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Performance Enhancement of Rankine Cycle using Reheating and Regeneration

Thermodynamics

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1 Introduction

As we know, the power cycle works to convert heat energy into mechanical work that will be used to generate power. The Carnot cycle is a type of power cycle that can generate power. We use the Carnot cycle because the Carnot cycle is a much more efficient cycle operating between specified temperature limits. However, the Carnot cycle is not a suitable model for the power cycle because:

- The Carnot cycle is based on reversible processes and operates between two constant temperature reservoirs. But it is difficult to make this model considering these conditions.
- The Carnot cycle would require working fluids to operate at fixed temperatures.
- Since the Carnot cycle is the most efficient, achieving this efficiency in the real world until now is impossible due to irreversibilities.

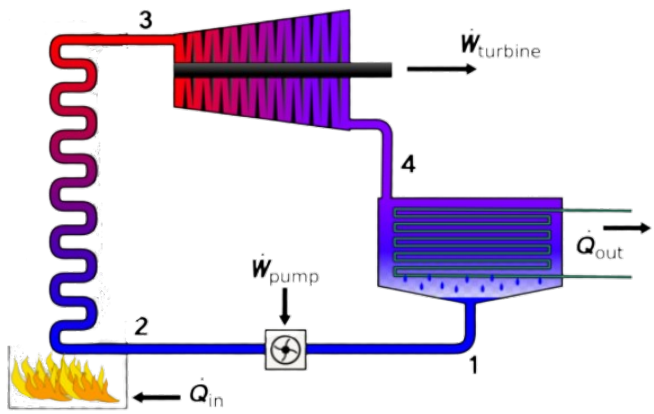


Figure 1: General Rankine Cycle

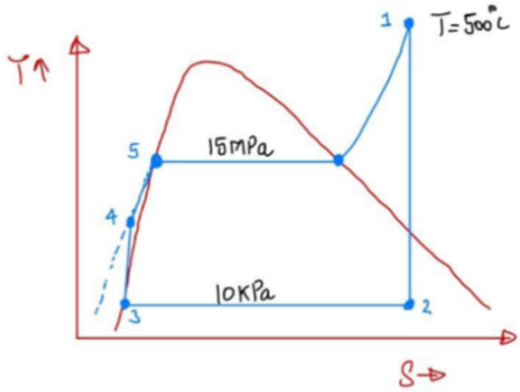
Due to these impracticalities associated with the Carnot cycle, the enhanced cycle that results is the Rankine cycle. The Rankine cycle is an ideal cycle for vapor power plants. In addition, the Rankine cycle describes how steam engines commonly found in thermal power generation plants harness thermal energy of a fuel or other heat source to generate electricity.

Carnot's theorem states that the larger the differential between the heat source and the heat sink, the more mechanical power may be effectively recovered from heat energy. The high heat of vaporization of the working fluid limits the efficiency of the Rankine cycle, unless boiler's pressure and temperature reach supercritical levels.

The system receives heat energy from a boiler, transforming the working fluid typically water into steam, a high-pressure gas that powers a turbine. The fluid is condensed back into liquid after the turbine and reintroduced to the boiler, completing the cycle.

2 Objectives

We must improve the performance of a power plant operating on a basic, ideal Rankine cycle.



The current cycle has:

- Thermal efficiency: 41%
- Steam quality (condenser inlet): 76%

The goal is to:

- Increase the efficiency above 46%
- Raise steam quality above 85%
- Keep boiler pressure P_b and condenser pressure P_c within $12 < P_b < 15$ MPa and $5 < P_c < 10$ kPa
- Ensure turbine temperature does not exceed $500°C$

A plot illustrating the effect of P_b and P_c variation on thermal efficiency and net work must be created.

3 Solution

To enhance the Rankine cycle:

- **Reheating:** Expand steam through multi-stage turbines with reheating between stages, while keeping $T < 500°C$.

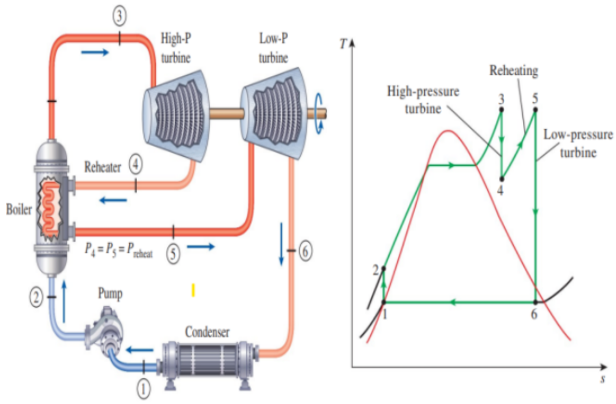


Figure 2: Ideal Reheat Rankine Cycle

- **Regeneration:** Employ feedwater heating (open feedwater heater) to enhance mean temperature of heat addition.

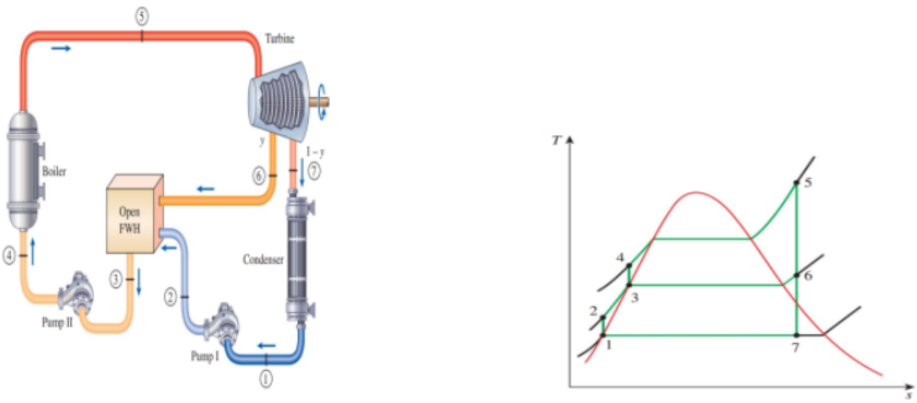
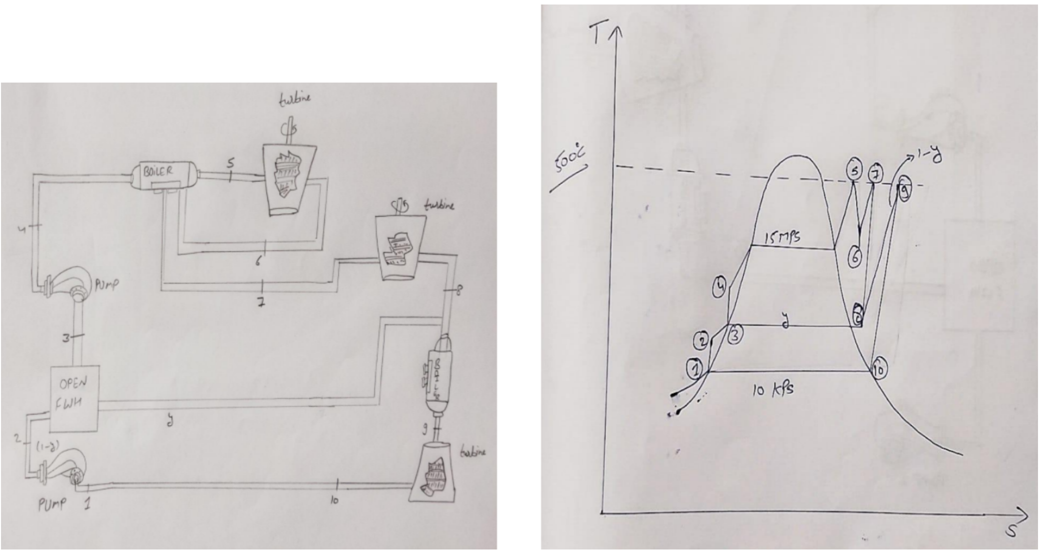


Figure 3: Ideal reheating with open feed water heater Rankine Cycle

4 T-s Diagram and Modified Rankine Cycle

The cycle stages are summarized below:



(a) Modified Rankine Cycle (b) T-s Diagram

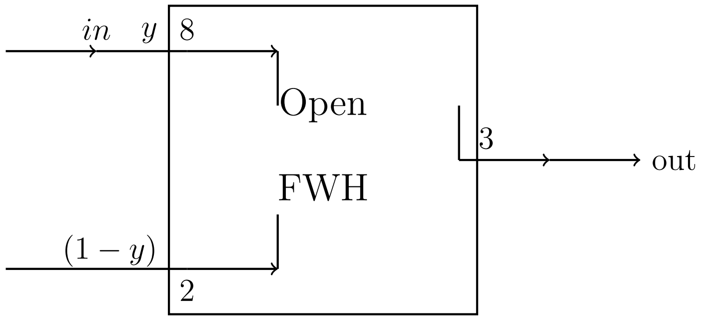
Figure 4: T-s Diagram of Modified Rankine Cycle

1. Condenser outlet, low-pressure liquid water
2. Pressurization by pump
3. Open feedwater heater (temperature rises)
4. Pumping to higher pressure
5. Heat addition in boiler, reaching superheated state
6. Partial pressure drop
7. Boiler reheating stage
8. Expansion through turbine
9. Steam split: one part to regeneration, other to reheating
10. Final expansion to condenser pressure (10 kPa)
11. Condensation and cycle repeats

Two reheating stages and one regeneration process with three turbines were used.

Control Volume and Energy Balance Equation

The fraction steam extracted is determined from the mass and energy balance of the feedwater heater:



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

$$yh_8 + (1-y)h_2 = 1 \times h_3$$

$$y(h_8 - h_2) = h_3 - h_2$$

$$y = \frac{h_3 - h_2}{h_8 - h_2}$$

$$y = 0.0068 \quad \text{(calculated using cantera)}$$

Heat Input Calculation

$$\dot{q}_{in} = h_5 - h_4 + h_7 - h_6 + (1-y)(h_9 - h_8)$$

or equivalently,

$$\dot{q}_{in} = h_5 + h_7 - h_4 - h_6 + (1-y)(h_9 - h_8)$$

$$\dot{q}_{in} = 4.6463 \times 10^6 \quad \frac{\text{kJ}}{\text{kg}} \quad \text{(using cantera)}$$

Heat Output Calculation

$$\dot{q}_{out} = (h_{10} - h_1) \times (1-y)$$

$$= 3.2193 \times 10^6 \quad \frac{\text{kJ}}{\text{kg}}$$

Efficiency Calculation

$$\eta = \frac{W_{net}}{q_{in}}$$

$$= \frac{q_{in} - q_{out}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

$$\eta = 46.108\% \quad \text{(using cantera)}$$

For $P_2 = 3$ MPa:

$$\text{Quality} = 87.779\% \quad \text{or} \quad 0.87779$$

5 Output & Observations

Effect of Boiler Pressure and Condenser Pressure on Efficiency

Higher boiler pressures and lower condenser pressures result in higher efficiencies. This is because a higher boiler pressure allows for a more significant temperature difference in the heat exchanger, improving the efficiency of the cycle.

Effect of Boiler Pressure and Condenser Pressure on Net Work Output

Higher boiler pressures generally lead to increased net work output, as the higher pressure allows more energy to be extracted from the steam. Lower condenser pressures also contribute to higher net work output because a lower pressure in the condenser allows for more expansion of the steam, extracting additional work.

Overall Observation

The plots suggest a trade-off between efficiency and net work output. While higher boiler pressures and lower condenser pressures can increase efficiency, they may also lead to higher net work output.

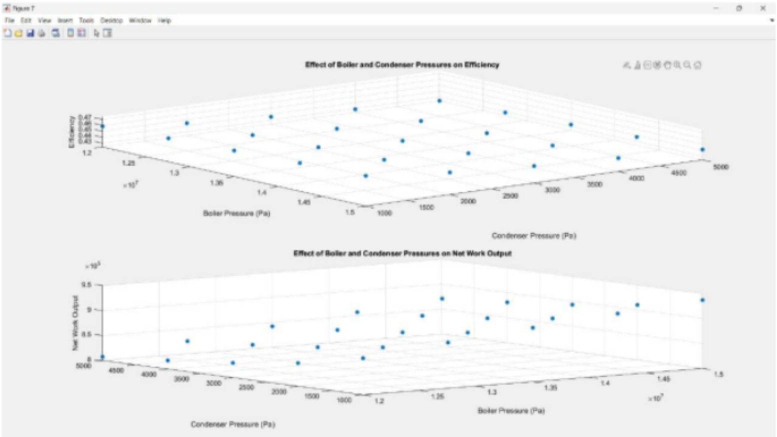


Photo 1 : 3D

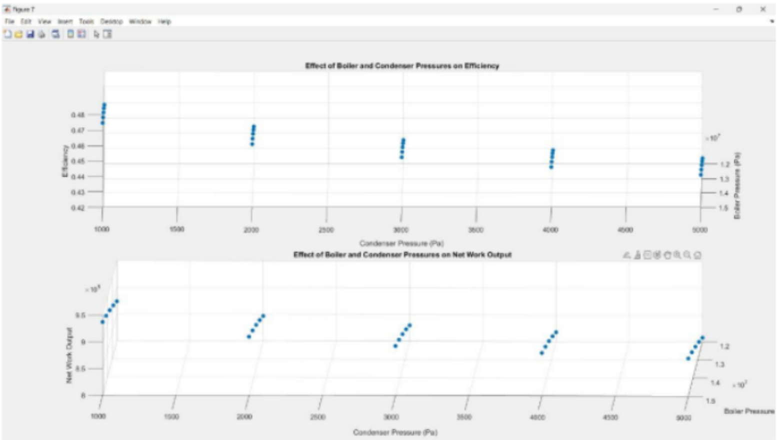


Photo 2: 2D

Figure 5: Outputs Of Cantera Code

6 Conclusion

By introducing multi-stage reheating and regeneration, the Rankine cycle performance significantly improved:

- Final thermal efficiency = 46.108% (target achieved)
- Steam quality = 87.779% (above target)

The T-s diagram demonstrates modifications, while the sensitivity analysis showed pressure's role in optimization. Energy balance equations highlighted efficient energy utilization inside the cycle.

Acknowledgment

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