PHYSICS FORMULA SERIES

THERMODYNAMICS & KINETIC THEORY OF GASES

Complete Formula Sheet

All formulas, conditions, and key results at one place

Universal Gas Const.	Boltzmann Const.	Key Values
$R = 8.314\ \text{J mol}^{-1}\text{K}^{-1}$	$k_B = 1.38 \times 10^{-23}\ \text{J/K}$	$N_A = 6.022 \times 10^{23}\ \text{mol}^{-1}$, $0°\text{C} = 273\ \text{K}$

PART I — KINETIC THEORY OF GASES (KTG)

1. Ideal Gas Laws

Ideal Gas Equation: $PV = nRT = Nk_BT$

Boyle's Law ($T = $ const): $P_1V_1 = P_2V_2$

Charles' Law ($P = $ const): $\dfrac{V_1}{T_1} = \dfrac{V_2}{T_2}$

Gay-Lussac's Law ($V = $ const): $\dfrac{P_1}{T_1} = \dfrac{P_2}{T_2}$

Combined Gas Law: $\dfrac{P_1V_1}{T_1} = \dfrac{P_2V_2}{T_2}$

Dalton's Law: $P_{\text{total}} = P_1 + P_2 + P_3 + \cdots$

n (moles) and N (molecules): $n = \dfrac{N}{N_A}\quad ; \quad k_B = \dfrac{R}{N_A}$

★ **Important:** For an ideal gas: **no intermolecular forces**, **negligible molecular volume**. Real gases deviate at high pressure and low temperature.

2. Kinetic Theory — Pressure and Energy

Pressure of Gas: $P = \dfrac{1}{3}\rho\overline{v^2} = \dfrac{1}{3}\dfrac{mN}{V}\overline{v^2}$

Also written as: $PV = \dfrac{1}{3}mN\overline{v^2} = \dfrac{2}{3}\overline{KE}_{\text{total}}$

KE per molecule: $\overline{KE} = \dfrac{1}{2}m\overline{v^2} = \dfrac{3}{2}k_BT$

KE per mole: $KE_{\text{mole}} = \frac{3}{2}RT$

Total KE of n moles: $KE_{\text{total}} = \frac{3}{2}nRT$

Relation P and KE: $P = \frac{2}{3}\frac{KE_{\text{total}}}{V} = \frac{2}{3}E$

3. Molecular Speeds

RMS Speed: $v_{\text{rms}} = \sqrt{\overline{v^2}} = \sqrt{\frac{3RT}{M}} = \sqrt{\frac{3k_BT}{m}}$

Mean (Average) Speed: $\bar{v} = \sqrt{\frac{8RT}{\pi M}} = \sqrt{\frac{8k_BT}{\pi m}}$

Most Probable Speed: $v_p = \sqrt{\frac{2RT}{M}} = \sqrt{\frac{2k_BT}{m}}$

Speed Ratio: $v_p : \bar{v} : v_{\text{rms}} = \sqrt{2} : \sqrt{\frac{8}{\pi}} : \sqrt{3} \approx 1 : 1.128 : 1.732$

Effect of Temperature: $v \propto \sqrt{T} \quad \Rightarrow \quad \frac{v_2}{v_1} = \sqrt{\frac{T_2}{T_1}}$

Effect of Molar Mass: $v \propto \frac{1}{\sqrt{M}}$ (at same T)

★ **Important:** $v_p < \bar{v} < v_{\text{rms}}$ always. M is molar mass in kg/mol. Temperature must be in Kelvin.

4. Degrees of Freedom & Law of Equipartition

Equipartition Theorem: $KE = \frac{1}{2}k_BT$ per degree of freedom per molecule

Total Energy per molecule: $E = \frac{f}{2}k_BT$ (f = degrees of freedom)

Total Energy per mole: $U = \frac{f}{2}RT$

Total Energy n moles: $U = \frac{f}{2}nRT$

Gas Type	f	C_V	C_P	$\gamma = C_P/C_V$
Monoatomic (He, Ar)	3	$\frac{3}{2}R$	$\frac{5}{2}R$	$\frac{5}{3} \approx 1.67$
Diatomic (H_2, N_2, O_2)	5	$\frac{5}{2}R$	$\frac{7}{2}R$	$\frac{7}{5} = 1.4$
Triatomic / Polyatomic	6	$3R$	$4R$	$\frac{4}{3} \approx 1.33$

5. Mean Free Path

Mean Free Path: $\ell = \dfrac{1}{\sqrt{2}\,\pi d^2 n} = \dfrac{k_B T}{\sqrt{2}\,\pi d^2 P}$

Collision Frequency: $Z = \dfrac{\bar{v}}{\ell} = \sqrt{2}\,\pi d^2 n \bar{v}$

Here: d = diameter of molecule, n = number density $= N/V$, P = pressure

PART II — THERMODYNAMICS

6. Laws of Thermodynamics

Zeroth Law: If A is in thermal equilibrium with B, and B with C, then A is in thermal equilibrium with C. This defines **temperature**.

First Law: $\Delta Q = \Delta U + \Delta W$

where ΔQ = heat supplied, ΔU = change in internal energy, ΔW = work done **by** the gas

Work Done by Gas: $\Delta W = \displaystyle\int_{V_i}^{V_f} P\,dV = P\,\Delta V \quad \text{(isobaric)}$

Second Law: Heat cannot flow spontaneously from a cold body to a hot body. Entropy of an isolated system never decreases.

Third Law:	Entropy of a perfect crystal at absolute zero ($T = 0$ K) is zero.

★ **Important:** Sign Convention: $\Delta Q > 0$ (heat absorbed by system), $\Delta W > 0$ (work done **by** system), $\Delta U > 0$ (internal energy increases).

7. Internal Energy

Internal Energy (n moles):	$U = \frac{f}{2}nRT$ (ideal gas, depends only on T)
Change in Internal Energy:	$\Delta U = \frac{f}{2}nR\,\Delta T = nC_V\,\Delta T$
Monoatomic:	$\Delta U = \frac{3}{2}nR\,\Delta T$
Diatomic:	$\Delta U = \frac{5}{2}nR\,\Delta T$
Key Result:	For an ideal gas, internal energy depends **only on temperature**, not on P or V.

8. Molar Heat Capacities

At Constant Volume (C_V):	$\Delta Q = nC_V\Delta T \quad ; \quad C_V = \frac{f}{2}R$
At Constant Pressure (C_P):	$\Delta Q = nC_P\Delta T \quad ; \quad C_P = \frac{f}{2}R + R = C_V + R$
Mayer's Relation:	$C_P - C_V = R$
Ratio of Heat Capacities:	$\gamma = \frac{C_P}{C_V} = 1 + \frac{2}{f} = \frac{f+2}{f}$
C_V in terms of γ:	$C_V = \frac{R}{\gamma - 1}$
C_P in terms of γ:	$C_P = \frac{\gamma R}{\gamma - 1}$

9. Thermodynamic Processes

Isothermal Process ($T = \text{const}$, ideal gas)

Condition: $PV = \text{const} \quad \Rightarrow \quad P_1V_1 = P_2V_2$

Work Done: $W = nRT\ln\left(\frac{V_f}{V_i}\right) = nRT\ln\left(\frac{P_i}{P_f}\right)$

Internal Energy: $\Delta U = 0 \quad \Rightarrow \quad \Delta Q = W$

Adiabatic Process ($\Delta Q = 0$)

Condition: $PV^\gamma = \text{const}$

Also: $TV^{\gamma-1} = \text{const} \quad ; \quad T^\gamma P^{1-\gamma} = \text{const}$

Work Done: $W = \frac{P_iV_i - P_fV_f}{\gamma - 1} = \frac{nR(T_i - T_f)}{\gamma - 1} = -\Delta U$

Isochoric Process ($V = \text{const}$)

Condition: $V = \text{const} \quad \Rightarrow \quad W = 0$

First Law: $\Delta Q = \Delta U = nC_V\Delta T$

Pressure ratio: $\frac{P_1}{T_1} = \frac{P_2}{T_2}$

Isobaric Process ($P = \text{const}$)

Condition: $P = \text{const}$

Work Done: $W = P\Delta V = nR\Delta T$

First Law: $\Delta Q = nC_P\Delta T \quad ; \quad \Delta U = nC_V\Delta T$

Volume ratio: $\frac{V_1}{T_1} = \frac{V_2}{T_2}$

10. Process Comparison Table

Process	ΔQ	ΔU	W	Condition
Isothermal	$nRT\ln\frac{V_f}{V_i}$	0	$nRT\ln\frac{V_f}{V_i}$	$T = \text{const}$
Adiabatic	0	$-W$	$\frac{nR\Delta T}{1-\gamma}$	$\Delta Q = 0$
Isochoric	$nC_V\Delta T$	$nC_V\Delta T$	0	$V = \text{const}$
Isobaric	$nC_P\Delta T$	$nC_V\Delta T$	$nR\Delta T$	$P = \text{const}$

11. Heat Engines & Efficiency

Thermal Efficiency: $\eta = \dfrac{W}{Q_1} = 1 - \dfrac{Q_2}{Q_1} = \dfrac{Q_1 - Q_2}{Q_1}$

Work Output: $W = Q_1 - Q_2$

Carnot Efficiency: $\eta_{\text{Carnot}} = 1 - \dfrac{T_2}{T_1}$ (maximum possible efficiency)

Carnot Cycle Steps:
1. Isothermal expansion at T_1 (absorbs Q_1)
2. Adiabatic expansion ($T_1 \to T_2$)
3. Isothermal compression at T_2 (releases Q_2)
4. Adiabatic compression ($T_2 \to T_1$)

★ **Important:** Carnot engine has the **maximum possible efficiency** between two temperatures T_1 (source) and T_2 (sink). No real engine can exceed Carnot efficiency. $\eta = 1$ only if $T_2 = 0$ K (impossible).

12. Refrigerator & Coefficient of Performance (COP)

COP of Refrigerator: $\beta = \dfrac{Q_2}{W} = \dfrac{Q_2}{Q_1 - Q_2} = \dfrac{T_2}{T_1 - T_2}$

COP of Heat Pump: $\beta' = \dfrac{Q_1}{W} = \dfrac{Q_1}{Q_1 - Q_2} = \dfrac{T_1}{T_1 - T_2}$

Relation: $\beta' = \beta + 1$

Relation with η: $\beta = \dfrac{1 - \eta}{\eta} \quad ; \quad \eta = \dfrac{1}{1 + \beta}$

13. Entropy

Change in Entropy: $\Delta S = \dfrac{\Delta Q_{\text{rev}}}{T}$ (reversible process)

Carnot Cycle: $\dfrac{Q_1}{T_1} = \dfrac{Q_2}{T_2} \quad \Rightarrow \quad \Delta S_{\text{cycle}} = 0$

Second Law (Entropy): For any irreversible process: $\Delta S_{\text{universe}} > 0$. For a reversible process: $\Delta S_{\text{universe}} = 0$.

15. Master Formula List at a Glance

#	Formula Name	Expression
1	**Ideal Gas Equation**	$PV = nRT = Nk_BT$
2	**Pressure of Gas**	$P = \frac{1}{3}\rho\,\overline{v^2}$
3	**KE per molecule**	$\overline{KE} = \frac{3}{2}k_BT$
4	**KE per mole**	$KE = \frac{3}{2}RT$
5	**RMS Speed**	$v_{\text{rms}} = \sqrt{\frac{3RT}{M}}$
6	**Mean Speed**	$\bar{v} = \sqrt{\frac{8RT}{\pi M}}$
7	**Most Probable Speed**	$v_p = \sqrt{\frac{2RT}{M}}$
8	**Equipartition**	$E = \frac{f}{2}k_BT$ per molecule
9	**Internal Energy**	$U = \frac{f}{2}nRT$
10	**Mayer's Relation**	$C_P - C_V = R$
11	γ	$\gamma = \frac{C_P}{C_V} = 1 + \frac{2}{f}$
12	**First Law**	$\Delta Q = \Delta U + \Delta W$
13	**Work (Isothermal)**	$W = nRT\ln\left(\frac{V_f}{V_i}\right)$
14	**Work (Adiabatic)**	$W = \frac{nR(T_i - T_f)}{\gamma - 1}$
15	**Adiabatic Condition**	$PV^\gamma = \text{const}; \quad TV^{\gamma-1} = \text{const}$
16	**Carnot Efficiency**	$\eta = 1 - \frac{T_2}{T_1}$
17	**COP (Refrigerator)**	$\beta = \frac{T_2}{T_1 - T_2}$
18	**Mean Free Path**	$\ell = \frac{k_BT}{\sqrt{2}\,\pi d^2 P}$
19	C_V **from** γ	$C_V = \frac{R}{\gamma - 1}$
20	ΔU **(any process)**	$\Delta U = nC_V\Delta T$

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