** Turbine Gross Power Output *****************************

\{ Gross power output of HP Turbine \}

\[ P_{hpt} = \frac{(G_1 \cdot H_1) - (G_{leak\_HPT\_out} \cdot H_{leak\_HPT\_out}) - (G_{htr1\_in} \cdot H_{htr1\_in}) - (G_{htr2\_in} \cdot H_{htr2\_in}) - G_2 \cdot 0 \cdot H_2}{3600[s/h]} / 1000[kW/MW] \]

\{ Gross Power output of IP Turbine \}

\[ P_{ipt} = \frac{(G_3 \cdot H_3) + (G_{leak\_IPT\_in} \cdot H_{leak\_IPT\_in}) - (G_{htr3\_in} \cdot H_{htr3\_in}) - (G_{htr4\_in} \cdot H_{htr4\_in}) - (G_4 \cdot H_4)}{3600[s/h]} / 1000[kW/MW] \]

\{ Gross Power output of LP Turbine \}

\[ P_{lpt} = \frac{(G_4 \cdot H_4) - (G_{htr5\_in} \cdot H_{htr5\_in}) - (G_{htr6\_in} \cdot H_{htr6\_in}) - (G_{htr7\_in} \cdot H_{htr7\_in}) - (G_{htr8\_in} \cdot H_{htr8\_in}) - (G_5 \cdot H_5)}{3600[s/h]} / 1000[kW/MW] \]

"************************** Other Calculations *****************************

\[ \eta_{internal\_turb} = 0.936 \] \{ Overall internal Efficiency of HP, IP and LP Turbines \}

\[ \eta_{elec\_gen} = 0.985 \] \{ Electrical Efficiency of Generator \}

\[ \eta_{boiler} = 0.88 \] \{ Net efficiency of the boiler \}

\[ P_{aux} = 23.5[MW] - 6.284[MW] + 0.31[MW] / \eta_{bpmotor} / \eta_{transformer} \]

\{ Auxiliary Electric Power consumption of plant \}

\[ P_{Turb} = (P_{hpt} + P_{ipt} + P_{lpt}) \]

\[ P_{Gen\_Gross} = (P_{hpt} + P_{ipt} + P_{lpt}) \cdot \eta_{internal\_turb} \cdot \eta_{elec\_gen} \]

\[ P_{Gen\_Net} = P_{Gen\_Gross} - P_{aux} \]

\[ Q_{Boiler} = \frac{(G_{1_0} \cdot h_{1_0}) + (G_{BD} \cdot H_{BD}) - (G_{16} \cdot h_{16}) + G_3 \cdot (h_3 - h_2)}{3600[s/h]} / 1000[kW/MW] \] \{ Heat added to system by boiler \}

\[ HR_{Gross\_turb} = Q_{Boiler} \cdot 3600[s/h] / (P_{Gen\_Gross} + P_{BFP}) \]

\[ HR_{Net\_turb} = Q_{Boiler} \cdot 3600[s/h] / (P_{Gen\_Gross}) \]

\[ \eta_{plant} = \frac{P_{Gen\_Net}}{Q_{Boiler} / \eta_{boiler}} \]

\[ SR = G_{1_0} / P_{Gen\_Net} / 1000 \]
8. Bibliography


PE, E. S. Key Specification Points for Turbine Driven Boiler Feed Water Pumps Used in Super Critical and Ultra Super Critical Coal Fired Power Plants .


