Study Material

BE-3 SEMESTER – Midterm Q.B&A – 2025

Engineering Thermodynamics- BE03000201

📘 CO-1: Unit- 1 Q&A

Q1: What do you mean by thermodynamic equilibrium? Explain in detail.

Answer:

A system is in a state of **thermodynamic equilibrium** when it meets the conditions for three distinct types of equilibrium simultaneously. This means the system's properties are uniform throughout and do not change with time unless disturbed by an external interaction.

- **1. Mechanical Equilibrium:**
  - **Condition:** There are no unbalanced forces acting within the system or between the system and its surroundings.
  - **Consequence:** The pressure throughout the system is the same at all points and remains constant over time.
  - **Example:** A gas confined in a rigid, stationary container with no pressure gradients.
- **2. Thermal Equilibrium:**
  - **Condition:** There is no temperature difference between any parts of the system or between the system and its surroundings.
  - **Consequence:** The temperature is uniform at every point in the system and does not change with time.
  - **Example:** A metal rod that has reached a uniform temperature after one end was heated.
- **3. Chemical Equilibrium:**
  - **Condition:** No chemical reactions are taking place within the system, and the mass of each chemical component remains constant.
  - **Consequence:** The chemical composition is homogeneous throughout the system and does not vary with time.
  - **Example:** A perfectly mixed, stable chemical solution with no ongoing reactions.

Conclusion: For a system to be in thermodynamic equilibrium, all three conditions must be satisfied at the same time. If any one condition is not met (e.g., a temperature difference exists), the system is not in equilibrium and will undergo a spontaneous change.

Q2: Explain an Open system, Closed System and Isolated System in Thermodynamics

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Answer:

Thermodynamic systems are classified based on the interactions of mass and energy across their boundaries.

- **A) Open System (Control Volume):**
  - **Mass Transfer: Yes.** Mass can cross the system boundary.
  - **Energy Transfer: Yes.** Energy in the form of heat and work can cross the system boundary.
  - **Analysis:** Typically analyzed using a **control volume**—a fixed region in space.
  - **Examples:**
    - **Air Compressor:** Air (mass) enters and leaves, while work is done on the system.
    - **Boiler:** Water enters, steam exits, and heat is supplied.
    - **Turbine:** Mass flow of steam or gas passes through, producing work.
- **B) Closed System:**
  - **Mass Transfer: No.** The mass within the system is fixed and constant.
  - **Energy Transfer: Yes.** Energy in the form of heat and work can cross the system boundary.
  - **Characteristics:** The system's volume can change (e.g., a moving piston), and the physical/chemical state of the fixed mass can change.
  - **Examples:**
    - **Piston-Cylinder Device:** A fixed amount of gas is compressed or expanded.
    - **Sealed Pressure Cooker:** Food is cooked inside a sealed container with heat addition.
    - **Bomb Calorimeter:** A fixed mass undergoes a combustion reaction inside a rigid vessel.

- **C) Isolated System:**
    - **Mass Transfer: No.**
    - **Energy Transfer: No.**
    - **Characteristics:** There is no interaction of any kind with the surroundings. It is a system of fixed mass and fixed energy.
    - **Examples:**
        - **The Universe** (by definition).
        - **A Perfectly Insulated, Rigid, and Sealed Vessel** (an idealized Thermos flask).

Q3: Explain Zeroth law of thermodynamics stating its application.

Answer:

- **Formal Statement:** "If two bodies are each in thermal equilibrium with a third body, then they are also in thermal equilibrium with each other."
- **Detailed Explanation:**
    - This law establishes that **thermal equilibrium is a transitive relation**. If body A is in thermal equilibrium with body C, and body B is also in thermal equilibrium with body C, then body A and body B must be in thermal equilibrium with each other.
    - This principle allows us to compare the temperatures of different objects without bringing them into direct contact.
- **Primary Application: Temperature Measurement**
    - **Basis for Thermometry:** The Zeroth Law is the fundamental principle that makes temperature measurement possible. The "third body" is replaced by a **thermometer**.
    - **How it works:** If a thermometer (body C) shows the same reading when placed in contact with two different objects (body A and body B) separately, we can conclude that objects A and B are at the same temperature.
    - **Foundation for Scales:** This law validates the use of reference points (like ice and steam points) to create consistent and universal temperature scales (Celsius, Fahrenheit, Kelvin, Rankine).

Q4: Define and explain: (i) Homogenous and Heterogeneous system (ii) Intensive and Extensive properties

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Answer:

(i) Homogeneous and Heterogeneous System

- **Homogeneous System:**
  - **Definition:** A system that consists of a **single, uniform phase**.
  - **Explanation:** The chemical composition and physical properties are identical throughout the entire system. There are no visible boundaries separating different compositions.
  - **Examples:**
    - A mixture of air and water vapor (a single gaseous phase).
    - A solution of salt completely dissolved in water (a single liquid phase).
    - A pure metal block like copper or steel (a single solid phase).
- **Heterogeneous System:**
  - **Definition:** A system that consists of **two or more distinct phases** separated by physical boundaries.
  - **Explanation:** The system is not uniform and contains regions with different properties or compositions.
  - **Examples:**
    - A glass of ice water (solid ice and liquid water phases).
    - Water and steam in a boiler (liquid and vapor phases).
    - Oil and water in a beaker (two immiscible liquid phases).

(ii) Intensive and Extensive Properties

- **Intensive Property:**
  - **Definition:** A property that is **independent of the mass** of the system.
  - **Characteristics:** Its value remains the same for the whole system or any part of it. These are **bulk properties**.
  - **Examples:** Pressure (P), Temperature (T), Density (ρ), Viscosity, Refractive Index, Specific Heat.
- **Extensive Property:**
  - **Definition:** A property that **depends on the mass or extent** of the system.

    - **Characteristics:** Its value for the whole system is equal to the sum of its values for all parts of the system.
    - **Examples:** Mass (m), Volume (V), Total Energy (E), Enthalpy (H), Entropy (S).
- **Practical Criterion for Differentiation:**
    - Imagine dividing the system into two identical halves.
    - **Intensive properties** (e.g., Temperature, Density) will have the **same value** in each half as in the original system.
    - **Extensive properties** (e.g., Mass, Volume) will have **half the value** in each half compared to the original system.

Q5: Define state, property, cycle, process

Answer:

- **State:**
    - **Definition:** The **condition** of a system as described by its thermodynamic properties (e.g., Pressure P, Volume V, Temperature T).
    - **Key Point:** At a given state, all the properties of a system have fixed, specific values. A change in any property signifies a change of state.
- **Property:**
    - **Definition:** Any **measurable characteristic** of a system that helps to describe its state.
    - **Key Characteristics:**
        - It is a **macroscopic** characteristic.
        - It is a **point function**, meaning its value depends only on the state, not on the path taken to reach that state.
        - The change in a property is given by the difference between its final and initial values (e.g., $\Delta V = V_2 - V_1$).
- **Process:**
    - **Definition:** The **path of successive states** through which a system passes when it changes from one equilibrium state to another.
    - **Key Point:** A process is defined by its **path**. To describe it fully, one must specify the initial and final states, the path followed, and the interactions with the surroundings (heat and work).

- **Cycle:**
  - **Definition:** A series of processes where a system undergoes various state changes and **finally returns to its initial state**.
  - **Key Characteristic:** The net change in any **property** for the entire cycle is zero ($\Delta P_{cycle} = 0, \Delta T_{cycle} = 0, \Delta V_{cycle} = 0$).
  - **Application:** All repetitive devices like engines and refrigerators operate on thermodynamic cycles.

Q6: Define the terms: (1) Thermodynamics System (2) Property (3) Cycle

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Answer:

- **1. Thermodynamic System:**
  - **Definition:** "It is defined as a **quantity of matter or a region in space** upon which attention is concentrated for the investigation or analysis of thermodynamic problems."
  - **Components:**
    - **Surroundings:** Everything external to the system.
    - **Boundary:** The real or imaginary surface that separates the system from its surroundings. It can be fixed or moving.
- **2. Property:**
  - **Definition:** "A thermodynamic property refers to the **characteristics which can be used to describe the physical condition or state of a system**."
  - **Nature:** Properties are **point functions**. Their values depend only on the state of the system and not on its history.
- **3. Cycle:**
  - **Definition:** A series of processes wherein a system, after undergoing a series of changes, **returns to its initial state**.
  - **Significance:** Since the initial and final states are identical, the **net change in any property is zero**. This is a fundamental concept for analyzing the performance of cyclic devices like heat engines.

📘 CO-2: Unit- 2 Q&A

Q1: Explain PMM of kind I and II.

Answer:

- **1.1 Perpetual-Motion Machine (PMM) - General Definition:**
  - A Perpetual-Motion Machine is a hypothetical device that violates a fundamental law of thermodynamics.
  - These are impossible to construct in reality but serve as important conceptual tools for understanding the laws of thermodynamics.
- **1.2 Perpetual-Motion Machine of the First Kind (PMM1):**
  - **Definition:** A device that violates the **First Law of Thermodynamics** is called a PMM1.
  - **Principle of Violation:** The First Law is the principle of conservation of energy. A PMM1 claims to create energy out of nothing or to destroy energy.
  - **Example:** A machine that produces work (e.g., shaft work) without any input of heat or other forms of energy, or one that produces more work output than the energy input.

  1.3 Perpetual-Motion Machine of the Second Kind (PMM2):
  - **Definition:** A device that violates the **Second Law of Thermodynamics** is called a PMM2.
  - **Principle of Violation:** It does not violate energy conservation. Instead, it violates the direction in which processes can occur. A PMM2 claims to achieve 100% thermal efficiency.
  - **Example:** A ship's engine that extracts heat from the ocean (a single thermal reservoir) to propel the ship, converting that heat entirely into work without rejecting any waste heat to a colder reservoir.

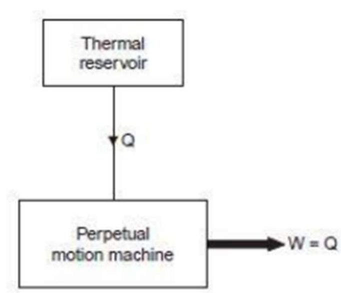

Fig.3.10 - Perpetual motion machine of second kind (PMM2)

Q2: Derive S.F.E.E. clearly stating assumptions. Reduce it for Boiler.

Answer:

The Steady Flow Energy Equation (SFEE) is an application of the First Law of Thermodynamics to an open system (control volume) where the flow is steady.

Assumptions for a Steady Flow System:

1. The mass flow rate through the system remains constant. ($\dot{m}_1 = \dot{m}_2 = \dot{m}$)
2. The state of the fluid at any point within the control volume does not change with time.
3. The rates of heat and work transfer across the control surface are constant.
4. The composition of the fluid is uniform.
5. Changes in potential, kinetic, and flow energies are considered.

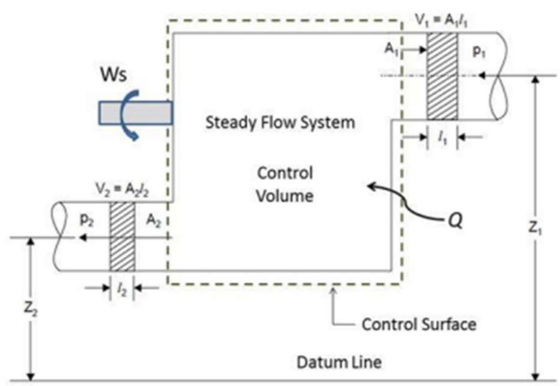

Fig.2.4 - Schematic flow process for an open system

Derivation of SFEE:

Consider an open system (control volume) with one inlet (section 1) and one outlet (section 2).

- **Energy Entering the System (per unit mass):**
  - Internal Energy: u_1
  - Flow Work (Work done to push the fluid into the CV): $P_1 v_1$
  - Kinetic Energy: $\frac{C_1^2}{2}$
  - Potential Energy: gZ_1
  - **Total Energy at Inlet:** $u_1 + P_1 v_1 + \frac{C_1^2}{2} + gZ_1 = h_1 + \frac{C_1^2}{2} + gZ_1$ (since $h = u + Pv$)

- **Energy Leaving the System (per unit mass):**
  - **Total Energy at Outlet:** $h_2 + \frac{C_2^2}{2} + gZ_2$
- **Energy Interactions (per unit mass):**
  - Heat *added to* the system: q
  - Shaft Work *done by* the system: w_s

Applying the First Law of Thermodynamics (Energy Conservation):
Total Energy Entering = Total Energy Leaving

$$(h_1 + \frac{C_1^2}{2} + gZ_1) + q = (h_2 + \frac{C_2^2}{2} + gZ_2) + w_s$$

This is the **Steady Flow Energy Equation (SFEE) on a unit mass basis**.

On a rate basis (for mass flow rate $\dot{m}$):

$$\dot{m}(h_1 + \frac{C_1^2}{2} + gZ_1) + \dot{Q} = \dot{m}(h_2 + \frac{C_2^2}{2} + gZ_2) + \dot{W}_s$$

Reduction of SFEE for a Boiler:

A boiler is a heat exchanger designed to transfer heat to the working fluid. The following simplifications apply:

- **No Shaft Work:** $w_s = 0$
- **Negligible Kinetic Energy Change:** The change in velocity of the fluid between inlet and outlet is very small. $\frac{C_1^2}{2} \approx \frac{C_2^2}{2}$
- **Negligible Potential Energy Change:** The elevation difference is typically small. $gZ_1 \approx gZ_2$

Substituting these into the SFEE:

$$h_1 + q = h_2$$
$$\Rightarrow q = h_2 - h_1$$

This confirms that in a boiler, the heat supplied is used entirely to increase the enthalpy of the working fluid (e.g., from subcooled water to superheated steam).

Q3: Derive the steady flow energy equation for (1) Steam Nozzle (2) Turbine

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Answer:

The general Steady Flow Energy Equation (SFEE) is:

$$h_1 + \frac{C_1^2}{2} + gZ_1 + q = h_2 + \frac{C_2^2}{2} + gZ_2 + w_s$$

(1) Steam Nozzle:
A nozzle is a device that increases the velocity of a fluid at the expense of its pressure. The following simplifications apply:

- **No Shaft Work:** $w_s = 0$
- **Adiabatic Process:** The flow is very fast, leaving no time for heat transfer. $q = 0$
- **Negligible Potential Energy:** $gZ_1 \approx gZ_2$

Substituting into SFEE:

$$h_1 + \frac{C_1^2}{2} = h_2 + \frac{C_2^2}{2}$$

Rearranging to find the exit velocity:

$$\frac{C_2^2}{2} - \frac{C_1^2}{2} = h_1 - h_2$$
$$\Rightarrow C_2 = \sqrt{2(h_1 - h_2) + C_1^2}$$

If the inlet velocity C_1 is much smaller than C_2, it can be neglected:

$$\Rightarrow C_2 = \sqrt{2(h_1 - h_2)}$$

(2) Turbine:
A turbine is a work-producing device where a fluid expands from high to low pressure. The following simplifications apply:

- **Significant Shaft Work:** w_s is positive and is the desired output.
- **Adiabatic Process:** Turbines are typically well-insulated. $q \approx 0$
- **Negligible Kinetic Energy Change:** The change in velocity is small compared to the enthalpy change. $\frac{C_1^2}{2} \approx \frac{C_2^2}{2}$
- **Negligible Potential Energy:** $gZ_1 \approx gZ_2$

Substituting into SFEE:

$$h_1 = h_2 + w_s$$
$$\Rightarrow w_s = h_1 - h_2$$

This shows that the work output from a turbine is equal to the drop in enthalpy of the fluid.

Q4: In a gas turbine unit, the gases flow through the turbine is 15 kg/s and the power developed by the turbine is 12000 kW. The enthalpies of gases at the inlet and outlet are 1260 KJ/kg and 400 KJ/kg respectively, and the velocity of gases at the inlet and outlet are 50 m/s and 110 m/s respectively. Calculate: (i) The rate at which heat is rejected to the turbine and (ii) The area of the inlet pipe given that the specific volume of the gases at the inlet is 0.45 m³/kg.

Answer:

Given Data:

- Mass flow rate, $\dot{m} = 15\ \text{kg/s}$
- Power developed (Shaft Work), $\dot{W}_s = 12000\ \text{kW}$
- Enthalpy at inlet, $h_1 = 1260\ \text{kJ/kg}$
- Enthalpy at outlet, $h_2 = 400\ \text{kJ/kg}$
- Velocity at inlet, $C_1 = 50\ \text{m/s}$
- Velocity at outlet, $C_2 = 110\ \text{m/s}$
- Specific volume at inlet, $v_1 = 0.45\ \text{m}^3/\text{kg}$

(i) Rate of Heat Rejection ($\dot{Q}$):
We apply the Steady Flow Energy Equation (SFEE) on a rate basis, assuming $gZ_1 \approx gZ_2$:

$$\dot{m}(h_1 + \frac{C_1^2}{2000}) + \dot{Q} = \dot{m}(h_2 + \frac{C_2^2}{2000}) + \dot{W}_s$$

(Note: Dividing kinetic energy terms by 1000 to convert J to kJ)

Substituting the values:

$$15(1260 + \frac{50^2}{2000}) + \dot{Q} = 15(400 + \frac{110^2}{2000}) + 12000$$
$$15(1260 + 1.25) + \dot{Q} = 15(400 + 6.05) + 12000$$
$$15(1261.25) + \dot{Q} = 15(406.05) + 12000$$
$$18918.75 + \dot{Q} = 6090.75 + 12000$$
$$18918.75 + \dot{Q} = 18090.75$$
$$\dot{Q} = 18090.75 - 18918.75$$
$$\dot{Q} = -828\ \text{kW}$$

Answer (i): The rate of heat rejected is $\dot{Q} = -828\,\text{kW}$. The negative sign confirms that heat is lost from the turbine to the surroundings.

(ii) Area of the Inlet Pipe (A_1):
The mass flow rate is given by:

$$\dot{m} = \frac{A_1 C_1}{v_1}$$

Rearranging for the area:

$$A_1 = \frac{\dot{m}\, v_1}{C_1}$$

$$A_1 = \frac{15\,\text{kg/s} \times 0.45\,\text{m}^3/\text{kg}}{50\,\text{m/s}}$$

$$A_1 = \frac{6.75}{50} = 0.135\,\text{m}^2$$

Answer (ii): The area of the inlet pipe is $A_1 = 0.135\,\text{m}^2$.

Q5: Steam enters a nozzle at 7 bar pressure and 20°C (initial enthalpy = 2850 kJ/kg) and leaves at a pressure of 1.5 bar. The initial and final velocities of steam are 40 m/s and 700 m/s respectively through the nozzle. The mass flow rate is 1400 kg/hr and heat loss from the nozzle is 11705 kJ/hr. Specific volume at exit is 1.24 m³/kg. Determine final enthalpy and exit area.

Answer:

Given Data:

- Inlet Enthalpy, $h_1 = 2850\,\text{kJ/kg}$
- Inlet Velocity, $C_1 = 40\,\text{m/s}$
- Exit Velocity, $C_2 = 700\,\text{m/s}$
- Mass flow rate, $\dot{m} = \frac{1400}{3600} = 0.3889\,\text{kg/s}$
- Heat Loss, $\dot{Q} = -\frac{11705}{3600} = -3.251\,\text{kJ/s} = -3.251\,\text{kW}$ (Negative as it is lost)
- Exit Specific Volume, $v_2 = 1.24\,\text{m}^3/\text{kg}$

(i) Final Enthalpy (h_2):
We apply the SFEE for a nozzle ($w_s = 0, Z_1 \approx Z_2$) on a rate basis:

$$\dot{m}(h_1 + \frac{C_1^2}{2000}) + \dot{Q} = \dot{m}(h_2 + \frac{C_2^2}{2000})$$

Divide the entire equation by $\dot{m}$ to get it on a per kg basis:

$$h_1 + \frac{C_1^2}{2000} + q = h_2 + \frac{C_2^2}{2000}$$

Where $q = \frac{\dot{Q}}{\dot{m}} = \frac{-3.251}{0.3889} = -8.36$ kJ/kg

Now, solve for h_2:

$$2850 + \frac{40^2}{2000} - 8.36 = h_2 + \frac{700^2}{2000}$$
$$2850 + 0.8 - 8.36 = h_2 + 245$$
$$2842.44 = h_2 + 245$$
$$h_2 = 2842.44 - 245$$
$$h_2 = 2597.44 \text{ kJ/kg}$$

Answer (i): The final enthalpy is $h_2 = 2597.44$ kJ/kg.

(ii) Exit Area (A_2):
Using the mass flow rate relation at the exit:

$$\dot{m} = \frac{A_2 C_2}{v_2}$$
$$A_2 = \frac{\dot{m}\, v_2}{C_2}$$
$$A_2 = \frac{0.3889 \text{ kg/s} \times 1.24 \text{ m}^3/\text{kg}}{700 \text{ m/s}}$$
$$A_2 = \frac{0.4822}{700} = 0.000689 \text{ m}^2 = 6.89 \text{ cm}^2$$

Answer (ii): The exit area of the nozzle is $A_2 = 6.89 \text{ cm}^2$.

Q6: Write two major statements of second law of thermodynamics and show that violation of one statement leads to violation of other one.

Answer:

The Second Law of Thermodynamics dictates the direction in which processes can occur and introduces the concept of irreversibility. It has two classical, equivalent statements.

The Two Major Statements:

1. **Kelvin-Planck Statement:**
   - "It is impossible to construct a device that operates in a thermodynamic cycle and produces no effect other than the production of work and exchange of heat with a single reservoir."
   - **Implication:** No heat engine can have 100% thermal efficiency. It is impossible to convert heat completely into work in a cyclic process. A heat engine must reject some heat to a low-temperature sink.

2. **Clausius Statement:**
    - "It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a cooler body to a hotter body."
    - **Implication:** Heat cannot flow spontaneously from a cold body to a hot body. A refrigerator requires an external work input to achieve this transfer.

Equivalency of the Two Statements (Proof by Contradiction):

The two statements are equivalent because the **violation of one leads to the violation of the other**.

- **Part 1: Violation of Kelvin-Planck leads to Violation of Clausius.**
    - Assume a Heat Engine (E) that violates the Kelvin-Planck statement by absorbing heat Q_1 from a single reservoir at T_1 and converting it entirely into work $W = Q_1$.
    - Now, couple this engine with a normal Refrigerator (R). The work output from the engine (W) is used to drive the refrigerator.
    - The refrigerator absorbs heat Q_2 from a cold reservoir at T_2 and rejects heat $Q_2 + W = Q_2 + Q_1$ to a hot reservoir at T_1.
    - The net result of this combined system is: Heat Q_2 is transferred from the cold reservoir to the hot reservoir **without any net work input** (since the work produced by the engine is entirely used by the refrigerator).
    - This is a direct **violation of the Clausius statement**. Therefore, a violation of the Kelvin-Planck statement implies a violation of the Clausius statement.
- **Conclusion:** Therefore, the violation of the Clausius statement implies the violation of the Kelvin-Planck statement, proving their equivalence.

Q7: Explain First law of thermodynamics for the closed system: (i) undergoing a cycle (ii) change of state/process.

Answer:

- **First Law for a Closed System (General Form):**
  For any process, the net energy transfer is stored as a change in the system's total energy.

$$\mathbf{Q - W = \Delta E}$$

  where $\Delta E = \Delta U + \Delta KE + \Delta PE$
  For stationary systems (most common), $\Delta KE = 0$ and $\Delta PE = 0$, so:

$$\mathbf{Q - W = \Delta U}$$

- **(i) First Law for a Closed System Undergoing a Cycle:**

- A cyclic process has identical initial and final states.
- Therefore, all properties return to their initial values. The change in internal energy is zero: **ΔU_cycle = 0**
- The First Law simplifies to:

$$\mathbf{Qnet - Wnet = 0} \text{ or } \oint \delta Q = \oint \delta W$$

Where,

- $\oint \delta Q$ = Net heat transfer during the cycle
- $\oint \delta W$ = Net work transfer during the cycle
  - **Interpretation:** For a closed system undergoing a cycle, the net heat transfer is equal to the net work transfer.
- **(ii) First Law for a Closed System Undergoing a Change of State (Process):**
  - The system moves from one equilibrium state (1) to another (2).
  - The First Law is given by:

$$\mathbf{Q - W = U_2 - U_1}$$

  - **Interpretation:** The net energy crossing the system boundary as heat and work is equal to the change in the internal energy of the system.
  - In differential form for a process: $Q - W = \Delta U$

Where,

- Q = Net heat transfer *to* the system during the process.
- W = Net work transfer *from* the system during the process.
- $\Delta U = U_2 - U_1$ = Change in internal energy of the system.

Q8: Compare steady flow processes with unsteady flow processes.

Answer:

Basis of Comparison	Steady Flow Process	Unsteady Flow Process
1. Definition	A process during which the fluid properties (P, V, T, etc.) **at any point within the control volume** remain constant with time.	A process during which the fluid properties at any point within the control volume **change with time**.

Basis of Comparison	Steady Flow Process	Unsteady Flow Process
2. Mathematical Condition	$\frac{\partial P}{\partial t} = 0, \frac{\partial T}{\partial t} = 0$, etc., for all points in the C.V.	$\frac{\partial P}{\partial t} \neq 0, \frac{\partial T}{\partial t} \neq 0$, etc.
3. Mass Flow Rate	The mass flow rate into the control volume is equal to the mass flow rate out of it. $\dot{m}_{in} = \dot{m}_{out}$	The mass flow rate in and out are not equal. The mass inside the control volume changes with time. $\dot{m}_{in} \neq \dot{m}_{out}$
4. Energy of the C.V.	The total energy (E) within the control volume remains constant with time.	The total energy within the control volume changes with time.
5. Governing Equation	**Steady Flow Energy Equation (SFEE):** $\dot{m}(h_1 + \frac{C_1^2}{2} + gZ_1) + \dot{Q} = \dot{m}(h_2 + \frac{C_2^2}{2} + gZ_2) + \dot{W}_s$	**Unsteady Flow Energy Equation (UFEE):** $(m_f - m_i)e_p + Q = (m_f u_f - m_i u_i) + W$ (For a filling/emptying process)
6. Complexity of Analysis	Relatively simpler to analyze.	More complex to analyze as it involves integration with respect to time.
7. Examples	• Turbines & Compressors running at constant load. • Nozzles and Diffusers. • Boilers and Condensers under steady operation.	• Filling or emptying of a gas cylinder. • Starting or stopping of a turbine or compressor. • A balloon being inflated or deflated.

Q9: In air compressor air enters at a 4 m/s, 1 bar, 0.5 m3/kg. the exit conditions 7 m/s, 6bar, 0.12 m3/kg. the inlet energy of air is gained after compression process is 38 kJ/kg. the system losses 3000 kJ/min of heat to surroundings during process. Mass flow rate of air 31 kg/min. calculate (i) shaft work input (ii) ratio of inlet to outlet areas.

Answer:

Given Data:

- **Inlet (1):** $C_1 = 4$ m/s, $P_1 = 1$ bar, $v_1 = 0.5\ \text{m}^3/\text{kg}$
- **Outlet (2):** $C_2 = 7$ m/s, $P_2 = 6$ bar, $v_2 = 0.12\ \text{m}^3/\text{kg}$
- Change in Internal Energy, $\Delta u = u_2 - u_1 = 38$ kJ/kg
- Heat Loss, $\dot{Q} = -3000$ kJ/min
- Mass flow rate, $\dot{m} = 31$ kg/min

Convert to consistent units (kJ and s):

- $\dot{m} = \frac{31}{60} = 0.5167$ kg/s
- $\dot{Q} = \frac{-3}{60} = -50$ kJ/s $= -50$ kW
- $q = \frac{\dot{Q}}{\dot{m}} = \frac{-5}{0.5167} = -96.77$ kJ/kg

(i) Shaft Work Input (w_s):
We use the Steady Flow Energy Equation (SFEE) on a unit mass basis, neglecting potential energy ($Z_1 \approx Z_2$):

$$h_1 + \frac{C_1^2}{2000} + q = h_2 + \frac{C_2^2}{2000} + w_s$$

We know $h = u + Pv$. So, $h_2 - h_1 = (u_2 + P_2 v_2) - (u_1 + P_1 v_1) = (u_2 - u_1) + (P_2 v_2 - P_1 v_1)$

Calculate Pv terms (remember 1 bar $= 100\ \text{kJ/m}^3$):

- $P_1 v_1 = (1 \times 100) \times 0.5 = 50$ kJ/kg
- $P_2 v_2 = (6 \times 100) \times 0.12 = 72$ kJ/kg
- $\Delta(Pv) = 72 - 50 = 22$ kJ/kg
- $\Delta h = h_2 - h_1 = \Delta u + \Delta(Pv) = 38 + 22 = 60$ kJ/kg

Now, plug into SFEE:

$$h_1 + \frac{4^2}{2000} - 96.77 = h_2 + \frac{7^2}{2000} + w_s$$
$$h_1 + 0.008 - 96.77 = h_2 + 0.0245 + w_s$$

Since $h_2 - h_1 = 60$, we can write $h_2 = h_1 + 60$.

$$h_1 - 96.762 = (h_1 + 60) + 0.0245 + w_s$$
$$-96.762 = 60.0245 + w_s$$
$$w_s = -96.762 - 60.0245$$
$$w_s = -156.7865\ \text{kJ/kg}$$

The negative sign indicates work is done *on* the system (compressor).

Shaft Power Input:

$$\dot{W}_s = \dot{m} \times w_s = 0.5167 \text{ kg/s} \times (-156.7865 \text{ kJ/kg}) = -81.0 \text{ kW}$$

Answer (i): The shaft work input is 156.79 kJ/kg or 81.0 kW.

(ii) Ratio of Inlet to Outlet Areas (A_1/A_2):
From the continuity equation, $\dot{m} = \frac{A_1C_1}{v_1} = \frac{A_2C_2}{v_2}$

$$\frac{A_1}{A_2} = \frac{C_2}{C_1} \times \frac{v_1}{v_2}$$
$$\frac{A_1}{A_2} = \frac{7}{4} \times \frac{0.5}{0.12}$$
$$\frac{A_1}{A_2} = 1.75 \times 4.1667 = 7.29$$

Answer (ii): The ratio of inlet to outlet pipe areas is $A_1/A_2 = 7.29$.

Q10: Discuss the Limitation of first law of thermodynamics.

Answer:

- The First Law of Thermodynamics is a fundamental principle of energy conservation, but it has several important limitations:
  - **1. No Directionality for Processes:**
    The First Law does not indicate the *direction* in which a process can occur. It only checks the energy balance.
    - **Example:** According to the First Law, a cup of hot coffee cooling down (heat loss = internal energy decrease) and a cup of coffee spontaneously heating up by absorbing heat from a cooler room (heat gain = internal energy increase) are both possible as long as energy is conserved. We know from experience only the first process happens.
  - **2. No Information on Feasibility:**
    It cannot predict whether a conceived process is possible or not in nature.
    - **Example:** It cannot explain why a bouncing ball eventually comes to rest (kinetic energy is converted to heat), but the reverse process where a stationary ball starts bouncing by absorbing heat from the floor is impossible, even though it doesn't violate energy conservation.
  - **3. No Limit on Energy Conversion:**
    It establishes equivalence between heat and work but does not specify the *conditions* under which heat can be converted into work. It suggests 100%

conversion of heat into work is possible from an energy balance perspective, which is not true in practice.

- **4. No Concept of Quality of Energy:**
  The First Law treats all forms of energy as equal. It does not account for the *degradation of energy quality*.
    - **Example:** It cannot explain why high-temperature heat (e.g., from a furnace) is more useful for doing work than the same amount of low-temperature heat (e.g., from warm water), even though both have the same energy quantity.
- **Conclusion:** These limitations led to the formulation of the **Second Law of Thermodynamics**, which introduces the concepts of entropy and process directionality, explaining why certain processes are irreversible and defining the maximum possible efficiency of heat engines.

📘 CO-4: Unit- 4 Q&A

Q1: Explain why the ideal Carnot vapor cycle is not a practical model for a steam power plant, even though it represents the maximum possible efficiency

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Answer:

- **1.1 Theoretical Superiority vs. Practical Limitations:**
  - The Carnot cycle operates between two temperature limits and achieves the maximum possible thermal efficiency, given by **$\eta carnot = 1 - (TL/TH)$**.
  - Despite this theoretical advantage, it faces several insurmountable practical difficulties that prevent its use in real steam power plants.
- **1.2 Major Practical Difficulties:**
  - **a) Difficulty in Controlling Isothermal Heat Addition with Superheated Steam:**
    - The Carnot cycle requires heat addition at a constant, high temperature (isothermal process).
    - In practice, supplying superheat at a constant temperature is extremely difficult. Heat is more conveniently added at constant pressure, as in the Rankine cycle.
  - **b) High Moisture Content and Turbine Blade Erosion:**
    - The cycle typically uses dry saturated steam at the turbine inlet.
    - During isentropic expansion, the steam quality drops significantly, resulting in a wet mixture at the turbine exit.
    - The presence of high-velocity water droplets causes erosion and wear of the turbine blades, reducing the turbine's lifespan and efficiency.
  - **c) Difficulty in Controlling Condensation:**
    - The cycle requires condensation to be stopped at a specific point (state 3) before the fluid becomes a saturated liquid.
    - In practice, it is very difficult to control the condensation process so precisely.
  - **d) Impracticality of Compressing a Wet Vapor:**
    - The compression process (3-4) involves isentropically compressing a low-quality, wet vapor.

- A vapor has a very large specific volume compared to a liquid. Compressing this mixture would require a massive compressor and a very high work input (Wcompressor).
- This large pump work would significantly reduce the net work output (Wnet = Wturbine - Wpump) and, consequently, the overall cycle efficiency, negating the Carnot efficiency advantage.

Q2: Draw and label the temperature-entropy (T-s) diagram for an ideal Carnot vapor cycle operating with water as the working fluid.

Answer:

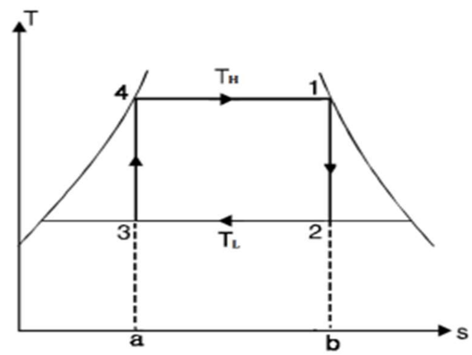


Figure: - T-s Diagram of Carnot vapor cycle

Processes and State Points:

1. **Process 4–1: Reversible Isothermal Heat Addition (in the Boiler)**
   - This is a horizontal line on the T-s diagram at the high temperature, T_H.
   - It starts from saturated liquid at state 4 and ends at dry saturated vapor at state 1.
   - Heat supplied, $q_s = T_H(s_1 - s_4)$.
2. **Process 1–2: Isentropic Expansion (in the Turbine)**
   - This is a vertical line on the T-s diagram.
   - The dry saturated vapor expands isentropically (at constant entropy) to a lower pressure and temperature, T_L.
   - The state at point 2 is a wet vapor. Turbine work, $w_t = h_1 - h_2$.
3. **Process 2–3: Reversible Isothermal Heat Rejection (in the Condenser)**
   - This is a horizontal line on the T-s diagram at the low temperature, T_L.

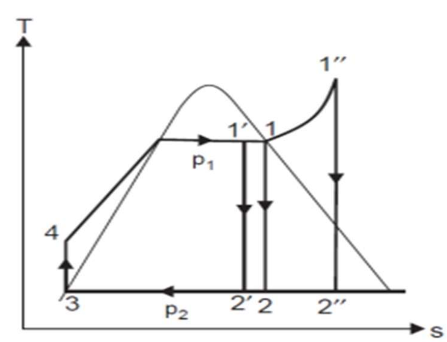
- The wet vapor is condensed at constant pressure and temperature until it reaches state 3, which is still a wet vapor (not a saturated liquid).
- Heat rejected, $q_r = T_L(s_2 - s_3)$. (Note: $s_2 = s_1$ and $s_3 = s_4$, so $s_2 - s_3 = s_1 - s_4$).

4. **Process 3–4: Isentropic Compression (in the Compressor)**
    - This is a vertical line on the T-s diagram.
    - The wet vapor is compressed isentropically back to the initial state 4 (saturated liquid at the boiler pressure).
    - Compressor work, $w_c = h_4 - h_3$.

Q3: Draw and label the process diagrams for an ideal Rankine cycle on both T-s and enthalpy-entropy (h-s or Mollier) charts.

Answer:

- **3.1 Process Details of the Ideal Rankine Cycle:**
    1. **Process 4-1: Constant Pressure Heat Addition (in Boiler)**
        - Subcooled liquid is heated to saturated liquid, vaporized to saturated steam, and often superheated.
    2. **Process 1-2: Isentropic Expansion (in Turbine)**
        - Superheated/high-pressure steam expands to a lower pressure, producing work.
    3. **Process 2-3: Constant Pressure Heat Rejection (in Condenser)**
        - Steam is condensed completely into saturated liquid.
    4. **Process 3-4: Isentropic Compression (in Pump)**
        - Saturated liquid is pumped to the boiler pressure.
- **3.2 Temperature-Entropy (T-s) Diagram:**



- **3.3 Enthalpy-Entropy (h-s / Mollier) Diagram:**

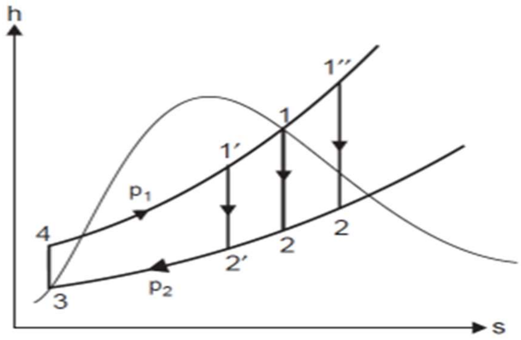


Fig.6.5 – h-s diagram of Rankine cycle

Q4: List the four basic processes of the Rankine cycle and describe what happens to the working fluid in each process.

Answer:

The ideal Rankine cycle consists of four fundamental processes, as described in the study material:

1. **Isentropic Compression in the Pump (Process 3–4)**
    - **Description:** Saturated liquid water from the condenser is fed to a pump. The pump performs isentropic (reversible adiabatic) compression on the liquid.
    - **Effect on Working Fluid:** The pressure of the water increases from the condenser pressure (P_2) to the boiler pressure (P_1). Its temperature increases slightly, but it remains in the liquid phase, becoming a **subcooled or compressed liquid**. The specific volume change is negligible.
    - **Work Interaction:** Work is done *on* the fluid (work input, $w_p = h_4 - h_3$).
2. **Constant Pressure Heat Addition in the Boiler (Process 4–1)**
    - **Description:** The high-pressure liquid is fed into a boiler where heat is supplied from an external source at constant pressure.
    - **Effect on Working Fluid:** The fluid undergoes three stages:
        - Sensible heating to the saturation temperature (becoming saturated liquid).
        - Latent heating during evaporation (changing phase from liquid to vapor, becoming dry saturated steam).
        - Superheating (raising the temperature of the vapor beyond the saturation point, becoming **superheated steam**).
    - **Heat Interaction:** Heat is added *to* the fluid ($q_s = h_1 - h_4$).

3. **Isentropic Expansion in the Turbine (Process 1–2)**
   - **Description:** The high-pressure, high-temperature superheated steam is expanded in a turbine isentropically.
   - **Effect on Working Fluid:** The pressure and temperature of the steam drop significantly. The steam typically becomes a **wet vapor** (mixture of steam and water droplets) at the turbine exit.
   - **Work Interaction:** Work is done *by* the fluid (work output, $w_t = h_1 - h_2$).
4. **Constant Pressure Heat Rejection in the Condenser (Process 2–3)**
   - **Description:** The low-pressure wet steam from the turbine is fed into a condenser, where it is cooled and condensed by rejecting heat to a cooling medium at constant pressure.
   - **Effect on Working Fluid:** The steam condenses completely, rejecting its latent heat, and is converted back into **saturated liquid**.
   - **Heat Interaction:** Heat is rejected *from* the fluid ($q_r = h_2 - h_3$).

Q5: Explain why the Rankine cycle's thermal efficiency is generally lower than the Carnot cycle's when operating between the same temperature limits.

Answer:

The Rankine cycle's efficiency is lower than the Carnot cycle's for the same temperature limits due to a fundamental difference in the **average temperature of heat addition**.

- **Carnot Cycle Principle:**
  - The Carnot cycle achieves the maximum possible efficiency because all heat is added isothermally at the maximum temperature (T_H). The average temperature of heat addition (T_m) is equal to T_H.
  - Efficiency: $\eta_{Carnot} = 1 - \frac{T_L}{T_H}$.
- **Rankine Cycle Reality:**
  - In the Rankine cycle, heat is **not** added at a constant high temperature. Referring to the T-s diagram (Question 3), the heat addition process (4-1) starts with the sensible heating of cold, compressed liquid and ends with superheating. A significant portion of the heat is added at relatively lower temperatures.
  - Therefore, the **mean temperature of heat addition (T_m)** for the Rankine cycle is **less than** the maximum temperature T_H.
  - Efficiency: $\eta_{Rankine} = 1 - \frac{T_L}{T_m}$.

   - Since $T_m < T_H$, it follows that $\eta_{Rankine} < \eta_{Carnot}$.
- **Conclusion:** The Rankine cycle sacrifices some theoretical efficiency for immense practical advantages, such as manageable pump work and safe turbine operation, making it the viable choice for real-world power plants.

Q6: Why is the pumping work of a liquid in the Rankine cycle much smaller than the compression work of the wet vapor in the Carnot cycle?

Answer:

- **6.1 Fundamental Reason: Difference in Specific Volume:**
   - The work required for a compression/ pumping process is given by $W = \int v\, dP$.
   - The key variable is the **specific volume (v)** of the working fluid during this process.
- **6.2 Pumping Work in the Rankine Cycle:**
   - The pump handles only **saturated liquid**.
   - The specific volume of a liquid (v_f) is extremely small (e.g., for water at 0.1 bar, $v_f \approx 0.001$ m³/kg).
   - Therefore, the pump work $w_p = v_f (P_{boiler} - P_{condenser})$ is very small.
- **6.3 Compression Work in the Carnot Cycle:**
   - The compressor handles a **wet vapor mixture**.
   - The specific volume of a vapor is orders of magnitude larger than that of a liquid (e.g., for steam at 0.1 bar, $v_g \approx 14.67$ m³/kg).
   - Even a wet vapor with a quality of 0.1 has a specific volume much larger than that of a liquid.
   - Therefore, the compression work $w_c = \int v\, dP$ is very large because v is large.
- **6.4 Impact on Cycle Efficiency:**
   - **Net Work, $w_{net} = w_{turbine} - w_{pump/compressor}$**
   - In the Rankine cycle, w_{pump} is negligible, so $w_{net} \approx w_{turbine}$.
   - In the Carnot cycle, the large $w_{compressor}$ significantly reduces the net work output, which is a major reason for its impracticality despite its high theoretical thermal efficiency.

Q7: Explain the Variables affecting the efficiency of the Rankine cycle.

Answer:

The thermal efficiency of the Rankine cycle can be improved by manipulating three key operating variables, all aimed at increasing the mean temperature of heat addition (T_m) or decreasing the heat rejection temperature (T_L).

1. Effect of Boiler Pressure

- **Action:** Increasing the boiler pressure while keeping the maximum temperature (T_1) and condenser pressure constant.
- **Effect on Cycle:**
  - The saturation temperature of heat addition increases, which raises the **mean temperature of heat addition (T_m)**.
  - According to $\eta = 1 - \frac{T_L}{T_m}$, this leads to an **increase in thermal efficiency**.
- **Negative Side Effect:** It increases the moisture content at the turbine exit (point 2 shifts left on the T-s diagram), which can cause turbine blade erosion. This side effect is corrected by **reheating**.

2. Effect of Condenser Pressure

- **Action:** Lowering the condenser pressure while keeping the boiler pressure and maximum temperature constant.
- **Effect on Cycle:**
  - The temperature of heat rejection (T_L) decreases.
  - According to $\eta = 1 - \frac{T_L}{T_m}$, this leads to an **increase in thermal efficiency**.
  - The colored area on the T-s diagram shows a significant increase in net work output.
- **Negative Side Effect & Limitation:**
  - It increases the moisture content at the turbine exit.
  - It is limited by the temperature of the cooling medium and the need for larger, more expensive condensers and vacuum pumps.

3. Effect of Superheating

- **Action:** Increasing the temperature of the steam at the turbine inlet (superheating) while keeping the boiler and condenser pressures constant.
- **Effect on Cycle:**
  - It increases the **mean temperature of heat addition (T_m)**.

  - It increases the net work output
  - Consequently, the **thermal efficiency increases**.
- **Additional Major Benefit:** Superheating significantly **decreases the moisture content** of the steam at the turbine exit, protecting the turbine blades from erosion.
- **Limitation:** The maximum superheat temperature is limited by the **metallurgical strength** of the turbine blades and superheater materials.

Q8: Compare the air-standard efficiencies of Otto, Diesel, and Dual cycles.

Answer:

The comparison of air-standard efficiencies for Otto, Diesel, and Dual cycles can be made effectively under three specific constraints, as outlined in the study material.

1. For the Same Compression Ratio and the Same Heat Input

- **Efficiency Order: η Otto > η Dual > η Diesel**
- **Explanation:**
  - The thermal efficiency is given by η = 1 - (Heat Rejected/Heat Supplied). Since the heat supplied (q_s) is the same for all cycles, the cycle with the **least heat rejected (**q_r**)** will be the most efficient.
  - On the T-S diagram, the heat rejected is represented by the area under the constant volume line 4-1.

2. For the Same Maximum Pressure and the Same Heat Input

- **Efficiency Order: η Diesel > η Dual > η Otto**
- **Explanation:**
  - In this scenario, the Otto cycle must operate with a very low compression ratio to avoid exceeding the maximum pressure limit, given that its entire heat addition is at constant volume. A low compression ratio directly leads to low efficiency.
  - The Diesel cycle can operate at a much higher compression ratio while still staying within the maximum pressure limit because its heat addition is at constant pressure. A higher compression ratio results in higher efficiency.
  - The Dual cycle, again, operates at a compression ratio between the two, resulting in an intermediate efficiency.

3. For the Same Maximum Pressure and the Same Maximum Temperature

- **Efficiency Order: η Diesel > η Dual > η Otto**
- **Explanation:**

- This condition is similar to the previous one. To reach the same maximum temperature (T_max) from the same maximum pressure (P_max), the Otto cycle requires the most heat addition. However, its initial compression must start from a lower pressure and temperature (i.e., a lower compression ratio) to not overshoot P_max.
- The Diesel cycle starts its heat addition at a higher initial temperature (due to a higher compression ratio), requiring less heat to reach the same T_max. The combination of a high compression ratio and a lower heat rejection (due to a lower volume ratio during expansion) makes it the most efficient.
- The Dual cycle, with characteristics of both, again has an efficiency between the two.

Q9: Derive the expression for air-standard efficiency of the Otto cycle.

Answer:

The air-standard efficiency of the Otto cycle is derived by considering the heat addition and rejection for a unit mass of air undergoing the cycle's four processes.

Assumptions:

1. Air is the working fluid and behaves as a perfect gas.
2. Compression and expansion processes are isentropic (reversible adiabatic).
3. Heat addition and rejection are constant volume processes.

Processes of the Otto Cycle:

1. **1-2: Isentropic Compression**
2. **2-3: Constant Volume Heat Addition**
3. **3-4: Isentropic Expansion**
4. **4-1: Constant Volume Heat Rejection**

Derivation:

1. **Heat Supplied (q_s):** This occurs during the constant volume process 2-3.

$$q_s = C_V(T_3 - T_2)$$

2. **Heat Rejected (q_r):** This occurs during the constant volume process 4-1.

$$q_r = C_V(T_4 - T_1)$$

3. **Net Work Done (w_{net}):** From the First Law of Thermodynamics for a cycle.

$$w_{net} = q_s - q_r = C_V(T_3 - T_2) - C_V(T_4 - T_1)$$

4. **Air-Standard Efficiency (η_{otto}):** Defined as the ratio of net work output to heat input.

$$\eta_{otto} = \frac{w_{net}}{q_s} = \frac{C_V(T_3 - T_2) - C_V(T_4 - T_1)}{C_V(T_3 - T_2)} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

...(Eq. 7.5)

5. **Expressing Temperatures in Terms of T_1 and Compression Ratio (r):**
   - **For Isentropic Compression (1-2):**

$$\frac{T_2}{T_1} = (\frac{V_1}{V_2})^{\gamma-1} = r^{\gamma-1}$$
$$\therefore T_2 = T_1 \cdot r^{\gamma-1}$$

...(Eq. 7.6)

   - **For Constant Volume Heat Addition (2-3):** Let the pressure ratio be $\alpha = P_3/P_2$.

$$\frac{P_2}{T_2} = \frac{P_3}{T_3} \Rightarrow T_3 = T_2 \cdot \frac{P_3}{P_2} = T_2 \cdot \alpha$$

Substituting T_2 from Eq. 7.6:

$$T_3 = T_1 \cdot r^{\gamma-1} \cdot \alpha$$

...(Eq. 7.7)

   - **For Isentropic Expansion (3-4):** Since $V_4 = V_1$ and $V_3 = V_2$.

$$\frac{T_4}{T_3} = (\frac{V_3}{V_4})^{\gamma-1} = (\frac{V_2}{V_1})^{\gamma-1} = (\frac{1}{r})^{\gamma-1}$$
$$\therefore T_4 = T_3 \cdot (\frac{1}{r})^{\gamma-1}$$

Substituting T_3 from Eq. 7.7:

$$T_4 = (T_1 \cdot r^{\gamma-1} \cdot \alpha) \cdot (\frac{1}{r})^{\gamma-1} = T_1 \cdot \alpha$$

...(Eq. 7.8)

6. **Final Expression for Efficiency:** Substitute T_2, T_3, and T_4 from Eqs. 7.6, 7.7, and 7.8 into Eq. 7.5.

$$\eta_{otto} = 1 - \frac{(T_1\alpha - T_1)}{(T_1 r^{\gamma-1}\alpha - T_1 r^{\gamma-1})} = 1 - \frac{T_1(\alpha - 1)}{T_1 r^{\gamma-1}(\alpha - 1)}$$
$$\therefore \eta_{otto} = 1 - \frac{1}{r^{\gamma-1}}$$

...(Eq. 7.9)

Q10: Explain the effect of operating variables (compression ratio, cut-off ratio, pressure ratio) on thermal efficiency of cycles.

Answer:

The thermal efficiency of air-standard cycles is primarily influenced by three key operating variables, each affecting different cycles.

1. Compression Ratio ($r = V_1/V_2$)

- **Definition:** The ratio of the maximum to minimum volume in the cylinder.
- **Effect on Otto and Diesel Cycles:**
  - For both cycles, a higher compression ratio results in **higher thermal efficiency**.
  - This is evident from the Otto efficiency formula $\eta = 1 - \frac{1}{r^{\gamma-1}}$ and the Diesel efficiency formula $\eta = 1 - \frac{1}{r^{\gamma-1}}[\frac{\rho^{\gamma}-1}{\gamma(\rho-1)}]$. In both cases, the term $\frac{1}{r^{\gamma-1}}$ decreases as r increases, leading to higher efficiency.
- **Practical Limitation:** In Spark-Ignition (SI) engines operating on the Otto cycle, the compression ratio is limited (typically 8-12) to prevent abnormal combustion (knocking). Compression-Ignition (CI) engines can use higher ratios (14-18) as the fuel is not prone to knocking.

2. Cut-off Ratio ($\rho = V_3/V_2$ in Diesel, V_4/V_3 in Dual)

- **Definition:** In the Diesel cycle, it is the ratio of the volume at the end of heat addition to the volume at the start of heat addition (both at constant pressure). It represents the duration of heat addition.
- **Effect on Diesel Cycle:**
  - For a **constant compression ratio (r)**, an increase in the cut-off ratio (ρ) **decreases the thermal efficiency** of the Diesel cycle.
  - This is because the factor $K = \frac{\rho^{\gamma}-1}{\gamma(\rho-1)}$ in the efficiency equation is always greater than 1 and increases with ρ. A larger K makes the efficiency lower.
  - A higher ρ means more heat is added later in the expansion stroke, which is less effective at producing work. In the limit where $\rho \to 1$, the Diesel cycle efficiency approaches that of the Otto cycle for the same r.

3. Pressure Ratio ($r_p = P_3/P_2$ in Otto/Dual, P_2/P_1 in Brayton)

- **Definition:** It has different contexts. In reciprocating cycles (Otto, Dual), it's the ratio of pressures after and before constant-volume heat addition. In the Brayton cycle, it's the ratio of compressor outlet to inlet pressure.
- **Effect on Brayton Cycle:**

- The efficiency of the ideal Brayton cycle is given by $\eta = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}}$.
- This shows that the thermal efficiency **increases with an increase in the pressure ratio (r_p)**.
- A higher pressure ratio leads to a higher temperature after compression (T_2), which allows for a greater temperature drop during expansion in the turbine, converting more heat into work.

- **Effect on Dual Cycle:**
  - In the Dual cycle, a higher pressure ratio ($\alpha = P_3/P_2$) for the constant volume part of heat addition, while keeping the total heat input and compression ratio constant, generally leads to higher efficiency. This is because adding more heat at constant volume is more efficient than adding it at constant pressure.

Q11: With neat sketches, explain the simple Brayton cycle (P–V and T–S diagrams).

Answer:

The Brayton cycle, also known as the Joule cycle, is the ideal cycle for gas turbine engines. It consists of two isentropic and two constant pressure processes.

Processes of the Simple Brayton Cycle:

1. **Process 1-2: Isentropic Compression**
   - **Description:** Ambient air is drawn into the compressor, where it is compressed isentropically (reversibly and adiabatically). The pressure increases from P_1 to P_2, and the temperature increases from T_1 to T_2.
   - **Work Interaction:** Work is done *on* the system (compressor work, W_C).
   - **Heat Interaction:** No heat transfer ($Q = 0$).
2. **Process 2-3: Constant Pressure Heat Addition**
   - **Description:** The high-pressure air enters the combustion chamber, where fuel is injected and burned at approximately constant pressure. The pressure remains at P_2, while the volume increases from V_2 to V_3 and the temperature rises from T_2 to T_3.
   - **Work Interaction:** No work interaction.
   - **Heat Interaction:** Heat is added *to* the system (Q_{in}).
3. **Process 3-4: Isentropic Expansion**
   - **Description:** The high-pressure, high-temperature gases expand isentropically in the turbine. The pressure drops from P_3 to P_4, and the temperature decreases from T_3 to T_4.

- **Work Interaction:** Work is done *by* the system (turbine work, W_T).
- **Heat Interaction:** No heat transfer ($Q = 0$).

4. **Process 4-1: Constant Pressure Heat Rejection**
   - **Description:** The exhaust gases from the turbine are rejected to the atmosphere at constant pressure. The pressure remains at P_1, while the volume decreases from V_4 to V_1 and the temperature drops from T_4 to T_1.
   - **Work Interaction:** No work interaction.
   - **Heat Interaction:** Heat is rejected *from* the system (Q_{out}).

P-V & T-S Diagram:

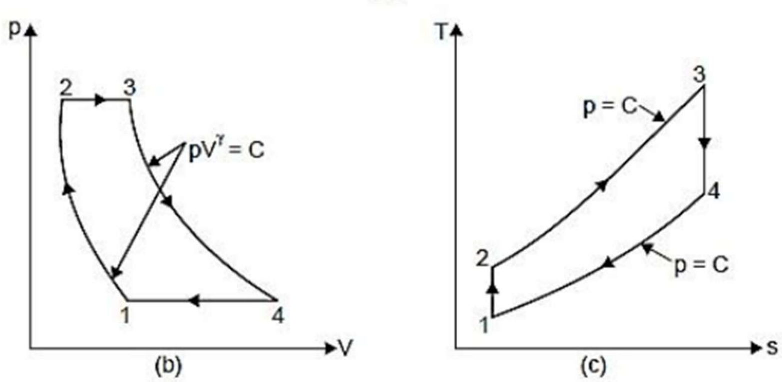


Fig.7.12 – Schematic, p-V, and T-s diagram of closed Brayton cycle

Q12: A gas engine working on Otto cycle has compression ratio 8. Calculate its air-standard efficiency. Assume γ = 1.4.

Answer:

Given:

- Compression ratio, $r = 8$
- Ratio of specific heats, $\gamma = 1.4$

To Find: Air-standard efficiency, η_{otto}

Solution:
The air-standard efficiency for the Otto cycle is given by:

$$\eta_{otto} = 1 - \frac{1}{r^{\gamma-1}}$$

Substituting the given values:

$$\eta_{otto} = 1 - \frac{1}{8^{(1.4-1)}} = 1 - \frac{1}{8^{0.4}}$$

Calculating $8^{0.4}$:

$$8^{0.4} = (2^3)^{0.4} = 2^{1.2} \approx 2.297$$

$$\eta_{otto} = 1 - \frac{1}{2.297} = 1 - 0.4353$$

$$\boxed{\eta_{otto} = 0.5647 \text{ or } 56.47\%}$$

Answer: The air-standard efficiency of the engine is **56.47%**.

Q13: A gas turbine plant operates on Brayton cycle with pressure ratio 6, maximum temperature 900°C, minimum temperature 27°C. Calculate the thermal efficiency and work ratio.

Answer:

Given:

- Pressure ratio, $r_p = 6$
- Maximum temperature, $T_3 = 900^\circ C = 900 + 273 = 1173\ K$
- Minimum temperature, $T_1 = 27^\circ C = 27 + 273 = 300\ K$
- Assume $\gamma = 1.4$ for air.

To Find:

1. Thermal Efficiency (η_{th})
2. Work Ratio (r_w)

Solution:

Part 1: Thermal Efficiency
The thermal efficiency for an ideal Brayton cycle is:

$$\eta_{th} = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}}$$

Substituting the values:

$$\eta_{th} = 1 - \frac{1}{6^{(1.4-1)/1.4}} = 1 - \frac{1}{6^{0.4/1.4}} = 1 - \frac{1}{6^{0.2857}}$$

Calculating $6^{0.2857}$:

$$6^{0.2857} \approx 1.668$$

$$\eta_{th} = 1 - \frac{1}{1.668} = 1 - 0.5995$$
$$\boxed{\eta_{th} = 0.4005 \text{ or } 40.05\%}$$

Part 2: Work Ratio

Work ratio (r_w) is defined as the ratio of net work output to the turbine work.

$$r_w = \frac{W_{net}}{W_T} = \frac{W_T - W_C}{W_T} = 1 - \frac{W_C}{W_T}$$

- **Calculate Compressor Work (W_C):**
  For isentropic compression 1-2:

$$\frac{T_2}{T_1} = (r_p)^{(\gamma-1)/\gamma}$$
$$T_2 = T_1 \times (r_p)^{(\gamma-1)/\gamma} = 300 \times 6^{0.2857} = 300 \times 1.668$$
$$T_2 = 500.4\ K$$

Assuming constant specific heats, $W_C = C_p(T_2 - T_1)$

- **Calculate Turbine Work (W_T):**
  For isentropic expansion 3-4:

$$\frac{T_3}{T_4} = (r_p)^{(\gamma-1)/\gamma}$$
$$T_4 = \frac{T_3}{(r_p)^{(\gamma-1)/\gamma}} = \frac{1173}{1.668}$$
$$T_4 = 703.24\ K$$

$$W_T = C_p(T_3 - T_4)$$

- **Calculate Work Ratio (r_w):**

$$r_w = 1 - \frac{W_C}{W_T} = 1 - \frac{C_p(T_2 - T_1)}{C_p(T_3 - T_4)} = 1 - \frac{(500.4 - 300)}{(1173 - 703.24)}$$
$$r_w = 1 - \frac{200.4}{469.76} = 1 - 0.4266$$
$$\boxed{r_w = 0.5734}$$

Answer:

- The thermal efficiency of the plant is **40.05%**.
- The work ratio is **0.5734**.

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