MCE 4705

Applied Thermodynamics

Project 1: Design and Thermodynamic Analysis of a Thermal Power Plant

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Contents

Introduction:

In this project, a thermal power plant design capable of powering a 250 MVA generator is done. At the same time, a detailed thermodynamic analysis of the plant is also shown. The plant must follow the design requirement, and these are:

- Output must be 250 MVA
- 1st law efficiency > 30%
- The cost of electricity should be like that of existing plants.

For the design, a coal-fired steam power plant is considered. To design the plant, the assumptions made are:

1. The plant will operate on the 'Reheat Rankine Cycle.'
2. Isentropic Efficiencies:
   - Turbines = 85%
   - Pump = 95%
3. The plant operates in steady conditions.
4. The change in kinetic and potential energy of the working fluid is negligible.

Operating conditions of the power plant are:

- Steam enters the high-pressure turbine at 15 MPa and 809.2 K.
- Steam enters the low-pressure turbine at 2 MPa and 809.2 K.
- Steam leaves the condenser at 10 KPa.
- The source temperature is 909.2 K.
- The sink/dead state temperature is 298 K.

System Description:

The steam power plant consists of the following major components:

1. High-Pressure Turbine
2. Low-Pressure Turbine
3. Generator
4. Boiler
5. Condenser
6. Pump
7. Cooling Tower
8. Auxiliaries (Different control and instrumentation equipment)

At state 1, the feedwater enters the pump. The pump raises the pressure of the water, and water leaves the pump at point 2 and enters the boiler. Superheated steam leaves the boiler at point 3 and enters into the high-pressure turbine. After giving off the energy of the superheated steam to the HPT, the colder superheated steam is circulated to the reheater and, after gaining heat, enters into the low-pressure turbine. Two turbines share a common shaft, and the output shaft of the low-pressure turbine is connected to the electrical generator. The fluid leaves the low-pressure turbine at point 6 and enters the condenser. Losing heat to the condenser, the high-quality vapour at point

6 returns to saturated liquid at point 1. The schematics and T-s diagram of the system are given below.

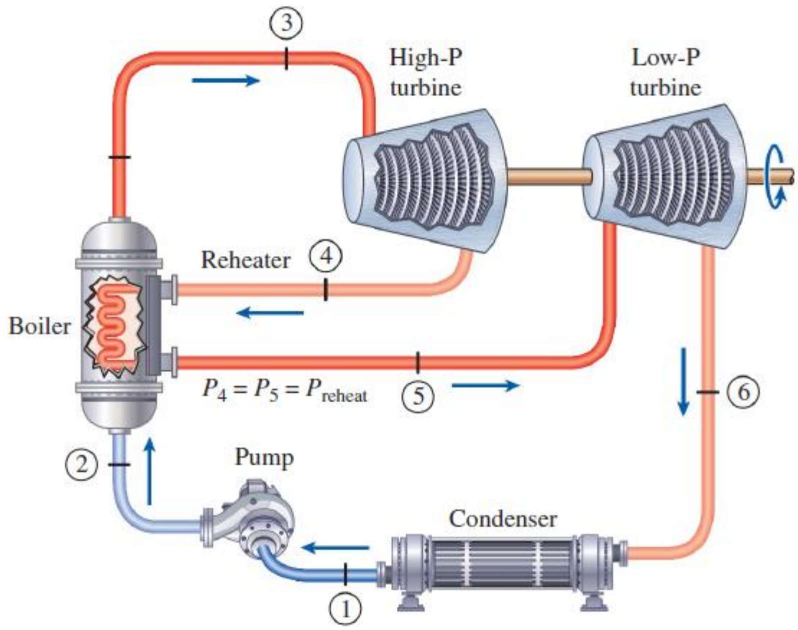


Figure 1: Schematics of the system

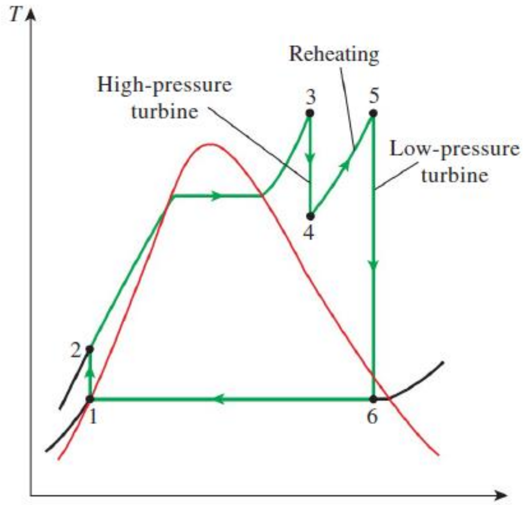


Figure 2: T-s Diagram of Reheat Rankine Cycle.

Processes:

1-2: Isentropic compression in the pump

2-3: Constant pressure heat addition in the boiler

3-4: Isentropic expansion in the high-pressure turbine

4-5: Constant pressure heat addition in the reheater

5-6: Isentropic expansion in the low-pressure turbine

6-1: Constant pressure heat rejection in the condenser

Thermodynamic Analysis

First Law Analysis:

State 1:

$$\begin{aligned} P_1 &= 10\ kPa \\ h_1 &= h_{f\,@\,10\,kPa} &&= 191.8\ kJ/kg \\ v_1 &= v_{f\,@\,10\,kPa} &&= 0.001010\ m^3/kg \\ s_1 &= s_{f\,@\,10\,kPa} &&= 0.6493\ kJ/kg.K \\ T_1 &= T_{sat\,@\,10\,kPa} &&= 319\ K \end{aligned}$$

State 2:

$$\begin{aligned} P_2 &= 15\ MPa \\ s_2 &= 0.6519\ kJ/kg.K \\ w_{pump,in} &= v_1(P_2 - P_1)\ /\eta_{pump} \\ &= 0.001010\ (15000 - 10)/0.95 \\ &= 15.94\ kJ/kg \end{aligned}$$

$$\begin{aligned} h_2 &= h_1 + w_{pump,in} \\ &= 207.8\ kJ/kg \end{aligned}$$

$$T_2 = 319.7\ K$$

State 3:

$$\begin{aligned} P_3 &= 15\ MPa \\ T_3 &= 809.2\ K \\ h_3 &= 3411\ kJ/kg \\ s_3 &= 6.474\ kJ/kg.K \end{aligned}$$

State 4:

$$\begin{aligned} P_4 &= 2\ MPa \\ s_{4s} &= s_3 \\ T_4 &= 541.4\ K \\ h_{4s} &= 2865\ kJ/kg \end{aligned}$$

$$\eta_{turb} = \frac{h_3 - h_4}{h_3 - h_{4s}}$$

$$h_4 = 2947\ kJ/kg$$

State 5:

$$\begin{aligned} P_5 &= P_4 \\ T_5 &= T_3 \\ s_5 &= 7.533\ kJ/kg.K \\ h_5 &= 3547\ kJ/kg \end{aligned}$$

State 6:

$$\begin{aligned} P_6 &= P_1 \\ s_{6s} &= s_5 \end{aligned}$$

$$\begin{aligned} x_6 &= \frac{s_{6s} - s_f}{s_{fg}} \\ &= 0.9179 \end{aligned}$$

$$\begin{aligned} h_{6s} &= h_f + x_6\, h_{fg} \\ &= 2387\ kJ/kg \end{aligned}$$

$$\begin{aligned} \eta_{turb} &= \frac{h_5 - h_6}{h_5 - h_{6s}} \\ h_6 &= 2561\ kJ/kg \end{aligned}$$

Thus,

$$
\begin{aligned}
w_{turb,out} &= (h_3 - h_4) + (h_5 - h_6) \\
&= 1450\ kJ/kg
\end{aligned}
$$

$$
\begin{aligned}
w_{net} &= w_{turb,\ out} - w_{pump,in} \\
&= 1434\ kJ/kg
\end{aligned}
$$

$$
\begin{aligned}
q_{in} &= (h_3 - h_2) + (h_5 - h_4) \\
&= 3803\ kJ/kg
\end{aligned}
$$

$$
\begin{aligned}
\dot{m} &= 250000 / w_{net} \\
&= 174.4\ kg/s
\end{aligned}
$$

Now, the thermal/ first law efficiency is:

$$
\begin{aligned}
\eta_{th} &= \frac{w_{net}}{q_{in}} \\
&= 0.377 = 37.7\ \%
\end{aligned}
$$

The coal furnace is maintained at 909.2 K, and waste heat is rejected to the dead environment at 298 K.

Second law analysis:

$$
\begin{aligned}
T_{source} &= 909.2\ K \\
T_0 &= 298\ K
\end{aligned}
$$

Exergy change in different components of the system:

Pump:

$$
\begin{aligned}
\Delta\varphi_{pump} = \varphi_2 - \varphi_1 &= (h_2 - h_1) - T_0(s_2 - s_1) \\
&= 15.23\ kJ/kg
\end{aligned}
$$

Boiler:

$$
\begin{aligned}
\Delta\varphi_{boiler} = \varphi_3 - \varphi_2 + \varphi_5 - \varphi_4 &= (h_3 - h_2) - T_0(s_3 - s_2) + (h_5 - h_4) - T_0(s_5 - s_4) \\
&= 1798.82\ kJ/kg
\end{aligned}
$$

High Pressure Turbine:

$$\Delta\varphi_{hp,turb} = \varphi_3 - \varphi_4 = (h_3 - h_4) - T_0(s_3 - s_4)$$
$$= 510.19\ kJ/kg$$

Low Pressure Turbine:

$$\Delta\varphi_{lp,turb} = \varphi_5 - \varphi_6 = (h_5 - h_6) - T_0(s_5 - s_6)$$
$$= 1148.41\ kJ/kg$$

Condenser:

$$\Delta\varphi_{condenser} = \varphi_1 - \varphi_6 = (h_1 - h_6) - T_0(s_1 - s_6)$$
$$= -155.45\ kJ/kg$$

The exergy destruction in each process:

Process 1-2:

$$x_{dest,12} = T_0 \times (s_2 - s_1)$$
$$= 0.7878\ kJ/kg$$

Process 2-3:

$$x_{dest,23} = T_0 \times \left(s_3 - s_2 - \frac{h_3 - h_2}{T_{source}}\right)$$
$$= 685\ kJ/kg$$

Process 3-4:

$$x_{dest,34} = T_0 \times (s_4 - s_3)$$
$$= 46.44\ kJ/kg$$

Process 4-5:

$$x_{dest,45} = T_0 \times \left(s_5 - s_4 - \frac{h_5 - h_4}{T_{source}}\right)$$
$$= 465.9\ kJ/kg$$

Process 5-6:

$$x_{dest,56} = T_0 \times (s_6 - s_5)$$
$$= 162.6\ kJ/kg$$

Exergy 6-1:

$$\begin{aligned} x_{dest,61} &= T_0 \times \left(s_6 - s_1 - \frac{h_6 - h_1}{T_0} \right) \\ &= 155.8\ kJ/kg \end{aligned}$$

Total exergy destruction in the whole system:

$$\begin{aligned} x_{dest,cycle} &= x_{dest,12} + x_{dest,23} + x_{dest,34} + x_{dest,45} + x_{dest,56} + x_{dest,61} \\ &= 1450\ kJ/kg \end{aligned}$$

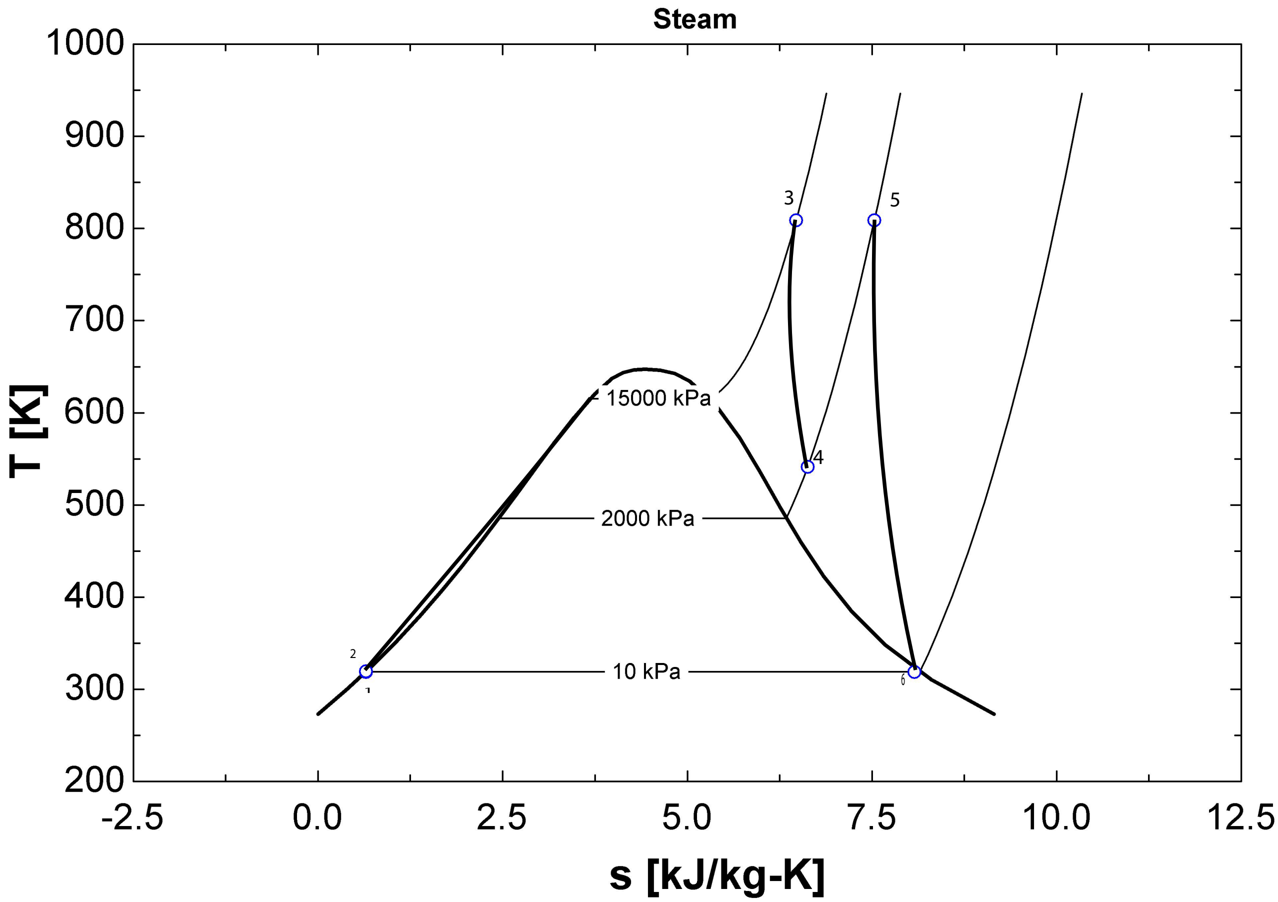
Exergy expense:

$$\begin{aligned} x_{expended} &= x_{heat,in} + x_{pump,in} \\ &= \left(1 - \frac{T_0}{T_{source}} \right) q_{in} \ + \ x_{pump,in} \\ &= 3251\ kJ/kg \end{aligned}$$

Therefore, second law efficiencyy:

$$\begin{aligned} \eta_{II} &= 1 - \frac{x_{destroyed}}{x_{expended}} \\ &= 0.4459 = 44.59\% \end{aligned}$$

T-s Diagram of the System



Description of the Major Components:

Turbines Specifications [1]:

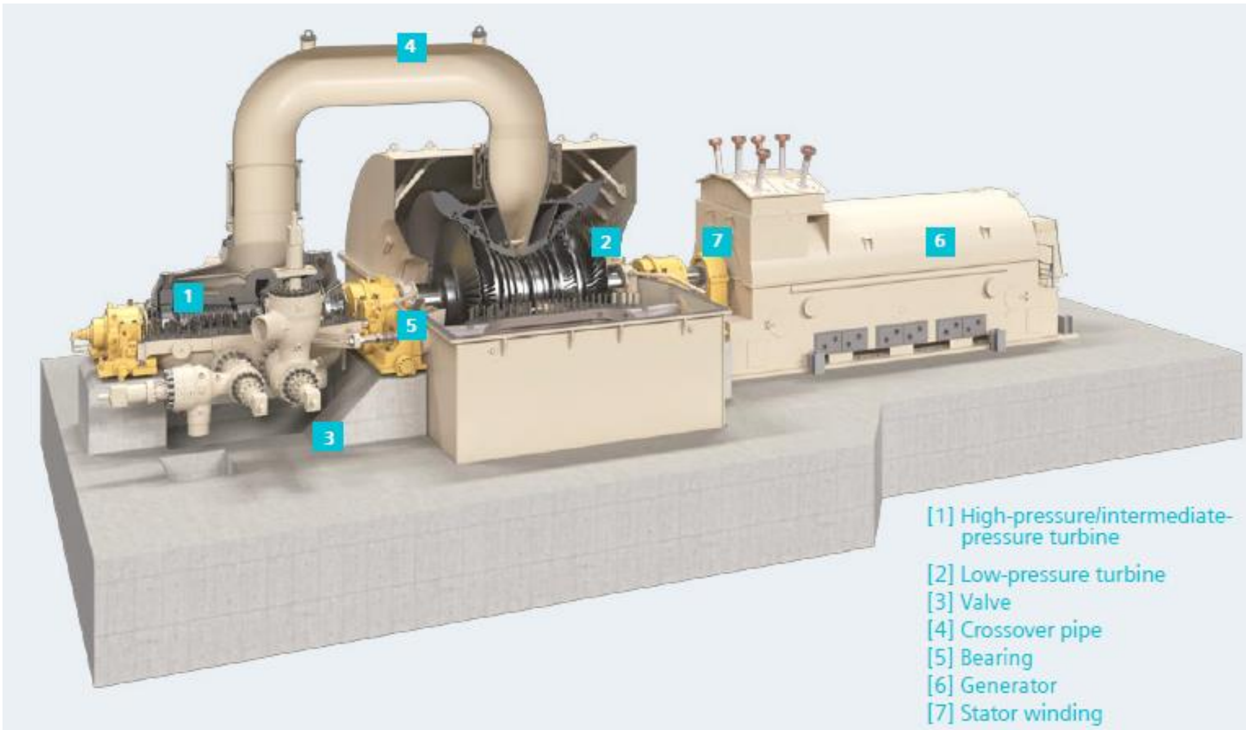


Figure 3: SST-5000 Series[1]

For this power plant, Siemens Steam Turbine Packages is chosen. This package includes a high-pressure turbine, one/two low-pressure turbines.

- Model: SST-PAC 5000
- Power Output: 250 to 500 MW
- Frequency: 50 Hz
- Speed: 3000 rpm
- Power Factor Generator: 0.8
- Main steam pressure: up to 26 MPa
- Temperature: up to 873 K
- Reheat Temperature: up to 873 K

Auxiliaries: Lube oil system, seal oil system, seal steam system, condenser air removal system etc.

Generator Specifications [2]:

In this project, the turbine has a power factor of 0.8. Thus, the generator considered must be designed for a power factor of 0.8. In this project generator from siemens is chosen as the turbine as they are designed to work in sync with each other.

Model: SGen5-1000A

Apparent Power: 180-370 MVA

Efficiency: up to 98.9%

Terminal Voltage: 10.5-20 kV

Boiler Specification[3]:
For this project, a 2-pass boiler from Mitsubishi is proposed to use. It requires lower fuel and lower power consumption. The emission is less with a high-reliability factor. An added benefit is that it can handle many different types of fuel, including lignite.

Figure 4: Mitsubishi 2-pass Boiler [3]

Output: 1,070 MW

Main Steam flow rate: up to 3,210 ton/hr

Steam Temperature: up to 883 K

Steam Pressure: up to 31MPa

Pump Specifications[4]:
Model: ZD Multistage Ring Section Pump

Figure 5: Pump[4]

Flow rate: 3.7-1100 m^3/h

Head: 50-18000 m

Pressure: up to 17.5 MPa

Working Liquid Temperature: 0 ^oC -120 ^oC

Condenser Specifications [5]:
Model: VR-HE 3500

Voltage: 380 V

Power: 1000 KW

Price: 1000 USD/Unit

Maximum Working Pressure: 4.5 MPa

Control System:
To maintain a secure and safe environment with highly efficient operation in the power plant, the SPPA-T300 Control System [6], [7] by Siemens is proposed to use.

Fuel for the Boiler:
Lignite is chosen for the boiler fuel as it is cheap, can be easily sourced, and its supply can easily be maintained.

Price of Lignite (as of 2019): 38.53 USD/short ton [8]

Calorific Value: 17000 kJ/kg [9]

Cost Estimation:

For estimating the capital cost, [10] is used to get information. The total capital cost to establish the power plant is around a 498million USD and the operating cost for a year is about a 27million USD, considering 12 hours of operation in a day. According to the CAPEX, the cost of one kilowatt

Capital Cost Estimation			
Boiler	$ 80,000,000.00		
Steam Turbine	$ 40,000,000.00		
Genreator	$ 30,000,000.00		
Pump	$ 1,000,000.00		
Condenser	$ 1,000,000.00		
Coal Handling	$ 14,000,000.00		
Ash Handling	$ 7,000,000.00		
Earthwork	$ 15,000,000.00		
Steel	$ 10,000,000.00		
Electrical	$ 5,000,000.00		
Piping	$ 10,000,000.00		
Other Facilities	$150,000,000.00		
Auxiliaries	$ 20,000,000.00		
Total	**$383,000,000.00**		
Indirect Cost+Contingency	$114,900,000.00		
Grand Total	**$497,900,000.00**		
Grand Total (in millions)	**$ 497.90**		
		Power Output(kW)	250000
USD/kW	**$ 1,991.60**		

of power is about 1992USD. It can be observed that about 59% of the operating cost is related to coal purchasing and handling that is common for coal-fired thermal power plants. Considering the coal cost, the cost of producing per unit is around 4cents or 1.11BDT.

Operating Cost Estimation	
Coal Cost	$ 13,132,800.00
Coal Handling Cost	$ 2,700,000.00
Maintenance of Machineries	$ 4,500,000.00
Other Maintenance Cost	$ 2,165,000.00
Salary	$ 2,500,000.00
Miscellanious	$ 2,000,000.00
Total	**$ 26,997,800.00**
Total(in millions)	**$ 26.998**

Per Unit Electricity Cost Estimation		
The mass flow rate of water	174.4	kg/s
Cp of water	4.2	kJ/kg.K
Temp. at state 2	319.7	K
Temp. at state 3	809.2	K
The energy needed at the boiler	358548.96	kJ/s
Coal Calorific Value	17000	kJ/kg
Coal Needed	21.091	kg/s
Coal Needed	**75928.01506**	**kg/h**
Price/short ton	$ 38.53	
Price/kg	**$ 0.04**	
Coal price of an hour	**$ 3,224.82**	
Price of a unit of electricity	**$ 0.01**	
Price of a unit of electricity	**1.11৳**	

Simple Break-Even Analysis:

We can observe that if only CAPEX is considered, it will take around 5 years to break even for the CAPEX at a selling price of 9cents or 7.9BDT (1 USD = 86BDT), that is the average electricity price in Bangladesh effective from March 2020.

Simple Break Even Analysis	
Power Output (kW)	250000
Power Output in 12 hours	3000000
Avg unit price	$ 0.09
CAPEX	$497,900,000.00
Total units for break-even	5420177215
Days Needed to break-even	1806.73
Years Needed to Break-Even	**4.950**

Result and Discussion:

Table 1: 1st and 2nd law efficiency of the proposed power plant

Efficiency	
1st Law Efficiency	37.7%
2nd Law Efficiency	44.59%

According to the requirement, the efficiency values are more than 30%.

Table 2: Different property values at 6 different points

State	Temperature(K)	Pressure (kPa)	Enthalpy(kJ/kg)	Entropy(kJ/kg-K)
Point 1	319	10	191.8	0.6493
Point 2	319.7	15,000	207.8	0.6519
Point 3	809.2	15,000	3411	6.474
Point 4	541.4	2,000	2947	6.629
Point 5	809.2	2,000	3547	7.533
Point 6	319	10	2561	8.078

Table 3: Exergy changes in the different components of the system are given below

Components	Exergy Change (kJ/kg)
Pump	15.23
Boiler	1798.82
High-Pressure Turbine	510.19
Low-Pressure Turbine	1148.41
Condenser	-155.45

Table 4: Exergy destruction in each of the processes

Processes	**Exergy Destruction (kJ/kg)**
1-2	0.7878
2-3	685
3-4	46.44
4-5	465.9
5-6	162.6
6-1	155.8

The value of temperature at point 3 was determined through a simple parametric study in EES. While designing the power plant, several values of T_3 was checked. Though the values were giving satisfactory efficiency values, problems come up when plotting the T-s diagram. Point 4 and point 6 were not in the position they should be. Point 4 must be in the superheated region, and point 6 must lie inside the dome of the T-s diagram, but it was not the case for most of the values. After the parametric study, this problem was solved, and the value 809.2K was taken as it gave the highest efficiencies.

1..9	1 T_3	2 T_1	3 T_6	4 s_4	5 T_4	6 η_{th}	7 η_{II}
Run 1	500	319	319	2.562	485.6	0.2582	0.2305
Run 2	538.7	319	319	2.916	485.6	0.2634	0.2424
Run 3	577.3	319	319	3.283	485.6	0.2723	0.2585
Run 4	616	319	319	5.418	485.6	0.3262	0.3326
Run 5	654.6	319	319	5.87	485.6	0.3396	0.3586
Run 6	693.3	319	319	6.125	485.6	0.3497	0.3807
Run 7	731.9	319	319	6.323	485.6	0.359	0.4024
Run 8	770.6	319	319	6.488	512	0.3681	0.4242
Run 9	809.2	319	319	6.629	541.4	0.377	0.4459

Figure 6: Parametric study for selecting T_3

Conclusion:

The designed thermal power plant has 1st law efficiency of 37.7 % and 2nd law efficiency of 44.59%. The total estimated capital cost is about 498 million USD, and the operating cost is about 27 million USD. These values may vary depending on the actual market rate. The cost of producing one unit of electricity is about 4 cents or 1.11BDT, which may vary in real life. The costs of different equipment depending on the manufacturers as these equipment are often customized for different types of plant capacity and location. Exact prices cannot be known without getting quotations from the manufacturers. Standard pricing is considered for estimating the cost. Also, a simple break-even analysis shows that the CAPEX can be break-even around 5 years of operation.

Appendix

EES Code

Isentropic Efficiencies

$$\eta_t = 0.85 \text{ efficiency of turbine } \eta_p \tag{1}$$

$$= 0.95 \text{ efficiency of pump} \tag{2}$$

State 1

$$P_1 = 10 \ [\mathrm{kPa}] \tag{3}$$

$$h_1 = \mathrm{h}\,(Steam,\ \mathrm{P}\ = P_1,\ \mathrm{x} = 0) \tag{4}$$

$$v_1 = \mathrm{v}\,(Steam,\ \mathrm{P}\ = P_1,\ \mathrm{x} = 0) \tag{5}$$

$$T_1 = \mathrm{T}_{\mathrm{sat}}\,(Steam,\ \mathrm{P} = P_1) \tag{6}$$

Work input to the pump

$$W_{p,in} = v_1 \cdot \frac{P_2 - P_1}{\eta_p} \tag{7}$$

State 2

$$P_2 = 15000 \ [\mathrm{kPa}] \tag{8}$$

$$h_2 = h_1 + W_{p,in} \tag{9}$$

$$T_2 = \mathrm{T}\,(Steam,\ \mathrm{P} = P_2,\ \mathrm{h} = h_2) \tag{10}$$

State 3

$$P_3 = P_2 \tag{11}$$

$$T_3 = 809.2 \quad [\mathrm{K}] \tag{12}$$

$$h_3 = \mathrm{h}\,(Steam,\ \mathrm{T} = T_3,\ \mathrm{P} = P_3) \tag{13}$$

$$s_3 = \mathrm{s}\,(Steam,\ \mathrm{T} = T_3,\ \mathrm{P} = P_3) \tag{14}$$

State 4

$$P_{4s} = 2000 \ [\mathrm{kPa}] \tag{15}$$

$$s_{4s} = s_3 \tag{16}$$

$$h_{4s} = \mathrm{h}\,(Steam,\ \mathrm{P} = P_{4s},\ \mathrm{s} = s_{4s}) \tag{17}$$

$$h_4 = h_3 - \eta_t \cdot (h_3 - h_{4s}) \tag{18}$$

$$T_4 = \mathrm{T}\,(Steam,\ \mathrm{P} = P_{4s},\ \mathrm{h} = h_4) \tag{19}$$

State 5

$$P_5 = P_{4s} \tag{20}$$

$$T_5 = T_3 \tag{21}$$

$$h_5 = \mathrm{h}\left(Steam,\ \mathrm{T} = T_5,\ \mathrm{P} = P_5\right) \tag{22}$$

$$s_5 = \mathrm{s}\left(Steam,\ \mathrm{T} = T_5,\ \mathrm{P} = P_5\right) \tag{23}$$

State 6

$$P_{6s} = P_1 \tag{24}$$

$$s_{6s} = s_5 \tag{25}$$

$$x_{6s} = \mathrm{x}\left(Steam,\ \mathrm{P} = P_{6s},\ \mathrm{s} = s_{6s}\right) \qquad \text{At the turbine outlet} \tag{26}$$

$$h_{6s} = \mathrm{h}\left(Steam,\ \mathrm{P} = P_{6s},\ \mathrm{x} = x_{6s}\right) \tag{27}$$

$$h_6 = h_5 - \eta_t \cdot (h_5 - h_{6s}) \tag{28}$$

$$T_6 = \mathrm{T}\left(Steam,\ \mathrm{P} = P_{6s},\ \mathrm{h} = h_6\right) \tag{29}$$

Turbine output

$$W_{t,out} = (h_3 - h_4) + (h_5 - h_6) \tag{30}$$

Heat input

$$Q_{in} = (h_3 - h_2) + (h_5 - h_4) \tag{31}$$

Net work output

$$W_{net} = W_{t,out} - W_{p,in} \tag{32}$$

Mass flow rate

$$\dot{m} = 250000/w_{net} \tag{33}$$

1st law efficiency(equal to thermal efficiency)

$$\eta_{th} = W_{net}/Q_{in} \tag{34}$$

2nd Law Analysis

$$T_0 = 298\ \mathrm{[K]} \tag{35}$$

$$T_{source} = T_3 + 100\ \mathrm{[K]} \tag{36}$$

$$s_1 = \mathrm{s}\left(Steam,\ \mathrm{P} = P_1,\ \mathrm{x} = 0\right) \tag{37}$$

$$s_2 = \mathrm{s}\left(Steam,\ \mathrm{P} = P_2,\ \mathrm{h} = h_2\right) \tag{38}$$

$$s_4 = \mathrm{s}\left(Steam,\ \mathrm{P} = P_{4s},\ \mathrm{h} = h_4\right) \tag{39}$$

$$s_6 = \mathrm{s}\left(Steam,\ \mathrm{P} = P_{6s},\ \mathrm{h} = h_6\right) \tag{40}$$

Process 1-2

$$X_{destroyed,12} = T_0 \cdot (s_2 - s_1) \tag{41}$$

Process 2-3

$$X_{destroyed,23} = T_0 \cdot \left(s_3 - s_2 - \frac{h_3 - h_2}{T_{source}} \right) \tag{42}$$

Process 3-4

$$X_{destroyed,34} = T_0 \cdot (s_4 - s_3) \tag{43}$$

Process 4-5

$$X_{destroyed,45} = T_0 \cdot \left(s_5 - s_4 + \frac{h_5 - h_4}{T_{source}} \right) \tag{44}$$

Process 5-6

$$X_{destroyed,56} = T_0 \cdot (s_6 - s_5) \tag{45}$$

Process 6-1

$$X_{destroyed,61} = T_0 \cdot \left(s_1 - s_6 + \frac{h_6 - h_1}{T_0} \right) \tag{46}$$

Exergy destruction associated with the combined pumping and heat addition process

$$X_{destruction,combined} = T_0 \cdot (s_3 - s_1 + s_5 - s_4 + q_{in}/T_{source}) \tag{47}$$

$$X_{recovered} = W_{t,out} \tag{48}$$

$$\eta_{II} = X_{recovered}/X_{destruction,combined} \tag{49}$$

Solution

$\boldsymbol{\eta_{II} = 0.4459}$	$\eta_p = 0.95$
$\eta_t = 0.85$	$\boldsymbol{\eta_{th} = 0.377}$
$h_1 = 191.8$ [kJ/kg]	$h_2 = 207.8$ [kJ/kg]
$h_3 = 3411$ [kJ/kg]	$h_4 = 2947$ [kJ/kg]
$h_{4s} = 2865$ [kJ/kg]	$h_5 = 3547$ [kJ/kg]
$h_6 = 2561$ [kJ/kg]	$h_{6s} = 2387$ [kJ/kg]
$\dot{m} = 174.4$ [kg/s]	$P_1 = 10$ [kPa]
$P_2 = 15000$ [kPa]	$P_3 = 15000$ [kPa]
$P_{4s} = 2000$ [kPa]	$P_5 = 2000$ [kPa]
$P_{6s} = 10$ [kPa]	$Q_{in} = 3803$ [kJ/kg]
$s_1 = 0.6493$ [kJ/kg-K]	$s_2 = 0.6519$ [kJ/kg-K]
$s_3 = 6.474$ [kJ/kg-K]	$s_4 = 6.629$ [kJ/kg-K]
$s_{4s} = 6.474$ [kJ/kg-K]	$s_5 = 7.533$ [kJ/kg-K]
$s_6 = 8.078$ [kJ/kg-K]	$s_{6s} = 7.533$ [kJ/kg-K]
$T_0 = 298$ [K]	$T_1 = 319$ [K]
$T_2 = 319.7$ [K]	$T_3 = 809.2$ [K]
$T_4 = 541.4$ [K]	$T_5 = 809.2$ [K]
$T_6 = 319$ [K]	$T_{source} = 909.2$ [K]

$v_1 = 0.00101$ [$\mathrm{m^3/kg}$]
$W_{p,in} = 15.94$ [kJ/kg]
$x_{6s} = 0.9179$
$X_{destroyed,23} = 685$ [K]
$X_{destroyed,45} = 465.9$ [K]
$X_{destroyed,61} = 155.8$ [kJ/kg]
$X_{recovered} = 1450$ [kJ/kg]

$W_{net} = 1434$ [kJ/kg]
$W_{t,out} = 1450$ [kJ/kg]
$X_{destroyed,12} = 0.7878$ [kJ/kg]
$X_{destroyed,34} = 46.44$ [kJ/kg]
$X_{destroyed,56} = 162.6$ [kJ/kg]
$X_{destruction,combined} = 3251$ [K]

T-s Diagram of the System

Equations

$$s_1 = 0.6493 \text{ [kJ/kg-K]} \quad (1)$$

$$s_2 = 0.6519 \text{ [kJ/kg-K]} \quad (2)$$

$$s_3 = 6.474 \text{ [kJ/kg-K]} \quad (3)$$

$$s_4 = 6.629 \text{ [kJ/kg-K]} \quad (4)$$

$$s_5 = 7.533 \text{ [kJ/kg-K]} \quad (5)$$

$$s_6 = 8.078 \text{ [kJ/kg-K]} \quad (6)$$

$$T_1 = 319 \text{ [K]} \quad (7)$$

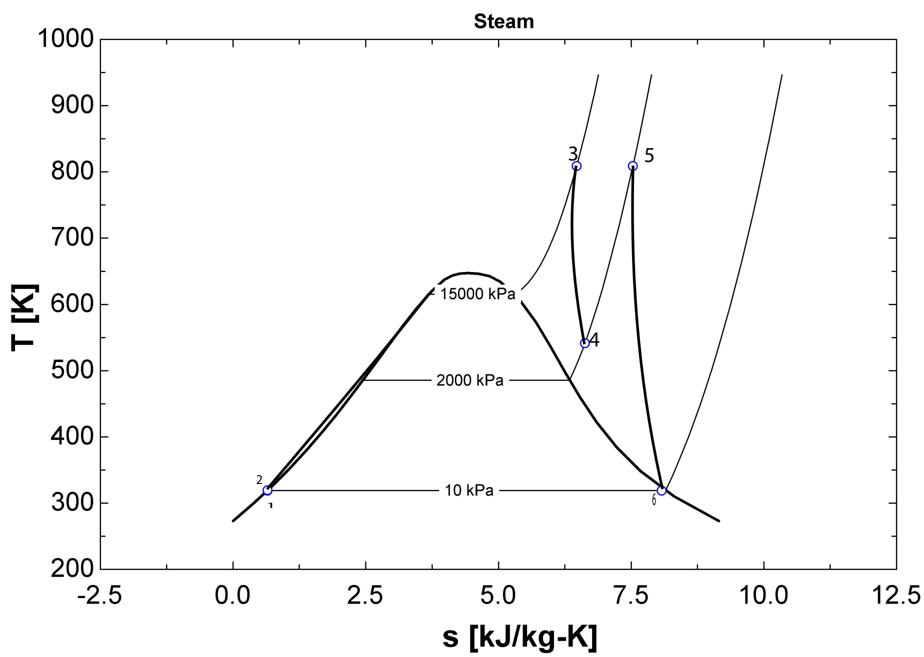
$$T_2 = 319.7 \text{ [K]} \quad (8)$$

$$T_3 = 809.2 \text{ [K]} \quad (9)$$

$$T_4 = 541.4 \text{ [K]} \quad (10)$$

$$T_5 = 809.2 \text{[K]} \quad (11)$$

$$T_6 = 319 \text{ [K]} \quad (12)$$



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