GUJARAT TECHNOLOGICAL UNIVERSITY

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

Subject Name & Code:
Engineering Thermodynamics (3131905)

Unit 2: First Law of Thermodynamics

Repeated Questions:

1. **Derive the Steady Flow Energy Equation (SFEE) and deduce it for a turbine/nozzle. (07 Marks - S23, S24, S25)**

Answer:

Derivation of SFEE:

Consider an open system (control volume) with steady flow conditions where properties do not change with time.

Energy Entering Control Volume:

1. Internal Energy: U_1
2. Flow Work: P_1V_1
3. Kinetic Energy: $\frac{1}{2}mC_1^2$
4. Potential Energy: mgZ_1
5. Heat Added: Q

Energy Leaving Control Volume:

1. Internal Energy: U_2
2. Flow Work: P_2V_2
3. Kinetic Energy: $\frac{1}{2}mC_2^2$
4. Potential Energy: mgZ_2
5. Work Done: W

Applying First Law (Energy Conservation):

$$Q + U_1 + P_1V_1 + \frac{1}{2}mC_1^2 + mgZ_1 = W + U_2 + P_2V_2 + \frac{1}{2}mC_2^2 + mgZ_2$$

Since enthalpy $h = u + Pv$ and dividing by mass m:

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

This is the **Steady Flow Energy Equation**:

$$q - w = (h_2 - h_1) + \frac{C_2^2 - C_1^2}{2} + g(Z_2 - Z_1)$$

Deduction for a Turbine:

For a steam/gas turbine:

- Heat transfer is negligible: $q \approx 0$
- Change in potential energy is negligible: $g\Delta Z \approx 0$
- Work is done by the system: w is positive

SFEE reduces to:

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

Deduction for a Nozzle:
For a nozzle:
- No heat transfer: $q = 0$
- No work transfer: $w = 0$
- Change in potential energy is negligible

SFEE reduces to:

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

2. **Explain the First Law for a closed system undergoing a cycle and a process. (07 Marks - W23)**

Answer:
For a Closed System Undergoing a Cycle:
When a closed system undergoes a **complete cycle** and returns to its initial state, the **net change in internal energy is zero**. The First Law states:

$$\oint \delta Q = \oint \delta W$$

This means the **net heat transfer** during the cycle equals the **net work transfer**. In differential form:

$$\delta Q - \delta W = dU$$

For a cycle: $\oint dU = 0$, so $\oint \delta Q = \oint \delta W$.
Numerical Example: If a system receives 100 kJ of heat and rejects 60 kJ of heat during a cycle, the net work output is:

$$W_{net} = Q_{in} - Q_{out} = 100 - 60 = 40 \text{ kJ}$$

For a Closed System Undergoing a Process:
For any **process** (not necessarily cyclic), the First Law is:

$$Q - W = \Delta U$$

Where:
- Q = Net heat transfer **to** the system
- W = Net work done **by** the system
- ΔU = Change in internal energy of the system

This can be written in differential form:

$$\delta Q - \delta W = dU$$

Example Applications:
1. **Constant Volume Process:** $W = 0$, so $Q = \Delta U$
2. **Constant Pressure Process:** $Q = \Delta H$ (change in enthalpy)
3. **Adiabatic Process:** $Q = 0$, so $-W = \Delta U$
4. **Isothermal Process (ideal gas):** $\Delta U = 0$, so $Q = W$

Sign Convention:
- $Q > 0$: Heat added to system
- $Q < 0$: Heat rejected from system
- $W > 0$: Work done by system

- $W < 0$: Work done on system
- $\Delta U > 0$: Internal energy increases
- $\Delta U < 0$: Internal energy decreases

3. **Discuss the limitations of the First Law of Thermodynamics. (03 Marks - S23, W22)**

Answer:

The First Law does **not** specify the **direction** or **quality** of energy conversion. Its limitations are:

1. **Cannot predict spontaneity** – Does not tell whether a process can occur naturally (e.g., heat flowing from cold to hot body obeys 1st Law but never happens).
2. **No restriction on efficiency** – Allows 100% conversion of heat to work, which is impossible per Second Law.
3. **No distinction between heat and work** – Treats both as energy, but work is more useful (higher quality).
4. **Cannot explain impossibility of PMM2** – A device that extracts heat from a single reservoir and converts fully to work (PMM2) does not violate 1st Law but is impossible.

➞ **Real-world implication:** The Second Law of Thermodynamics was formulated to overcome these limitations.

4. **Explain PMM1 (Perpetual Motion Machine of the First Kind) with a diagram.**
   ➤ Appeared in: W23 (Q1a, 03 marks), W24 (Q2a, 03 marks), S25 (Q2b, 04 marks)

Answer:

Definition: A PMM1 is a hypothetical device that produces **work continuously without any energy input**, violating the **First Law of Thermodynamics** (energy conservation).

Why impossible?

The First Law states: Energy cannot be created or destroyed. Any machine that claims $\dot{W}_{out} > 0$ with $\dot{Q} = 0$ and no fuel is impossible.

Key characteristics:

- Delivers net work over a cycle without receiving heat or mass.
- Would require **100% efficiency** or more – impossible.
- Often disguised as "over-unity" devices.

[DG PROMPT] – Perpetual Motion Machine of First Kind

Title: PMM1 – Violation of First Law

Description: Draw a large wheel with 8 attached weights on pivots (self-shifting weights). Label **"Self-rotating wheel"**. Connect the axle to a generator labeled **"Electrical output (work)"**. No energy input arrows. Add a crossed-out circle near the wheel with text: "No fuel, no heat input". Below, write a red banner: **"IMPOSSIBLE – Violates 1st Law: Energy cannot be created."** Also show a small inset: 1st Law equation $\Delta U = Q - W$ with $Q = 0, W > 0$ causing ΔU negative forever – not possible.

Real-world warning: Any product claiming "free energy" or "self-running generator" is a PMM1 scam.

Other Important Questions:

1. **Compare heat pump and refrigerator.**
   ➤ Appeared in: S24 (Q2b, 04 marks)

Answer:

Aspect	**Refrigerator**	**Heat Pump**

Aspect	Refrigerator	Heat Pump
Purpose	Maintains a space at **low temperature** by removing heat from it	Maintains a space at **high temperature** by supplying heat to it
Desired Effect	Cooling effect (Q_2 from cold space)	Heating effect (Q_1 to warm space)
Energy Source	Work input (W)	Work input (W)
COP Definition	$COP_R = \frac{Q_2}{W} = \frac{\text{Desired Effect}}{\text{Work Input}}$	$COP_{HP} = \frac{Q_1}{W} = \frac{\text{Desired Effect}}{\text{Work Input}}$
Relationship	$COP_{HP} = COP_R + 1$	$COP_R = COP_{HP} - 1$
Typical Applications	Domestic refrigerators, air conditioners	Room heaters, water heaters
Energy Flow	Absorbs Q_2 from cold space, rejects Q_1 to surroundings	Absorbs Q_2 from surroundings, delivers Q_1 to warm space
Diagram	Both use same vapor compression cycle but different focus	Same cycle but different utilization

Key Difference: Both operate on the same cycle, but a **refrigerator's purpose is cooling** while a **heat pump's purpose is heating**.

2. **Show that COP of a heat pump is greater than COP of a refrigerator by unity.**
   ➤ **Appeared in: S23 (Q3b, 04 marks), S25 (Q2a, 03 marks)**

Answer:

Given: For both refrigerator and heat pump operating between same temperatures T_1 (hot) and T_2 (cold):

For **Refrigerator**:

- Heat absorbed from cold space: Q_2
- Heat rejected to hot space: Q_1
- Work input: W
- By First Law: $Q_1 = Q_2 + W$
- $COP_R = \frac{Q_2}{W}$

For **Heat Pump**:

- Heat delivered to hot space: Q_1
- Heat absorbed from cold space: Q_2
- Work input: W
- $COP_{HP} = \frac{Q_1}{W}$

Proof:

From First Law: $Q_1 = Q_2 + W$

Divide both sides by W:

$$\frac{Q_1}{W} = \frac{Q_2}{W} + 1$$

Substitute definitions:

$$COP_{HP} = COP_R + 1$$

Therefore: $COP_{HP} > COP_R$ by exactly 1.
Physical Explanation: The heat pump delivers all the energy (heat extracted plus work input) to the warm space, while the refrigerator only uses the extracted heat as useful effect. The work input appears as additional heat in the heat pump's output.

3. **At the inlet to an insulated nozzle, steam enters at 687 kPa and 205°C with 3000 m/min velocity and leaves at a pressure of 137 kPa and 30000 m/min velocity. Determine enthalpy of leaving steam. Mention the assumptions made.**
   ➤ Appeared in: W23 (Q2c, 07 marks)

Answer:
Given:

- Inlet: P_1 = 687 kPa, T_1 = 205°C, C_1 = 3000 m/min = 50 m/s (converted)
- Outlet: P_2 = 137 kPa, C_2 = 30000 m/min = 500 m/s (converted)
- Nozzle is insulated: Q = 0
- Assume: Steady flow, negligible change in potential energy

To Find:

- Enthalpy at outlet (h_2)

Formula:
Steady Flow Energy Equation (SFEE) for nozzle:

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

Solution:
Step 1: Find h_1 from steam tables at P_1 = 687 kPa ≈ 6.87 bar, T_1 = 205°C
At 6.87 bar, saturation temperature is ~165°C. Since T_1 = 205°C > 165°C, steam is superheated.
From superheated steam tables at 6.87 bar:

$$h_1 \approx 2850 \text{ kJ/kg(typical value for these conditions)}$$

Step 2: Convert velocities to consistent units and calculate kinetic energy terms

$$C_1 = 50 \text{ m/s}, C_2 = 500 \text{ m/s}$$
$$\frac{C_1^2}{2} = \frac{(50)^2}{2 \times 1000} = \frac{2500}{2000} = 1.25 \text{ kJ/kg}$$
$$\frac{C_2^2}{2} = \frac{(500)^2}{2 \times 1000} = \frac{250000}{2000} = 125 \text{ kJ/kg}$$

Step 3: Apply SFEE

$$h_2 = h_1 + \frac{C_1^2}{2} - \frac{C_2^2}{2}$$
$$h_2 = 2850 + 1.25 - 125$$
$$h_2 = 2850 - 123.75 = 2726.25 \text{ kJ/kg}$$

Assumptions Made:

1. Steady flow conditions
2. No heat transfer (adiabatic nozzle)
3. Negligible change in potential energy
4. No work transfer

5. Nozzle is properly insulated

Final Answer:

$$\boxed{h_2 = 2726.25 \text{ kJ/kg}}$$

4. **A stream of gases at 750 kPa, 750°C and 140 m/s is passed through a gas turbine of a jet engine. The stream comes out of the turbine at 200 kPa, 550°C and 280 m/s. The enthalpies of gas at the entry and exit of the turbine are 950 kJ/kg and 650 kJ/kg of gas respectively. Determine the capacity of the turbine if the gas flow is 5 kg/s. Assume the process is adiabatic.**
   ➤ **Appeared in: S24 (Q2c, 07 marks)**

Answer:

Given:

- Inlet: $P_1 = 750$ kPa, $T_1 = 750°C$, $C_1 = 140$ m/s, $h_1 = 950$ kJ/kg
- Outlet: $P_2 = 200$ kPa, $T_2 = 550°C$, $C_2 = 280$ m/s, $h_2 = 650$ kJ/kg
- Mass flow rate: $\dot{m} = 5$ kg/s
- Process is adiabatic: Q = 0

To Find:

- Turbine capacity (power output, W)

Formula:

SFEE for turbine:

$$\dot{Q} - \dot{W} = \dot{m}[(h_2 - h_1) + \frac{C_2^2 - C_1^2}{2} + g(Z_2 - Z_1)]$$

Neglecting potential energy change and with Q = 0:

$$-\dot{W} = \dot{m}[(h_2 - h_1) + \frac{C_2^2 - C_1^2}{2}]$$

Solution:

Step 1: Calculate enthalpy change

$$\Delta h = h_2 - h_1 = 650 - 950 = -300 \text{ kJ/kg}$$

Step 2: Calculate kinetic energy change

$$\frac{C_2^2 - C_1^2}{2} = \frac{(280)^2 - (140)^2}{2 \times 1000} \text{ kJ/kg}$$

$$= \frac{78400 - 19600}{2000} = \frac{58800}{2000} = 29.4 \text{ kJ/kg}$$

Step 3: Calculate specific work

$$-w = \Delta h + \frac{\Delta KE}{2} = -300 + 29.4 = -270.6 \text{ kJ/kg}$$

$$w = 270.6 \text{ kJ/kg}$$

(Negative sign indicates work output from system)

Step 4: Calculate turbine capacity (power)

$$\dot{W} = \dot{m} \times w = 5 \times 270.6 = 1353 \text{ kJ/s}$$

$$\dot{W} = 1353 \text{ kW}$$

Final Answer:

$$\boxed{\text{Turbine Capacity} = 1353 \text{ kW}}$$

5. **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.**

   ➤ **Appeared in: W24 (Q2c, 07 marks)**

Answer:

Given:

- Mass flow rate: $\dot{m} = 15$ kg/s
- Power output: $\dot{W} = 12000$ kW
- Inlet enthalpy: $h_1 = 1260$ kJ/kg
- Outlet enthalpy: $h_2 = 400$ kJ/kg
- Inlet velocity: $C_1 = 50$ m/s
- Outlet velocity: $C_2 = 110$ m/s
- Inlet specific volume: $v_1 = 0.45$ m³/kg

To Find:

(i) Heat rejection rate ($\dot{Q}$)

(ii) Inlet pipe area (A_1)

Formula:

SFEE for turbine:

$$\dot{Q} - \dot{W} = \dot{m}[(h_2 - h_1) + \frac{C_2^2 - C_1^2}{2}]$$

Mass flow rate: $\dot{m} = \frac{A_1 C_1}{v_1}$

Solution:

(i) Heat rejection rate:

Step 1: Calculate enthalpy change

$$\Delta h = h_2 - h_1 = 400 - 1260 = -860 \text{ kJ/kg}$$

Step 2: Calculate kinetic energy change

$$\frac{C_2^2 - C_1^2}{2} = \frac{(110)^2 - (50)^2}{2 \times 1000}$$
$$= \frac{12100 - 2500}{2000} = \frac{9600}{2000} = 4.8 \text{ kJ/kg}$$

Step 3: Apply SFEE

$$\dot{Q} - (-12000) = 15[(-860) + 4.8]$$

(Negative W as work is done by system)

$$\dot{Q} + 12000 = 15 \times (-855.2)$$
$$\dot{Q} + 12000 = -12828$$
$$\dot{Q} = -12828 - 12000 = -24828 \text{ kJ/s}$$
$$\dot{Q} = -24828 \text{ kW}$$

(Negative sign indicates heat rejected)

(ii) Inlet pipe area:

Step 4: Use mass flow rate equation

$$\dot{m} = \frac{A_1 C_1}{v_1}$$
$$15 = \frac{A_1 \times 50}{0.45}$$

$$A_1 = \frac{15 \times 0.45}{50} = \frac{6.75}{50} = 0.135 \text{ m}^2$$

Final Answers:

$$\boxed{\text{(i) Heat rejection rate} = 24828 \text{ kW}}$$

$$\boxed{\text{(ii) Inlet pipe area} = 0.135 \text{ m}^2}$$