

Thermal Engineering (313310)

MSBTE K-Scheme · Model Question Paper — Set A · 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) Intensive and extensive property

2 M

i) Intensive property: A property whose value does **not depend on the mass** (size) of the system is called an intensive property. Examples: pressure, temperature, density, specific volume.

ii) Extensive property: A property whose value **depends on the mass** of the system is called an extensive property. Examples: total volume, mass, total energy, total enthalpy.

(Each definition with example 1 M)

b) Universal gas constant

2 M

Universal gas constant ($\bar{R}$ or R_u): It is the product of the molecular mass (M) of a gas and its characteristic gas constant (R). It has the same value for all gases: $\bar{R} = M R$.

Value: $\bar{R} = 8.314 \text{ kJ/kmol K}$ (8314 J/kmol K). Unit: J/kmol K or kJ/kmol K. For air, $R = 8.314/28.97 = 0.287 \text{ kJ/kg K}$.

(Definition 1 M, value and unit 1 M)

c) Dryness fraction and degree of superheat

2 M

i) Dryness fraction (x): It is the ratio of the mass of dry steam actually present to the total mass of wet steam (dry steam + water particles) in which it is contained. $x = m_g/(m_g + m_f)$. For dry saturated steam $x = 1$.

ii) Degree of superheat: It is the difference between the temperature of superheated steam and the saturation temperature at the same pressure: degree of superheat = $t_{\text{sup}} - t_s$.

(Each definition 1 M)

d) 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.

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

(Statement 2 M)

e) Applications of steam nozzles

2 M

1. Steam turbines — to convert enthalpy of steam into high velocity jet striking the blades.
2. Steam/gas injectors — for feeding water into boilers.

3. Jet engines and rockets — to produce thrust.
4. Ejectors and steam jet air pumps (air extraction from condensers).
5. Gas turbines and flow measuring devices (flow nozzle).

(Any four, $\frac{1}{2}$ M each)

f) Black body and gray body

2 M

i) Black body: A body which absorbs all the radiation falling on it (absorptivity $\alpha = 1$, $\rho = 0$, $\tau = 0$) is called a black body. It is also the best emitter (emissivity $\varepsilon = 1$).

ii) Gray body: A body whose absorptivity (and emissivity) is less than one but is the same for all wavelengths and temperatures ($0 < \alpha = \varepsilon < 1$) is called a gray body.

(Each definition 1 M)

g) Compression ratio and swept volume

2 M

i) Compression ratio (r): The ratio of total cylinder volume to the clearance volume: $r = (V_c + V_s)/V_c$. (Petrol engine 6–10, diesel engine 14–22.)

ii) Swept (stroke) volume (V_s): The volume swept by the piston in moving from TDC to BDC: $V_s = (\pi/4) D^2 L$.

(Each definition 1 M)

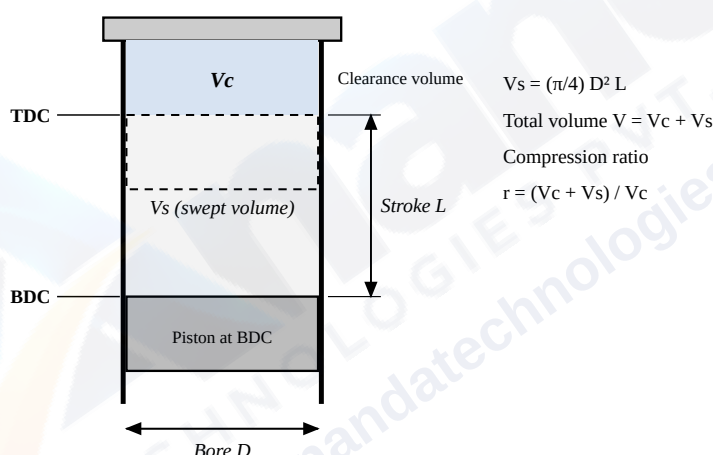


Fig.: Engine terminology

Q.2

a) Heat engine, heat pump and refrigerator

4 M

- **Heat engine (H.E.):** A device which works in a cycle, receives heat Q_1 from a high temperature source, converts part of it into work W and rejects the remaining heat Q_2 to a low temperature sink. $W = Q_1 - Q_2$; thermal efficiency $\eta = W/Q_1$. Example: I.C. engine, steam power plant.
- **Heat pump (H.P.):** A reversed heat engine which takes heat Q_2 from a low temperature body (atmosphere) and, with the help of work input W , delivers heat $Q_1 = Q_2 + W$ to a high temperature body (room to be heated). $COP_{HP} = Q_1/W$.

- **Refrigerator (R):** A reversed heat engine which extracts heat Q_2 from a low temperature space (refrigerated space) with work input W and rejects Q_1 to the atmosphere. Its aim is cooling.
 $COP_R = Q_2/W$.

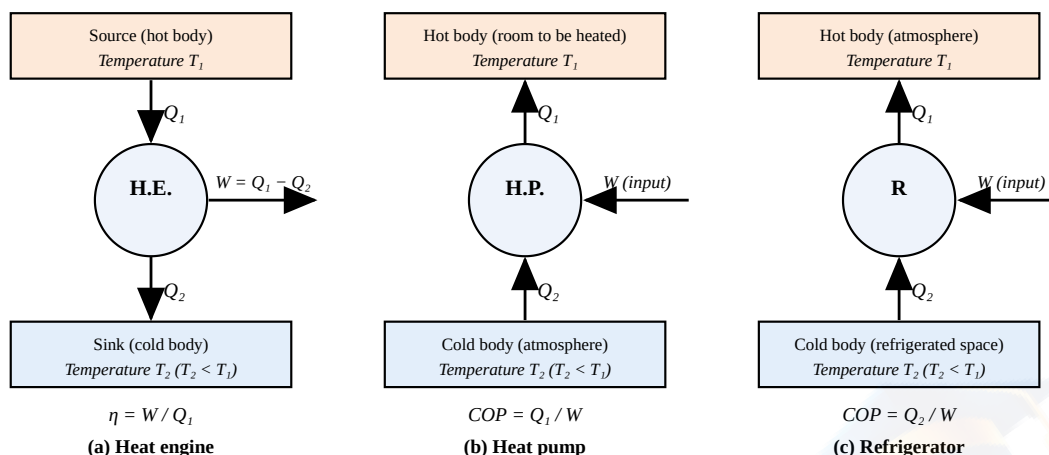


Fig.: Block diagrams of heat engine, heat pump and refrigerator

(Each concept with block diagram — about $1\frac{1}{3}$ M each)

b) Kelvin–Planck and Clausius statements

4 M

Kelvin–Planck statement: It is impossible to construct an engine which, operating in a cycle, will produce no effect other than the extraction of heat from a single reservoir and the performance of an equivalent amount of work. i.e. no heat engine can have 100 % thermal efficiency; some heat must be rejected to a sink.

Clausius statement: It is impossible to construct a device which, operating in a cycle, will produce no effect other than the transfer of heat from a cooler body to a hotter body. i.e. heat cannot flow from a low temperature body to a high temperature body without external work (a refrigerator needs work input).

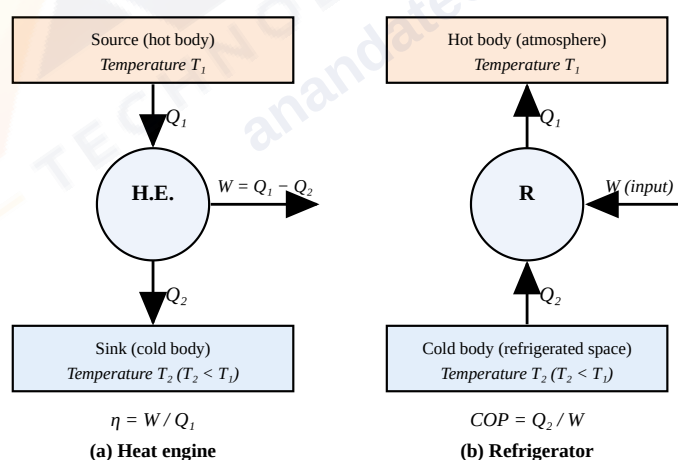


Fig.: Kelvin–Planck — engine must reject Q_2 ; Clausius — refrigerator needs W

(Each statement 2 M)

c) Isothermal process on P-V and T-S

4 M

In an isothermal process the temperature remains constant ($T = C$), so for a perfect gas $pV = \text{constant}$ (Boyle's law). The P-V curve is a rectangular hyperbola and on the T-S diagram it is a horizontal line.

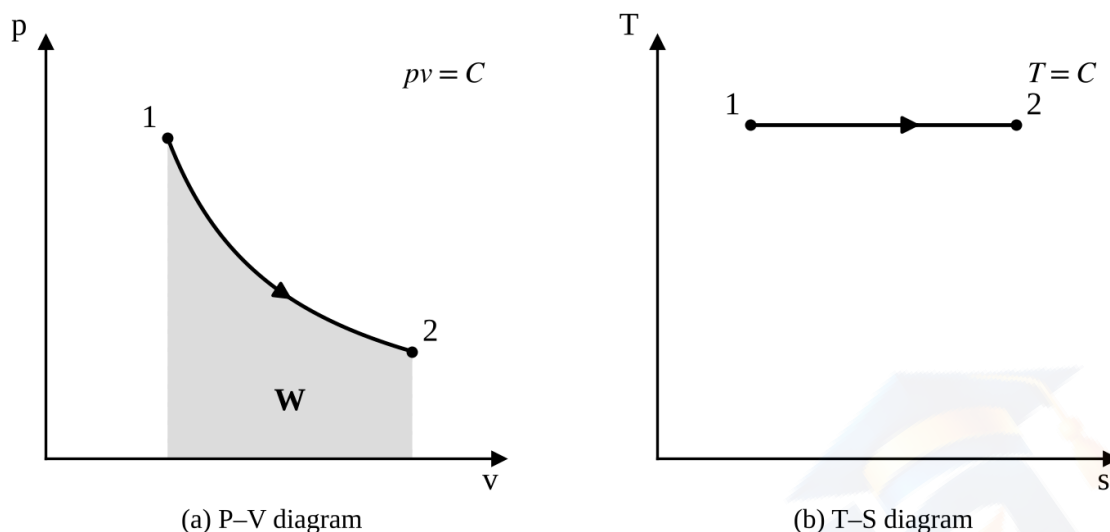


Fig.: Isothermal expansion 1-2 (computed for air, $v_2 = 3v_1$)

Work done: $W = \int p \, dV = p_1 V_1 \ln(V_2/V_1) = mRT \ln(V_2/V_1) = p_1 V_1 \ln(p_1/p_2)$

Since T is constant, $\Delta U = 0$, so heat supplied $Q = W$.

(P-V 1 M, T-S 1 M, work relation 2 M)

d) Numerical — constant volume heating of air

4 M

Given: $m = 1.5 \text{ kg}$, $T_1 = 30 + 273 = 303 \text{ K}$, $v = \text{constant}$, $p_2 = 2.5 p_1$, $C_v = 0.718 \text{ kJ/kg K}$

i) Final temperature: For constant volume process, $p_1/T_1 = p_2/T_2$

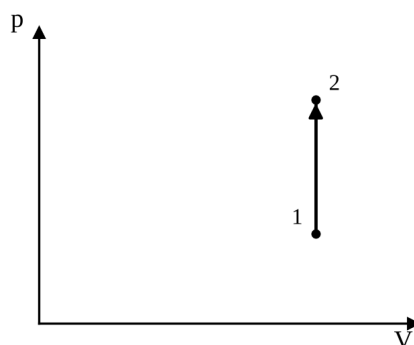
$$T_2 = T_1 \times (p_2/p_1) = 303 \times 2.5 = \mathbf{757.50 \text{ K}}$$

$$t_2 = 757.50 - 273 = \mathbf{484.50 \text{ }^\circ\text{C}}$$

ii) Change in internal energy:

$$\Delta U = m C_v (T_2 - T_1) = 1.5 \times 0.718 \times (757.50 - 303) = \mathbf{489.50 \text{ kJ}}$$

iii) Work done: $W = \int p \, dV = 0$ (volume constant), so heat supplied $Q = \Delta U + W = \mathbf{489.50 \text{ kJ}}$



P-V sketch: constant volume process

(T_2 1 M, ΔU 2 M, Q 1 M)

Q.3

a) Formation of steam — T–H diagram

4 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:

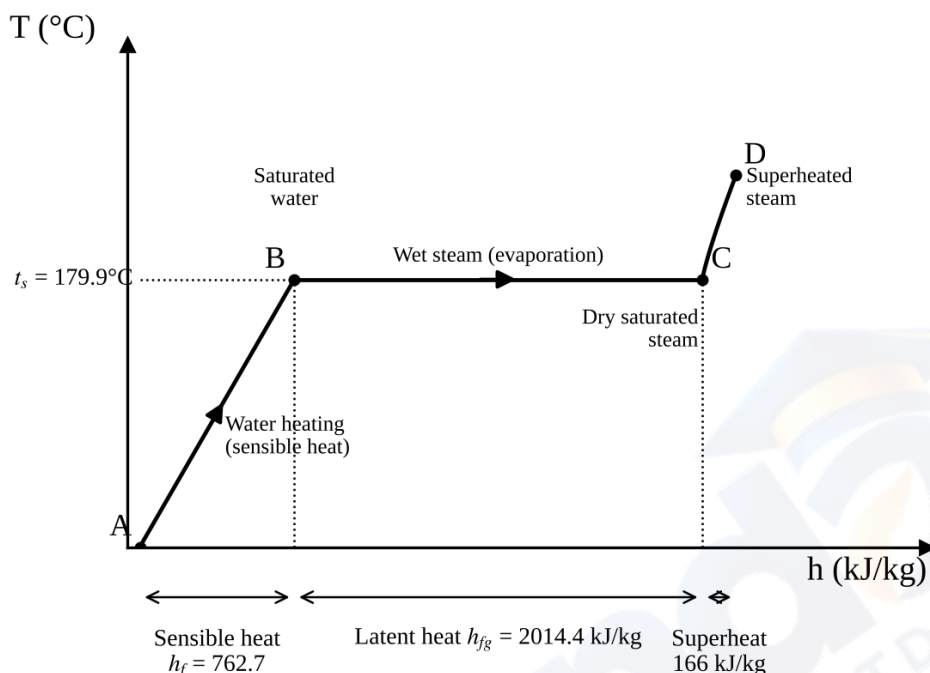


Fig.: T–H diagram for formation of steam at constant pressure (values for 10 bar, IAPWS-IF97)

- 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 2 M)

b) Classification of boilers

4 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
Method of water circulation	Natural circulation (by density difference) — Babcock & Wilcox; Forced circulation (by pump) — Lamont, Benson

Steam pressure	Low pressure (below 10 bar), medium pressure (10–80 bar), high pressure (above 80 bar)
Axis of shell	Vertical (Cochran) and horizontal (Lancashire, Babcock & Wilcox)
Nature of draught / firing	Natural draught or artificial (forced / induced) draught; stoker-fired or pulverised fuel fired
Use	Stationary, portable, locomotive and marine boilers

(Four bases asked, 1 M each)

c) Surface condenser

4 M

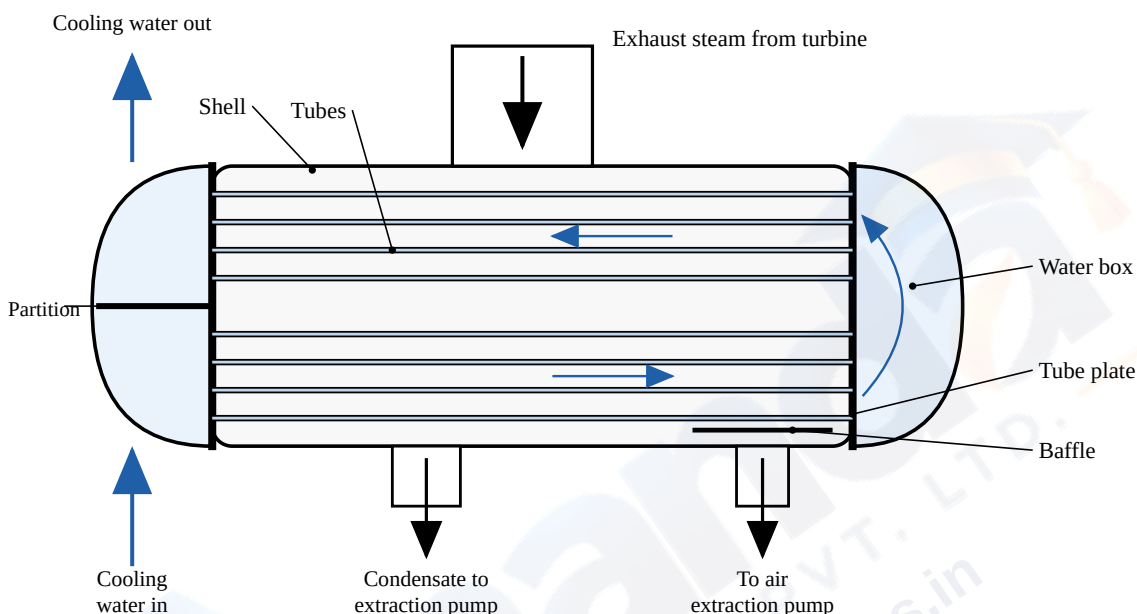


Fig.: Two-pass surface condenser

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).

(Labelled sketch 2 M, construction and working 2 M)

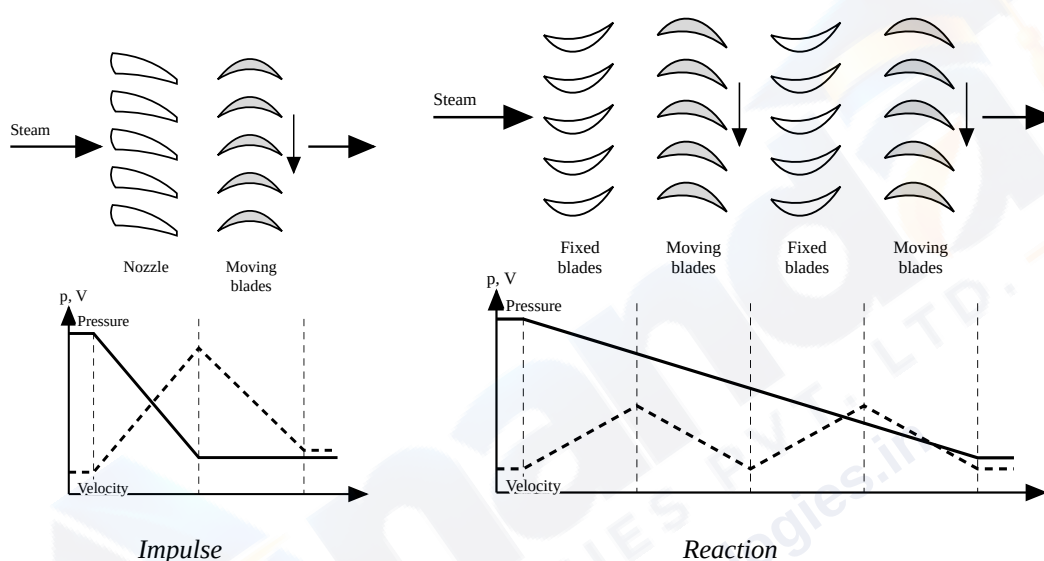
d) Impulse turbine vs reaction turbine

4 M

Impulse turbine	Reaction turbine
Steam expands completely in the nozzles; pressure remains constant over the moving blades.	Steam expands partly in fixed blades and partly in moving blades; pressure drops continuously.

Blades are symmetrical (profile type), passage area constant.	Blades are aerofoil (asymmetrical); passage area converging.
Rotation is due to impulse of the steam jet only.	Rotation is due to impulse as well as reaction of the leaving steam.
Nozzles and moving blades are used; fixed guide blades only in compounding.	Fixed blades (act as nozzles) and moving blades are used alternately.
Few stages; high blade velocity, high rotor speed (De Laval up to 30 000 rpm).	More stages; comparatively lower speed.
Suitable for small power; efficiency lower.	Suitable for medium and large power; efficiency higher.

(Any 4 points, 1 M each)



Q.4

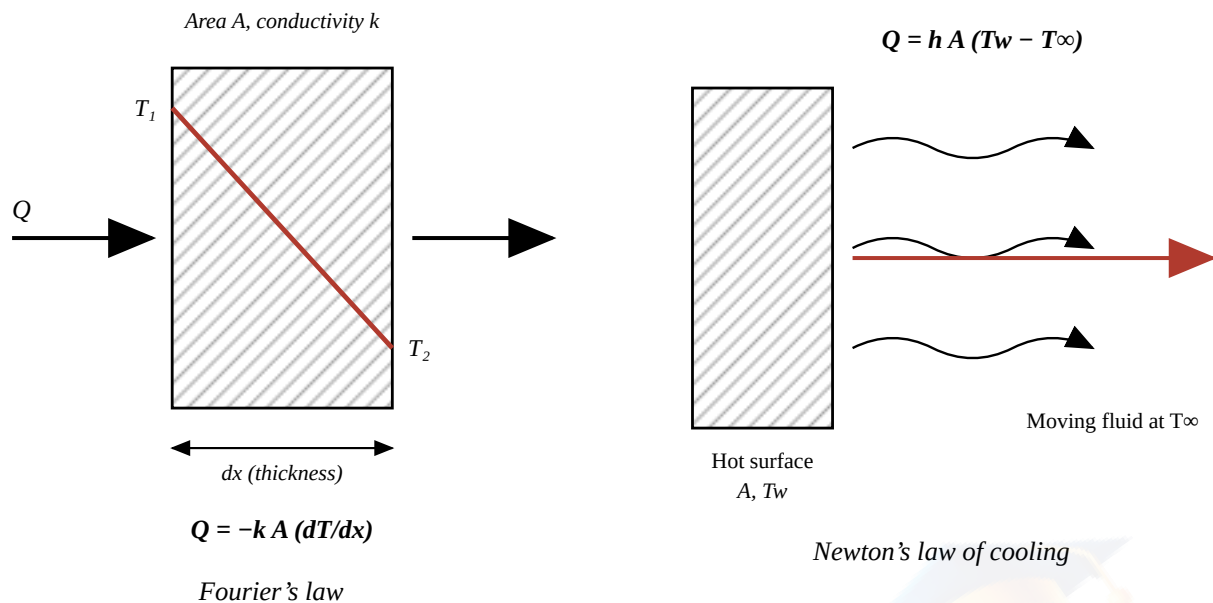
a) Fourier's law and Newton's law of cooling

4 M

Fourier's law of heat conduction: The rate of heat flow by conduction through a homogeneous solid is directly proportional to the area of the section at right angles to the direction of heat flow and to the temperature gradient in that direction.

$$Q = -k A (dT/dx)$$

k = thermal conductivity (W/m K); negative sign because heat flows in the direction of decreasing temperature.



Newton's law of cooling (convection): The rate of heat transfer by convection between a surface and the surrounding fluid is proportional to the surface area and the temperature difference between the surface and the fluid.

$$Q = h A (T_w - T_\infty)$$

h = convective heat transfer coefficient ($\text{W/m}^2 \text{K}$).

(Each law with expression 2 M)

b) Numerical — heat flow through composite boiler wall

4 M

Given: Steel: $x = 20 \text{ mm} = 0.02 \text{ m}$, $k = 50 \text{ W/m K}$, Insulation: $x = 6 \text{ mm} = 0.006 \text{ m}$, $k = 0.1 \text{ W/m K}$; $T_1 = 320^\circ \text{C}$, $T_3 = 45^\circ \text{C}$; per unit area ($A = 1 \text{ m}^2$)

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

$$R_1 (\text{Steel}) = 0.02 / (50 \times 1) = \mathbf{0.00040 \text{ K/W}}$$

$$R_2 (\text{Insulation}) = 0.006 / (0.1 \times 1) = \mathbf{0.06000 \text{ K/W}}$$

$$\text{Total resistance } \Sigma R = 0.00040 + 0.06000 = \mathbf{0.06040 \text{ K/W}}$$

Rate of heat flow:

$$Q = (T_1 - T_3) / \Sigma R = (320 - 45) / 0.06040 = \mathbf{4,552.98 \text{ W}}$$

Interface temperatures (same Q flows through each layer):

$$T_2 = T_1 - Q R_1 = 320.00 - 4,552.98 \times 0.00040 = \mathbf{318.18^\circ \text{C}}$$

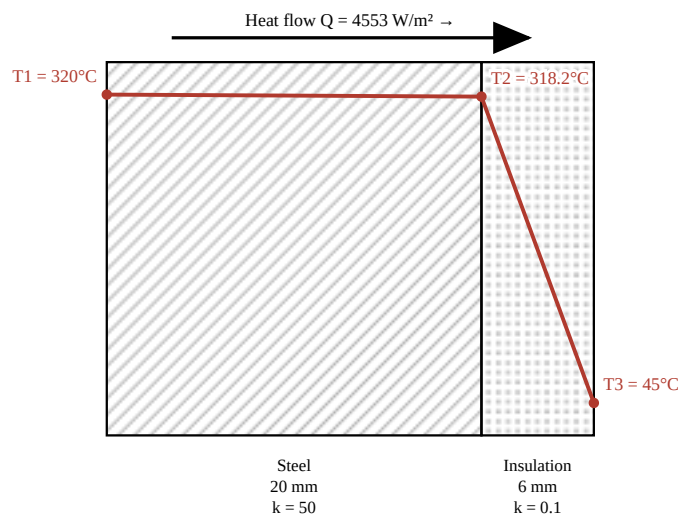


Fig.: Composite wall with computed temperature profile

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

c) Otto cycle on P-V and T-S

4 M

Otto cycle (constant volume cycle) is the ideal air-standard cycle for **petrol (S.I.) engines**.

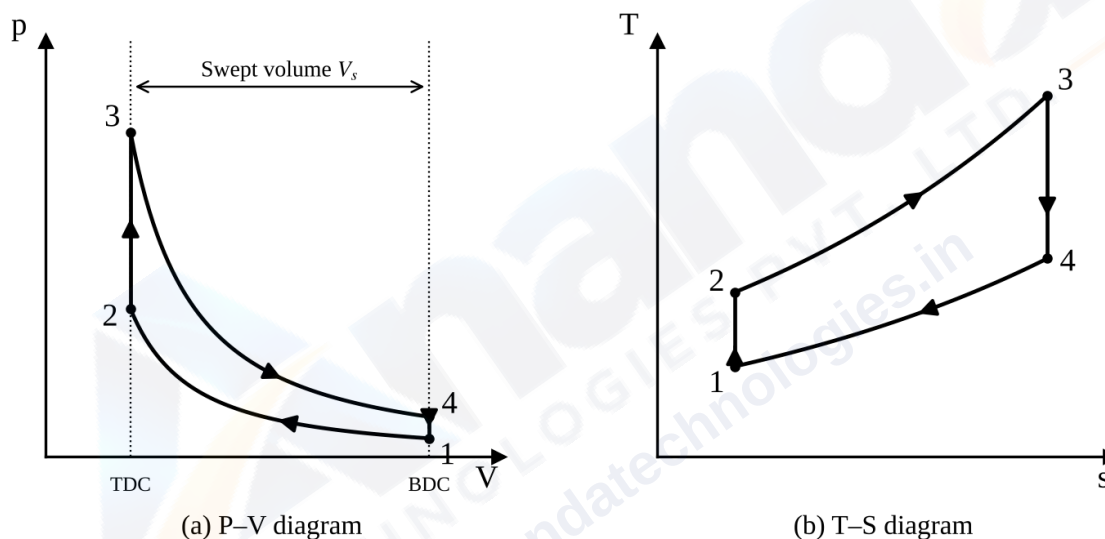


Fig.: Otto cycle on P-V and T-S diagrams (computed, $r = 4.5$)

- 1-2: Isentropic (reversible adiabatic) compression of air.
- 2-3: Constant volume heat addition (combustion at TDC).
- 3-4: Isentropic expansion (power stroke).
- 4-1: Constant volume heat rejection (exhaust).

Efficiency $\eta = 1 - 1/r^{\gamma-1}$, where r = compression ratio.

(P-V 1 M, T-S 1 M, processes 2 M)

d) Two stroke vs four stroke engine

4 M

Four stroke engine	Two stroke engine
One power stroke in every two revolutions of crankshaft (four strokes).	One power stroke in every revolution of crankshaft (two strokes).

Valves (inlet and exhaust) are used, operated by cam mechanism.	Ports are used, covered and uncovered by the piston.
Heavy flywheel needed — turning moment is not uniform.	Lighter flywheel — more uniform turning moment.
Thermal efficiency higher; fuel consumption less.	Thermal efficiency lower; part of fresh charge escapes with exhaust.

(Any 4 points, 1 M each)

e) Numerical — polytropic compression

4 M

Given: $V_1 = 0.05 \text{ m}^3$, $p_1 = 1 \text{ bar}$, $T_1 = 300 \text{ K}$, $V_2 = 0.008 \text{ m}^3$, $pV^{1.25} = C$, $R = 0.287 \text{ kJ/kg K}$

i) Final pressure: $p_1 V_1^n = p_2 V_2^n$

$$p_2 = p_1 (V_1/V_2)^n = 1 \times (0.05/0.008)^{1.25} = \mathbf{9.882 \text{ bar}}$$

ii) Final temperature: $T_2/T_1 = (V_1/V_2)^{n-1}$

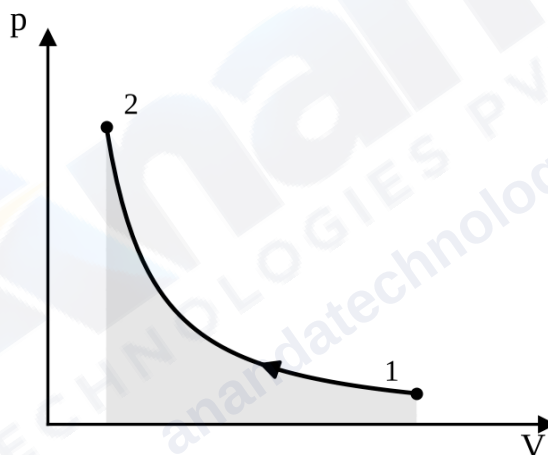
$$T_2 = 300 \times (0.05/0.008)^{0.25} = \mathbf{474.34 \text{ K}}$$

$$t_2 = \mathbf{201.34 \text{ }^\circ\text{C}}$$

iii) Work done:

$$W = (p_1 V_1 - p_2 V_2)/(n - 1) = (100 \times 0.05 - 988.21 \times 0.008) / (1.25 - 1) = \mathbf{-11.623 \text{ kJ}}$$

Negative sign shows that work is **done on** the air during compression ($\approx 11.62 \text{ kJ}$).



P-V sketch (computed curve $pV^{1.25} = C$)

(p_2 1 M, T_2 1 M, work 2 M)

Q.5

a) SFEE — application to boiler and turbine

6 M

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

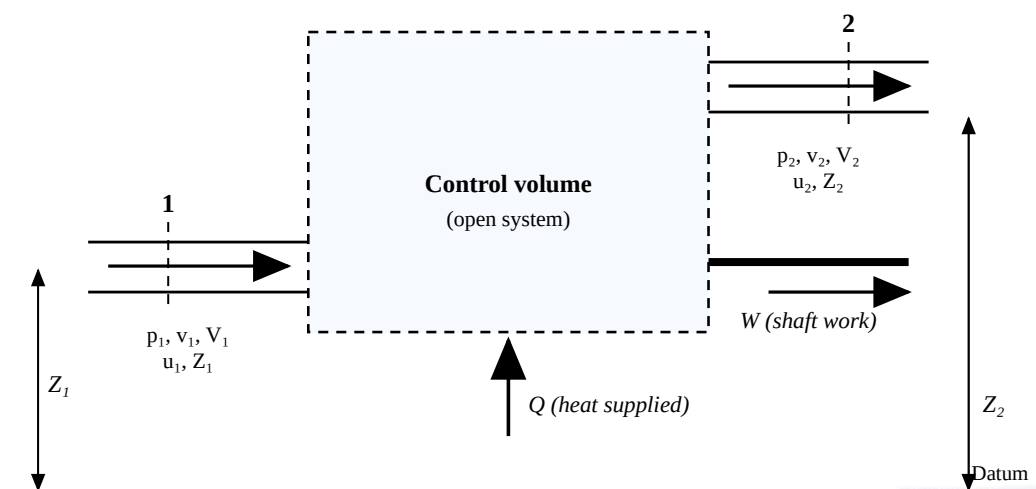


Fig.: Steady flow system (control volume)

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
$\frac{V^2}{2}$	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)

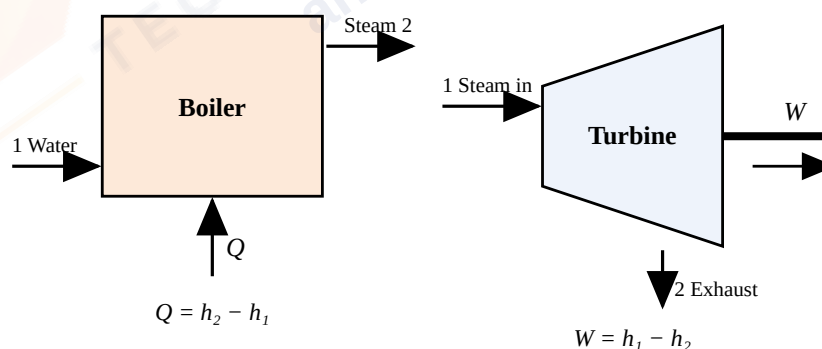


Fig.: Application of SFEE

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 → steam).

Steam turbine: Expansion is adiabatic ($q = 0$, well insulated); $\Delta K.E.$ and $\Delta P.E.$ are negligible. SFEE becomes

$$w = h_1 - h_2$$

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

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

b) Numerical — wet and superheated steam (12 bar)

6 M

From steam table at 12 bar: $t_s = 188.0^\circ\text{C}$, $v_g = 0.1632 \text{ m}^3/\text{kg}$, $h_f = 798.5$, $h_{fg} = 1985.3$, $h_g = 2783.8 \text{ kJ/kg}$

i) Wet steam, $x = 0.88$:

$$h = h_f + x h_{fg} = 798.5 + 0.88 \times 1985.3 = \mathbf{2,545.56 \text{ kJ/kg}}$$

$$v = x v_g = 0.88 \times 0.1632 = \mathbf{0.1436 \text{ m}^3/\text{kg}}$$

(volume of water, $x v_f$, is neglected)

ii) Superheated steam at 250°C : degree of superheat = $250 - 188.0 = 62.0^\circ\text{C}$

$$h_{\text{sup}} = h_g + C_{ps}(t_{\text{sup}} - t_s) = 2783.8 + 2.1 \times (250 - 188.0) = \mathbf{2,914.00 \text{ kJ/kg}}$$

$$v_{\text{sup}} = v_g \times T_{\text{sup}}/T_s = 0.1632 \times 523/461.0 = \mathbf{0.1851 \text{ m}^3/\text{kg}}$$

(superheated steam behaves approximately like a perfect gas — Charles' law)

iii) Heat required for 2 kg (constant pressure, $Q = m(h_2 - h_1)$):

$$Q = 2 \times (2,914.00 - 2,545.56) = \mathbf{736.87 \text{ kJ}}$$

Answers: Wet steam: $h = 2545.56 \text{ kJ/kg}$, $v = 0.1436 \text{ m}^3/\text{kg}$; superheated steam: $h = 2914.00 \text{ kJ/kg}$, $v = 0.1851 \text{ m}^3/\text{kg}$; heat required = 736.9 kJ .

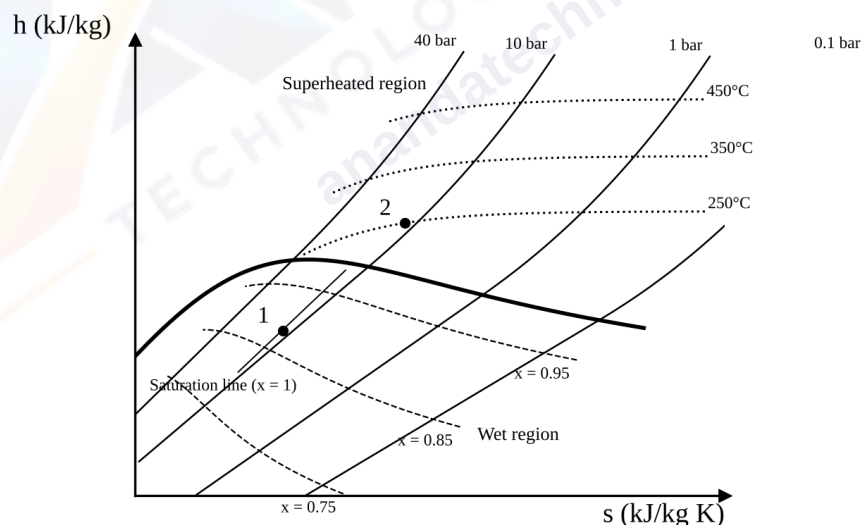


Fig.: States on h - s (Mollier) chart: 1 = wet steam $x = 0.88$, 2 = superheated 250°C (12 bar)

Check with Mollier chart (IAPWS-IF97): $h_1 = 2545.5 \text{ kJ/kg}$ and $h_2 = 2935.7 \text{ kJ/kg}$. The $C_{ps} = 2.1 \text{ kJ/kg K}$ approximation gives $h_2 = 2914.0 \text{ kJ/kg}$ — within about 1 %, which is acceptable for the exam method.

(Wet steam h , v 2 M; superheated h , v 2 M; heat 2 M)

c) Forced draught cooling tower

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.

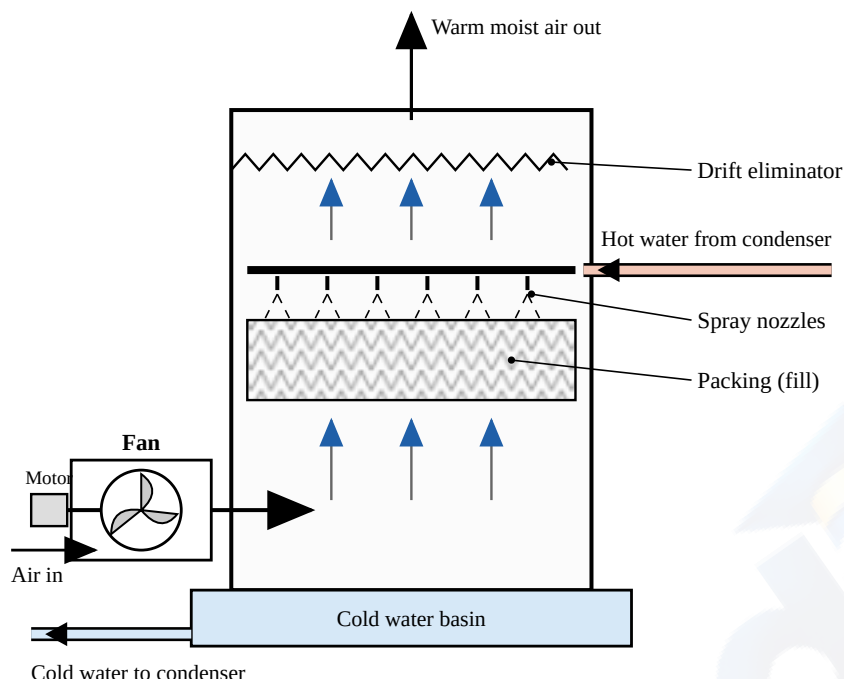


Fig.: Forced draught cooling tower

Construction: A rectangular tower made of RCC/wood/FRP, with a fan (blower) driven by a motor at the **bottom** side, water distribution pipes with spray nozzles, packing (fill), drift eliminators at the top and a cold water basin at the bottom.

Working: Hot water from the condenser is sprayed through nozzles over the packing, which breaks it into thin films and droplets to increase the contact surface. The fan at the base **forces** atmospheric air into the tower; air flows upward, counter to the falling water. Part of the water evaporates, taking latent heat from the remaining water, so the water is cooled and collects in the basin from where it is pumped back to the condenser. Warm moist air leaves from the top; drift eliminators prevent the loss of water droplets.

Features: air flow does not depend on atmospheric conditions; compact; but fan power is required and hot moist air may recirculate (fan works on cold air, which is an advantage for fan life).

(Labelled sketch 3 M, construction and working 3 M)

Q.6

a) Lamont boiler

6 M

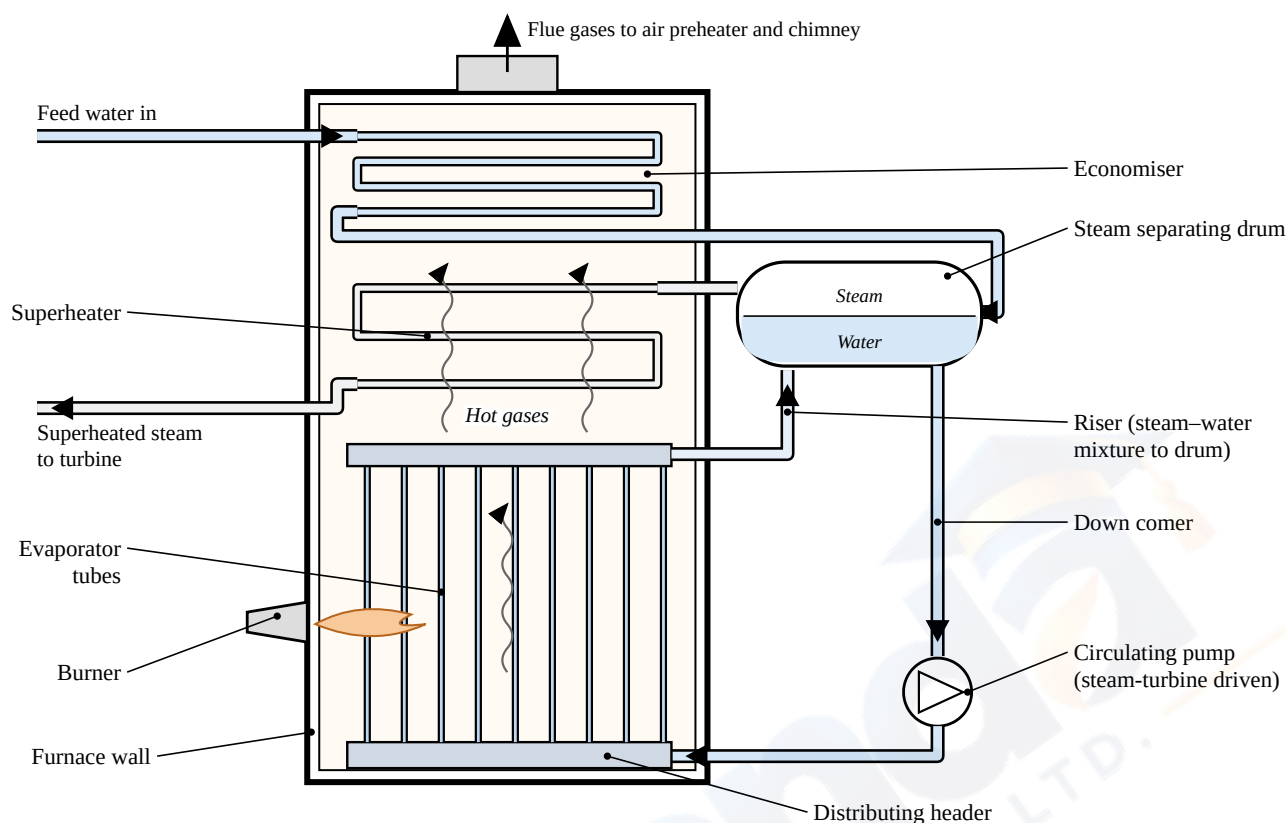


Fig.: Lamont boiler (forced circulation, water tube, high pressure)

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.

(Labelled sketch 3 M, construction and working 3 M)

b) Classification of heat exchangers; shell and tube heat exchanger

6 M

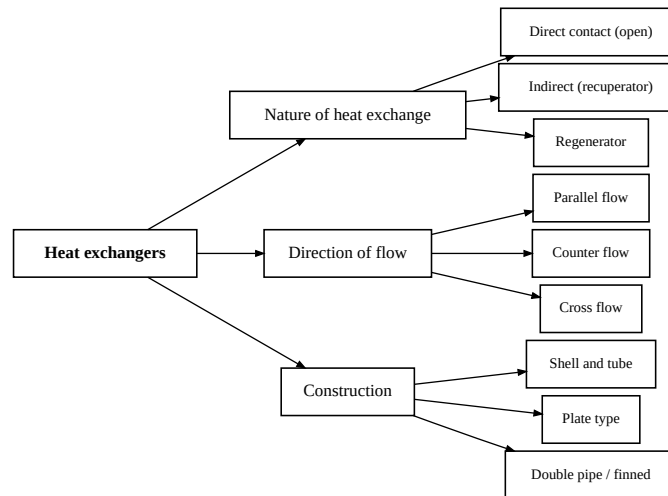


Fig.: Classification of heat exchangers

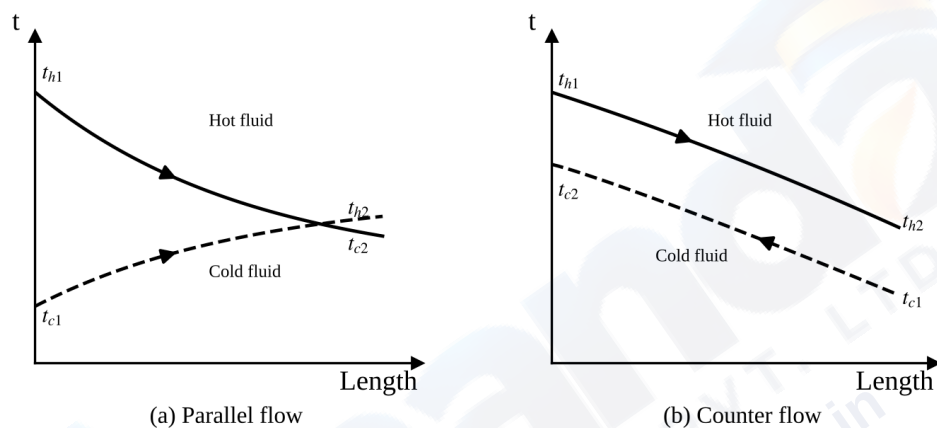


Fig.: Temperature distribution in parallel and counter flow heat exchangers

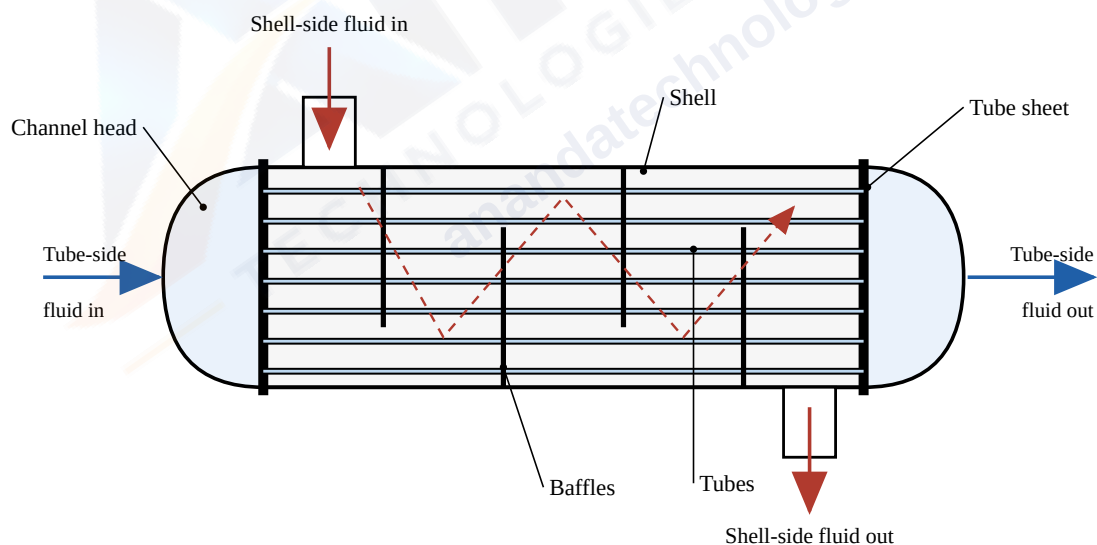


Fig.: Shell and tube heat exchanger (one shell pass, one tube pass)

Construction: A bundle of tubes is fixed between two tube sheets and enclosed in a cylindrical shell. Channel heads at both ends distribute the tube-side fluid. Baffles are fitted in the shell to direct the shell-side fluid across the tubes and to support the tubes.

Working: One fluid (e.g. cooling water) flows inside the tubes and the other fluid (e.g. steam or hot oil) flows over the tubes in the shell. Heat is transferred through the tube walls by conduction and by convection on both sides; the fluids do not mix. Baffles make the shell-side flow zig-zag, increasing turbulence and heat transfer. In a steam power plant, the **surface condenser** and feed water heaters are shell and tube heat exchangers.

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

c) Four stroke C.I. engine

6 M

Construction: cylinder, cylinder head with inlet valve, exhaust valve and fuel injector (fed by fuel pump), piston with rings, connecting rod, crank, crankshaft and flywheel. One power stroke is obtained in two revolutions of the crankshaft.

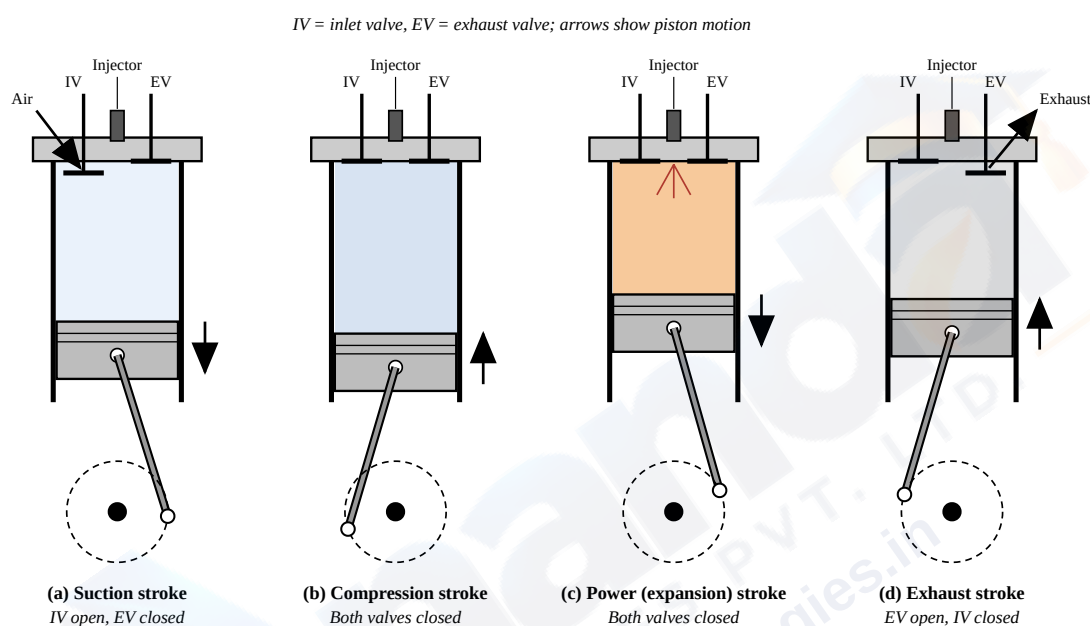


Fig.: Working of four stroke C.I. (diesel) engine

- Suction stroke:** Piston moves from TDC to BDC; inlet valve open, exhaust valve closed. Only **air** is sucked into the cylinder.
- Compression stroke:** Piston moves from BDC to TDC; both valves closed. Air is compressed to about 30–40 bar (compression ratio 14–22) and its temperature rises to about 600 °C, above the self-ignition temperature of diesel.
- Power (expansion) stroke:** Near the end of compression, diesel is **injected** by the fuel injector in fine spray; it ignites by itself. Combustion takes place at nearly constant pressure; the hot gases push the piston from TDC to BDC — work is obtained.
- Exhaust stroke:** Piston moves from BDC to TDC; exhaust valve open. Burnt gases are pushed out.

(Sketch 3 M, working of four strokes 3 M)

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