

Power Plant Engineering

Lecture 2

Analysis of Steam Cycles

Lecturer: Dr. Melaku Desta

Lecture learning outcomes:

At the end of this lecture, you will be able to:

- i. Understand the Carnot Cycle's role as the theoretical benchmark for maximum possible thermal efficiency between two temperature reservoirs and recognize its practical limitations.
- ii. Grasp the Rankine Cycle's components and processes as the practical, foundational model for modern steam power plants, and be able to analyze its performance.
- iii. Identify sources of irreversibility that cause actual vapor cycles to deviate from idealized models, resulting in lower overall performance.
- iv. Explain the efficiency benefits of reheat and regeneration: reheat increases average heat addition temperature and reduces turbine exhaust moisture, while regeneration raises the average temperature of heat addition by using internal energy transfer.
- v. Differentiate between the two main types of feed-water heaters: open heaters and closed heaters, and understand their distinct roles and integration points within a regenerative cycle.

Content

1. Power Plant Cycles
2. The Carnot Cycle
3. The Rankine Cycle
4. Deviation of Actual Vapor Power Cycles from Idealized Ones
5. The Ideal Reheat Rankine Cycle
6. The Ideal Regenerative Rankine Cycle
7. Types of Feed-Water Heaters

Summary

References

1. Power Plant Cycles

- A **power plant cycle** is a conceptual and engineering model that describes the series of thermodynamic processes through which a **working fluid** (like water, steam, or gas) is circulated to convert **heat** into useful **mechanical work**, which is then almost always used to generate **electricity** [1].
- In short, a **power plant cycle** is the fundamental blueprint that defines how a power plant operates to convert **thermal energy** into **electrical energy**.
- The key principle behind these cycles is the **Second Law of Thermodynamics**: heat cannot be completely converted into work in a continuous process.

1. Power Plant Cycles

Cont...

- Therefore, a cycle must also reject a portion of the heat to a **cold reservoir** (like a river, ocean, or atmosphere via cooling towers).
- **Characteristics of all power plant cycles:**
 - i. Working fluid
 - ii. Heat Addition
 - iii. Work Output
 - iv. Heat Rejection
 - v. Compression/Pumping
- Understanding power plant cycles is fundamental to:
 - Increasing efficiency
 - Designing power plants
 - Selecting the right technology

1. Power Plant Cycles

Cont...

Classification of Power Plant Cycles

- Power plant cycles are generally categorized by their **working fluid** and **process**.
- Thermal power plants in general may work on vapor or gas power cycles.

1. Vapor power cycles:

- Vapor power cycles are thermodynamic cycle where the working fluid is alternately **vaporized** and **condensed**.
- The key characteristic is that the working fluid undergoes a **phase change** from **liquid** to **vapor** and back again during the cycle.

Example: Rankine cycle, Reheat cycle, Regenerative cycle,
Binary vapor cycle

1. Power Plant Cycles

Cont...

2. Gas power cycles

- A gas power cycle is a thermodynamic cycle in which the **working fluid** remains in the **gaseous phase** throughout the entire cycle.
- Unlike vapor power cycles (like the Rankine cycle), there is **no phase change** from liquid to vapor; the working fluid is always a gas.
- The most common working fluid is air, which is treated as an **ideal gas** for analysis.

Example: Otto cycles, Dual combustion cycle, Diesel cycles,
Gas turbine cycles

2. The Carnot Cycle

- The Carnot cycle is a theoretical, idealized thermodynamic cycle that provides the **maximum possible efficiency** that any heat engine can achieve when converting heat into work, operating between **two constant-temperature thermal reservoirs** (a hot source and a cold sink) [2].
- The fluid is heated reversibly and isothermally in a **boiler** (process 1-2), expanded isentropically in a **turbine** (process 2-3), condensed reversibly and isothermally in a **condenser** (process 3-4), and compressed isentropically by a **compressor** to the initial state (process 4-1).

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

$$\eta_{th,carnot} = 1 - \frac{T_L}{T_H}$$

2. The Carnot Cycle

Cont...

Key Characteristics of Carnot Heat Engines:

1. Idealized and reversible process:
 - The Carnot cycle consists of **four** reversible processes: **two isothermal** (constant temperature) and **two adiabatic** (no heat exchange) processes.
2. Operates between two heat reservoirs
 - A Carnot engine absorbs heat Q_H from a hot reservoir at temperature T_H , and rejects heat Q_C to a cold reservoir at temperature T_C .
3. Maximum possible efficiency
4. No irreversibilities or friction
5. Heat-to-work conversion
6. Cycle-based operation

$$\eta_{th,carnot} = 1 - \frac{T_L}{T_H}$$

2. The Carnot Cycle

Cont...

The P-v and T-s Diagrams of a Carnot Cycle

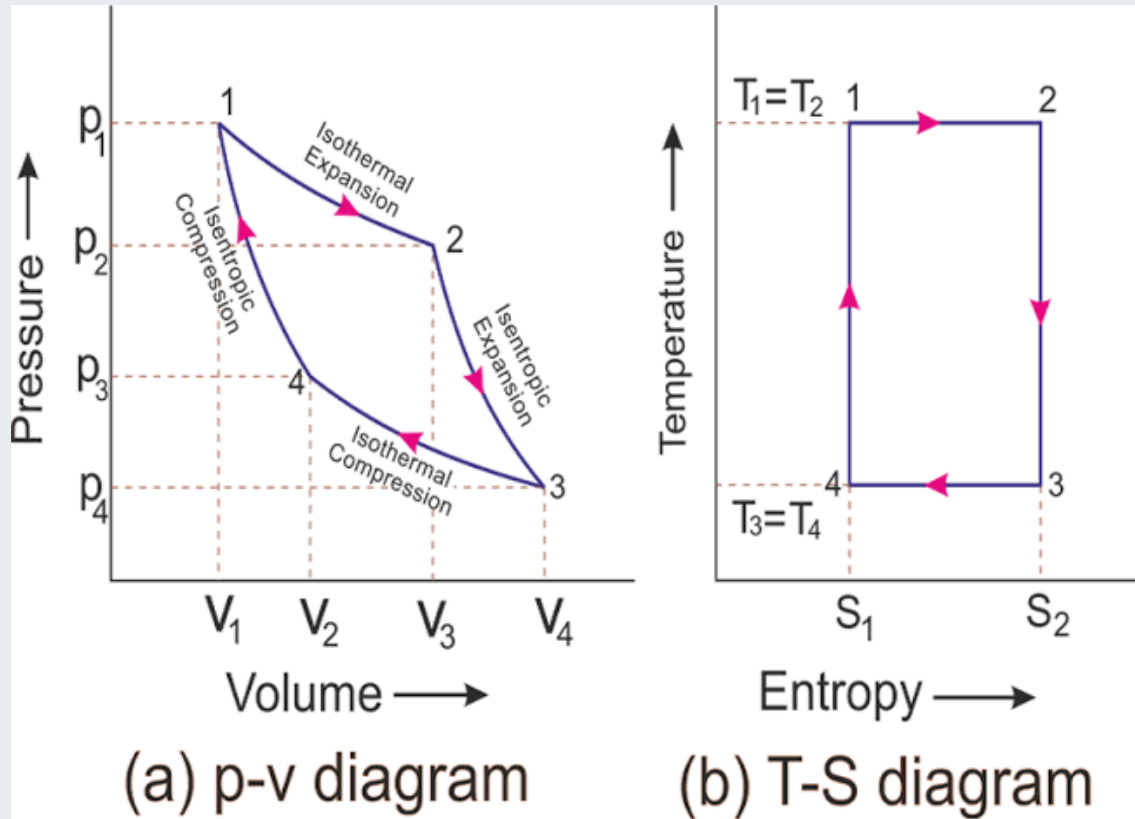


Figure 1: P-V diagram (a) and T-s diagram (b) of a Carnot Cycle, Lignell, D., Brigham Young University

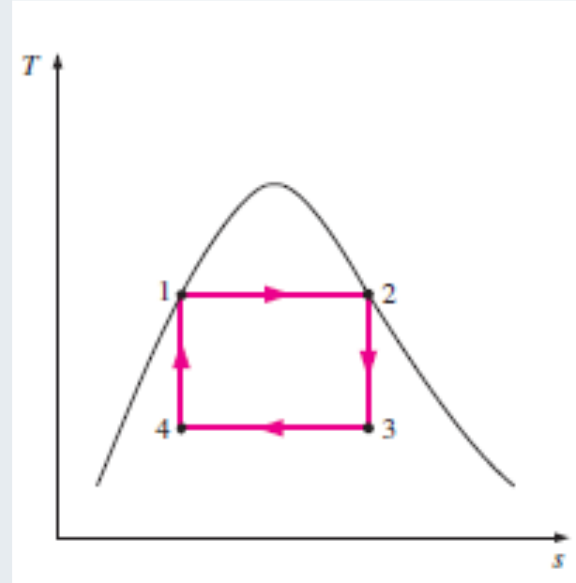
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2. The Carnot Cycle

Cont...

- **Practical Limitations of the Carnot Cycle:**

- Temperature Constraints
- Turbine Erosion
- Fluid Selection
- Control Challenges
- Compressor Issues



3. The Rankine Cycle

- Many of the limitations inherent in the Carnot cycle can be overcome by **superheating the steam** within the boiler and ensuring **complete condensation** in the condenser.
- The cycle that results is the **Rankine cycle**, which is the **ideal cycle** for **vapor power plants**.
- The **Rankine Cycle** is a thermodynamic cycle widely used in **steam power plants** to convert heat into mechanical work, which is then transformed into electricity [1].
- As an idealized representation of vapor power cycles, Rankine cycle forms the foundation for modern power generation technologies.

3. The Rankine Cycle

Cont...

The Rankine cycle consists of **four** main components:

1. **Pump** – Compresses liquid water to high pressure (isentropic process).
 2. **Boiler (heat addition)** – Heats high-pressure water to produce steam (isobaric process).
 3. **Turbine** – Expands steam to produce work (isentropic expansion).
 4. **Condenser** – Condenses exhaust steam back into liquid (isobaric heat rejection).
- The Rankine cycle follows the following four processes on a T-s (Temperature-Entropy) diagram:

3. The Rankine Cycle

Cont...

Four processes of a Rankine Cycle:

Process 1-2: Isentropic compression in a pump

Process 2-3: Constant pressure heat addition in a boiler

Process 3-4: Isentropic expansion in a turbine

Process 4-1: Constant pressure heat rejection in a condenser

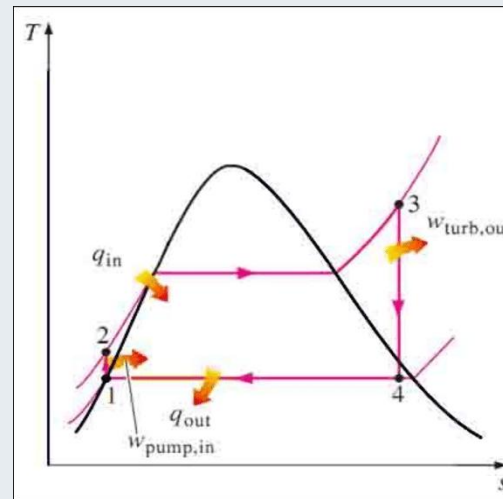
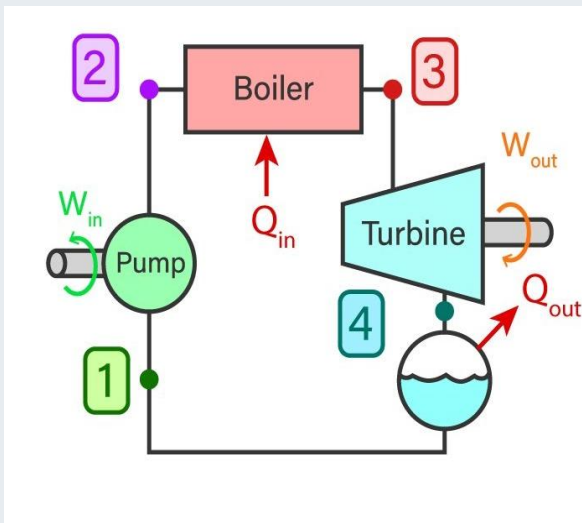


Figure 2: Components of a Rankine Cycle, Modi Mechanical Engineering Tutorials, (2019)

[url: https://i.ytimg.com/vi/21XFZaxity8/maxresdefault.jpg](https://i.ytimg.com/vi/21XFZaxity8/maxresdefault.jpg)

Figure 3: T-s diagram of a Rankine Cycle, Alhwayzee, M., Kadhim, H. J., & Rashid, F. L. (2021).

[url: https://www.researchgate.net/publication/336647595/figure/fig1/AS:815342993547265@1571404326643/deal-Rankine-Cycle.png](https://www.researchgate.net/publication/336647595/figure/fig1/AS:815342993547265@1571404326643/deal-Rankine-Cycle.png)

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3. The Rankine Cycle

Cont...

Comparison with Carnot Cycle

- **Rankine Cycle** is more practical than the Carnot cycle because:
 - It avoids two-phase compression (pump handles only liquid).
 - It allows superheating steam to higher temperatures.
- However, **Carnot efficiency is higher** for the same temperature limits.

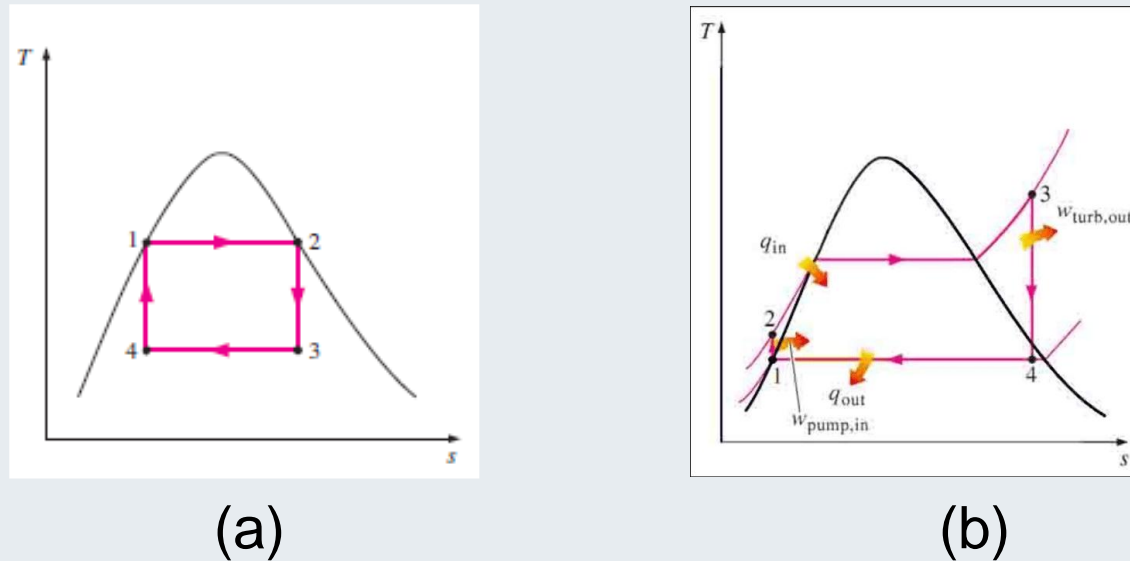


Figure 4: T-s diagram of (a) Carnot Cycle, (b) Rankine Cycle

3. The Rankine Cycle

Cont...

Energy Analysis of the Rankine Cycle

- Rankine cycle can be analyzed as **steady-flow processes**.
- Neglecting changes in **kinetic** and **potential** energies.
- The **steady-flow energy equation** per unit mass of steam

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$

Assumptions:

- The boiler and the condenser do not involve any work.
- The pump and the turbine are assumed to be isentropic.

3. The Rankine Cycle

Cont...

The conservation of energy relation for each device can be expressed as follows:

1. Isentropic Compression (Pump Work Input)

- Since this process is **ideally isentropic**, there is **no entropy generation**.

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$

- The **work input** to the pump is given by:

$$\text{Pump } (q = 0): w_{pump,in} = h_2 - h_1 \quad \begin{array}{l} dh = Tds + vdp, \\ \text{and } Tds = 0 \text{ for isentropic pump} \end{array}$$

$$w_{pump,in} = v(P_2 - P_1)$$

Where, $h_1 \cong h_{f@P_1}$, and $v \cong v_1 = v_{f@P_1}$

3. The Rankine Cycle

Cont...

2. Isobaric Heat Addition (Boiler)

- The high-pressure liquid enters the boiler and absorbs heat, causing it to evaporate into steam.
- This process occurs **at constant pressure**.
- The **heat energy** added is:

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$

$$q_{in} = h_3 - h_2$$

3. The Rankine Cycle

Cont...

3. Isentropic Expansion (Turbine Work Output)

- The high-energy steam expands in the **turbine**, producing **mechanical work**.
- Since the process is ideally **isentropic**, no entropy is generated.
- The **turbine work output** is:

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$

$$w_{out} = h_3 - h_4$$

3. The Rankine Cycle

Cont...

4. Isobaric Heat Rejection (Condenser)

- The steam rejects heat to the surroundings, **condensing** back into a liquid state.
- This process occurs at **constant pressure**.
- The **heat rejected** is:

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$

$$q_{out} = h_4 - h_1$$

- The **thermal efficiency** of the Rankine Cycle is:

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

Where: $w_{net} = q_{in} - q_{out}$, $w_{net} = w_{turb,out} - w_{pump,in}$

4. Deviation of Actual Vapor Power Cycles from Idealized Ones

- In real-world power plants, **actual vapor power cycles** deviate from the ideal Rankine cycle due to various **irreversibilities** and **practical limitations**.
- These deviations **reduce efficiency** and **affect performance**.
- Below are the key reasons for these differences:
 - Turbine and pump irreversibilities (friction, turbulence, and heat losses)
 - Pressure drops in pipes and heat exchangers
 - Heat losses to the surroundings
 - Incomplete condensation & subcooling
 - Fluid property variations

4. Deviation of Actual Vapor Power Cycles from Idealized Ones Cont...

The T-s Diagram of an Ideal and Actual Vapor Power Cycles

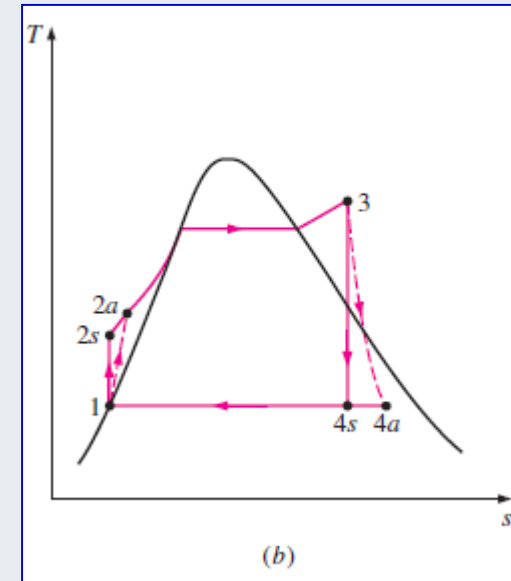
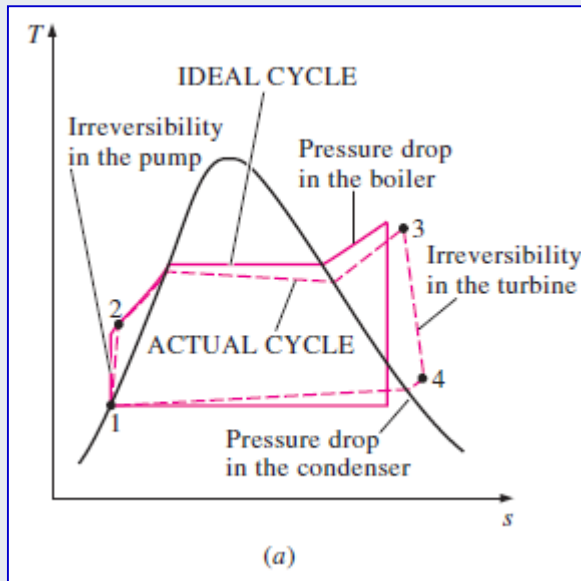


Figure 5: Deviation of Actual Vapor Power Cycles from Idealized One, Skill-Lync. (2020)

url: https://sklc-tinymce-2021.s3.amazonaws.com/2020/11/mceclip5_1605032619.png

4. Deviation of Actual Vapor Power Cycles from Idealized Ones Cont...

- A pump requires a **greater work input**, and a turbine produces a **smaller work output** as a result of irreversibilities.
- Under ideal conditions, the flow through these devices is **isentropic**.
- The deviation of actual pumps and turbines from the isentropic ones can be accurately accounted for, however, by utilizing **adiabatic efficiencies**, defined as:

$$\eta_P = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

$$\eta_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

4. Deviation of Actual Vapor Power Cycles from Idealized Ones Cont...

How can we increase the efficiency of the Rankine Cycle?

- Improving the efficiency of the Rankine cycle-a widely used thermodynamic cycle in power plants-can lead to better energy output and lower operational costs [3].
- The basic idea behind all the modifications to increase the thermal efficiency of a power cycle is the same:
 - **Increase** the **average temperature** at which heat is transferred to the working fluid in the boiler, or
 - **decrease** the **average temperature** at which heat is rejected from the working fluid in the condenser.

4. Deviation of Actual Vapor Power Cycles from Idealized Ones Cont...

Some of the ways to **enhance the efficiency** of a Rankine Cycle are [3]:

- Lowering the condenser pressure
- Superheating the steam to high temperatures
- Increasing the boiler pressure
- Using reheat cycles
- Regenerative feedwater heating
- Improved turbine design

4. Deviation of Actual Vapor Power Cycles from Idealized Ones

Cont...

Lowering the Condenser Pressure (Lowers $T_{low,av}$)

- Decreasing the pressure in the condenser reduces the temperature at which heat is rejected, increasing the thermal efficiency.
- The colored area on this diagram represents the increase in **net work output** as a result of lowering the condenser pressure from P_4 to P_4' .
- The heat input requirements also increase, but this increase is very small.
- The overall effect of lowering the condenser pressure is an **increase in the thermal efficiency** of the cycle.

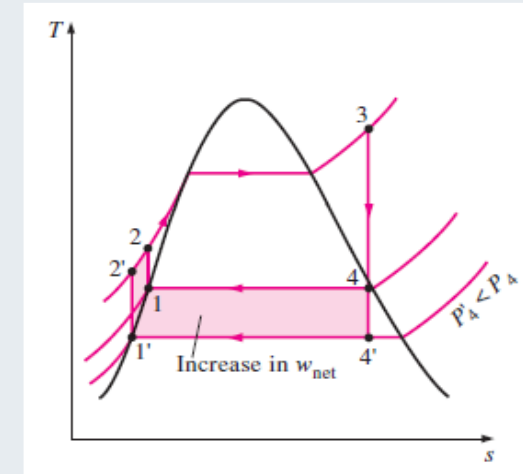


Figure 6: T-s diagram of a Rankine Cycle with Lowering Condenser Pressure, Khalid, N. (2015)

[url: https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcS5ByxSCRb5CAo-kkO1buQliHLy0Pyv7nj-asDjq3DbGDeH3wiElbCpsm-4t&s](https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcS5ByxSCRb5CAo-kkO1buQliHLy0Pyv7nj-asDjq3DbGDeH3wiElbCpsm-4t&s)

4. Deviation of Actual Vapor Power Cycles from Idealized Ones Cont...

Superheating the Steam to High Temperatures (Increases $T_{\text{high,av}}$)

- Increasing the temperature of the steam beyond the saturation point (before entering the turbine) helps improve efficiency by **reducing moisture content** in the later turbine stages.
- The colored area on this diagram represents the increase in the **net work**.
- The total area under the process curve 3-3' represents the increase in the **heat input**.

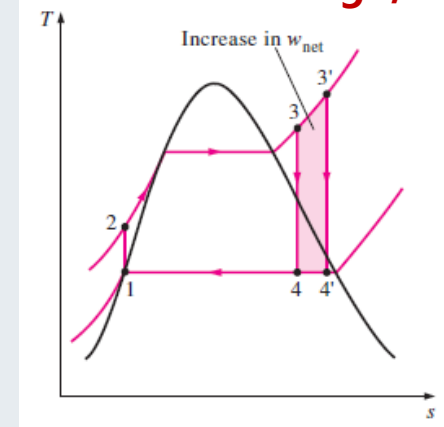


Figure 7: T-s diagram of a Rankine Cycle with Superheating the Steam, Kosasih, Buyung. 2013, University of Wollongong
[url: https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcSrnuU9zg3wGZAIY7SFpjSli-cxvRtLdlsMda&s](https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcSrnuU9zg3wGZAIY7SFpjSli-cxvRtLdlsMda&s)

4. Deviation of Actual Vapor Power Cycles from Idealized Ones Cont...

- Thus, both **the net work** and **heat input** increase as a result of superheating the steam to a higher temperature.
- The **overall effect** is an **increase** in **thermal efficiency**.
- The temperature to which **steam** can be **superheated** is limited by **metallurgical considerations**.
- Presently, the **highest steam temperature allowed** at the turbine inlet is about 620°C (1150°F) [1] .

4. Deviation of Actual Vapor Power Cycles from Idealized Ones Cont...

Increasing the Boiler Pressure (Increase $T_{high,av}$)

- Raising the steam pressure in the boiler increases the average temperature at which heat is added, boosting efficiency.
- This, in turn, raises the average temperature at which heat is added to the steam and thus **raises** the **thermal efficiency** of the cycle.
- However, this requires materials that can withstand higher pressures.

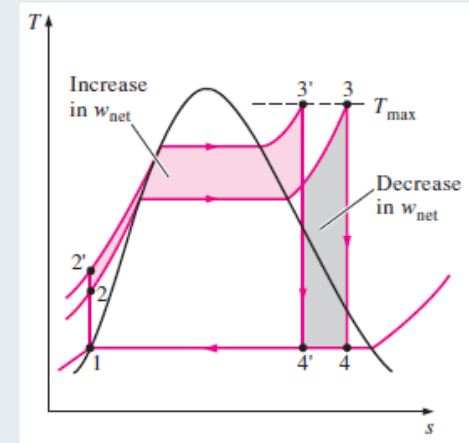


Figure 8: T-s diagram of a Rankine Cycle with Increasing the Boiler Pressure, Osman, Mohd Zulkifli, et.al. (2020)

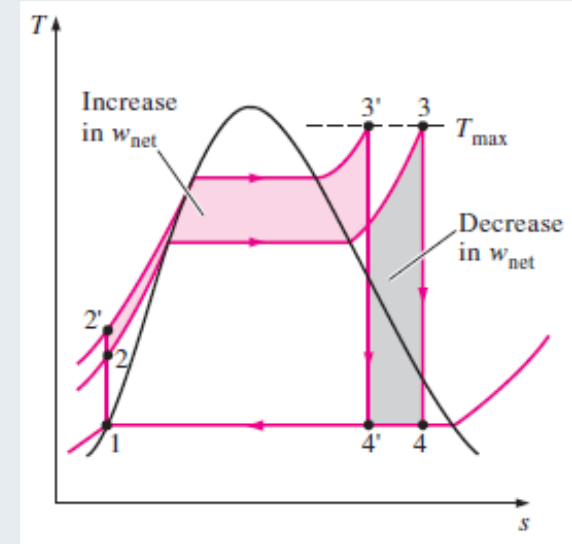
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5. The Ideal Reheat Rankine Cycle

- 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.

Then,

- How can we harness the improved efficiencies of higher boiler pressures while mitigating the risk of excessive moisture in the turbine's final stages?



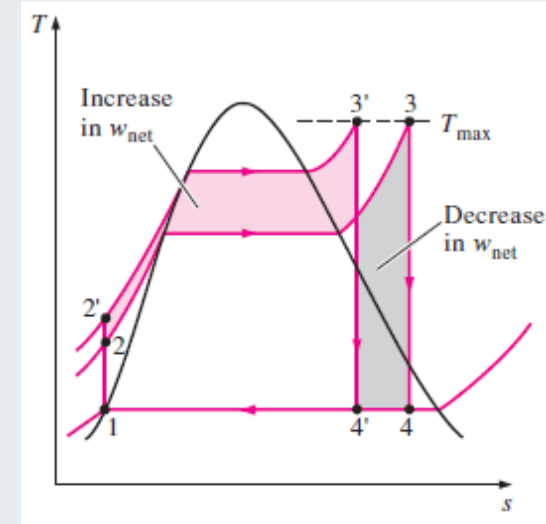
5. The Ideal Reheat Rankine Cycle

Cont...

Two possibilities to mind:

1. Superheating the steam to very high temperatures before it enters the turbine

- This would be the ideal solution because increasing the steam temperature raises the average heat addition temperature, thereby improving cycle efficiency.
- However, this approach is not feasible, as it would require steam temperatures beyond safe **metallurgical limits** for the turbine materials.



5. The Ideal Reheat Rankine Cycle

Cont...

2. Expand the steam in the turbine in two stages, and reheat it in between

- The simple ideal Rankine cycle can be enhanced by incorporating a **reheat** process.
- Reheating effectively addresses the issue of excessive moisture in turbine stages, making it a widely adopted solution in modern steam power plants [4].
- Therefore, the **Ideal Reheat Rankine Cycle** is a modification of the simple Rankine cycle designed to **improve efficiency** and **reduce moisture content** in the later stages of the turbine.
- This is achieved by **expanding the steam in two turbine stages** and **reheating it between expansions**.

5. The Ideal Reheat Rankine Cycle

Cont...

- The T-s diagram of the **ideal reheat Rankine cycle** and the schematic of the power plant operating on this cycle are shown below:

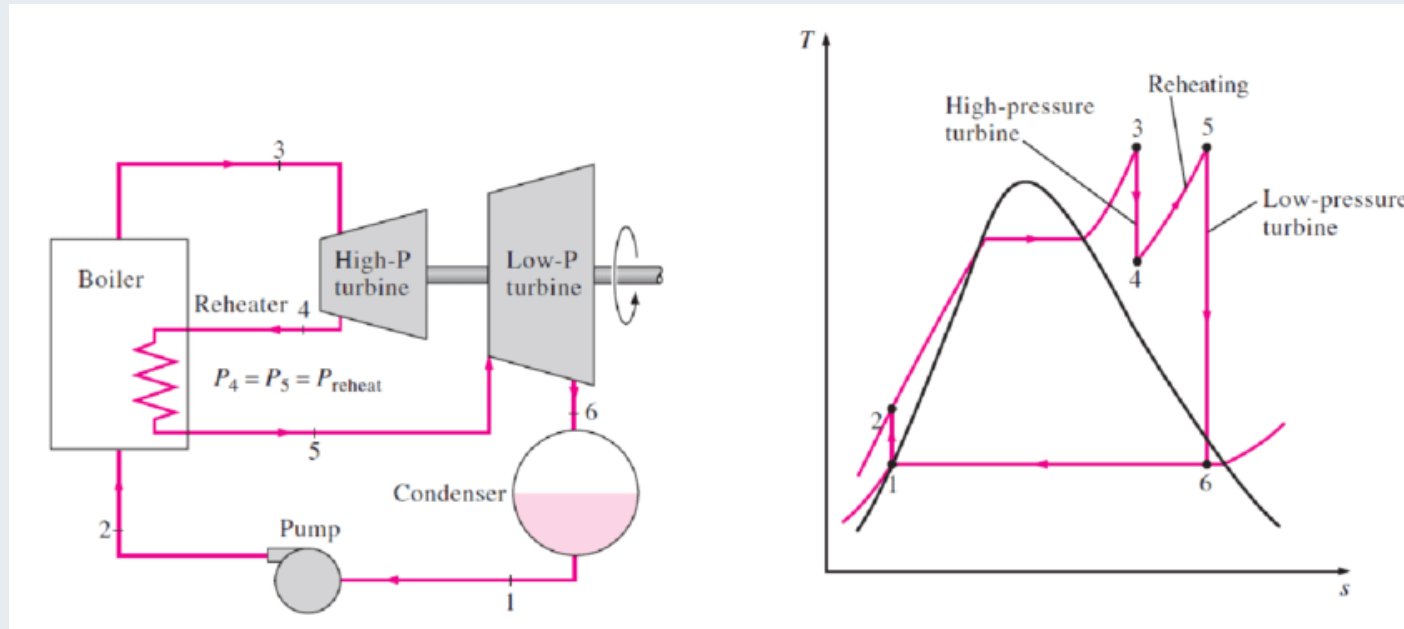


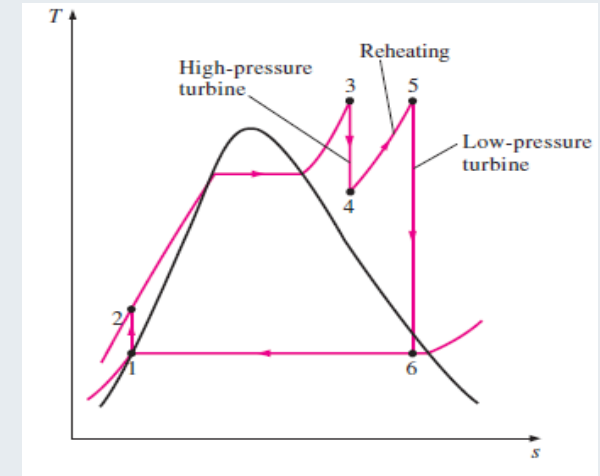
Figure 9: Schematic and T-s diagram of an Ideal Rehaet Rankine Cycle, Dadach, Z.-E. (2020)

[url: https://www.researchgate.net/profile/Zin-Eddine-Dadach/publication/348295259/figure/fig7/AS:977200316702723@1609994119970/deal-Reheat-Rankine-Cycle-18.png](https://www.researchgate.net/profile/Zin-Eddine-Dadach/publication/348295259/figure/fig7/AS:977200316702723@1609994119970/deal-Reheat-Rankine-Cycle-18.png)

5. The Ideal Reheat Rankine Cycle

Cont...

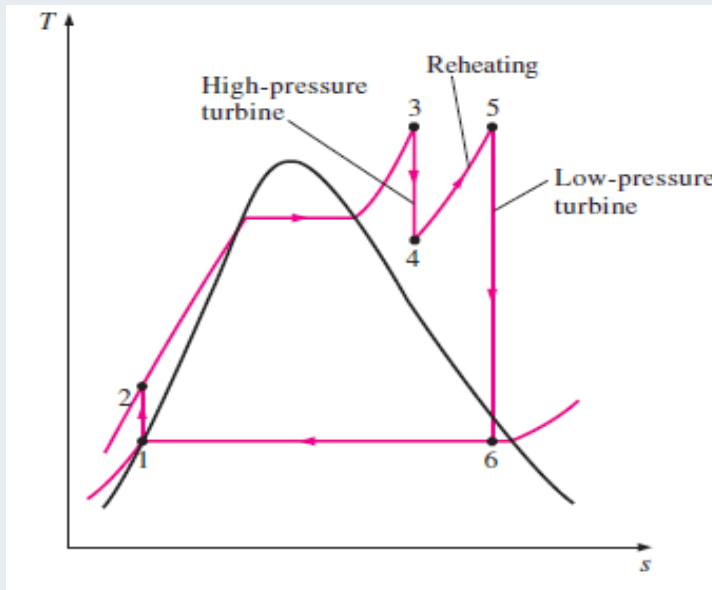
- The **ideal reheat Rankine cycle** differs from the **simple ideal Rankine cycle** in that the expansion process takes place in **two stages**.
- In the first stage (the high-pressure turbine), steam is expanded **isentropically** to an intermediate pressure and sent back to the boiler where it is reheated at constant pressure, usually to the inlet temperature of the first turbine stage.
- Steam then expands **isentropically** in the second stage (low-pressure turbine) to the condenser pressure.



5. The Ideal Reheat Rankine Cycle

Cont...

- The total heat input and the total turbine work output for a reheat cycle become

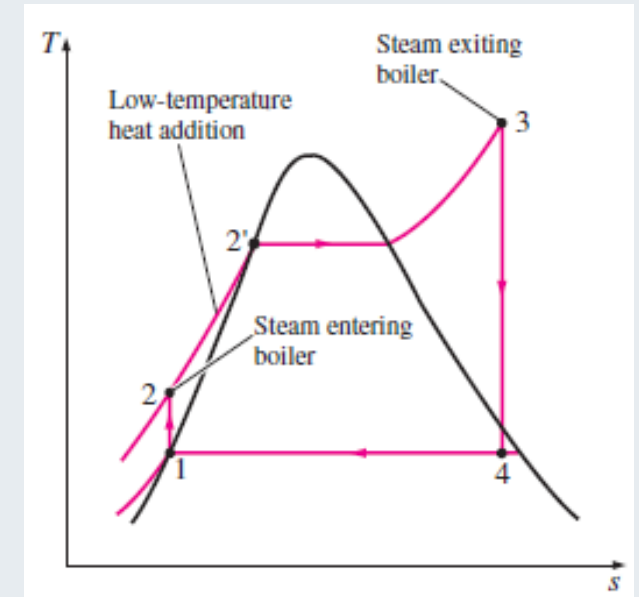


$$q_{in} = q_{primary} + q_{reheat} = (h_3 - h_2) + (h_5 - h_4)$$

$$w_{turb,out} = w_{turb I} + w_{turb II} = (h_3 - h_4) + (h_5 - h_6)$$

6. The Ideal Regenerative Rankine Cycle

- A careful examination of the T-s diagram of the Rankine cycle shown reveals that heat is added to the working fluid during **process 2-2'** at a relatively low temperature.
- This lowers the average temperature at which heat is added and thus the cycle efficiency.
- To remedy this shortcoming, we look for ways to raise the temperature of the liquid leaving the pump (called the **feedwater**) before it enters the boiler.



6. The Ideal Regenerative Rankine Cycle

Cont...

- A **practical regeneration process** in steam power plants is accomplished by extracting, or “**bleeding,**” steam from the turbine at various points [5].
- This steam, which could have produced more work by expanding further in the turbine, is used to heat the feedwater instead.

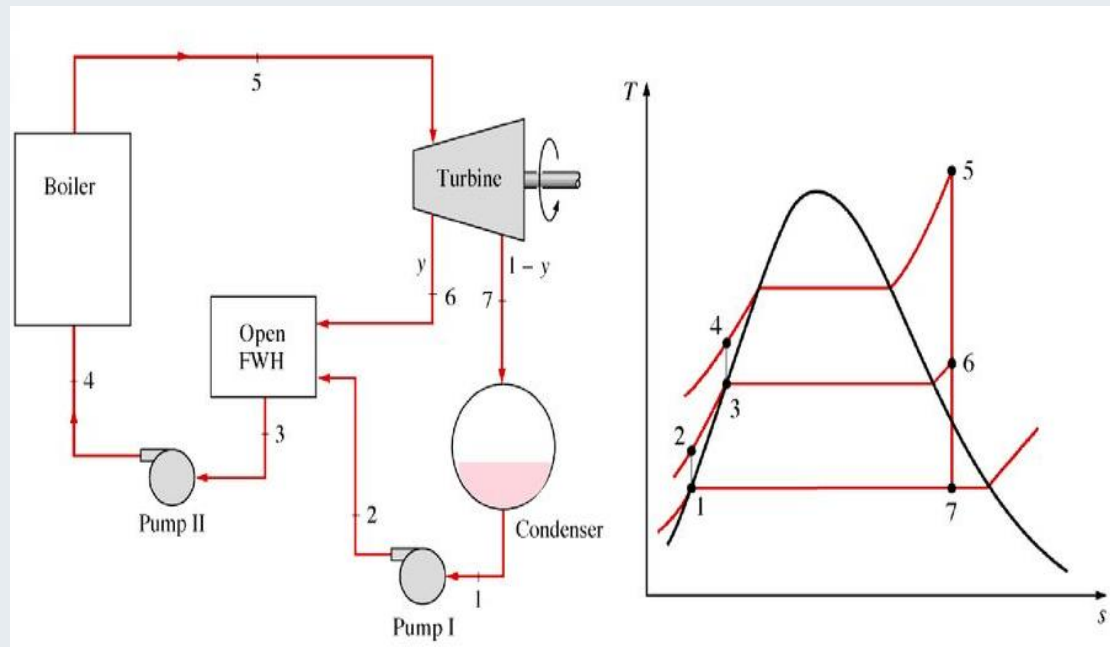


Figure 10: Schematic and T-s diagram of an Ideal Regenerative Rankine Cycle, Jung Jin Lee, (2023).

[url: https://image4.slideserve.com/9116143/the-ideal-regenerative-rankine-cycle-with-an-open-l.jpg](https://image4.slideserve.com/9116143/the-ideal-regenerative-rankine-cycle-with-an-open-l.jpg)

6. The Ideal Regenerative Rankine Cycle

Cont...

- The device where the feedwater is heated by regeneration is called a **regenerator**.
- A feedwater heater is basically a heat exchanger where heat is transferred from the steam to the feedwater either by mixing the two fluid streams (**open feedwater heaters**) or without mixing them (**closed feedwater heaters**) [6].

7. Types of Feed-Water Heaters

- Feedwater heaters are essential components in steam power plants, designed to **preheat** the water before it enters the boiler.
- This process improves **thermal efficiency**, **reduces fuel consumption**, and **minimizes thermal stress** on boiler components.
- Purpose of Feedwater Heating
 - Increases cycle efficiency by reducing irreversibilities.
 - Lowers fuel requirements for steam generation.
 - Prevents thermal shock to boiler tubes.
 - Enhances overall plant reliability and lifespan.

7. Types of Feed-Water Heaters

Classification of Feedwater Heaters

- Based on **mode of heat transfer** between the extracting steam and the feedwater, feedwater heaters are broadly classified into two types:
 1. **Open Feedwater Heaters (Direct Contact Type)**
 - An open, or direct-contact, feedwater heater functions as a mixing chamber in which steam extracted from the turbine directly combines with feedwater discharged from the pump [6].
 - Under ideal conditions, this mixture exits the heater as a saturated liquid corresponding to the heater's operating pressure.

7. Types of Feed-Water Heaters

Open Feedwater Heaters

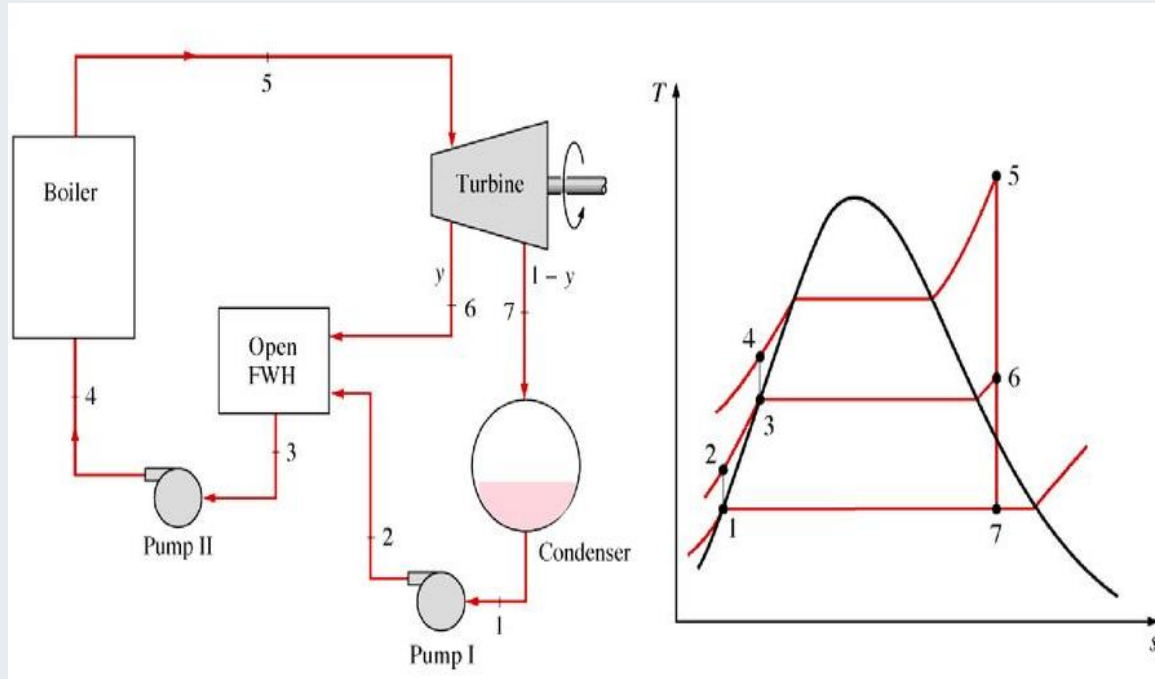


Figure 11: Schematic and T-s diagram of Open Feed-Water Heater, Jung Jin Lee, (2023).

[url: https://image4.slideserve.com/9116143/the-ideal-regenerative-rankine-cycle-with-an-open-l.jpg](https://image4.slideserve.com/9116143/the-ideal-regenerative-rankine-cycle-with-an-open-l.jpg)

7. Types of Feed-Water Heaters

2. Closed (Surface) Feedwater Heaters

- A closed feedwater heater is a **shell-and-tube heat exchanger** used in the regenerative Rankine cycle to **preheat** feedwater before it enters the boiler.
- Its core principle is the **indirect transfer of thermal energy** from extracted steam to the feedwater, without the two streams mixing. That is:
 - ✓ The extracted steam and the feedwater do not mix.
 - ✓ They are separated by metal tubes or plates.
- Heat is transferred from the steam to the feedwater through these solid surfaces via conduction and convection.

7. Types of Feed-Water Heaters

Closed (Surface) Feedwater Heaters

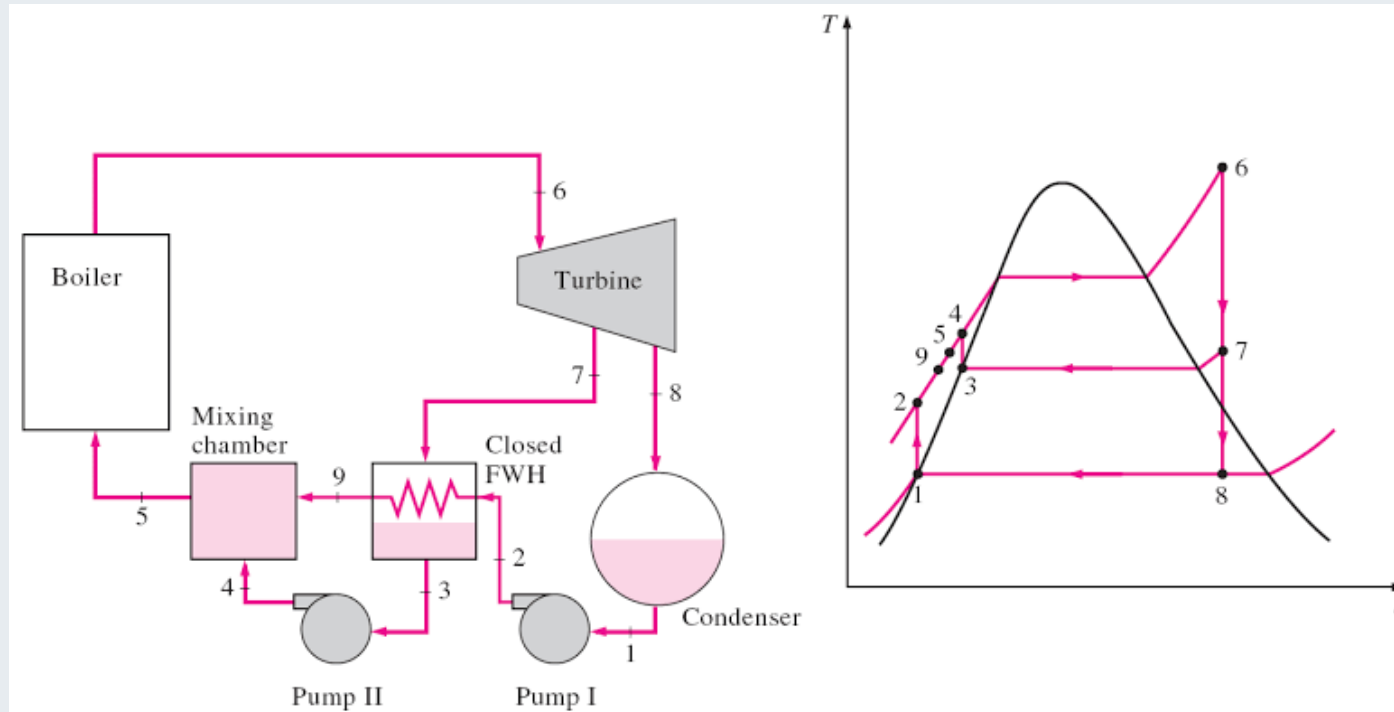


Figure 12: Schematic and T-s diagram of Closed Feed-Water Heater, Kim, K. B. (2016)

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7. Types of Feed-Water Heaters

More Ways to Increase Power plant Thermal Efficiency

- The overall thermal efficiency of a power plant can be increased by using:
 - ✓ Binary cycles or,
 - ✓ Combined cycles.

Mercury-Water Binary Vapor Cycle

- Binary vapor cycles use **two different working fluids** to optimize thermal efficiency.
- The Mercury-Water Binary Vapor Cycle is a classic example, combining **mercury** for the high-temperature heat addition and **water/steam** for the low-temperature heat rejection and mid-temperature expansion, creating a more efficient combined cycle.

7. Types of Feed-Water Heaters

- By using mercury for high-temperature heat addition, the cycle operates over a wider temperature range with less irreversibility.
- The steam cycle operates at lower pressures than it would if it tried to use the same high-temperature heat source directly.

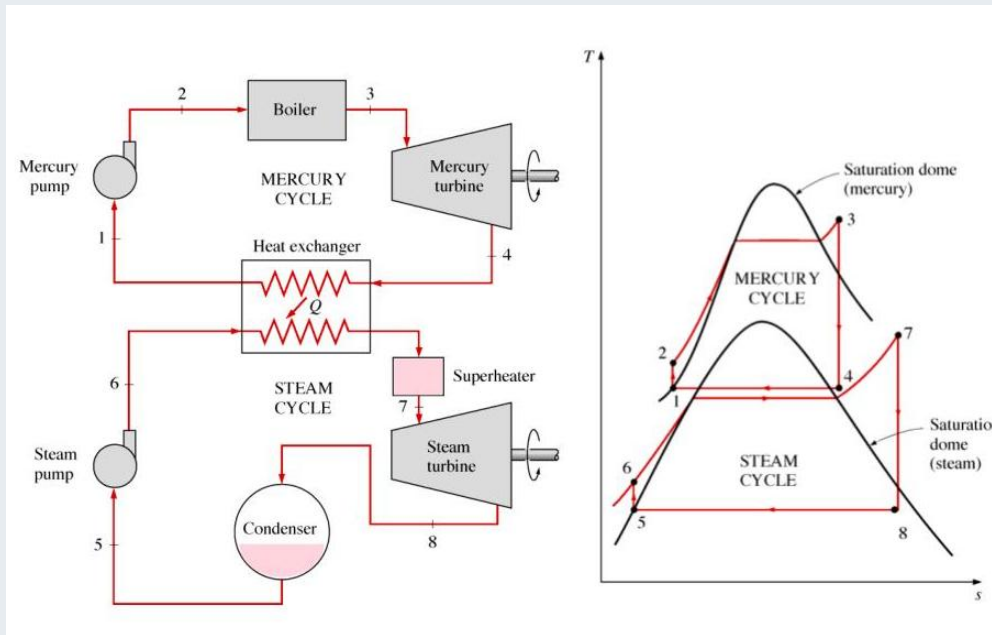


Figure 13: Schematic and T-s diagram of Mercury-Water Binary Vapor Cycle, Kim, K. B. (2016)

Summary

- Carnot Cycle represents the theoretical maximum efficiency a heat engine can achieve between two temperature limits;
- Rankine Cycle is a more realistic and widely used cycle for steam power plants, involving four key processes; pressurization, heat addition, expansion, and condensation.
- Real-world vapor power cycles differ from ideal ones due to irreversibilities like friction, pressure drops, and non-isentropic turbine and pump behavior, reducing overall efficiency.
- Ideal Reheat Rankine Cycle improves efficiency and reduces moisture content at turbine exit by expanding steam in multiple stages with reheating between stages.
- Ideal Regenerative Rankine Cycle & Feedwater Heaters enhances cycle efficiency by preheating feedwater using extracted steam, typically using open or closed feedwater heaters to reduce fuel consumption and thermal stress on boiler components.

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Thank you !