Indian Institute of Technology Gandhinagar

ES211 PROJECT 1 REPORT

ES211 Project Report

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1. Introduction

Project Objective:

The goal of this project is to elevate the performance of the power plant by modifying the existing ideal Rankine cycle. The set targets include surpassing the current thermal efficiency of 41% and raising the steam quality to above 85%. To achieve these objectives, enhancements must be implemented while adhering to specific constraints. These constraints mandate the maintenance of the boiler pressure (Pb) and condenser pressure (Pc) at 15 MPa and 10 kPa, respectively. Furthermore, it is crucial to ensure that the turbine temperature does not exceed 500 °C during the modification process.

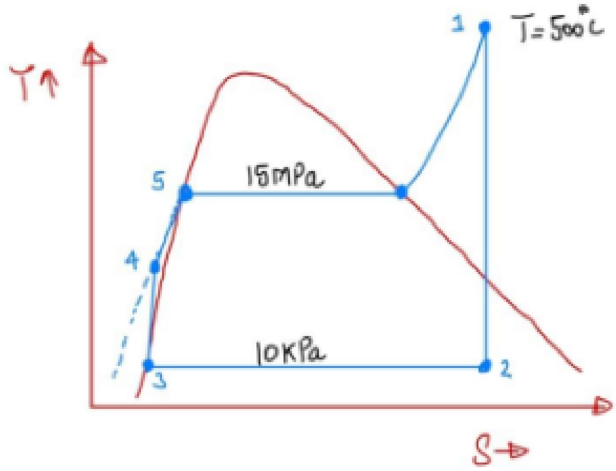
Power plants are essential components of our energy infrastructure, and optimizing their performance is crucial for both economic and environmental reasons. In the context of this project, our task is to enhance the efficiency and steam quality of a power plant operating on the basic ideal Rankine cycle. Currently, the cycle exhibits a thermal efficiency of 41% and a steam quality of 76%.

The ideal Rankine cycle is a theoretical framework representing a common method of power generation. It consists of four main components: a boiler, a turbine, a condenser, and a pump. Steam is generated in the boiler, expanded through the turbine, condensed in the condenser, and then compressed back to the boiler pressure by the pump. While the ideal Rankine cycle provides a foundation for understanding power generation, its practical implementation often requires modifications to meet specific performance targets.

Traditionally, to enhance the efficiency and steam quality of a Rankine cycle, engineers adjust parameters such as boiler pressure, condenser pressure, and turbine temperature. However, in this particular project, we face a unique challenge — we are mandated to keep the boiler pressure and condenser pressure fixed at 15 MPa and 10 kPa, respectively, and the turbine temperature below 500 °C.

Under these constraints, the typical approaches of increasing boiler pressure or decreasing condenser pressure are not viable. Instead, we turn to alternative strategies, such as reheating and regenerative closed and open feedwater heating, to achieve our performance goals. These techniques involve introducing additional components and processes to the cycle, providing new avenues for improving efficiency and steam quality without violating the specified restrictions.

In the sections that follow, we will delve into the modifications made to the ideal Rankine cycle, exploring how reheating and feedwater heating contribute to achieving a thermal efficiency exceeding 46% and a steam quality surpassing 85%. Additionally, we will investigate the impact of varying boiler and condenser pressures within defined ranges to optimize the performance of the modified Rankine cycle.



T-s diagram of the ideal Rankine cycle

2. Assumptions for Modified Rankine Cycle

1. **General Assumptions:**

   1.) Steady Operating Conditions:

   We assume that the power plant operates under steady-state conditions, implying a constant and uniform flow of working fluid through the cycle.

   2.) Negligible Kinetic and Potential Energy Changes:

   Changes in kinetic and potential energy are considered negligible. This assumption simplifies the analysis, focusing on the primary components and processes without accounting for the variations in kinetic or potential energy.

2. **Assumptions for the Modified Rankine Cycle:**

   1.) Isentropic Processes:

   We assume that the expansion and compression processes in the turbine and pump, respectively, are isentropic. This implies that the working fluid undergoes reversible adiabatic processes, allowing for simplified calculations and analysis.

   2.) No Pressure Drops in Heat Exchangers:

   We neglect pressure drops in the heat exchangers, assuming that the pressures at the inlet and outlet of these components are the same. While this simplification may not hold true in real-world scenarios, it is a common assumption in idealized thermodynamic cycles.

3. **Additional Assumptions for Reheating and Regenerative Feedwater Heating:**

   1.) Reheating Process:

   For the reheating process, we assume ideal conditions, where steam is expanded isentropically in the high-pressure turbine, then reheated to the maximum temperature allowed before entering the low-pressure turbine. The reheating process adds complexity to the cycle but enables better efficiency by mitigating the negative effects of moisture content.

   2.) Regenerative Feedwater Heating:

   In both open and closed feedwater heaters, we assume that feedwater is heated to the saturation temperature at the feedwater heater pressure. This assumption simplifies the calculation of the amount of heat transferred to the feedwater.

3. Modified Rankine cycle

Modified Rankine Cycle with Reheating and Regenerative Feedwater Heating

To achieve the specified goals of increasing the efficiency to over 46% and raising steam quality to above 85%, our project introduces modifications to the basic ideal Rankine cycle. In our enhanced configuration, we employ three turbines and two reheating stages, along with regenerative feedwater heating, to optimize the cycle's performance.

key Modifications:

Three-Turbine Configuration:

We incorporate three turbines to improve the overall efficiency. The high-pressure turbine (Turbine 1) is followed by two additional turbines (Turbines 2 and 3) to extract additional work from the expanding steam.

Reheating Stages:

Reheating is introduced to mitigate the effects of moisture content in the steam, enhancing the overall efficiency of the cycle. Steam from the high-pressure turbine (Turbine 1) after splitting is passed through a reheater before entering the low-pressure turbine (Turbine 2), and similarly, steam from Turbine 2 is passed through a reheater before entering Turbine 3 we are using 3 turbines and 2 reheating just to obtain the desired efficiency and

Regenerative Feedwater Heating:

We implement both closed and open feedwater heaters to preheat the feedwater before entering the boiler. A portion of the steam extracted from Turbine 1 is directed to the closed feedwater heater, while another portion from Turbine 3 is sent to the open feedwater heater.

Steam Splitting and Pressure Selection:

1. Closed Feedwater Heater:

   To achieve efficient closed feedwater heating, we split a portion of the steam from Turbine 1. The split stream is then directed to the closed feedwater heater, where it transfers heat to the feedwater. We strategically chose the pressure for this split stream to be 4 MPa, ensuring that it is lower than the boiler pressure (15 MPa) but still high enough to provide effective feedwater heating.

2. Open Feedwater Heater:

   Another portion of the steam from Turbine 3 is split and directed to the open feedwater heater. This split occurs at a pressure of 0.5 MPa, which is higher than the condenser pressure (10 kPa) but lower than the closed feedwater heater pressure. This choice optimizes the efficiency by utilizing the available pressure differentials.

Pressure Selection Rationale:

1. Closed Feedwater Heater Pressure (4 MPa):

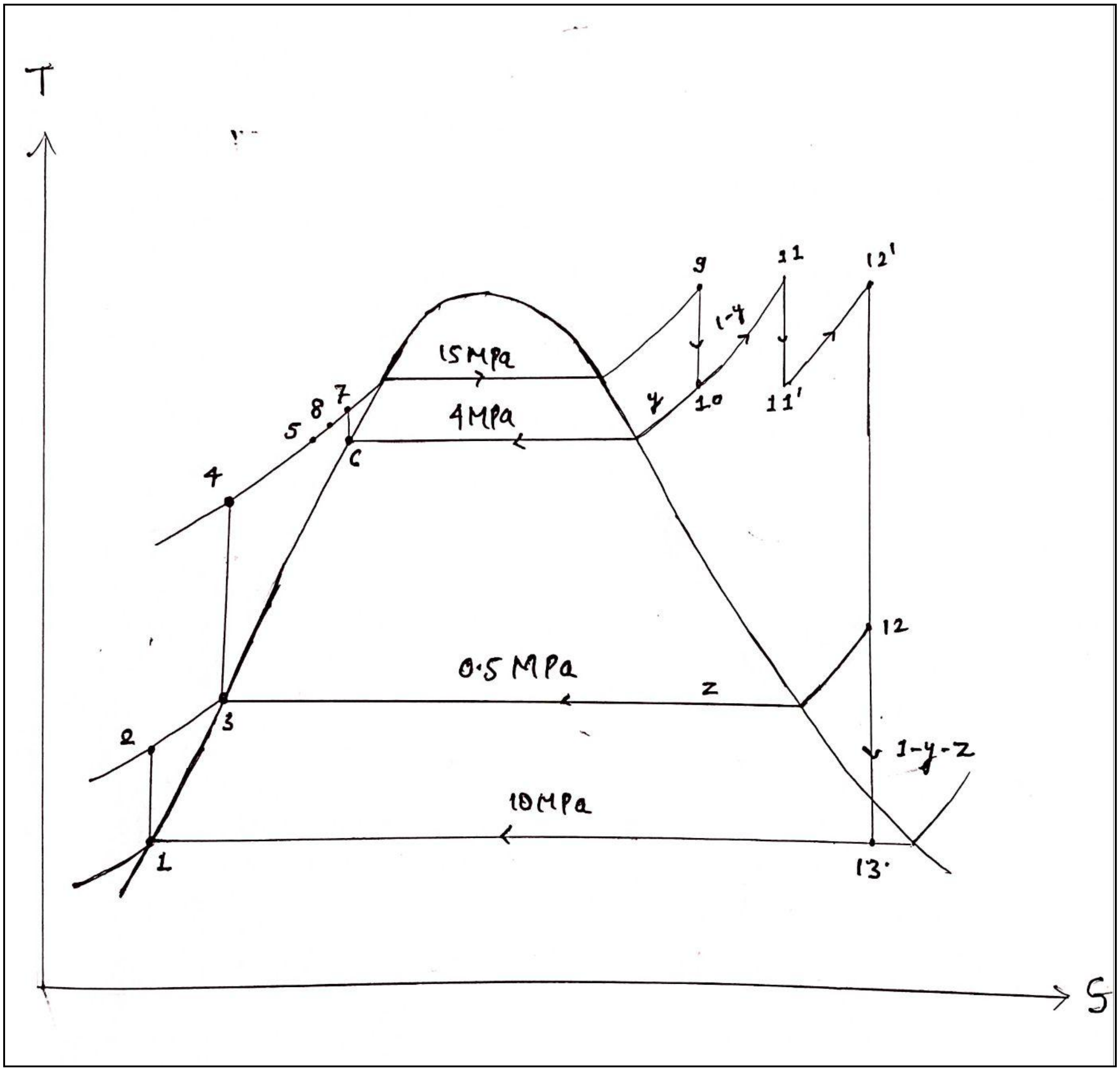
   By selecting 4 MPa for the closed feedwater heater split, we strike a balance between effective feedwater heating and ensuring the pressure remains below the boiler pressure. This facilitates efficient heat transfer while adhering to the project constraints.

2. Open Feedwater Heater Pressure (0.5 MPa):

   The 0.5 MPa pressure for the open feedwater heater split ensures that it is above the condenser pressure, allowing for effective heating without compromising the overall cycle performance. This pressure choice aligns with the project objectives and the available equipment specifications.

   These modifications collectively contribute to achieving the desired thermal efficiency exceeding 46% and steam quality surpassing 85%. Through careful design and pressure selection, we optimize the cycle's performance while adhering to the constraints outlined in the project requirements.

4. Modified Rankine cycle T-s diagram



This T-s diagram shows the modified Rankine cycle

Step-by-Step description of the modified Rankine cycle

State 1 to State 2: Compression in Pump 1

Steam at State 1 undergoes compression by Pump 1.

Results in Steam at State 2.

State 2 to State 3: Mixing in Open Feedwater Heater

Steam from State 2 mixes with the steam from State 12 in the open feedwater heater.

Reaches State 3, where its temperature is increased.

State 3 to State 4: Compression in Pump 2

Pump 2 compresses the steam from State 3.

Reaches State 4.

State 4 to State 5: Closed Feedwater Heater

Steam at State 4 goes into a closed feedwater heater.

Temperature increases by heat exchange with steam from State 10.

Results in Steam at State 5.

State 6 to State 7: Compression to Saturation Curve

Steam at State 6 is compressed by Pump 3.

Reaches State 7, which is on the saturation curve.

Pressure at State 7 becomes equal to that of State 5.

States 5 and 7 Mixing to State 8

Steam from State 5 and State 7 are mixed in the mixing chamber.

Reaches State 8.

State 8 to State 9: Heating in Boiler

Steam at State 8 is put into the boiler at 15 Mpa pressure.

Gains heat and reaches State 9.

Heating is carried out in multiple stages to increase cycle efficiency.

State 9 to State 10: Turbine and First Reheating

Turbine expands the steam from State 9 to State 10.

Steam splits at State 10 for the closed feedwater heater, and one goes to Turbine 2 at State 11.

State 11 to 11 prime: Turbine 2 and second Reheating

Steam from State 11 goes to 11 prime.

State 11 prime has a pressure of 2 MPa, chosen for reheating.

11prime to State 12prime: Third Reheating

Steam from 12prime goes into Turbine 3.

State 12 prime to States 12 and 13: Turbine 3 Splitting

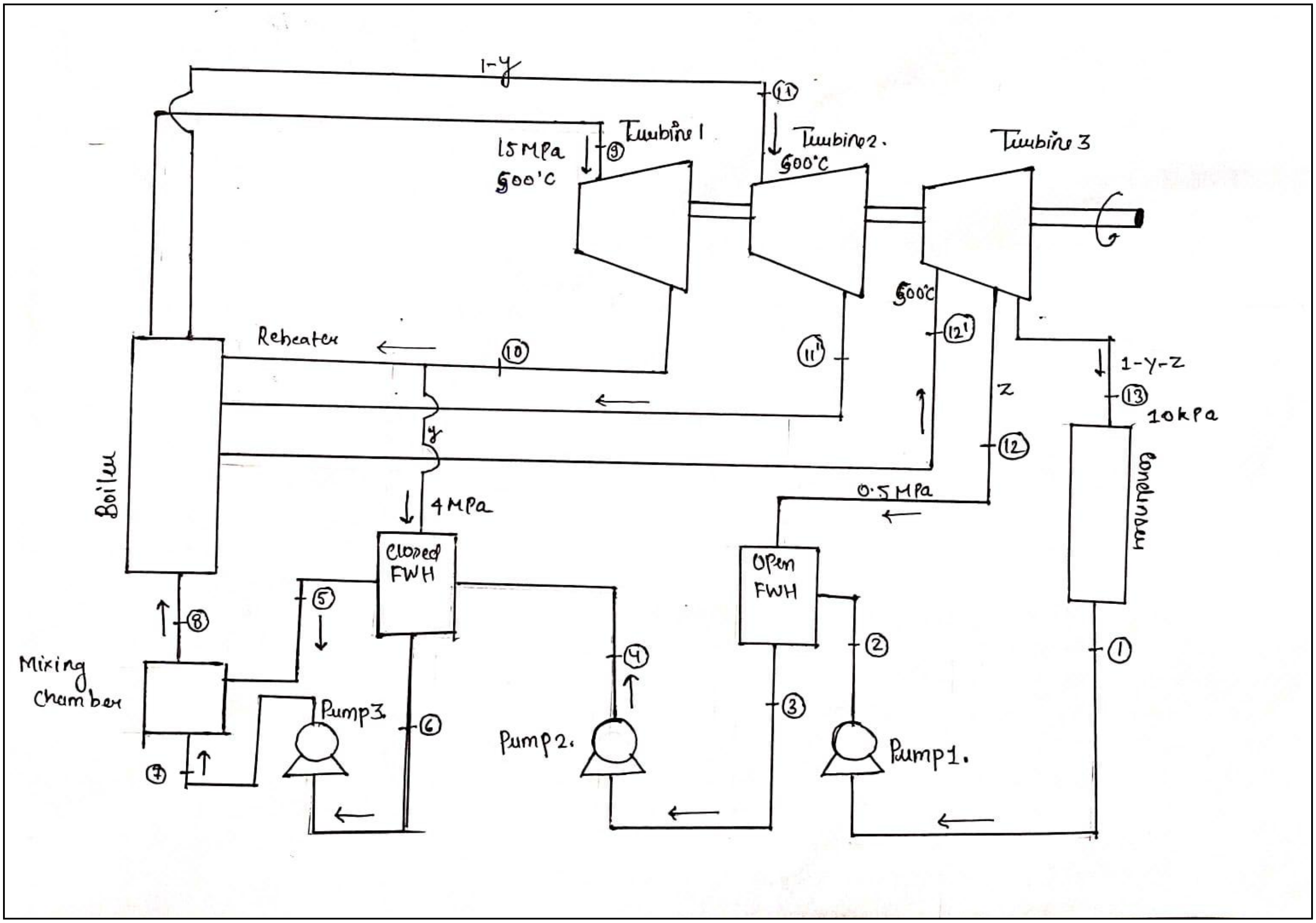
Steam at State 12 splits.

One goes to the open feedwater heater.

The other goes to the condenser at State 13.

State 13 to State 1: condenser

Condenses the steam at 10 kpa.



Schematic for the modified Rankine cycle

States defined on the rankine cycle

State 1

$P_1 = 10\ kPa$ $\quad$ S_1 = specific entropy

Saturated Liquid $(x=0)$ $\quad$ h_1 = specific enthalpy

State 2

$P_2 = 0.5MPa$ $\quad$ S_2 = specific entropy

$S_2 = S_1$ $\quad$ h_2 = specific enthalpy

State 3

$P_3 = 0.5MPa$ $\quad$ S_3 = specific entropy

Saturated Liquid $(x=0)$ $\quad$ h_3 = specific enthalpy

State 4

$P_4 = 15MPa$ $\quad$ S_4 = specific entropy

$S_4 = S_3$ $\quad$ P_4 = specific enthalpy

State 6

$P_6 = 4MPa$ $\quad$ T_6 = Temperature

Saturated Liquid $(x=0)$ $\quad$ S_6 = specific entropy

h_6 = specific enthalpy

S~~a~~tate 5

$P_5 = 15MPa$ $\quad$ h_5 = specific enthalpy

$T_5 = T_6$ $\quad$ S_5 = specific entropy.

State 7

$P_7 = 15\,MPa$ h_7 = specific enthalpy

$S_7 = S_6$ s_7 = specific entropy

state 9

$P_9 = 15\,MPa$ h_9 = specific enthalpy

$T_9 = 500°C$ s_9 = specific entropy

State 10

$P_{10} = 4\,MPa$ h_{10} = specific enthalpy

$S_{10} = S_9$ S_{10} = specific entropy

State 11

$P_{11} = 4\,MPa$ S_{11} → specific entropy

$T_{11} = 500°C$ h_{11} → specific enthalpy

State 11'

$S_{11'} = S_{11}$ $S_{11'}$ = specific entropy

$P_{11'} = 2\,MPa$ $h_{11'}$ = specific enthalpy

State 12'

$P_{12'} = P_{11'}$ $S_{12'}$ = specific entropy

$T_{12'} = 500°C$ $h_{12'}$ = specific enthalpy

State 12

$P_{12} = P_3 = 0.5\,MPa$

$S_{12} = S_{121}$

h_{12} = specific enthalpy

S_{12} = specific entropy

State 13

$S_{13} = S_{12}$

$P_{13} = 10\,kPa$

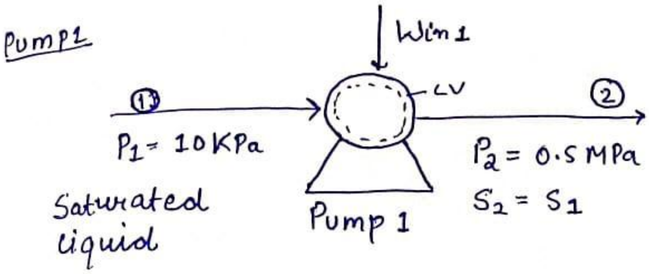
h_{13} = specific enthalpy

S_{13} = specific entropy

5. Energy balance equation

Energy Balances

Pump1



$h_1 \rightarrow$ specific enthalpy at 1
$h_2 \rightarrow$ specific enthalpy at 2

fraction of steam fed into pump 1 = $1 - y - z$

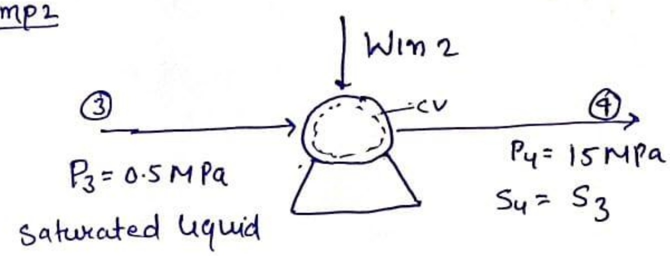
$s_1 \rightarrow$ specific entropy at 1
$s_2 \rightarrow$ specific entropy at 2

$S_2 = S_1$ (Isentropic)

$$W_{in,1} + (1-y-z)h_1 = (1-y-z)h_2$$

$$W_{in\,1} = (1-y-z)(h_2 - h_1)$$

Pump2



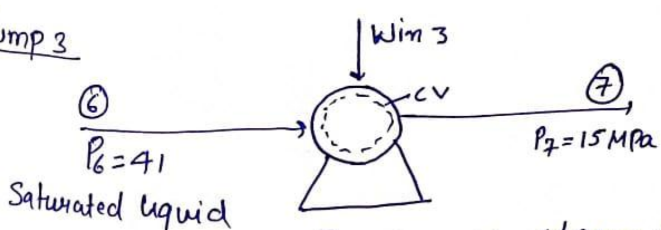
$h_3 \rightarrow$ specific enthalpy at 3
$h_4 \rightarrow$ specific enthalpy at 4
$s_3 \rightarrow$ specific entropy at 3
$s_4 \rightarrow$ specific entropy at 4

fraction of steam fed into pump 2 = $(1-y)$

$$W_{in\,2} + (1-y)h_3 = (1-y)h_4$$

$$W_{in\,2} = (1-y)(h_4 - h_3)$$

Pump 3



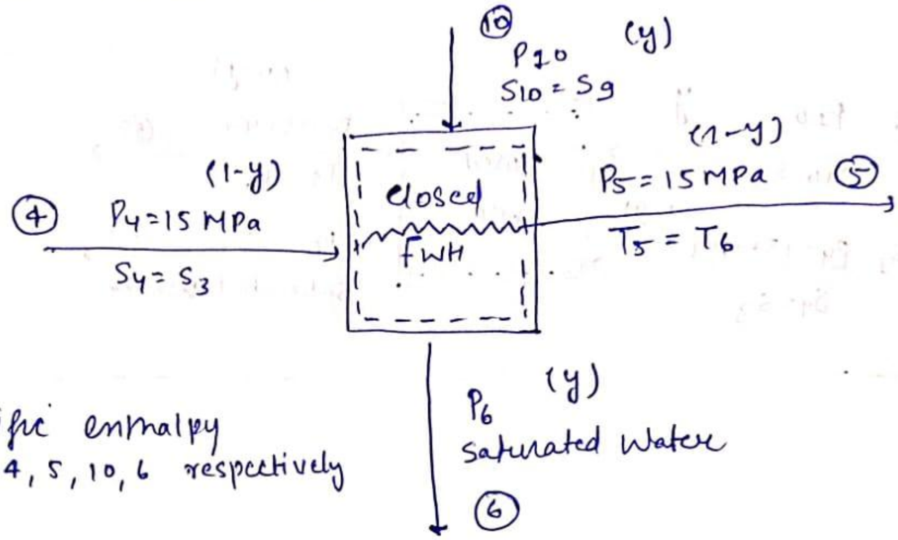
$h_6 \rightarrow$ specific enthalpy at 6
$h_7 \rightarrow$ specific enthalpy at 7
$s_6 \rightarrow$ specific entropy at 6
$s_7 \rightarrow$ specific entropy at 7

Fraction of steam feel into pump 3 = y

$$W_{in\,3} + y h_6 = y h_7$$

$$W_{in\,3} = y(h_7 - h_6)$$

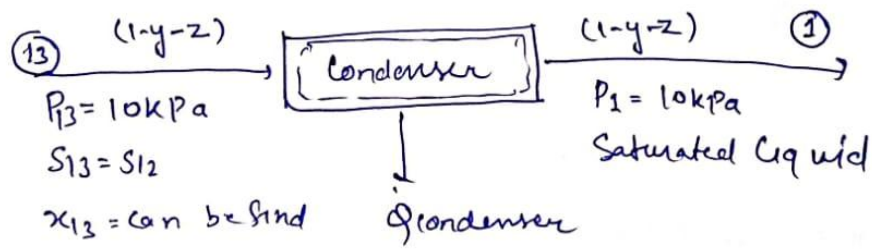
Closed feed water heater



h_4, h_5, h_{10}, h_6] specific enthalpy at 4, 5, 10, 6 respectively

$$(1-y)h_5 - (1-y)h_4 = y h_{10} - y h_6$$
$$(1-y)(h_5-h_4) = y(h_{10}-h_6)$$
$$y = \frac{(h_5-h_4)}{(h_{10}-h_6)+(h_5-h_4)}$$

Condenser

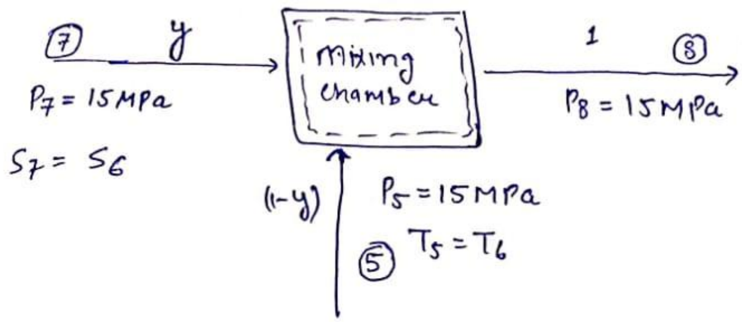


h_1, h_{13} = specific enthalpy at 1, 13 respectively.

$$\dot{Q}_{condenser} + (1-y-z)h_1 = (1-y-z)h_{13}$$

$$\dot{Q}_{condenser} = (1-y-z)(h_{13}-h_1)$$

Mixing Chamber

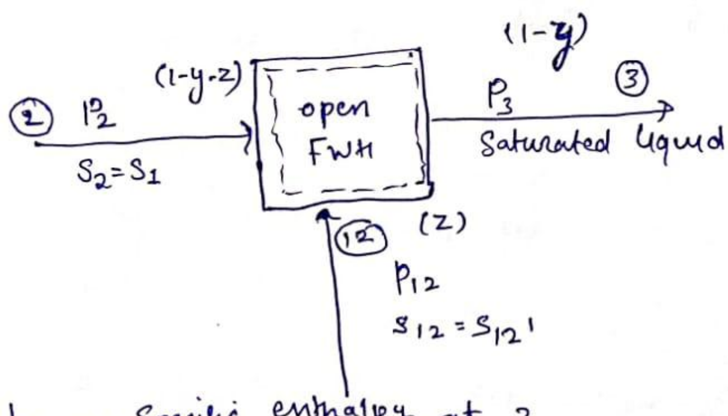


$h_7 \rightarrow$ specific enthalpy at 7
$h_8 \rightarrow$ specific enthalpy at 8
$h_5 \rightarrow$ specific enthalpy at 5

$$(1-y)h_5 + y h_7 = 1 \cdot h_8$$

$$h_8 = (1-y)h_5 + y h_7$$

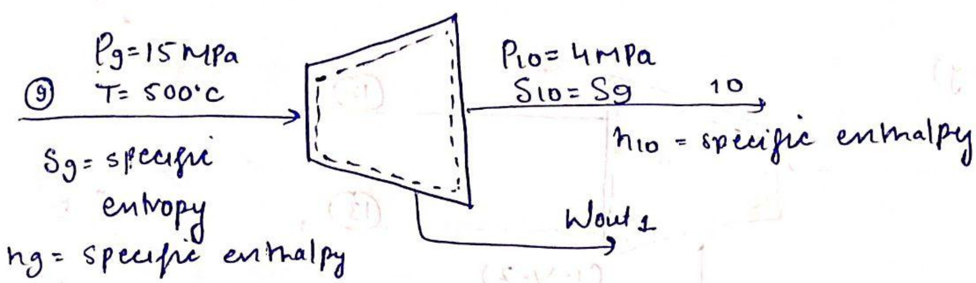
open feed Water heater



$h_2 \rightarrow$ Specific enthalpy at 2
$h_3 \rightarrow$ specific enthalpy at 3
$h_{12} \rightarrow$ Specific enthalpy at 12

$$(1-y-z)h_2 + (z)h_{12} = (1-y)h_3$$

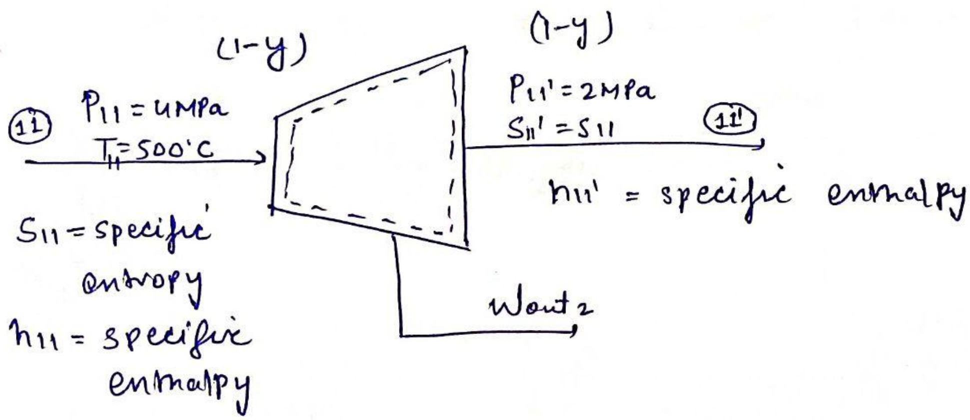
Turbine 1



$$W_{out1} + h_{10} = h_9$$

$$W_{out1} = h_9 - h_{10}$$

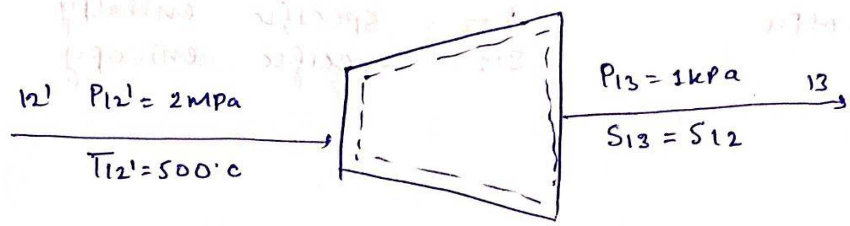
Turbine 2



$$W_{out2} + (1-y)\,h_{11'} = (1-y)\,h_{11}$$

$$W_{out2} = (1-y)(h_{11} - h_{11'})$$

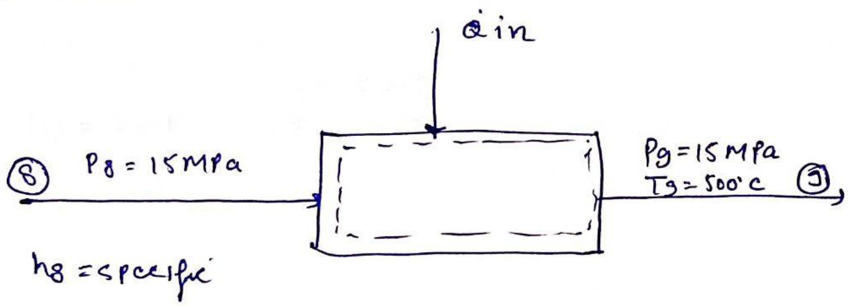
Turbine 3



$$\dot{W}out_3 = (1-y)(h_{12'} - h_{12}) + (1-y-z)(h_{12} - h_{13})$$

$$W_{out} = W_{out\,1} + W_{out\,2} + W_{out\,3}$$

Boiler



$$\dot{Q}in = (h_9 - h_8) + (1-y)(h_{11} - h_{10}) + (1-y)(h_{12'} - h_{11'})$$

$$\eta = \frac{W_{out} - W_{in}}{Q_{in}}$$

Specific enthalpy values at all states

Specific Enthalpy	Values (in J/kg)
h_1	-1.5779e+07
h_2	-1.5778e+07
h_3	-1.5330e+07
h_4	-1.5315e+07
h_5	-1.4883e+07
h_6	-1.4883e+07
h_7	-1.4870e+07
h_8	-1.4880e+07
h_9	-1.2662e+07
h_{10}	-1.3020e+07
h_{11}	-1.2526e+07
h_{12}	-1.2923e+07
h_{13}	-1.3615e+07
h'_{11}	-1.2748e+07
h'_{12}	-1.2503e+07

Formulas for calculating net work done and efficiency

$W_{out} = (h_9 - h_{10}) + (1\text{-y})\times\ (h_{11} - h'_{11}) + (1\text{-y})\times\ (h'_{12} - h_{12}) + \ (1 - y - z)\times\ (h_{12} - h_{13})$

$W_{in} = (1 - y - z)\times\ (h_2 - h_1)\ +\ (1 - y)\times\ (h_4 - h_3) + (y)\times\ (h_7 - h_6)$

$Q_{in} = (h_9 - h_8) + (1\text{-y})\times\ (h_{11} - h_{10}) + (1\text{-y})\times\ (h'_{12} - h'_{11})$

$\eta = (W_{out} - W_{in}) / (q_{in})$

Results & Conclusion

In the modified rankine cycle

thermal efficiency = 47.45%

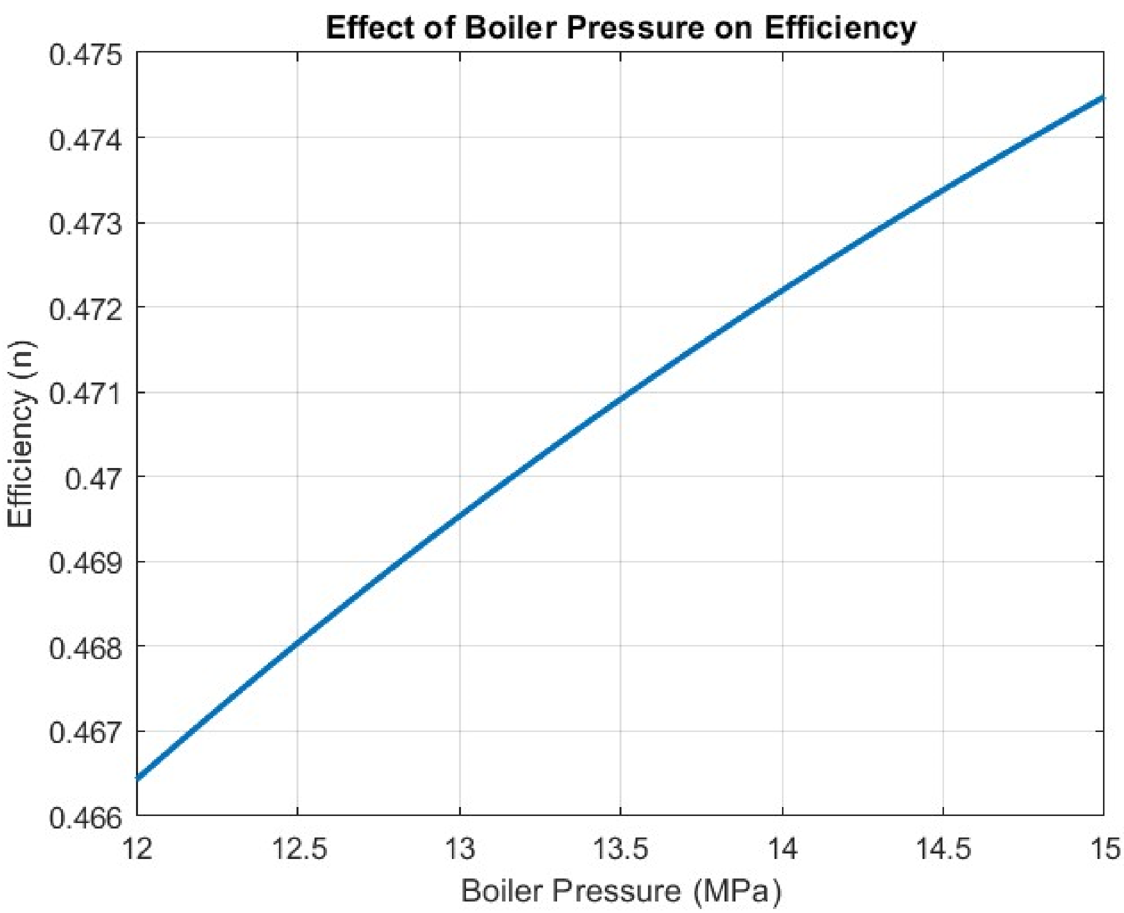
Steam quality = 90.42%

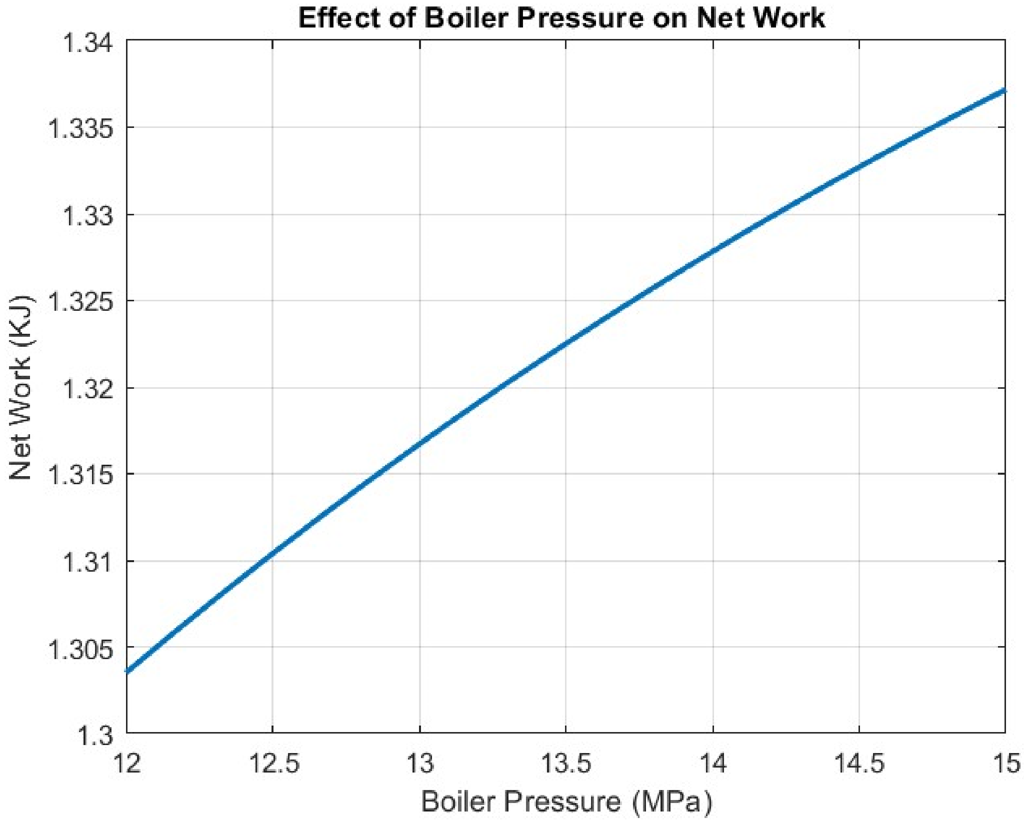
In our analysis of the developed modified Rankine cycle, efficiency and steam quality were computed using Cantera and MATLAB. The results indicate that the modified Rankine cycle achieves an efficiency of 47.45% and a steam quality of 90.42% at the condenser inlet. With an efficiency surpassing 46% and a steam quality exceeding 85%, our objectives for the modified Rankine cycle have been successfully met. These findings affirm the efficacy and superior performance of the proposed modifications to the Rankine cycle.

6. Part B

You need to vary the boiler pressure (Pb) and condenser pressure (Pc) within the ranges of 12 MPa< Pb < 15 MPa and 5 kPa < Pc < 10 kPa. Then, create a plot that illustrates how changes in this pressure impact the thermal efficiency and net work output of the modified ideal Rankine cycle.

Initially, we maintained a constant condenser pressure at 10 kPa and systematically adjusted the boiler pressure within the specified range. Employing MATLAB, we generated plots illustrating the impact of varying boiler pressure on the efficiency and net work output of the modified Rankine cycle.





Through our analysis, we noted a consistent trend: by keeping the condenser pressure constant and progressively elevating the boiler pressure, both the efficiency and net work output of the Rankine cycle increases.

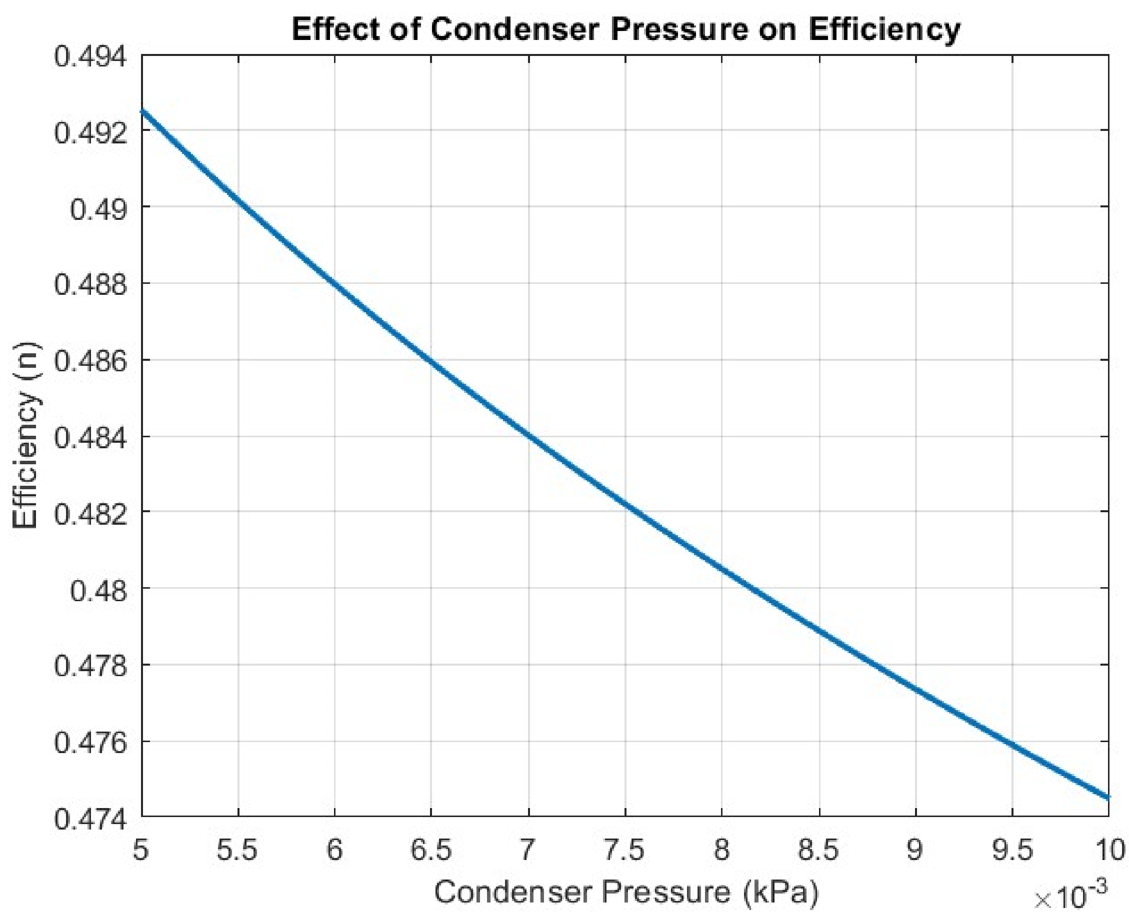
Efficiency in a Rankine cycle, defined as the net work output divided by the heat input, demonstrates improvement with increasing boiler pressure. This is attributed to several factors:

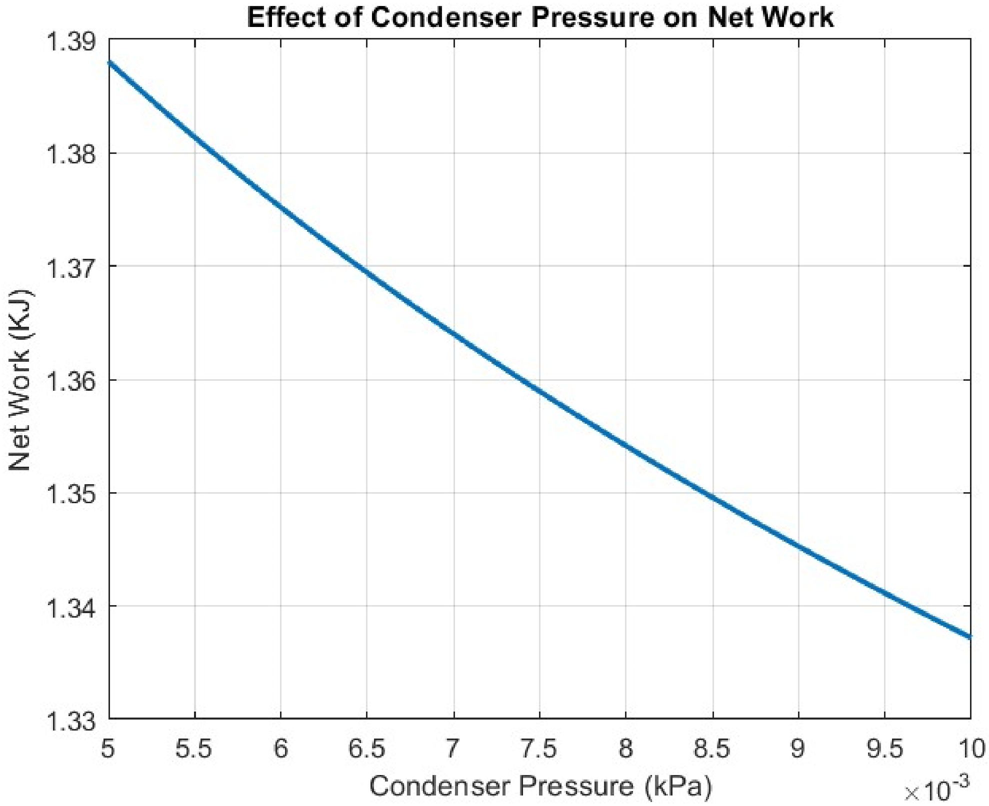
- The elevated temperature of steam at the turbine inlet (State 5) leads to a higher work output during the expansion in the turbine (State 5 to State 6).
- The expanded temperature difference between the heat source (boiler) and the heat sink (condenser) enhances the overall efficiency of the cycle.

Hence, the efficiency (n) increases with a higher boiler pressure. A similar observation holds for the net work done in a Rankine cycle, which is the difference between work output and work input. The specific points include:

- The work output in the turbine rises due to the higher enthalpy of steam entering the turbine at State 5.
- Although additional work input is required to pump the working fluid from the condenser to the boiler, the overall trend leans towards an increase in net work done.

Then, we maintained a constant Boiler pressure at 15 MPa and systematically adjusted the condenser pressure within the specified range. Employing MATLAB, we generated plots illustrating the impact of varying condenser pressure on the efficiency and net work output of the modified Rankine cycle.





In our analysis, we noted a consistent trend when maintaining a constant boiler pressure and progressively increasing the condenser pressure in the Rankine cycle.
When we increase the condenser pressure both efficiency and net work done decreases.
This adjustment positively influences both the efficiency and net work output of the cycle. The condenser pressure, denoted as P1, emerges as a critical parameter affecting the efficiency of the Rankine cycle. Elevated condenser pressures typically result in a higher temperature at the condenser exit (State 1), consequently reducing the temperature difference between the heat source (boiler) and the heat sink (condenser). The net work done in a Rankine cycle, representing the difference between work output and work input, is significantly influenced by condenser pressure. An increase in condenser pressure can impact the enthalpy of the working fluid at the condenser exit (State 1), affecting the work input and, consequently, the overall net work done. Specifically, higher condenser pressures may contribute to the extraction of less work in the turbine (States 5 to 6), resulting in a potential decrease in net work done.

Drive link for all the matlab codes:

https://drive.google.com/drive/folders/1sYNu3MRfuiTVadqD7FrOATw-bJneCI9S?usp=sharing

7. Citation

1. *Çengel, Yunus A, Michael A Boles, and Mehmet Kanoglu. 2019. Thermodynamics : An Engineering Approach. 9th ed. New York: Mcgraw-Hill Education.*
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4. *"ES 211 - Thermodynamics - YouTube." n.d. Www.youtube.com. Accessed November 21, 2023. https://youtube.com/playlist?list=PLRfu94TCePTuKcMfv9OWtwJSrnNlrgKnT&si=FBZiSVhYWefWtrNd.*

8. Acknowledgement:

I would like to express my deepest gratitude to Professor Atul Bhargav for his invaluable guidance and unwavering support throughout the course of our project. Professor Bhargav's expertise in thermodynamics has been instrumental in shaping the direction and success of our endeavor to enhance the efficiency of the Rankine cycle.