# GUJARAT TECHNOLOGICAL UNIVERSITY

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

## Subject Name & Code:
## Engineering Thermodynamics (3131905)

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## Unit 3: Second Law of Thermodynamics

**Repeated Questions:**

1. **State and prove the equivalence of Kelvin-Planck and Clausius statements of the Second Law. (07 Marks - W23, S24, S23)**

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**Answer:**

**Kelvin-Planck Statement:** "It is impossible to construct a device that, operating in a cycle, will produce no effect other than the extraction of heat from a single reservoir and the performance of an equivalent amount of work."

**Clausius Statement:** "It is impossible to construct a device that, operating in a cycle, will produce no effect other than the transfer of heat from a cooler body to a hotter body."

**Proof of Equivalence (by Contradiction):**

**Part 1: Violation of Clausius Statement leads to violation of Kelvin-Planck Statement**

Assume a device **C** violates Clausius statement (transfers heat $Q_2$ from cold to hot without any external work). Combine this with a reversible heat engine **E** operating between same reservoirs:

1. Engine **E** takes heat $Q_1$ from hot reservoir, produces work $W = Q_1 - Q_2$, and rejects $Q_2$ to cold reservoir.
2. Device **C** takes the rejected $Q_2$ from cold reservoir and transfers it back to hot reservoir.
3. Net effect: Hot reservoir receives $Q_2$ from C and loses $Q_1$ to E → net loss = $Q_1 - Q_2$
4. Cold reservoir gains $Q_2$ from E and loses $Q_2$ to C → net change = 0
5. The combination produces work $W = Q_1 - Q_2$ while extracting heat $(Q_1 - Q_2)$ from a single reservoir (hot).

This violates Kelvin-Planck statement.

**Part 2: Violation of Kelvin-Planck Statement leads to violation of Clausius Statement**

Assume a device **K** violates Kelvin-Planck statement (produces work W by extracting heat Q from a single reservoir). Use this work to drive a refrigerator **R**:

1. Device **K** extracts heat Q from cold reservoir and produces work $W = Q$.
2. Refrigerator **R** uses work W to extract heat $Q_2$ from cold reservoir and reject $Q_1 = Q_2 + W$ to hot reservoir.
3. For the combination: Heat extracted from cold = $Q + Q_2$, Heat delivered to hot = $Q_1 = Q_2 + W = Q_2 + Q$
4. Net effect: Heat Q is transferred from cold to hot without any external work.

This violates Clausius statement.

**Conclusion:** Since violation of one statement implies violation of the other, the two statements are **equivalent**.

2. **Explain PMM-I and PMM-II. (03 Marks - S23, S24, S25, W24)**

**Answer:**

**PMM-I (Perpetual Motion Machine of First Kind):**

- **Violates:** First Law of Thermodynamics
- **Claim:** Produces work continuously without any energy input
- **Impossibility:** Would create energy from nothing
- **Example Concept:** Over-balance wheel that rotates forever

**PMM-II (Perpetual Motion Machine of Second Kind):**

- **Violates:** Second Law of Thermodynamics
- **Claim:** Converts all heat extracted from a single reservoir completely into work (100% efficiency)
- **Impossibility:** Would violate Kelvin-Planck statement
- **Example Concept:** Ship engine extracting heat from ocean to power itself

**Key Difference:**

- PMM-I violates energy conservation (quantity)
- PMM-II violates entropy principle (quality/direction)

3. **Show that the efficiency of a reversible heat engine operating between two constant temperatures is maximum. (07 Marks - S23, S25)**

**Answer:**

**Statement:** No heat engine operating between the same two reservoirs ($T_H$ and $T_L$) can have efficiency greater than that of a reversible (Carnot) engine.

**Proof using Carnot's theorem:**

Let:

- **RE** = Reversible engine (Carnot) with efficiency $\eta_R$
- **IE** = Any other irreversible engine (or any engine) with efficiency $\eta_I$

Assume $\eta_I > \eta_R$. Couple IE to drive RE as a heat pump (reverse Carnot).

**[DG PROMPT] – Proof of maximum efficiency of reversible engine**

**Title:** Carnot's Theorem – Reversible Engine has Maximum Efficiency

**Description:** Draw two reservoirs: top $T_H$, bottom $T_L$. On left, draw an irreversible engine IE taking $Q_H$ from hot, producing work $W_I$, rejecting $Q_{L,I}$ to cold. On right, draw a Carnot heat pump (reverse RE) taking work $W_I$ (from IE), absorbing $Q_{L,R}$ from cold, rejecting $Q_{H,R}$ to hot. Show that if $\eta_I > \eta_R$, then $W_I > W_R$ for same $Q_H$, leading to net heat transfer from cold to hot without work – impossible by Clausius. Therefore $\eta_I \leq \eta_R$.

**Mathematical proof:**

For reversible engine: $\eta_R = 1 - \frac{T_L}{T_H} = \frac{W_R}{Q_H}$

For any engine: $\eta_I = \frac{W_I}{Q_H}$

If $\eta_I > \eta_R$, then $W_I > W_R$ for same $Q_H$. Use $W_I$ to drive reverse Carnot (refrigerator) that requires work $W_R$ to move $Q_L$ from cold to hot. Since $W_I > W_R$, the surplus work can be used to produce net work while the net effect is transferring heat from cold to hot – violates Second Law. Hence $\eta_I \leq \eta_R$.

**Conclusion:** Carnot efficiency is the **maximum** possible.

4. **Explain Carnot cycle and its limitations.**
   **➤ Appeared in: W23 (Q2a, 03 marks), S23 (Q5a, 03 marks), S24 (Q3a, 03 marks)**

**Answer:**

**Carnot Cycle:** A theoretical thermodynamic cycle proposed by Sadi Carnot that gives the **maximum possible efficiency** for a heat engine operating between two temperature limits.

**Four Processes:**

1. **Isothermal Expansion** ($T_1$ constant): Heat $Q_1$ absorbed from source
2. **Adiabatic Expansion**: Temperature falls from $T_1$ to $T_2$
3. **Isothermal Compression** ($T_2$ constant): Heat $Q_2$ rejected to sink
4. **Adiabatic Compression**: Temperature rises from $T_2$ to $T_1$

**Efficiency:** $\eta_{Carnot} = 1 - \frac{T_2}{T_1}$

**Limitations:**

1. **Impractical to Execute:** Isothermal heat transfer requires infinitesimally small temperature difference, making process extremely slow.
2. **Adiabatic Processes Idealization:** Perfect insulation and frictionless processes are not achievable in practice.
3. **Difficulty with Two-Phase Systems:** Not suitable for steam cycles where condensation and evaporation occur.
4. **Low Work Output:** The area enclosed on P-V diagram is small compared to practical cycles.
5. **Cannot Handle Real Fluids:** Assumes ideal gas behavior or reversible phase changes.

Despite limitations, Carnot cycle remains important as it sets the **theoretical maximum limit** for all heat engines.

**Other Important Questions:**

1. **S25: State and prove Clausius theorem. (03 Marks)**

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**Answer:**

**Clausius theorem:** For any cyclic process (reversible or irreversible) operating between a system and its surroundings, the cyclic integral of $\frac{\delta Q}{T}$ is **less than or equal to zero**. Equality holds for a reversible cycle.

$$\oint \frac{\delta Q}{T} \leq 0$$

**Proof:**

Consider a cycle operating between multiple reservoirs. For a reversible cycle, entropy change of system + surroundings = 0, thus $\oint \frac{\delta Q_{rev}}{T} = 0$. For an irreversible cycle, entropy generation > 0, leading to $\oint \frac{\delta Q}{T} < 0$. Combining gives the inequality.

**Significance:** Forms the basis for the **definition of entropy** ($dS = \frac{\delta Q_{rev}}{T}$) and the **entropy principle** ($\Delta S_{universe} \geq 0$).

2. **W22: Carnot cycle is not practical – Justify the statement. (03 Marks)**

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**Answer:**

**Justification:**

Carnot cycle is theoretically the most efficient but **practically impossible** because:

1. **Isothermal heat transfer requires infinite time** – To maintain constant temperature during expansion/compression, heat transfer must occur at infinitesimal temperature difference, making the process extremely slow.
2. **Adiabatic processes require perfect insulation** – No real cylinder can prevent heat loss completely.
3. **Frictionless piston** – Friction is unavoidable in real engines.
4. **Reversible processes are quasi-static** – Piston movement must be infinitely slow to maintain equilibrium, giving zero power output.
5. **Condensation issues** – In steam cycles, isothermal expansion leads to wet steam which

damages turbine blades.

**Conclusion:** Carnot cycle is a **theoretical ideal** – real cycles (Rankine, Otto, Diesel) are practical approximations.

3. **W23: Carnot cycle is practically impossible. Justify the statement. (03 Marks)**

**Answer:[As Above]**

4. **300 kJ/s of heat is supplied at a constant fixed temperature of 290°C to a heat engine. The heat rejection takes place at 8.5°C. The following results were obtained: (i) 215 kJ/s are rejected, (ii) 150 kJ/s are rejected, (iii) 75 kJ/s are rejected. Classify which of the result report a reversible cycle or irreversible cycle or impossible results.**
➤ **Appeared in: W24 (Q2c, 07 marks)**

**Answer:**

**Given:**

- $Q_1 = 300$ kJ/s
- $T_1 = 290^\circ\text{C} = 563$ K
- $T_2 = 8.5^\circ\text{C} = 281.5$ K

**Carnot (Maximum) Efficiency:**

$$\eta_{max} = 1 - \frac{T_2}{T_1} = 1 - \frac{281.5}{563} = 1 - 0.5 = 0.5 \text{ or } 50\%$$

**Maximum Work Output:**

$$W_{max} = \eta_{max} \times Q_1 = 0.5 \times 300 = 150 \text{ kJ/s}$$

**Minimum Heat Rejection (for reversible engine):**

$$Q_{2,min} = Q_1 - W_{max} = 300 - 150 = 150 \text{ kJ/s}$$

**Analysis:**

**(i)** $Q_2 = 215$ kJ/s

$$W = Q_1 - Q_2 = 300 - 215 = 85 \text{ kJ/s}$$
$$\eta = \frac{W}{Q_1} = \frac{85}{300} = 0.283 \text{ or } 28.3\% < 50\%$$

This is **possible and irreversible** (actual efficiency less than Carnot).

**(ii)** $Q_2 = 150$ kJ/s

$$W = 300 - 150 = 150 \text{ kJ/s}$$
$$\eta = \frac{150}{300} = 0.5 \text{ or } 50\% = \eta_{max}$$

This represents a **reversible cycle** (Carnot efficiency achieved).

**(iii)** $Q_2 = 75$ kJ/s

$$W = 300 - 75 = 225 \text{ kJ/s}$$
$$\eta = \frac{225}{300} = 0.75 \text{ or } 75\% > 50\%$$

This is **impossible** (efficiency greater than Carnot efficiency violates Second Law).

**Final Answer:**

- (i) **Irreversible cycle**
- (ii) **Reversible cycle**

- (iii) **Impossible result**

5. **Determine the least rate of heat rejection per kW net output of the cyclic heat engine which operates between a source temperature of 1000°C and a sink temperature of 40°C.**
   **➤ Appeared in: S24 (Q2c, 07 marks)**

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**Answer:**

**Given:**

- $T_1 = 1000^\circ\text{C} = 1273\text{ K}$
- $T_2 = 40^\circ\text{C} = 313\text{ K}$
- Net work output: $W_{net} = 1\text{ kW}$

**To Find:** Minimum heat rejection rate $Q_{2,min}$

**Formula:** For maximum efficiency (reversible engine):

$$\eta_{max} = 1 - \frac{T_2}{T_1}$$
$$W = \eta_{max} \times Q_1$$
$$Q_2 = Q_1 - W$$

**Solution:**

**Step 1:** Calculate Carnot efficiency

$$\eta_{max} = 1 - \frac{313}{1273} = 1 - 0.2459 = 0.7541 \text{ or } 75.41\%$$

**Step 2:** For $W = 1$ kW, find $Q_1$

$$Q_1 = \frac{W}{\eta_{max}} = \frac{1}{0.7541} = 1.326\text{ kW}$$

**Step 3:** Calculate $Q_{2,min}$

$$Q_{2,min} = Q_1 - W = 1.326 - 1 = 0.326\text{ kW}$$

**Alternative Method using $\frac{Q_2}{W}$ ratio:**

$$\frac{Q_2}{Q_1} = \frac{T_2}{T_1} = 0.2459$$
$$Q_1 = \frac{W}{1 - \frac{T_2}{T_1}} = \frac{1}{0.7541} = 1.326\text{ kW}$$
$$Q_2 = Q_1 \times \frac{T_2}{T_1} = 1.326 \times 0.2459 = 0.326\text{ kW}$$

**Final Answer:**

$$\boxed{Q_{2,min} = 0.326\text{ kW}}$$

This is the **minimum possible** heat rejection rate for 1 kW output. Any actual engine will reject more heat.

6. **An inventor claims that his engine develops 75 kW of power while operating between 1023K and 298K temperature. The amount of fuel (C.V. of fuel = 74500 kJ/kg) burnt per**

**hour is 3.9 kg. Comment about the validity of his claim and justify your comment.**
**➤ Appeared in: S25 (Q2c, 07 marks)**

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**Answer:**
**Given:**
- Power output: $P = 75$ kW
- Source temperature: $T_1 = 1023$ K
- Sink temperature: $T_2 = 298$ K
- Calorific value of fuel: $CV = 74500$ kJ/kg
- Fuel consumption rate: $\dot{m}_f = 3.9$ kg/h

**To Find:** Validity of the inventor's claim
**Formulas:**
1. Maximum possible efficiency (Carnot): $\eta_{max} = 1 - \frac{T_2}{T_1}$
2. Actual efficiency: $\eta_{actual} = \frac{\text{Power Output}}{\text{Heat Input Rate}}$
3. Heat input rate: $\dot{Q}_{in} = \dot{m}_f \times CV$

**Solution:**
**Step 1:** Calculate Carnot (maximum possible) efficiency

$$\eta_{max} = 1 - \frac{T_2}{T_1} = 1 - \frac{298}{1023} = 1 - 0.2913 = 0.7087 \text{ or } 70.87\%$$

**Step 2:** Calculate actual heat input rate
Fuel consumption: 3.9 kg/h $= \frac{3.9}{3600}$ kg/s $= 0.001083$ kg/s

$$\dot{Q}_{in} = \dot{m}_f \times CV = 0.001083 \times 74500 = 80.68 \text{ kJ/s} = 80.68 \text{ kW}$$

**Step 3:** Calculate actual efficiency

$$\eta_{actual} = \frac{P}{\dot{Q}_{in}} = \frac{75}{80.68} = 0.9296 \text{ or } 92.96\%$$

**Step 4:** Compare efficiencies

$$\eta_{actual} = 92.96\% > \eta_{max} = 70.87\%$$

**Analysis:**
The actual efficiency (92.96%) is **greater than** the maximum possible Carnot efficiency (70.87%) for the given temperature limits. This violates the **Second Law of Thermodynamics** (Kelvin-Planck statement).
**Conclusion:**
The inventor's claim is **NOT VALID/IMPOSSIBLE**. No heat engine can have an efficiency greater than the Carnot efficiency between the same temperature limits.
**Reason:** The Second Law establishes the Carnot efficiency as the absolute upper limit for any heat engine operating between two reservoirs. An efficiency of 92.96% would require either:
1. A higher source temperature than 1023K, or
2. A lower sink temperature than 298K, or
3. Violation of the Second Law (which is impossible).

7. **An inventor claims that a new heat cycle will develop 0.4 kW for a heat addition of 32.5 kJ/min. The temperature of heat source is 1990 K and that of sink is 850 K. Is his claim possible?**
   **➤ Appeared in: W24 (Q5a, 03 marks)**

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**Answer:**

**Given:**

- Power output: $W = 0.4$ kW $= 0.4$ kJ/s
- Heat addition rate: $Q_1 = 32.5$ kJ/min $= \frac{32.5}{60}$ kJ/s $= 0.5417$ kJ/s
- Source temperature: $T_1 = 1990$ K
- Sink temperature: $T_2 = 850$ K

**Solution:**

**Step 1:** Calculate claimed efficiency

$$\eta_{claimed} = \frac{W}{Q_1} = \frac{0.4}{0.5417} = 0.7384 \text{ or } 73.84\%$$

**Step 2:** Calculate Carnot (maximum possible) efficiency

$$\eta_{max} = 1 - \frac{T_2}{T_1} = 1 - \frac{850}{1990} = 1 - 0.4271 = 0.5729 \text{ or } 57.29\%$$

**Step 3:** Compare

$$\eta_{claimed} = 73.84\% > \eta_{max} = 57.29\%$$

**Conclusion:**

The claim is **IMPOSSIBLE**. The claimed efficiency (73.84%) exceeds the maximum possible Carnot efficiency (57.29%) for the given temperature limits, violating the Second Law of Thermodynamics.