

Thermal Engineering (313310)

MSBTE K-Scheme · Model Question Paper — Set B · 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) Zeroth law of thermodynamics

2 M

Zeroth law of thermodynamics: When two bodies are each in thermal equilibrium with a third body, then they are also in thermal equilibrium with each other.

i.e. if $T_A = T_C$ and $T_B = T_C$, then $T_A = T_B$. This law is the basis of temperature measurement — body C acts as a **thermometer**.

(Statement 2 M)

b) Sensible heat and latent heat

2 M

i) Sensible heat (h_f): The amount of heat required to raise the temperature of 1 kg of water from 0 °C to the saturation temperature (boiling point) at a given constant pressure. It causes a rise in temperature which can be sensed by a thermometer.

ii) Latent heat (h_{fg}): The amount of heat required to convert 1 kg of water at saturation temperature into 1 kg of dry saturated steam at the same temperature and pressure. Temperature remains constant (only phase changes). At 1.01325 bar, $h_{fg} \approx 2257$ kJ/kg.

(Each definition 1 M)

c) Assumptions for ideal gas

2 M

- The gas molecules are perfectly elastic spheres and their volume is negligible compared with the volume of the gas.
- There is no force of attraction or repulsion between the molecules.
- The gas obeys the characteristic equation $pV = mRT$ at all temperatures and pressures.
- Specific heats C_p and C_v remain constant.

(Any two, 1 M each)

d) Dalton's law and condenser relation

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.

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

In a condenser: $p_c = p_s + p_a$, where p_c = condenser pressure, p_s = partial pressure of steam, p_a = partial pressure of air.

(Statement 1 M, condenser relation 1 M)

e) Classification of boilers (two bases)

2 M

Basis	Types with examples
Relative position of water and hot gases	Fire tube boiler (hot gases inside tubes) — Cochran, Lancashire, locomotive; Water tube boiler (water inside tubes) — Babcock & Wilcox, Lamont
Position of furnace	Internally fired (furnace inside shell) — Cochran, Lancashire; Externally fired (furnace outside) — Babcock & Wilcox

(Each basis 1 M)

f) Applications of heat exchangers

2 M

1. Condensers and boilers (economiser, superheater, air preheater) in thermal power plants.
2. Radiators of automobiles (engine cooling).
3. Evaporators and condensers of refrigerators and air conditioners.
4. Oil coolers, intercoolers and after-coolers of compressors.
5. Milk pasteurisers and food processing; chemical and petroleum industries.

(Any four, ½ M each)

g) Mean effective pressure

2 M

Mean effective pressure (p_m): It is the hypothetical constant (average) pressure which, if acting on the piston during the whole power (expansion) stroke, would produce the same work as is actually produced in one cycle.

$p_m = \text{work done per cycle} / \text{swept volume} = (\text{net area of indicator diagram} \times \text{spring constant}) / \text{length of diagram}.$

(Definition 2 M)

Q.2

a) Proof: $\text{COP(HP)} = \text{COP(R)} + 1$

4 M

Consider a heat pump and a refrigerator working between the same temperatures T_1 (hot body) and T_2 (cold body). Heat Q_2 is taken from the cold body, work W is supplied and heat Q_1 is rejected to the hot body.

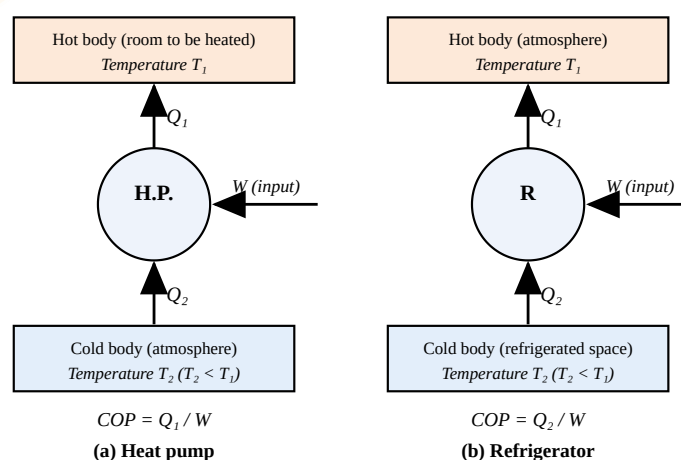


Fig.: Heat pump and refrigerator

By the first law for the cycle (energy balance): $Q_1 = Q_2 + W \dots\dots(1)$

$$\text{COP}_{\text{HP}} = Q_1/W = (Q_2 + W)/W = Q_2/W + W/W$$

But $Q_2/W = \text{COP}_R$, therefore

$$(\text{COP})_{\text{HP}} = (\text{COP})_R + 1$$

Hence the COP of a heat pump is always greater than that of a refrigerator by one, when both work between the same temperature limits.

(Diagram 1 M, energy balance 1 M, proof 2 M)

b) Thermodynamic system and its classification

4 M

System: A thermodynamic system is a definite quantity of matter or a prescribed region in space upon which attention is focused for analysis. Everything outside the system is the **surroundings**, and the real or imaginary surface separating them is the **boundary**.

Classification:

1. **Open system:** Both mass and energy (heat and work) cross the boundary. Example: steam turbine, air compressor, boiler, I.C. engine (during suction/exhaust).
2. **Closed system:** Only energy crosses the boundary; mass remains fixed. Example: gas compressed in a cylinder with closed valves, pressure cooker (without vent).
3. **Isolated system:** Neither mass nor energy crosses the boundary. Example: thermos flask (ideal), the universe.

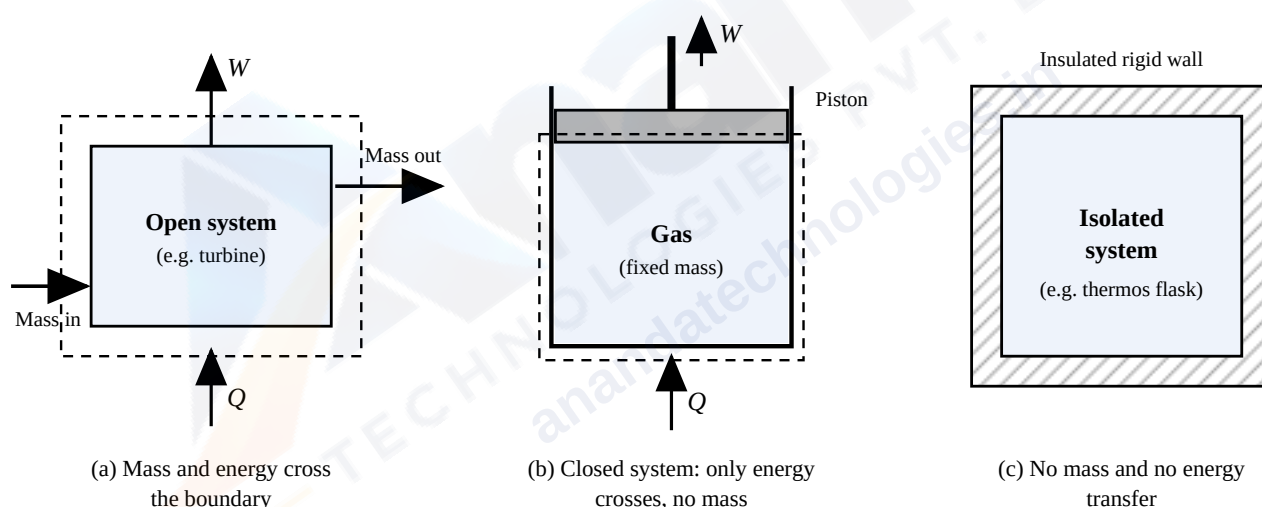


Fig.: Types of thermodynamic systems

(Definition 1 M, classification with examples 3 M)

c) Isobaric and isochoric processes

4 M

i) Isobaric (constant pressure) process: $p = C$, $V/T = C$ (Charles' law). P–V: horizontal line; T–S: curve rising more gently than the constant-volume line. $W = p(V_2 - V_1)$, $Q = m C_p(T_2 - T_1)$.

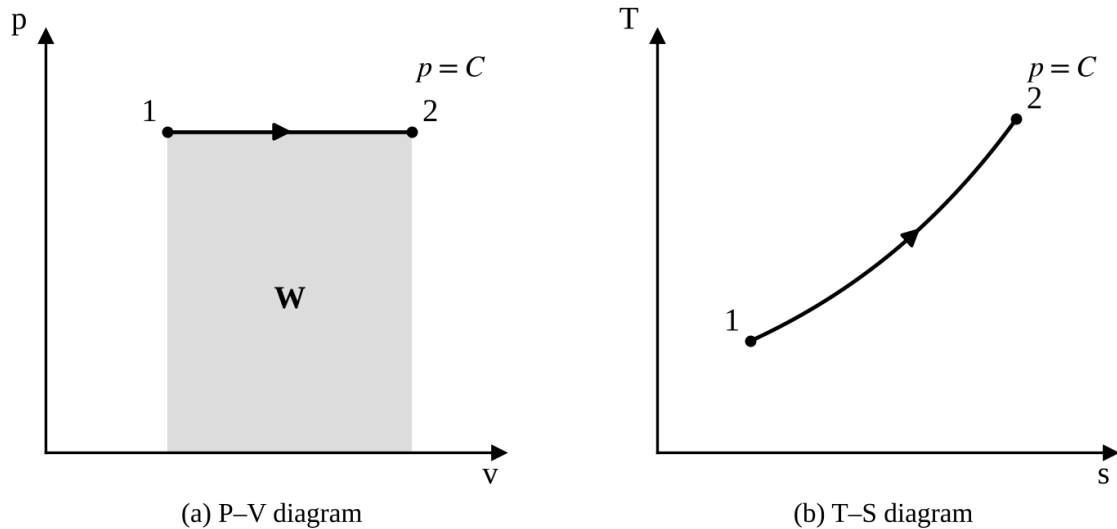


Fig.: Constant pressure heating 1-2

ii) Isochoric (constant volume) process: $V = C$, $p/T = C$. P-V: vertical line; T-S: steeper curve than constant-pressure line. $W = 0$, $Q = \Delta U = m C_v(T_2 - T_1)$.

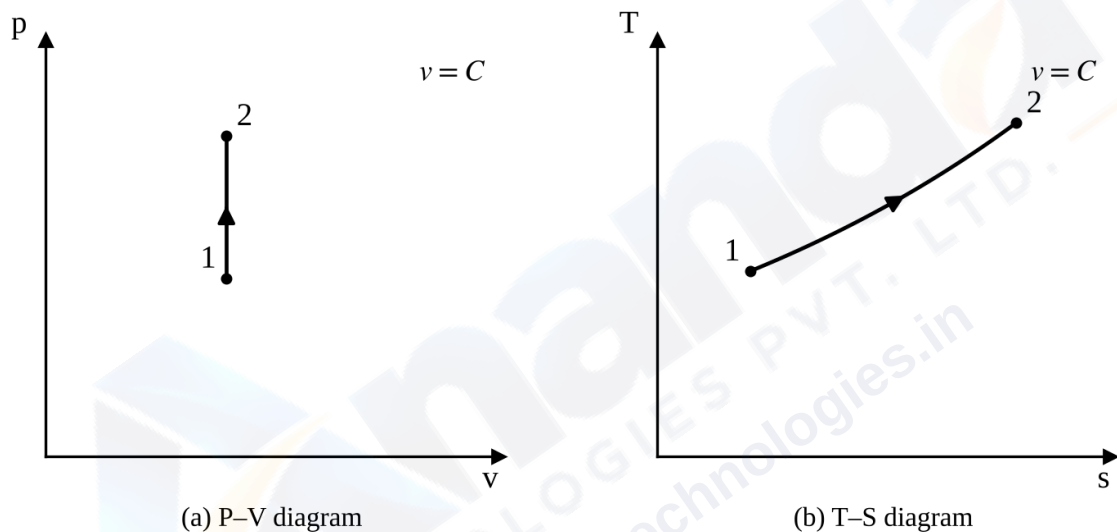
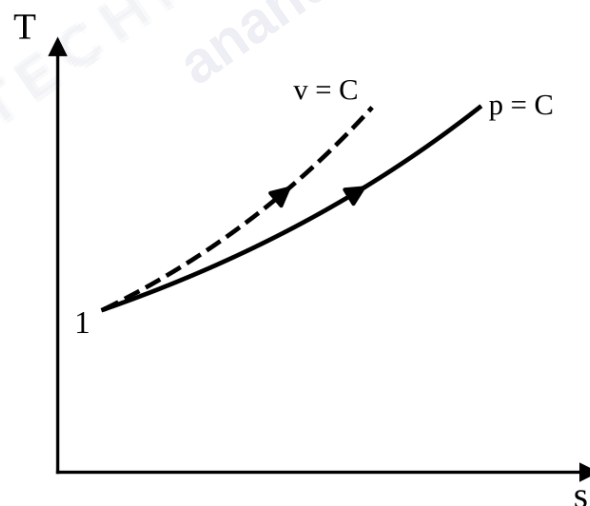


Fig.: Constant volume heating 1-2



Both from the same state on one T-S diagram: the constant-volume line is steeper (slope $T/C_v > T/C_p$)

(Each process: P-V 1 M, T-S 1 M)

d) Numerical — constant pressure expansion

4 M

Given: $p = 4 \text{ bar} = 400 \text{ kN/m}^2$ (constant), $V_1 = 0.2 \text{ m}^3$, $V_2 = 0.45 \text{ m}^3$, $T_1 = 150 + 273 = 423 \text{ K}$, $C_p = 1.005$, $C_v = 0.718 \text{ kJ/kg K}$

$$R = C_p - C_v = 1.005 - 0.718 = 0.287 \text{ kJ/kg K}$$

$$\text{Mass } m = pV_1 / (R T_1) = (400 \times 0.2) / (0.287 \times 423) = \mathbf{0.6590 \text{ kg}}$$

$$T_2 = T_1 \times V_2/V_1 = 423 \times 0.45/0.2 = \mathbf{951.75 \text{ K}}$$

Work done:

$$W = p (V_2 - V_1) = 400 \times (0.45 - 0.2) = \mathbf{100.00 \text{ kJ}}$$

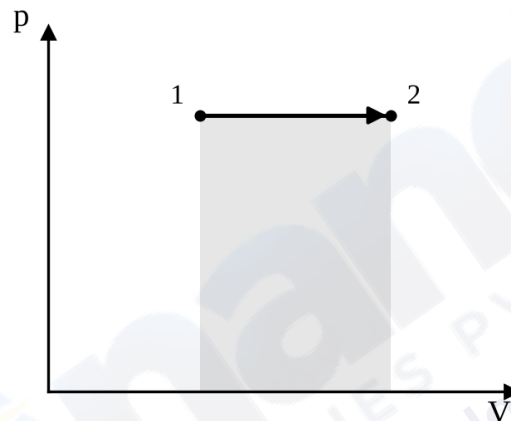
Change in internal energy:

$$\Delta U = m C_v (T_2 - T_1) = 0.6590 \times 0.718 \times (951.75 - 423) = \mathbf{250.17 \text{ kJ}}$$

Heat transfer:

$$Q = m C_p (T_2 - T_1) = 0.6590 \times 1.005 \times (951.75 - 423) = \mathbf{350.17 \text{ kJ}}$$

$$\text{Check (first law): } \Delta U + W = 250.17 + (100.00) = 350.17 \text{ kJ} = Q \checkmark$$



P-V sketch: $W = \text{shaded area}$

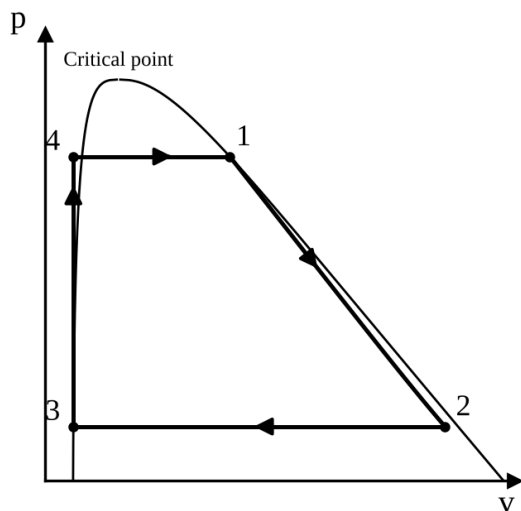
(W 1 M, ΔU 1½ M, Q 1½ M)

Q.3

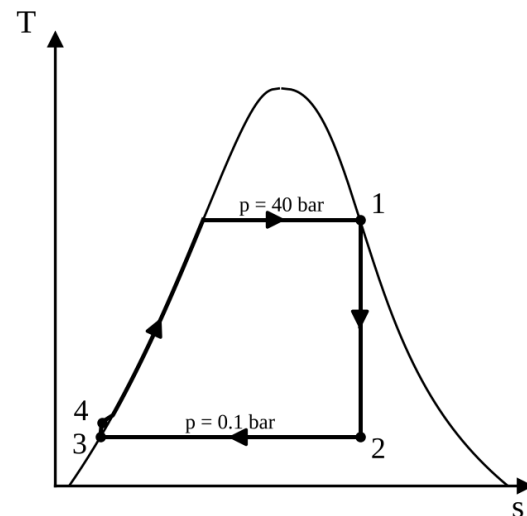
a) Rankine cycle on P-V and T-S

4 M

The Rankine cycle is the ideal cycle for a steam power plant. Steam is **dry saturated** at turbine inlet (state 1).



(a) P-V diagram (log scales)



(b) T-S diagram

Fig.: Simple Rankine cycle with dry saturated steam at turbine inlet (40 bar $\rightarrow$ 0.1 bar, computed with IAPWS-IF97)

1. **1–2 Isentropic expansion** in the turbine — work is obtained; steam becomes wet (here $x_2 \approx 0.72$).
2. **2–3 Constant pressure (and temperature) condensation** in the condenser — heat rejected to cooling water.
3. **3–4 Isentropic (adiabatic) pumping** of water by the feed pump from condenser pressure to boiler pressure (small work; exaggerated on T–S).
4. **4–1 Constant pressure heat addition** in the boiler — water is heated to saturation and evaporated into dry saturated steam.

(P–V 1½ M, T–S 1½ M, processes 1 M)

b) Layout of steam power plant

4 M

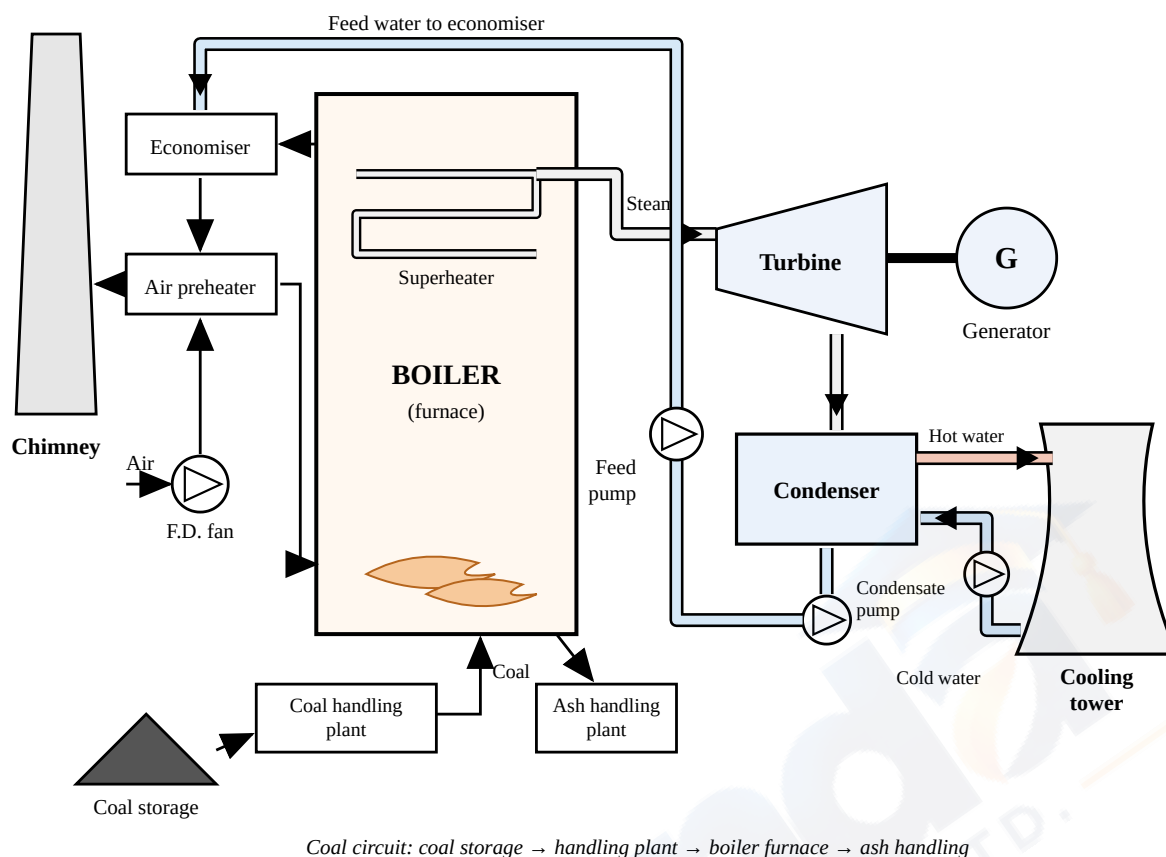


Fig.: Layout of a thermal (steam) power plant

Circuits: (1) **Coal and ash circuit** — coal storage → coal handling plant → boiler furnace → ash handling plant. (2) **Air and flue gas circuit** — F.D. fan → air preheater → furnace → economiser → air preheater → chimney. (3) **Feed water and steam circuit** — boiler → superheater → turbine → condenser → condensate pump → feed pump → economiser → boiler. (4) **Cooling water circuit** — condenser ↔ cooling tower. The turbine drives the **generator**.

(Layout 3 M, labelling 1 M)

c) Natural 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.

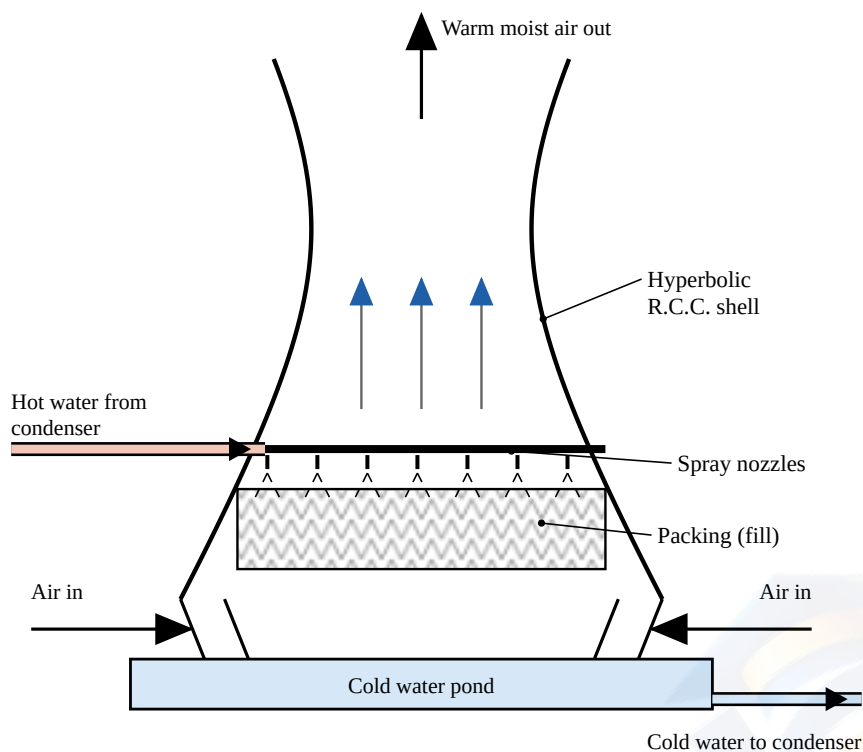


Fig.: Natural draught (hyperbolic) cooling tower

Construction: A tall hyperbolic RCC shell (up to 150 m high) supported on columns, with air inlet openings at the base, water distribution sprays and packing (fill) in the lower part, and a cold water pond at the bottom. No fan is used.

Working: Hot water from the condenser is sprayed over the packing. Atmospheric air enters at the bottom openings and rises through the tower due to the **natural draught** created by the difference in density between the cool outside air and the warm, moist, lighter air inside. Water is cooled by evaporation and convection and collects in the pond. The hyperbolic shape gives strength with less material and increases the air velocity at the throat.

Use: Large thermal power plants (e.g. 500–660 MW units), especially where water is limited, because no fan power is needed and evaporation loss is small (water is recirculated).

(Sketch 2 M, working 2 M)

d) Surface condenser sketch; sources of air leakage

4 M

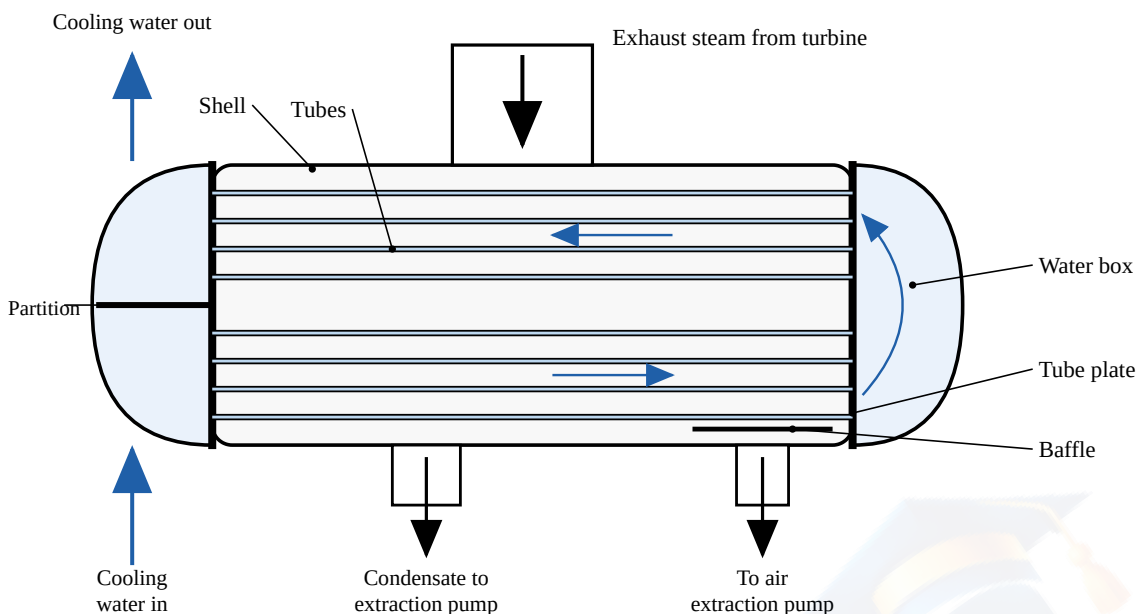


Fig.: Two-pass surface condenser

Sources of air leakage in a condenser:

1. Air dissolved in the boiler feed water comes out with steam and enters the condenser along with exhaust steam.
 2. Atmospheric air leaks in through the joints, flanges, glands and packing of the turbine and condenser which work below atmospheric pressure (vacuum).
 3. In jet condensers, air dissolved in the injection (cooling) water is released under vacuum.
- (Effects, for reference: vacuum and turbine work decrease, heat transfer reduces, corrosion increases.)

(Labelled sketch 2 M, sources 2 M)

Q.4

a) Modes of heat transfer

4 M

1. **Conduction:** Transfer of heat from one part of a body to another part (or between bodies in contact) from molecule to molecule, without any bulk movement of the molecules. Mainly in solids. Example: heat flow through the wall of a boiler/furnace; a spoon in hot tea gets hot at the handle.
2. **Convection:** Transfer of heat by the actual movement of the fluid particles (liquid or gas) from one place to another. Natural convection — motion due to density difference; forced convection — motion by fan/pump. Example: heating of water in a pan; cooling of a car radiator by fan.
3. **Radiation:** Transfer of heat in the form of electromagnetic waves, without any medium (can pass through vacuum). Example: heat received from the sun; heat from a furnace flame to boiler tubes.

Laws: conduction — Fourier's law $Q = -kA \frac{dT}{dx}$; convection — Newton's law $Q = hA \Delta T$; radiation — Stefan-Boltzmann law $Q = \sigma A T^4$.

(Each mode with example — about 1½ M)

b) Stefan–Boltzmann law, emissivity, gray body

4 M

Stefan–Boltzmann law: The total emissive power of a black body is directly proportional to the fourth power of its absolute temperature.

$$E_b = \sigma T^4 \quad (\text{W/m}^2)$$

σ = Stefan–Boltzmann constant = $5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$. For a real (gray) body $E = \epsilon \sigma T^4$.

Emissivity (ϵ): ratio of emissive power of a body to that of a black body at the same temperature ($\epsilon = E/E_b$).

Gray body: a body whose emissivity/absorptivity is less than 1 and constant for all wavelengths.

(Law with expression 2 M, two definitions 2 M)

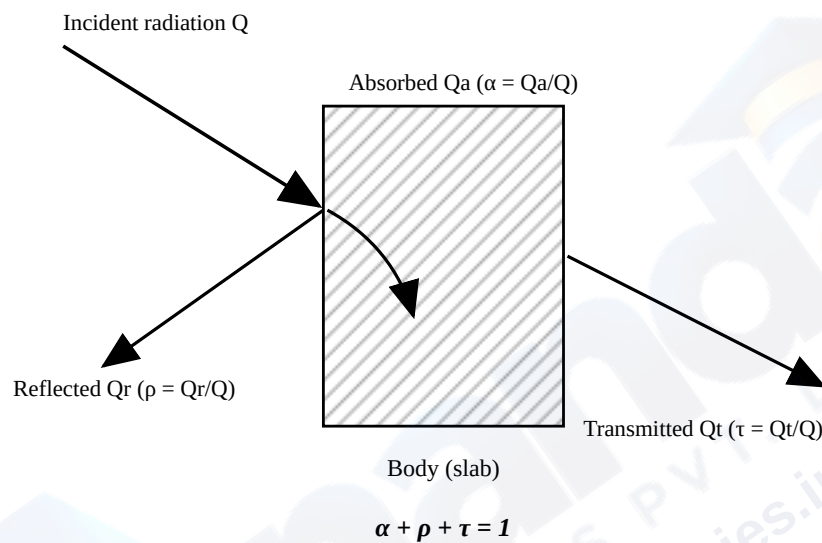


Fig.: Absorbed, reflected and transmitted radiation

c) Diesel cycle

4 M

Diesel cycle (constant pressure cycle) is the ideal air-standard cycle for **diesel (C.I.) engines**.

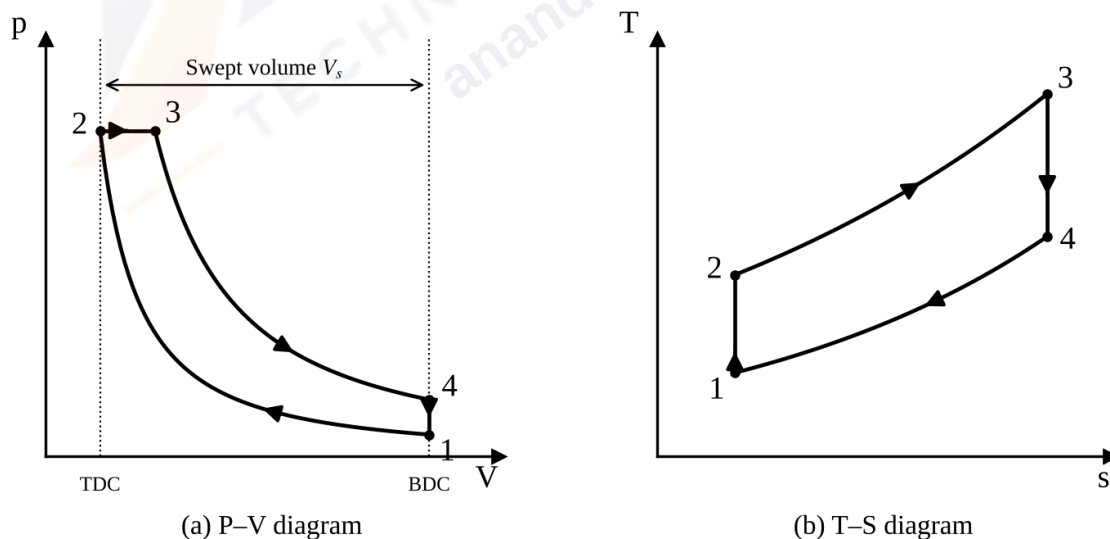


Fig.: Diesel cycle on P–V and T–S diagrams (computed, $r = 7$, $\rho = 2$)

1. 1–2: Isentropic compression of air (only air is compressed to high pressure and temperature).

2. 2–3: Constant pressure heat addition (fuel injected and burnt) — cut-off at 3; $p = V_3/V_2$.

3. 3–4: Isentropic expansion.

4. 4–1: Constant volume heat rejection.

$$\eta = 1 - [1/(\gamma r^{\gamma-1})] \times (p^{\gamma} - 1)/(p - 1)$$

(P–V 1 M, T–S 1 M, explanation 2 M)

d) Classification of I.C. engines

4 M

Basis	Types
Working cycle	Otto cycle (S.I.) engine, Diesel cycle (C.I.) engine, dual cycle engine
Number of strokes per cycle	Four stroke engine, two stroke engine
Method of ignition	Spark ignition (S.I.), compression ignition (C.I.)
Fuel used / fuel supply	Petrol (carburettor / petrol injection), diesel (fuel injection), gas, bi-fuel
Method of cooling	Air cooled, water cooled
Number and arrangement of cylinders	Single / multi cylinder; in-line, V-type, radial, opposed
Speed / application	Low, medium, high speed; automotive, marine, stationary, locomotive

(Four bases asked, 1 M each)

e) Numerical — condition of steam at 8 bar

4 M

From steam table at 8 bar: $t_s = 170.4\text{ }^{\circ}\text{C}$, $v_g = 0.2403\text{ m}^3/\text{kg}$, $h_f = 721.0$, $h_{fg} = 2047.3$, $h_g = 2768.3\text{ kJ/kg}$

Case i) $v = 0.2\text{ m}^3/\text{kg}$: Since $v (0.2) < v_g (0.2403)$, the steam is **wet**.

$$\text{Dryness fraction } x = v / v_g = 0.2 / 0.2403 = \mathbf{0.8323}$$

$$\text{Enthalpy } h = h_f + x h_{fg} = 721.0 + 0.8323 \times 2047.3 = \mathbf{2,425.0\text{ kJ/kg}}$$

Case ii) $h = 2900\text{ kJ/kg}$: Since $h (2900) > h_g (2768.3)$, the steam is **superheated**.

$$h = h_g + C_{ps}(t_{\text{sup}} - t_s) \Rightarrow 2900 = 2768.3 + 2.1(t_{\text{sup}} - 170.4)$$

$$t_{\text{sup}} = 170.4 + (2900 - 2768.3) / 2.1 = \mathbf{233.1\text{ }^{\circ}\text{C}}$$

$$\text{Degree of superheat} = 233.1 - 170.4 = \mathbf{62.7\text{ }^{\circ}\text{C}}$$

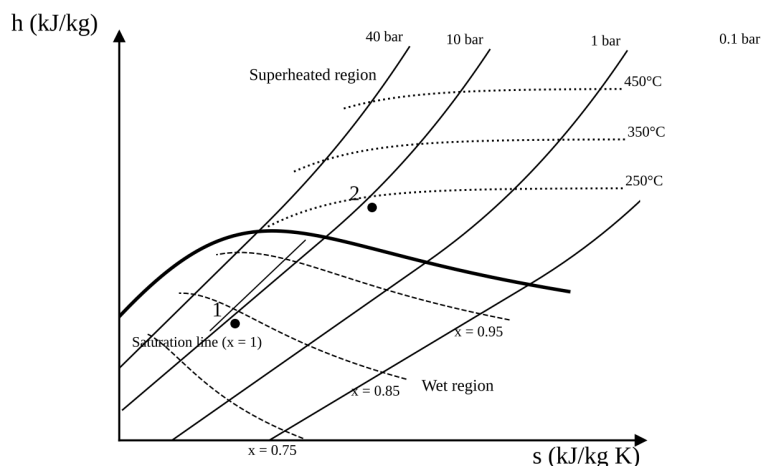


Fig.: Both states on the h - s chart (8 bar): 1 = wet, 2 = superheated

(Each case 2 M)

Q.5

a) SFEE applied to boiler, nozzle 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.

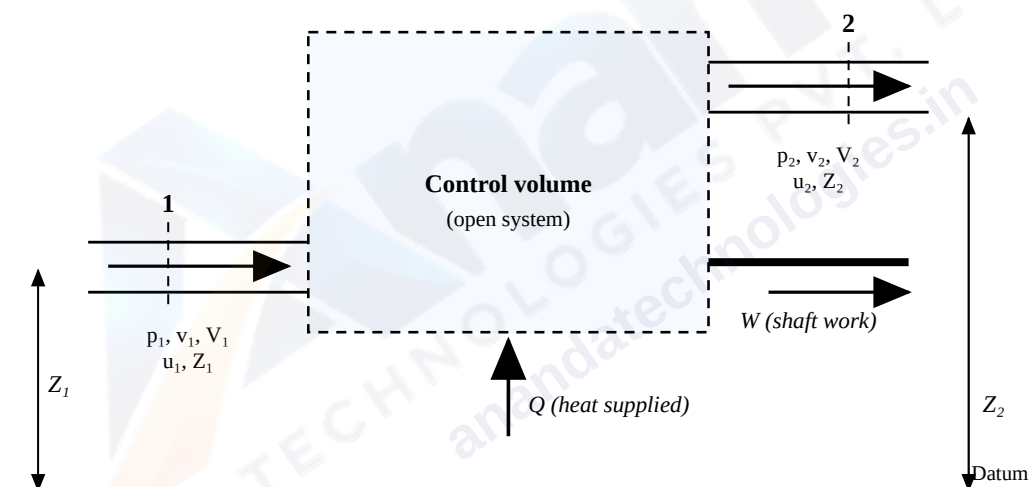


Fig.: Steady flow system (control volume)

Steady flow energy equation (per kg of fluid):

$$u_1 + p_1 v_1 + \frac{V_1^2}{2} + gZ_1 + q = u_2 + p_2 v_2 + \frac{V_2^2}{2} + gZ_2 + w$$

Since $h = u + pv$, $h_1 + \frac{V_1^2}{2} + gZ_1 + q = h_2 + \frac{V_2^2}{2} + gZ_2 + w$ (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)

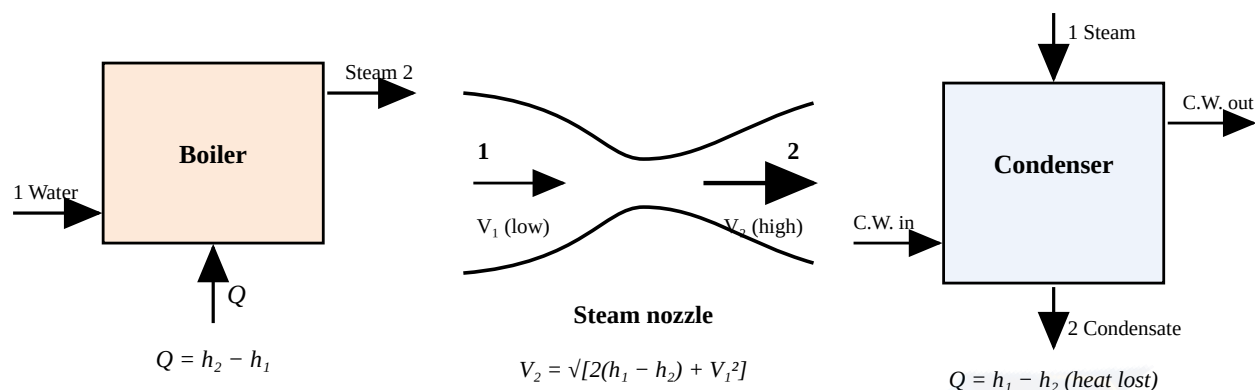


Fig.: Application of SFEE

Boiler: Water enters and steam leaves; no shaft work ($w = 0$); change in K.E. and P.E. is negligible ($V_1 \approx V_2$, $Z_1 \approx Z_2$). SFEE becomes

$$q = h_2 - h_1$$

i.e. heat supplied in the boiler is used only to **increase the enthalpy** of the working fluid (water $\rightarrow$ steam).

Steam nozzle: No work ($w = 0$), no heat transfer ($q = 0$, adiabatic), $Z_1 \approx Z_2$. SFEE becomes

$$V_2^2/2 - V_1^2/2 = h_1 - h_2 \Rightarrow V_2 = \sqrt{2(h_1 - h_2) + V_1^2}$$

i.e. the drop in enthalpy is converted into kinetic energy. If V_1 is small, $V_2 = 44.72 \sqrt{(h_1 - h_2)}$ with h in kJ/kg.

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

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

This heat is gained by the cooling water: $m_s(h_1 - h_2) = m_w c_{pw} (t_{w0} - t_{wi})$.

(SFEE with terms 3 M, applications 1 M each)

b) Formation of steam — T-H diagram

6 M

Consider 1 kg of water at 0 °C in a cylinder under a piston carrying a constant load (constant pressure p). Heat is supplied:

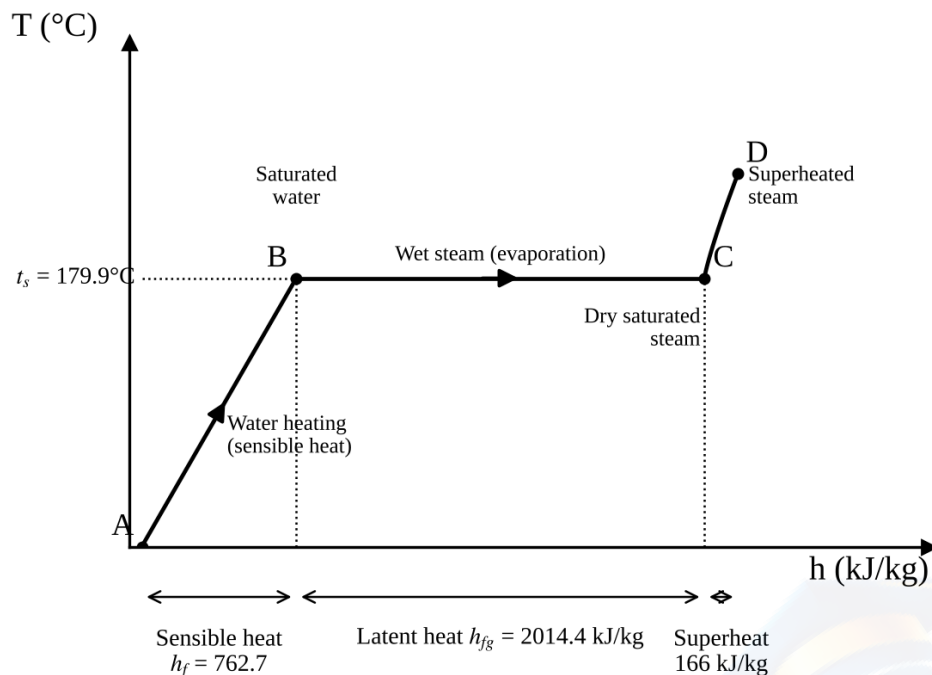


Fig.: T-H diagram for formation of steam at constant pressure (values for 10 bar, IAPWS-IF97)

- A–B (sensible heating):** Temperature of water rises from 0 °C to the saturation (boiling) temperature t_s . Heat supplied = sensible heat h_f . Volume increases slightly.
 - B–C (evaporation):** At t_s , water starts boiling; temperature remains constant. The mixture between B and C is **wet steam**. At C all water becomes **dry saturated steam**. Heat supplied = latent heat h_{fg} . Total heat $h_g = h_f + h_{fg}$.
 - C–D (superheating):** Further heating at the same pressure raises the temperature above t_s ; steam becomes **superheated**. Heat supplied = $C_{ps}(t_{sup} - t_s)$. $h_{sup} = h_g + C_{ps}(t_{sup} - t_s)$.
- At 10 bar: $t_s = 179.9$ °C, $h_f = 762.7$, $h_{fg} = 2014.4$, $h_g = 2777.1$ kJ/kg (shown on the figure).

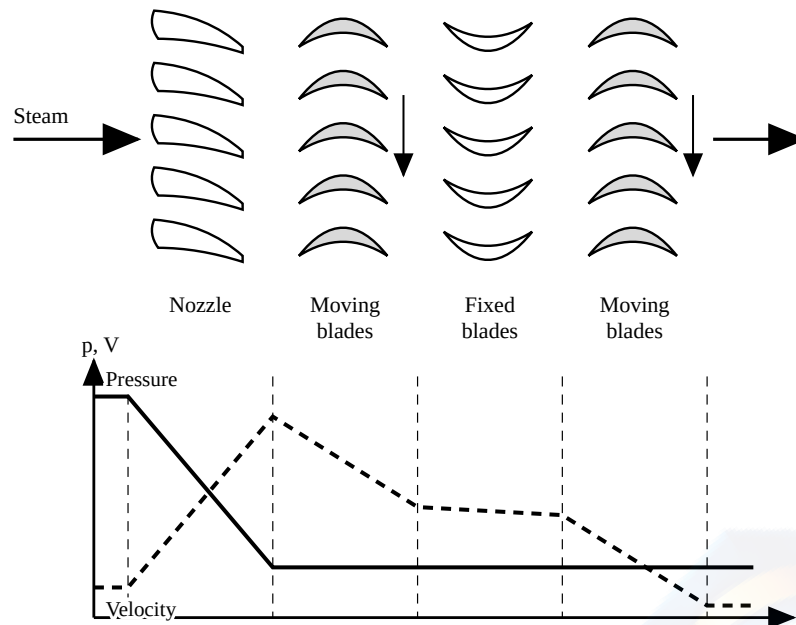
(T-H diagram 2 M, explanation of three stages 3 M, terms 1 M)

c) Compounding — velocity compounded impulse turbine

6 M

Need of compounding: In a single-stage impulse turbine the whole pressure drop occurs in one nozzle, so steam velocity and rotor speed are very high ($\approx 30\,000$ rpm) with large leaving-velocity loss. Compounding means using more than one set of blades (or nozzles) in series to absorb the energy in stages, so that rotor speed is reduced to a practical value.

Velocity compounding (Curtis stage): The whole pressure drop takes place in one set of nozzles. The high-velocity steam then passes through rows of **moving blades** and **fixed guide blades** placed alternately. Part of the velocity is absorbed in the first row of moving blades; the fixed blades only redirect the steam (no pressure or velocity change except friction) onto the second row of moving blades where the remaining velocity is absorbed. Since the velocity is absorbed in two or more rows, the blade speed (rotor speed) is reduced.



Velocity compounded impulse turbine — pressure and velocity variation

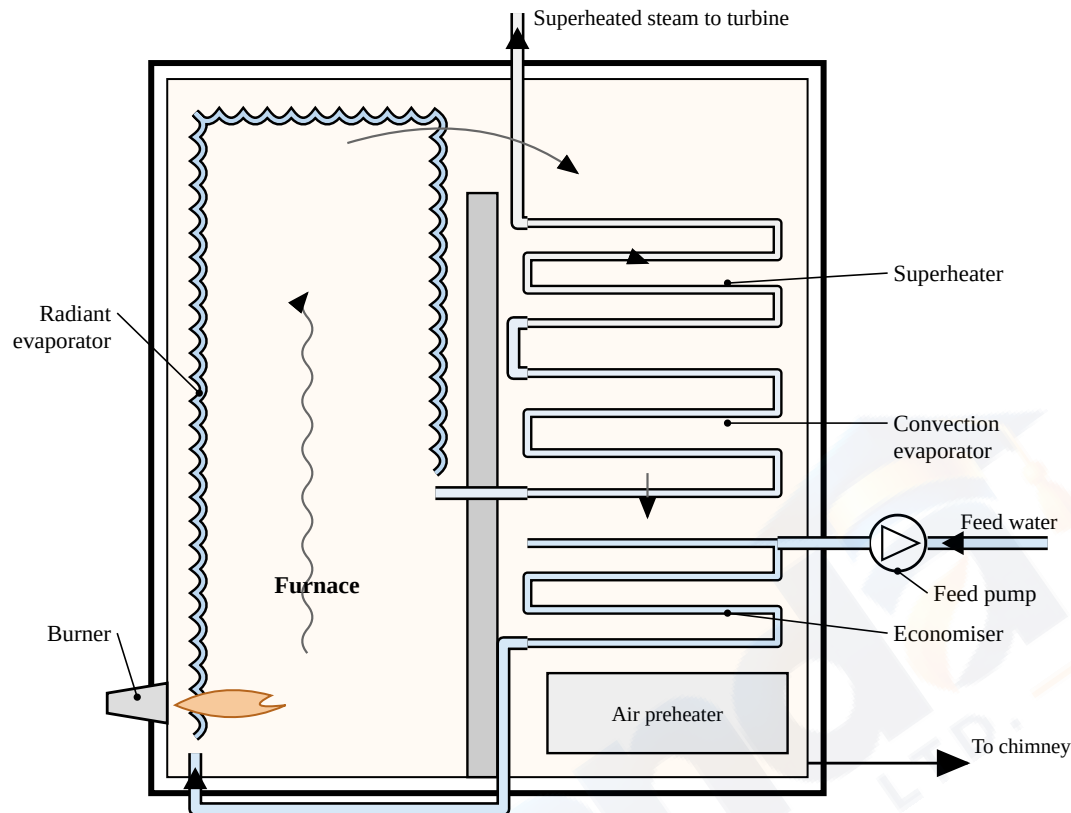
Advantages: few stages, less space, cheap; **disadvantage:** friction losses are high, efficiency decreases with more rows.

(Need 1 M, explanation 2 M, diagram with p - V variation 3 M)

Q.6

a) Benson boiler; difference from Lamont

6 M



Water flows once through: economiser → radiant evaporator → convection evaporator → superheater (no drum)

Fig.: Benson boiler (once-through, drumless)

Principle: Benson boiler is a drumless, once-through, forced circulation water tube boiler working at or above the **critical pressure** (221.2 bar). At critical pressure water changes into steam directly, without boiling (latent heat is zero), so no drum is needed for separation.

Working: Feed pump raises water to supercritical pressure and forces it through the **economiser** → **radiant evaporator** (water walls in the furnace) where most water is converted to steam → **convection evaporator** where the remaining water is evaporated → **superheater**, from which superheated steam goes to the turbine. Flue gases pass over the convection evaporator, superheater, economiser and air preheater before going to the chimney.

Difference from Lamont boiler: Lamont has a steam separating drum and a circulating pump (recirculation ratio 8–10), whereas Benson has **no drum** — water passes only once through the tubes; Benson works at very high (critical) pressure, about 250 bar, capacity up to about 150 t/h.

Advantages: no drum, so lighter and cheaper; quick starting; no bubble formation hence no scale; can be operated at varying loads.

(Labelled sketch 3 M, working 2 M, difference 1 M)

b) Numerical — heat transfer through cold storage wall

6 M

Area $A = 4 \times 2.5 = 10 \text{ m}^2$.

Given: Brick: $x = 115 \text{ mm} = 0.115 \text{ m}$, $k = 0.7 \text{ W/m K}$, Cork: $x = 75 \text{ mm} = 0.075 \text{ m}$, $k = 0.045 \text{ W/m K}$, Wood: $x = 20 \text{ mm} = 0.02 \text{ m}$, $k = 0.18 \text{ W/m K}$; $T_1 = 30^\circ\text{C}$, $T_4 = -8^\circ\text{C}$; area $A = 10 \text{ m}^2$

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

$$R_1 (\text{Brick}) = 0.115 / (0.7 \times 10) = \mathbf{0.01643 \text{ K/W}}$$

$$R_2 (\text{Cork}) = 0.075 / (0.045 \times 10) = \mathbf{0.16667 \text{ K/W}}$$

$$R_3 (\text{Wood}) = 0.02 / (0.18 \times 10) = \mathbf{0.01111 \text{ K/W}}$$

$$\text{Total resistance } \Sigma R = 0.01643 + 0.16667 + 0.01111 = \mathbf{0.19421 \text{ K/W}}$$

Rate of heat flow:

$$Q = (T_1 - T_4) / \Sigma R = (30 - (-8)) / 0.19421 = \mathbf{195.67 \text{ W}}$$

$$\text{Heat transfer per hour} = 195.67 \times 3600 / 1000 = \mathbf{704.4 \text{ kJ/h}}$$

Interface temperatures (same Q flows through each layer):

$$T_2 = T_1 - Q R_1 = 30.00 - 195.67 \times 0.01643 = \mathbf{26.79^\circ\text{C}}$$

$$T_3 = T_2 - Q R_2 = 26.79 - 195.67 \times 0.16667 = \mathbf{-5.83^\circ\text{C}}$$

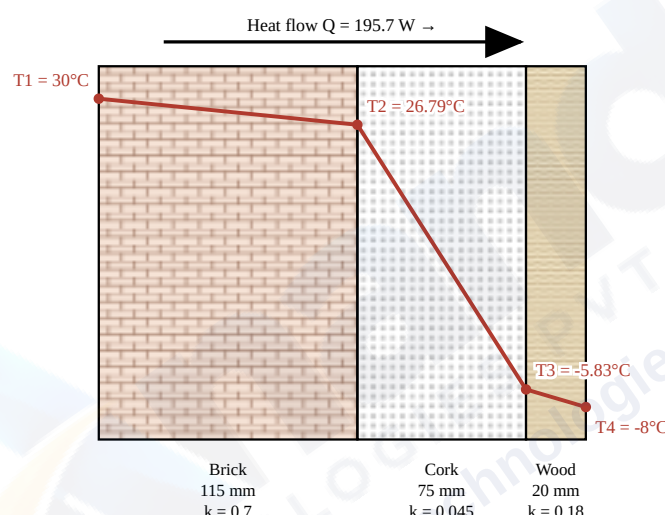


Fig.: Temperature profile through the cold storage wall (computed)

Note: the largest temperature drop occurs across the cork, which has the highest thermal resistance — that is why cork is used as insulation.

(Resistances 2 M, Q per hour 2 M, interface temperatures 2 M)

c) S.I. engine vs C.I. engine

6 M

Basis	S.I. (petrol) engine	C.I. (diesel) engine
Fuel used	Petrol (high self-ignition temperature, volatile)	Diesel (low self-ignition temperature)
Working cycle	Otto cycle (constant volume)	Diesel cycle (constant pressure)
Air–fuel ratio / mixture	A/F mixture prepared in carburettor; ratio about 10:1 to 20:1 (quantity governing)	Only air sucked; fuel injected; A/F ratio 18:1 to 100:1 (quality governing)
Method of ignition	Spark plug	Heat of compressed air (self ignition); fuel injector

Compression ratio	6 to 10	14 to 22
Noise and vibration	Less noise and vibration (smooth running)	More noise and vibration (high pressure, knocking)

(6 points, 1 M each)

Note: This is a **model question paper prepared by Ananda Technologies** only for practice and exam preparation, based on the pattern of previous MSBTE question papers and the K-scheme syllabus. It is **not an official MSBTE paper**, and it does **not** mean that these questions will come in the exam. Answers follow standard textbook points; marks shown are indicative. Free for students — anandatechnologies.in

