FREE NOTES · NCERT + JEE/NEET LEVEL

Thermodynamics

The zeroth, first and second laws, internal energy, isothermal, adiabatic, isobaric and isochoric processes, PV graphs, heat engines, refrigerators and the Carnot engine. Every process's formulas in one table.

01 System, surroundings & equilibrium
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01 System, surroundings & equilibrium

System: the thing we study (gas in a cylinder). **Surroundings:** everything else. Heat and work are exchanged between them.

Thermodynamic equilibrium: when the system's macroscopic variables (P, V, T, mass) don't change with time.

STATE VARIABLES

P, V, T, U depend only on the state, not the path. **Heat (Q) and work (W) are not state variables**; they depend on the path (process). Intensive (independent of size): P, T, density. Extensive (grow with size): V, U, mass.

02 Zeroth law

STATEMENT

If A and B are each in thermal equilibrium with C, then A and B are in thermal equilibrium with each other.

This gives the concept of **temperature**: bodies in equilibrium have equal temperatures. A thermometer (C) works on this.

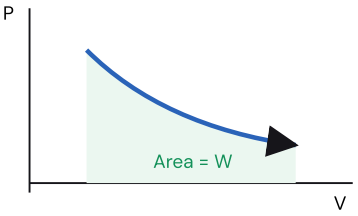
03 Heat, work & internal energy

- **Internal energy U:** total KE + PE of the molecules. For an ideal gas only KE, and **U depends only on T**.
- **Heat Q:** energy exchanged because of a temperature difference.
- **Work W:** an expanding gas pushes a piston.

WORK BY A GAS

$$W = \int P \, dV$$

Area under the PV graph. Expansion: W positive. Compression: W negative.



In expansion, the area = work done by the gas

04 First law of thermodynamics

STATEMENT (ENERGY CONSERVATION)

$\Delta Q = \Delta U + \Delta W$

Heat given to the system = change in internal energy + work done by the system.

Quantity	Positive (+)	Negative (−)
ΔQ	Heat given to the system	Heat given out by the system
ΔW	Work done by the system (expansion)	Work done on the system (compression)
ΔU	Temperature rises	Temperature falls

LIMITATION

The first law doesn't tell which direction a process goes (hot to cold or the reverse). The second law does.

05 Specific heats of gases

C_v: heat to raise 1 mol by 1 K at constant volume

C_p: at constant pressure

$$C_p - C_v = R$$

$$\gamma = C_p/C_v$$

$C_p > C_v$: at constant pressure part of the heat goes into expansion (work).

Gas	C_v	C_p	γ
Monoatomic (He, Ar)	3R/2	5R/2	5/3 ≈ 1.67
Diatomic (O_2, N_2)	5R/2	7R/2	7/5 = 1.4
Polyatomic (CO_2)	3R	4R	4/3 ≈ 1.33

For an ideal gas in any process: $\Delta U = n\, C_v\, \Delta T$ (depends only on the change in T).

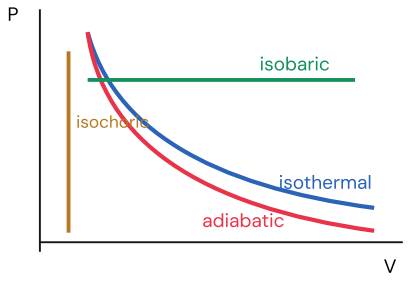
06 Thermodynamic processes

Process	Constant	Equation	Work W	First law
Isothermal	T	$PV = \text{const}$	$nRT \ln(V_2/V_1)$	$\Delta U = 0,\ Q = W$
Adiabatic	Q = 0	$PV^\gamma = \text{const},\ TV^{\gamma-1} = \text{const}$	$(P_1V_1 - P_2V_2)/(\gamma - 1)$	$W = -\Delta U$
Isobaric	P	$V/T = \text{const}$	$P\Delta V = nR\Delta T$	$Q = nC_p\Delta T$
Isochoric	V	$P/T = \text{const}$	0	$Q = \Delta U = nC_v\Delta T$
Cyclic	Returns to initial state	—	Area of the loop	$\Delta U = 0,\ Q = W$

WHICH PROCESS WHEN

- **Isothermal:** very slow, in a conducting vessel, in contact with a heat reservoir.
- **Adiabatic:** very fast, or in an insulated vessel. A bursting bicycle tyre (the air feels cold), sound waves.
- In adiabatic expansion the gas **cools**; in compression it **heats up** (diesel engine).

07 PV diagrams



The adiabatic curve is steeper (by a factor γ)

SLOPES

Isothermal: $dP/dV = -P/V$

Adiabatic: $dP/dV = -\gamma P/V$

CYCLIC PROCESS

Area of the loop = net work. **Clockwise** loop: net work positive (engine). **Anticlockwise**: negative (refrigerator).

Expanding from the same V_1 to V_2: isobaric > isothermal > adiabatic (work).

08 Second law of thermodynamics

KELVIN-PLANCK STATEMENT

No engine can take heat from a single source and convert **all** of it into work. Some heat must be given to a cold sink. So **a 100% efficient engine is impossible**.

CLAUSIUS STATEMENT

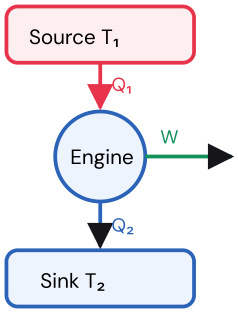
Heat cannot flow **by itself** from a colder body to a hotter one. External work is needed (a refrigerator).

The two statements are equivalent forms of the same law.

09 Reversible & irreversible processes

Reversible	Irreversible
Running it backward returns both system and surroundings to their original states	Cannot return to the original state
Extremely slow (quasi-static), no friction, no heat loss	Friction, fast processes, free expansion, heat flow
Ideal (doesn't actually occur)	All real-world processes

10 Heat engine & refrigerator



Engine: $Q_1 = W + Q_2$

HEAT ENGINE EFFICIENCY

$$\eta = W/Q_1 = 1 - Q_2/Q_1$$

REFRIGERATOR (COP)

$$\beta = Q_2/W = Q_2/(Q_1 - Q_2)$$

Takes Q_2 out of the cold interior using work W and dumps Q_1 outside. β can exceed 1. For an engine and fridge between the same T_1, T_2 (reversible): $\beta = (1 - \eta)/\eta$.

11 Carnot engine

The **most efficient** ideal (reversible) engine working between two temperatures. Cycle: isothermal expansion → adiabatic expansion → isothermal compression → adiabatic compression.

$$\eta_{\text{Carnot}} = 1 - T_2/T_1$$

T in kelvin. For Carnot, $Q_2/Q_1 = T_2/T_1$. For a fridge, $\beta = T_2/(T_1 - T_2)$.

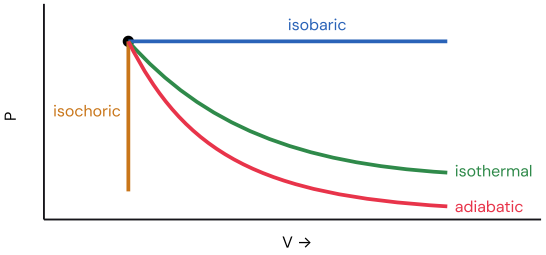
CARNOT THEOREM

(1) No engine between the same source and sink can be more efficient than a Carnot engine. (2) Carnot efficiency doesn't depend on the working substance. 100% only if $T_2 = 0$ K, which is impossible.

12 JEE Extra + Tricks

JEE LEVEL

- Work by gas = area under P–V curve; cyclic process: $\Delta U = 0$, net work = enclosed area (clockwise = positive work).
- Isothermal $W = nRT \ln(V_2/V_1)$; adiabatic $W = (P_1V_1 - P_2V_2)/(\gamma - 1)$; isobaric $W = P\Delta V$; isochoric $W = 0$.
- Slope of adiabatic = $\gamma \times$ slope of isothermal (adiabatic is steeper).
- Mayer: $C_p - C_v = R$. $\Delta U = nC_v\Delta T$ for **any** process of an ideal gas.
- Carnot efficiency $\eta = 1 - T_2/T_1$; refrigerator COP $\beta = T_2/(T_1 - T_2) = (1 - \eta)/\eta$.



Four processes starting from the same state

13 Solved numericals (R = 8.3 J/mol·K)

Q1. A gas is given 500 J of heat and does 200 J of work. ΔU?
$\Delta U = Q - W = 300$ J. **Ans: 300 J (temperature rises)**

Q2. 2 mol of ideal gas at 300 K expands isothermally to twice its volume. Work? (ln 2 = 0.693)
$W = nRT \ln 2 = 2 \times 8.3 \times 300 \times 0.693 \approx 3451$ J. $Q = W$ ($\Delta U = 0$). **Ans: ≈ 3.45 kJ**

Q3. 1 mol of monoatomic gas is heated by 10 K at constant pressure. Find Q, ΔU, W.
$Q = nC_p\Delta T = 2.5 \times 8.3 \times 10 = 207.5$ J. $\Delta U = 1.5 \times 8.3 \times 10 = 124.5$ J. $W = 83$ J. **Ans: 207.5 J, 124.5 J, 83 J**

Q4. A diatomic gas (γ = 1.4) at 300 K is compressed adiabatically to 1/32 of its volume. Final T?
$TV^{\gamma-1}$ const $\Rightarrow T_2 = 300 \times 32^{0.4} = 300 \times 4 = 1200$ K. **Ans: 1200 K**

Q5. A Carnot engine works between 527 °C and 127 °C. Efficiency?
$T_1 = 800$ K, $T_2 = 400$ K $\Rightarrow \eta = 1 - 0.5 = 50\%$. **Ans: 50%**

Q6. A (Carnot) fridge: inside −3 °C, outside 27 °C. COP? Heat removed from inside per 1 kJ of work?
$\beta = 270/30 = 9$. $Q_2 = 9$ kJ. **Ans: 9, 9 kJ**

14 Common mistakes

- Using °C in Carnot efficiency. Use kelvin.
- Thinking "no heat is given" in an isothermal process. Heat is given, but ΔU = 0.
- Treating adiabatic and isothermal as the same. In adiabatic Q = 0 and T changes.
- Taking the wrong sign for work (W is negative in compression).
- Treating Q and W as state variables.
- Being surprised by a fridge COP above 1: that's normal.

15 Formula sheet

First law	$\Delta Q = \Delta U + \Delta W$
Work	$W = \int P\, dV$
Internal energy	$\Delta U = nC_v\Delta T$
Mayer, γ	$C_p - C_v = R,\ \gamma = C_p/C_v$
Isothermal work	$nRT \ln(V_2/V_1)$
Adiabatic	$PV^\gamma = \text{const},\ W = (P_1V_1 - P_2V_2)/(\gamma - 1)$
Isobaric	$W = P\Delta V$
Engine	$\eta = 1 - Q_2/Q_1$
Carnot	$\eta = 1 - T_2/T_1$
Refrigerator	$\beta = Q_2/W = T_2/(T_1 - T_2)$

16 Practice questions

1. In a cyclic process the net heat absorbed is 100 J. Net work?
2. In an isochoric process a gas is given 50 J. Find ΔU and W.
3. An engine's efficiency is 25% with a 400 K source. Sink temperature?
4. A gas has γ = 1.5. C_v in terms of R?
5. A Carnot engine takes 1000 J and gives 600 J to the sink. Efficiency and work?

ANSWERS

1) 100 J · 2) ΔU = 50 J, W = 0 · 3) 300 K · 4) C_v = R/(γ − 1) = 2R · 5) 40%, 400 J

17 Quick revision: 5 minutes before the exam

LAWS

- Zeroth: the concept of temperature.
- First: $\Delta Q = \Delta U + \Delta W$.
- Second: no 100% engine; heat doesn't flow cold → hot by itself.

PROCESSES

- Isothermal: $\Delta U = 0$, $W = nRT \ln(V_2/V_1)$.
- Adiabatic: $Q = 0$, PV^{γ} const.
- Isochoric: $W = 0$. Isobaric: $W = P\Delta V$.
- Cyclic: $\Delta U = 0$, W = loop area.

GASES

- $C_p - C_v = R$.
- γ: mono 5/3, di 7/5, poly 4/3.
- $\Delta U = nC_v\Delta T$ (any process).

ENGINES

- $\eta = 1 - Q_2/Q_1$; Carnot $1 - T_2/T_1$.
- Fridge $\beta = T_2/(T_1 - T_2)$.
- Clockwise loop = engine.

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