Thermal Engineering (313310)

MSBTE K-Scheme · Model Question Paper — Set C · Model Answers

Note: Steam property values used here are from the IAPWS-IF97 formulation (the standard on which modern steam tables are based), rounded as printed in steam tables. All numericals are computed step by step; small differences in the last digit due to rounding are acceptable.

Q.1

a) Heat and work with SI units — 2 M

Heat: Heat is the form of energy which is transferred across the boundary of a system due to temperature difference between the system and surroundings. SI unit: **joule (J)** or kJ.

Work: Work is said to be done by a system if the sole effect on things external to the system can be reduced to the raising of a weight; in mechanics W = force × distance moved in the direction of force. SI unit: **joule (J) = N·m**.

(Each definition with unit 1 M)

b) Dry saturated steam and wet steam — 2 M

i) Dry saturated steam: Steam at saturation temperature which does not contain any water particles in suspension (dryness fraction x = 1). Its enthalpy is h_g.

ii) Wet steam: Steam which contains water particles in suspension along with dry steam; dryness fraction x < 1. Its enthalpy $h = h_f + x\, h_{fg}$.

(Each definition 1 M)

c) Dalton's law of partial pressures — 2 M

Dalton's law of partial pressures: The total pressure exerted by a mixture of gases (which do not react chemically) is equal to the sum of the partial pressures which each gas would exert if it alone occupied the whole volume of the mixture at the same temperature.

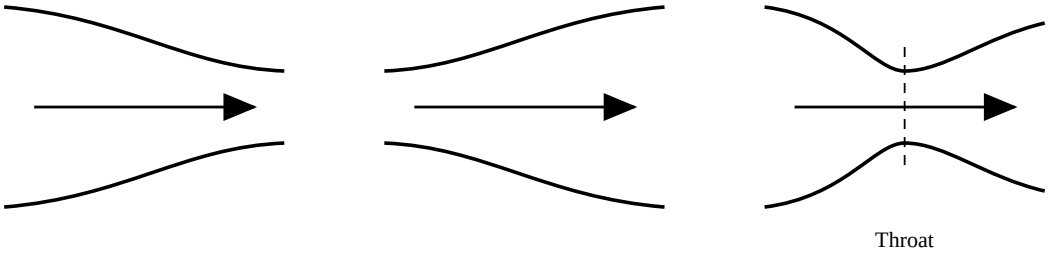
$$p = p_1 + p_2 + p_3 + \ldots$$

(Statement 2 M)

d) Function and types of steam nozzle — 2 M

Steam nozzle: A passage of varying cross-section in which the pressure energy (enthalpy) of steam is converted into kinetic energy, i.e. a high velocity jet is produced.

Types: (i) Convergent nozzle (ii) Divergent nozzle (iii) Convergent–divergent nozzle.



(a) Convergent **(b) Divergent** **(c) Convergent–divergent**

Fig.: Types of nozzles

(Function 1 M, types 1 M)

e) Thermal conductivity 2 M

Thermal conductivity (k): It is the quantity of heat conducted per unit time through a material of unit area and unit thickness when a unit temperature difference is maintained across its opposite faces. From Fourier's law $k = Q \cdot dx/(A \cdot dT)$.

SI unit: W/m K (or W/m °C). Example: copper ≈ 385 W/m K, steel ≈ 45–60 W/m K.

(Definition 1 M, unit 1 M)

f) Transmissivity and emissivity 2 M

i) Transmissivity (τ): The fraction of incident radiation energy which is transmitted through the body: $\tau = Q_t/Q$.

ii) Emissivity (ε): The ratio of the emissive power of a body to the emissive power of a black body at the same temperature: $\varepsilon = E/E_b$ $(0 \le \varepsilon \le 1)$.

(Each definition 1 M)

g) Cut-off ratio and clearance volume 2 M

i) Cut-off ratio (ρ): In the Diesel cycle, it is the ratio of the volume at the end of heat addition (fuel cut-off) to the volume at the beginning of heat addition: $\rho = V_3/V_2$.

ii) Clearance volume (V_c): The volume of the cylinder above the piston when the piston is at TDC (the combustion space).

(Each definition 1 M)

Q.2

a) Heat engine vs refrigerator 4 M

Heat engine	Refrigerator
Converts heat energy into mechanical work.	Uses mechanical work to transfer heat from a low temperature to a high temperature.
Receives heat from a high temperature source and rejects heat to a low temperature sink.	Extracts heat from a low temperature space and rejects heat to the high temperature atmosphere.
Work is the output.	Work is the input.

Performance is measured by thermal efficiency η = W/Q_1 (always < 1).	Performance is measured by COP = Q_2/W (may be > 1).
Works on the direct cycle (e.g. Otto, Diesel, Rankine).	Works on the reversed cycle (e.g. vapour compression cycle).
Examples: I.C. engine, steam turbine plant.	Examples: domestic refrigerator, water cooler.

(Any four points, 1 M each)

b) Boyle's law, Charles' law; characteristic gas equation 4 M

Boyle's law: At constant temperature, the volume of a given mass of gas varies inversely as its absolute pressure: $V \propto 1/p$, i.e. pV = constant (T constant).

Charles' law: At constant pressure, the volume of a given mass of gas varies directly as its absolute temperature: $V \propto T$, i.e. V/T = constant (p constant).

Derivation: Let a gas change from state 1 (p_1, V_1, T_1) to state 2 (p_2, V_2, T_2) in two steps:

Step (a) — constant temperature T_1 from p_1 to p_2 (Boyle's law): $p_1V_1 = p_2V' \Rightarrow V' = p_1V_1/p_2$ …… (1)

Step (b) — constant pressure p_2 from T_1 to T_2 (Charles' law): $V'/T_1 = V_2/T_2 \Rightarrow V' = V_2T_1/T_2$ …… (2)

Equating (1) and (2): $p_1V_1/p_2 = V_2T_1/T_2$ $\Rightarrow$ **$p_1V_1/T_1 = p_2V_2/T_2$ = constant**

For m kg of gas this constant = mR, where R is the characteristic gas constant. Hence the **characteristic gas equation**:

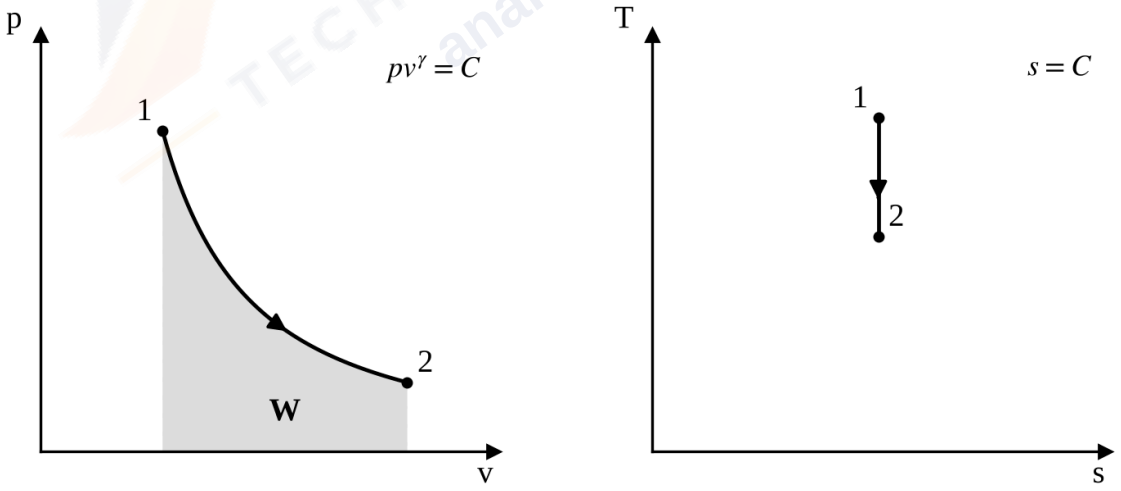
$$\mathbf{pV = mRT} \quad \text{(or } pv = RT \text{ per kg)}$$

R for air = 0.287 kJ/kg K; $R = \bar{R}/M$ where $\bar{R}$ = 8.314 kJ/kmol K.

(Laws 1 M, derivation 3 M)

c) Isentropic and polytropic processes 4 M

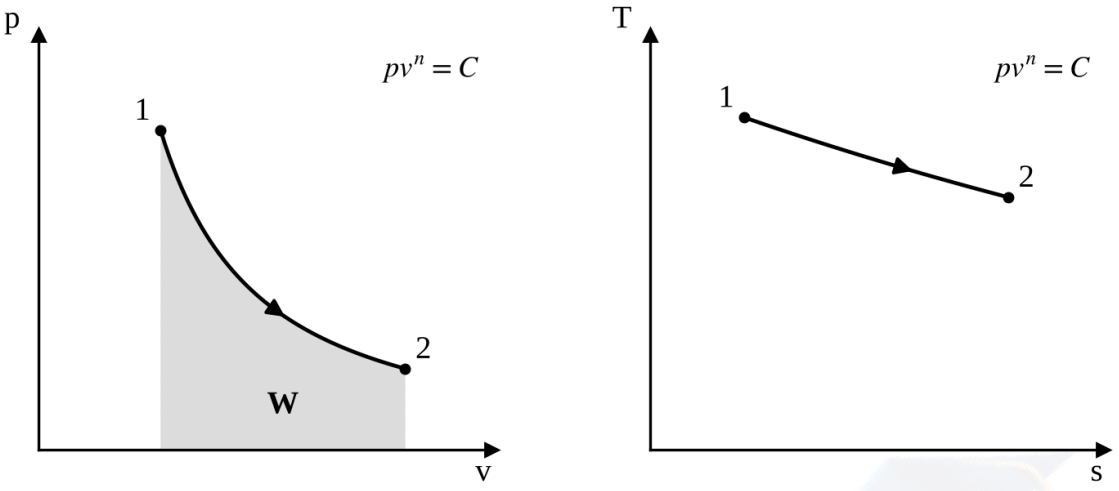
i) Isentropic (reversible adiabatic) process: No heat transfer ($Q = 0$) and entropy remains constant; law $pV^\gamma = C$. On the T–S diagram it is a vertical line. $W = (p_1V_1 - p_2V_2)/(\gamma - 1)$.



(a) P–V diagram (b) T–S diagram

Fig.: Isentropic expansion 1–2

ii) Polytropic process: Follows the law $pV^n = C$ ($1 < n < \gamma$ for usual expansion). Heat is transferred and entropy changes. $W = (p_1V_1 - p_2V_2)/(n - 1)$; $Q = W \times (\gamma - n)/(\gamma - 1)$.



(a) P–V diagram (b) T–S diagram

Fig.: Polytropic expansion 1–2 (n = 1.25, computed)

(Each process: P–V 1 M, T–S 1 M)

d) Numerical — constant pressure cooling 4 M

Given: p = 1.8 bar = 180 kN/m² (constant), m = 0.3 kg, $V_2 = V_1/2$, $T_1 = 120 + 273 = 393$ K, C_p = 1.0, C_v = 0.71 kJ/kg K

$R = C_p - C_v = 1.0 - 0.71 = 0.29$ kJ/kg K

Initial volume $V_1 = mRT_1 / p = (0.3 \times 0.29 \times 393) / 180 =$ **0.1899 m³**

$V_2 = V_1 / 2 =$ **0.0950 m³**

$T_2 = T_1 \times V_2/V_1 = 393 \times 0.0950/0.1899 =$ **196.50 K**

Work done:

$W = p\,(V_2 - V_1) = 180 \times (0.0950 - 0.1899) =$ **-17.10 kJ**

Change in internal energy:

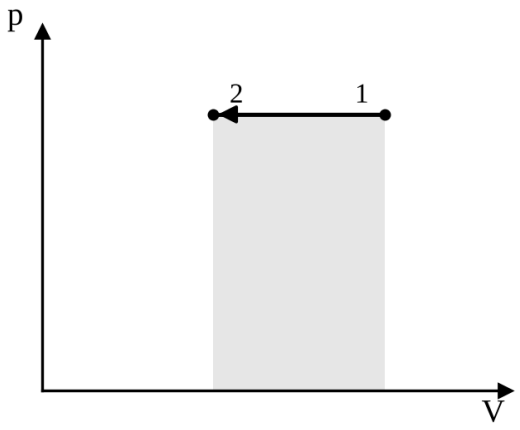
$\Delta U = m\,C_v\,(T_2 - T_1) = 0.3000 \times 0.71 \times (196.50 - 393) =$ **-41.85 kJ**

Heat transfer:

$Q = m\,C_p\,(T_2 - T_1) = 0.3000 \times 1.0 \times (196.50 - 393) =$ **-58.95 kJ**

Check (first law): $\Delta U + W = -41.85 + (-17.10) = -58.95$ kJ = Q ✓

Heat rejected by the gas = **58.95 kJ** (Q negative); work is done on the gas (W negative).



P–V sketch: compression at constant pressure

(V_1 1 M, W 1 M, ΔU 1 M, Q 1 M)

Q.3

a) Generation of steam on T–S diagram

4 M

When water is heated at constant pressure, the process on the T–S diagram follows the constant pressure line A–B–C–D:

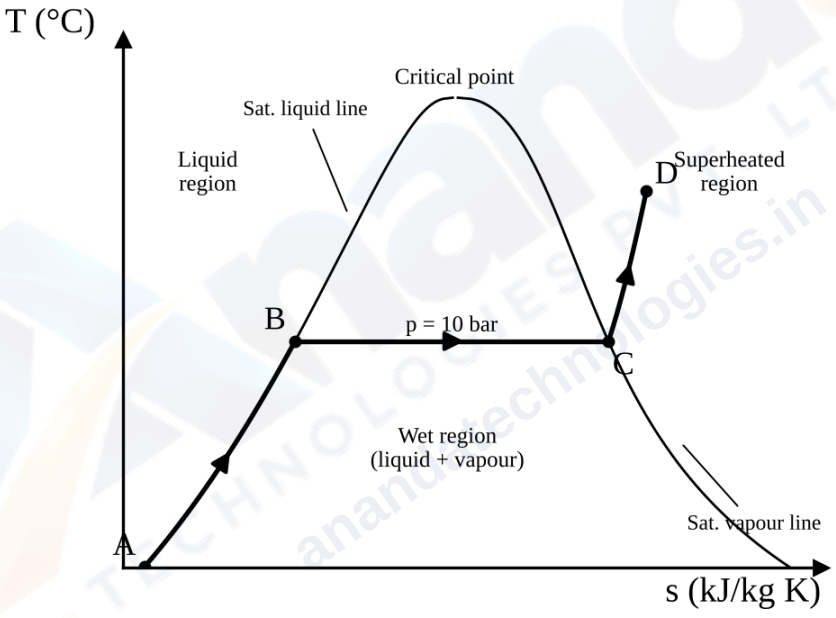


Fig.: Generation of steam at constant pressure on T–S diagram (10 bar, computed)

- **A–B:** Sensible heating of water from 0 °C to t_s; follows the saturated liquid line; entropy rises from 0 to s_f.
- **B–C:** Evaporation at constant temperature t_s (horizontal line inside the dome); entropy increases by $s_{fg} = h_{fg}/T_s$. Region inside the dome is wet steam.
- **C–D:** Superheating; temperature rises above t_s; $s_{sup} = s_g + C_{ps} \ln(T_{sup}/T_s)$.
- The saturated liquid line and saturated vapour line meet at the **critical point** (221.2 bar, 374.15 °C).

(Diagram 2 M, explanation 2 M)

b) Induced draught cooling tower

4 M

Function: A cooling tower cools the hot water coming from the condenser so that the same water can be reused; water is cooled mainly by **evaporation** of a small part of it into the air stream.

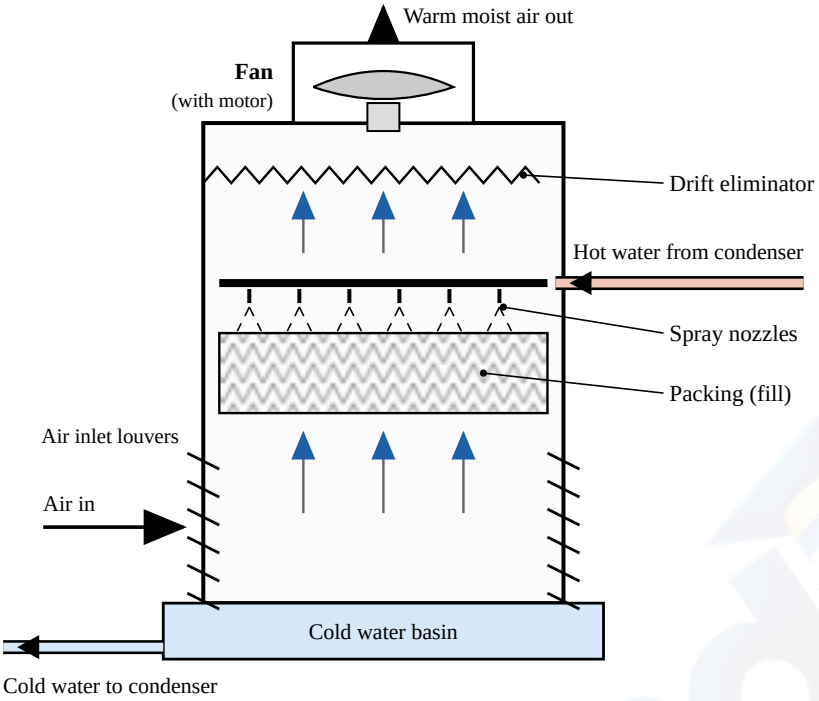


Fig.: Induced draught cooling tower

Construction: A rectangular tower with a fan and motor at the **top**, air inlet louvers on the sides near the bottom, spray nozzles, packing, drift eliminator and cold water basin.

Working: The fan at the top **sucks** (induces) air through the louvers at the base; air moves upward through the packing against the falling water sprays. Evaporation of a small part of the water cools the rest, which collects in the basin. Warm moist air is thrown out at a high velocity from the top, so recirculation of hot air is avoided.

Features: uniform air distribution, less recirculation, smaller than natural draught tower; fan handles hot moist air (more corrosion) and needs power.

(Sketch 2 M, working 2 M)

c) Classification of condensers; surface condenser

4 M

Function of condenser: To condense the exhaust steam from the turbine at a pressure below atmospheric (vacuum), so that the work output increases, and to recover the pure condensate as boiler feed water.

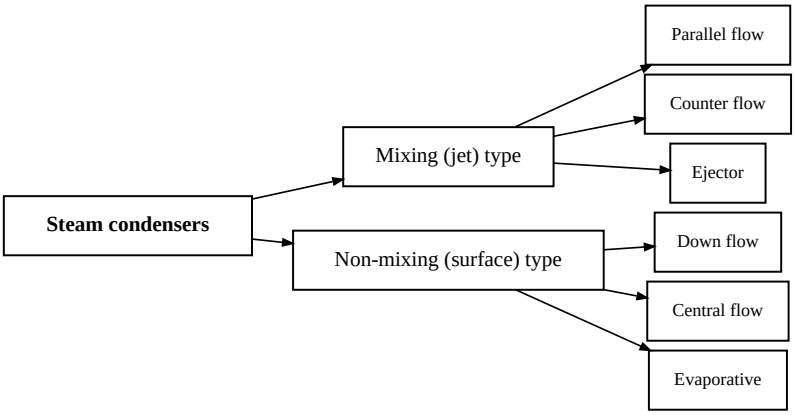


Fig.: Classification of steam condensers

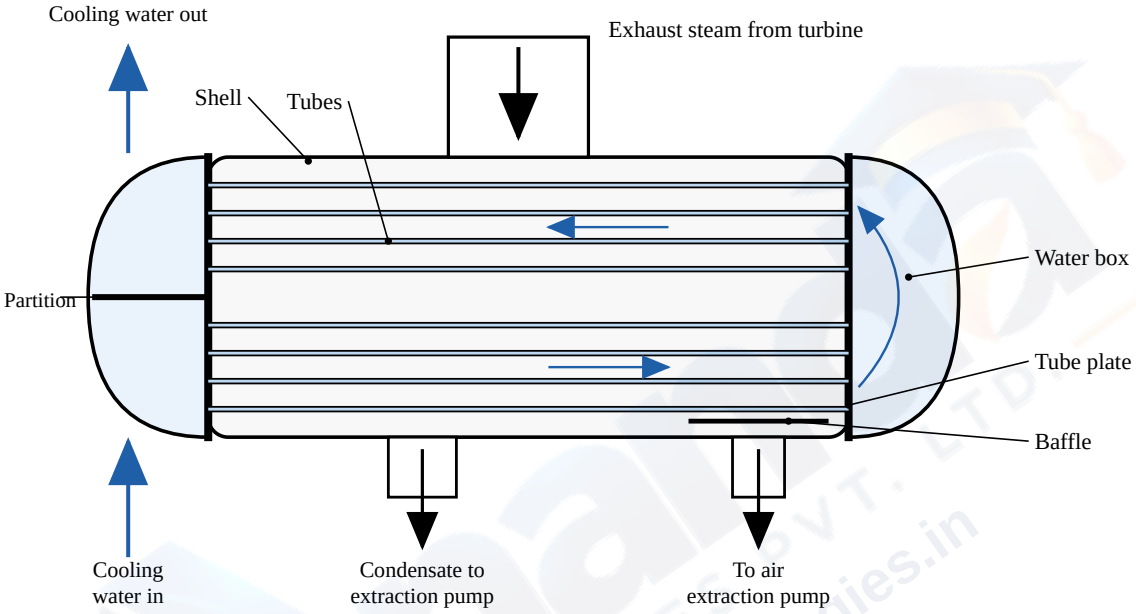


Fig.: Two-pass surface condenser

Construction: It consists of a cast-iron or steel cylindrical **shell** closed at both ends by **tube plates** and **water boxes**. A large number of brass/cupro-nickel **tubes** are fixed between the tube plates. The left water box is divided by a **partition plate**, giving two passes for cooling water. Exhaust steam inlet is at the top; condensate outlet and air extraction outlet are at the bottom.

Working: Cooling water enters the lower half of the water box, flows through the lower tubes, returns through the upper tubes and leaves from the upper half. Exhaust steam from the turbine enters at the top and flows over the outer surface of the cold tubes; it gives its latent heat to the water and condenses. Steam and cooling water do **not mix**. The condensate is removed by the extraction pump and sent to the hot well; the air is removed separately by the air extraction pump from the coolest part (shielded by a baffle).

(Classification 1 M, sketch 2 M, working 1 M)

d) Regenerative feed heating and bleeding 4 M

Regenerative feed heating: It is the process of heating the feed water, before it enters the boiler, by steam **bled (extracted)** from the turbine at one or more intermediate stages. **Bleeding** is the process of draining a part of the steam from the turbine at a selected point after it has done some work, and using it to heat the feed water in a feed water heater.

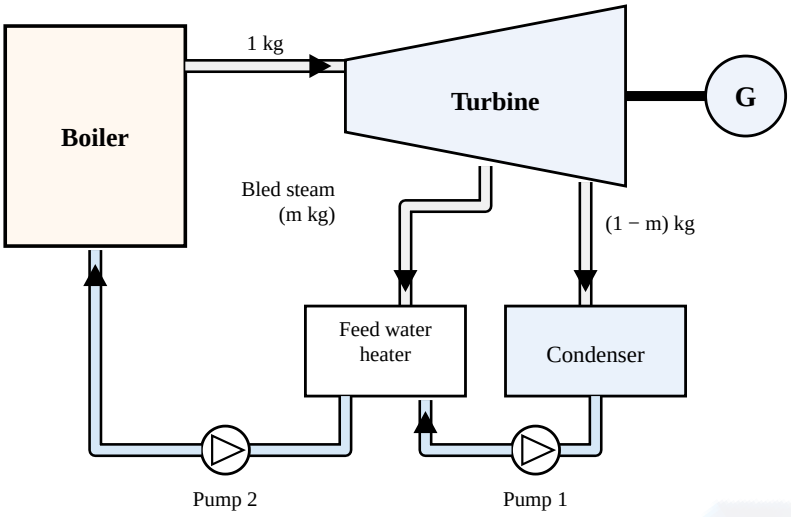


Fig.: Regenerative feed heating with one bleed point (open feed water heater)

Working: Out of 1 kg of steam entering the turbine, m kg is bled at an intermediate pressure and sent to the feed water heater; the remaining (1 − m) kg expands fully and goes to the condenser. The condensate pumped from the condenser is heated by the bled steam, so feed water enters the boiler at a higher temperature.

Advantages: (i) mean temperature of heat addition increases, so thermal efficiency of the cycle increases; (ii) less heat is rejected in the condenser, so a smaller condenser is required; (iii) thermal stresses in the boiler are reduced; (iv) dissolved air/gases are removed in an open heater.

(Concept 1 M, sketch 2 M, advantages 1 M)

Q.4

a) Natural vs forced convection

4 M

Natural (free) convection	Forced convection
Fluid motion is caused by density differences due to temperature variation (buoyancy).	Fluid motion is caused by external means such as fan, blower or pump.
Velocity of fluid is low.	Velocity of fluid is high.
Heat transfer coefficient is low, so rate of heat transfer is less.	Heat transfer coefficient is high, so rate of heat transfer is more.
No external power is required.	External power is required to drive fan/pump.
Example: cooling of hot tea in a cup, room heater, transformer cooling fins.	Example: car radiator with fan, air-cooled condenser, hair dryer.

(Any four points, 1 M each)

b) Numerical — heat loss through furnace wall

4 M

Given: Fire brick: x = 225 mm = 0.225 m, k = 1.4 W/m K, Insulating brick: x = 115 mm = 0.115 m, k = 0.2 W/m K; T_1 = 1000 °C, T_3 = 80 °C; per unit area (A = 1 m²)

Thermal resistance of each layer R = x / (k A):

R_1 (Fire brick) = 0.225 / (1.4 × 1) = **0.16071 K/W**

R_2 (Insulating brick) = 0.115 / (0.2 × 1) = **0.57500 K/W**

Total resistance ΣR = 0.16071 + 0.57500 = **0.73571 K/W**

Rate of heat flow:

$Q = (T_1 - T_3) / \Sigma R = (1000 - (80)) / 0.73571 =$ **1,250.49 W**

Interface temperatures (same Q flows through each layer):

$T_2 = T_1 - Q\,R_1 = 1{,}000.00 - 1{,}250.49 \times 0.16071 =$ **799.03 °C**

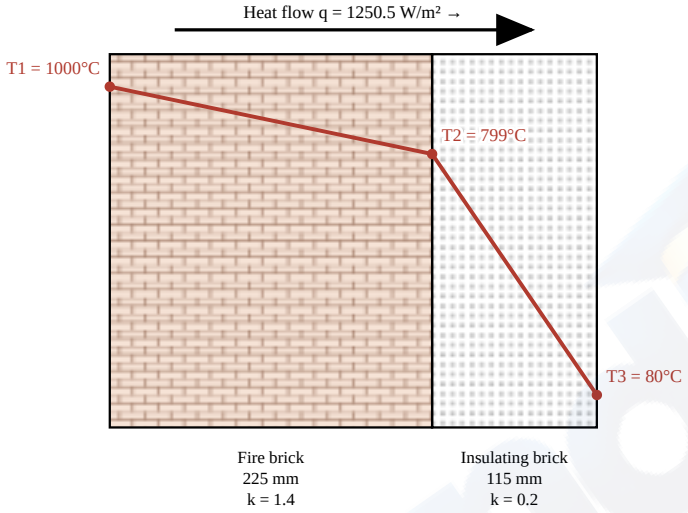


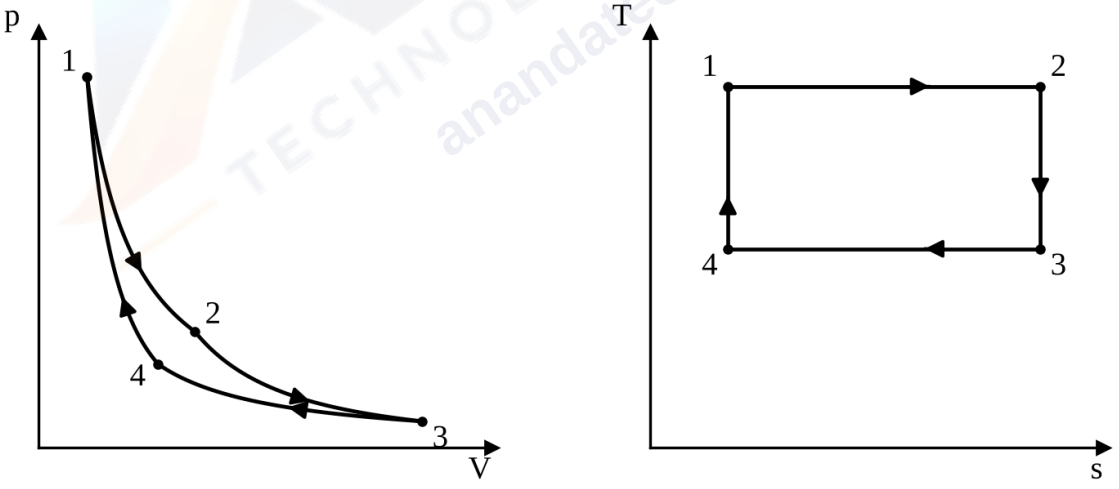
Fig.: Temperature profile through the furnace wall (computed)

(Resistances 1 M, q 2 M, interface temperature 1 M)

c) Carnot cycle and its limitations

4 M

The Carnot cycle is an ideal reversible cycle consisting of two reversible isothermal and two reversible adiabatic (isentropic) processes.



(a) P–V diagram (b) T–S diagram

Fig.: Carnot cycle on P–V and T–S diagrams (computed for an ideal gas, γ = 5/3, T_1/T_2 = 1.8)

1. 1–2: Isothermal expansion at T_1 — heat Q_1 supplied from source.
2. 2–3: Isentropic expansion — temperature falls from T_1 to T_2.

3. 3–4: Isothermal compression at T_2 — heat Q_2 rejected to sink.
4. 4–1: Isentropic compression — temperature rises from T_2 to T_1.

$\eta_{Carnot} = 1 - T_2/T_1$ (maximum possible efficiency between T_1 and T_2).

Limitations (why it is not practical):

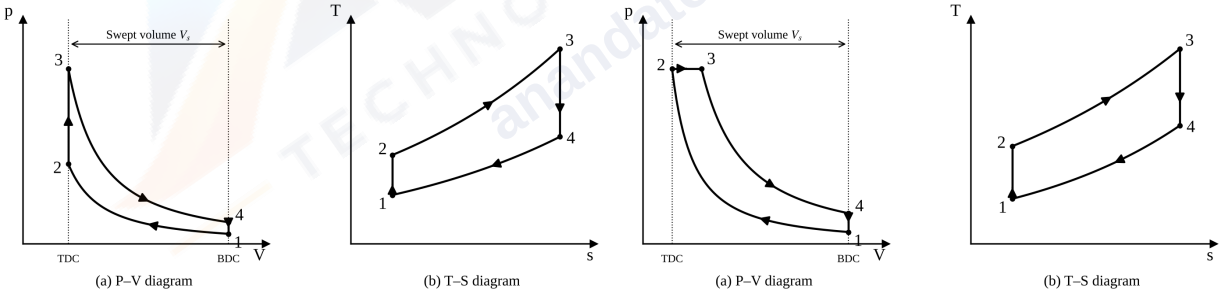
- Isothermal processes need very slow piston speed, while isentropic processes need very fast speed — not possible in the same stroke.
- Perfect insulation for adiabatic processes and frictionless (reversible) processes cannot be achieved.
- The net work (area of P–V diagram) is very small compared with the large cylinder volume and pressure — very large engine is needed.
- Heat transfer at constant temperature is difficult; there are always losses due to friction and heat leakage.

(Diagrams 2 M, limitations 2 M)

d) Otto cycle vs Diesel cycle

4 M

Basis	Otto cycle	Diesel cycle
P–V and T–S	Two isentropic + two constant volume processes (see fig.)	Two isentropic + one constant pressure + one constant volume process
Heat addition	At constant volume	At constant pressure
Compression ratio	Low: 6 to 10	High: 14 to 22
Efficiency (same r)	Higher	Lower
Application	Petrol (S.I.) engines — cars, scooters	Diesel (C.I.) engines — trucks, tractors, generators



Otto *Diesel*

(Each point 1 M)

e) Numerical — adiabatic compression of air

4 M

Given: m = 0.2 kg, p_1 = 1 bar, T_1 = 300 K, p_2 = 8 bar, γ = 1.4, R = 0.287 kJ/kg K, C_v = 0.718 kJ/kg K

i) Final temperature: $T_2/T_1 = (p_2/p_1)^{(\gamma-1)/\gamma}$

$T_2 = 300 \times (8/1)^{0.2857} =$ **543.43 K**

t_2 = **270.43 °C**

ii) Volumes (pV = mRT):

$V_1 = mRT_1/p_1 = 0.2 \times 0.287 \times 300 / 100 =$ **0.17220 m³**

$V_2 = mRT_2/p_2 = 0.2 \times 0.287 \times 543.43 / 800 =$ **0.03899 m³**

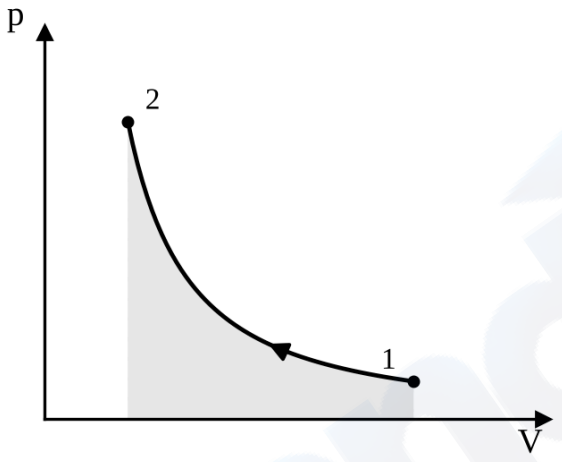
iii) Work done:

$W = mR(T_1 - T_2)/(\gamma - 1) = 0.2 \times 0.287 \times (300 - 543.43) / 0.4 =$ **-34.933 kJ**

(negative: work is done on the air)

iv) Change in internal energy: (Q = 0 for adiabatic process, so ΔU = −W)

$\Delta U = m\, C_v(T_2 - T_1) = 0.2 \times 0.718 \times (543.43 - 300) =$ **34.957 kJ**



P–V sketch (computed curve $pV^{1.4} = C$)

(T_2 1 M, volumes 1 M, W 1 M, ΔU 1 M)

Q.5

a) SFEE — application to steam turbine and condenser 6 M

Consider an open system (control volume) through which m kg/s of fluid flows steadily from section 1 to section 2, with heat Q supplied and shaft work W done by the system.

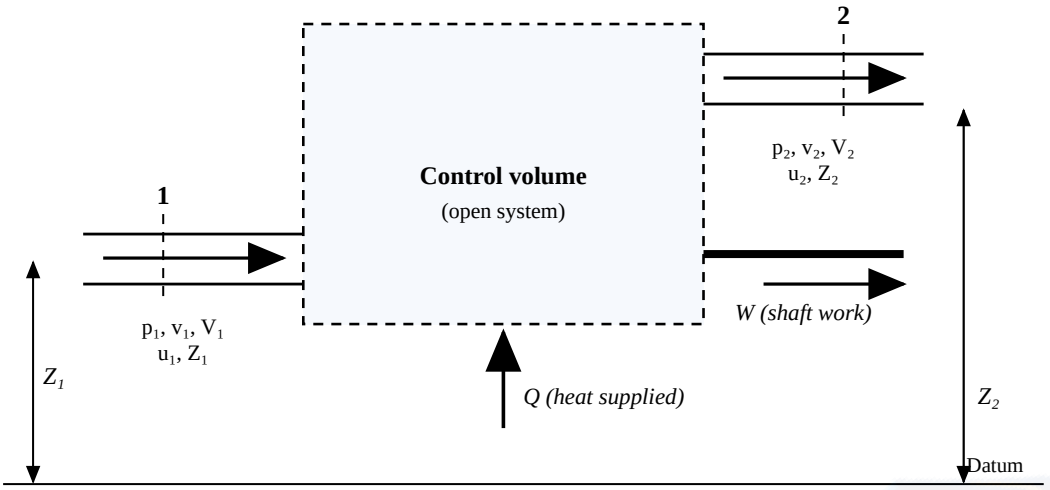


Fig.: Steady flow system (control volume)

Steady flow energy equation (per kg of fluid):

$$\mathbf{u_1 + p_1v_1 + V_1^2/2 + gZ_1 + q = u_2 + p_2v_2 + V_2^2/2 + gZ_2 + w}$$

Since h = u + pv, $\mathbf{h_1 + V_1^2/2 + gZ_1 + q = h_2 + V_2^2/2 + gZ_2 + w}$ (all terms in J/kg)

Term	Meaning
u	Specific internal energy (energy stored due to molecular motion)
pv	Flow work — work needed to push unit mass across the boundary
h = u + pv	Specific enthalpy
$V^2/2$	Kinetic energy per kg (V = velocity, m/s)
gZ	Potential energy per kg (Z = height above datum)
q	Heat supplied per kg (+ve when supplied)
w	Shaft work done per kg by the system (+ve when done by system)

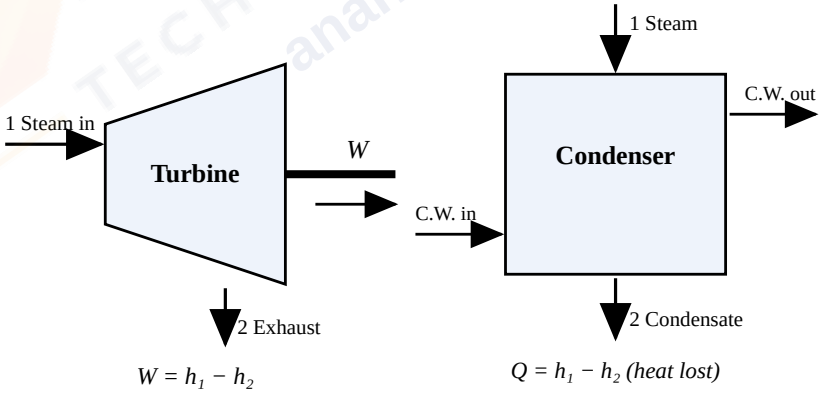


Fig.: Application of SFEE

Steam turbine: Expansion is adiabatic (q = 0, well insulated); ΔK.E. and ΔP.E. are negligible. SFEE becomes

$$\mathbf{w = h_1 - h_2}$$

i.e. the work output of the turbine is equal to the **decrease in enthalpy** of steam.

Condenser: No work (w = 0); ΔK.E., ΔP.E. negligible. Heat is removed by cooling water (q is negative). SFEE becomes

$$-q = h_1 - h_2 \quad \text{i.e. heat lost by steam} = h_1 - h_2$$

This heat is gained by the cooling water: $m_s(h_1 - h_2) = m_w\, c_{pw}\, (t_{wo} - t_{wi})$.

(SFEE 2 M, significance of terms 2 M, application 1 M each)

b) Numerical — wet steam at 9 bar 6 M

From steam table at 9 bar: $t_s = 175.4$ °C, $v_g = 0.2149$ m³/kg, $h_f = 742.7$, $h_{fg} = 2030.3$ kJ/kg

Specific volume v = V/m = 0.45/2.5 = **0.1800 m³/kg**

$v < v_g$, hence the steam is wet.

i) Dryness fraction:

$x = v / v_g = 0.1800 / 0.2149 =$ **0.8376**

ii) Total enthalpy:

$h = h_f + x\, h_{fg} = 742.7 + 0.8376 \times 2030.3 =$ **2,443.28 kJ/kg**

$H = m\, h = 2.5 \times 2,443.28 =$ **6,108.2 kJ**

iii) Internal energy: $u = h - p\, v$ (p in kN/m²)

$u = 2,443.28 - 900 \times 0.1800 =$ **2,281.28 kJ/kg**

$U = m\, u = 2.5 \times 2,281.28 =$ **5,703.2 kJ**

iv) Heat to make it dry saturated at constant pressure: only the remaining latent heat $(1 - x)\, h_{fg}$ is needed.

$Q = m\,(1 - x)\, h_{fg} = 2.5 \times (1 - 0.8376) \times 2030.3 =$ **824.3 kJ**

(x 1 M, enthalpy 2 M, internal energy 2 M, heat 1 M)

c) Simple impulse turbine with pressure–velocity variation 6 M

Principle: In an impulse turbine, the whole pressure drop of steam takes place in the **nozzle**. The high-velocity steam jet strikes the curved **moving blades**; the change in direction (momentum) of the jet produces an impulsive force which rotates the rotor. Pressure of steam remains constant while passing over the moving blades.

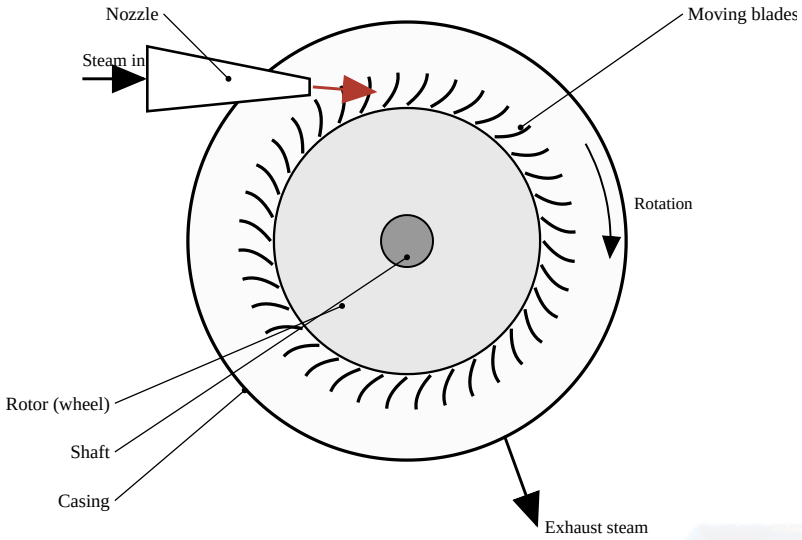
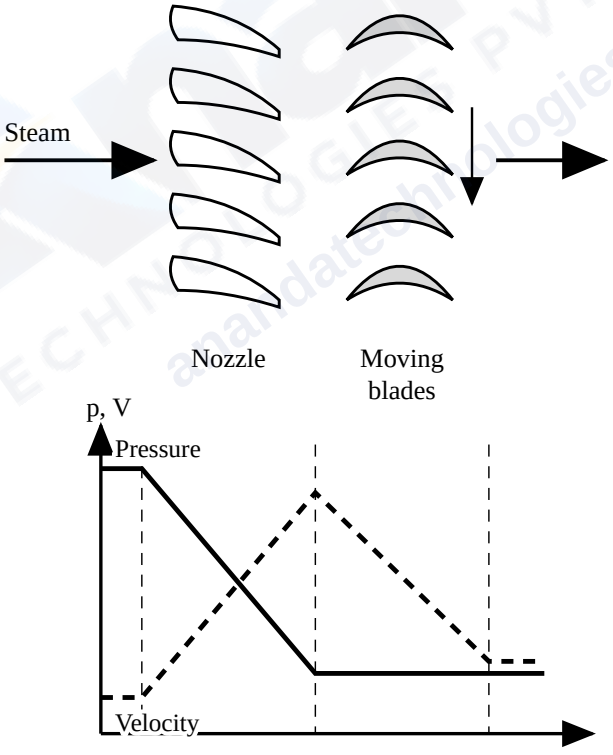


Fig.: Simple impulse (De Laval) turbine

Construction: Nozzle(s), rotor (wheel) mounted on shaft with symmetrical moving blades fixed on its rim, and the casing.

Working: Steam expands in the nozzle from boiler pressure to condenser pressure, so its velocity becomes very high. The jet glides over the moving blades and its velocity falls; the kinetic energy is converted into mechanical work on the shaft. Steam then leaves at low velocity to the exhaust (condenser).



Pressure and velocity variation in a simple impulse turbine

(Sketch 2 M, working 2 M, p–V variation 2 M)

Q.6

a) IBR definition and Lamont boiler 6 M

Boiler (as per Indian Boilers Act 1923 / IBR): A boiler is a closed vessel having a capacity exceeding 22.75 litres (5 gallons) used expressly for generating steam under pressure, including any mounting or fitting attached to it which is wholly or partly under pressure when steam is shut off.

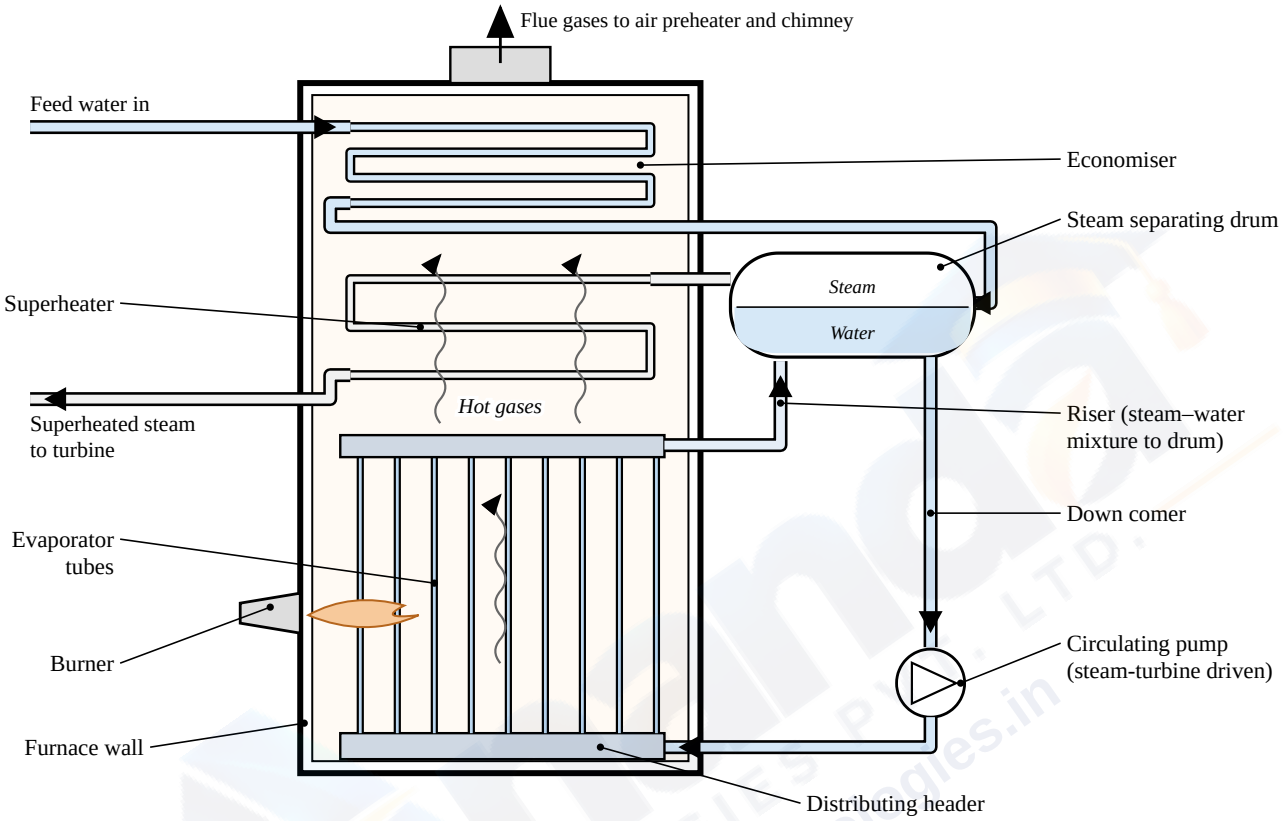


Fig.: Lamont boiler (forced circulation, water tube, high pressure)

Construction: Lamont boiler is a forced-circulation, externally fired, water tube high pressure boiler. Main parts: economiser, steam separating drum (outside the furnace), steam-turbine driven centrifugal circulating pump, distributing header, evaporator (water wall) tubes, convective superheater, air preheater and burner.

Working:

1. Feed water is passed through the economiser, where it is preheated by flue gases, and is delivered to the steam separating drum.
2. Water from the drum passes through the down comer to the **circulating pump**, which circulates 8 to 10 times the mass of steam evaporated, through the distributing header into the evaporator tubes.
3. In the evaporator tubes (placed in the furnace walls) water is partly converted into steam; the steam–water mixture returns to the drum.
4. In the drum, steam is separated from water. The steam goes to the **superheater**, gets superheated and is supplied to the turbine. The unevaporated water recirculates.

5. Flue gases from the furnace pass over the superheater, economiser and air preheater and go to the chimney.

Features: Typical capacity about 45–50 t/h of superheated steam at about 130 bar and 500 °C. Forced circulation prevents overheating of tubes and allows small-diameter tubes.

(IBR definition 1 M, sketch 2 M, construction and working 3 M)

b) Classification of heat exchangers; plate type heat exchanger 6 M

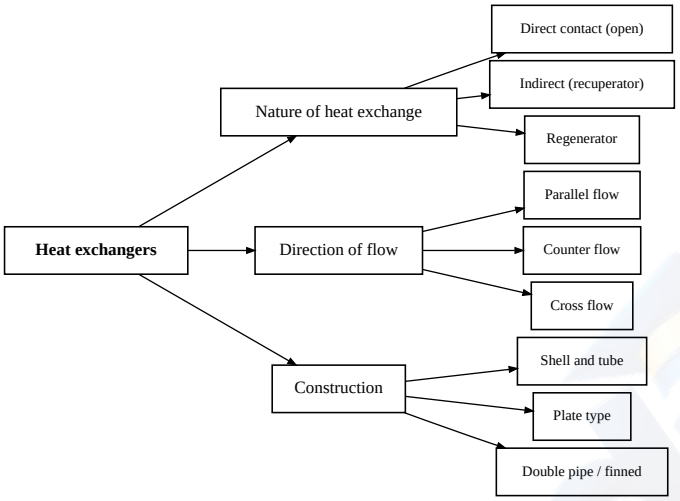


Fig.: Classification of heat exchangers

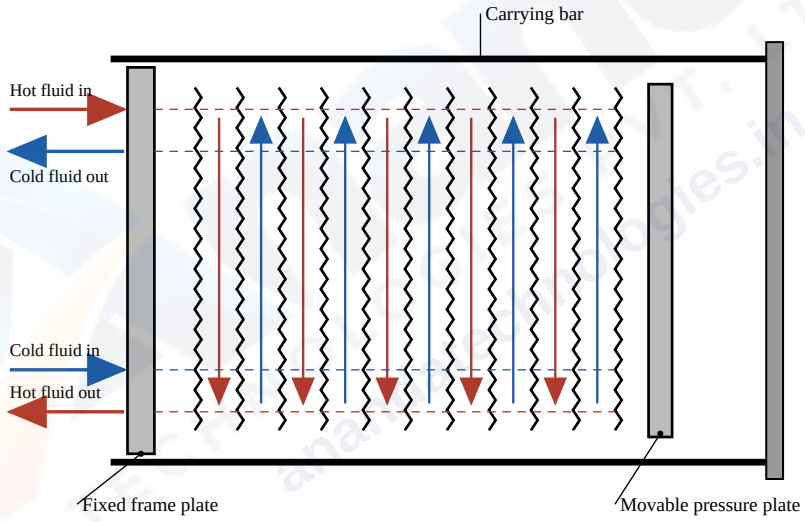


Fig.: Plate type heat exchanger (cold and hot fluids in alternate channels)

Construction: A number of thin corrugated metal (stainless steel) plates with gaskets are clamped between a fixed frame plate and a movable pressure plate by tightening bolts and hung on a carrying bar. Each plate has four corner ports; the gaskets direct the fluids.

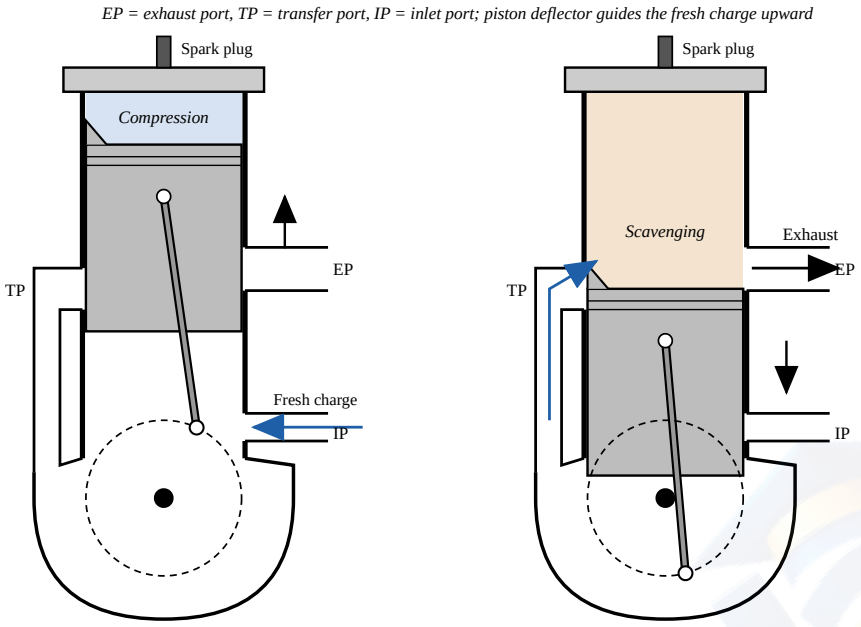
Working: The hot and cold fluids enter through the ports of the frame plate and flow in **alternate channels** between the plates (usually in counter flow). Heat passes from the hot fluid to the cold fluid through the thin plates. Corrugations create turbulence and large surface area, giving a high heat transfer coefficient.

Applications: dairy (milk pasteurisation), food and beverage, pharmaceutical, HVAC chillers, marine and oil cooling. **Advantages:** compact, high efficiency, easy cleaning and capacity can be changed by adding plates; **limitation:** not suitable for very high pressure/temperature.

(Classification 1 M, sketch 2 M, working 2 M, applications 1 M)

c) Two stroke petrol engine

6 M



(a) Piston moving up (near TDC)
Compression above piston; fresh charge drawn into crankcase through inlet port

(b) Piston near BDC
Exhaust port open: burnt gases leave; transfer port open: charge enters cylinder

Fig.: Working of a two stroke petrol (S.I.) engine — crankcase scavenged, three port

Construction: Valves are replaced by three ports in the cylinder wall — **inlet port** (to crankcase), **transfer port** (crankcase to cylinder) and **exhaust port** — opened and closed by the piston itself. The crankcase is air-tight; the piston top has a **deflector**. A spark plug is fitted in the cylinder head.

Working: The cycle is completed in two strokes (one revolution):

1. **Upward stroke (BDC → TDC):** Piston closes the transfer and exhaust ports and compresses the charge above it. At the same time, a partial vacuum is created in the crankcase and fresh air–petrol mixture enters the crankcase through the uncovered inlet port. Near TDC the spark plug ignites the compressed charge.
2. **Downward stroke (TDC → BDC):** The burnt gases expand and push the piston down — power is obtained. The piston first uncovers the exhaust port and burnt gases escape; then it uncovers the transfer port and the slightly compressed charge from the crankcase enters the cylinder. The deflector directs the fresh charge upward, which helps to push out the remaining exhaust gases (**scavenging**).

Thus one power stroke is obtained in every revolution of the crankshaft.

(Sketch 3 M, working 3 M)

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