PROJECT 1

‘DESIGN AND THERMODYNAMIC ANALYSIS OF A THERMAL POWER PLANT’

COURSE NO: MCE 4705
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1. Thermodynamic Power Cycle

Reheat Single Stage Regenerative Rankine Cycle Steam Power Plant has been considered for this project. The system components are –

1. High-pressure turbine (HPT)
2. Low-pressure turbine (LPT)
3. Regenerator
4. Condenser
5. Boiler
6. Pump I
7. Pump II

1.1 Cycle Description

In Ideal regenerative Rankine cycle, steam enters the high-pressure turbine at boiler pressure (maximum pressure/high pressure turbine inlet pressure) (state 1) and expands isentropically (deviation in actual cycle) to an intermediate pressure (20% of high-pressure turbine pressure) (state 2). Then steam is reheated to boiler temperature (state 3). After that stream enters the low-pressure turbine and here stream is expanded isentropically to regenerative pressure (state 4). Some stream(x) is extracted at this state and routed to regenerator (feedwater heater), while remaining steam continues to expand isentropically (deviation in actual cycle) to the condenser pressure (state 5). This steam leaves the condenser a saturated liquid at the condenser pressure(state 6). The condensed water then enters a pump, where it is compressed to regenerator pressure (state 7) and is routed to regenerator where it mixes with the steam extracted from the turbine. The fraction of stream from low pressure turbine is extracted is such that the mixture leaves the regenerator as a saturated liquid at the regenerator pressure (state 8). A second pump raises the pressure of the water to the boiler pressure (state 9). The cycle is completed by heating the water in the boiler to the high-pressure turbine initial state (state 1).

1.2 Property Diagram

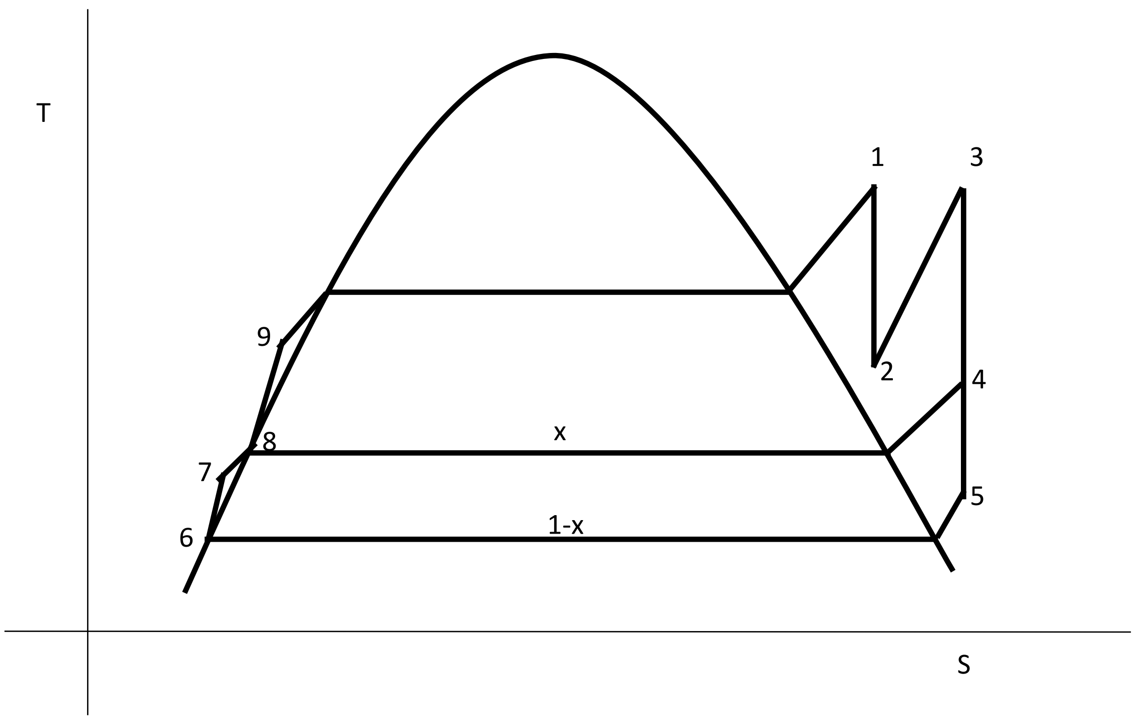

Figure 1 T-S diagram of the Rankine cycle reheat regenerative steam power plant

1.3 Process Flow Diagram

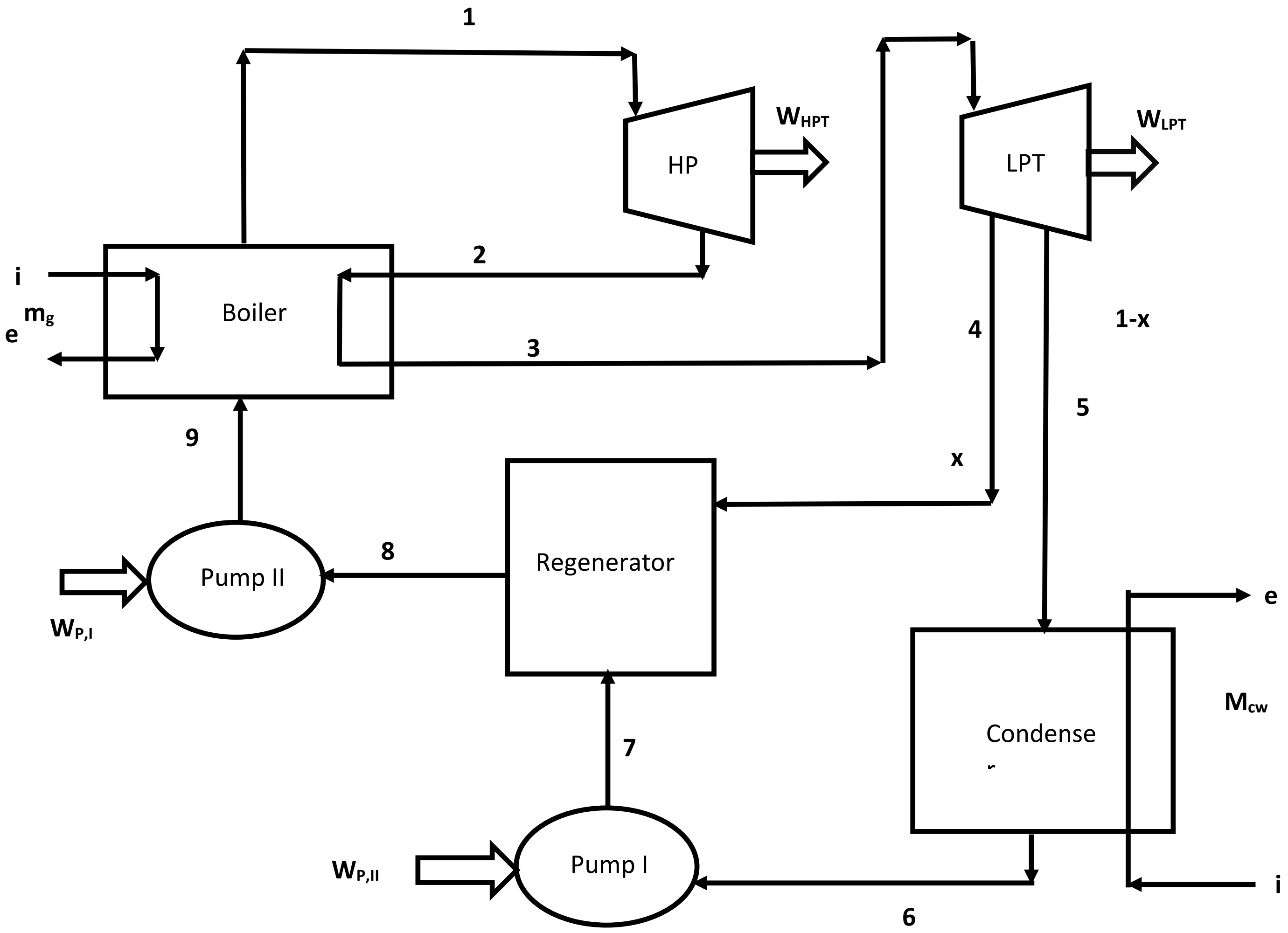

Figure 2 A schematic representation of the Rankine cycle reheat steam power plant

1.4 Energy & Exergy Analysis – Equations

For every individual component in Figure 2, the three balance equations are applied to find the work output, the heat added, the rate of exergy decrease, the rate of irreversibility, and the energy and exergy efficiencies. The balance equations are then written as follows:

The mass balance:

$$\sum \dot{m}_i = \sum \dot{m}_e$$

The energy balance equation: At steady state and neglecting potential and kinetic energy changes

$$\dot{Q}_{CV} + \sum_i \dot{m}_i h_i = \dot{W}_{CV} + \sum_e \dot{m}_e h_e$$

Where, $\dot{Q}_{CV}, \dot{W}_{CV}, h_i, h_e$ are heat transfer rate, rate of energy transfer by work, enthalpy at inlet and enthalpy at exit respectively over the boundary of the control volume.

The exergy balance equation:

$$\sum_i \dot{E_{f,i}} + \sum_j \left[1 - \frac{T_o}{T_j}\right]\dot{Q}_{CV} = \sum_e \dot{E_{f,e}} + \dot{W}_{CV} + \dot{E}_d$$

Where,
E_d = Irreversibility rate/ destruction rate
$\dot{E_f}$= Rate of flow availability or flow Exergy
T_o = Surrounding temperature and reference temperature
T_j = Temperature at boundary

For the cycle outlined in Figure 1 and Figure 2, the complete balance equations for each individual components are summarized in Table 1

Table 1 The Balance Equation for system components

Balance Equations			
Component	**Energy Analysis**	**Exergy available** $\dot{E}_{available}$	**Exergy Destruction** $\dot{E}_{dest}$
High-Pressure Turbine	$w_{HPT} = h_1 - h_2$	$(h_1 - h_2) - T_o(s_1 - s_2)$	$-T_o(s_1 - s_2)$
Low-Pressure Turbine	$w_{LPT} = h_3 - x \times h_4 - (1 - x)h_5$	$(h_3 - x \times h_4 - (1-x)h_5 - T_o[(s_3 - x \times s_4 - (1-x)s_5)]$	$-T_o[(s_3 - x \times s_4 - (1-x)s_5)]$
Regenerator	$x \times (h_4 - h_7) = (h_8 - h_7)$	$-T_o[x \times s_4 + (1-x)(s_7 - s_8)] + (1-x)\left(\dot{E_{f,8}} - \dot{E_{f,7}}\right)]$	$-T_o[x \times s_4 + (1-x)(s_7 - s_8)]$
Condenser	$\dot{m}_{cw} = \dfrac{(1-x)(h_5 - h_6)}{(h_{co} - h_{ci})}$	$\dot{m}_{cw} * [(h_{co} - h_{ci}) - T_o * (s_{co} - s_{ci})]$	$-T_o[(1-x)(s_5 - s_6) + \dot{m}_{cw}(s_{ci} - s_{co})]$
Boiler	$\dot{m}_g = \dfrac{(h_1 - h_9) + (h_3 - h_2)}{C_p(T_{gi} - T_{go})}$	$\dot{m}_g * [(h_{gi} - h_{go}) - T_o * (s_{gi} - s_{go})]]$	$-T_o[(s_9 - s_1) + (s_2 - s_3) + \dot{m}_g(s_{g1} - s_{g2})]$
Pump I	$w_{P1} = (1-x)(h_6 - h_7)$	$(1-x)[(h_6 - h_7) - T_o(s_6 - s_7)]$	$(1-x) * [-T_o(s_6 - s_7)]$
Pump II	$w_{p2} = h_8 - h_9$	$(h_8 - h_9) - T_o(S_8 - S_9)$	$-T_o(S_8 - S_9)$

2. Cycle Analysis

2.1 Initial Operation Parameters and Assumptions

The inlet temperature of the high-pressure turbine (or the outlet temperature of the boiler) is considered between 400° and 600°C in steps of 10°C. For each individual temperature, the inlet pressure will be varied between 10 and 15 MPa in steps of 1 MPa. These are the variables for the system which are consistent with actual values [1] and based on these, an optimization is conducted for getting required output with maximum 1st law efficiency. The pressure at the inlet of the low-pressure turbine is considered as 20% of that of the high-pressure turbine. The temperature is assumed to be equal to that of the high-pressure turbine. These two conditions are believed to be crucial to have the maximum efficiency of the cycle.[2] [3]Practical value of the temperature of the condenser ranges between 25°C and 40°C. Temperature could be taken depending on weather condition and source and condition of cooling water. As For this project, a temperature of 39° C is chosen for which the saturation pressure of water is 7 kPa. It was chosen keeping in mind that any surrounding water source can easily be used as cooling water having temperature below of 39 °C. The pressure at the regenerator is set to equal 0.15 MPa. This is a in between value of turbine and condenser pressure. An optimization can also be done for this pressure value for finding maximum efficiency, but it is out of scope of this project. The water coming out of the regenerator is saturated. The isentropic efficiencies of the turbines and pumps are assumed to be 0.9. Assumed flue gas inlet conditions: P=102 kPa, T= 1500°C and flue gas outlet conditions: P=101 kPa, T=400°C. [3]

2.2 Cycle Optimization

Cycle optimization was done for the operation condition and assumptions mentioned above. An optimization python code (provided in appendix A) was written integrated with 'Coolprop' module for thermodynamic property calculation to find efficiencies for different boiler pressure and boiler temperature input combination. After running the script for 120 combinations the efficiencies range between 39% to 45% and among them 5 combinations gave an efficiency above 44% shown below:

Boiler Pressure (Maximum Pressure), MPa	**Boiler Temperature (Turbine Inlet Temperature), °C**	**1st Law Efficiency, %**
15	580	44.03
14	590	44.01
15	590	44.23
14	600	44.20
15	600	44.41

To find out which condition to be chosen, the exergy efficiency of cycle for these conditions are calculated. Another python code(Appendix A) was written to find out 2nd law efficiency of the cycle. The results are:

Boiler Pressure (Maximum Pressure), MPa	**Boiler Temperature (Turbine Inlet Temperature), °C**	**2nd Law Efficiency, %**
15	580	59.66
14	590	59.62
15	590	59.92
14	600	59.88
15	600	60.17

From above two analysis it can be concluded that the boiler pressure of 15MPa and 600°C of boiler temperature gives maximum first law and second law efficiency. But other combinations give close values. Considering the design constraints, cost and component working capability, the values for boiler pressure and turbine inlet temperature is chosen 15MPa and 590°C respectively.

Other parameters can also be optimized in a similar way, but these optimizations are out of scope of this project.

2.3 Final Operating Parameters

For the design of the powerplant the following values are considered:

Table 2 Operation Parameters

Parameters	Values	Parameters	Values
Maximum Pressure	15 MPa (Optimized)	Condensing Temperature	39°C
Turbine inlet Temperature (Maximum Temperature)	590 °C (Optimized)	Saturation pressure in condensing temperature	7 kPa
Pressure at the inlet of the low-pressure turbine	20 % of that of the high-pressure turbine	Regenerator Pressure	0.15 MPa
Turbine Efficiency	90%	Flue gas inlet condition	P= 102 kPa T=1500 °C
Pump Efficiency	90%	Flue gas outlet condition	P= 101 kPa T=400 °C
Surrounding Temperature	25 °C	Specific heat of flue gas	Cp =1.1058 kJ/kgK
Cooling water Inlet Condition	P= 101 kPa T= 25 °C	Specific heat ratio of flue gas	1.35
Cooling water outlet condition	P= 101 kPa T= 39 °C		

3. Detailed Calculations

3.1 State Properties

Using Coolprop module integrated with python, the state properties were found (Appendix A)

Table 3 State enthalpy and entropy values

State	Enthalpy, kJ/kg	Entropy, kJ/kg K
1	3556.96	6.65
2	3107.66	6.73
3	3660.14	7.48
4	2886.12	7.67
5	2458.53	7.91
6	163.35	0.56
7	163.51	0.56
8	467.13	1.43
9	484.44	1.48

3.2 Parameters for 250MVA output

Power factor of 1 is considered
Therefore, MW = MVA x Power Factor
= 250 x 1
= 250 MW
Required turbine work, W = 250MW
Using python script,
Mass fraction feeding regenerator, $x = \frac{(h_8-h_7)}{(h_4-h_7)} = 0.112$
Turbine specific work, $w_{net} = w_{HPT} + w_{LPT} = (h_1 - h_2) + [h_3 - x \times h_4 - (1-x)h_5] = 1603.225$ kJ/kg
$\therefore Turbine\ Work = mass\ flow\ rate\ of\ water\ \times Turbine\ Specific\ Work$
$Or, W_{net} = \dot{M}_w \times w_{net}$
$Or \dot{M}_w = \frac{W_{net}}{w_{net}} = \frac{250 \times 10^3\ kJ/s}{1603.225\ kj/kg} = 155.94 \frac{kg}{s} \cong 156\ kg/sec$

Specific Heat Transfer/ Heat addition to the system, $q_{in} = (h_1 - h_9) + (h_3 - h_2) = 3624.997\ kJ/kg$
$\therefore Total\ Heat\ Transfer$
$= mass\ flow\ rate\ of\ flue\ gas\ \times Specific\ heat\ of\ flue\ gas\ \times (\ Flue\ gas\ inlet\ temperature$
$-\ flue\ gas\ outlet\ temperatur)$
Again, $Total\ Heat\ Transfer = mass\ flow\ rate\ of\ water\ \times Specific\ heat\ transfer$
$\therefore\ Q_{in} = \dot{M}_w \times q_{in} = \dot{M}_g \times C_p \times (T_{g,i} - T_{g,o})$

$$Or, \dot{M}_g = \frac{\dot{M}_w \times q_{in}}{C_p \times (T_{g,i} - T_{g,o})} = \frac{156 \frac{kg}{s} \times 3624.997 kJ/kg}{1.1058 \frac{kJ}{kgk} \times (1500 - 400)K} = 464.904 \cong 465\ kg/s$$

Again,
$Q_{out} = \dot{M}_w \times q_{out} = \dot{M}_{cw} \times C_{pw} \times (T_{c,o} - T_{c,i})$

$$Or, \dot{M}_{cw} = \frac{\dot{M}_w \times q_{out}}{C_{pw} \times (T_{c,o} - T_{c,i})} = \frac{156 \frac{kg}{s} \times 2039.228\ kJ/kg}{4.186 \frac{kJ}{kgk} \times (39 - 25)K} = 464.904 \cong 5428.29\ kg/s$$

3.3 1st law and 2nd law analysis of the system

3.3.1 1st law efficiency of the system

From, Cycle optimization for 15 MPa maximum pressure and 590 °C maximum temperature the 1st law efficiency is, $\eta_I = 44.23\%$

Detailed Computation

Mass fraction feeding regenerator, $x = \frac{(h_8-h_7)}{(h_4-h_7)} = 0.112$

Turbine specific work, $w_{net} = w_{HPT} + w_{LPT} = (h_1 - h_2) + [h_3 - x \times h_4 - (1-x)h_5] = 1603.225$ kJ/kg
Specific Heat Transfer/Heat addition to the system, $q_{in} = (h_1 - h_9) + (h_3 - h_2) = 3624.997\ kJ/kg$
1st law efficiency, $\eta_I = \frac{w_{net}}{q_{in}} \times 100 = 44.23\ \%$

3.3.2 2nd law efficiency of the system

From, Cycle optimization for 15 MPa maximum pressure and 590 °C maximum temperature the 2nd law efficiency is, $\eta_{II} = 59.92\ \%$

Detailed Computation

Mass flow rate of flue gas when steam flow rate 1 kg/s, $\dot{m}_g = \frac{q_{in}}{C_p \times (T_{g,i} - T_{g,o})} = \frac{3624.997 kJ/kg}{1.1058 \frac{kJ}{kgk} \times (1500-400)K} = 2.98\ kg/s$

Exergy available in boiler, $\dot{E}_{available} = \dot{m}_g * [(h_{gi} - h_{go}) - T_o * (s_{gi} - s_{go})]$

Here,

$$s_{go} = C_p \times (\ln \frac{T_{g,o}}{T_{g,i}} - \frac{k-1}{k} \times \ln \frac{P_{g,o}}{P_{g,i}}) = 1.1058 \times (\ln \frac{400 + 273.15}{1500 + 273.15} - \frac{1.35 - 1}{1.35} \times \ln \frac{101}{102}) = -1.068\ kJ/kgk$$

$$h_{go} = C_p \times (T_{g,o} - T_{g,i}) = 1.1058 \times (673.15 - 1773.15) = -1216.38\ kJ/kg$$

$$s_{gi} = 0$$

$$h_{gi} = 0$$

$$\dot{E}_{available} = 2.98 * [(0 - h_{go}) - T_o * (s_{gi} - s_{go})] = 2.98 \times [1216.38 - (298.15 \times 1.068)] = 2675.6339 kW$$

2nd law efficiency, $\eta_{II} = \frac{w_{net}}{\dot{E}_{available}} \times 100 = \frac{1603.225}{2675.6339} \times 100 = 59.92\ \%$

3.4 1st law and 2nd law analysis of individual components

3.4.1 1st law analysis of the components

The table 4 shows the values for unit mass flow rate of steam and water through the components. For the actual values of the powerplant they need to be multiplied by mass flow rate of steam and water through the components for 250MVA output found in section 3.2, Every value was calculated using python script.

Mass fraction feeding regenerator, $x = \frac{(h_8 - h_7)}{(h_4 - h_7)} = 0.112$

Table 4 Results of 1st law analysis

Component	Energy Analysis For unit mass flow rate	Values for $\dot{m}_w = 1kg/s$, kJ/kg	Values for $\dot{m}_w = 156\ kg/s$ MW (approx.)
High-Pressure Turbine (Work produced)	$w_{HPT} = h_1 - h_2$	449.2998	70
Low-Pressure Turbine (Work produced)	$w_{LPT} = h_3 - x \times h_4 - (1-x)h_5$	1153.9251	180
Regenerator (Heat Transfer)	$q_{regen} = x \times (h_4 - h_7) = (h_8 - h_7)$	303.6155	47
Condenser (Heat rejected)	$q_{cond} = (1-x)(h_5 - h_6)$	2039.2277	318
Boiler (Heat added)	$q_{boiler} = (h_1 - h_9) + (h_3 - h_2)$	3624.9974	565.5
Pump I (Work consumed)	$w_{P1} = (1-x)(h_6 - h_7)$	-0.1422	-0.022
Pump II (Work consumed)	$w_{P2} = h_8 - h_9$	-17.3131	-2.7

3.4.2 2nd law analysis of the components

Mass fraction feeding regenerator, $x = \frac{(h_8 - h_7)}{(h_4 - h_7)} = 0.112$

Table 5 Results of 2nd law analysis

Component	**Exergy available** $\dot{E}_{available}$ $\boldsymbol{\dot{m}_w = 1\ kg/s}$ $\boldsymbol{\dot{m}_g = 2.98\ kg/s}$ $\boldsymbol{\dot{m}_{cw} = 0.0348\ kg/s}$ **kJ/kg**	**Exergy Destruction** $\dot{E}_{dest}$ $\boldsymbol{\dot{m}_w = 1\ kg/s}$ $\boldsymbol{\dot{m}_g = 2.98\ kg/s}$ $\boldsymbol{\dot{m}_{cw} = 0.0348\ kg/s}$ **kJ/kg**	**Exergy available** $\dot{E}_{available}$ $\boldsymbol{\dot{M}_w = 156\ kg/s}$ $\boldsymbol{\dot{M}_g = 465\ kg/s}$ $\boldsymbol{\dot{M}_{cw} = 5428.29\ kg/s}$ **MW**	**Exergy Destruction** $\dot{E}_{dest}$ $\boldsymbol{\dot{M}_w = 156\ kg/s}$ $\boldsymbol{\dot{M}_g = 465\ kg/s}$ $\boldsymbol{\dot{M}_{cw} = 5428.29\ kg/s}$ **MW**
High-Pressure Turbine	473.738	24.438	74	4
Low-Pressure Turbine	1273.474	119.549	199	19
Regenerator	358.544	320.472	56	50
Condenser	46.426	45.031	252	244
Boiler	2675.634	816.710	1244	380
Pump I	-0.129	0.014	-0.02	0.002
Pump II	-3.888	13.425	-0.61	2.094

3.5 Component Sizing and Selecting Models

For some component models, component with exact requirement could not be found because of the fact that manufacturing companies usually take order from the customers of what their requirements are and based on that they customize and manufacture their components.

Table 6 Market models of components

Component	Required size (calculated)	Available Market Model	Market model specs
High-Pressure Turbine	Power output: 70MW Inlet temperature: 590 °C Inlet pressure: 15MPa/150 Bar	SST-700 / 900[4]	Power output: upto 250MW Speed: 3000 to 3600 rpm Inlet pressure: upto 180 bar Inlet temperature: upto 585 °C
Low-Pressure Turbine	Power output: 180 MW Inlet temperature: 590 °C Inlet pressure: 15MPa/150 Bar	SST-700 / 900[4]	Power output: upto 250MW Speed: 3000 to 3600 rpm Inlet pressure: upto 180 bar Inlet temperature: upto 585 °C
Regenerator	Heat transfer upto 47000 kW	No exact model is found for this heat exchanger	Component should be specially designed and manufactured based on heat transfer amount and heat transfer area
Condenser	Heat transfer upto 318000 kW	No exact model is found for this heat exchanger	Component should be specially designed and manufactured based on heat transfer amount and heat transfer area
Boiler	Steam outlet pressure: 15MPa Steam outlet temperature: 590°C	Top in technology co limited ZZ220/9.8-M1[5]	Steam outlet pressure: 10 MPa Steam outlet temperature: 540°C
Pump I	Power required: 22 kW Inlet temperature: 39 °C Pressure: From 7 kPa to 0.15MPa/From 0.07 bar to 1.5 bar Flow rate: 0.14 m^3/s= 504 m^3/h	Flowserve CSB[6] HORIZONTAL – MULTISTAGE – DOUBLE-CASE	Flows to: 1000 m3 /h (4500 gpm) Heads to: 3650 m (12 000 ft) Press. to: 427 bar (6190 psi) Temp: to 250°C (480°F)
Pump II	Power required: 2700 kW Inlet temperature: 111.35 °C Pressure: From 0.15 MPa to 15MPa/ From 1.5 bar to 150 bar Flow rate: 0.16 m^3/s = 576 m^3/h	Flowserve CSB[6] HORIZONTAL – MULTISTAGE – DOUBLE-CASE	Flows to: 1000 m3 /h (4500 gpm) Heads to: 3650 m (12 000 ft) Press. to: 427 bar (6190 psi) Temp: to 250°C (480°F)

4. Cost Analysis

The cost per unit electricity or per kWh_{net} electricity is determined by [2]:

- Fuel cost
- Fixed Costs, mainly interest, depreciation, insurance, taxes, depending on the capital invested or CAPEX. CAPEX-Capital Expenditures is the investment cost for the power-generation project, mainly consists of the equipment supply cost, installation cost, cost of land etc.
- Operation and maintenance costs which is also known as OPEX-Operational Expenditures covering the cost of operating an equipped facility and consists of the direct costs (ex. Salaries, wages, material, repair/maintenance, etc.) as indirect costs such as the tax burden and revenue.
- kWh_{net} of electricity sent out per year

The total annual costs (C_t) in a powerplant can be calculated from [2]

$$C_t = \frac{I + D + T}{100} C_c + OPEX + C_f$$

Where, I is the interest rate, %
D is the depreciation rate, %
T is the taxes and insurance, %
(Other rates can be incorporated)
C_c is the construction/capital cost (CAPEX)
C_f is the fuel cost
The annual amount of electricity sent out by powerplant kWh_{net} is given by[2]

$$kWh_{net} = kW_{installed} \times (24 \times 365) \left(\frac{hr}{year}\right) \times (1 - \frac{L_{aux}}{100}) \times n$$

Where,
$kWh_{installed}$ = Installed output
L_{aux} = power consumption by auxiliaries, %
In coal-based power plants generally the auxiliary power consumption is about 5 to 8 %[7] For this powerplant capacity factor is assumed 7 %
n = plant capacity factor= $\frac{average\ load}{capacity\ of\ plant}$
Average load is determined from load distribution curve which is a curve representing the variation in energy demands with time. Generally, average load is less than the capacity of plant. Therefore, plant capacity factor is less than 1. For this powerplant capacity factor is assumed 0.9

4.1 Fuel Cost

Assuming a coal based powerplant, the fuel cost of the powerplant depends on coal consumption.

<u>Energy content of coal</u>
Energy content of coal is given in terms of kiloJoules per kilogram (kj/kg) of coal as the Gross calorific value (GCV) or the Higher Heating value (HHV) of coal. This value can vary from 10500 kJ/kg to 25000 kJ/kg depending on the quality and type of the coal.[8]
The HHV value for coal is taken 25000 kj/kg for this project.

<u>Conversion efficiency</u>
Energy conversion in a plant takes place in two stages. The first part of the conversion is efficiency of the boiler and combustion. For this project 90 % is considered for the conversion efficiency of boiler which is the normal range for a well-optimized power plant. Second part is the steam cycle efficiency. Calculated efficiency for this project is 44.23%. The overall conversion efficiency then is (44.23% x 90%) = 39.807%

Heat rate

Heat rate is the heat input required to produce one unit (1 kWh) of electricity. 1 kW is 3600 kJ/h. If the energy conversion is 100 % efficient then to produce one unit (1 kWh) of electricity, it requires 3600 kJ of heat input.

Considering the conversion efficiency in a power plant it is required a heat input of $= \frac{3600\ (\frac{kj}{kWh})}{39.807\%} = 9043.64\ \frac{kj}{kWh}$

Required quantity of coal

Higher heating value of coal 25,000 kJ/kg.

For producing 1 kWh required amount of coal = $= \frac{9043.64\ \frac{kj}{kWh}}{25{,}000\ \frac{\mathrm{kJ}}{\mathrm{kg}}} = 0.362\ kg/kWh$

Therefore, for producing 250 MW or 250x10^3 kW the required amount of coal = $0.362\ \frac{kg}{kWh}\ \times 250 \times 10^3 kW$ = 90500 kg/h = 90.5 Ton/h

Yearly requirement of coal = $90.5\ \left(\frac{Ton}{h}\right) \times 24\ (\frac{h}{day}) \times 365(\frac{day}{yr})$ = 792780 Ton

Coal Cost

It is assumed coal price of around = 80 $ / Ton

Fuel cost per hour = $90.5 \times \$80 = 7240\ (\frac{\$}{h})$

Fuel cost per year will be, $C_f = 792780 \times 80\$ = 6{,}34{,}22{,}400\ (\frac{\$}{yr})$

4.2 Fixed cost

4.2.1 CAPEX or Capital cost

A pulverized coalfired power plant fitted with conventional emission control systems is expected to cost $2,078/kW[9]

Therefore, Capital cost of 250MW powerplant C_c = ($\$2078\ \times 250 \times 10^3) = \$51{,}95{,}00{,}000$

4.2.2 Calculation of fixed cost

Assumptions: [10]

Tax = 20%

Interest rate = 6%

Depreciation = 10%

Fixed cost = $\frac{I+D+T}{100} C_c = \frac{6+10+20}{100} \times \$519500000 =\ 18{,}70{,}20{,}000(\frac{\$}{\mathrm{yr}})$

4.3 OPEX or O&M costs

Annual O&M cost for coal fired powerplant is about $43 per kilowatt (kW) [11]

Therefore, O&M cost of 250MW powerplant C_c = ($\$43\ \times 250 \times 10^3) = 1{,}07{,}50{,}000\ (\frac{\$}{yr})$

4.4 Cost of Electricity of Designed powerplant

Total annual costs (C_t),

$$C_t = \frac{I+D+T}{100} C_c + OPEX + C_f = \$18{,}70{,}20{,}000 + \$1{,}07{,}50{,}000\ + \$6{,}34{,}22{,}400 = \$26{,}11{,}92{,}400$$

The annual amount of electricity sent out by powerplant (kWh_{net})

$$kWh_{net} = 250 \times 10^3 \times (24 \times 365)\ \left(\frac{h}{year}\right) \times \left(1 - \frac{7}{100}\right) \times 0.9 = 1833030000$$

Cost for production of 1 unit of electricity = $\frac{261192400\ \left(\frac{\$}{yr}\right)}{1833030000\ \left(\frac{kWh}{yr}\right)} = \$0.14$

5. References

[1] Y. A. Çengel, *Thermodynamics : an engineering approach*. Ninth edition. Boston : McGraw-Hill Higher Education, [2019] ©2019.

[2] P. K. Nag, *Power plant engineering*. New Delhi: McGraw Hill Education (India) Private, 2015.

[3] M. A. Habib, S. A. M. Said, and J. J. Al-Bagawi, "Thermodynamic performance analysis of the Ghazlan power plant," *Energy*, vol. 20, no. 11, pp. 1121–1130, 1995, doi: 10.1016/0360-5442(95)00057-N.

[4] Siemens, "Siemens steam turbine portfolio." https://assets.siemens-energy.com/siemens/assets/api/uuid:e238c50b-4533-452b-b116-61ad97f93bd9/steam-turbine-overview-2019.pdf.

[5] T. in technology C. Limited, "Boiler Product Catalog." http://www.zibco.com.tw/image/files/Boiler Products.pdf.

[6] Flowserve, "PUMP PRODUCT PORTFOLIO." https://www.flowserve.com/sites/default/files/2018-01/fls-1001-ea4.pdf.

[7] T. N. Raval and R. N. Patel, "Optimization of Auxiliary Power Consumption of Combined Cycle Power Plant," *Procedia Eng.*, vol. 51, pp. 751–757, 2013, doi: https://doi.org/10.1016/j.proeng.2013.01.107.

[8] "How to Calculate the Coal Quantity Used in a Power Plant." https://www.brighthubengineering.com/power-plants/52544-basic-calculations-for-a-power-plant-calculating-the-coal-quantity/.

[9] B. P. Breeze, "The Cost of Power Generation."

[10] C. S. Hong and E. B. Lee, "Power plant economic analysis: Maximizing lifecycle profitability by simulating preliminary design solutions of steam-cycle conditions," *Energies*, vol. 11, no. 9, 2018, doi: 10.3390/en11092245.

[11] "Power plant O&M: how does the industry stack up on cost?" https://www.power-technology.com/features/featurepower-plant-om-how-does-the-industry-stack-up-on-cost-4417756/.

6. Appendices

6.1 Appendix A Code Implemented in Python

6.1.1 Optimization Code – 1st Law Efficiency

```
import numpy as np
import CoolProp
import CoolProp.CoolProp as CP
from CoolProp.CoolProp import PropsSI , get_global_param_string

#Input Data

P_list = [10e6,11e6,12e6,13e6,14e6,15e6]          #Pa      #For Maximum pressure
P_percentage = 0.2                          #Pa    #The pressure at inlet of LPT is considered this
                                                   #percentage of the HPT
T_list = [400,410,420,430,440,450,460,470,480,490,500,510,520,530,540,550,560,570,580,590,600]
                                                 #Boiler Temperature List
eta_turb = .90                              #Turbine efficiency
eta_pump = .90                              #Pump efficiency
T_sat = 39+273.15                           #K      #Temperature of Condenser
P_sat = 7e3                                 #Pa     #Saturation pressure at the Temperature of
Condenser
P_regen = 0.15e6                            #Pa     #Pressure at Regenerator which is set
T_surr = 25+273.15                          #K      # Surrounding Temperature

#Cycle Optimisation

for i in T_list:
    for j in P_list:
        T_max = i+273.15                     #K
        P_max = j                            #Pa
        # State 1
        P_1 = P_max
        T_1 = T_max
        h_1 = PropsSI('H', 'P', P_1, 'T', T_1, 'Water')
        s_1 = PropsSI('S', 'P', P_1, 'T', T_1, 'Water')

        # State 2
        P_int = P_max * P_percentage
        P_2s = P_int
        s_2s = s_1
        h_2s = PropsSI('H', 'P', P_2s, 'S', s_2s, 'Water')
        # eta_turb = (h_1 -h_2)/(h_1-h_2s)
        h_2 = h_1 - (eta_turb * (h_1 - h_2s))
        P_2 = P_int
        T_2 = PropsSI('T', 'P', P_2, 'H', h_2, 'Water')
        s_2 = PropsSI('S', 'P', P_2, 'H', h_2, 'Water')
        )
        # State 3
        P_3 = P_int
        T_3 = T_max
        h_3 = PropsSI('H', 'P', P_3, 'T', T_3, 'Water')
        s_3 = PropsSI('S', 'P', P_3, 'T', T_3, 'Water')

        # State 4
        P_4s = P_regen
        s_4s = s_3
        h_4s = PropsSI('H', 'P', P_4s, 'S', s_4s, 'Water')
        # eta_turb = (h_3 -h_4)/(h_3-h_4s)
        h_4 = h_3 - (eta_turb * (h_3 - h_4s))
        P_4 = P_regen
        T_4 = PropsSI('T', 'P', P_4, 'H', h_4, 'Water')
        s_4 = PropsSI('S', 'P', P_4, 'H', h_4, 'Water')

        # State 5
        P_5s = P_sat
        s_5s = s_3
        h_5s = PropsSI('H', 'P', P_5s, 'S', s_5s, 'Water')
        # eta_turb = (h_3 -h_5)/(h_3-h_5s)
        h_5 = h_3 - (eta_turb * (h_3 - h_5s))
        P_5 = P_sat
        T_5 = PropsSI('T', 'P', P_5, 'H', h_5, 'Water')
        s_5 = PropsSI('S', 'P', P_5, 'H', h_5, 'Water')
```

```
# State 6
P_6 = P_sat
q_6 = 0   # Quality
h_6 = PropsSI('H', 'P', P_6, 'Q', q_6, 'Water')
s_6 = PropsSI('S', 'P', P_6, 'Q', q_6, 'Water')

# State 7
P_7s = P_regen
s_7s = s_6
h_7s = PropsSI('H', 'P', P_7s, 'S', s_7s, 'Water')
# eta_pump = (h_7s -h_6)/(h_7-h_6)
h_7 = h_6 + (h_7s - h_6) / eta_pump
P_7 = P_regen
T_7 = PropsSI('T', 'P', P_7, 'H', h_7, 'Water')
s_7 = PropsSI('S', 'P', P_7, 'H', h_7, 'Water')

# State 8
P_8 = P_regen
q_8 = 0   # Quality
h_8 = PropsSI('H', 'P', P_8, 'Q', q_8, 'Water')
s_8 = PropsSI('S', 'P', P_8, 'Q', q_8, 'Water')

# State 9
P_9s = P_max
s_9s = s_8
h_9s = PropsSI('H', 'P', P_9s, 'S', s_9s, 'Water')
# eta_pump = (h_9s -h_8)/(h_9-h_8)
h_9 = h_8 + (h_9s - h_8) / eta_pump
P_9 = P_regen
T_9 = PropsSI('T', 'P', P_9, 'H', h_9, 'Water')
s_9 = PropsSI('S', 'P', P_9, 'H', h_9, 'Water')


x = (h_8 - h_7) / (h_4 - h_7)
w_net = (h_1 - h_2) + (h_3 - x * h_4 - (1 - x) * h_5)
q_in = (h_1 - h_9) + (h_3 - h_2)
eta = ((w_net) / (q_in))* 100

print(i,j,eta)
```

6.1.2 Optimization - 2nd Law Efficiency and Overall calculation code

```
import math
import CoolProp
import CoolProp.CoolProp as CP
from CoolProp.CoolProp import PropsSI , get_global_param_string

#Input Data

T_max = 590 + 273.15                    # K
P_max = 15e6                            # Pa
P_percentage = 0.2                      #Pa   #The pressure at inlet of LPT is considered this
                                              #percentage of the HPT
eta_turb = .90                          #Turbine efficiency
eta_pump = .90                          #Pump efficiency
T_sat = 39+273.15                       #K      #Temperature of Condenser
P_sat = 7e3                             #Pa     #Saturation pressure at the Temperature of
Condenser
P_regen = 0.15e6                        #Pa     #Pressure at Regenerator which is set
T_surr = 25+273.15                      #K      # Sourrounding Temperature
m_water = 1
    #Flue gas property
Cp_gas = 1.1058                         #Initial State of flue gas as reference state
T_gas_in = 1500+273.15
T_gas_out = 400+273.15
P_gas_out = 101e3
P_gas_in = 102e3
h_gas_in = 0
s_gas_in = 0
k = 1.35
    #Cooling water
P_cold_in = 101e3
T_cold_in = 25 +273.15
T_cold_out = 39 +273.15
P_cold_out = 101e3
#Cycle Analysis with optimized parameter

# State 1
P_1 = P_max
T_1 = T_max
h_1 = PropsSI('H', 'P', P_1, 'T', T_1, 'Water')
s_1 = PropsSI('S', 'P', P_1, 'T', T_1, 'Water')
print('Properties of state 1: h_1 =', h_1 / 1000, 'kJ/kg , s_1 = ', s_1 / 1000, 'kJ/kg K and T_1
= ',T_1-273.15,'C')
# State 2
P_int = P_max * P_percentage
P_2s = P_int
s_2s = s_1
h_2s = PropsSI('H', 'P', P_2s, 'S', s_2s, 'Water')
# eta_turb = (h_1 -h_2)/(h_1-h_2s)
h_2 = h_1 - (eta_turb * (h_1 - h_2s))
P_2 = P_int
T_2 = PropsSI('T', 'P', P_2, 'H', h_2, 'Water')
s_2 = PropsSI('S', 'P', P_2, 'H', h_2, 'Water')
print('Properties of state 2: h_2 =', h_2 / 1000, 'kJ/kg , s_2 = ', s_2 / 1000, 'kj/kg K and T_2
= ',T_2-273.15,'C')
# State 3
P_3 = P_int
T_3 = T_max
h_3 = PropsSI('H', 'P', P_3, 'T', T_3, 'Water')
s_3 = PropsSI('S', 'P', P_3, 'T', T_3, 'Water')
print('Properties of state 3: h_3 =', h_3 / 1000, 'kJ/kg, s_3 = ', s_3 / 1000, 'kj/kg K and T_3
= ',T_3-273.15,'C')
# State 4
P_4s = P_regen
s_4s = s_3
h_4s = PropsSI('H', 'P', P_4s, 'S', s_4s, 'Water')
# eta_turb = (h_3 -h_4)/(h_3-h_4s)
h_4 = h_3 - (eta_turb * (h_3 - h_4s))
P_4 = P_regen
T_4 = PropsSI('T', 'P', P_4, 'H', h_4, 'Water')
s_4 = PropsSI('S', 'P', P_4, 'H', h_4, 'Water')
print('Properties of state 4: h_4 =', h_4 / 1000, 'kJ/kg , s_4 = ', s_4 / 1000, 'kj/kg K and T_4
= ',T_4-273.15,'C')
# State 5
```

```
P_5s = P_sat
s_5s = s_3
h_5s = PropsSI('H', 'P', P_5s, 'S', s_5s, 'Water')
# eta_turb = (h_3 -h_5)/(h_3-h_5s)
h_5 = h_3 - (eta_turb * (h_3 - h_5s))
P_5 = P_sat
T_5 = PropsSI('T', 'P', P_5, 'H', h_5, 'Water')
s_5 = PropsSI('S', 'P', P_5, 'H', h_5, 'Water')
print('Properties of state 5: h_5 =', h_5 / 1000, 'kJ/kg , s_5 = ', s_5 / 1000, 'kj/kg K and T_5
= ',T_5-273.15,'C')
# State 6
P_6 = P_sat
q_6 = 0  # Quality
h_6 = PropsSI('H', 'P', P_6, 'Q', q_6, 'Water')
s_6 = PropsSI('S', 'P', P_6, 'Q', q_6, 'Water')
T_6 = PropsSI('T', 'P', P_6, 'Q', q_6, 'Water')
print('Properties of state 6: h_6 =', h_6 / 1000, 'kJ/kg ,s_6 = ', s_6 / 1000, 'kj/kg K and T_6
= ',T_6-273.15,'C')
# State 7
P_7s = P_regen
s_7s = s_6
h_7s = PropsSI('H', 'P', P_7s, 'S', s_7s, 'Water')
# eta_pump = (h_7s -h_6)/(h_7-h_6)
h_7 = h_6 + (h_7s - h_6) / eta_pump
P_7 = P_regen
T_7 = PropsSI('T', 'P', P_7, 'H', h_7, 'Water')
s_7 = PropsSI('S', 'P', P_7, 'H', h_7, 'Water')
print('Properties of state 7: h_7 =', h_7 / 1000, 'kJ/kg, s_7 = ', s_7 / 1000, 'kj/kg K and T_7
= ',T_7-273.15,'C')
# State 8
P_8 = P_regen
q_8 = 0  # Quality
h_8 = PropsSI('H', 'P', P_8, 'Q', q_8, 'Water')
s_8 = PropsSI('S', 'P', P_8, 'Q', q_8, 'Water')
T_8 = PropsSI('T', 'P', P_8, 'Q', q_8, 'Water')

print('Properties of state 8: h_8 =', h_8 / 1000, 'kJ/kg, s_8 = ', s_8 / 1000, 'kj/kg K and T_8
= ',T_8-273.15,'C')
# State 9
P_9s = P_max
s_9s = s_8
h_9s = PropsSI('H', 'P', P_9s, 'S', s_9s, 'Water')
# eta_pump = (h_9s -h_8)/(h_9-h_8)
h_9 = h_8 + (h_9s - h_8) / eta_pump
P_9 = P_regen
T_9 = PropsSI('T', 'P', P_9, 'H', h_9, 'Water')
s_9 = PropsSI('S', 'P', P_9, 'H', h_9, 'Water')
print('Properties of state 9: h_9 =', h_9 / 1000, 'kJ/kg, s_9 = ', s_9 / 1000, 'kj/kg K and T_9
= ',T_9-273.15,'C','\n')

x = (h_8 - h_7) / (h_4 - h_7)
print('Mass fraction feeding regenerator X = ', x,'\n')

w_hpt = (h_1 - h_2)
print('HPT Specific Work w = ', w_hpt / 1000,'kJ/kg')
w_lpt = (h_3 - x * h_4 - (1 - x) * h_5)
print('LPT Specific Work w = ', w_lpt / 1000,'kJ/kg')
w_net = w_hpt + w_lpt
print('Turbine Specific Work w = ', w_net / 1000,'kJ/kg\n')

q_regen = h_8 - h_7
print('Specific Heat transfer in regenerator = ', q_regen / 1000,'kJ/kg')

q_in = (h_1 - h_9) + (h_3 - h_2)
print('Specific Heat input from boiler = ', q_in / 1000,'kJ/kg')

q_out = (1-x) * (h_5-h_6)
print('Specific Heat outgoing from condenser = ', q_out / 1000,'kJ/kg')

w_pumpI = (1-x) * (h_6-h_7)
print('PUMP I Specific Work input = ', w_pumpI / 1000,'kJ/kg')

w_pumpII = (h_8-h_9)
print('PUMP II Specific Work input = ', w_pumpII / 1000,'kJ/kg')
```

```
eta = (w_net) / (q_in)
print('1st law Efficiency = ', eta * 100, '%\n')

E_hpt_avail = (h_1-h_2)-T_surr*(s_1-s_2)
print('E_hpt_avail = ', E_hpt_avail/1000, 'kJ/kg')
E_hpt_dest = -T_surr*(s_1-s_2)
print('E_hpt_dest = ', E_hpt_dest/1000, 'kJ/kg')

E_lpt_avail = (h_3-x*h_4-(1-x)*h_5)-T_surr*((s_3-x*s_4-(1-x)*s_5))
print('E_lpt_avail = ', E_lpt_avail/1000, 'kJ/kg')
E_lpt_dest = -T_surr*((s_3-x*s_4-(1-x)*s_5))
print('E_lpt_dest = ', E_lpt_dest/1000, 'kJ/kg')

E_regen_avail =  -T_surr*(x*s_4-(1-x)*s_7-s_8)+(1-x)*((h_8-h_7)-T_surr*(s_8-s_7))
print('E_regen_avail = ', E_regen_avail/1000, 'kJ/kg')
E_regen_dest =  -T_surr*(x*s_4-(1-x)*s_7-s_8)#+(1-x)*((h_8-h_7)-T_surr*(s_8-s_7))
print('E_regen_dest = ', E_regen_dest/1000, 'kJ/kg')

h_cold_in = PropsSI('H', 'P', P_cold_in, 'T', T_cold_in, 'Water')
print('h cold_in = ',h_cold_in/1000)
h_cold_out = PropsSI('H', 'P', P_cold_out, 'T', T_cold_out, 'Water')
print('h cold_out = ',h_cold_out/1000)
s_cold_in = PropsSI('S', 'P', P_cold_in, 'T', T_cold_in, 'Water')
print('s cold_in = ',s_cold_in/1000)
s_cold_out = PropsSI('S', 'P', P_cold_out, 'T', T_cold_out, 'Water')
print('s cold_out = ',s_cold_out/1000)
m_cold = q_out/(h_cold_out- h_cold_in)
print('Cold water mass flow rate, m_cold = ', m_cold/1000, 'kg/s')
E_cond_avail = m_cold*((h_cold_out-h_cold_in)-T_surr*(s_cold_out-s_cold_in))
print('E_cond_available = ', E_cond_avail/1000, 'kJ/kg')
E_cond_dest =  -T_surr*((1-x)*(s_5-s_6)+m_cold*(s_cold_in-s_cold_out))
print('E_cond_destruction = ', E_cond_dest/1000, 'kJ/kg')

m_gas = q_in/(Cp_gas*(T_gas_in-T_gas_out))
a = math.log(T_gas_out/T_gas_in)
b = math.log(P_gas_out/P_gas_in)
s_gas_out = Cp_gas*a - (((k-1)/k) *b)
h_gas_out = Cp_gas*(T_gas_out-T_gas_in)
print('Flue gas mass flow rate, m_gas = ', m_gas/1000, 'kg/s')
E_boiler_avail = m_gas*((h_gas_in-h_gas_out)-T_surr*(s_gas_in-s_gas_out))
print('E_boiler_available = ', E_boiler_avail/1000, 'kJ/kg')
E_boiler_dest = -T_surr*((s_9-s_1)+(s_2-s_3)+m_gas*(s_gas_in-s_gas_out))
print('E_boiler_destruction = ', E_boiler_dest/1000, 'kJ/kg')


E_pumpI_avail = (1-x)*((h_6-h_7)-T_surr*(s_6-s_7))
print('E_pumpI_available = ', E_pumpI_avail/1000, 'kJ/kg')
E_pumpI_dest = -(1-x)*(T_surr*(s_6-s_7))
print('E_pumpI_dest = ', E_pumpI_dest/1000, 'kJ/kg')
E_pumpII = ((h_8-h_9)-T_surr*(s_8-s_9))
print('E_pumpII_available = ', E_pumpII/1000, 'kJ/kg')
E_pumpII_dest = (-T_surr*(s_8-s_9))
print('E_pumpII_dest = ', E_pumpII_dest/1000, 'kJ/kg')
#a_gas_in = h_gas_in - T_surr * s_gas_in
#print('a_gas_in = ', a_gas_in/1000, 'kJ/kg')
#a_gas_out = Cp_gas*((T_gas_out-T_gas_in)-T_surr*a - ((k-1)/k) *b) #a_gas out = h_gas_out - 
T_sutt*s_gas_out
#print('a_gas_out = ', a_gas_out, 'kJ/kg')
#RED = m_gas*(a_gas_in-a_gas_out)
#print('Rate of exergy decrease of the system',RED/1000,'KW')

eta_II= w_net/E_boiler_avail
print('2nd law Efficiency = ', eta_II * 100, '%')
```