GUJARAT TECHNOLOGICAL UNIVERSITY

BE- 3 SEMESTER – OLD PAPER – S23 TO S25- QUESTION BANK & SOLUTION

Subject Name & Code:
Engineering Thermodynamics (3131905)

Unit 6: Vapor Power Cycles (Rankine Cycle)

Repeated Questions:

1. **Compare Carnot and Rankine cycles. (03 Marks - W22, W23, S24, W24)**

Answer:

Aspect	Carnot Cycle	Rankine Cycle
Working Fluid	Any (ideal gas or vapor)	Water/Steam (phase-changing)
Processes	1. Isothermal Expansion 2. Adiabatic Expansion 3. Isothermal Compression 4. Adiabatic Compression	1. Isobaric Heat Addition (Boiler) 2. Adiabatic Expansion (Turbine) 3. Isobaric Heat Rejection (Condenser) 4. Adiabatic Compression (Pump)
Efficiency	$\eta = 1 - \frac{T_2}{T_1}$ (Maximum theoretical)	$\eta = \frac{W_{net}}{Q_{in}}$ (Lower than Carnot)
Practicality	**Not practical** - Isothermal heat transfer difficult	**Practical** - Used in actual power plants
Heat Addition	At constant temperature (isothermal)	At constant pressure (isobaric) with phase change
Compression	Two-phase mixture compression (difficult)	Liquid compression (easy with pump)
Moisture Content	Can have high moisture at turbine exit	Controlled by superheating
Applications	Theoretical benchmark	Actual steam power plants
Advantages	Maximum efficiency possible	Practical, handles wet steam better
Disadvantages	Impractical, difficult compression	Lower efficiency than Carnot

Key Difference: Carnot cycle gives **maximum efficiency limit** but is impractical; Rankine cycle is **practically implementable** with water/steam as working fluid.

2. **Draw the Rankine cycle on P-v, T-s, and h-s diagrams and derive its efficiency. (07 Marks - S23, S25)**

Answer:

Rankine Cycle Processes:

1. **1→2:** Adiabatic pumping (Pump) - Liquid compressed
2. **2→3:** Isobaric heat addition (Boiler) - Water heated to steam
3. **3→4:** Adiabatic expansion (Turbine) - Steam expands
4. **4→1:** Isobaric heat rejection (Condenser) - Steam condensed

Diagram Generation Prompts:

P-v Diagram: "Draw pressure-volume diagram for Rankine cycle. Show: 1→2 steep upward line (pump), 2→3 horizontal line rightward (boiler), 3→4 downward curve (turbine), 4→1 horizontal line leftward (condenser). Label points 1,2,3,4 and processes."

T-s Diagram: "Draw temperature-entropy diagram for Rankine cycle. Show: 1→2 almost vertical line (pump), 2→3 upward curve along saturation line then horizontal in superheat (boiler), 3→4 downward line (turbine), 4→1 horizontal line in wet region (condenser). Mark saturation dome."

h-s Diagram (Mollier): "Draw enthalpy-entropy diagram for Rankine cycle. Show: 1→2 vertical upward (pump), 2→3 upward to right (boiler), 3→4 downward to right (turbine), 4→1 horizontal left (condenser). Show constant pressure lines."

Efficiency Derivation:

Step 1: Energy transfers per kg of steam

- Pump work (input): $w_p = h_2 - h_1$
- Turbine work (output): $w_t = h_3 - h_4$
- Heat input (boiler): $q_{in} = h_3 - h_2$
- Heat rejected (condenser): $q_{out} = h_4 - h_1$

Step 2: Net work output

$$w_{net} = w_t - w_p = (h_3 - h_4) - (h_2 - h_1)$$

Step 3: Rankine cycle efficiency

$$\eta_{Rankine} = \frac{w_{net}}{q_{in}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}$$

Step 4: Approximation (pump work negligible)

$$\eta \approx \frac{h_3 - h_4}{h_3 - h_2}$$

Step 5: Using enthalpies from steam tables

Typically:

- $h_1 = h_f$ at condenser pressure
- $h_2 = h_1 + v_1(P_2 - P_1)$ (pump work)
- $h_3 = h$ at boiler pressure and temperature
- $h_4 = h_f + xh_{fg}$ at condenser pressure

Final Efficiency Formula:

$$\boxed{\eta_{Rankine} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}}$$

3. **Explain effect of regeneration on Rankine cycle with diagram.**
   ➤ Appeared in: W24 (Q4b, 04 marks), S25 (Q4b, 04 marks)

Answer:

Regeneration: Using extracted steam from turbine to preheat feedwater before it enters boiler.
Process: Steam is **bled** at intermediate pressures from turbine, mixed with or used to heat feedwater in **feedwater heaters**.
Types:

1. **Open/Contact Feedwater Heater:** Direct mixing of bled steam with feedwater
2. **Closed Feedwater Heater:** Indirect heat exchange through tubes

Diagram Generation Prompt: "Draw schematic of regenerative Rankine cycle with one closed feedwater heater. Show: Boiler → High-pressure turbine → Extraction point → Low-pressure turbine → Condenser → Pump 1 → Feedwater heater → Pump 2 → Boiler. Show bled steam line to feedwater heater."
T-s Diagram: "Draw T-s diagram showing regenerative Rankine cycle. Show main cycle plus internal heat exchange lines showing reduced heat addition area."
Effects on Performance:

1. **Increased Efficiency:**
    - Average temperature of heat addition increases
    - Heat input required decreases (Q_in reduces)
    - Efficiency $\eta = \frac{W_{net}}{Q_{in}}$ increases
2. **Reduced Heat Rate:** Less fuel needed for same output
3. **Lower Moisture Content:** At turbine exhaust, reduces erosion
4. **Smaller Components:** Boiler and condenser size reduce
5. **Disadvantages:**
    - Increased complexity
    - More equipment cost
    - Reduced turbine work (some steam extracted)

Typical Efficiency Gain: 5-10% improvement over simple Rankine cycle

4. **Solve a numerical problem on an ideal Rankine cycle (find efficiency, work done, etc.). (07 Marks - S24, W23, S23, W24, S25)**

Answer:

5. **In an ideal Rankine cycle, steam at 20 bar and 350°C expands in steam turbine to 0.05 bar. The saturated water after condensation fed back to the boiler. Determine (i) net work done per kg of steam, (ii) Rankine cycle efficiency.**
   ➤ Appeared in: W23 (Q4c, 07 marks)

Answer:

Given:

- Boiler: $P_3 = 20$ bar $= 2$ MPa, $T_3 = 360°\text{C}$
- Condenser: $P_1 = 0.08$ bar $= 8$ kPa
- Ideal Rankine cycle

To Find: (a) Net work per kg (b) Cycle efficiency
Solution using Steam Tables:
Step 1: State point properties
Point 1: Condenser exit, saturated liquid at 0.08 bar
From steam tables at 0.08 bar:

$$h_1 = h_f = 173.88 \text{ kJ/kg}, v_1 = 0.0010084 \text{ m}^3/\text{kg}$$

Point 2: Pump exit, compressed liquid at 20 bar

Pump work: $w_p = v_1(P_2 - P_1)$

$$= 0.0010084 \times (2000 - 8) = 0.0010084 \times 1992 = 2.01 \text{ kJ/kg}$$
$$h_2 = h_1 + w_p = 173.88 + 2.01 = 175.89 \text{ kJ/kg}$$

Point 3: Turbine inlet, 20 bar, 360°C (superheated)
From superheated steam tables at 20 bar, 360°C:
Point 4: Turbine exit, isentropic expansion to 0.08 bar

At 0.08 bar:
Dryness fraction: $x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.9917- \ .5926}{7.6361} = \frac{6.3991}{7.6361} = 0.838$

$$h_4 = h_f + x_4 h_{fg} = 173.88 + 0.838 \times 2403.1 = 173.88 + 2013.8 = 2187.68 \text{ kJ/kg}$$

Step 2: Calculate energy transfers
Turbine work: $w_t = h_3 - h_4 = 3159.3 - 2187.68 = 971.62$ kJ/kg
Pump work: $w_p = 2.01$ kJ/kg (already calculated)
Net work: $w_{net} = w_t - w_p = 971.62 - 2.01 = 969.61$ kJ/kg
Heat input: $q_{in} = h_3 - h_2 = 3159.3 - 175.89 = 2983.41$ kJ/kg
Step 3: Calculate efficiency

$$\eta = \frac{w_{net}}{q_{in}} = \frac{969.61}{2983.41} = 0.325 \text{ or } 32.5\%$$

Final Answer:

$$\boxed{w_{net} = 969.61 \text{ kJ/kg}} \boxed{\eta = 32.5\%}$$

6. **In a Rankine cycle, the steam at inlet to turbine is saturated at a pressure of 35 bar and the exhaust pressure is 0.2 bar. Determine: (i) The pump work, (ii) The turbine work, (iii) The Rankine efficiency, (iv) The condenser heat flow, (v) The dryness at the end of expansion. Assume the mass flow rate of steam equals to 9.5 kg/s.**
   ➤ **Appeared in: S24 (Q4c, 07 marks)**

Answer:
Given:

- Turbine inlet: Saturated vapor at $P_3 = 35$ bar $= 3.5$ MPa
- Condenser: $P_1 = 0.2$ bar $= 20$ kPa
- Mass flow: $\dot{m} = 9.5$ kg/s
- Ideal cycle

Solution using Steam Tables:
Step 1: State point properties
Point 1: Saturated liquid at 0.2 bar
From tables at 0.2 bar:

$$h_1 = h_f = 251.4 \text{ kJ/kg}, v_1 = 0.001017 \text{ m}^3/\text{kg}$$

Point 2: Pump exit at 35 bar
Pump work (per kg): $w_p = v_1(P_2 - P_1)$

$$= 0.001017 \times (3500 - 20) = 0.001017 \times 3480 = 3.54 \text{ kJ/kg}$$
$$h_2 = h_1 + w_p = 251.4 + 3.54 = 254.94 \text{ kJ/kg}$$

Point 3: Saturated vapor at 35 bar
From tables at 35 bar:
Point 4: Turbine exit at 0.2 bar, isentropic expansion

At 0.2 bar:
Dryness: $x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.1253-0.8320}{7.0766} = \frac{5.2933}{7.0766} = 0.748$

$$h_4 = h_f + x_4 h_{fg} = 251.4 + 0.748 \times 2358.3 = 251.4 + 1764.0 = 2015.4 \text{ kJ/kg}$$

Step 2: Calculate required parameters
(i) Pump work:
Per kg: $w_p = 3.54$ kJ/kg
Total: $\dot{W}_p = \dot{m} \times w_p = 9.5 \times 3.54 = 33.63$ kW
(ii) Turbine work:
Per kg: $w_t = h_3 - h_4 = 2802.3 - 2015.4 = 786.9$ kJ/kg
Total: $\dot{W}_t = 9.5 \times 786.9 = 7475.6$ kW
(iii) Rankine efficiency:
Net work: $w_{net} = w_t - w_p = 786.9 - 3.54 = 783.36$ kJ/kg
Heat input: $q_{in} = h_3 - h_2 = 2802.3 - 254.94 = 2547.36$ kJ/kg

$$\eta = \frac{w_{net}}{q_{in}} = \frac{783.36}{2547.36} = 0.3075 \text{ or } 30.75\%$$

(iv) Condenser heat flow:
Per kg: $q_{out} = h_4 - h_1 = 2015.4 - 251.4 = 1764.0$ kJ/kg
Total: $\dot{Q}_{out} = 9.5 \times 1764.0 = 16758.0$ kW
(v) Dryness at end of expansion:
Already calculated: $x_4 = 0.748$ or 74.8%
Final Answers:
(i) $\dot{W}_p = 33.63$ kW
(ii) $\dot{W}_t = 7475.6$ kW
(iii) $\eta = 30.75\%$
(iv) $\dot{Q}_{out} = 16758.0$ kW
(v) $x_4 = 0.748$

Other Important Questions:

4. S24: Explain with a neat schematic diagram the Reheat Rankine cycle. (04 Marks)

Answer:

Reheat Rankine Cycle: A modification of the simple Rankine cycle where steam is **expanded in two stages** with **reheating in between** to reduce moisture content at turbine exhaust and improve efficiency.
Processes:
1. **1→2:** Pump work (feedwater compression)
2. **2→3:** Heat addition in boiler (to superheated steam)
3. **3→4: First expansion** in High-Pressure (HP) turbine
4. **4→5: Reheating** in boiler (constant pressure heat addition)
5. **5→6: Second expansion** in Low-Pressure (LP) turbine
6. **6→1:** Condensation in condenser

Diagram Generation Prompt:
"Draw a schematic diagram of a reheat Rankine cycle. Show: Boiler → HP Turbine → Reheater (in boiler) → LP Turbine → Condenser → Pump → Back to boiler. Label all components and show steam flow direction with arrows. Indicate points 1 through 6 for cycle analysis."
T-s Diagram Prompt:
"Draw T-s diagram for reheat Rankine cycle. Show: 1→2 vertical line (pump), 2→3 upward curve to

superheat (boiler), 3→4 downward line (HP turbine), 4→5 horizontal rightward line (reheater), 5→6 downward line (LP turbine), 6→1 horizontal line (condenser). Show saturation dome."

Advantages:

1. **Reduced Moisture:** Final dryness fraction increases (typically > 90%)
2. **Increased Efficiency:** 4-5% improvement over simple Rankine
3. **Reduced Erosion:** Less blade damage in LP turbine
4. **Higher Average Temperature** of heat addition

Disadvantages:

1. Increased complexity and cost
2. Additional piping and controls
3. Not economical for small plants

Typical Applications: Large steam power plants (> 80 MW)

5. W23: Explain variables affecting the efficiency of the Rankine cycle. (03 Marks)

Answer:

Three main variables affect Rankine cycle efficiency:

1. **Boiler pressure (high pressure):** Increasing boiler pressure raises the average temperature of heat addition → increases efficiency. However, very high pressure leads to low exhaust quality (wet steam) damaging turbine blades.
2. **Condenser pressure (low pressure):** Lowering condenser pressure reduces the temperature of heat rejection → increases efficiency. Practical limit is around 0.04 bar (saturation temperature ~29°C) to avoid air leakage and large specific volume.
3. **Superheat temperature:** Increasing superheat temperature at constant boiler pressure increases average heat addition temperature → improves efficiency and also increases turbine exhaust quality (reduces moisture).

Other factors: Reheat, regeneration, and cycle losses (irreversibilities) also affect efficiency.

➞ **Real-world application:** Power plant designers optimize these parameters – typically 150–300 bar, 540–600°C superheat, and 0.05 bar condenser pressure.

6. W23: Discuss the effect of superheat and condenser pressure variation on the Rankine cycle. (03 Marks)

Answer:

Effect of superheat (increasing $T_{superheat}$):

- Increases average temperature of heat addition → higher cycle efficiency.
- Increases turbine work output (higher h_3).
- Increases steam quality at turbine exit (higher x_4) → reduces blade erosion.
- Limits: material strength at high temperature (currently ~620°C for steel).

Effect of decreasing condenser pressure (P_{cond}):

- Lowers saturation temperature T_{sat} → lower heat rejection temperature → increases Carnot efficiency.
- Increases turbine work output (greater expansion).
- Disadvantages: Very low pressures (below 0.04 bar) cause:
    - Increased specific volume of steam → larger turbine size.
    - Air leakage into condenser.
    - Higher moisture content at turbine exit (if no reheat).
    - Increased pump work (negligible).

➞ **Real-world application:** Modern plants use condenser pressure around 0.05 bar and superheat up to 600°C.

7. S25: Explain the simple regenerative Rankine cycle. (04 Marks)

Answer:

Simple regenerative Rankine cycle uses an **open feedwater heater** (direct contact) where extracted steam from the turbine mixes with condensate to raise the feedwater temperature before it enters the boiler.

Working:

1. Pump 1 sends condensate from condenser to feedwater heater at extraction pressure.
2. Extraction steam from turbine (at same pressure) enters the heater and mixes.
3. Mixed flow becomes saturated liquid at that pressure.
4. Pump 2 (boiler feed pump) sends the high-pressure water to boiler.

[DG PROMPT] – Simple regenerative cycle with open FWH

Title: Regenerative Cycle – Open Feedwater Heater

Description: Draw: Boiler → HP turbine → extraction line to Open FWH → LP turbine → Condenser → Pump 1 → Open FWH (mixing) → Pump 2 → Boiler. Label extraction fraction y. Show T-s diagram with extraction point.

Efficiency gain: By increasing feedwater temperature, the average heat addition temperature rises, approaching Carnot efficiency. Typical improvement: 5–10 percentage points.

Advantages: Higher efficiency, reduced condenser heat load, better thermal stress management in boiler.

8. W24: State advantages and disadvantages of regenerative feed heating. (03 Marks)

Answer:

Advantages:

1. Increases cycle efficiency (average heat addition temperature rises).
2. Reduces heat rejected in condenser → smaller cooling tower/less thermal pollution.
3. Reduces boiler thermal stress because feedwater enters at higher temperature.
4. Improves turbine blade life by reducing moisture in low-pressure stages (extraction removes wet steam).

Disadvantages:

1. Increases plant complexity and capital cost (additional heaters, pumps, piping).
2. Requires larger boiler for same net output (due to extraction steam not producing full work).
3. Maintenance cost higher.
4. Part-load performance can be affected.

9. S23: What is the mean temperature of heat addition? Explain its significance. (04 Marks)

Answer:

Mean temperature of heat addition (T_m) is the constant temperature that would give the same heat transfer as the actual variable-temperature process in the boiler. For the Rankine cycle:

$$T_m = \frac{h_3 - h_2}{s_3 - s_2} = \frac{\text{Heat added per kg}}{\text{Entropy increase during heat addition}}$$

On a T-s diagram, T_m is the height of a rectangle having the same area (heat) and same base (entropy change).

Significance:

- Rankine cycle efficiency can be expressed as $\eta = 1 - \frac{T_{out}}{T_m}$, where T_{out} is the heat rejection temperature (condenser).
- Higher T_m → higher efficiency.
- Regeneration increases T_m by raising the temperature at which heat is absorbed.
- T_m is always less than the peak superheat temperature but greater than the saturation temperature.

- It allows direct comparison of different cycles (e.g., reheat, regeneration) via their mean heat addition temperature.

➞ **Real-world application:** Used in cycle optimization to guide design changes that raise T_m (superheat, reheat, regeneration).

1. **Steam at 20 bar, 360°C is expanded in a steam turbine to 0.08 bar. It then enters a condenser, where it is condensed to saturated liquid water. The pump feeds back the water into the boiler. Assuming ideal processes, find per kg steam the network and the cycle efficiency.**
   ➤ Appeared in: S23 (Q5c, 07 marks)

Answer:

Given:

$P_3 = 20\text{ bar} = 2000\text{ kPa}, T_3 = 360°\text{C}$

$$P_4 = 0.08\text{ bar} = 8\text{ kPa}$$

Steam tables:

At 8 kPa (0.08 bar):

$$T_{sat} = 41.5°\text{C}$$

$h_f = 173.88, h_g = 2577.0, s_f = 0.5926, s_g = 8.2287$

$$v_f = 0.001008\text{ m}^3/\text{kg}$$

At 20 bar, 360°C:

From superheated table (20 bar): at 350°C $h = 3137$, $s = 6.956$; at 400°C $h = 3248$, $s = 7.128$.

Interpolate for 360°C:

$$h_3 = 3137 + \frac{10}{50} \times (3248 - 3137) = 3137 + 0.2 \times 111 = 3137 + 22.2 = 3159.2\text{ kJ/kg}$$

$$s_3 = 6.956 + 0.2 \times (7.128 - 6.956) = 6.956 + 0.0344 = 6.9904\text{ kJ/kg}\cdot\text{K}$$

Turbine outlet: Isentropic $s_4 = s_3 = 6.9904$

At 8 kPa: $s_f = 0.5926, s_g = 8.2287, s_{fg} = 7.6361$

$$x_4 = \frac{6.9904 - 0.5926}{7.6361} = \frac{6.3978}{7.6361} = 0.8378$$

$$h_4 = h_f + x_4 h_{fg} = 173.88 + 0.8378 \times (2577.0 - 173.88)$$

$h_{fg} = 2403.12 \rightarrow h_4 = 173.88 + 0.8378 \times 2403.12 = 173.88 + 2013.6 = 2187.48\text{ kJ/kg}$

Pump work: $w_p = v_f(P_2 - P_1) = 0.001008 \times (2000 - 8) = 0.001008 \times 1992 = 2.01\text{ kJ/kg}$

$$h_2 = h_1 + w_p = 173.88 + 2.01 = 175.89\text{ kJ/kg}$$

Turbine work: $w_t = h_3 - h_4 = 3159.2 - 2187.48 = 971.72\text{ kJ/kg}$

Net work: $w_{net} = 971.72 - 2.01 = 969.71\text{ kJ/kg}$

Heat added: $q_{in} = h_3 - h_2 = 3159.2 - 175.89 = 2983.31\text{ kJ/kg}$

Efficiency: $\eta = \frac{969.71}{2983.31} = 0.3250 = 32.50\%$

Final Answer:

$$\boxed{w_{net} = 969.71\text{ kJ/kg}, \eta = 32.50\%}$$

2. **In a steam power cycle, the steam supply is at 15 bar and dry and saturated. The condenser pressure is 0.4 bar. Calculate the Carnot and Rankine efficiencies of the cycle. Neglect pump work.**
   ➤ Appeared in: W24 (Q4c, 07 marks), S25 (Q5c, 07 marks)

Answer:

Given:

- Boiler: $P = 15\text{ bar} = 1.5\text{ MPa}$, dry saturated
- Condenser: $P = 0.4\text{ bar} = 40\text{ kPa}$

- Neglect pump work

To Find: (a) Carnot efficiency (b) Rankine efficiency
Solution:
Step 1: Find temperatures from steam tables
At 15 bar (saturated):

$$T_{sat} = 198.3°\text{C} = 471.3 \text{ K}$$

At 0.4 bar (saturated):

$$T_{sat} = 75.9°\text{C} = 349.0 \text{ K}$$

Step 2: Carnot efficiency

$$\eta_{Carnot} = 1 - \frac{T_2}{T_1} = 1 - \frac{349.0}{471.3} = 1 - 0.7406 = 0.2594 \text{ or } 25.94\%$$

Step 3: Rankine efficiency (neglecting pump work)
From steam tables:
At 15 bar, dry saturated:
At 0.4 bar:
For isentropic expansion: $s_4 = s_3 = 6.4448$
Dryness: $x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.4448 - 1.0261}{6.6448} = \frac{5.4187}{6.6448} = 0.815$

$$h_4 = h_f + x_4 h_{fg} = 317.6 + 0.815 \times 2319.2 = 317.6 + 1889.1 = 2206.7 \text{ kJ/kg}$$

Step 4: Rankine efficiency (pump work neglected)

$$\eta_{Rankine} = \frac{h_3 - h_4}{h_3 - h_1} = \frac{2792.2 - 2206.7}{2792.2 - 317.6} = \frac{585.5}{2474.6} = 0.2366 \text{ or } 23.66\%$$

Observation: $\eta_{Rankine}(23.66\%) < \eta_{Carnot}(25.94\%)$ as expected.
Final Answer:

$$\boxed{\eta_{Carnot} = 25.94\%} \boxed{\eta_{Rankine} = 23.66\%}$$