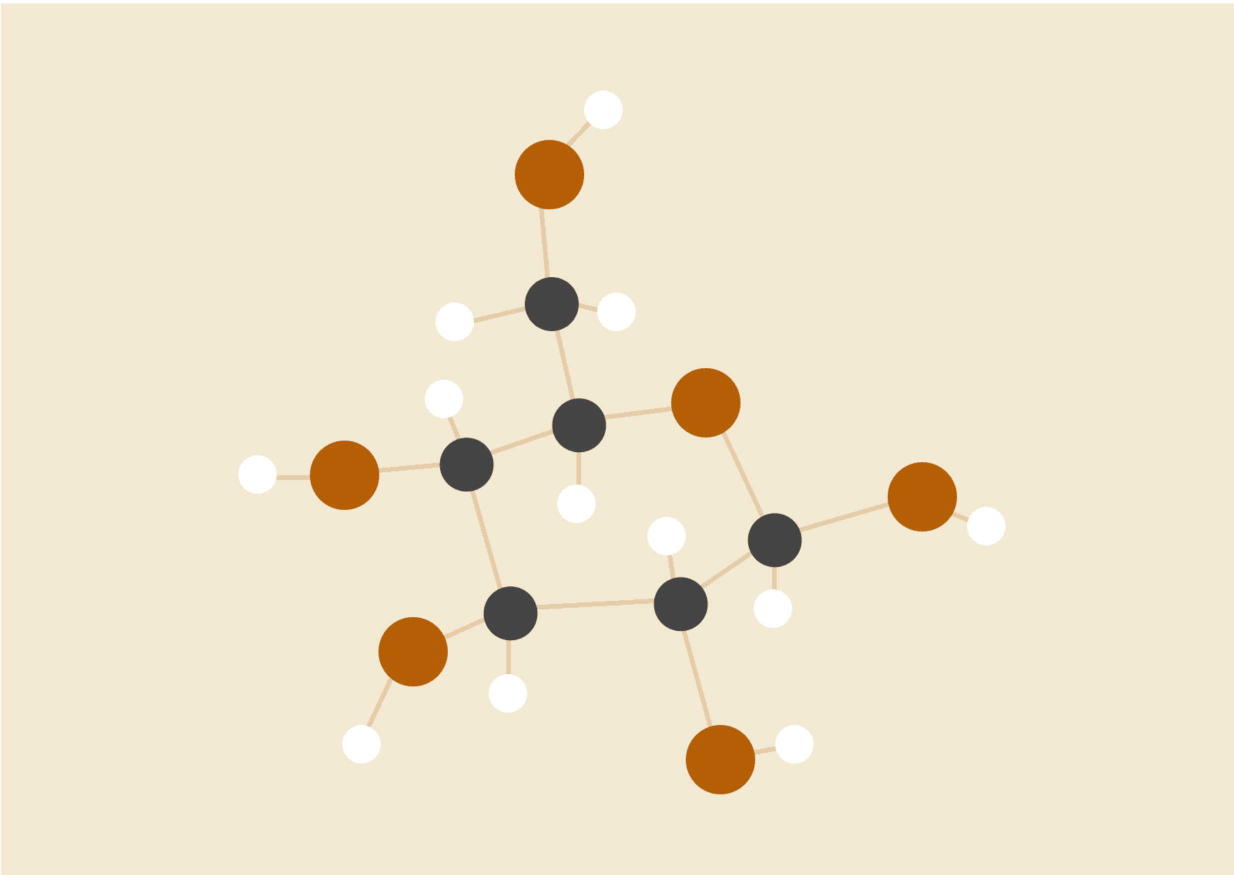
ES 211: PROJECT

Improving the efficiency of a power-plant operating on a basic ideal Rankine cycle



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INTRODUCTION

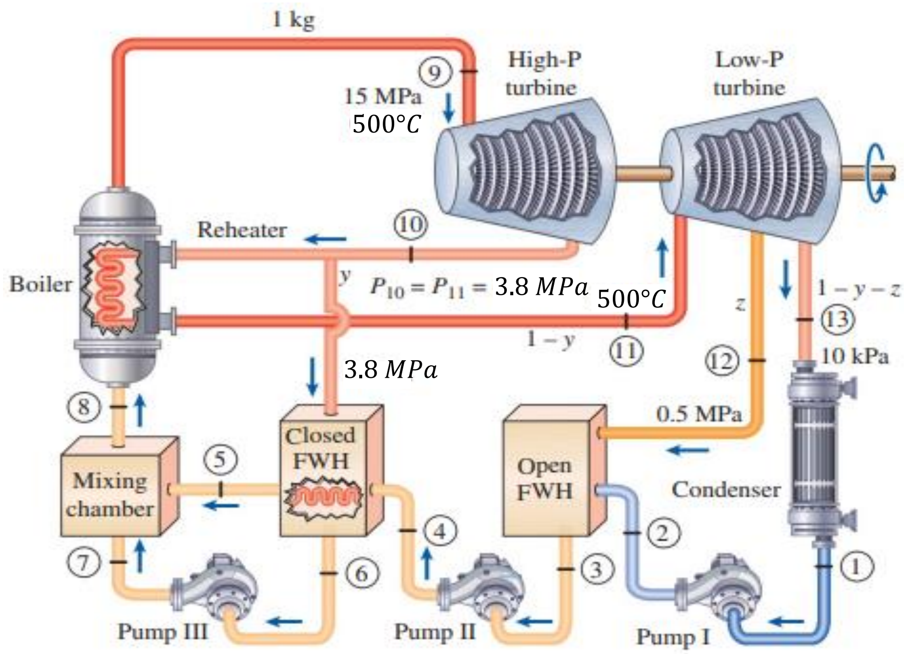
In the ever-evolving realm of energy innovation, engineers and researchers persistently strive to enhance the performance of power plant cycles, aiming for improved efficiency and sustainable power generation. This project is singularly focused on optimizing the venerable Rankine cycle, a cornerstone in the thermodynamics of steam power plants. The primary goal is to elevate thermal efficiency and steam quality within set constraints, posing a challenge that necessitates a meticulous exploration of the parameter space.

Presently operating at a thermal efficiency of 41% and a steam quality of 76%, with a boiler pressure (Pb) of 15 MPa and a condenser pressure (Pc) of 10 kPa, the primary objective is to surpass the 46% thermal efficiency mark while simultaneously pushing the steam quality beyond 85%.

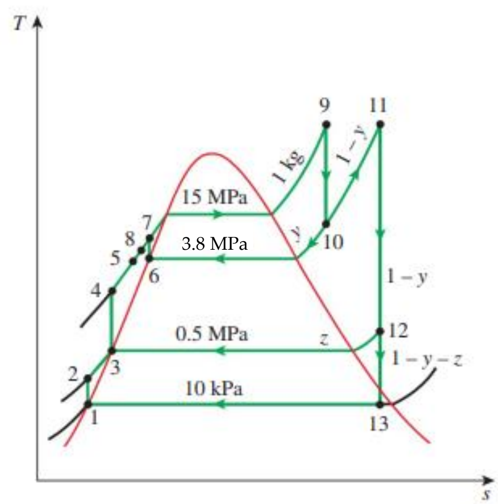
Maintaining specific pressures and temperatures demands a thoughtful exploration of the parameter space to discover the optimal combination that realizes the desired performance improvements.

This undertaking involves a systematic examination of the modified Rankine cycle, with a focus on varying key parameters illustrated through a Temperature-Entropy (T-s) diagram. Additionally, a detailed analysis will be presented, delving into control volumes and energy balance equations for each component in the cycle. The insights derived from these analyses will be woven into a comprehensive discussion, exploring the nuanced impact of parameter variations on the thermal efficiency and net-work output of the modified ideal Rankine cycle. These insights aspire to contribute valuable knowledge to the ongoing enhancement of power plant performance, all in the relentless pursuit of sustainable and efficient energy solutions.

PROCESS



Schematic diagram of the components in the Power Plant



T-s diagram for the above process

Assumptions:
All pumps are adiabatic.
Only work is done by the pump
Here we assumed $\dot{m}$ = 1 kg/s
Boiler and condenser are not doing any work.
We are assuming the turbine to be adiabatic and isentropic.
The system is steady. Changes in the Kinetic and Potential Energy are negligible.

Pump: (valid for all pump 1, 2, and 3)
In the Ideal Reheat–Regenerative Rankine Cycle, pumps play a vital role in maintaining the flow of the working fluid. There are typically two pumps in this cycle:

1. **Feedwater Pump:**
   - Role: Raises the pressure of the feedwater before it enters the boiler.
   - Importance: Ensures an adequate and pressurized supply of water to the boiler for steam generation.
2. **Condensate Pump:**
   - Role: Increases the pressure of the condensed water before it enters the closed feedwater heater.
   - Importance: Facilitates the efficient transfer of heat in the regenerative part of the cycle by maintaining proper pressure levels.

$$\dot{E}_{in} - \dot{E}_{out} + \dot{E}_{gen} = \frac{dE}{dt}|_{sys}$$
$$\dot{E}_{gen} = 0$$
$$\frac{dE}{dt}|_{sys} = 0$$
$$\dot{E}_{in} = \dot{E}_{out}$$
$$h_{in} + \frac{\dot{W}}{\dot{m}} = h_{out}$$
Units: J/kg

Energy balance on Pump 1:
$W_1 = (h_2 - h_1)$
$W_1 = 495.03$ J/kg

Open FWH:
In the Ideal Reheat–Regenerative Rankine Cycle, the open Feedwater Heater (FWH) is responsible for further preheating the feedwater by direct contact with steam extracted from the turbine. This process enhances the feedwater temperature before it enters the boiler, improving overall cycle efficiency by reducing the amount of external heat input required.

$\dot{E}_{in} - \dot{E}_{out} + \dot{E}_{gen} = \frac{dE}{dt}|_{sys}$
$\dot{E}_{gen} = 0$
$\frac{dE}{dt}|_{sys} = 0$
$\dot{E}_{in} = \dot{E}_{out}$
$h_{in} = h_{out}$
Units: J/kg

Energy balance on Open FWH:
$zh_{12} + (1 - y - z)h_2 = (1 - y)h_3$
$z(h_{12} - h_2) = (1 - y)(h_3 - h_2)$
$\frac{z}{1 - y} = \frac{h_3 - h_2}{h_{12} - h_2}$
$z = \frac{h_3 - h_2}{h_{12} - h_2}(1 - y)$
$z = 0.1354$

Energy balance on Pump 2:
$W_2 = (h_4 - h_3)$
$W_2 = 3.60\ kJ/kg$

Closed FWH:
In the Ideal Reheat–Regenerative Rankine Cycle, the closed Feedwater Heater (FWH) is responsible for preheating the feedwater by transferring heat from steam extracted at various turbine stages. This preheating reduces the amount of heat that needs to be supplied in the boiler, improving the overall efficiency of the cycle.
$\dot{E}_{in} - \dot{E}_{out} + \dot{E}_{gen} = \frac{dE}{dt}|_{sys}$
$\dot{E}_{gen} = 0$
$\frac{dE}{dt}|_{sys} = 0$
$\dot{E}_{in} = \dot{E}_{out}$
$h_{in} = h_{out}$
Units: J/kg

Energy balance on closed FWH:
$yh_{10} + (1 - y)h_4 = yh_6 + (1 - y)h_5$
$y(h_{10} + h_5 - h_6 - h_4) = h_5 - h_4$
$y = \frac{h_5 - h_4}{h_{10} + h_5 - h_6 - h_4}$
$y = 0.1869$

Energy balance on Pump 3:
$W_3 = (h_7 - h_6)$
$W_3 = 13.948\ kJ/kg$

Mixing Chamber:
In the Ideal Reheat–Regenerative Rankine Cycle, the mixing chamber is responsible for combining steam from the high-pressure turbine with reheated steam before entering the low-pressure turbine. This mixing optimizes the overall temperature and pressure conditions for improved efficiency during the expansion process.
$\dot{E}_{in} - \dot{E}_{out} + \dot{E}_{gen} = \frac{dE}{dt}|_{sys}$
$\dot{E}_{gen} = 0$
$\frac{dE}{dt}|_{sys} = 0$
$\dot{E}_{in} = \dot{E}_{out}$
$h_{in} = h_{out}$
Units: J/kg

Energy balance on the Mixing Chamber:
$yh_7 + (1-y)h_5 = h_8$
$y(h_7 - h_5) = h_8 - h_5$
$y = \frac{h_8 - h_5}{h_7 - h_5}$
$y = 0.1869$

Boiler:
The boiler performs two key functions in the cycle:
Reheat Process: The boiler reheats steam that has passed through the high-pressure turbine, maintaining a high average temperature during the expansion process. This enhances cycle efficiency.
Regeneration: The boiler is involved in the regeneration process, where heat extracted from steam at different turbine stages is used to preheat feedwater before entering the boiler. This reduces the heat input needed, improving overall cycle efficiency.
$\dot{E}_{in} - \dot{E}_{out} + \dot{E}_{gen} = \frac{dE}{dt}|_{sys}$
$\dot{E}_{gen} = 0$
$\frac{dE}{dt}|_{sys} = 0$
$\dot{E}_{in} = \dot{E}_{out}$

$$h_{in} + \frac{\dot{Q}}{\dot{m}} = h_{out}$$
Units: J/kg

Energy balance on Boiler:

$$Q_{in} = (h_9 - h_8) + (h_{11} - h_{10})$$
$$Q_{in} = 2.74\ MJ/kg$$

High Pressure Turbine:

In the Ideal Reheat–Regenerative Rankine Cycle, the high-pressure turbine is responsible for expanding high-pressure steam, converting its thermal energy into mechanical work. The role of the high-pressure turbine is to extract work from the steam before it undergoes reheating, contributing to the overall efficiency of the power generation cycle.

$$\dot{E}_{in} - \dot{E}_{out} + \dot{E}_{gen} = \frac{dE}{dt}|_{sys}$$
$$\dot{E}_{gen} = 0$$
$$\frac{dE}{dt}|_{sys} = 0$$
$$\dot{E}_{in} = \dot{E}_{out}$$
$$h_{in} = h_{out} + \frac{\dot{W}}{\dot{m}}$$
Units: J/kg

Energy balance on High Pressure Turbine:

$$W_{1_{out}} = h_9 - h_{10}$$
$$W_{1_{out}} = 369.5\ kJ/kg$$

Low Pressure Turbine:

In the Ideal Reheat–Regenerative Rankine Cycle, the low-pressure turbine expands the reheated steam, converting its thermal energy into mechanical work. This turbine's role is to extract additional work from the steam after the reheat process, contributing to the overall efficiency of the power generation cycle.

$$\dot{E}_{in} - \dot{E}_{out} + \dot{E}_{gen} = \frac{dE}{dt}|_{sys}$$
$$\dot{E}_{gen} = 0$$
$$\frac{dE}{dt}|_{sys} = 0$$
$$\dot{E}_{in} = \dot{E}_{out}$$
$$h_{in} = h_{out} + \frac{\dot{W}}{\dot{m}}$$

Units: J/kg

Energy balance on Low Pressure Turbine:

$W_{2_{out}} = (1-y)(h_{11}-h_{12}) + (1-y-z)(h_{12}-h_{13})$

$W_{2_{out}} = 884.89\ kJ/kg$

Condenser:

The condenser performs the following function in the cycle:

In the Ideal Reheat–Regenerative Rankine Cycle, the condenser plays a crucial role in condensing the exhaust steam from the turbine into liquid water. This condensation releases heat, allowing the working fluid to be pumped back into the boiler, completing the cycle. The condenser's role is to maximize the efficiency of the cycle by facilitating the heat rejection process and maintaining a pressure difference across the turbine.

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

$\dot{E}_{gen} = 0$

$\frac{dE}{dt}|_{sys} = 0$

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

$h_{in} = h_{out} + \frac{\dot{Q}}{\dot{m}}$

Units: J/kg

Energy balance on Condenser:

$Q_{out} = h_{13} - h_1$

$Q_{out} = 2.06\ MJ/kg$

CODE

```
clc;
clear;

w=Solution('liquidvapor.cti','water');

P1= 10*10^3;    % P1 - condenser pressure (Pc)
P2= 15*10^6;    % P2 - boiler pressure (Pb)
P3= 3.8*10^6;   % P3 - reheat pressure, extraction pressure for closed fwh
P4= 0.5*10^6;   % P4 - extraction pressure for open fwh

T9= 500+273.15;

%state 9
set(w,'P',P2,'T',T9);
h9=enthalpy_mass(w);
s9=entropy_mass(w);

%state 10
s10 = s9;
setState_SP(w,[s10,P3]);
h10=enthalpy_mass(w);

%state 11
set(w,'P',P3,'T',T9)
h11=enthalpy_mass(w);
s11=entropy_mass(w);

%state 12
s12 = s11;
setState_SP(w,[s12,P4]);
h12=enthalpy_mass(w);
x12=vaporFraction(w);

% state 13
s13 = s11;
setState_SP(w,[s13,P1]);
h13=enthalpy_mass(w);
x13=vaporFraction(w);

% steam quality (x13)
if (x13 < 0.85 )
    disp('Steam quality less than 85%.');
end

% state 1
set(w,'P',P1,'Vapor',0);
T9=temperature(w);
v1=1/density(w);
h1=enthalpy_mass(w);
s1=entropy_mass(w);

% state 2
h2 = h1 + v1*(P4-P1);

```

```
% state 3
x3=0;
set(w,'P',P4,'Vapor',x3);
h3=enthalpy_mass(w);
s3=entropy_mass(w);
v3=1/density(w);

% state 4
h4 = h3 + v3*(P3 - P4);

% state 6
P6=P3;
x6=0;
set(w,'P',P6,'Vapor',x6);
h6=enthalpy_mass(w);
s6=entropy_mass(w);
v6=1/density(w);

%state 5
h5 = h6;

% calculating y
y = (h5 - h4)/(h10 - h6 + h5 - h4);

% calculating z
z = ((1-y)*(h3 - h2))/(h12 - h2);

```

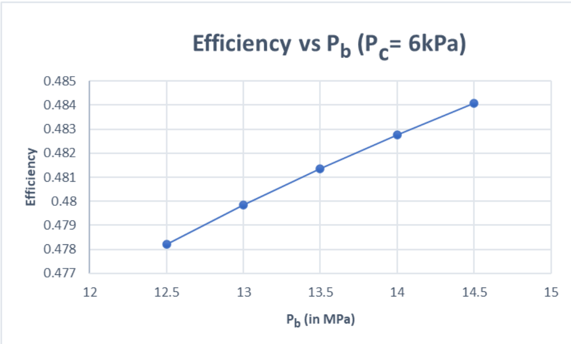
```
% state 7
h7 = h6 + v6*(P2 - P3);

% state 8
h8 = h5*(1 - y) + y*h7;

% calculating pump work, turbine work and Qin
Wp = (1-y-z)*(h2 - h1) + (1-y)*(h4 - h3) + y*(h7 - h6);
Wt = h9 - h10 + (1-y)*(h11 - h12) + (1-y-z)*(h12 - h13);
Qin = h9 - h8 + (1-y)*(h11 - h10);

%calculating efficiency
eff = (Wt - Wp)/Qin;

%calculating net work output
Wnet=Wt-Wp;
```

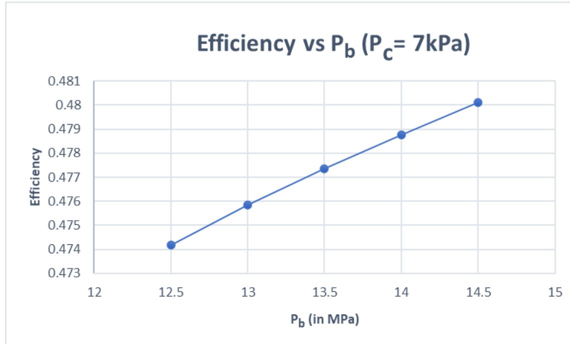
Output of the code:

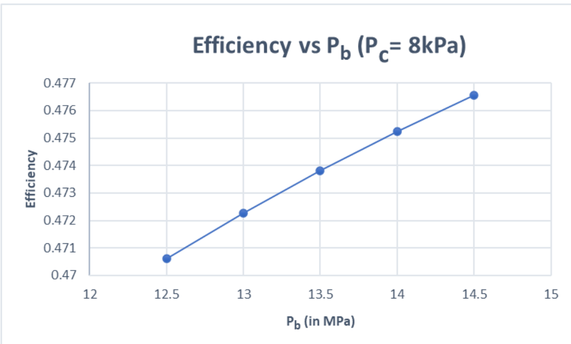
```
>> eff

eff =

    0.4718

>> x13

x13 =

    0.8621
```

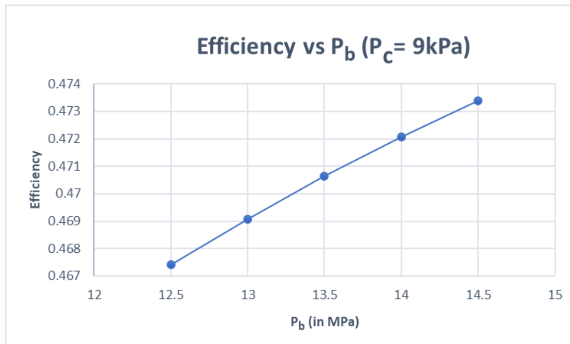
GRAPHS OBTAINED

<u>**Efficiency vs. P_b**</u>







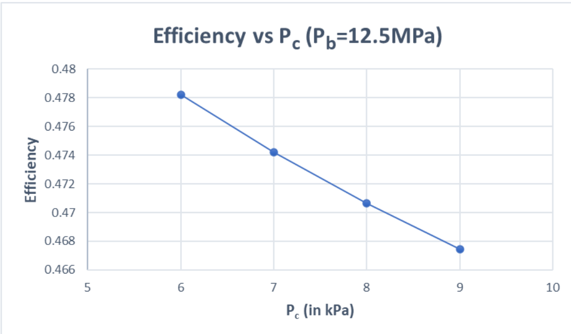


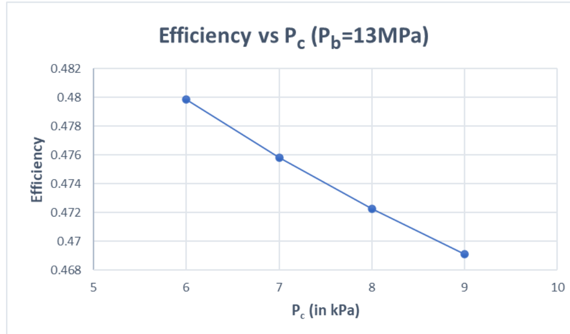
Analysis:

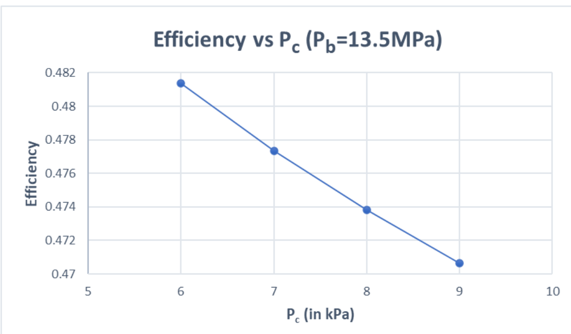
After observing the above graphs, we can see that thermal efficiency increases as we increase the boiler pressure.

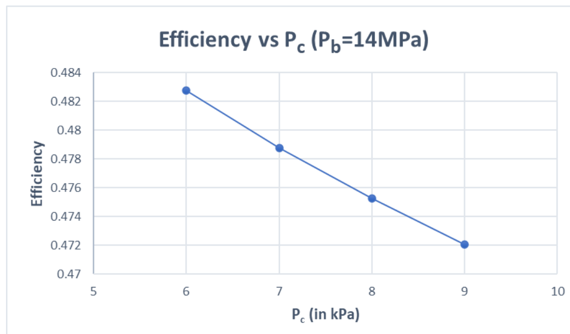
Raising the operational pressure of the boiler is a method to enhance the average temperature during the heat-addition process. This elevation in pressure automatically increases the boiling temperature, subsequently elevating the average temperature for heat transfer to the steam. As a result, the thermal efficiency of the cycle is raised.

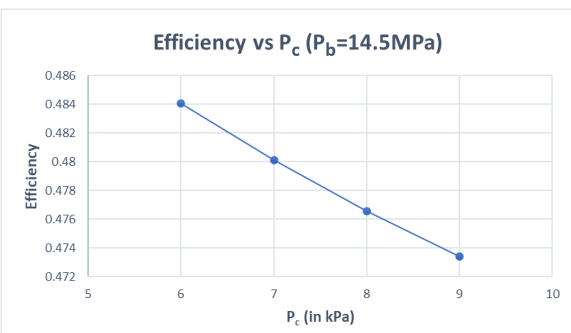
Efficiency vs. P_c









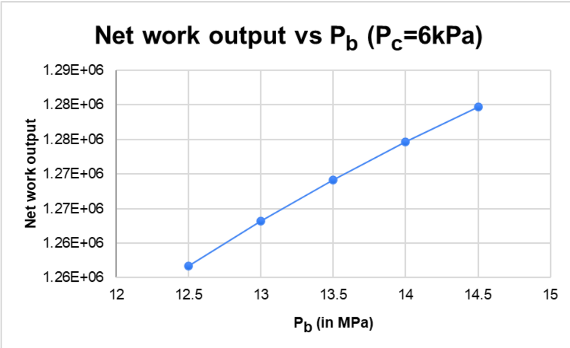


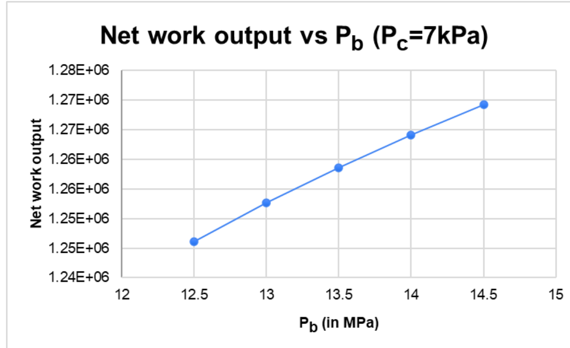
Analysis:

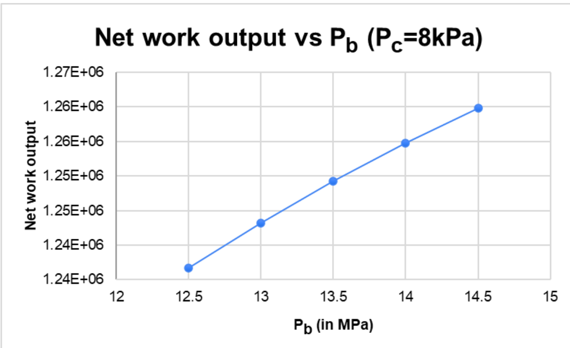
After observing the above graphs, we can see that thermal efficiency decreases as we increase the condenser pressure.

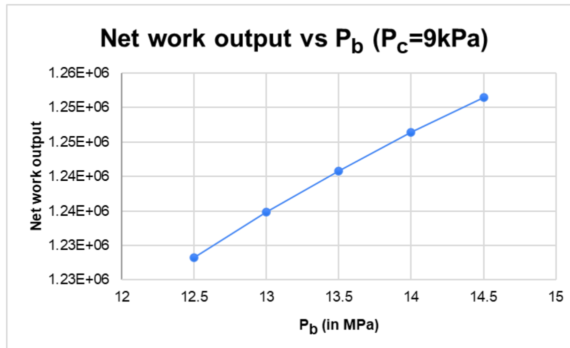
In the condenser, steam is present as a saturated mixture at the saturation temperature corresponding to the condenser's internal pressure. Consequently, reducing the operating pressure of the condenser results in an automatic reduction in the steam temperature and, consequently, the temperature at which heat is expelled. Thus, the overall outcome of decreasing the condenser pressure is an improvement in the thermal efficiency of the cycle.

Net work output vs. P_b







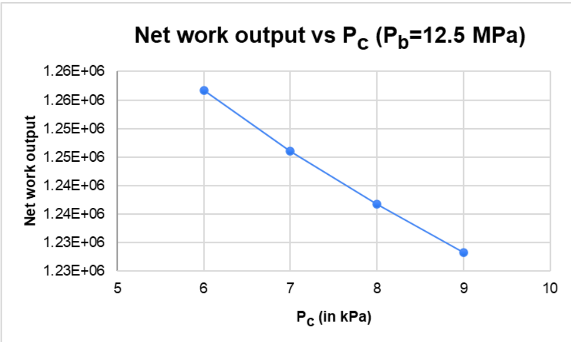


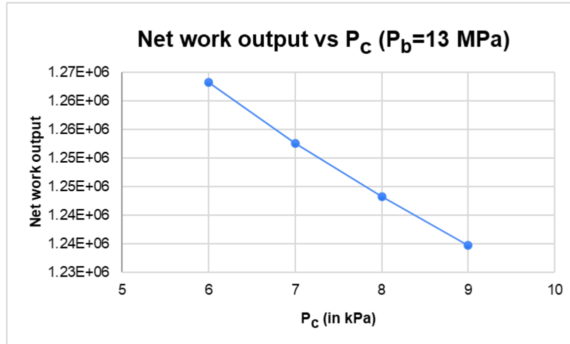
Analysis:

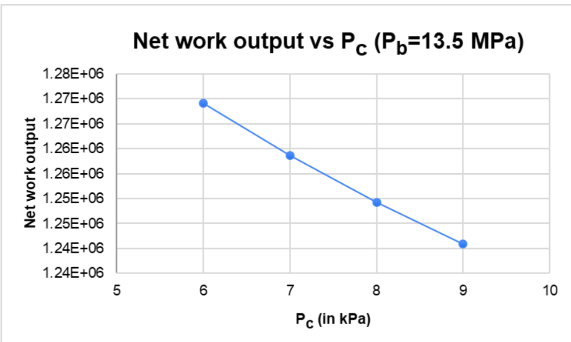
After observing the above graphs, we can see that net work output increases as we increase the boiler pressure.

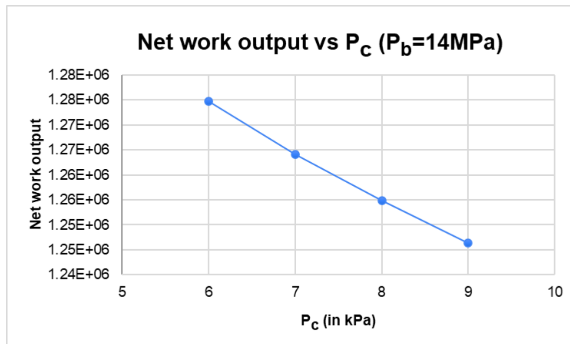
Increasing the boiler pressure in an ideal reheat-regenerative Rankine cycle leads to a higher average temperature during heat addition, resulting in increased thermodynamic efficiency. This, in turn, boosts the work output from the turbines, especially during the expansion phases, contributing to a higher overall net work output for the cycle.

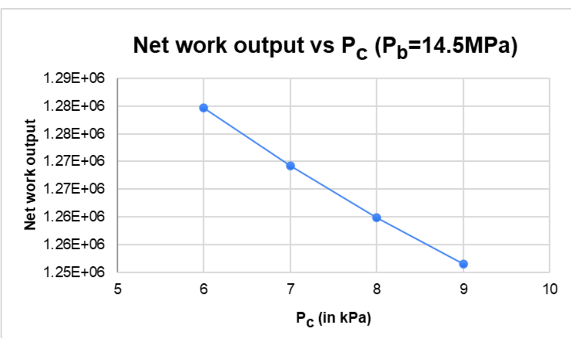
<u>Net work output vs. P_c</u>











Analysis:

After observing the above graphs, we can see that net work output decreases as we increase the condenser pressure.

Increasing the condenser pressure in an ideal reheat-regenerative Rankine cycle leads to a reduction in the temperature at which heat is rejected. This decreases the Carnot efficiency and results in lower net work output from the turbines, particularly during the expansion phases, leading to a decrease in the overall work output for the cycle.

IMPROVEMENT OF THE IDEAL REHEAT-REGENERATIVE RANKINE CYCLE OVER THE IDEAL RANKINE CYCLE

The ideal reheat-regenerative Rankine cycle presents a notable improvement over the ideal Rankine cycle with respect to thermal efficiency. Key advantages of the ideal reheat-regenerative cycle over the ideal Rankine cycle include:

1. Enhanced Thermal Efficiency:
   - Incorporation of a Reheat Process: The introduction of a reheat process in the reheat-regenerative cycle facilitates the reheating of steam before its entry into the low-pressure turbine. This sustains a higher average temperature during expansion, resulting in heightened thermal efficiency compared to the Rankine cycle.
   - Implementation of Regeneration: The regenerative process, which entails extracting heat from steam at various turbine stages to preheat the feedwater, further elevates the cycle's efficiency by reducing the external heat input required.
2. Increased Net Work Output:
   - The reheat-regenerative cycle achieves a greater net work output due to the effects of reheating and regeneration. Reheating optimizes temperature levels during expansion, while regeneration minimizes the heat input necessary by preheating the feedwater.
3. Mitigation of Heat Losses:
   - Regeneration diminishes heat losses by utilizing extracted steam for preheating the feedwater. This minimization of the temperature difference between the steam and its surroundings during heat addition contributes to a reduction in thermal losses.
4. Enhanced Overall Cycle Performance:
   - The reheat-regenerative cycle is meticulously designed to maximize the utilization of available heat by incorporating both reheat and regeneration. This results in a more efficient conversion of thermal energy into mechanical work, making the cycle's overall performance superior to that of the basic Rankine cycle.

While the ideal reheat-regenerative Rankine cycle offers notable advantages in terms of efficiency and work output, it is crucial to acknowledge that these benefits may be accompanied by increased complexity and cost in practical implementations. Engineers need to carefully consider these factors when designing power plants based on these cycles.

REFERENCES

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