PROJECT: INCREASING EFFICIENCY OF RANKINE CYCLE

ES211: THERMODYNAMICS

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November 21, 2023

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1 Problem Statement

The current power plant operates on an ideal Rankine cycle with a thermal efficiency of 41% and a steam quality of 76%. The objective of this project is to enhance the performance of the power plant by modifying the Rankine cycle to achieve a thermal efficiency exceeding 46% and raising the steam quality to above 85%. The boiler pressure (P_b) and condenser pressure (P_c) must be constrained to 15 MPa and 10 kPa, respectively, and the turbine temperature should not exceed 500 °C. The project also involves the variation of boiler pressure (P_b) and condenser pressure (P_c) within the specified ranges of 12 MPa $<$ P_b $<$ 15 MPa and 5 kPa $<$ P_c $<$ 10 kPa. The goal is to create a modified ideal Rankine cycle that meets the efficiency and steam quality targets while adhering to the given constraints. The project must include a comprehensive report showcasing the steam quality and the modified ideal Rankine cycle's efficiency.

Additionally, A plot illustrating how changes in boiler pressure and condenser pressure impact the thermal efficiency and net work of the modified ideal Rankine cycle.

2 Introduction

The Rankine cycle is a theoretical thermodynamic model depicting the operation of steam power plants. Comprising four stages—compression, heat addition, expansion, and heat rejection—it illustrates the transformation of water into steam to generate power. The cycle begins with water compression, followed by isobaric heating in a boiler, expansion through a turbine, and concludes with isobaric heat rejection in a condenser. While idealized, the Rankine cycle provides fundamental insights into the efficiency of steam-based power systems, guiding the analysis and optimization of practical applications.

2.1 The Ideal Rankine Cycle

The ideal Rankine cycle models the operation of steam power plants. Comprising four main processes—compression, heat addition, expansion, and heat rejection—it provides a framework to analyze the efficiency and performance of power generation systems. The cycle begins with the compression of liquid water, typically through a pump, to elevate its pressure. Subsequently, the water undergoes isobaric heating in a boiler, transforming it into high-pressure steam. This steam then expands through a turbine, producing mechanical work. The final stage involves isobaric heat rejection in a condenser, where the steam condenses back into liquid form.

Key assumptions of the ideal Rankine cycle include the absence of irreversibilities, no heat losses, and the use of an ideal working fluid. Practical implementations often deviate due to real-world complexities such as friction, thermal losses, and the limitations of actual working fluids. Despite these deviations, the ideal Rankine cycle remains a valuable tool for optimizing the performance of steam-based power generation systems.

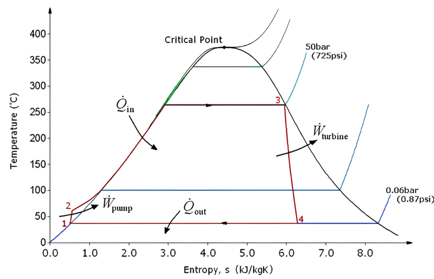

Figure 1: T-s diagram for Ideal Rankine cycle

- The efficiency of the above ideal rankine cycle is given as $\eta = 1 - \frac{q_{\text{out}}}{q_{\text{in}}}$

3 The Given Rankine Cycle

The current Rankine cycle operates with a thermal efficiency of 41% and a steam quality of 76% at the condenser inlet. This cycle follows the ideal Rankine model, comprising processes of compression, isobaric heat addition, expansion, and isobaric heat rejection. The thermal efficiency represents the ratio of net work output to the heat input. The steam quality indicates the fraction of vapor in the steam.

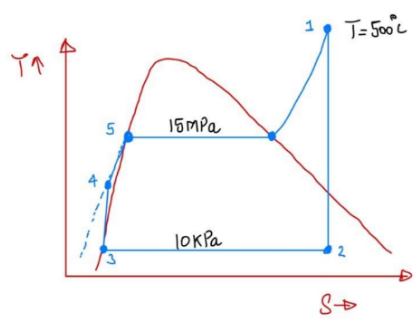

Figure 2: T-s diagram for given rankine cycle

4 Methods used to modify the Current Rankine Cycle

To enhance the given Rankine cycle, two effective modifications can be considered: reheating and regeneration.

4.1 Reheating

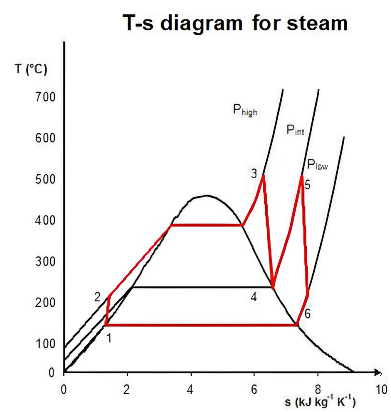

Figure 3: T-s diagram for rankine cycle with reheating

Increasing the boiler pressure increases the thermal efficiency of the Rankine cycle, but it also increases the moisture content of the steam to unacceptable levels. Two possibilities come to mind:

- Superheat the steam to very high temperatures before it enters the turbine. This would be the desirable solution since the average temperature at which heat is added would also increase, thus increasing the cycle efficiency. This is not a viable solution, however, since it requires raising the steam temperature to metallurgically unsafe levels.

- Expand the steam in the turbine in two stages, and reheat it in between. In other words, modify the simple ideal Rankine cycle with a reheat process. Reheating is a practical solution to the excessive moisture problem in turbines, and it is commonly used in modern steam power plants.

The sole purpose of the reheat cycle is to remove the moisture content of the steam at the final stages of the expansion process. If such types of materials existed which could withstand the high temperatures, then there was no need for a reheat cycle.

4.2 Regeneration

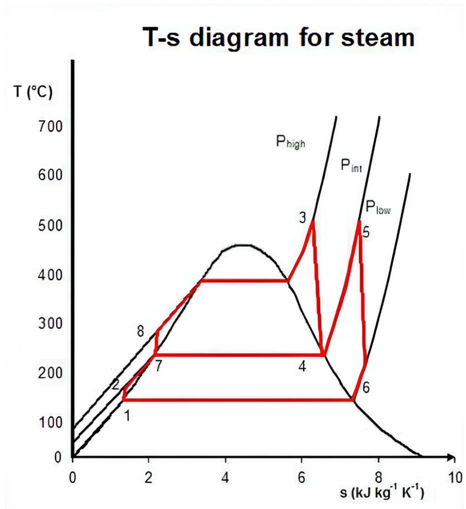

Figure 4: T-s diagram for rankine cycle with regeneration involvde

Concurrently, regeneration optimizes energy usage by extracting heat from turbine-exiting steam to preheat feedwater before entering the boiler.

This dual approach improves overall thermal efficiency and performance. Reheating ensures more effective expansion in the turbine, while regeneration maximizes heat recovery, reducing fuel consumption. These modifications collectively elevate the efficiency and sustainability of the Rankine cycle, making it a more robust and economically viable solution for power generation.

5 Modifying the current Rankine cycle

5.1 Adding One Reheater

The addition of a reheater to the current Rankine cycle involves introducing a reheating process between the high-pressure and low-pressure turbines. This modification aims to improve the cycle's thermal efficiency and steam quality. In a Rankine cycle with a reheater, the steam undergoes an additional heating phase after partial expansion in the high-pressure turbine. This reheating process is strategically positioned to maintain steam temperature, preventing a decline as the steam expands further.

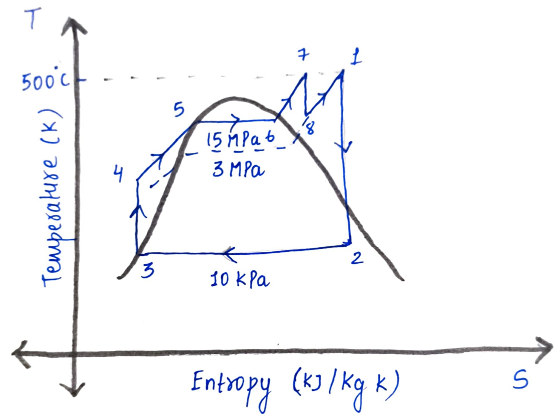

Figure 5: T-s diagram for rankine cycle with One Reheater.

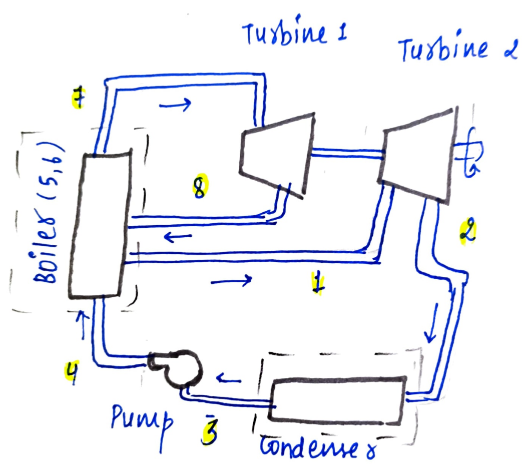

Figure 6: Control Volume diagram for rankine cycle with One Reheater.

- The efficiency of the above ideal rankine cycle is given as

$$\eta = 1 - \frac{h_2 - h_3}{h_7 - h_4 + h_1 - h_8} \tag{1}$$

- The efficiency of this cycle is 42.8025 %
- The quality at condenser inlet is 87.788 %

5.2 Adding One Reheater and One Regeneration

Integrating a reheater into the Rankine cycle involves reheating steam after its initial expansion, mitigating temperature drop issues. This addition enhances overall steam quality. By maintaining higher steam temperatures, the reheater allows for increased energy extraction, resulting in improved thermal efficiency and steam quality at the condenser inlet. Rankine cycle regeneration involves using extracted turbine steam to preheat feedwater before entering the boiler. This process optimizes heat utilization, boosting cycle efficiency by recovering otherwise wasted heat. Steam, extracted at an intermediate pressure, transfers its energy to feedwater in a heat exchanger, reducing fuel consumption. Regeneration is especially beneficial when a significant portion of heat is discarded at low temperatures.

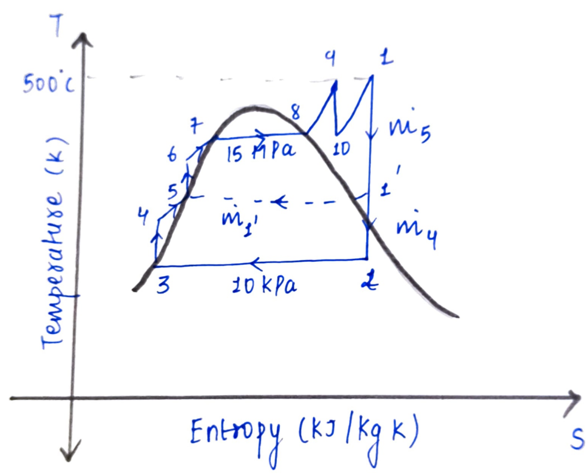

Figure 7: T-s diagram for rankine cycle with One Reheater and One Regeneration .

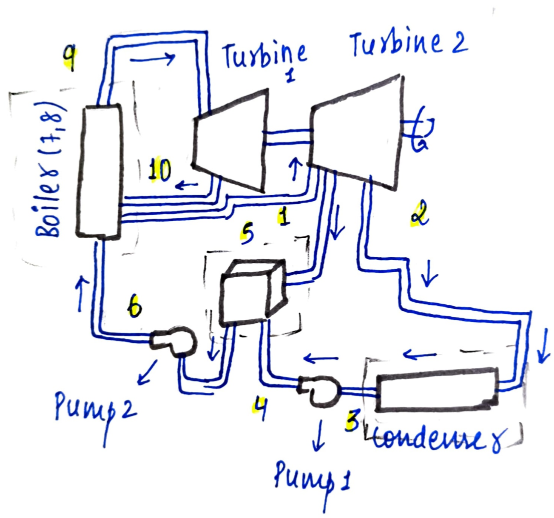

Figure 8: Control Volume diagram for rankine cycle with One Reheater and One Regenertion.

- Mass Balance : $\dot{m}_5 = \dot{m}_{1'} + \dot{m}_4$
- The efficiency of the above ideal rankine cycle is given as

$$\eta = 1 - \frac{(h_5 - h_{1'})(h_2 - h_3)}{(h_4 - h_{1'})(h_9 - h_{10} + h_1 - h_6)} \tag{2}$$

- The Quality of this cycle is 86.2073 %
- The Efficiency of this cycle is 45.6765 %

5.3 Adding One Reheater and Two Regeneration

The reheater reintroduces heat to steam between turbine stages, countering temperature drops and elevating thermal efficiency. Simultaneously, two regenerations involve extracting steam at different pressures to preheat feedwater, optimizing heat recovery. This dual-regeneration strategy significantly enhances efficiency by tapping into additional sources of waste heat. The first regeneration typically occurs between the high and intermediate turbine stages, while the second takes place between the intermediate and low-pressure stages. This sequential extraction and feedwater preheating ensure that more thermal energy is harnessed throughout the cycle, minimizing fuel consumption.

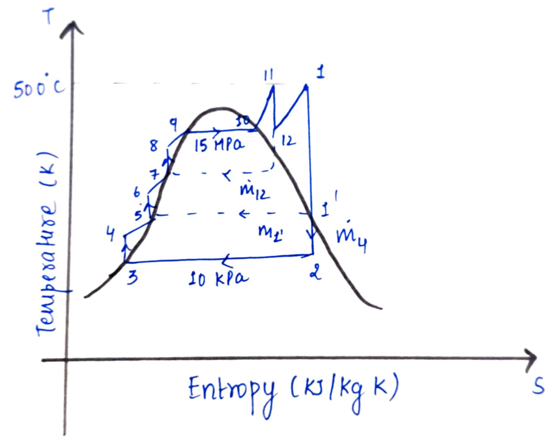

Figure 9: T-s diagram for rankine cycle with One Reheater and Two Regeneration .

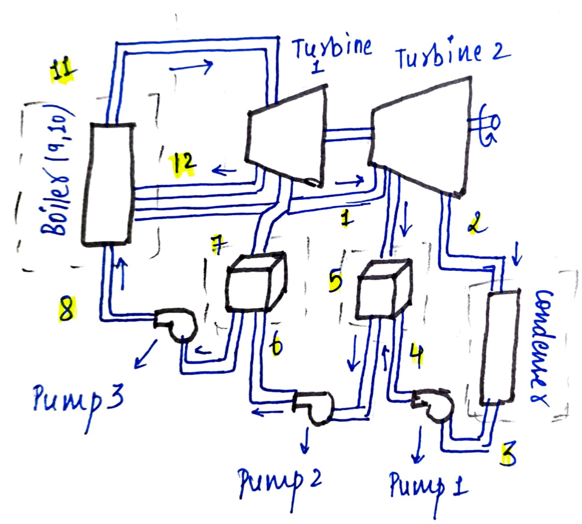

Figure 10: Control Volume diagram for rankine cycle with One Reheater and Two Regeneration .

- Mass Balance :

$$\dot{m_6} = \dot{m_{1'}} + \dot{m_4} \tag{3}$$

$$\dot{m_7} = \dot{m_6} + \dot{m_{12}} \tag{4}$$

- Energy Balance :

$$\dot{m_6}h_6 = \dot{m_{1'}}h_{1'} + \dot{m_4}h_4 \tag{5}$$

$$\dot{m_7}h_7 = \dot{m_6}h_6 + \dot{m_{12}}h_{12} \tag{6}$$

- The efficiency of the above ideal rankine cycle is given as

$$\eta = 1 - \frac{(h_5 - h_1)(h_2 - h_3)(h_7 - h_2)}{(h_4 - h_1)((h_6 - h_2)(h_{11} - h_5) + (h_1 - h_{12})(h_7 - h_2))} \tag{7}$$

- The Quality of this cycle is 86.3861 %
- The Efficiency of this cycle is 46.7726 %

5.4 Two Reheaters and One Regeneration

The two reheaters reintroduce heat into the steam at different stages, effectively addressing temperature variations and optimizing thermal performance. By operating between the high and intermediate turbine stages, and subsequently between the intermediate and low-pressure stages, the reheaters contribute to increased energy extraction from the steam. Simultaneously, a single regeneration process efficiently recovers waste heat, preheating the feedwater before it enters the boiler. This combination ensures a balanced integration of reheating and regeneration, maximizing the utilization of available heat and improving overall cycle efficiency.

- Mass Balance :

$$\dot{m_5} = \dot{m_{1'}} + \dot{m_4} \tag{8}$$

- Energy Balance :

$$\dot{m_5}h_5 = \dot{m_{1'}}h_{1'} + \dot{m_4}h_4 \tag{9}$$

- The efficiency of the above ideal Rankine cycle is given as

$$\eta = 1 - \frac{(h_5 - h_{1'})(h_3 - h_2)}{(h_4 - h_{1'})(h_9 - h_8 + h_{11} - h_{10} + h_{1'} - h_{12})} \tag{10}$$

- The Quality of this cycle is 90.4173 %
- The Efficiency of this cycle is 46.3797 %

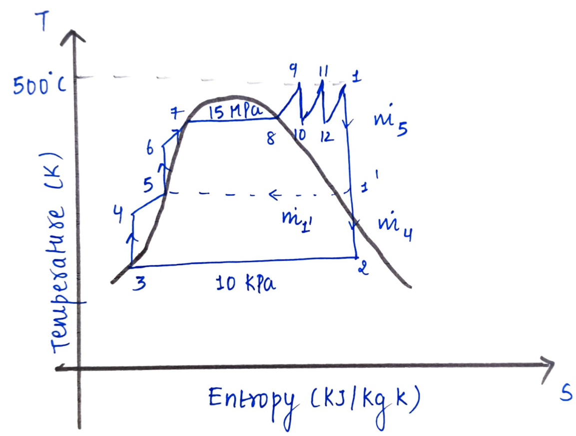

Figure 11: T-s diagram for rankine cycle with Two Reheater and One Regeneration .

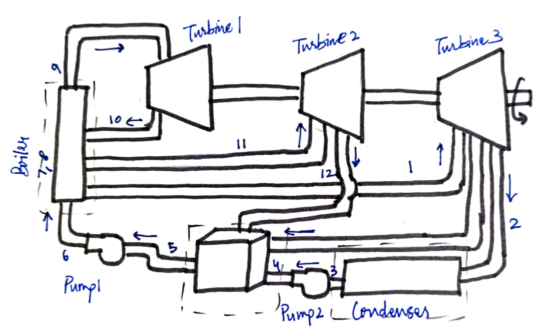

Figure 12: Control Volume diagram for rankine cycle with Two Reheater and One Regeneration .

5.5 Two Reheaters and Two Regenerations

Dual reheaters introduce additional heat to the steam at distinct points, effectively mitigating temperature declines and enhancing overall thermal efficiency. Meanwhile, two regenerations extract steam at different pressures, facilitating dual-stage feedwater preheating. The first reheater strategically reinstates heat between the high and intermediate turbine stages, and the second reheater operates between the intermediate and low-pressure stages. Simultaneously, the dual-regeneration process optimally recovers waste heat, preheating the feedwater before entering the boiler. This intricate configuration ensures thorough utilization of available heat, resulting in a substantial improvement in energy efficiency.

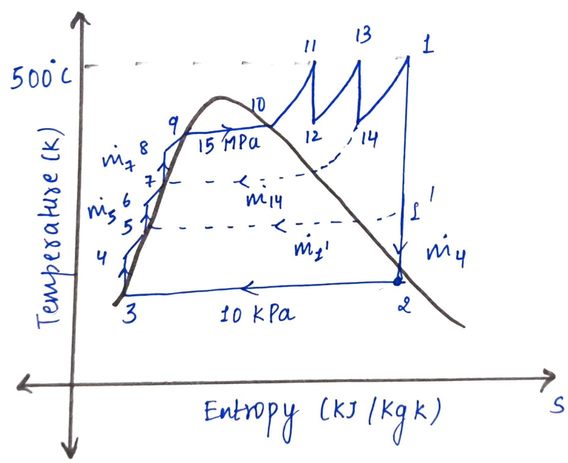

Figure 13: T-s diagram for Rankine cycle with Two Reheater and Two Regeneration.

- Mass Balance :

$$\dot{m_5} = \dot{m_{1'}} + \dot{m_4} \tag{11}$$

$$\dot{m_7} = \dot{m_5} + \dot{m_{14}} \tag{12}$$

- Energy Balance :

$$\dot{m_5} h_5 = \dot{m_{1'}} h_{1'} + \dot{m_4} h_4 \tag{13}$$

$$\dot{m_7} h_7 = \dot{m_5} h_6 + \dot{m_{14}} h_{14} \tag{14}$$

- The efficiency of the above ideal Rankine cycle is given as

$$\eta = 1 - \frac{(h_{1'} - h_5)(h_2 - h_3)(h_7 - h_{14})}{(h_{1'} - h_4)((h_6 - h_{14})(h_{11} - h_8 + h_{13} - h_{12} + h_1 - h_{12}) + (h_7 - h_{14})(h_1 - h_4))} \tag{15}$$

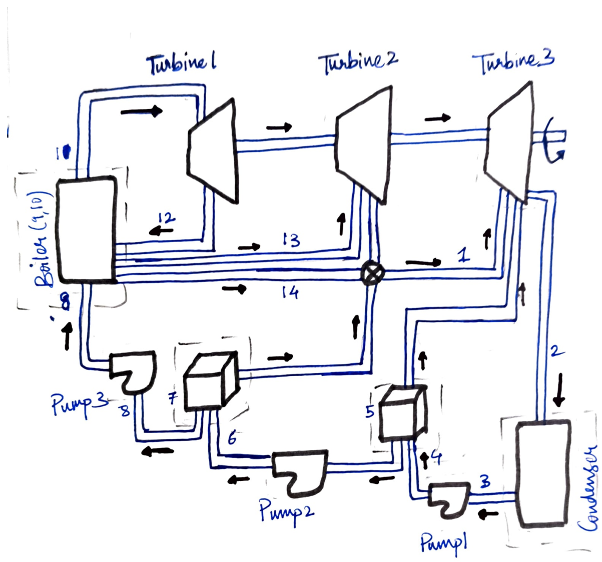

Figure 14: Control Volume diagram for Rankine cycle with Two Reheater and Two Regeneration.

- The Quality of this cycle is 90.1028 %
- The Efficiency of this cycle is 48.8825 %
- The most optimized cycle among the modified cycles used.

6 Matlab Code Snippets for Modified Rankine cycle

6.1 One Reheater

```
w = Solution('liquidvapor.cti', 'water');
P3 = 10e+3;         % inlet condenser pressure (in Pa)
P2 = P3;
P4 = 15e+6;         % inlet boiler pressure (in Pa)
P5 = P4;
P7 = P4;
T7 = 500 + 273.15;
%% state 7
set(w, 'P', P7, 'T', T7);
h7 = enthalpy_mass(w);
s7 = entropy_mass(w);
%% state 8
s8 = s7;
P8 = 3e+6;
setState_SP(w, [s8, P8]);
h8 = enthalpy_mass(w);
%% state 1
P1 = P8;
T1 = T7;
set(w, 'P', P1, 'T', T1);
h1 = enthalpy_mass(w);
s1 = entropy_mass(w);
%% state 2
s2 = s1;
setState_SP(w, [s2, P2]);
h2 = enthalpy_mass(w);
%% state 3
setState_Psat(w, [P3, 0]);
h3 = enthalpy_mass(w);
s3 = entropy_mass(w);
%% state 4
s4 = s3;
setState_SP(w, [s4, P4]);
h4 = enthalpy_mass(w);
%% Calculating the efficiency
efficiency = 1 - (h2 - h3)/(h7 - h4 + h1 - h8);
%% quality at state 2
setState_Psat(w, [P2, 0.0]);
sf = entropy_mass(w);
setState_Psat(w, [P2, 1.0]);
sg = entropy_mass(w);
sfg = sg - sf;
x = (s2 - sf)/sfg;
```

6.2 One Reheater and One Regeneration

```
%% water object
w = Solution('liquidvapor.cti','water');
%% given values of states
P3 = 10E+3;
P4 = 0.8E+6;
P5 = P4;
P6 = 15E+6;                 % inlet boiler pressure (in Pa)
P7 = P6;
P8 = P6;
P9 = P6;
T9 = 500 + 273.15;
P10 = 3.8E+6;                            % vary
P1 = P10;
T1 = 500+273.15;                         % vary (but less than 500 degree C)
P1_ = P4;
P2 = P3;                     % inlet condensor pressure (in Pa)
%% State 3
setState_Psat(w ,[P3 ,0]);
h3 = enthalpy_mass(w);
s3 = entropy_mass(w);
%% State 4
s4 = s3;
setState_SP(w, [s4 ,P4]);
h4 = enthalpy_mass(w);
%% State 5
setState_Psat(w ,[P5 ,0]);
h5 = enthalpy_mass(w);
s5 = entropy_mass(w);
%% State 6
s6 = s5;
setState_SP(w ,[s5,P6]);
h6 = enthalpy_mass(w);
%% State 7
setState_Psat(w, [P7,0]);
h7 = enthalpy_mass(w);
s7 = entropy_mass(w);
%% State 8
setState_Psat(w ,[P8 ,1]);
h8 = enthalpy_mass(w);
s8 = entropy_mass(w);
```

```
%% State 9
set(w,'P',P9,'T',T9);
h9 = enthalpy_mass(w);
s9 = entropy_mass(w);
%% State 10
s10 = s9;
setState_SP(w, [s10,P10]);
h10 = enthalpy_mass(w);
%% State 1
set(w,'P',P1,'T',T1);
h1 = enthalpy_mass(w);
s1 = entropy_mass(w);
%% State 1_
s1_ = s1;
setState_SP(w,[s1_,P1_]);
h1_ = enthalpy_mass(w);
%% State 2
s2 = s1;
setState_SP(w ,[s2 ,P2]);
h2 = enthalpy_mass(w);
setState_Psat(w ,[P2,0]);
hf = enthalpy_mass(w);
setState_Psat(w ,[P2,1]);
hg = enthalpy_mass(w);
hfg = hg-hf;
x = (h2-hf)/hfg;
m4_5 = ((h1_-h5)/(h1_-h4));
qout = m4_5*(h2-h3);
qin = h9-h6+h1-h10;
efficiency = 1-(qout/qin);
```

6.3 One Reheater and Two Regeneration

```
%% water object
w = Solution('liquidvapor.cti','water');
%% given states
P3 = 10E+3;
P4 = 0.8E+6;                % Vary
P5 = P4;
P6 = 3.7E+6;                % vary
P7 = P6;
P8 = 15E+6;
P9 = P8;                   % inlet boiler pressure (in Pa)
P10 = P8;
P11 = P8;
T11 = 500 + 273.15;
P12 = P6;
P1 = P6;
T1 = 500 + 273.15;                  % vary (but less than 500 degree C)
P1_ = P4;
P2 = P3;                   % inlet condenser pressure (in Pa)
%% State 3
setState_Psat(w, [P3 ,0]);
h3 = enthalpy_mass(w);
s3 = entropy_mass(w);
%% State 4
s4 = s3;
setState_SP(w ,[s4 ,P4]);
h4 = enthalpy_mass(w);
%% State 5
setState_Psat(w ,[P5 ,0]);
h5 = enthalpy_mass(w);
s5 = entropy_mass(w);
%% State 6
s6 = s5;
setState_SP(w ,[s6 ,P6]);
h6 = enthalpy_mass(w);
%% State 7
setState_Psat(w, [P7 ,0]);
h7 = enthalpy_mass(w);
s7 = entropy_mass(w);
%% State 8
s8 = s7;
setState_SP(w, [s8 ,P8]);
h8 = enthalpy_mass(w);
```

```
%% State 9
setState_Psat(w, [P9 ,0]);
h9 = enthalpy_mass(w);
%% State 10
setState_Psat(w, [P10,1]);
h10 = enthalpy_mass(w);
%% State 11
set(w,'P',P11,'T',T11);
h11 = enthalpy_mass(w);
s11 = entropy_mass(w);
%% State 12
s12 = s11;
setState_SP(w, [s12,P12]);
h12 = enthalpy_mass(w);
%% State 1
set(w,'P',P1,'T',T1);
h1 = enthalpy_mass(w);
s1 = entropy_mass(w);
%% State 1_
s1_ = s1;
setState_SP(w, [s1_,P1_]);
h1_ = enthalpy_mass(w);
%% State 2
s2 = s1;
setState_SP(w, [s2 ,P2]);
h2 = enthalpy_mass(w);
setState_Psat(w, [P2, 0]);
hf = enthalpy_mass(w);
setState_Psat(w, [P2, 1]);
hg = enthalpy_mass(w);
hfg = hg-hf;
x = ((h2-hf)/hfg)*100;
m4_6 = ((h1_-h5)/(h1_-h4));
m7_6 = ((h6-h12)/(h7-h12));
qout = m4_6*(h2-h3);
qin = (m7_6*(h11-h8))+h1-h12;
efficiency = (1-(qout/qin))*100;
```

6.4 Two Reheater and One Regeneration

```
%% water object
w = Solution('liquidvapor.cti','water');
%% given states
P3 = 10E+3;
P4 = 0.7E+6;                                       % Vary
P5 = P4;
P6 = 15E+6;                    % inlet boiler pressure (in Pa)
P7 = P6;
P8 = P6;
P9 = P6;
T9 = 499 + 273.15;             % vary (but less than 500 degree C)
P10 = 6.5E+6;                                      % vary
P11 = P10;
T11 = 500 + 273.15;
P12 = 2E+6;                                        % vary
P1 = P12;
T1 = 500 + 273.15;             % vary (but less than 500 degree C)
P1_ = P4;
P2 = P3;                       % inlet condensor pressure (in Pa)
%% State 3
setState_Psat(w, [P3, 0]);
h3 = enthalpy_mass(w);
s3 = entropy_mass(w);
%% State 4
s4 = s3;
setState_SP(w, [s4, P4]);
h4 = enthalpy_mass(w);
%% State 5
setState_Psat(w, [P5,0]);
h5 = enthalpy_mass(w);
s5 = entropy_mass(w);
%% State 6
s6 = s5;
setState_SP(w, [s6, P6]);
h6 = enthalpy_mass(w);
%% State 7
setState_Psat(w, [P7, 0]);
h7 = enthalpy_mass(w);
s7 = entropy_mass(w);
%% State 8
setState_Psat(w, [P8, 1]);
h8 = enthalpy_mass(w);
```

```
%% State 9
set(w,'P',P9,'T',T9);
h9 = enthalpy_mass(w);
s9 = entropy_mass(w);
%% State 10
s10 = s9;
setState_SP(w, [s10, P10]);
h10 = enthalpy_mass(w);
%% State 11
set(w,'P',P11,'T',T11);
h11 = enthalpy_mass(w);
s11 = entropy_mass(w);
%% State 12
s12 = s11;
setState_SP(w, [s12, P12]);
h12 = enthalpy_mass(w);
%% State 1
set(w,'P',P1,'T',T1);
h1 = enthalpy_mass(w);
s1 = entropy_mass(w);
%% State 1_
s1_ = s1;
setState_SP(w, [s1_, P1_]);
h1_ = enthalpy_mass(w);
%% State 2
s2 = s1;
setState_SP(w, [s2, P2]);
h2 = enthalpy_mass(w);
setState_Psat(w, [P2,0]);
sf = entropy_mass(w);
hf = enthalpy_mass(w);

setState_Psat(w, [P2, 1]);
sg = entropy_mass(w);
hg = enthalpy_mass(w);

hfg = hg-hf;
sfg = sg-sf;
%% calculations
x = (h2 - hf)/hfg;
m4_5 = ((h1_ - h5)/(h1_ - h4));
qout = m4_5 * (h2 - h3);
qin = h9 - h6 + h11 - h10 + h1 - h12;
efficiency = 1 - (qout/qin);
```

6.5 Two Reheater and Two Regeneration

```
w = Solution('liquidvapor.cti','water');
%% states
P3 = 10E+3;
P4 = 0.05E+6;                % Vary
P5 = P4;
P6 = 2.1E+6;                 % vary
P7 = P6;
P8 = 15E+6;              % inlet boiler pressure (in Pa)
P9 = P8;
P10 = P8;
P11 = P8;
T11 = 500 + 273.15;
P12 = 1.8E+6;            % vary
P13 = P12;
T13 = 500 + 273.15;
P14 = P6;
P1 = P6;
T1 = 500 + 273.15;
P1_ = P4;
P2 = P3;                 % inlet condenser pressure (in Pa)
%% State 3
setState_Psat(w, [P3, 0]);
h3 = enthalpy_mass(w);
s3 = entropy_mass(w);
%% State 4
s4 = s3;
setState_SP(w, [s4, P4]);
h4 = enthalpy_mass(w);
%% State 5
setState_Psat(w, [P5, 0]);
h5 = enthalpy_mass(w);
s5 = entropy_mass(w);
%% State 6
s6 = s5;
setState_SP(w,[s6, P6]);
h6 = enthalpy_mass(w);
%% State 7
setState_Psat(w, [P7, 0]);
h7 = enthalpy_mass(w);
s7 = entropy_mass(w);
%% State 8
s8 = s7;
setState_SP(w, [s8, P8]);
h8 = enthalpy_mass(w);
```

```
%% State 9
setState_Psat(w, [P9, 0]);
h9 = enthalpy_mass(w);
%% State 10
setState_Psat(w, [P10, 1]);
h10 = enthalpy_mass(w);
%% State 11
set(w,'P',P11,'T',T11);
h11 = enthalpy_mass(w);
s11 = entropy_mass(w);
%% State 12
s12 = s11;
setState_SP(w, [s12, P12]);
h12 = enthalpy_mass(w);
%% State 13
set(w,'P',P13,'T',T13);
h13 = enthalpy_mass(w);
s13 = entropy_mass(w);
%% State 14
s14 = s13;
setState_SP(w, [s14,P14]);
h14 = enthalpy_mass(w);
%% State 1
set(w,'P',P1,'T',T1);
h1 = enthalpy_mass(w);
s1 = entropy_mass(w);
%% State 1_
s1_ = s1;
setState_SP(w ,[s1_, P1_]);
h1_ = enthalpy_mass(w);
%% State 2
s2 = s1;
setState_SP(w, [s2, P2]);
h2 = enthalpy_mass(w);
setState_Psat(w, [P2, 0]);
hf = enthalpy_mass(w);
setState_Psat(w,[P2, 1]);
hg = enthalpy_mass(w);
hfg = hg-hf;
x = ((h2-hf)/hfg)*100;
m4_5 = ((h1_-h5)/(h1_-h4));
m7_5 = ((h6-h12)/(h7-h12));
qout = m4_5*( h2 - h3 );
qin = ( m7_5 * (h11-h8+h13-h12) )+h1-h14;
efficiency = (1-(qout/qin))*100;
```

7 Discussion on Varying the Boiler and Condenser Pressure

To visualize the changes in efficiency and net work output while changing the condenser and boiler pressure. A contour plot has been made. A contour plot is a graphical representation of three-dimensional data in two dimensions. It is used to display the variation of a dependent variable (usually represented by color, here efficiency/net work done) with respect to two independent variables (here boiler and condenser pressure). Contour plots are particularly useful for visualizing the behavior of a function over a specific range of input values.

7.1 For One Reheater and Two Regeneration

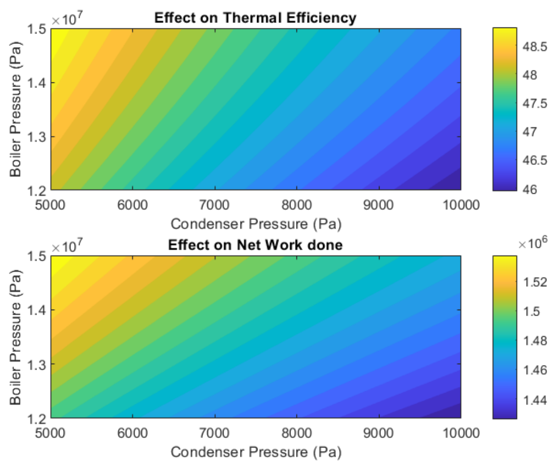

Figure 15: Efficiency and Net work distribution as condensor and boiler pressure is varied.

From the above contour plot, we can clearly see that on keeping either the condenser or boiler pressure, both the efficiency and net work output decreases. The maximum efficiency is 48.5 % and maximum work done is 1.52 MW at boiler pressure of 1.5 MPa and condenser pressure of 5kPa. This shows that reducing the Condenser pressure increases the efficiency of the modified rankine cycle, we can further change the efficiency by changing other parameters which were varied in part a of the project.

7.2 For Two Reheater and One Regeneration

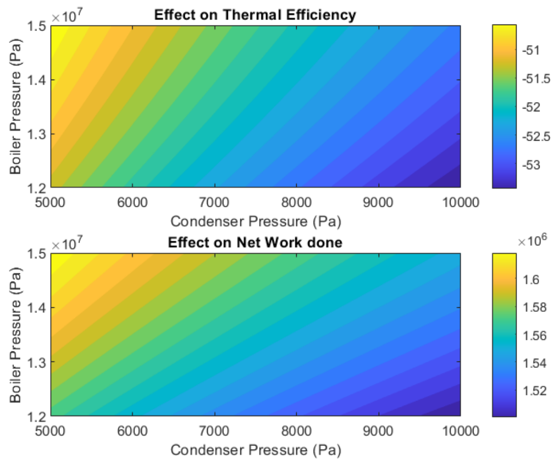

Figure 16: Efficiency and Net work distribution as condensor and boiler pressure is varied.

From the above contour plot, we can clearly see that on keeping either the condenser or boiler pressure, the efficiency and net work output decrease. The maximum efficiency is 51 %, and the maximum work done is 1.6 MW at a boiler pressure of 15 MPa and Condenser pressure of 5 kPa. This shows that reducing the Condenser pressure increases the efficiency of the modified Rankine cycle; we can further change the efficiency by changing other parameters, which were varied in part a of the project.

7.3 For Two Reheater and Two Regeneration

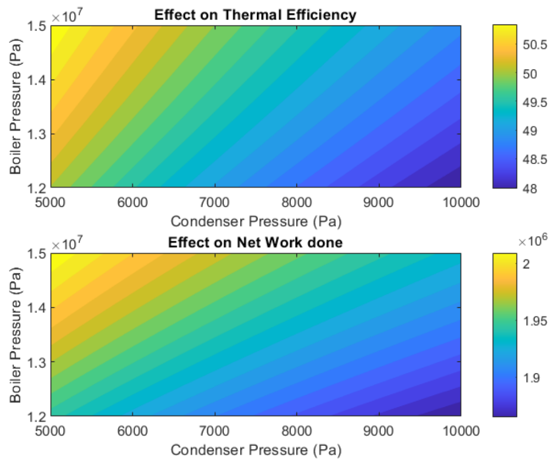

Figure 17: Efficiency and Net work distribution as condensor and boiler pressure is varied.

From the above contour plot, we can clearly see that on keeping either the condenser or boiler pressure, the efficiency and net work output decrease. The maximum efficiency is 50.5 %, and the maximum work done is 2 MW at a boiler pressure of 15 MPa and Condenser pressure of 5 kPa. This shows that reducing the Condenser pressure increases the efficiency of the modified Rankine cycle; we can further change the efficiency by changing other parameters, which were varied in part a of the project. From all the three modified rankine cycles which we have done, we can say the following:

- If the boiler and condenser pressure are kept constant, then most of the work can be extracted from the last modification (i.e, two reheaters and two regenerations)
- The cycles may be able to beat the last modification; even then, we may not be able to extract the maximum amount of work (two reheaters and two regeneration).
- It is important to know that the quality will also be maximum for two reheaters and two regenerations. Of course, we can increase the quality by adding reheaters, but to be more on an efficient side, this case seems to work the best.

8 Code Snippets for Part b

8.1 For One Reheater and Two Regeneration

```
Pb_range = linspace(12E+6, 15E+6, 20); % range of boiler pressures from 12 MPa to 15 MPa
Pc_range = linspace(5E+3, 10E+3, 20);  % range of condenser pressures from 5 kPa to 10 kPa

%% initialize arrays to store results
efficiency_results = zeros(length(Pc_range), length(Pb_range));
w_net_results = zeros(length(Pc_range), length(Pb_range));

%% loop through different values of Pb and Pc
for i = 1:length(Pb_range)
    for j = 1:length(Pc_range)
        P8 = Pb_range(i);
        P2 = Pc_range(j);
        [efficiency, w_net] = calculate_cycle_performance(P2, P8);
        efficiency_results(j, i) = efficiency;
        w_net_results(j, i) = w_net;
    end
end

%% plots
figure;
subplot(2, 1, 1);
contourf(Pc_range, Pb_range, efficiency_results', 20, 'LineColor', 'none');
colorbar;
xlabel('Condenser Pressure (Pa)');
ylabel('Boiler Pressure (Pa)');
title('Effect on Thermal Efficiency');

subplot(2, 1, 2);
contourf(Pc_range, Pb_range, w_net_results', 20, 'LineColor', 'none');
colorbar;
xlabel('Condenser Pressure (Pa)');
ylabel('Boiler Pressure (Pa)');
title('Effect on Net Work done');

%% cycle performance
function [efficiency, w_net] = calculate_cycle_performance(P2, P8)
    %% water object
    w = Solution('liquidvapor.cti','water');
    %% given state
    P3 = 10E+3;
    P4 = 0.8E+6;                % Vary
    P5 = P4;
```

The rest of the code is same as part a.

8.2 For Two reheaters and One regenerations

```
Pb_range = linspace(12E+6, 15E+6, 20); % range of boiler pressures from 12 MPa to 15 MPa
Pc_range = linspace(5E+3, 10E+3, 20);  % range of condenser pressures from 5 kPa to 10 kPa
%% initialize arrays to store results
efficiency_results = zeros(length(Pc_range), length(Pb_range));
w_net_results = zeros(length(Pc_range), length(Pb_range));
%% loop through different values of Pb and Pc
for i = 1:length(Pb_range)
    for j = 1:length(Pc_range)
        P6 = Pb_range(i);
        P2 = Pc_range(j);
        [efficiency, w_net] = calculate_cycle_performance(P2, P6);
        efficiency_results(j, i) = efficiency;
        w_net_results(j, i) = w_net;
    end
end

%% plots
figure;
subplot(2, 1, 1);
contourf(Pc_range, Pb_range, efficiency_results', 20, 'LineColor', 'none');
colorbar;
xlabel('Condenser Pressure (Pa)');
ylabel('Boiler Pressure (Pa)');
title('Effect on Thermal Efficiency');

subplot(2, 1, 2);
contourf(Pc_range, Pb_range, w_net_results', 20, 'LineColor', 'none');
colorbar;
xlabel('Condenser Pressure (Pa)');
ylabel('Boiler Pressure (Pa)');
title('Effect on Net Work done');

%% cycle performance
function [efficiency, w_net] = calculate_cycle_performance(P2, P6)
    w = Solution('liquidvapor.cti','water');
    %% given states
    P3 = 10E+3;
    P4 = 0.7E+6;                                       % Vary
    P5 = P4;
    P7 = P6;
    P8 = P6;
    P9 = P6;
    T9 = 499 + 273.15;                  % vary (but less than 500 degree C)
    P10 = 6.5E+6;                                      % vary
    P11 = P10;
```

The rest of the code is same as part a.

8.3 For Two reheaters and Two regenerations

```
Pb_range = linspace(12E+6, 15E+6, 20); % Range of boiler pressures from 12 MPa to 15 MPa
Pc_range = linspace(5E+3, 10E+3, 20);  % Range of condenser pressures from 5 kPa to 10 kPa
%% initialize arrays to store results
efficiency_results = zeros(length(Pc_range), length(Pb_range));
w_net_results = zeros(length(Pc_range), length(Pb_range));
%% loop through different values of Pb and Pc
for i = 1:length(Pb_range)
    for j = 1:length(Pc_range)
        P8 = Pb_range(i);
        P2 = Pc_range(j);
        [efficiency, w_net] = calculate_cycle_performance(P2, P8);
        efficiency_results(j, i) = efficiency;
        w_net_results(j, i) = w_net;
    end
end
%% plots
figure;
subplot(2, 1, 1);
contourf(Pc_range, Pb_range, efficiency_results', 20, 'LineColor', 'none');
colorbar;
xlabel('Condenser Pressure (Pa)');
ylabel('Boiler Pressure (Pa)');
title('Effect on Thermal Efficiency');

subplot(2, 1, 2);
contourf(Pc_range, Pb_range, w_net_results', 20, 'LineColor', 'none');
colorbar;
xlabel('Condenser Pressure (Pa)');
ylabel('Boiler Pressure (Pa)');
title('Effect on Net Work done');

%% cycle performance
function [efficiency, w_net] = calculate_cycle_performance(P2, P8)
    %% water object
    w = Solution('liquidvapor.cti','water');
    %% states
    P3 = 10E+3;
    P4 = 0.05E+6;               % Vary
    P5 = P4;
    P6 = 2.1E+6;                % vary
    P7 = P6;
    P9 = P8;
    P10 = P8;
    P11 = P8;
    T11 = 500 + 273.15;
```

The rest of the code is same as part a.

9 Acknowledgment

We extend our heartfelt appreciation to all those who have contributed to the successful completion of the project. This endeavor would not have been possible without the combined efforts, expertise, and support of various individuals, my team and labs.

First and foremost, we express our gratitude to Prof. Atul, our project advisor, whose invaluable guidance, insightful suggestions, and unwavering encouragement have been instrumental in shaping the direction of this project. Your dedication to fostering our learning and research journey has been truly inspiring.We would also want to thank all of the Teaching Assistants for their assistance.

We are also indebted to the faculty members and staff of IIT Gandhinagar, whose constant encouragement and resources facilitated the seamless execution of this project. The academic environment provided by each department has been an essential catalyst in nurturing our curiosity and fueling our intellectual growth.

We extend our appreciation to our fellow peers and colleagues who provided valuable insights, engaged in stimulating discussions, and shared their diverse perspectives throughout the project's duration. Your collaboration has enriched our understanding and broadened our horizons.

In essence, this project stands as a testament to the combined efforts of a multitude of individuals and entities, all of whom have contributed their expertise, time, and enthusiasm. We are deeply grateful for the opportunity to work on this project and for the support we have received throughout its journey.

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