Engineering Thermodynamics

Short notes for B.Tech Mechanical · GATE ME

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I. Basic Concepts

- **Thermodynamics** = study of energy, heat, work and how they change the properties of matter.
- **System** = the part we study. **Surroundings** = everything else. **Boundary** = the surface between them.

➤ Types of system

System	Mass crosses?	Energy crosses?	Example
Closed	No	Yes	Gas in a piston–cylinder
Open (control volume)	Yes	Yes	Turbine, nozzle, pump
Isolated	No	No	Universe, perfect thermos flask

- **Property**: measurable feature of a system (p, V, T, U, H, S).
  - **Intensive**: does not depend on mass (p, T, density).
  - **Extensive**: depends on mass (V, U, H, S). Extensive / mass = specific property (intensive).
- **State**: condition described by its properties. **Process**: change from one state to another. **Cycle**: final state = initial state.
- **Quasi-static process**: very slow, system always close to equilibrium. Only these can be drawn on p–V diagrams.
- **Thermodynamic equilibrium** = thermal + mechanical + chemical equilibrium together.
- **Zeroth law**: if A and B are each in thermal equilibrium with C, then A and B are in equilibrium with each other. It is the basis of temperature measurement.

REMEMBER Property = point function (exact differential). Heat and work = path functions (inexact differentials).

2. Work and Heat

- **Work** (displacement work) $W = \int p\,dV$. Work done BY the system is positive.
- **Heat** = energy crossing the boundary due to temperature difference. Heat added TO the system is positive.
- Free expansion (into vacuum): $W = 0$.

➤ Ideal gas processes (closed system, per mass m)

Process	Law	Work W	Heat Q
Isochoric	$V = C$	0	$m\,cv\,(T2 - T1)$
Isobaric	$p = C$	$p(V2 - V1)$	$m\,cp\,(T2 - T1)$
Isothermal	$pV = C$	$p1V1\,\ln(V2/V1)$	$Q = W$
Adiabatic (reversible)	$pV^\gamma = C$	$(p1V1 - p2V2)/(\gamma - 1)$	0
Polytropic	$pV^n = C$	$(p1V1 - p2V2)/(n - 1)$	$W\,(\gamma - n)/(\gamma - 1)$

FORMULA Ideal gas: $pV = mRT$. $cp - cv = R$, $\gamma = cp / cv$. For air $R = 0.287$, $cp = 1.005$, $cv = 0.718$ kJ/kg·K, $\gamma = 1.4$.

FORMULA Adiabatic: $T2/T1 = (V1/V2)^{(\gamma-1)} = (p2/p1)^{((\gamma-1)/\gamma)}$.

3. First Law of Thermodynamics

- Energy can neither be created nor destroyed. For a cycle: $\Sigma Q = \Sigma W$.
- For a process (closed system): $Q = \Delta U + W$.
- Internal energy and enthalpy of an ideal gas depend only on temperature: $dU = m\,cv\,dT$, $dH = m\,cp\,dT$. Enthalpy $H = U + pV$.
- **PMMI** (perpetual motion machine of the first kind) gives work without any energy input. It breaks the first law, so it is impossible.

➤ Steady flow energy equation (SFEE)

FORMULA $q + h1 + V1^2/2 + g\,z1 = w + h2 + V2^2/2 + g\,z2$ (per kg, steady flow).

Device	Simplification of SFEE
Nozzle	$q = 0$, $w = 0$: $V2 = \sqrt{2(h1 - h2)}$ ($V1$ small)
Turbine / compressor	Adiabatic, ΔKE and ΔPE small: $w = h1 - h2$
Throttling valve	$h1 = h2$ (isenthalpic)
Boiler / condenser	$w = 0$: $q = h2 - h1$

EXAMPLE Steam enters a nozzle with negligible velocity; enthalpy drop is 100 kJ/kg. Exit velocity = $\sqrt{2 \times 100 \times 1000} = \sqrt{200000} =$ 447 m/s.

EXAM POINT Always convert kJ to J (x 1000) before using $V^2/2$ in SFEE.

4. Second Law of Thermodynamics

- The first law tells how much energy; the second law tells direction and quality of energy.
- **Kelvin–Planck statement**: no engine working in a cycle can take heat from one reservoir and turn all of it into work. (No 100% efficient heat engine; violation = PMM2.)
- **Clausius statement**: heat cannot flow from a cold body to a hot body by itself, without work input.
- The two statements are equivalent: breaking one breaks the other.

➤ Heat engine, refrigerator, heat pump

Device	Purpose	Performance
Heat engine	Heat to work	$\eta = W / Q1 = 1 - Q2/Q1$
Refrigerator	Keep cold space cold	$COP_R = Q2 / W$
Heat pump	Keep hot space hot	$COP_{HP} = Q1 / W$

FORMULA Carnot: $\eta = 1 - T2/T1$, $COP_R = T2/(T1 - T2)$, $COP_{HP} = T1/(T1 - T2)$, and $COP_{HP} = COP_R + 1$.

- **Carnot cycle**: 2 reversible isothermal + 2 reversible adiabatic processes. Most efficient cycle between two temperatures.
- **Carnot theorem**: no engine between two reservoirs is more efficient than a reversible engine; all reversible engines between the same reservoirs have the same efficiency.

- **Causes of irreversibility**: friction, heat transfer through finite ΔT, free expansion, mixing, unrestrained expansion.

EXAMPLE Carnot engine between 800 K and 300 K takes 1000 kJ. Find η, work and heat rejected.

- $\eta = 1 - 300/800 =$ 0.625 (62.5%).
- $W = 0.625 \times 1000 = 625$ kJ. $Q2 = 1000 - 625 =$ 375 kJ.

5. Entropy

- **Clausius inequality**: $\oint dQ/T <= 0$. Equal to 0 for a reversible cycle, less than 0 for an irreversible one.
- **Entropy** S: $dS = dQrev / T$. It is a property. Unit kJ/K.
- **Principle of increase of entropy**: for an isolated system (or universe), $\Delta S >= 0$. Entropy generation Sgen = 0 only for reversible processes.

FORMULA Ideal gas: $\Delta s = cv \ln(T2/T1) + R \ln(v2/v1) = cp \ln(T2/T1) - R \ln(p2/p1)$.

FORMULA Solid or liquid (c constant): $\Delta S = m\ c \ln(T2/T1)$. Heat reservoir: $\Delta S = Q / T$.

- Reversible adiabatic process = **isentropic** (s = constant).
- On a T–s diagram, area under the curve = heat transfer. On a p–V diagram, area = work.

EXAMPLE 1 kg of water is heated from 300 K to 350 K ($c = 4.18$ kJ/kg·K). $\Delta s = 4.18 \ln(350/300) = 4.18 \times 0.1542 =$ 0.644 kJ/K.

6. Availability (Exergy)

- **Available energy**: the part of heat that can be turned into work (with surroundings at T0). **Unavailable energy** = T0 x ΔS.
- **Exergy** = maximum useful work possible when a system comes to equilibrium with the surroundings (dead state).

FORMULA Flow exergy $\psi = (h - h0) - T0(s - s0) + V^2/2 + g z$. Irreversibility $I = T0 \times Sgen$ (Gouy–Stodola theorem).

- **Second law efficiency** = actual useful work / maximum possible (reversible) work.

7. Properties of Pure Substances

- **Pure substance**: same chemical composition everywhere (water, steam, or a water–steam mix).
- Phases on heating water at constant pressure: compressed liquid → saturated liquid → wet steam → saturated vapour → superheated steam.
- **Critical point** (water): about 22.06 MPa, 374°C. Above it, liquid and vapour cannot be told apart and $h_{fg} = 0$.
- **Triple point** (water): 0.01°C, 0.611 kPa. All three phases exist together.

FORMULA Dryness fraction x = mass of vapour / total mass. Wet steam: $h = h_f + x h_{fg}$, $v \approx x v_g$, $s = s_f + x s_{fg}$.

- Measuring x: throttling calorimeter (for nearly dry steam), separating + throttling calorimeter (for very wet steam).
- **Mollier chart** = h–s chart, used for steam turbine and nozzle problems.

➤ Thermodynamic relations

- **Maxwell relations** link p, v, T, s, e.g. $(\partial T/\partial v)_s = -(\partial p/\partial s)_v$ and $(\partial s/\partial v)_T = (\partial p/\partial T)_v$.
- **Clausius–Clapeyron equation**: $dp/dT = h_{fg} / (T v_{fg})$. It gives the slope of the saturation curve.
- **Joule–Thomson coefficient** $\mu_{JT} = (\partial T/\partial p)_h$. For an ideal gas it is zero. Cooling on throttling happens below the inversion temperature.

8. Gas Power and Vapour Power Cycles

➤ Air standard assumptions

- Working fluid = air as an ideal gas, constant specific heats, combustion replaced by heat addition, exhaust replaced by heat rejection.

Cycle	Heat added at	Used in	Efficiency
Otto	Constant volume	Petrol (SI) engine	1 − 1/r^(γ−1)
Diesel	Constant pressure	Diesel (CI) engine	Less than Otto for same r
Brayton	Constant pressure	Gas turbine	1 − 1/rp^((γ−1)/γ)
Rankine	Constant pressure (boiler)	Steam power plant	(WT − WP)/Q1

FORMULA Brayton: optimum pressure ratio for max net work rp = (Tmax/Tmin)^(γ/(2(γ−1))).

EXAMPLE Air at 300 K is compressed adiabatically with V1/V2 = 8. Find T2 and work per kg.

- T2 = 300 × 8^0.4 = 300 × 2.297 = 689 K.
- W = cv (T2 − T1) = 0.718 × 389 = 279 kJ/kg (done on the gas).

➤ Rankine cycle

- Processes: 1-2 isentropic expansion in turbine, 2-3 condensation, 3-4 pumping, 4-1 heating in boiler.
- Pump work is small (v dp with small v for liquid), so the work ratio of Rankine is high.
- Ways to raise efficiency: higher boiler pressure, superheating, lower condenser pressure, **reheat** (also keeps steam drier at turbine exit), **regeneration** (feed water heating with bled steam).

TIP Rankine is preferred over Carnot for steam because pumping liquid is easy and wet compression is avoided.

9. Most Asked Questions (practice)

1. Define system, property, state, process and cycle. Intensive vs extensive.
2. State the zeroth law and explain its use in temperature measurement.
3. Apply SFEE to nozzle, turbine, compressor and throttling valve.
4. State Kelvin–Planck and Clausius statements. Prove they are equivalent.
5. Prove that Carnot efficiency depends only on reservoir temperatures.
6. State Clausius inequality. Prove that entropy is a property.
7. Find entropy change of the universe when hot metal is dropped in water.

8. Define available energy and irreversibility. State the Gouy–Stodola theorem.

9. Find dryness fraction using a throttling calorimeter.

10. Derive the efficiency of Otto and Brayton cycles. Explain reheat in Rankine.

TIP In GATE ME, expect numericals on first law (SFEE), Carnot / COP, entropy change and generation, exergy, steam tables and Rankine / Brayton cycles. Always use absolute temperature (K).