# Indian Institute of Technology Gandhinagar

## <u>ES 211</u>

## THERMODYNAMICS

<u>COURSE PROJECT REPORT</u>

**Project Title**: IMPROVING THE EFFICIENCY OF RANKINE CYCLE


| | |
|---|---|
| 22110152 | Mihika Desai |
| 22110172 | Nishit Mistry |
| 22110276 | Vatsal Trivedi |
| 22110278 | Utkarsh Srivastava |
| 22110286 | Vidhi Shah |


20 Nov 2023

**Mentored by-**
Prof. Atul Bhargav

# Overview of the Project

The primary objective of this study is explicitly stated - to improve the efficiency of the Rankine cycle. By pinpointing inefficiencies in the existing system and proposing targeted modifications, we aim to achieve a notable increase in thermal efficiency, laying the groundwork for more sustainable and economically viable power generation.The existing Rankine cycle's baseline performance is rigorously examined, offering a comprehensive understanding of its strengths and weaknesses. Key parameters are identified, and inefficiencies are scrutinized to provide a clear picture of the starting point for our enhancement endeavors.

# Introduction to Rankine cycle

Power plants play a crucial role in modern society, converting energy sources into electricity to meet the ever-increasing demand for power. Among various power generation technologies, the Rankine cycle stands out as a widely adopted method due to its simplicity and efficiency. However, even the ideal Rankine cycle has inherent limitations that restrict its performance. In this project, we explore strategies to enhance the performance of a power plant operating on a basic ideal Rankine cycle.

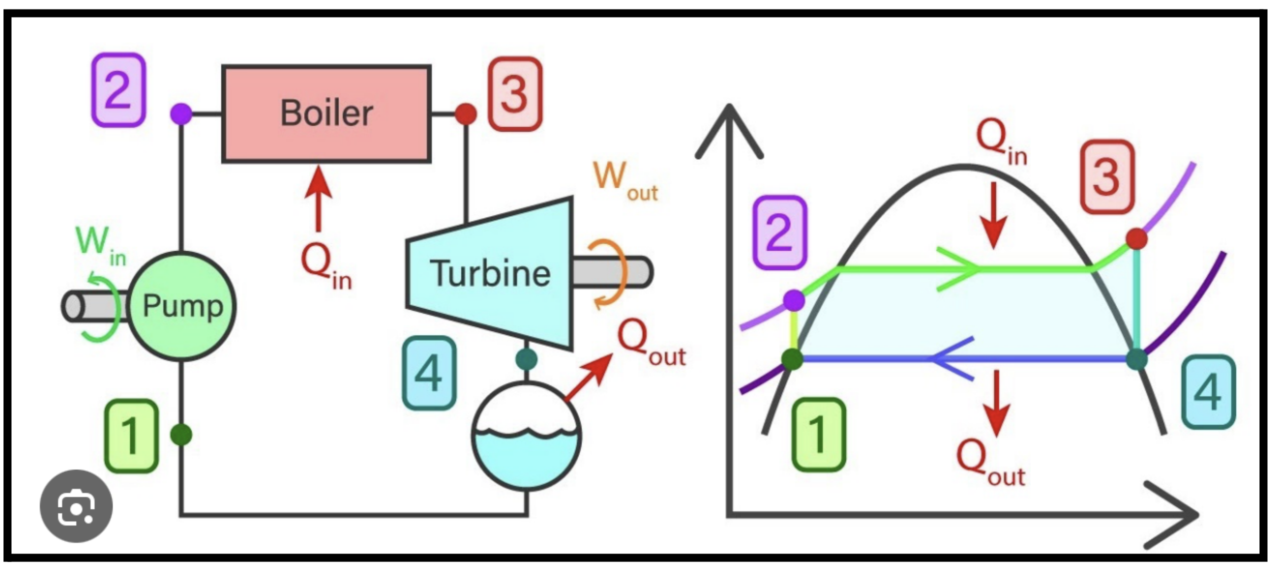



Fig. The Ideal Rankine Cycle

The current power plant, operating with a thermal efficiency of 41% and a steam quality of 76%, presents an opportunity for improvement. Our aim is to modify the given ideal Rankine cycle to achieve a thermal efficiency exceeding 46% while simultaneously raising the steam quality to above 85%. This endeavor requires a careful consideration of the cycle parameters and the implementation of optimization techniques.

The constraints imposed on the boiler pressure, condenser pressure, and turbine temperature further challenge the task. Maintaining the boiler pressure at 15 MPa and the condenser pressure at 10 kPa limits the temperature range within which the cycle operates. Additionally, restricting the turbine temperature to 500 ℃ imposes practical considerations for material selection and component design.

Despite these constraints, we believe that significant improvements in the power plant's performance can be achieved. Our approach will involve analyzing the existing cycle, identifying potential areas for optimization, and implementing strategies to enhance efficiency while maintaining steam quality. We will utilize thermodynamic principles and cycle analysis techniques to guide our efforts and evaluate the effectiveness of the proposed modifications.

# The Problem Statement 1

In this project you are tasked with improving the performance of a power plant operating on a basic ideal Rankine cycle (shown in Fig). The current cycle has a thermal efficiency of 41 % and a steam quality (at the condenser inlet) of 76 %. Your goal is to modify the given ideal Rankine cycle to increase the efficiency over 46 % and raise the steam quality (x) to above 85 %. The boiler pressure and condenser pressure must remain at 15 MPa and 10 kPa, respectively, and the turbine temperature should not exceed 500 °C.

## Solution to Problem Statement 1

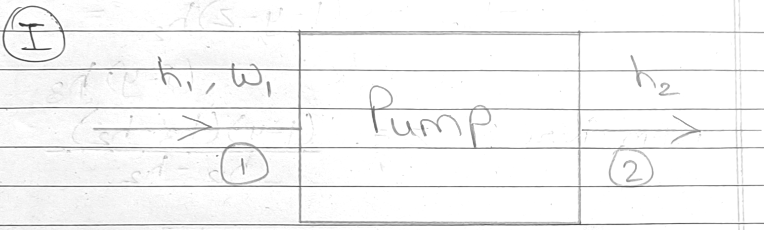
The steam power plant works on the basic principle of reheat-regenerative rankine cycle with one open feedwater heater ,one closed feedwater heater  and one reheater.

Assumptions:

1. Steady operating conditions exist.
2. Kinetic energy and potential energy changes are negligible.
3. In both open and closed feedwater heaters,feedwater is heated to saturation temperature at feedwater heater pressure.

The control volumes and their corresponding energy balance equations for each component involved in the cycle are as follows:-

I




Applying Energy balance equation :-

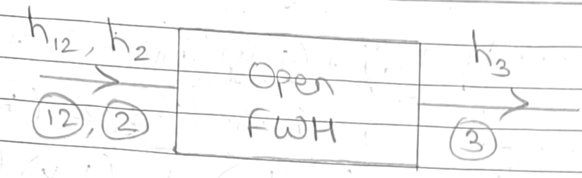
$$\dot{E}_{in} - \dot{E}_{out} + \cancelto{0}{\dot{E}_{gen}} = \cancelto{0}{\frac{dE}{dt}}\bigg|_{CV}$$

[Steady state]

$$\therefore (1-y-z)h_1\dot{m} + \dot{m}w = (1-y-z)h_2\dot{m}$$

$$\therefore w_1 = (1-y-z)(h_2-h_1)$$

II



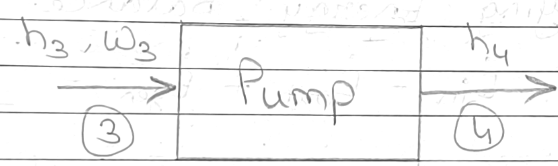

Energy balance equation -

$$\dot{E}_{in} - \dot{E}_{out} + \cancel{\dot{E}_{gen}} = \cancel{\frac{dE}{dt}}\bigg|_{CV}$$

$$\therefore zh_{12} + (1-y-z)h_2 = (1-y)h_3$$

From here, $z = \dfrac{(1-y)(h_3-h_2)}{h_{12}-h_2}$

III



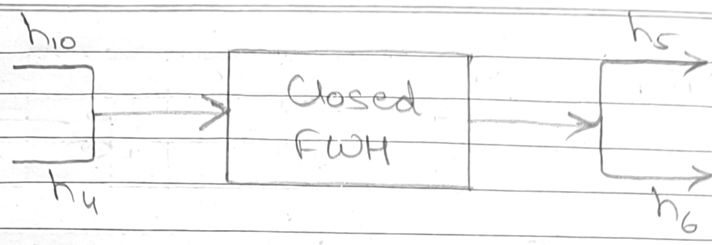

Energy balance equation –

$$\dot{E}_{in} - \dot{E}_{out} + \cancel{\dot{E}_{gen}} = \cancel{\frac{dE}{dt}}\Big|_{cv}$$

$$\therefore \quad (1-y)h_3 + \omega_3 = (1-y)h_4$$

$$\therefore \quad \omega_3 = (1-y)(h_4 - h_3)$$

IV



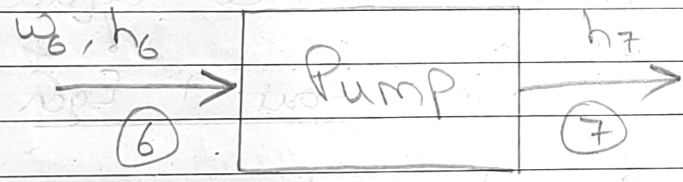

Energy balance equation –

$$\dot{E}_{in} - \dot{E}_{out} + \cancel{\dot{E}_{gen}} = \cancel{\frac{dE}{dt}}\Big|_{cv}$$

$$\therefore \quad y_{10} + (1-y)h_4 = (1-y)h_5 + yh_6$$

From here, $y = \dfrac{h_5 - h_4}{(h_5 - h_4) + (h_{10} - h_6)}$

V



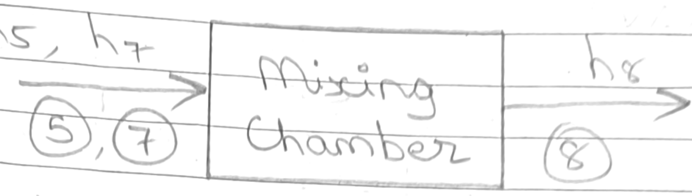

Energy balance equation -

$$\dot{E}_{in} - \dot{E}_{out} + \cancel{\dot{E}_{gen}} = \cancel{\frac{dE}{dt}}\Big|_{CV}$$

$$\therefore \; y h_6 + w_6 = y h_7$$

$$\therefore \; w_6 = y(h_7 - h_6)$$

VI

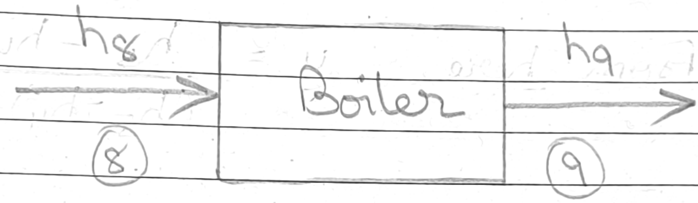



Energy balance equation -

$$\dot{E}_{in} - \dot{E}_{out} + \cancel{\dot{E}_{gen}} = \cancel{\frac{dE}{dt}}\Big|_{CV}$$

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

VII

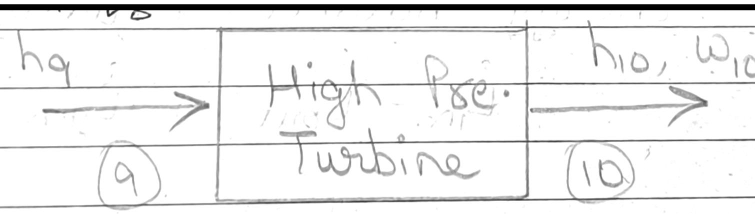



Energy balance equation —

$$\dot{E}_{in} - \dot{E}_{out} + \cancel{\dot{E}_{gen}} = \cancel{\frac{dE}{dt}}\Big|_{cv}$$

$$\therefore \quad h_8 + q_8 = h_9 \Rightarrow q_8 = h_9 - h_8$$

VIII



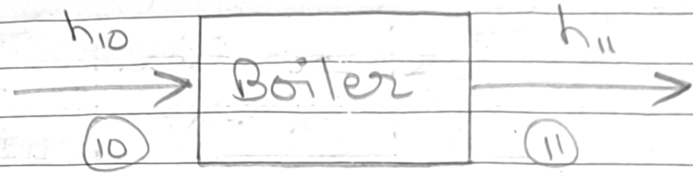

Energy balance equation —

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\therefore \quad h_9 = h_{10} + w_{10}$$

$$\therefore \quad w_{10} = h_9 - h_{10}$$

IX



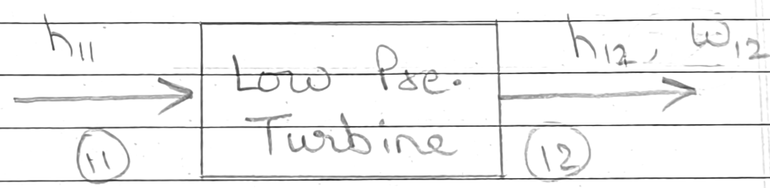

Energy balance equation –

$$\dot{E}_{in} - \dot{E}_{out} + \cancel{\dot{E}_{gen}} = \cancel{\frac{dE}{dt}}\Big|_{cv}$$

$$\therefore \quad q_{10} + \underset{(1-y)}{h_{10}} = \underset{(1-y)}{h_{11}}$$

$$\therefore \quad q_{10} = (1-y)(h_{11} - h_{10})$$

X



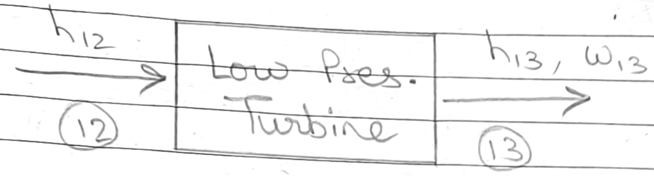

Energy balance equation –

$$\dot{E}_{in} - \dot{E}_{out} + \cancel{\dot{E}_{gen}} = \cancel{\frac{dE}{dt}}\Big|_{cv}$$

$$\therefore (1-y)h_{11} = \underset{(1-y)}{h_{12}} + w_{12}$$

$$\therefore \quad w_{12} = (h_{11} - h_{12})(1-y)$$

XI



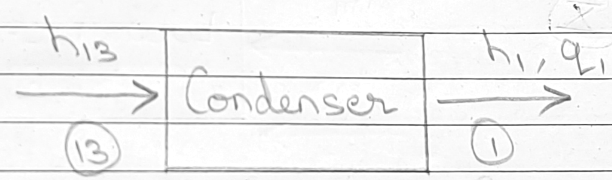

Energy balance equation -

$$\dot{E}_{in} - \dot{E}_{out} + \cancel{\dot{E}_{gen}} = \cancel{\frac{dE}{dt}}\Big|_{CV}$$

$$\therefore \quad h_{12}(1-y-z) = (1-y-z)(h_{13}) + w_{13}$$

$$\therefore \quad w_{13} = (1-y-z)(h_{12} - h_{13})$$

XII

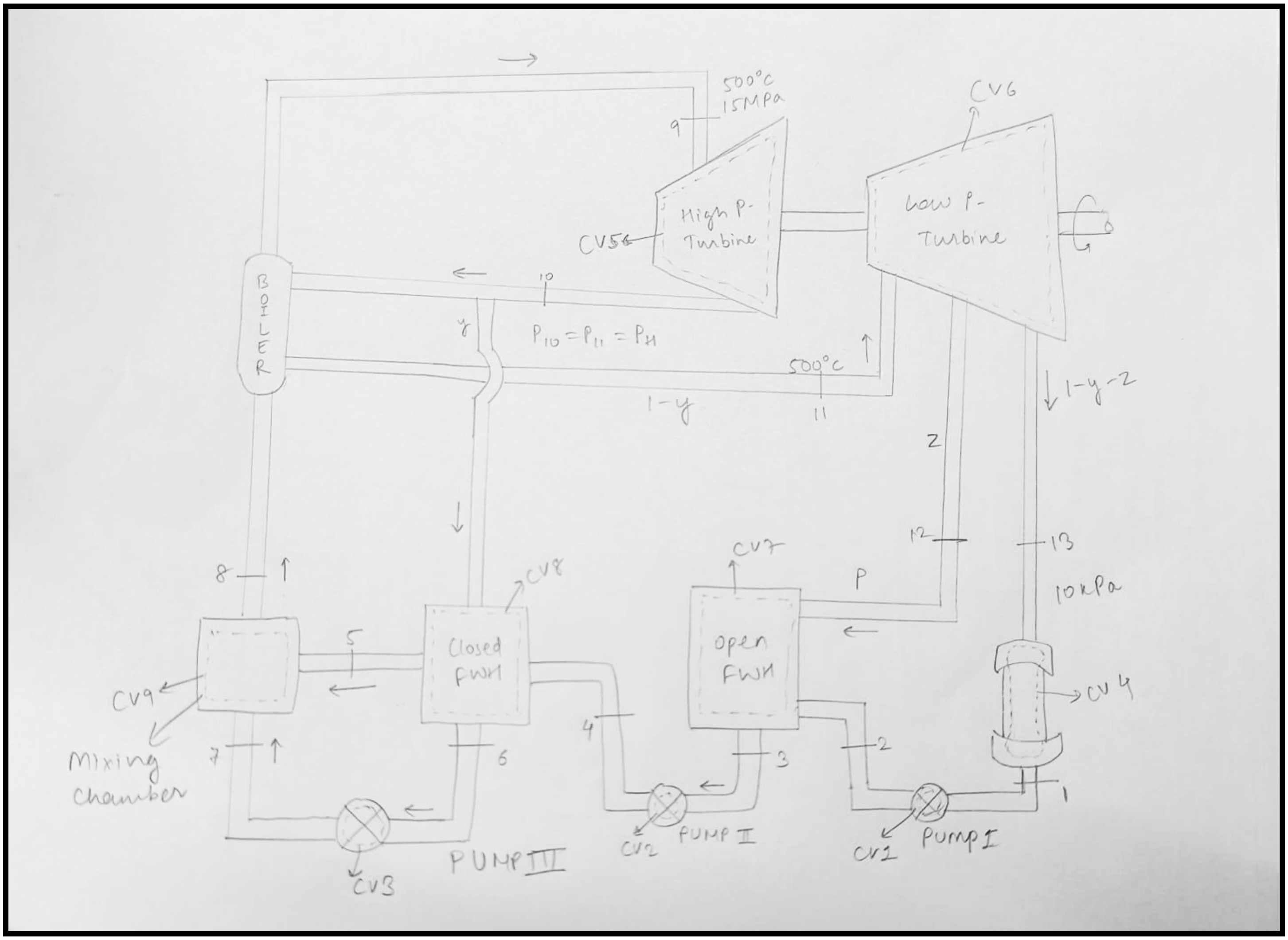



Energy balance equation -

$$\dot{E}_{in} - \dot{E}_{out} + \cancel{\dot{E}_{gen}} = \cancel{\frac{dE}{dt}}\Big|_{CV}$$

$$\therefore \quad (1-y-z)\,h_{13} = (1-y-z)h_1 + q_1$$

$$\therefore \quad q_1 = (1-y-z)(h_{13} - h_1)$$




**Cantera code for the modified Rankine cycle:**

```
%% main code
clear all;
clc;
a= Solution('liquidvapor.xml', 'water');
p1= 10E+3;                                    %% set state 1
x1=0;
setState_Psat(a, [p1; x1]);
h1= enthalpy_mass(a);
s1= entropy_mass(a);
s2=s1;                                         %% set state 2
p2= 0.5E+6;
setState_SP(a, [s2; p2]);
```

```
h2= enthalpy_mass(a);
p3=p2;                                  %% set state 3
x3=0;
setState_Psat(a, [p3; x3]);
h3= enthalpy_mass(a);
s3= entropy_mass(a);
s4=s3;                                  %% set state 4
p4= 15E+6;
setState_SP(a, [s4; p4]);
h4= enthalpy_mass(a);
p6= 4E+6;                               %% set state 6
x6=0;
setState_Psat(a, [p6; x6]);
h6= enthalpy_mass(a);
s6= entropy_mass(a);
h5=h6;
s7=s6;                                  %% set state 7
p7=p4;
setState_SP(a, [s7; p7]);
h7= enthalpy_mass(a);
T9= 500+273.15;                         %% set state 9
p9=p4;
set(a, 'T', T9, 'P', p9);
h9= enthalpy_mass(a);
s9= entropy_mass(a);
s10=s9;                                 %% set state 10
p10= p6;
setState_SP(a, [s10; p10]);
h10= enthalpy_mass(a);
p11=p6;                                 %% set state 11
T11=T9;
set(a, 'T', T11, 'P', p11);
h11= enthalpy_mass(a);
s11= entropy_mass(a);
p12=p2;                                 %% set state 12
s12=s11;
setState_SP(a, [s12; p12]);
h12= enthalpy_mass(a);
p13=p1;                                       %% set state 13
s13=s11;
setState_SP(a, [s13; p13]);
h13= enthalpy_mass(a);
x13=0;
setState_Psat(a, [p13; x13]);
hf13= enthalpy_mass(a);
sf13= entropy_mass(a);
xg13=1;
setState_Psat(a, [p13; xg13]);
hg13= enthalpy_mass(a);
```

```
sg13= entropy_mass(a);
y= (h5-h4)/((h10-h6)+(h5-h4));                %% regeneration at state 10
z= ((1-y)*(h3-h2))/(h12-h2);                  %% regeneration at state 12
h8= (1-y)*h5 + y*h7;
Qin= (h9-h8) + (1-y)*(h11-h10);               %% Qin
Qout= (1-y-z)*(h13-h1);                       %% Qout
efficiency= 1-(Qout/Qin);                     %% efficiency
Quality= (s13 - sf13)/(sg13 - sf13);          %% Quality
disp(efficiency);
disp(Quality);
```

Command Window

```
    0.4697

    0.8586
```

- From the output of the above code in problem statement 1 shows that the efficiency of the modified rankine cycle is 46.9745% at boiler pressure and condenser pressure between 15 Mpa and 10 kpa and the turbine temperature at 500°C.

$$\eta_{modified\ rankine\ cycle} = 46.9745\%$$

$$x_{modified\ rankine\ cycle} = 85.86\%$$

# The Problem Statement 2

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.

## Solution to Problem Statement 2

1) By Varying the condenser pressure between 5kPa to 10kPa and boiling pressure 15MPa :-

```
%% Varying Condenser Pressure
clear all;
clc;
array1=[];
array2=[];
i=1;
a= Solution('liquidvapor.xml', 'water');
for p1 = 5000:50:10000
   x1=0;
   setState_Psat(a, [p1; x1]);          %% set state 1
   h1= enthalpy_mass(a);
   s1= entropy_mass(a);

   s2=s1;                               %% set state 2
   p2= 0.5E+6;
   setState_SP(a, [s2; p2]);
   h2= enthalpy_mass(a);

   p3=p2;                               %% set state 3
   x3=0;
   setState_Psat(a, [p3; x3]);
   h3= enthalpy_mass(a);
   s3= entropy_mass(a);

   s4=s3;                               %% set state 4
   p4= 15E+6;
   setState_SP(a, [s4; p4]);
   h4= enthalpy_mass(a);

   p6= 4E+6;                            %% set state 6
   x6=0;
   setState_Psat(a, [p6; x6]);
   h6= enthalpy_mass(a);
   s6= entropy_mass(a);
```

```
h5=h6;

s7=s6;                                  %% set state 7
p7=p4;
setState_SP(a, [s7; p7]);
h7= enthalpy_mass(a);

T9= 500+273.15;                         %% set state 9
p9=p4;
set(a, 'T', T9, 'P', p9);
h9= enthalpy_mass(a);
s9= entropy_mass(a);

s10=s9;                                 %% set state 10
p10= p6;
setState_SP(a, [s10; p10]);
h10= enthalpy_mass(a);

p11=p6;                                 %% set state 11
T11=T9;
set(a, 'T', T11, 'P', p11);
h11= enthalpy_mass(a);
s11= entropy_mass(a);

p12=p2;                                 %% set state 12
s12=s11;
setState_SP(a, [s12; p12]);
h12= enthalpy_mass(a);

p13=p1;                                 %% set state 13
s13=s11;
setState_SP(a, [s13; p13]);
h13= enthalpy_mass(a);
x13=0;
setState_Psat(a, [p13; x13]);
hf13= enthalpy_mass(a);
sf13= entropy_mass(a);
xg13=1;
setState_Psat(a, [p13; xg13]);
hg13= enthalpy_mass(a);
sg13= entropy_mass(a);

y= (h5-h4)/((h10-h6)+(h5-h4));                %% regeneration at state 10

z= ((1-y)*(h3-h2))/(h12-h2);                  %% regeneration at state 12

h8= (1-y)*h5 + y*h7;

Qin= (h9-h8) + (1-y)*(h11-h10);               %% Qin
```

```
   Qout= (1-y-z)*(h13-h1);                     %% Qout

   efficiency= 1-(Qout/Qin);                   %% efficiency
   array1(i) = efficiency;
   Win= (1-y-z)*(h2-h1) + (1-y)*(h4-h3) + y*(h7-h6);
   Wout= (h9-h10) + (1-y)*(h11-h12) + (1-y-z)*(h12-h13);
   work= Wout-Win;
   array2(i) = work/1E+6;
   i = i+1;
End
```

2) By Varying the boiler pressure between 12MPa to 15MPa and condenser pressure 10kPa:-

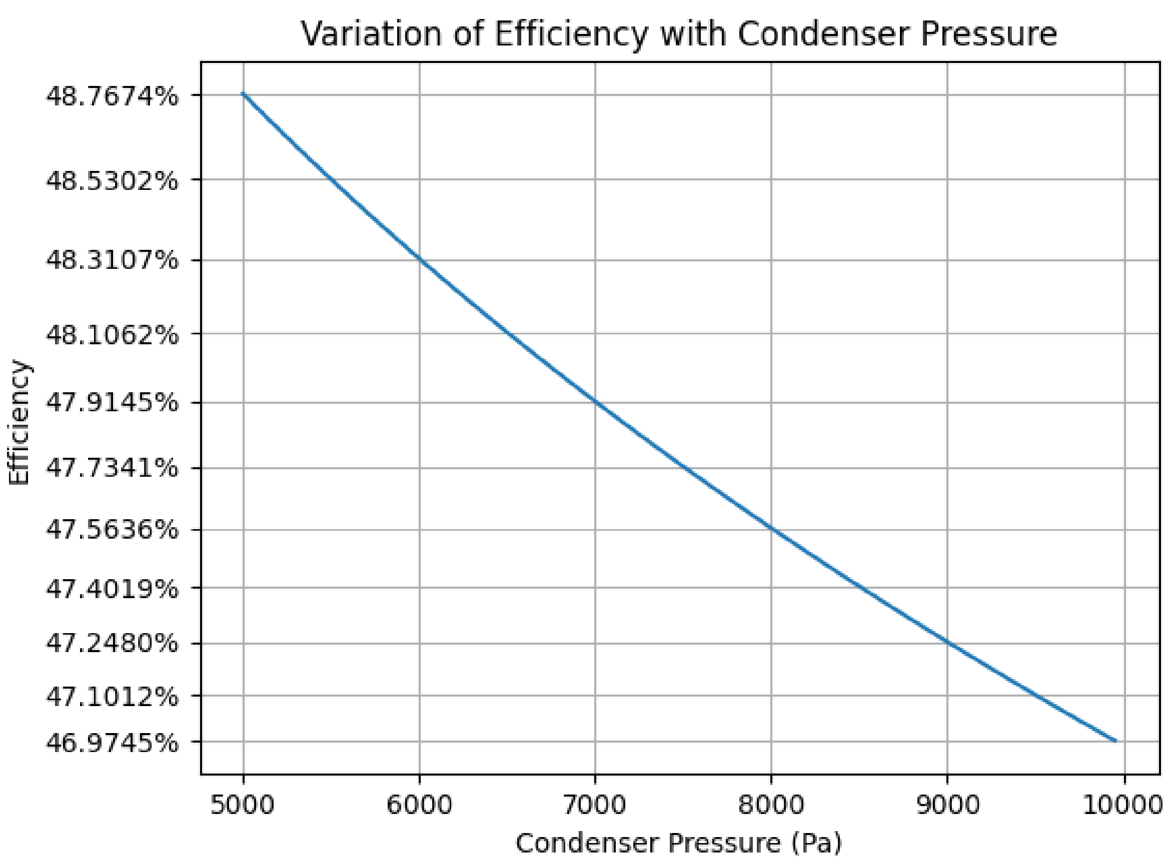
```
%% Varying Boiler Pressure
clear all;
clc;
array1=[];
array2=[];
i=1;
a= Solution('liquidvapor.xml', 'water');
for p4 = 12E+6:30E+3:15E+6
   p1= 10E+3;                                  %% set state 1
   x1=0;
   setState_Psat(a, [p1; x1]);
   h1= enthalpy_mass(a);
   s1= entropy_mass(a);

   s2=s1;                                      %% set state 2
   p2= 0.5E+6;
   setState_SP(a, [s2; p2]);
   h2= enthalpy_mass(a);

   p3=p2;                                      %% set state 3
   x3=0;
   setState_Psat(a, [p3; x3]);
   h3= enthalpy_mass(a);
   s3= entropy_mass(a);

   s4=s3;                                      %% set state 4
   setState_SP(a, [s4; p4]);
   h4= enthalpy_mass(a);

   p6= 4E+6;                                   %% set state 6
   x6=0;
   setState_Psat(a, [p6; x6]);
   h6= enthalpy_mass(a);
```

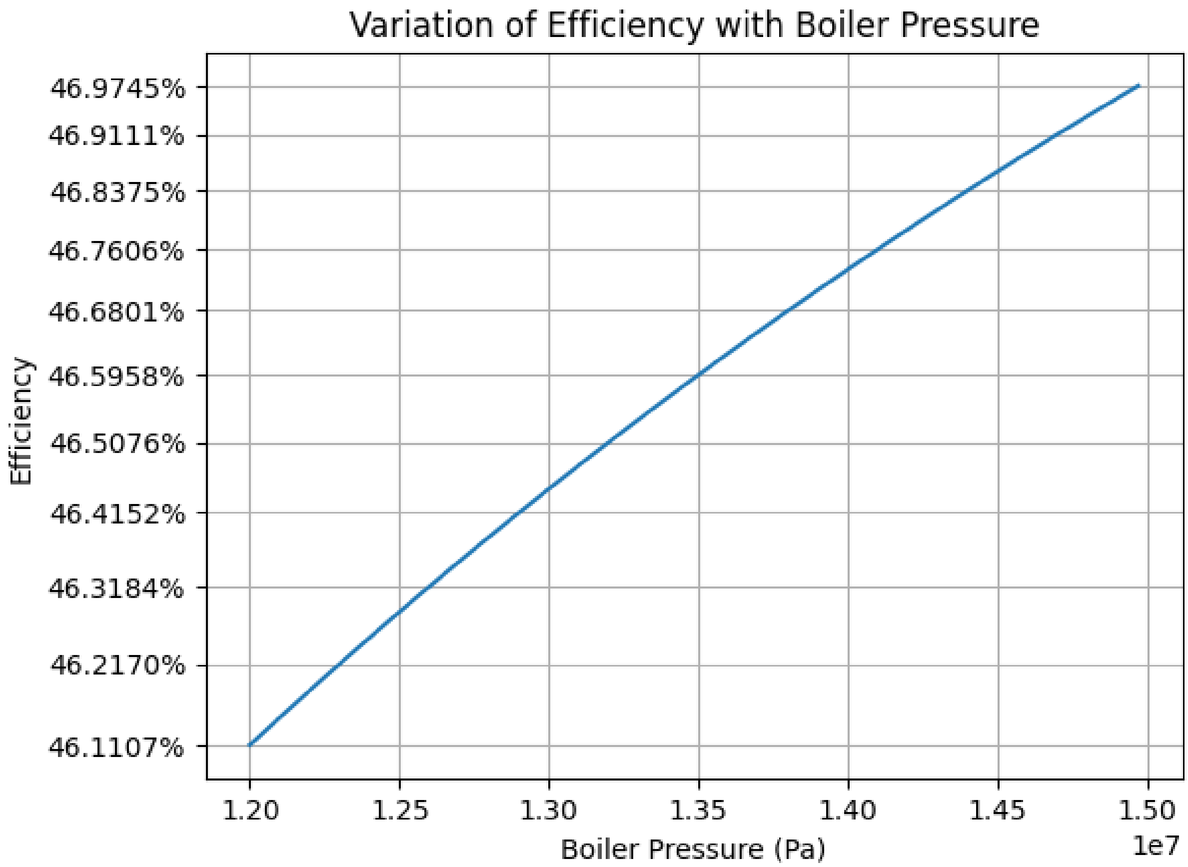
```
s6= entropy_mass(a);

h5=h6;

s7=s6;                                  %% set state 7
p7=p4;
setState_SP(a, [s7; p7]);
h7= enthalpy_mass(a);

T9= 500+273.15;                         %% set state 9
p9=p4;
set(a, 'T', T9, 'P', p9);
h9= enthalpy_mass(a);
s9= entropy_mass(a);

s10=s9;                                 %% set state 10
p10= p6;
setState_SP(a, [s10; p10]);
h10= enthalpy_mass(a);

p11=p6;                                 %% set state 11
T11=T9;
set(a, 'T', T11, 'P', p11);
h11= enthalpy_mass(a);
s11= entropy_mass(a);

p12=p2;                                 %% set state 12
s12=s11;
setState_SP(a, [s12; p12]);
h12= enthalpy_mass(a);

p13=p1;                                 %% set state 13
s13=s11;
setState_SP(a, [s13; p13]);
h13= enthalpy_mass(a);
x13=0;
setState_Psat(a, [p13; x13]);
hf13= enthalpy_mass(a);
sf13= entropy_mass(a);
xg13=1;
setState_Psat(a, [p13; xg13]);
hg13= enthalpy_mass(a);
sg13= entropy_mass(a);

y= (h5-h4)/((h10-h6)+(h5-h4));          %% regeneration at state 10

z= ((1-y)*(h3-h2))/(h12-h2);            %% regeneration at state 12

h8= (1-y)*h5 + y*h7;
```

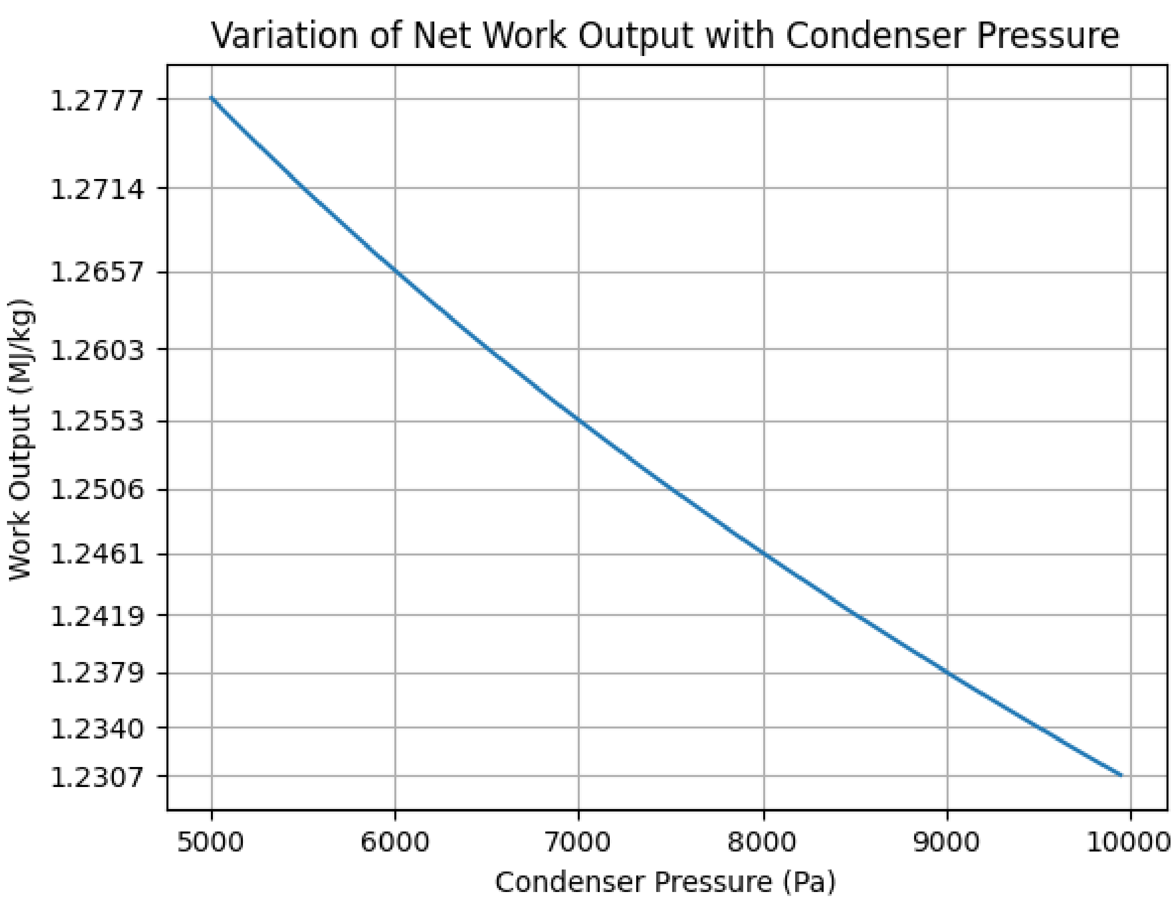
```
    Qin= (h9-h8) + (1-y)*(h11-h10);          %% Qin

    Qout= (1-y-z)*(h13-h1);                  %% Qout

    efficiency= 1-(Qout/Qin);                %% efficiency
    array1(i) = efficiency;
    Win= (1-y-z)*(h2-h1) + (1-y)*(h4-h3) + y*(h7-h6);
    Wout= (h9-h10) + (1-y)*(h11-h12) + (1-y-z)*(h12-h13);
    work= Wout-Win;
    array2(i) = work/1E+6;
    i = i+1;
End
```

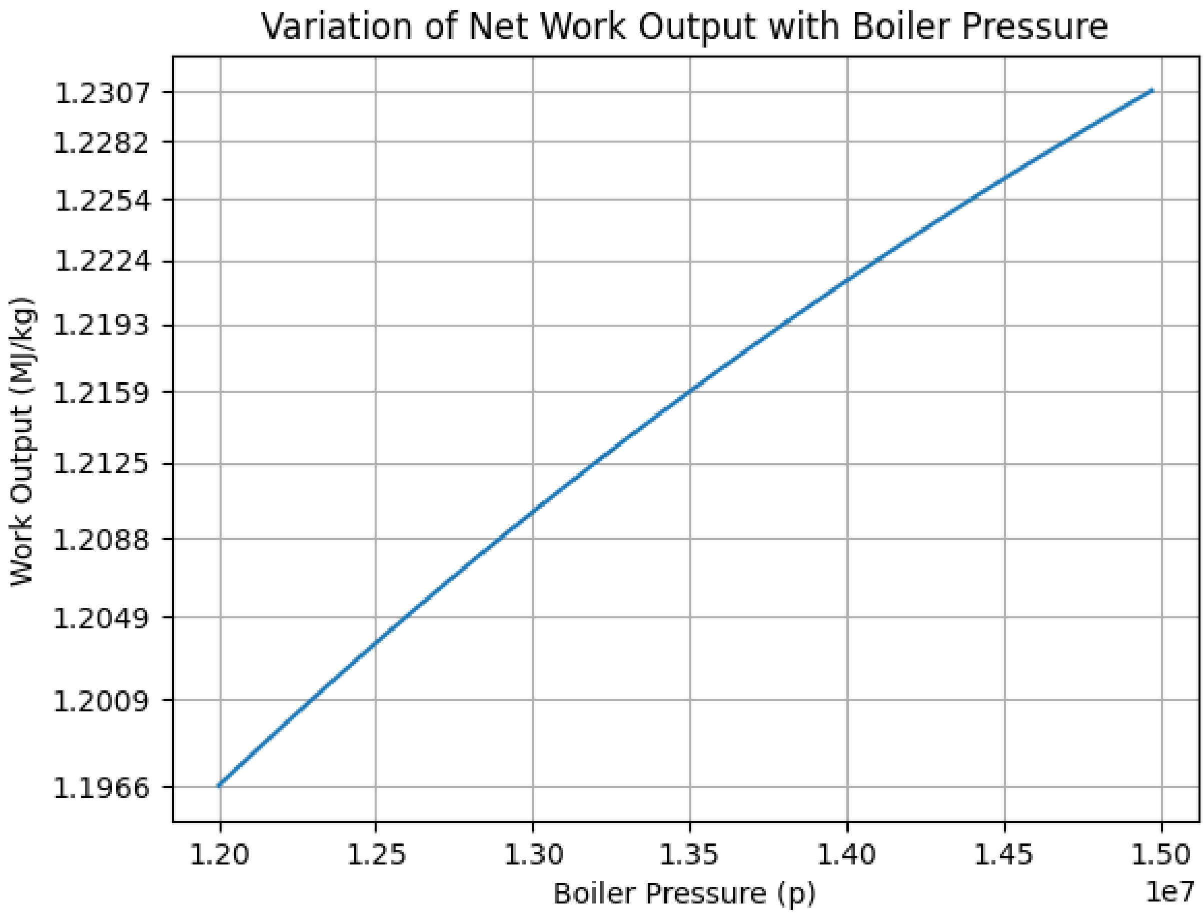
# PLOTS:

From the arrays taken from the Cantera code, we have plotted graphs with the matplotlib library in python.

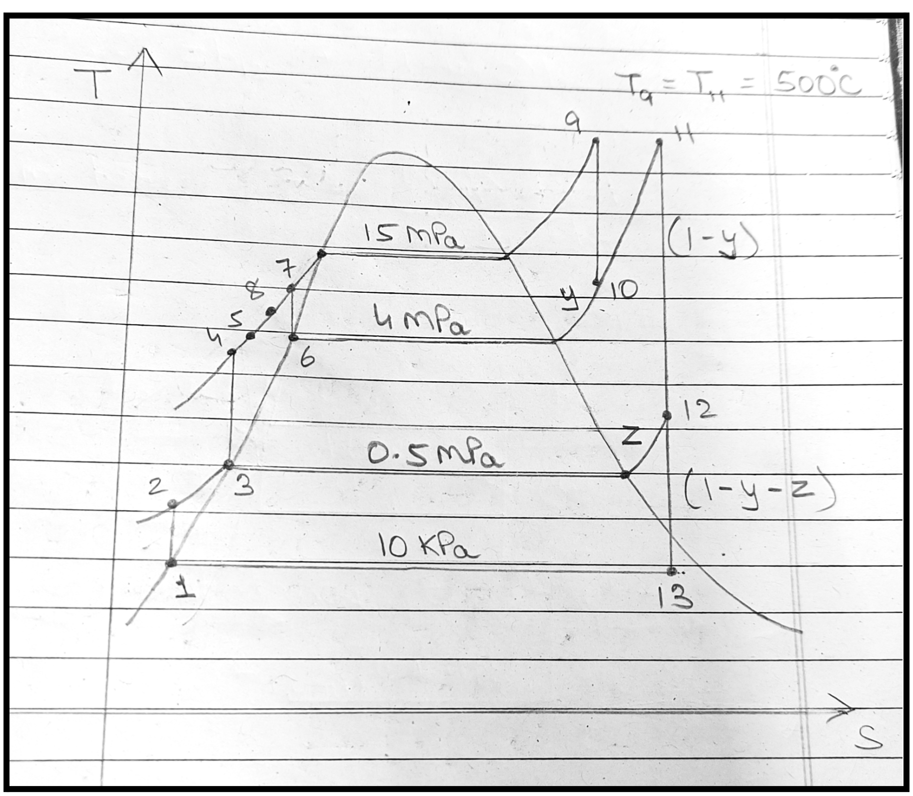



Variation of Efficiency with Boiler Pressure
Efficiency
46.9745%
46.9111%
46.8375%
46.7606%
46.6801%
46.5958%
46.5076%
46.4152%
46.3184%
46.2170%
46.1107%
1.20
1.25
1.30
1.35
1.40
1.45
1.50
1e7
Boiler Pressure (Pa)


Variation of Net Work Output with Condenser Pressure
Work Output (MJ/kg)
1.2777
1.2714
1.2657
1.2603
1.2553
1.2506
1.2461
1.2419
1.2379
1.2340
1.2307
5000
6000
7000
8000
9000
10000
Condenser Pressure (Pa)




T-s diagram of modified rankine cycle



# Plot discussion

From the plots of part-B of the question, the underlying discussions could be inferred and were looked upon to :-

- An inverse correlation is observed between condenser pressure and net work output, as evidenced by graphical representation. An increase in condenser pressure corresponds to a decrease in net work output, underscoring its pivotal role in operational efficiency.

- Similarly, analysis of the condenser pressure versus efficiency graph indicates a proportional decrease in efficiency as condenser pressure is elevated. This outcome aligns with the anticipated reduction in efficiency due to the decrease in work output associated with condenser pressure in thermodynamic processes.

- The graph depicting boiler pressure against net work output indicates a direct proportionality, signifying a positive correlation between boiler pressure and resulting net work output within the thermodynamic cycle.

- With increasing boiler pressure in boiler pressure v/s efficiency graph, the corresponding work output from the high as well as low pressure turbines gets increased. Due to this increased work output, the efficiency of the modified Rankine cycle increases.

- Hence, it is deduced that optimizing net work output and efficiency entails maintaining lower condenser pressure and elevating boiler pressure, within the structural limits dictated by the capabilities of contemporary materials in the latest generation systems.

- Furthermore, it is noteworthy that an elevated steam temperature upon entry into the turbine increases in both net work output and efficiency. This observation underscores the influential role of steam temperature in optimizing the performance parameters of the thermodynamic system under consideration.

# References

*[1]* Contributor, T. (2019, March 1). *Rankine cycle*. WhatIs.com. https://www.techtarget.com/whatis/definition/Rankine-cycle

*[2]* Latarche, M. (2021, January 1). Waste heat recovery. Elsevier eBooks. https://doi.org/10.1016/b978-0-08-102748-6.00012-8

*[3]* Leader, A. P. P. M. (2019, January 20). *How to Calculate Thermal Efficiency of Rankine Cycle*.Medium. https://medium.com/@ashwinpalo/how-to-calculate-thermal-efficiency-of-rankine-cycle-37a7dbcadc12

# Acknowledgements

I would like to express my sincere gratitude to Atul Bhargav Sir, who supervised and guided us throughout this project. His valuable feedback and suggestions helped me to improve the quality of my work and to overcome the challenges we faced during the experiment. He also provided us with the theoretical background and the relevant literature for this project, which enhanced our understanding of the topic and the research methods.

We would also like to express my gratitude to Ravinder Sir, who always serves as a backbone to our understanding in the project.He guided us throughout the timeline and made us understand each and every details and corners of the project.He also provided us with the guidance in the cantera programming.

We would like to acknowledge the contribution of fellow teammates. Their involvement and support made the data collection process easier and more enjoyable. They also shared their insights and experiences with us, which enriched our analysis and interpretation of the results. This project would not have been possible without the help and support of all these people. We are truly grateful for their generosity and kindness.