DREXEL UNIVERSITY
College of
Engineering

MEM 310

Design Project: Maximizing the Efficiency of Rankine Cycle Power Plant

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Summary:

As the main requirement of power plant owners, the team's consulting firm was asked to maximize the overall efficiency of a Rankine reheat and regenerative cycle steam power plant. Along with that assignment, the team was given a variety of specifications from the owners including an overall power output of 300 MW. Furthermore, the given turbine pressures ranged from 6.9 kPa to 12,100 kPa, and the efficiencies of the pumps and turbines ranged from 60% to 89%. In order to maximize efficiency, the team had to first assign values to the intermediate pressure turbine exit pressure and conduct a series of trials to find the ideal pressure. Additionally, the team was required to find the steam flow rates and other key values of the final design. The final results yielded the pressure needed at the extraction point of the open feedwater heater (intermediate pressure turbine exit pressure) to be 1000 kPa, which allows for the highest efficiency of 50.4%.

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Problem Statement/System Definition:

The objective of this task is to optimize the efficiency as well as determine the steam flow rate for a power plant operating under the Rankine cycle. As a consulting firm, the team is asked to improve the system based on an initial design. This plant specifically implements the Rankine reheat and regenerative cycle. During the Rankine cycle, operating fluid is constantly being evaporated and condensed. The first three steps of the process include isobaric heat transfer, which is when high pressure liquid enters the boiler and is heated (Point 5) then goes into a high pressure turbine. The liquid then goes to a reheater then an intermediate pressure turbine (IPT), where the resulting steam then splits paths (Point 8). Precisely at this split is where pressure needs to be found. Some of the working fluid coming from the IPT goes directly to the open heater as the rest travels to a low pressure turbine (LTP). The steam that enters the LTP goes to a condenser, then a condenser pump, where it ends up at the open heater with the other steam. The last step consists of the steam entering a boiler feed pump that is used to bring the steam back to the boiler.

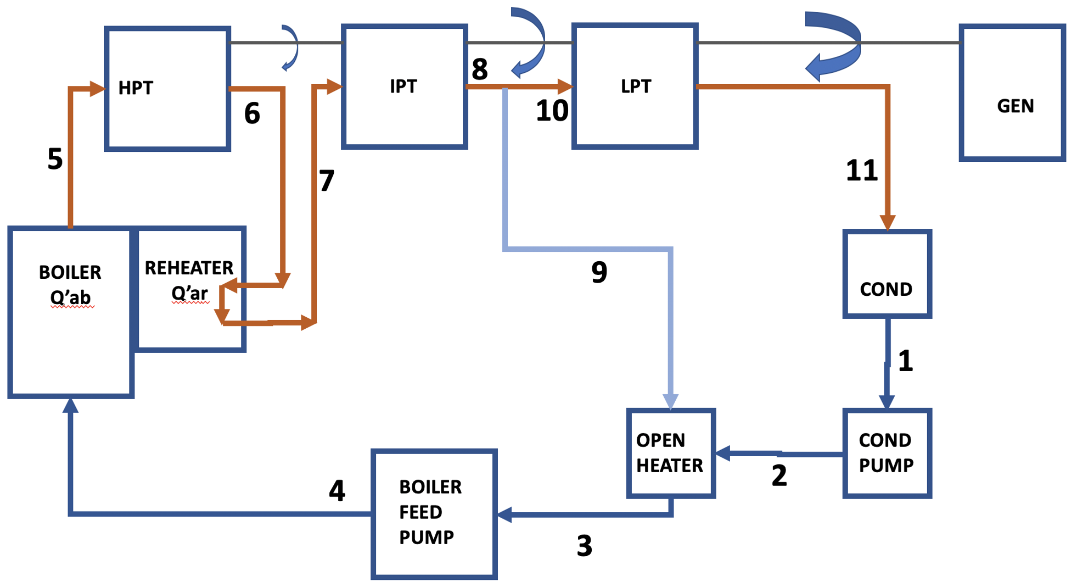

Figure 1: Animation of the Rankine-Reheat-Regenerative Cycle with numbered processes

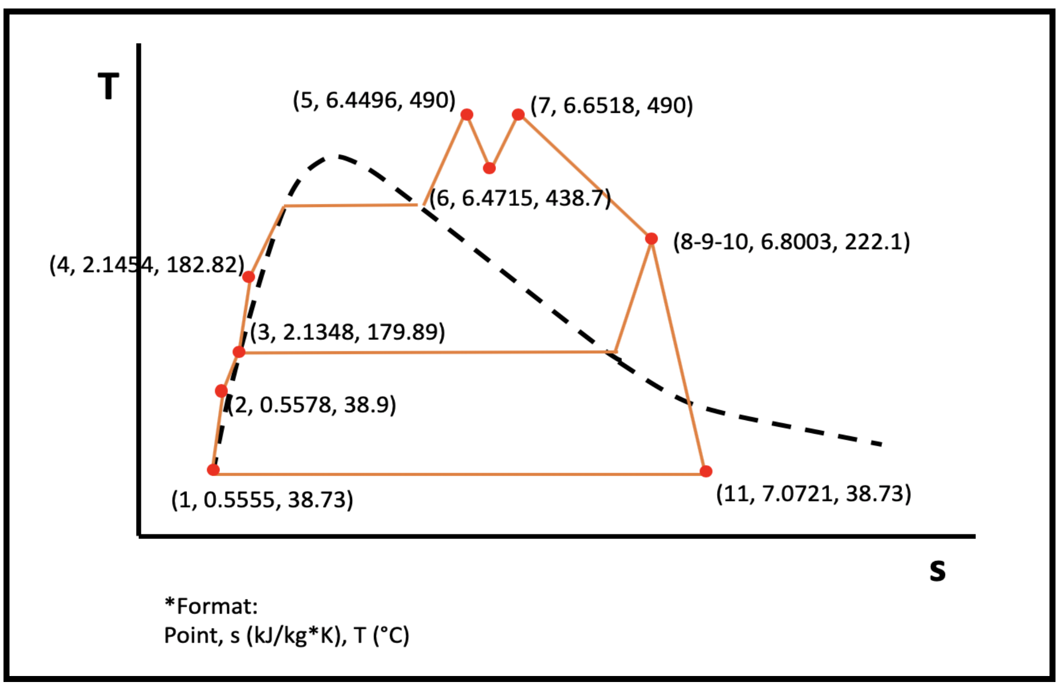

Figure 2: T-s Diagram of the team's analyzed Rankine Cycle with steps and values

Solution:

To yield the best overall efficiency, different exit pressures of the feedwater heater steam (P2) were tested. First, the team was given a set of fixed constraints that were created by the client, which can be found in Table I. Additionally,. Table II features a set of fixed values in each state that remain constant throughout each trial. Sample calculations for the first trial can be found in Appendix A.

Table I: Given Constraints from Clients

Given	Value
Net Power	300 MW
Number of Reheaters	1
Reheater Outlet Temperature	490°C
Number of Open Feedwater Heaters	1
HPT Inlet Steam Pressure	12.1 MPa
HPT Inlet Steam Temperature	490°C
IPT Inlet Pressure	8.62 MPa
Condenser Pressure	6.9 kPa
HPT Efficiency	85%
IPT Efficiency	87%
LPT Efficiency	89%
Boiler Feed Pump Efficiency	80%
Condensate Pump Efficiency	60%

Table II: Each state of the cycle explaining the values that vary between trials

State	P (kPa)	T (°C)	v (m^3/kg)	h (kJ/kg)	s (kJ/kg*K)
1	6.9	38.73	0.0010074	162.25	0.5555
2	Varies	Varies	Varies	Varies	Varies
3	Varies	Varies	Varies	Varies	Varies
4	12100	Varies	Varies	Varies	Varies
5	12100	490	0.026069161	3321.5	6.4496
6	8620	438.7	0.034376074	3233.8289	6.4715
7	8620	490	0.037891562	3366.7	6.6518
8	Varies	Varies	Varies	Varies	Varies
9	Varies	Varies	Varies	Varies	Varies
10	Varies	Varies	Varies	Varies	Varies
11	6.9	38.73	Varies	Varies	Varies

Following the calculations from Table II, a value for the pressure at point 8 was chosen and each varying value was determined. After these values were determined for each state, the work done by the turbines and pumps could be calculated. The heat that entered the heater and reheater was also determined. Next, the mass flow rate was found using the net work out value as well as the per-unit mass work values (see Table I). The total efficiency of the system was found by dividing the net work by the total heat on the system. After the efficiency was determined, the process would be repeated with a new pressure value.

The team decided to begin the calculations using a high pressure value. After deciding to steadily decrease the pressure for each trial, the team noticed that the efficiency was trending up. As the pressure dropped steadily for each trial, the efficiency would increase until reached a peak high. The highest efficiency occurred with a pressure of 1000 kPa and efficiency of 40.8% (see Table III). The last trial at 500 kPa exhibits the decline in efficiency, which supports the notion that 1000 kPa is the ideal exit pressure for the feedwater heater.

Table III: IPT exhaust state properties for each trial

	IPT Exhaust State Properties		
Trial	**P (kPa)**	**T (°C)**	**Enthalpy (kJ/kg)**
1	9250	501.1	3386.94
2	8620	490	3366.7
3	8000	478.5	3345.70
4	3000	342.8	3099.14
5	2000	294.7	3011.99
6	1000	222.1	2880.45
7	500	159.5	2766.12

Table IV: Individual work output from turbines, work in from pumps, and heat addition for the boiler and reheater for each trial

		Individual Turbine/Pump Works and Heat Added						
Trial	**IPT Exit P (kPa)**	**HPT Work (kW)**	**IPT Work (kW)**	**LPT Work (kW)**	**CP Work (kW)**	**BP Work (kW)**	**Boiler Heat (kW)**	**Reheat (kW)**
1	**9250**	33218.72	-7667.53	280045.60	3674.13	1922.66	735647.11	50345.07
2	**8620**	32592.89	0	273079.49	3393.55	2278.83	732038.97	49396.58
3	**8000**	31978.72	7658.75	266079.89	3121.95	2595.40	728532.39	48465.77
4	**3000**	26779.46	81728.23	196777.07	1088.43	4196.32	702357.66	40585.96
5	**2000**	25551.24	103376.55	176095.37	714.79	4308.36	698911.58	38724.51
6	**1000**	24091.81	133621.77	146914.69	351.4	4276.86	698880.69	36512.66
7	**500**	23272.74	159427.03	121666.13	173.59	4192.32	707575.18	35271.32

Table V: Overall cycle efficiencies for each trial

Trial	Efficiency (%)
1 (IPT Exhaust = 9250 kPa)	38.2%
2 (IPT Exhaust = 8620 kPa)	38.4%
3 (IPT Exhaust = 8000 kPa)	38.6%
4 (IPT Exhaust = 3000 kPa)	40.4%
5 (IPT Exhaust = 2000 kPa)	40.7%
6 (IPT Exhaust = 1000 kPa)	40.8%
7 (IPT Exhaust = 500 kPa)	40.4%

Figure 3 exhibits the best fit curve for the relationship between cycle efficiency and IPT exit pressure. The data was truncated to negate the high pressure values and therefore yield a better fit line, seen in Figure 4.

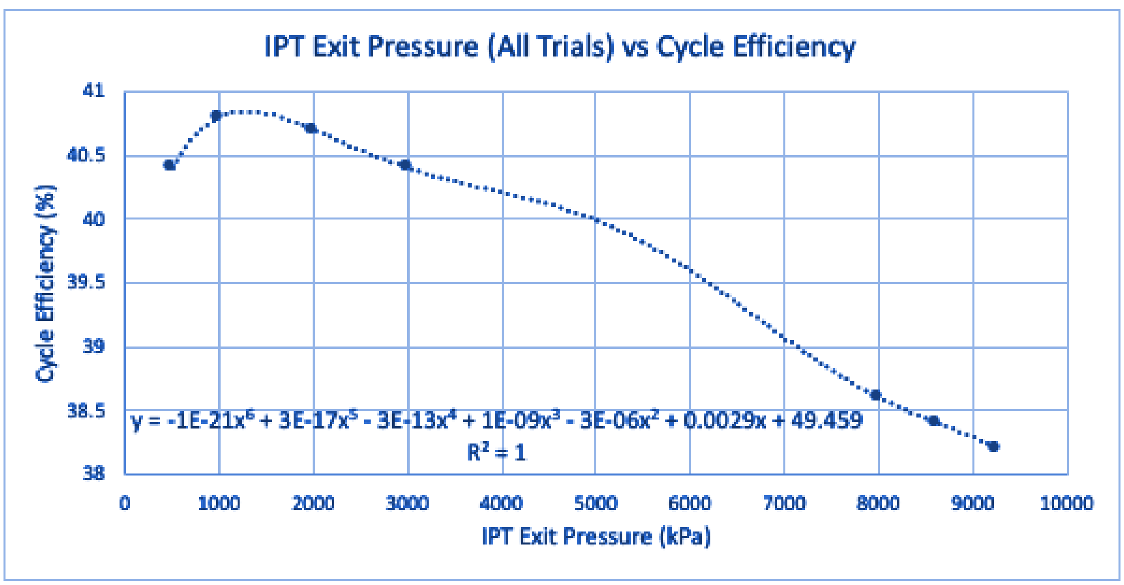

Figure 3: IPT Exit Pressure that was chosen to maximize efficiency plotted against the corresponding efficiency

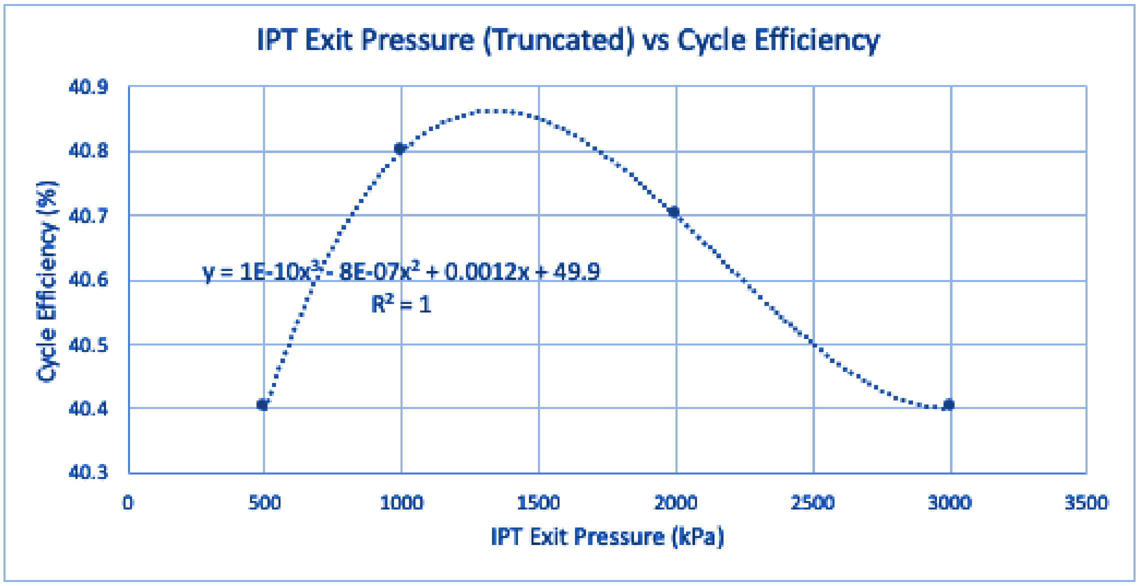

Figure 4: IPT Exit Pressure plotted against the corresponding efficiency with large outliers removed

After the completion of the seven trials, it was determined that the optimal exit pressure for the feedwater heater steam is 1000 kPa because it has the highest recorded efficiency on the system. All of the results for top efficiency are summarized in Table VI. The temperature of the steam would be 222.1°C and the mass flow rate of the steam at the IPT would be 60.57 kg/s. The total efficiency of the system would be 40.8%. The efficiency of this system is represented as a percentage, and implies that 40.8% of the heat that enters the system will be converted into mechanical energy as it leaves the system. The mass flow rate of 214.23 kg/s would work throughout the LPT, condenser, and condenser turbine. A Mass flow rate of 274.80 kg/s would travel through the boiler. These conditions are required to obtain the client specified power of 300 MW. Additionally, these conditions would result in power outputs of: 24091.81 kW for the high pressure turbine, 133621.77 kW for the intermediate pressure turbine, and 146914.69

kW for the low pressure turbine. The heat input to the boiler system requires 698880.69 kW and 36512.66 kW for the reheater.

Table VI: Important values from the best trial

Pressure of exhaust steam at IPT	1000 kPa
Temperature of exhaust steam at IPT	222.1°C
Mass flow rate of steam at Point 9	60.57 kg/s
Cycle Efficiency	40.8 %
Mass Flow Rate at Points 3, 4, 5, 6, 7, 8	274.80 kg/s
Mass flow rate of steam at Points 1, 2, 10, 11	214.23 kg/s
High Pressure Turbine Power Produced	24091.81 kW
Intermediate Pressure Turbine Power Produced	133621.77 kW
Low Pressure Turbine Power Produced	146914.69 kW
Condenser Pump Power Required	351.40 kW
Boiler Pump Power Required	4276.86 kW
Rate of Heat Added in Boiler	698880.69 kW
Rate of Heat Added in Reheater	36512.66 kW

Discussion and Conclusions:

From the calculations performed, it was determined that a 1000 kPa intermediate turbine exit pressure results in the most efficient system. A pressure of 1000 kPa creates a thermal efficiency of 50.4%. For this pressure, the whole system requires a mass flow rate of 274.8 kg/s in order to produce 300 MW of power.

The data calculated during the trial pressures was used to create two figures modeling the pressure-efficiency relationship. The graphs reinforce the solution and show that peak efficiency is achieved around a pressure of 1000 kPa. Small rounding errors made during the calculations account for any possible deformities in both figures. Any errors of this nature are negligible and should be ignored.

Recommendations for Future Analysis:

There are multiple ways in which the efficiency of the system could be improved in the future. The first option is to replace all turbines and pumps with more efficient models. This would improve the overall efficiency by minimizing energy loss through these machines. Though this method would be effective in increasing the efficiency, the overall cost of implementing this option would be very expensive as it would involve the replacement of five of the most important parts of the system.

The second option would be to conduct more calculations, and by doing so would result in calculating a more accurate pressure. The new pressure would be somewhere between 500 and 1500 kPa, and would have a higher efficiency. The increase in efficiency would likely be minimal, however the increase in efficiency, however minimal, would possibly increase the profit margins of the system.

The third option involves raising the working temperature of the boiler and reheater. By raising the working temperature, the steam will have a higher enthalpy and the thermal efficiency will increase, because the turbines will be able to extract more energy. One side effect of this option is that the work required to keep the working fluid at the correct state will increase. Before implementing this option, the cost of replacing the respective components would have to be evaluated.

Option four involves a similar theory as option three, as consists of lowering the temperature at which the condenser operates at. By doing this, the temperature gap between the system high and low will increase which will increase the energy generated during the system. Again, the side effects of this include an increase in the work required to keep the working fluid at the correct state. This option could also be quite expensive as it might require replacing some components of the system.

Appendix A: Detailed Process Calculations:

State 1:

1. Assumption: Pressure losses through the boiler, reheater, condenser and any connecting piping can be neglected.
    a. Inlet pressure of condenser = exhaust pressure of condenser
    b. $P_1 = P_{11} = 6.9$ kPa
2. Assumption: Outlet of a condenser produces saturated liquid
    a. **T_1 = 38.73℃**
3. Specific volume, enthalpy, and entropy utilizing saturated liquid values at P = 6.9 kPa
    a. **v_1 =0.0010074 m3/kg; h_1 = 162.25 kJ/kg ; s_1 = 0.5555 kJ/kg*K**

State 2:

1. Assumption: Exit pressure of the condensate pump and the inlet pressure of the boiler feed pump are equal to the exit pressure of the intermediate pressure turbine
2. Assumption: Condensate pump is isentropic
    a. **P_2 = 1000 kPa; $s_{2S} = s_1$ = 0.5555 kJ/kg*K**
3. Rankine pump equation: $T * ds = dh - vd$
    a. Isentropic (ds = 0): $dh = vdP$
4. Assumption: liquid at condensate pump inlet and compressed liquid at condensate pump outlet, so specific volume remains constant.
    a. $h_{2s} - h_1 = v_1 * (P_2 - P_1)$
    b. **h_{2S} = 163.2342 kJ/kg**

5. Use condensate pump efficiency to find actual enthalpy at state 2
    a. Assumption: Changes in potential and kinetic energy are negligible
    b. Assumption: turbines, pumps, piping, and open heater are well insulated
    c. η = *isentropic pump work / actual pump work*
        i. η = (h1-h2s)/(h1-h2a)
        ii. **h2a = 163.8903 kJ/kg**
        iii. Using the Excel calculator we get the following values
            1. **T_{2A} = 38.9 °C ; v_{2A} = 0.0010073 m3/kg; s_{2A} = 0.5578 kJ/kg*k**

State 3:

1. Assumption: $P_3 = P_8 = P_2$
2. Assumption: Open feedwater heater mixture of steam and liquid leaves as a saturated liquid at the heater pressure
    a. T_3, v_3, $h_{3,}$ s_3 are found at pressure P_3 = 1000 kPa
        i. **T_3 = 179.89 °C; v_3 = 0.0011272 m3/kg; h_3 = 762.68 kJ/kg; s_3 = 2.1384 kJ/kg*K**

State 4:

1. Same process as State 2, however, we replace the state 1 and 2 values with state 3 and 4 values respectively
    a. **$s_{4S} = s_3$ =2.1384 kJ/kg*K; h_{4S} = 775.13095 kJ/kg**
    b. With the efficiency being 0.8
        i. **h_{4A} = 778.24369 kJ/kg**
    c. Using the Excel calculator

i. **T_{4A} = 182.1 °C; v_{4A} = 0.0011211 m3/kg; s_{4A} = 2.1454 kJ/kg*K**

State 5:

1. HPT Inlet Pressure is given
    a. **P_5 = 12100 kPa**
2. HPT Inlet Temperature is given
    a. **T_5 = 490 °C**
3. All other values can be found on the Excel calculator using temperature and pressure
    a. **v_5 =0.0260691 m3/kg; h_5 =3321.5 kJ/kg; s_5 = 6.4496 kJ/kg*K**

State 6:

1. Assumption: Pressure losses through the boiler, reheater, condenser and piping can be neglected.
    a. Outlet pressure of HPT = Inlet pressure of IPT
    b. $P_6 = P_7$
2. IPT Inlet Pressure is given
    a. P_7 = 8620 kPa
    b. **P_6** = P_7 = **8620 kPa**
3. Assumption: HPT is isentropic
    a. $s_{6S} = s_5$ = 6.4496 kJ/kg*K
    b. From the excel calculator we get **h_{6S} = 3218.3575 kJ/kg**
4. Use turbine efficiency equation to find actual enthalpy at state 6
    a. Assumption: Changes in potential and kinetic energy are negligible
    b. Assumption: turbines, pumps, piping, and open heater are well insulated

c. η = *isentropic pump work / actual pump work*

i. η = (h5-h6s)/(h5-h6a)

d. **h6a = 3233.8289 kJ/kg**

e. Using the Excel calculator we get the following values

i. **T_{6A} = 438.7 °C ; v_{6A} = 0.0343761 m3/kg; s_{6A} = 6.4715 kJ/kg*k**

State 7:

1. HPT Inlet Pressure is given
   a. **P_7 = 8620 kPa**
2. HPT Inlet Temperature is given
   a. **T_7 = 490 °C**
3. All other values can be found on the Excel calculator using temperature and pressure
   a. **v_7 =0.0378916 m3/kg; h_7 =3366.7 kJ/kg; s_7 = 6.6518 kJ/kg*K**

State 8:

1. IPT Inlet Pressure is the changing pressure for each trial which for thistrial is **P_8 = 1000 kPa**
2. IPT efficiency is given to be η = 0.87
3. Same Process as State 6 but replace states 5 and 6 values with the values for states 7 and 8 respectively
   a. s_{8S} = s_7 = 6.6518 kJ/kg*K, **h_{8S} = 2807.7859 kJ/kg**
   b. η = (h7-h8s)/(h7-h8a)
   c. **h8a = 2880.4473 kJ/kg**
   d. Using the Excel calculator we get the following values

i. **T_{8A} = 222.1 °C ; v_{8A} = 0.2183406 m3/kg; s_{8A} = 6.8003 kJ/kg*k**

State 9:

1. Assumption: Pressure losses through the boiler, reheater, condenser and piping can be neglected.
2. Since state 9 is a part of state 8, no properties will change
    a. **h_9 = 2880.4473 kJ/kg; T_9 = 222.1 °C ; v_9 = 0.2183406 m3/kg; s_9 = 6.8003 kJ/kg*k**

State 10:

1. Assumption: Pressure losses through the boiler, reheater, condenser and piping can be neglected.
2. Since state 10 is a part of state 8, no properties will change
    a. **h_{10} = 2880.4473 kJ/kg; T_{10} = 222.1 °C ; v_{10} = 0.2183406 m3/kg; s_{10} = 6.8003 kJ/kg*k**

State 11:

1. Assumption: Pressure losses through the boiler, reheater, condenser and piping can be neglected.
    a. Inlet pressure of condenser = exhaust pressure of condenser
    b. $P_{11} = P_1$ = 6.9 kPa
2. LPT Turbine Efficiency is given to be η = 0.89
3. Same Process as State 6 but replace states 5 and 6 values with the values for states 10 and 11 respectively
    a. $s_{11S} = s_{10}$ = 6.8003 kJ/kg*K, **h_{11S} = 2109.8937 kJ/kg**

b. η = (h10-h11s)/(h10-h11a)

c. **h11a = 2194.6546 kJ/kg**

d. Using the Excel calculator and the information we found for state 11 we can find the quality of the steam at that point

   i. x = 0.8437 = 84.37%

e. Using the Excel calculator, our pressure, and quality we get the following values

   i. **T_{8A} = 38.73 °C ; v_{8A} = 16.66667 m3/kg; s_{8A} = 7.0721 kJ/kg*k**

<u>Mass Flow Rate and Efficiencies</u>

1. The total work output for the plant was given to be 300MW = 300,000 kW
2. Mass flow rates
   a. The flow rates from states 3-8 are all equal
      i. $\dot{m}_3 = \dot{m}_4 = \dot{m}_5 = \dot{m}_6 = \dot{m}_7 = \dot{m}_8$
   b. The flow rate coming out of the IPT is equal to the flow rates going to the LPT and the open heater
      i. $\dot{m}_8 = \dot{m}_9 + \dot{m}_{10}$
   c. The flow rates from states 10-2 are all equal
      i. $\dot{m}_{10} = \dot{m}_{11} = \dot{m}_1 = \dot{m}_2$
   d. At the open heater:
      i. $(\dot{m}_9 \cdot h_9) + (\dot{m}_2 \cdot h_2) = \dot{m}_3 \cdot h_3$
   e. Combining all previous parts to equation in part d:
      i. $\dot{m}_{10} = \dot{m}_3 * (h_3 - h_9) / (h_2 - h_9)$
3. Total Plant Output
   a. $\dot{W}_{TOTALout} = \dot{W}_{HPTout} + \dot{W}_{IPTout} + \dot{W}_{LPTout} + \dot{W}_{CPout} + \dot{W}_{BPout}$

b. $\dot{W}_{TOTALout} = \dot{m}_5 \cdot (h_5 - h_6) + \dot{m}_7 \cdot (h_7 - h_8) + \dot{m}_{10} \cdot (h_{10} - h_{11}) - \dot{m}_1 \cdot (h_2 - h_1) - \dot{m}_3 \cdot (h_4 - h_3)$

c. Applying what we found in part 2, the equation is simplified

   i. $\dot{W}_{TOTALout} = \dot{m}_3 \cdot (h_5 - h_6) + \dot{m}_3 \cdot (h_7 - h_8) + \dot{m}_{10} \cdot (h_{10} - h_{11}) - \dot{m}_{10} \cdot (h_2 - h_1) - \dot{m}_3 \cdot (h_4 - h_3)$

d. Combining this equation with $\dot{m}_{10} = \dot{m}_3 * (h3 - h9) / (h2 - h9)$, and solving for $\dot{m}_3$

   i. $\dot{m}_3 = 274.80$ kg/s

e. Solving for $\dot{m}_{10}$ after knowing the value for $\dot{m}_3$

   i. $\dot{m}_{10} = 214.23$ kg/s

4. For turbines

   a. $-\dot{W}_{out} = \dot{m} \cdot (h_2 - h_1)$

      i. $\dot{W}_{HPTout} = \dot{m}_3 \cdot (h_5 - h_6)$

      ii. **$\dot{W}_{HPTout}$ = 24091.81 kW**

      iii. $\dot{W}_{IPTout} = \dot{m}_3 \cdot (h_7 - h_8)$

      iv. **$\dot{W}_{IPTout}$ = 133621.77 kW**

      v. $\dot{W}_{LPTout} = \dot{m}_{10} \cdot (h_{10} - h_{11})$

      vi. **$\dot{W}_{LPTout}$ = 146914.69 kW**

5. For condenser pump and boiler pumps

   a. $-\dot{W}_{out} = \dot{m} \cdot (h_2 - h_1)$

      i. $\dot{W}_{CP,in} = \dot{m}_{10} \cdot (h_2 - h_1)$

      ii. **$\dot{W}_{CP,in}$ = 351.40 kW**

      iii. $\dot{W}_{BP,in} = \dot{m}_3 \cdot (h_4 - h_3)$

      iv. **$\dot{W}_{BP,in}$ = 4276.86 kW**

6. For boiler and reheater

a. Assumption: No heat or pressure loss in the boiler or the reheater

i. $\dot{Q}_{Boiler} = \dot{m}_3 \cdot (h_5 - h_4)$

ii. **$\dot{Q}_{Boiler}$ = 698880.69 kW**

iii. $\dot{Q}_{Reheater} = \dot{m}_3 \cdot (h_7 - h_6)$

iv. **$\dot{Q}_{Reheater}$ = 36512.66 kW**

7. Total Efficiency of the Plant

a. η= actual work out / heat into system

i. Work out was given as 300,000 kW

ii. Heat into system = $\dot{Q}_{Boiler} + \dot{Q}_{Reheater}$

iii. Heat into System = 735393.35 kW

b. η= 0.4080 = 40.80%

Appendix B: Trial 1 - Pressure 9250 kPa (Efficiency = 38.2%)

Yellow = varies between trials; Gray = not calculated isentropic state value

State	P (kPa)	T (℃)	v (m3/kg)	h (kJ/kg)	s (kJ/kh*K)	x (Quality)
1	6.9	38.73	0.0010074	162.25	0.5555	
2s	9250			171.52992	0.5555	
2a	9250	40.5	0.0010040	177.7165	0.5753	
3	9250	305.32	0.0014266	1374.9	3.3054	
4s	12100			1378.9594	3.3054	
4a	12100	306.9	0.0014203	1379.9743	3.3074	
5	12100	490	0.0260691	3321.5	6.4496	
6s	8620			3218.3575	6.4496	
6a	8620	438.7	0.0343761	3233.8289	6.4715	
7	8620	490	0.0378916	3366.7	6.6518	
8s	9250			3389.96	6.6518	
8a	9250	501.1	0.0357910	3386.9362	6.6479	
9	9250	501.1	0.0357910	3386.9362	6.6479	
10	9250	501.1	0.0357910	3386.9362	6.6479	
11s	6.9			2062.3628	6.6479	
11a	6.9	38.73	16.666667	2208.0659	7.1151	0.8492

W_{out} (kW)		W_{in} (kW)		Q_{in} (kW)		Mass flow rate (kg/s)	
HPT	33218.72	**CP**	3674.13	**Boiler**	735647.11	**ṁ total**	378.90
IPT	-7667.53	**BP**	1922.66	**R'Heater**	50345.07	**ṁ @ state 2**	237.55
LPT	280045.60					**ṁ @ state 9**	141.35

Appendix C: Trial 2 - Pressure 8620 kPa (Efficiency = 38.4%)

Yellow = varies between trials; Gray = not calculated isentropic state value

State	P (kPa)	T (℃)	v (m3/kg)	h (kJ/kg)	s (kJ/kh*K)	x (Quality)
1	6.9	38.73	0.0010074	162.25	0.5555	
2s	8620			170.89751	0.5555	
2a	8620	40.4	0.0010044	176.6625	0.5739	
3	8620	300.27	0.0014053	1346.27	3.2573	
4s	12100			1351.1738	3.2573	
4a	12100	302.1	0.0013985	1352.3998	3.2596	
5	12100	490	0.0260691	3321.5	6.4496	
6s	8620			3218.3575	6.4496	
6a	8620	438.7	0.0343761	3233.8289	6.4715	
7	8620	490	0.0378916	3366.7	6.6518	
8s	8620			3366.7	6.6518	
8a	8620	490	0.0378916	3366.7	6.6518	
9	8620	490	0.0378916	3366.7	6.6518	
10	8620	490	0.0378916	3366.7	6.6518	
11s	6.9			2063.5792	6.6518	
11a	6.9	38.73	16.666667	2206.9225	7.1114	0.8488

W_{out} (kW)		W_{in} (kW)		Q_{in} (kW)		Mass flow rate (kg/s)	
HPT	32592.89	**CP**	3393.55	**Boiler**	732038.97	**ṁ total**	371.76
IPT	0	**BP**	2278.83	**R'Heater**	49496.58	**ṁ @ state 2**	235.46
LPT	27309.49					**ṁ @ state 9**	136.30

Appendix D: Trial 3 - Pressure 8000 kPa (Efficiency = 38.6%)

Yellow = varies between trials; Gray = not calculated isentropic state value

State	P (kPa)	T (℃)	v (m3/kg)	h (kJ/kg)	s (kJ/kh*K)	x (Quality)
1	6.9	38.73	0.0010074	162.25	0.5555	
2s	8000			170.27496	0.5555	
2a	8000	40.2	0.0010045	175.6249	0.5276	
3	8000	295.01	0.0012847	1310.08	3.2077	
4s	12100			1322.7723	3.2077	
4a	12100	297	0.0013771	1324.1954	3.2103	
5	12100	490	0.0260691	3321.5	6.4496	
6s	8620			3218.3575	6.4496	
6a	8620	438.7	0.0343761	3233.8289	6.4715	
7	8620	490	0.0378916	3366.7	6.6518	
8s	8000			3343.5658	6.6518	
8a	8000	478.5	0.0402576	3345.7032	6.656	
9	8000	478.5	0.0402576	3345.7032	6.656	
10	8000	478.5	0.0402576	3345.7032	6.656	
11s	6.9			2064.8891	6.656	
11a	6.9	38.73	16.666667	2205.7787	7.1077	0.8483

W_{out} (kW)		W_{in} (kW)		Q_{in} (kW)		Mass flow rate (kg/s)	
HPT	31978.72	**CP**	3121.95	**Boiler**	728532.39	**ṁ total**	364.76
IPT	7658.75	**BP**	2595.40	**R'Heater**	48465.77	**ṁ @ state 2**	233.42
LPT	266079.89					**ṁ @ state 9**	131.34

Appendix E: Trial 4 - Pressure 3000 kPa (Efficiency = 40.4%)

Yellow = varies between trials; Gray = not calculated isentropic state value

State	P (kPa)	T (°C)	v (m3/kg)	h (kJ/kg)	s (kJ/kh*K)	x (Quality)
1	6.9	38.73	0.0010074	162.25	0.5555	2
2s	3000			165.24812	0.5555	
2a	3000	39.3	0.0010062	167.24687	0.562	
3	3000	233.86	0.0012167	1008.37	2.6456	
4s	12100			1019.3604	2.6456	
4a	12100	236.4	0.001209	1022.108	2.6508	
5	12100	490	0.0260691	3321.5	6.4496	
6s	8620			3218.3575	6.4496	
6a	8620	438.7	0.0343761	3233.8289	6.4715	
7	8620	490	0.0378916	3366.7	6.6518	
8s	3000			3059.1558	6.6518	
8a	3000	342.8	0.0892857	3099.1365	6.7176	
9	3000	342.8	0.0892857	3099.1365	6.7176	
10	3000	342.8	0.0892857	3099.1365	6.7176	
11s	6.9			2084.101	6.7176	
11a	6.9	38.73	16.666667	2195.7549	7.0756	0.8441

W_{out} (kW)		W_{in} (kW)		Q_{in} (kW)		Mass flow rate (kg/s)	
HPT	26779.46	CP	1088.43	Boiler	702357.66	ṁ total	305.45
IPT	81728.23	BP	4196.32	R'Heater	40585.96	ṁ @ state 2	217.82
LPT	196777.07					ṁ @ state 9	87.63

Appendix F: Trial 5 - Pressure 2000 kPa (Efficiency = 40.7%)

Yellow = varies between trials; Gray = not calculated isentropic state value

State	P (kPa)	T (°C)	v (m3/kg)	h (kJ/kg)	s (kJ/kh*K)	x (Quality)
1	6.9	38.73	0.0010074	162.25	0.5555	
2s	2000			164.24139	0.5555	
2a	2000	39.1	0.0010065	165.56898	0.5599	
3	2000	212.38	0.0011767	908.62	2.4470	
4s	12100			920.42624	2.4470	
4a	12100	214.9	0.0011697	923.4028	2.4531	
5	12100	490	0.0260691	3321.5	6.4496	
6s	8620			3218.3575	6.4496	
6a	8620	438.7	0.0343761	3233.8289	6.4715	
7	8620	490	0.0378916	3366.7	6.6518	
8s	2000			2958.9938	6.6518	
8a	2000	294.7	0.1240695	3011.9956	6.747	
9	2000	294.7	0.1240695	3011.9956	6.747	
10	2000	294.7	0.1240695	3011.9956	6.747	
11s	6.9			2093.2704	6.747	
11a	6.9	38.73	16.666667	2194.3302	7.071	0.8435

W_{out} (kW)		W_{in} (kW)		Q_{in} (kW)		Mass flow rate (kg/s)	
HPT	25551.24	**CP**	714.79	**Boiler**	698911.58	**ṁ total**	291.44
IPT	103376.55	**BP**	4308.36	**R'Heater**	38724.51	**ṁ @ state 2**	215.36
LPT	176095.37					**ṁ @ state 9**	76.08

Appendix G: Trial 6 - Pressure 1000 kPa (Efficiency = 40.8%)

Yellow = varies between trials; Gray = not calculated isentropic state value

State	P (kPa)	T (℃)	v (m3/kg)	h (kJ/kg)	s (kJ/kh*K)	x (Quality)
1	6.9	38.73	0.0010074	162.25	0.5555	
2s	1000			163.2342	0.5555	
2a	1000	38.9	0.0010073	163.8903	0.5578	
3	1000	179.89	0.0011272	762.68	2.1384	
4s	12100			775.13095	2.1384	
4a	12100	182.1	0.0011211	778.24369	2.1454	
5	12100	490	0.0260691	3321.5	6.4496	
6s	8620			3218.3575	6.4496	
6a	8620	438.7	0.0343761	3233.8289	6.4715	
7	8620	490	0.0378916	3366.7	6.6518	
8s	1000			2807.7859	6.6518	
8a	1000	222.1	0.2183406	2880.4473	6.8003	
9	1000	222.1	0.2183406	2880.4473	6.8003	
10	1000	222.1	0.2183406	2880.4473	6.8003	
11s	6.9			2109.8937	6.8003	
11a	6.9	38.73	16.666667	2194.6546	7.0721	0.8437

W_{out} (kW)		W_{in} (kW)		Q_{in} (kW)		Mass flow rate (kg/s)	
HPT	24091.81	**CP**	351.40	**Boiler**	698880.69	**ṁ total**	274.80
IPT	133621.77	**BP**	4276.86	**R'Heater**	36512.66	**ṁ @ state 2**	214.23
LPT	146914.69					**ṁ @ state 9**	60.57

Appendix H: Trial 7 - Pressure 500 kPa (Efficiency = 40.4%)

Yellow = varies between trials; Gray = not calculated isentropic state value

State	P (kPa)	T (°C)	v (m3/kg)	h (kJ/kg)	s (kJ/kh*K)	x (Quality)
1	6.9	38.73	0.0010074	162.25	0.5555	
2s	500			162.73043	0.5555	
2a	500	38.8	0.0010072	163.05071	0.5567	
3	500	151.84	0.0010926	640.19	1.8606	
4s	12100			652.82435	1.8606	
4a	12100	153.9	0.0010871	655.98293	1.8682	
5	12100	490	0.0260691	3321.5	6.4496	
6s	8620			3218.3575	6.4496	
6a	8620	438.7	0.0343761	3233.8289	6.4715	
7	8620	490	0.0378916	3366.7	6.6518	
8s	500			2676.3782	6.6518	
8a	500	159.5	0.3831418	2766.1200	6.8826	
9	500	159.5	0.3831418	2766.1200	6.8826	
10	500	159.5	0.3831418	2766.1200	6.8826	
11s	6.9			2135.5616	6.8826	
11a	6.9	38.73	16.666667	2204.9230	7.105	0.8479

W_{out} (kW)		W_{in} (kW)		Q_{in} (kW)		Mass flow rate (kg/s)	
HPT	23272.74	**CP**	173.59	**Boiler**	707575.18	**ṁ total**	265.46
IPT	159427.03	**BP**	4192.32	**R'Heater**	35271.32	**ṁ @ state 2**	216.80
LPT	121666.12					**ṁ @ state 9**	48.66