Engineering Thermodynamics I

Lecture 12

Vapor Power Cycles

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Lecture learning outcomes:

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

- i. Understand the Carnot Cycle and learn the principles of the idealized Carnot Cycle and its four reversible processes.
- ii. Analyze the Rankine Cycle and study the components and processes of the basic Rankine Cycle and its role in steam power plants.
- iii. Recognize how actual vapor power cycles differ from idealized ones due to irreversibilities (friction, heat losses, etc.) and practical limitations.
- iv. Explore how reheating steam between turbine stages improves efficiency and reduces moisture content in later turbine stages.
- v. Examine the Regenerative Rankine Cycle and understand how feedwater heating improves cycle efficiency.
- vi. Assess and compare the advantages and limitations of these cycles for practical engineering applications in power generation.

Content

1. The Carnot Cycle

- As emphasized repeatedly, the Carnot cycle represents the highest possible thermal efficiency for any heat engine operating between two fixed temperature limits.
- Consider a steady-flow Carnot cycle executed within the saturation dome of a pure substance.

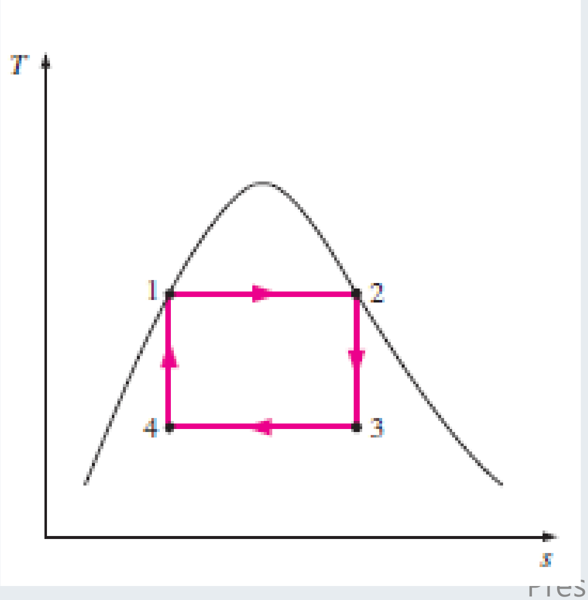

Figure 1: T-s Diagram of a Carnot Cycle
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1. The Carnot Cycle Cont…

- 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).

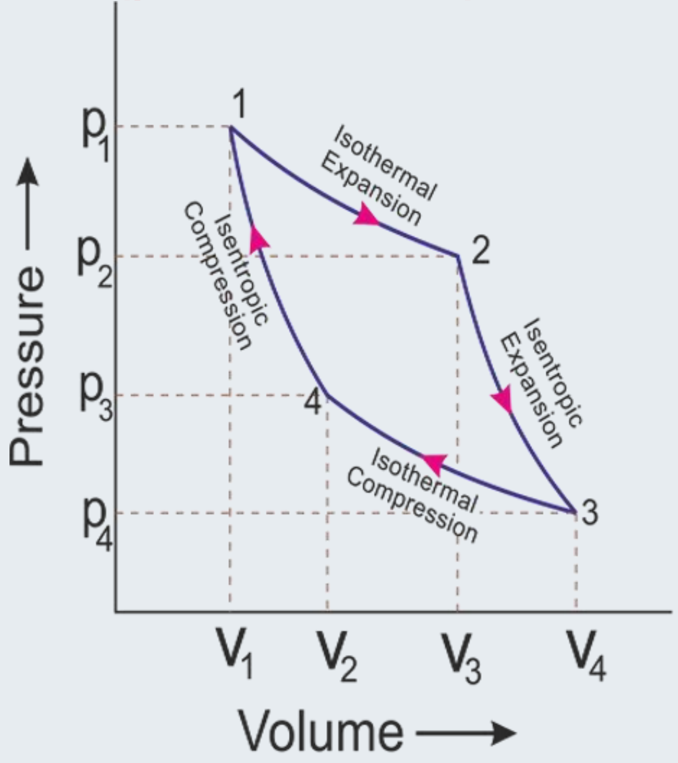


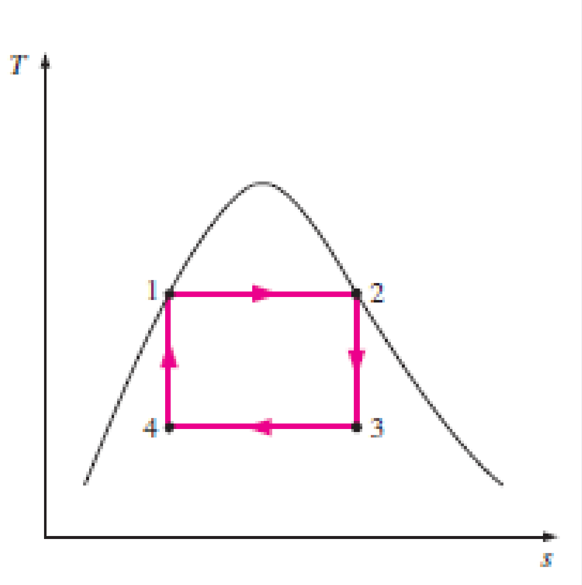
Figure 2: P-v Diagram of a Carnot Cycle
url: https://www.mechanicaltutorial.com/pictures/content_picture/carnot_cycle/carnot_cycle_graph.png

$$\eta_{th} = \frac{T_H - T_L}{T_H} = \left[1 - \frac{T_L}{T_H}\right]$$

1. The Carnot Cycle

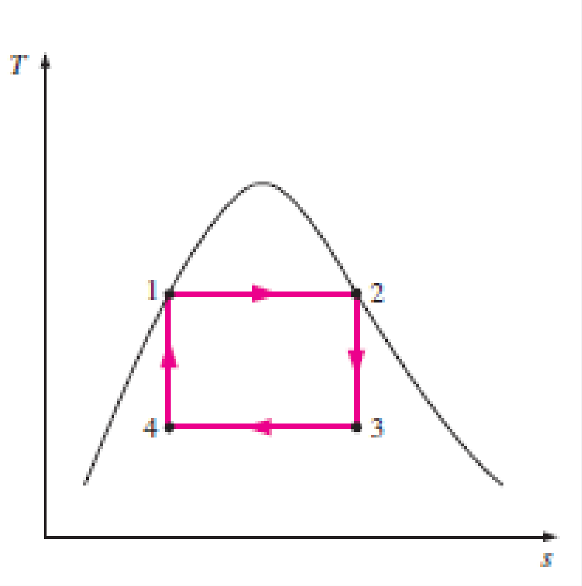
Cont…

- **Practical Limitations of the Carnot Cycle**:
  - Temperature Constraints: Heat transfer is restricted to two-phase systems, limiting the maximum temperature to below the critical point.
  - Turbine Erosion: Liquid droplet formation damages turbine blades, leading to wear and inefficiency.
  - Fluid Selection: A working fluid with a steep saturated vapor line could minimize two-phase flow in the turbine.



1. The Carnot Cycle Cont…

- **Practical Limitations of the Carnot Cycle**:
  - Control Challenges: Precise condensation control is difficult, making it hard to achieve the desired vapor quality at the cycle's end state.
  - Compressor Issues: Handling two-phase flow in a compressor is mechanically impractical.



2. The Rankine Cycle

- Many of the impracticalities associated with the Carnot cycle can be eliminated by superheating the steam in the boiler and condensing it completely 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].
- It is the idealized model for vapor power cycles, serving as

  the basis for real-world power generation systems.

2. The Rankine Cycle Cont…

The 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:

2. 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

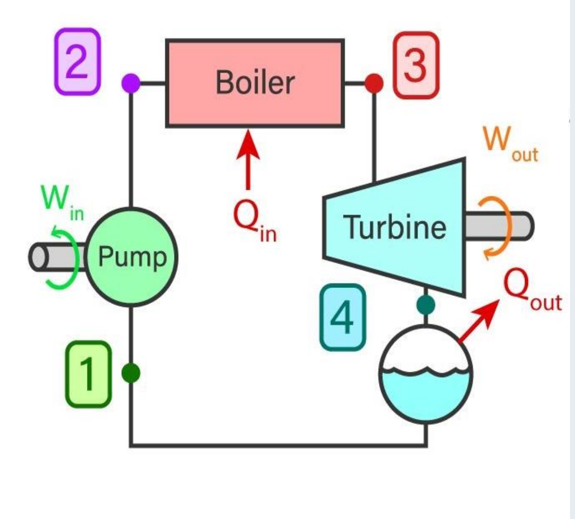


Figure 3: Components of a Rankine Cycle

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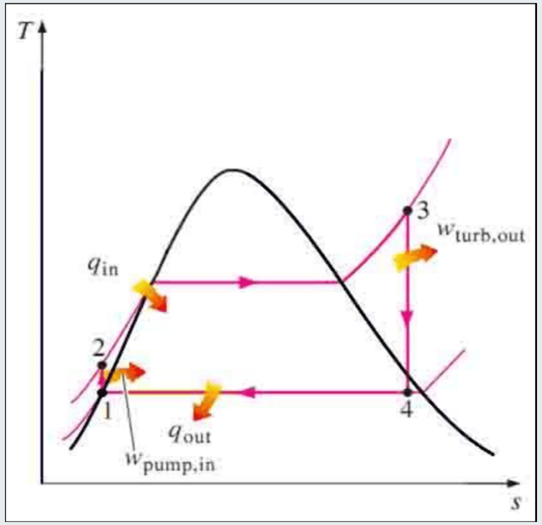


Figure 4: T-s diagram of a Rankine Cycle

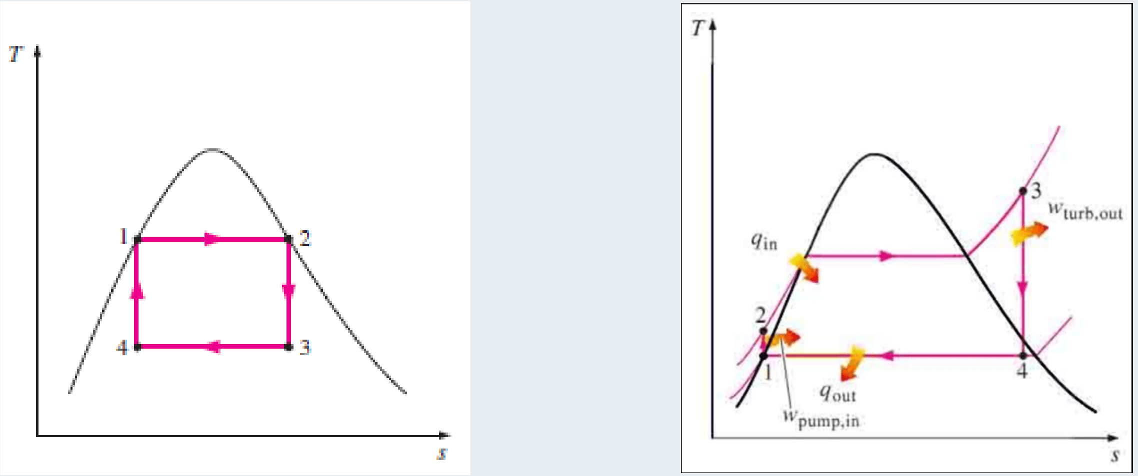
[url: https://www.researchgate.net/publication/336647595/figure/fig1/AS:815342993547265@1571404326643/deal-Rankine-Cycle.png](https://www.researchgate.net/publication/336647595/figure/fig1/AS:815342993547265@1571404326643/deal-Rankine-Cycle.png)

2. 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.



(a)

(b)

Figure 5: T-s diagram of (a) Carnot Cycle, (b) Rankine Cycle

2. 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.

2. 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:

$$Pump\ (q = 0){:}\ w_{pump,in} = h_2 - h_1$$

$$dh = Tds + vdp,$$
$$and\ Tds = 0\ for\ Isentropic\ pump$$

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

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

2. 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:

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

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

2. 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:

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

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

2. 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: $w_{net} = q_{in} - q_{out},\qquad w_{net} = w_{turb,out} - w_{pump,in}$

2. The Rankine Cycle

Cont…

Example 1:

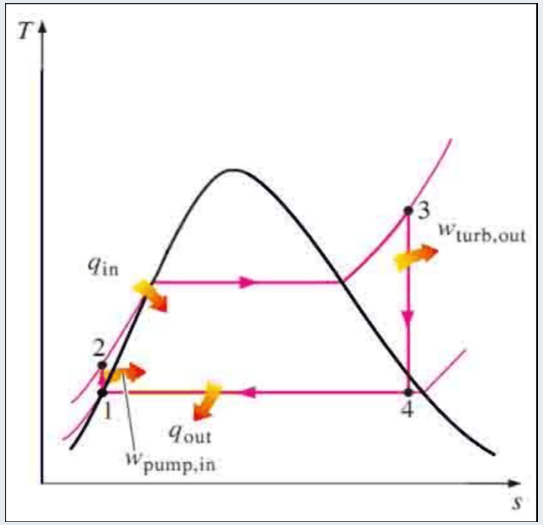
A steam power plant operates on a simple ideal Rankine cycle with a net power output of 45 MW. Steam enters the turbine at 7 MPa and 500°C and is condensed in the condenser at 10 kPa. Cooling water from a lake flows through the condenser tubes at 2000 kg/s.

- Determine the thermal efficiency of the cycle.
- Find the mass flow rate of steam ($\dot{m}$).
- Calculate the temperature rise of the cooling water (ΔT).

2. The Rankine Cycle

Cont…

Solution



State 3:

Turbine inlet, $P_3 = 7\ MPa, T_3 = 500\ ℃$

Condenser Pressure: $P_4 = P_1 = 10\ kPa$

Pump inlet: Saturated liquid at 10 kPa

State	P (kPa)	T (°C)	h (kJ/kg)	s (kJ/kg·K)	Phase
1	10	45.81	$h_1 = 191.81$	$s_1 = 0.6492$	Sat. liquid
2	7000	-	$h_2 = h_1 + v_1(P_2 - P_1)$	$s_1 = s_2$	Compressed liquid
3	7000	500	$h_3 = 3410.3$	$s_3 = 6.7975$	Superheated steam
4	10	-	h_4 (from $s_4 = s_3$)	$s_4 = s_3$	Two-phase mixture

2. The Rankine Cycle

Cont…

Pump Work: $\boldsymbol{W_P} = v(P_2 - P_1) = 0.001010(7000 - 10) = \mathbf{7.06\ kPa}$ where $v_1 = 0.001010\ m^3/kg$

Determine h_2 $h_2 = h_1 + W_P$

$$h_2 = 191.81 + 0.001010(7000 - 10)$$

$$h_2 = 198.87\ kJ/kg$$

Turbine Work:

Since $s_4 = s_3 = 6.7975$ is between s_f and s_g, steam is wet at state 4

$$x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.7975 - 0.6492}{7.499} = 0.820$$

Now, find h_4

$$h_4 = h_f + x_4 h_{fg} = 191.81 + 0.820\ x\ 2392.1 = 2153.5\ kJ/kg$$

$$\boldsymbol{W_{out}} = h_3 - h_4 = 3410.3 - 2153.5 = \mathbf{1256.8\ kJ/kg}$$

2. The Rankine Cycle

Cont…

Heat input ($\boldsymbol{Q_{in}}$)

$$\boldsymbol{Q_{in}} = h_3 - h_2 = 3410.3 - 198.87 = \mathbf{3211.43}\ \boldsymbol{kJ/kg}$$

Heat Rejected ($\boldsymbol{Q_{out}}$)

$$\boldsymbol{Q_{out}} = h_4 - h_1 = 2153.5 - 191.81 = \mathbf{1961.69}\ \boldsymbol{kJ/kg}$$

Thermal Efficiency (η)

$$W_{net} = W_{out} - W_{pump} = 1256.8 - 7.06 = 1249.74\ kJ/kg$$

$$\eta = \frac{W_{net}}{Q_{in}} = \frac{1249.74}{3211.43} = 0.389 = \mathbf{38.9}\%$$

Mass flow rate of steam ($\boldsymbol{\dot{m}}$)

$$\dot{m} = \frac{\dot{W}_{net}}{W_{net}} = \frac{45000}{1249.74} = \mathbf{36.01}\ \boldsymbol{kg/s}$$

2. The Rankine Cycle Cont…

Temperature rise of cooling water (ΔT)

Cooling water absorbs Q_{out}:

$$\dot{Q}_{out} = \dot{m}_{steam} \, x \, Q_{out} = 36.01 \, x \, 1961.69 = 70650 \, kJ/s$$

Given cooling water rate $\dot{m}_{water} = 2000 \, kg/s \quad and$

$$\dot{Q}_{out} = \dot{m}_{water} \; C_p \Delta T \qquad\qquad C_p = 4.18 \, kJ/kgK$$

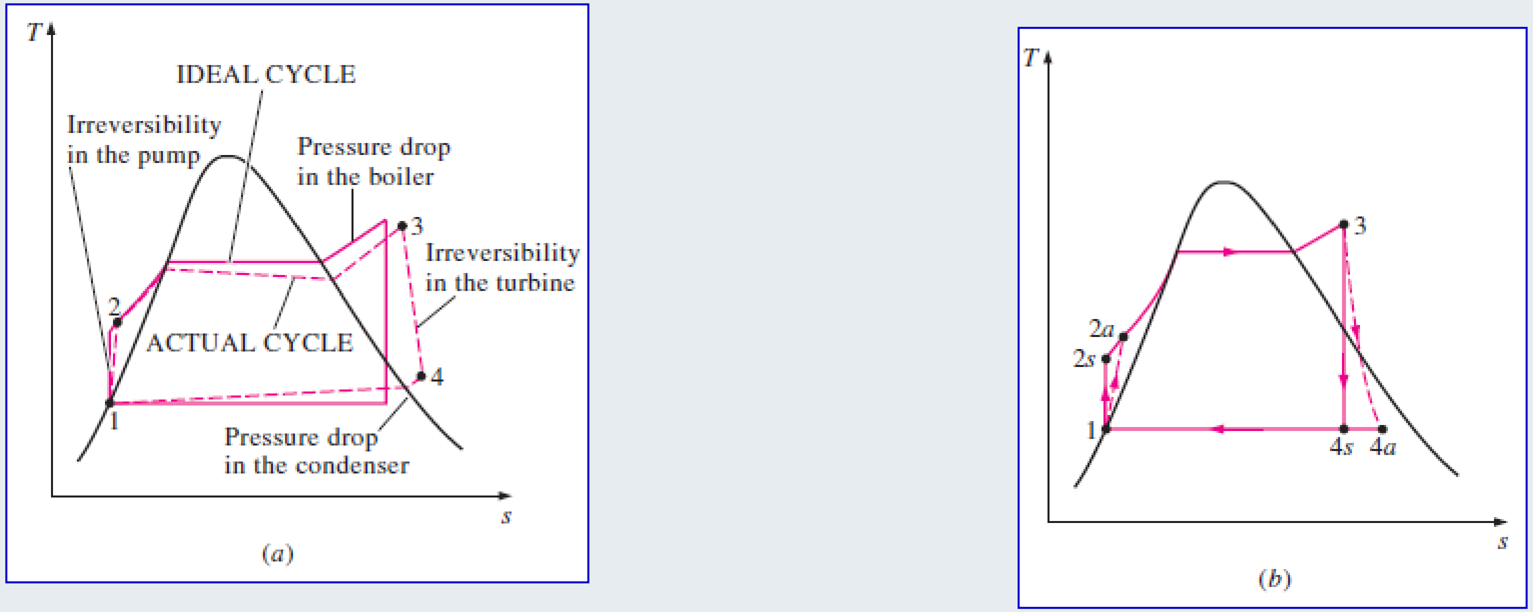
$$\Delta T = \frac{70650}{8360} = \mathbf{8.45} \, ℃$$

3. 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

3. Deviation of Actual Vapor Power Cycles from Idealized Ones

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



(a)

(b)

Figure 5: Deviation of Actual Vapor Power Cycles from Idealized One

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3. 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:

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

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

3. Deviation of Actual Vapor Power Cycles from Idealized Ones Cont…

Example 2:

Repeat Example 1, assuming an adiabatic efficiency of 87 percent for both the turbine and the pump.

A steam power plant operates on a simple ideal Rankine cycle with a net power output of 45 MW. Steam enters the turbine at 7 MPa and 500°C and is condensed in the condenser at 10 kPa. Cooling water from a lake flows through the condenser tubes at 2000 kg/s.

- Determine the thermal efficiency of the cycle.
- Find the mass flow rate of steam ($\dot{m}$).
- Calculate the temperature rise of the cooling water (ΔT).

3. Deviation of Actual Vapor Power Cycles from Idealized Ones Cont…

Solution:

Pump inlet

From steam tables: $h_1 = 191.81 kJ/kg,$ $v_1 = 0.001010\ m^3/kg\ ,$ $s_1 = 0.6492$

$$h_{2s} = h_1 + v_1(P_2 - P_1) = 191.81 + 0.001010\ (7000 - 10) = 198.87\ kJ/kg$$

Actual Pump work with $\eta_P = 87\%$:

$$h_{2a} = h_1 + \frac{h_{2s} - h_1}{\eta_P} = 191.81 + \frac{198.87 - 191.81}{0.87} = 199.92\ kJ/kg$$

From superheated steam tables:

$$h_3 = 3410.3\ kJ/kg \qquad s_3 = 6.7975$$

3. Deviation of Actual Vapor Power Cycles from Idealized Ones **Cont…**

Ideal Turbine outlet

At $P_4 = 10\ kPa$

$$x_{4s} = \frac{s_{4s} - s_f}{s_{fg}} = \frac{6.7975 - 0.6492}{7.499} = 0.820$$

$$h_{4s} = h_f + x_{4s}h_{fg} = 191.81 + 0.820\ x\ 2392.1 = 2153.5\ kJ/kg$$

Actual Turbine work with $\eta_T = 87\%$:

$$h_4 = h_3 - \eta_T\,(h_3 - h_{4s}) = 3410.3 - 0.87(3410.3 - 2153.5) = 2317.1\ kJ/kg$$

Thermal Efficiency (η)

$$\eta = \frac{W_{net}}{Q_{in}} = \frac{(W_T - W_P)}{Q_{in}}$$

3. Deviation of Actual Vapor Power Cycles from Idealized Ones Cont…

Turbine Work: $W_T = h_3 - h_4 = 3410.3 - 2317.1 = 1093.2\ kJ/kg$

Pump Work: $W_P = h_2 - h_1 = 199.92 - 191.81 = 8.11\ kJ/kg$

Network: $W_{net} = W_T - W_P = 1093.2 - 8.11 = 1085.1\ kJ/kg$

Heat Input: $Q_{in} = h_3 - h_2 = 3410.3 - 199.92 = 3210.4\ kJ/kg$

Efficiency: $\eta = \frac{W_{net}}{Q_{in}} = \frac{1085.1}{3210.4} = 0.338 = 33.8\%$

Mass Flow rate of steam ($\dot{m}$):

$$\dot{m} = \frac{\dot{W}_{net}}{W_{net}} = \frac{45000\ kW}{1085.1\ kJ/kg} = 41.47\ kg/s$$

3. Deviation of Actual Vapor Power Cycles from Idealized Ones **Cont…**

Temperature Rise of Cooling Water:

Heat rejected in condenser

$$Q_{out} = h_4 - h_1 = 2317.1 - 191.81 = 2125.3\ kJ/kg$$

$$\dot{Q}_{out} = \dot{m}Q_{out} = 41.47\ x\ 2125.3 = 88{,}140\ kW$$

Cooling water temperature rise:

$$\dot{Q}_{out} = \dot{m}_{cv}C_p\Delta T$$

$$\Delta T = \frac{\dot{Q}_{out}}{\dot{m}_{cv}C_p} = \frac{88{,}140}{2000\ x\ 4.18}$$

$$\Delta T = \mathbf{10.54}℃$$

3. 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 [2].
- 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.

3. 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

3. 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 P4 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.

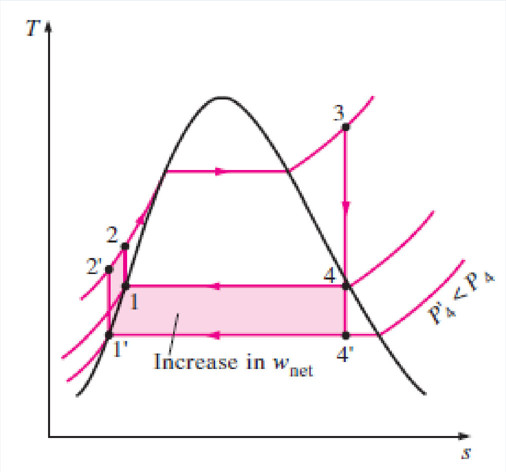

Figure 6: T-s diagram of a Rankine Cycle with Lowering Condenser Pressure

url: https://slideplayer.com/slide/5779348/19/images/10/Effect+of+Lowering+Condenser+Pressure+on+the+Ideal+Rankine+cycle.jpg

3. Deviation of Actual Vapor Power Cycles from Idealized Ones **Cont…**

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

- 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.

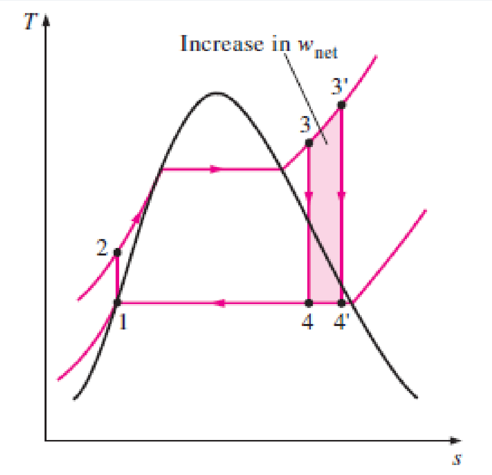

Figure 7: T-s diagram of a Rankine Cycle with Superheating the Steam
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3. Deviation of Actual Vapor Power Cycles from Idealized Ones Cont…

  - 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℃ (1150°F) [1] .

3. 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.

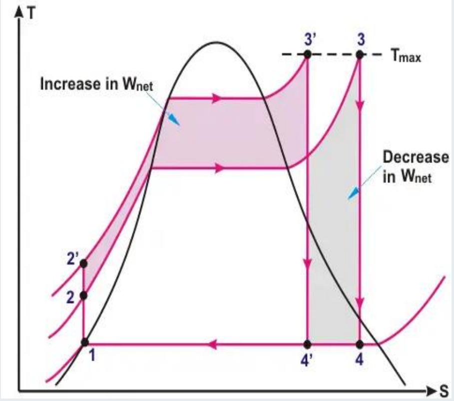

Figure 8: T-s diagram of a Rankine Cycle with Increasing the Boiler Pressure

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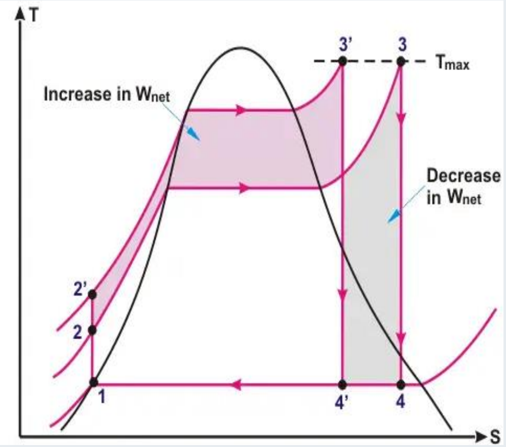
4. The Ideal Reheat Rankine Cycle



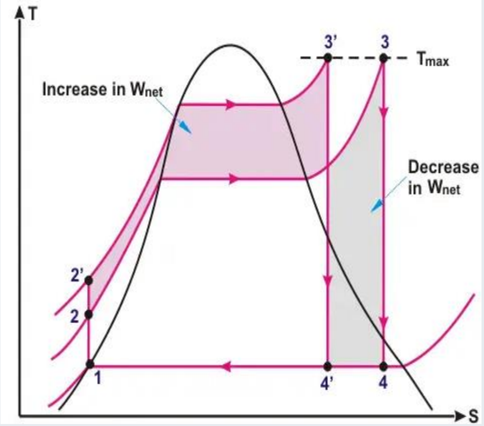
- Increasing the boiler pressure increases the thermal efficiency of the Rankine cycle, but it also increases the moisture content of the steam to unacceptable levels.

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?

4. 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.

4. 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.

4. 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:

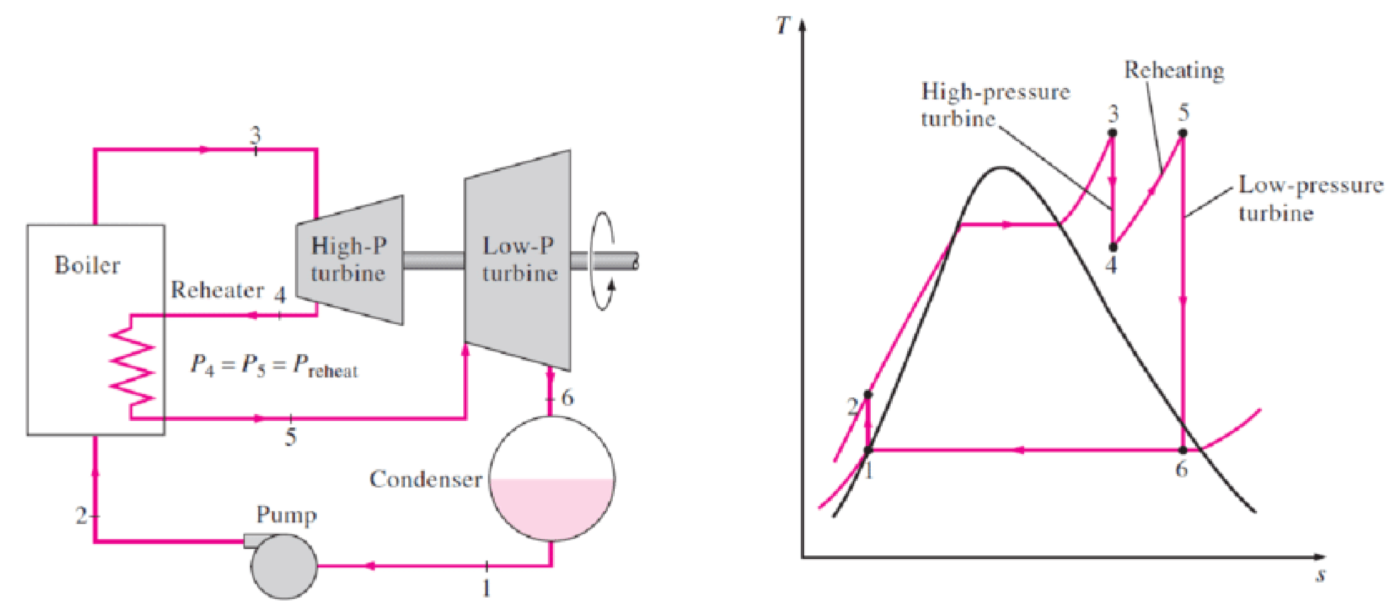


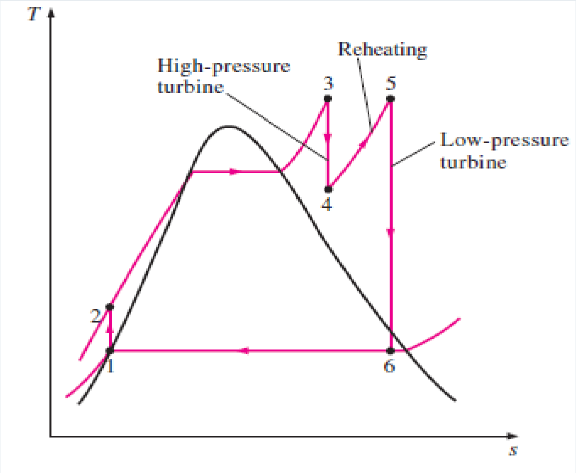
Figure 9: Schematic and T-s diagram of an Ideal Rehaet Rankine Cycle

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

4. The Ideal Reheat Rankine Cycle

Cont…

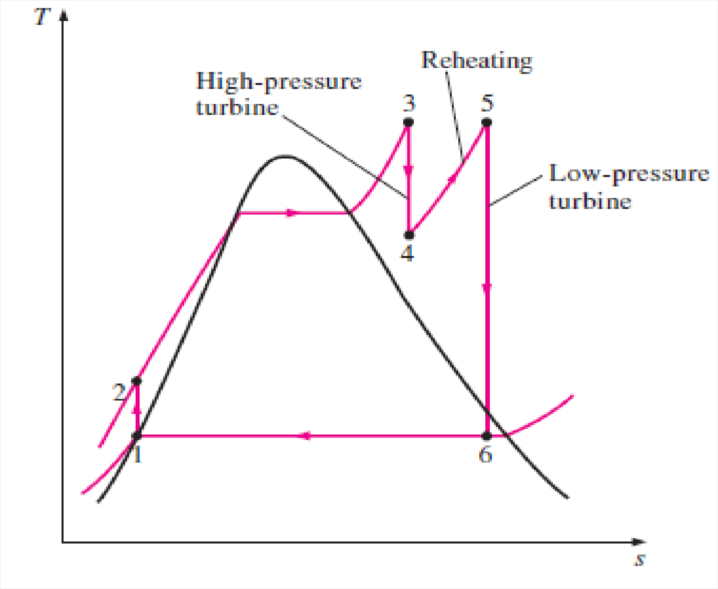
- The ideal reheat Rankine cycle differs from the simple ideal Rankine cycle in that the expansion process takes place in two stages.
- In the first stage (the high-pressure turbine), steam is expanded isentropically to an intermediate pressure and sent back to the boiler where it is reheated at constant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



4. The Ideal Reheat Rankine Cycle

Cont…

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

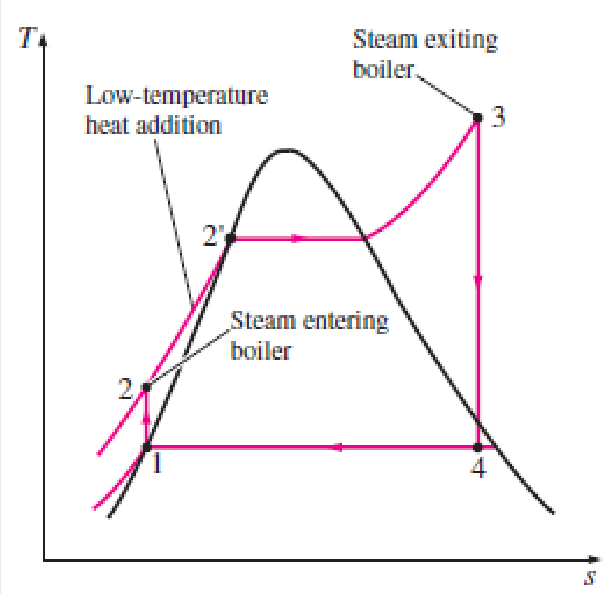


$$q_{in} = q_{primary} + q_{reheat} = (h_3 - h_2) + (h_5 - h_4)$$

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

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.

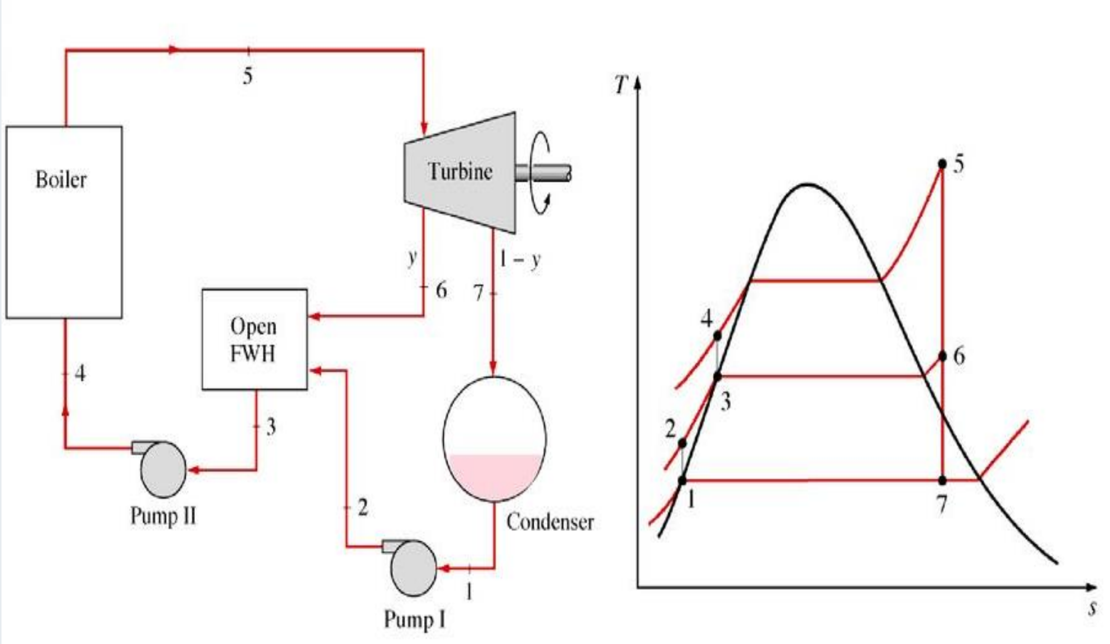


Figure 10: Schematic and T-s diagram of an Ideal Regenerative Rankine Cycle
url: https://image4.slideserve.com/9116143/the-ideal-regenerative-rankine-cycle-with-an-open-l.jpg

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).

Summary

- The Rankine Cycle is the fundamental thermodynamic cycle used in steam power plants.
- Real cycles experience inefficiencies due to irreversibilities such as friction, heat losses, and pressure drops, leading to lower actual efficiency compared to ideal cycles.
- The ideal Reheat Rankine Cycle improves efficiency by reheating steam between turbine stages to reduce excessive moisture content and increase the work output of the cycle.
- The Ideal Regenerative Rankine Cycle enhances efficiency by preheating the feedwater using extracted steam from the turbine, reducing the amount of fuel needed for heat addition in the boiler.
- While these cycles guide power plant design, real-world systems require engineering adaptations to optimize performance while accounting for material limitations and economic factors.

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Thank you !