MADE EASY

ESE 2025

Main Exam Detailed Solutions

Mechanical Engineering

PAPER-I

EXAM DATE : 10-08-2025 | 09:00 AM to 12:00 PM

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Corporate Office : 44-A/1, Kalu Sarai, Near Hauz Khas Metro Station, New Delhi-110016

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9021300500 www.madeeasy.in

ANALYSIS

Mechanical Engineering Paper-I
ESE 2025 Main Examination

Sl.	Subjects	Marks
1	Fluid Mechanics	64
2	Thermodynamics	52
3	Heat Transfer	72
4	IC Engines	52
5	Refrigeration & Air-Conditioning	72
6	Power Plant Engineering	44
7	Turbo Machinery	72
8	Renewable Sources of Energy	52
		Total 480

Scroll down for detailed solutions

SECTION : A

Q.1 (a) Prove that in case of forced vortex, the rise of liquid level at the ends is equal to the fall of liquid level at the axis of rotation.

[12 marks : 2025]

Solution:

Let R = Radius of the cylinder

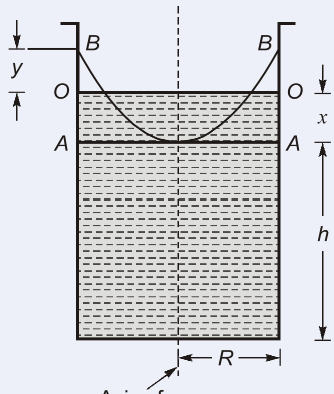
O-O = Initial level of liquid in cylinder when the cylinder is not rotating

$\therefore$ Initial height of liquid = $h + x$

$\therefore$ Volume of liquid in cylinder = $\pi R^2 \times$ Height of liquid

$= \pi R^2 \times (h + x)$ ...(i)

Let the cylinder is rotated at constant angular velocity ω. The liquid will rise at the ends and will fall at the centre.



Let y = Rise of liquid at the ends from O-O

x = Fall of liquid at the centre from O-O

Then volume of liquid = [Volume of cylinder upto level B-B]

– [Volume of paraboloid]

= [πR^2 × Height of liquid upto level B-B]

$-\left[\dfrac{\pi R^2}{2} \times \text{Height of paraboloid}\right]$

$$= \pi R^2 \times (h + x + y) - \frac{\pi R^2}{2} \times (x + y)$$

$$= \pi R^2 \times h + \pi R^2 (x + y) - \frac{\pi R^2}{2} \times (x + y)$$

$$= \pi R^2 \times h + \frac{\pi R^2}{2}(x + y) \quad \text{...(ii)}$$

Equating (i) and (ii), we get

$$\pi R^2 (h + x) = \pi R^2 \times h + \frac{\pi R^2}{2}(x + y)$$

$$\Rightarrow \quad \pi R^2 h + \pi R^2 x = \pi R^2 \times h + \frac{\pi R^2}{2} x + \frac{\pi R^2}{2} y$$

$$\Rightarrow \quad \pi R^2 x - \frac{\pi R^2}{2} x = \frac{\pi R^2}{2} y$$

$$\Rightarrow \quad \frac{\pi R^2}{2} x = \frac{\pi R^2}{2} y$$

$$\Rightarrow \quad x = y$$

or Fall of liquid at centre = Rise of liquid at the ends

End of Solution

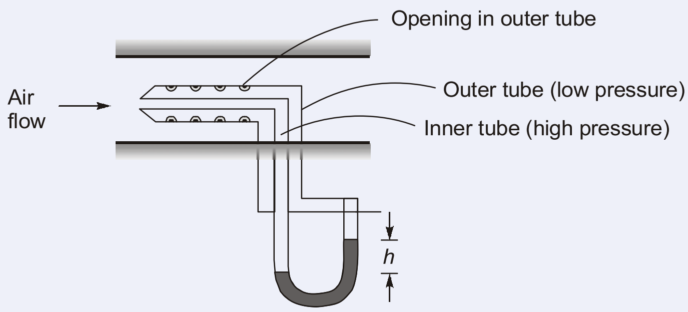
Q.1 (b) Explain, with the aid of neat sketch, the working principle of a Pitot static tube. Further, explain how the Pitot static tube differs from the Pitot tube.

[12 marks : 2025]

Solution:

The pitot tube is suitable for measuring velocity of the flow in open channel or used for measuring speed of flying aircraft. Special type of pitot tube known as pitot-static tube is used with aircraft. This consists of two concentric tubes. Inside tube faces the flow of air and it acts similar to pitot tube i.e. converting the kinetic energy of air into high pressure energy. The outer tube has openings perpendicular to the flow of air and it measures the static pressure of air (low pressure side). These two tubes are connected individually to each limb of the manometer so that the manometer level difference is the dynamic head (h).

Speed of aircraft, $V = \sqrt{2gh}$



Pitot Static Tube

Pitot Tube	Pitot-Static Tube
Pitot tube is commonly used to estimate the liquid stream in stationary fluid collections.	Pitot-static tube is a pressure-measuring device that is used in fluid dynamics and aerodynamics.
It's a pressure gauge that measures the total pressure the total pressure in a liquid framework.	Pitot-static tube, also known as a velocity test, is an instrument used to measure velocity.
It is also a pressure-detecting instrument that is commonly used to calculate liquid speed in a line or vessel.	Pitot-static tubes are aircraft instruments that combine a Pitot tube and a static port.

End of Solution

Q.1 (c) Using an ideal gas as working fluid, show that the thermal efficiency of an Ericsson cycle is identical to the efficiency of a Carnot cycle operating between the same temperature limits.

[12 marks : 2025]

Solution:

It is to be shown that the thermal efficiencies of Carnot and Ericsson cycles are identical. Heat is transferred to the working fluid isothermally from an external source at temperature T_H during process 1-2, and it is rejected again isothermally to an external sink at temperature T_L during process 3-4. For a reversible isothermal process, heat transfer is related to the entropy change by

$$q = T\Delta s$$

The entropy change of an ideal gas during an isothermal process is

$$\Delta s = c_p \ln\frac{T_e}{T_i} - R\ln\frac{P_e}{P_i} = -R\ln\frac{P_e}{P_i}$$

The heat input and heat output can be expressed as

$$q_{in} = T_H(s_2 - s_1) = T_H\left(-R\ln\frac{P_2}{P_1}\right) = RT_H\ln\frac{P_1}{P_2}$$

and

$$q_{out} = T_L(s_4 - s_3) = -T_L\left(-R\ln\frac{P_4}{P_3}\right) = RT_L\ln\frac{P_4}{P_3}$$

Then the thermal efficiency of the Ericsson cycle becomes

$$\eta_{th,\ Ericsson} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{RT_L\ln\left(\frac{P_4}{P_3}\right)}{RT_H\ln\left(\frac{P_1}{P_2}\right)} = 1 - \frac{T_L}{T_H} \qquad [\text{Since } P_1 = P_4 \text{ and } P_3 = P_2]$$

Hence, the thermal efficiency of an ericsson cycle is identical to the efficiency of a Carnot cycle operating between the same temperature limits.

End of Solution

Q.1 (d) Distinguish between the following:
(i) Thermodynamics and Heat transfer
(ii) Free convection and Forced convection
(iii) Black body and Gray body

[12 marks : 2025]

Solution:

(i)

Thermodynamics is concerned with the equilibrium states of matter, and precludes the existence of a temperature gradient. For heat exchange, temperature gradient must exist and as such heat transfer is inherently a non-equilibrium process. Thermodynamics helps to determine the quantity of work and heat interactions when a system changes from one equilibrium state to another. The analysis, however, does not provide any information on the nature of interactions and the time rate at which interactions and the time rate at which interactions occur. It simply describes how much heat is to be exchanged during a process without caring to explain how that could be achieved.

Heat transfer helps to predict he temperature distribution, which may be the function of both spatial co-ordinates and time within regions of matter. Heat transfer also helps to determine the rate at which energy is transferred across a surface of interest due to temperature gradients at the surface, and temperature difference between the different surfaces.

(ii)

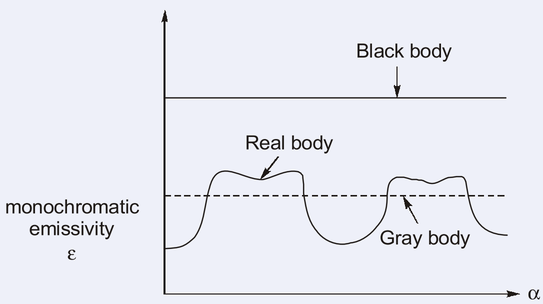
Free convection : Circulation of bulk fluid motion is caused by changes in fluid density resulting from temperature gradients between the solid surface and the main mass of fluid. The stagnant layer of fluid in the immediate vicinity of the hot body gets thermal energy by conduction. The energy thus transferred serves to increase the temperature and internal energy of fluid particles. Because of temperature rise, these particles becomes less dense and hence lighter than the surrounding fluid particles. The lighter fluid particles move upwards to a region of low temperature where they mix with the transfer a part of their energy to the cold particles. Simultaneously the cool heavier particles descend downwards to fill the space vacated by the warm fluid particles. The circulation pattern, upward movement of the warm fluid and downward movement of cool fluid, is called convection currents. These currents are setup naturally due to gravity alone and are responsible for heat convection.

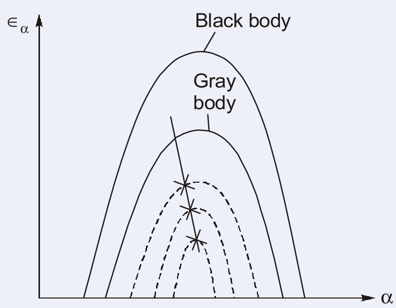
Forced convection : Flow of fluid is caused by a pump, a fan or by the atmospheric winds. These mechanical devices provide a definite circuit for the circulating currents and that speeds up the heat transfer rate. Examples of forced convection are cooling of internal combustion engines, air conditioning installations and nuclear reactors, condenser and other heat exchange equipment.

(iii)

Black body: A body is said to be a black body if it is perfect absorber and perfect emitter of radiations. A black body absorbs all the radiations incident upon it and reflects the radiation absorbed by it. Also it emits radiation equally in all direction.

Gray body: A body is said to be gray with respect to radiation if all its radiation properties are independent of wavelength. Hence monochromatic emissivity of a grey body stay constant and does not change with wavelength of emission.





End of Solution

Q.1 (e) Explain the effects of the following variables on the volumetric efficiency of an IC engine:
(i) Types of fuel
(ii) Valve overlap
(iii) Inlet valve timing
(iv) Exhaust residual
(v) Exhaust gas recirculation
(vi) Engine speed

[12 marks : 2025]

Solution:

Factors Affecting Volumetric Efficiency:

(i) Type of Fuel:
- Gaseous fuels (e.g., CNG, LPG) displace more intake air due to their volume, reducing volumetric efficiency.
- Liquid fuels like petrol or diesel, injected directly, occupy less space, hence allowing more air intake and improving volumetric efficiency.

(ii) Valve Overlap:
- Valve overlap (when both intake and exhaust valves remain open momentarily) improves scavenging at high speeds but can cause backflow of exhaust gases at low speeds, reducing volumetric efficiency.

(iii) Inlet Valve Timing:
- Advancing the intake valve closure allows more charge to enter at low rpm, improving efficiency.
- Delayed closing benefits high-speed operation via ram effect, but may reduce efficiency at lower speeds.

(iv) Exhaust Residual Gases:
- Residual gases reduce the volume available for fresh charge, thereby lowering volumetric efficiency.
- Proper scavenging and timing help minimize this effect.

(v) Exhaust Gas Recirculation (EGR):
- EGR is used to reduce NOx emissions by recirculating a portion of exhaust gases.
- It dilutes the intake mixture and reduces the oxygen content, thereby lowering volumetric efficiency, though beneficial from an emissions perspective.

(vi) Engine Speed:
- At low to moderate speeds, intake air fills the cylinder more completely.
- At very high speeds, less time is available for air induction, leading to reduced volumetric efficiency due to flow inertia and restriction losses.

End of Solution

Q.2 (a) (i) Enumerate, with the aid of illustrative sketches, the condition of equilibrium of a submerged body.

(ii) A solid cone of relative density 0.70 floats in water. What should be its minimum apex angle so that it may float its apex downwards in stable equilibrium?

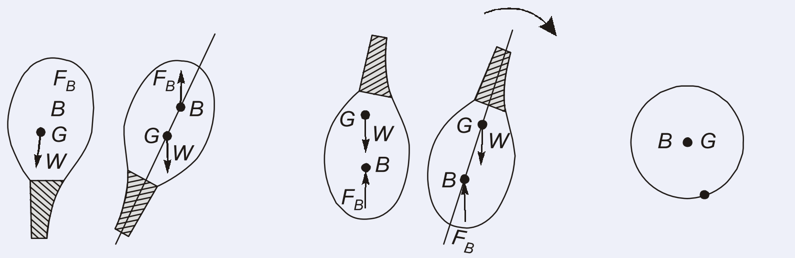
[8 + 12 marks : 2025]

Solution:

(i)

A submerged body is said to be stable if it comes back to its original position after a slight disturbance. The relative position of the centre of gravity (G) and centre of buoyancy (B) of a body determines the stability of a submerged body.

Stability of a Submerged Body: The position of centre of gravity and centre of buoyancy in case of a completely submerged body are fixed. Consider a balloon, which is completely submerged in air. Let the lower portion of the balloon contains heavier material, so that its centre of gravity is lower than its centre of buoyancy as shown in figure (a). Let the weight of the balloon is W. The weight W is acting through G, vertically in the downward direction, while the buoyant force F_B is acting vertically up, through B. For the equilibrium of the balloon $W = F_B$. If the balloon is given an angular displacement in the clockwise direction as shown in Figure (a), then W and F_B constitute a couple acting in the anti-clockwise direction and brings the balloon in the original position. Thus the balloon in the position, shown by Figure (a) is in stable equilibrium.



(a) Stable equilibrium (b) Unstable equilibrium (c) Neutral equilibrium

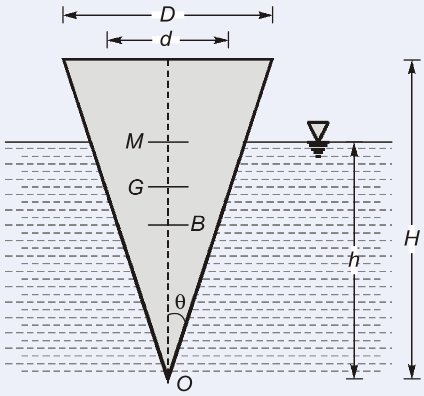
Stabilities of submerged bodies

(a) **Stable Equilibrium:** When $W = F_B$ and point B is above G, the body is said to be in stable equilibrium.

(b) **Unstable Equilibrium:** If $W = F_B$, but the centre of buoyancy (B) is below centre of gravity (G), the body is in unstable equilibrium shown in figure (b). A slight displacement to the body, in the clockwise direction, gives the couple due to W and F_B also in the clockwise direction. Thus the body does not return to its original position and hence the body is in unstable equilibrium.

(c) **Neutral Equilibrium:** If $F_B = W$ and B and G are at the same point, as shown in figure (c), the body is said to be in Neutral Equilibrium.

(ii)



The weight of the cone must be equal the weight of displaced water:

$$\gamma_{cone} V_{cone} = \gamma_{water} V_{displaced\ water}$$

$$0.7 \times \frac{1}{3}\pi R^2 H = \frac{1}{3}\pi R^2 h$$

$$h = \frac{0.7R^2 H}{r^2}$$

Substituting $R = H\tan\theta$ and $r = h\tan\theta$

$$h = \frac{0.7(H\tan\theta)^2 H}{(h\tan\theta)^2}$$

$$h = 0.8879H$$

The center of gravity of the cone:

$$OG = \frac{3}{4}H = 0.75H$$

The center of buoyancy is at the centroid of the submerged volume

$$OB = \frac{3}{4}h = 0.75 \times 0.8879H = 0.6659H$$

$$BG = OG - OB = 0.75H - 0.6657H = 0.0841H$$

The metacentric radius (MB) is given by

$$\text{MB} = \frac{I}{V}$$

The moment of inertia about the vertical axis:

$$I = \frac{1}{4}\pi r^4$$

The displaced volume: $V = \frac{1}{3}\pi r^2 h$

$$\text{MB} = \frac{\frac{1}{4}\pi r^4}{\frac{1}{3}\pi r^2 h} = \frac{0.75r^2}{h}$$

Substituting $r = h\tan\theta$

$$MB = 0.75h\tan^2\theta$$

$$MB = 0.75 \times 0.8879H\tan^2\theta = 0.6659H\tan^2\theta$$

$$GM = MB - BG$$

$$GM = 0.6659H\tan^2\theta - 0.0841H$$

For stability, GM > 0

$$0.6659H\tan^2\theta - 0.0841H > 0$$

$$\tan^2\theta > 0.1263$$

$$\tan\theta > 0.3553$$

$$\theta > 19.56°$$

$$2\theta = 2 \times 19.56 = 39.12°$$

End of Solution

Q.2 (b) Ethylene glycol (1800 kg / hr) is cooled from 100°C to 60°C by cooling water that enters the annular space of a single-pass counterflow heat exchanger at 15°C and has a mass flow rate of 1200 kg/hr. Calculate

(i) the overall heat transfer coefficient if convective heat transfer coefficient of water-side is 8.72 kW/(m^2)-deg;

(ii) the necessary length of copper tubing if it has an internal diameter of 1.25 cm;

(iii) also the length of the tube required if water flows in the same direction as ethylene glycol.

For turbulent flow of fluid inside the tube, the Dittus-Boelter relationship $Nu = 0.023(Re)^{0.8}(Pr)^{0.4}$ is to be used.

The relevant physical properties of ethylene glycol at its bulk temperature of 80°C are C_p = 2.64 kJ/kg-K; μ = 11.72 kg/hr-m, $k = 0.26 \times 10^{-3}$ kW/m-d.

[20 marks : 2025]

[Incorect internal diameter given1.25 m, so consider diameter as 1.25 cm]

Solution:

Given : d = 1.25 cm; m_g = 1800 kg/hr; m_w = 1200 kg/hr; t_{w_1} = 15°; t_{g_1} = 100°;

t_{g_2} = 60°C; μ = 11.72 kg/hr-m, c_p = 2.64 kJ/kgK;

$k = 0.26 \times 10^{-3}$ kJ/m-deg = 0.936 kW/m-deg;

h_w = 8.72 kW/m^2-deg = 31392 kJ/m^2-hr-deg

(i)

The mass flow rate of ethylene glycol is

$$m_g = \frac{\pi}{4}d^2V\rho$$

or
$$1800 = \frac{\pi}{4}(0.0125)^2 \times V\rho$$

or
$$V\rho = 14.668 \times 10^6 \text{ kg/hr-m}^2$$

$$Re = \frac{Vd\rho}{\mu} = \frac{14.668 \times 10^6 \times 0.0125}{11.72} = 15644.19$$

$$\text{Prandtl number, Pr} = \frac{\mu c_p}{k} = \frac{11.72 \times 2.64}{0.936} = 33.056$$

From the given Dittus-Boelter relationship,

$$Nu = 0.023(15644.19)^{0.8}(33.056)^{0.4}$$
$$= 211.305$$

Since $Nu = \frac{hd}{k}$, the heat transfer coefficient on the ethylene glycol side is

$$h_g = \frac{Nu \times k}{d} = \frac{211.305 \times 0.936}{0.0125}$$
$$= 15822.5184 \text{ m}^2\text{-hr-deg}$$

If thermal resistance of the tube is negligible, then overall heat transfer coefficient is given by following equation

$$\frac{1}{U} = \frac{1}{h_g} + \frac{1}{h_w}$$

where subscripts w and g refer to water and glycol respectively.

$$U = \frac{h_w \times h_g}{h_w + h_g} = \frac{31392 \times 15822.5184}{31392 + 15822.5184}$$
$$= 10520.079 \text{ kJ/m}^2\text{-hr-deg or } 2.922 \text{ kW/m}^2\text{deg.}$$

(ii)

The unknown exit temperature of the cooling water may be found from an energy balance on the two fluids, i.e.

$$m_w c_w (t_{w_2} - t_{w_1}) = m_g c_g (t_{g_2} - t_{g_1})$$
$$1200 \times 4.186(t_{w_2} - 15) = 1800 \times 2.64 (100 - 60)$$

$$\therefore \quad \text{Water outlet temperature, } t_{w_2} = \frac{1800 \times 2.64(100-60)}{1200 \times 4.186} + 15 = 52.84°\text{C}$$

From an energy balance on ethylene glycol, the heat transfer is given by,

$$Q = m_g c_g (t_{g_1} - t_{g_2}) = 1800 \times 2.64(100 - 60)$$
$$= 190080 \text{ kJ/hr}$$

$$\text{LMTD, } \theta_m = \frac{\theta_1 - \theta_2}{\log_e \frac{\theta_1}{\theta_2}}$$

where;

$$\theta_1 = t_{g1} - t_{w2} = 100 - 52.84 = 47.16°\text{C}$$
$$\theta_2 = t_{g2} - t_{w1} = 60 - 15 = 45°\text{C}$$

$$\theta_m = \frac{47.16 - 45.00}{\log_e \frac{47.16}{45.00}} = 46.072°C$$

Heat exchanger, $Q = U\,A\,\theta_m$

$\therefore$ Heating surface area, $A = \dfrac{190080}{10520.079 \times 46.072} = 0.392\ m^2$

The surface area also equals $\pi\, d\, l$ where d and l represent the tube diameter and length respectively.

$\therefore$ Required length of tube, $l = \dfrac{0.392}{\pi \times 0.0125} = 9.982\ m$

(iii) For parallel flow arrangement, $\theta_1 = t_{g1} - t_{w1} = 100 - 15 = 85°C$

$$\theta_2 = t_{g2} - t_{w2} = 60 - 52.84 = 7.16°C$$

LMTD (Parallel flow), $\theta_m = \dfrac{\theta_1 - \theta_2}{\log_e \dfrac{\theta_1}{\theta_2}} = \dfrac{85 - 7.16}{\log_e \dfrac{85}{7.16}} = 31.46°C$

For the same heat exchange rate, the area required is inversely proportional to θ_m; obviously the length of tube required is inversely proportional to θ_m. Therefore the length required for parallel flow arrangement is

$$l_P = 9.982 \times \frac{46.072}{31.46} = 14.618\ m$$

End of Solution

Q.2 (c) A 4-cylinder, 4-stroke SI engine having 70 mm bore and 84 mm stroke runs at 4000 r.p.m. and uses a fuel having 84% carbon and 16% hydrogen by mass. The volumetric efficiency of the engine is 80%. The ambient conditions are 1.0 bar and 27°C The depression at the venturi throat is 0.65 bar. Assuming the stoichiometric A / F ratio, calculate the fuel flow rate, the air velocity at the throat and the throat diameter.
[Take, R_{air} = 287 J/kg-K, $R_{fuel\ vapour}$ = 98 J/kg-K]

[20 marks : 2025]

Solution:

As the gas constant R for fuel vapour is given, instead of only volume of air supplied to the engine, the volume of mixture can be considered which is more accurate.

$\therefore$ Volume of mixture supplied to the engine,

$$V = \frac{\pi}{4} d^2 L \times \eta_v \times \frac{N}{2 \times 60} \times \text{ Number of cylinders}$$

$$= \frac{\pi}{4} \times (0.07)^2 \times (0.084) \times 0.8 \times \frac{4000}{2 \times 60} \times 4$$

$$= 0.03448\ m^3/s$$

Stoichiometric air / fuel ratio $= \frac{100}{23}\left(C \times \frac{32}{12} + H \times 8\right) = \frac{100}{23}\left(0.84 \times \frac{32}{12} + 0.16 \times 8\right)$

$= 15.3 : 1$

The density of air at 1 bar and 27°C

$$\rho_a = \frac{P}{RT} = \frac{10^5}{287 \times 300} = 1.1614 \text{ kg/m}^3$$

The density of fuel vapour, $\rho_v = \frac{10^5}{98 \times 300} = 3.4014 \text{ kg/m}^3$

The distribution of air and fuel is usually approximated by volume flow rate of air + Volume flow rate of fuel = Volume flow rate of mixture

$$\frac{\dot{m}_a}{\rho_a} + \frac{\dot{m}_f}{\rho_v} = 0.03448$$

$$\frac{\dot{m}_a}{1.1614} + \frac{\dot{m}_a}{15.3 \times 3.4104} = 0.03448 \qquad \left[\text{As} \quad \dot{m}_f = \frac{\dot{m}_a}{15.3}\right]$$

$$\dot{m}_a\left[\frac{1}{1.1614} + \frac{1}{52.179}\right] = 0.03448$$

$$\dot{m}_a = 0.0392 \text{ kg/s}$$

and $\dot{m}_f = \frac{0.0392}{15.3} = 2.56 \times 10^{-3} \text{ kg/s}$ **Ans.**

The depression at the venturi throat = 0.65 bar

$\therefore$ $\Delta P = P_1 - P_2 = 0.65$ bar

$$P_2 = P_1 - 0.65$$

$$= 1 - 0.65$$

$$P_2 = 0.35$$

or $\frac{P_2}{P_1} = 0.35$

Velocity of air at the throat,

$$C_2 = \sqrt{2C_pT_1\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

$$= \sqrt{2 \times 1005 \times 300\left[1 - (0.35)^{0.286}\right]}$$

$C_2 = 395.47$ m/s **Ans.**

Density of air at throat, $\rho_t = \frac{P_2}{RT_2}$

Also, $T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = 300(0.35)^{0.286} = 222.19$ K

$\therefore$ $\rho_t = \frac{0.35\times10^5}{287\times222.19} = 0.5489$ kg/m^3

Assuming coefficient of discharge for the throat to be unity.

The cross-sectional area of the venturi throat,

$$A_2 = \frac{\dot{m}_a}{\rho_t C_2} = \frac{0.0392}{0.5489\times395.47} = 1.8058\times10^{-4}\ \text{m}^2$$

$$\frac{\pi}{4}\times d_2^2 = 1.8058\times10^{-4}$$

$$d_2^2 = \frac{1.8058\times10^{-4}}{\pi}\times4$$

$$d_2 = 15.163\ \text{mm}$$ **Ans.**

End of Solution

Q.3 (a) (i) Let us define a thermal time constant $\tau = \frac{mC_v}{C_qA}$; mass m with an initial uniform temperature T_0 and then lower into a water bath with temperature T_∞ and the heat transfer between mass and water has a heat transfer coefficient C_q with surface area A and C_v is specific heat at constant volume. Assume radiation to be negligible. Show, with the help of suitable equations, that for a quick response, thermocouple needs a small thermal time constant while for a house, a large thermal time constant is needed.

(ii) On a hot day of summer, a car is left in sunlight with all the windows closed. After some time, it is found that inside of the car is considerably warmer than the air outside. Why?

[10+10 marks : 2025]

Solution:

(i)

The thermal time constant (τ) is a key parameter that describes how quickly a body responds to changes in its thermal environment. It represents the time taken by a body to reach approximately 63.2% of the difference between its initial and final temperatures during a thermal transient.

For a lumped system (Bi < 0.1), the thermal time constant τ is given

$$\Rightarrow \quad \tau = \frac{mc_v}{c_qA}$$

The temperature variation of a body exposed to a step change in surrounding temperature is:

$$T(t) = T_\infty + (T_0 - T_\infty)e^{-t/T}$$

Where:

$T(t)$: Temperature of the body at time t

T_0 : Initial temperature

T_0 : Surrounding (final) temperature

τ : Thermal time constant

This equation shows how quickly the temperature approaches the ambient condition.

A thermocouple is used to measure temperature changes rapidly and accurately.

For fast and accurate tracking of transient temperatures, we need:

Small τ = Fast Response

From $$\tau = \frac{mc_v}{c_q A}$$

- Small Volume (fine wires, thin junctions).
- High Surface Area to Volume Ratio.
- High heat transfer coefficient h (e.g., gas or liquid environments).
- Low mass: reduces ρV.

To respond quickly to changing temperatures, a thermocouple must have a small thermal time constant, which is achieved by using small, low-mass, high-surface-area sensors.

In building design (e.g., a house), the aim is to maintain thermal comfort and reduce fluctuation due to outside temperature variations.

A large thermal time constant ensures that: $T(t) = T_\infty + (T_0 - T_\infty)e^{-t/T}$

the temperature changes slowly over time, providing thermal inertia and reducing heating/cooling loads.

From $$\tau = \frac{mc_v}{c_q A}$$

- Large mass and volume: Walls, concrete slabs, etc.
- High specific heat capacity materials (thermal mass).
- Low surface area to volume ratio.
- Lower h due to insulation or air layers.

This slows down heat exchange and makes internal temperature stable over time.

A house should be designed with a large thermal time constant to resist rapid temperature fluctuations, leading to thermal stability and energy efficiency.

(ii)

Closed cars can get super hot quickly because sunlight heats up elements inside, such as the dashboard, upholstery, steering wheel and more. Those elements radiate their stored heat into the air, increasing the ambient temperature inside the car. This phenomenon whereby the inside of a car gets really very hot, much hotter than the outside is known as the Green House effect.

Sun light travels from the sun in the visible part of the spectrum (i.e. we can see it!) and strikes the inside surface of the car. The sunlight is absorbed by the surface of the car (say the dashboard and the carpet) and since radiation is energy, the absorption of the visible radiation causes the surface that is struck to heat up. Now----and this is the key part---- EVERY OBJECT emits energy at a wave length that is a function of the temperature of the object. Human beings around 100 deg F emit radiation in the INFRARED part of the spectrum. The human EYE cannot see this emitted radiation unless one uses special Goggles that enable this radiation to be converted to a range that the eye CAN see. In fact, this principle is the basis for NIGHT VISION goggles. Also SNAKES that catch rodents in the desert at night have such IR heat sensors!!!...

In simple terms this is a greenhouse problem in which the solar radiation entering through the windows of the vehicle is partially trapped inside the cabin of the vehicle. What actually happens is much more complex. Incident or indirect radiation from the Sun is partly reflected and partially transmitted from all external surfaces of the vehicle. Radiation (of all wavelengths) hitting the external metal surfaces is either reflected or absorbed (being opaque to all wavelengths). Glass is however transparent to light (short wavelength) radiation, but opaque to thermal (long wave length) radiation, so that the primary heat input into the cabin during daytime is sunlight transmitted directly through the windows; there is little sunlight absorption in the glass. This light radiation is subsequently absorbed (and thus converted into heat) by the dashboard, the seats and the floor of the vehicle. Furthermore, since almost all of the (short wavelength) light radiation entering the vehicle is absorbed and the windows as well as the vehicle interior are opaque to the (long wavelength) heat radiation thus generated, we have radiation trapping; the heat loss from the cabin occurs through other mechanisms. Convection currents generated within the vehicle by differential surface heating redistribute the heat to the air within the cabin. Heat losses from the vehicle occur by conduction (primarily through the roof and windows of the vehicle) combined with convective exchanges with the environment from all external surfaces.

End of Solution

Q.3 (b) (i) Establish a relation for the time taken to form a layer of ice on the surface of a pond.

(ii) Name the various types of insulating materials used in engineering and mention applications for which they are used.

[12 + 8 marks : 2025]

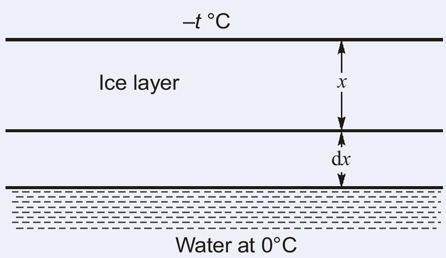
Solution:

(i)

Let x = Thickness of ice layer

$-t$°C = Temperature of air over ice

0°C = Temperature of water below ice



Let the thickness of ice layer increase by dx in time $d\tau$.

A = Surface area of pond

ρ = Mass density of ice

L = Latent heat of fusion of ice

Then Mass of ice formed = $Adx\rho$

$$\text{Heat lost by water} = Adx\rho L \quad \text{...(i)}$$

This heat has to be conducted across a layer of ice of thickness dx upwards to the surroundings at $-t$°C.

$$\text{Heat conducted} = kA\frac{dT}{x}d\tau = kA\frac{[0-(-t)]}{x}d\tau = \frac{kAt}{x}d\tau \quad \text{...(ii)}$$

Equating equation (i) and (ii), we get

$$kA\frac{t}{x}d\tau = Adx\rho L$$

$$\frac{dx}{d\tau} = \frac{kt}{\rho Lx}$$

$$d\tau = \frac{\rho L}{kt}\cdot xdx$$

Total time taken by the ice layer to increase in thickness by x.

$$\int d\tau = \frac{\rho L}{kt}\int xdx$$

$$\tau = \frac{\rho L}{kt}\frac{x^2}{2} + \text{constant}$$

When $\tau = 0$, $x = 0$, thus constant = 0

$$\therefore \quad \tau = \frac{\rho Lx^2}{2kt}$$

(ii)

There are certain situations in engineering design when the objective is to reduce the flow of heat e.g., heat exchangers, building insulation, thermos flask and so on. Thermal insulation materials must have a low thermal conductivity. In most cases this is achieved by trapping air or some other gas inside small cavities in a solid. It uses the inherently low conductivity of a gas to inhibit heat flow. Heat can, however, be transferred by natural convection inside the gas pockets and by radiation between the solid enclosure walls. The conductivity of insulating materials is, therefore, the result of a combination of heat flow mechanisms.

There are essentially three types of insulating materials:

1. **Fibrous:** Fibrous materials consist of small-diameter particles or filaments of low density that can be poured into a gap as “loose-fill” or formed into boards or blankets. Fibrous materials have very high porosity (~90%). Mineral wool is a common fibrous material for applications at temperatures below 700°C and fibreglass is often used for temperatures below 200°C. Between 700°C and 1700°C one can use refractory fibres such as alumina (Al_2O_3) or silica (SiO_2).

2. **Cellular:** Cellular insulations are closed- or open-cell materials that are usually in the form of flexible or rigid boards. They can also be foamed or sprayed to achieve desired geometrical shapes. Low density, low heat capacity and good compressive strength are their advantages. Examples are polyurethane and expanded polystyrene foam.
3. **Granular:** Granular insulation consists of small flakes or particles of inorganic materials bonded into desired shapes or used as powders. Examples are perlite powder, diatomaceous silica, and vermiculite.

End of Solution

Q.3 (c) (i) A cylinder/piston setup contains 1 L of saturated liquid refrigerant (R-410A) at 40°C. The piston now moves slowly, expands maintaining constant temperature to a final pressure of 500 kPa in a reversible process. Calculate the work done and heat transfer required to accomplish this process.

State-1

Temp (°C)	Pressure (kPa)	Specific volume, m³/kg			Enthalpy, kJ/kg-K		
		v_f	v_{fg}	v_g	h_f	h_{fg}	h_g
40	2420.7	0.001025	0.00865	0.00967	124.09	159.04	283.13

Entropy, kJ/kg-K			Internal energy, kJ/kg		
s_f	s_{fg}	s_g	u_f	u_{fg}	u_g
0.4473	0.5079	0.9552	121.61	138.11	259.72

State-2

500 kPa, −13.89°C; v (m³/kg) = 0.06775; u (kJ/kg) = 290.32

h (kJ/kg) = 324.20; s (kJ/kg-K) = 1.2398

(ii) 1. 1 kg of water at 100 kPa, 120 °C receives 50 kJ/kg in a reversible process by heat transfer. Which thermodynamic process, from the given below, will generate the largest entropy change? Justify your answer:

A. Constant temperature; B. Constant pressure

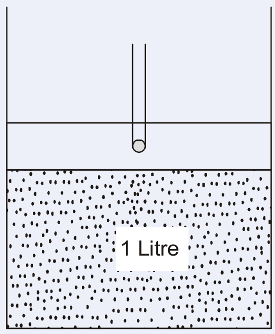
C. Constant volume

2. How can you change entropy of a substance going through a reversible process? Keep in mind the second law of thermodynamics.

[10+6+4 = 20 marks : 2025]

Solution:

(i)



Given : v_1 = 0.001025 m³/kg; v_g = 0.00967 m³/kg;

v_2 = 0.06775 m³/kg;

u_1 = 121.61 kJ/kg, u_2 = 290.32 kJ/kg

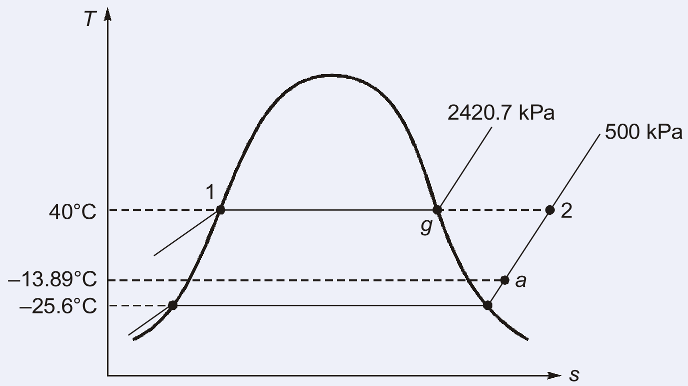
At 40°C

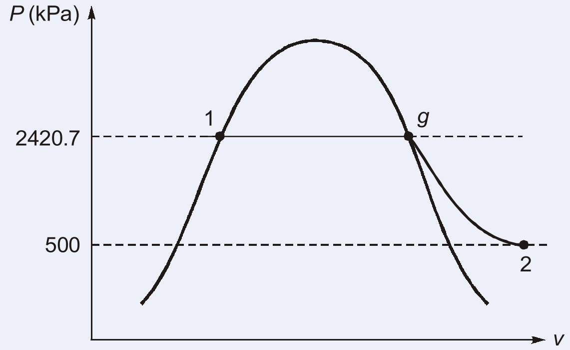
Initial specific volume of liquid, Refrigerant,

$$v_1 = 0.001025 \text{ m}^3/\text{kg}$$

Initial volume of liquid refrigerant, $V_1 = 1 \text{ L} = \frac{1}{1000} \text{m}^3$

$$\text{Mass of liquid refrigerant, } m = \frac{V_1}{v_1} = \frac{1}{1000 \times 0.001025} = 0.9756 \text{ kg}$$





Work done, $W = W_{1g} + W_{g2}$ [W_{1g} = Work constant pressure; W_{g2} = Isothermal ideal gas work]

$$= 2420.7 \times m\,(v_g - v_1) + \rho_g \times (mv_g) \ln \frac{v_2}{v_g}$$

$$= 2420.7 \times 0.9756 \times (0.00967 - 0.001025)$$
$$+ 500 \times (0.9756 \times 0.00967) \ln\left(\frac{0.06775}{0.00967}\right)$$

$$\text{Work done} = 20.416 + 9.183 = 29.599 \text{ kJ}$$

$$\Delta U = m\,(u_2 - u_1)$$
$$= 0.9756(290.32 - 121.61)$$
$$= 164.59 \text{ kJ}$$

Heat transfer required for this process,

$$Q = \Delta U + W = 164.59 + 29.599 = 194.189 \text{ kJ}$$

(ii)

1.

Given : Q = 50 kJ/kg; m = 1 kg; P = 100 kPa; T = 120°C

(A) For constant temperature process:

$$\text{Change in entropy } (\Delta s) = \frac{Q}{T} = \frac{50}{273 + 120} = \frac{50}{393} = 0.1272 \text{ kJ/kgK}$$

(B) For constant pressure process

$$\text{Change in entropy } (\Delta s) = mc_p \ln\left(\frac{T_f}{T}\right)$$

By energy balance,

$$Q = mc\ln(T_f - T)$$

$$50 = 1 \times 4.18 \times (T_f - 120)$$

$$T_f = 131.96°$$

$$\Delta s = 1 \times 4.18 \times \ln\left(\frac{404.96}{393}\right) = 0.1253 \text{ kJ/kgK}$$

$$\Delta s = 0.1253 \text{ kJ/kgK}$$

(C) Similarly for constant volume process

$$\text{Change in entropy } (\Delta s) = mc_v \ln\left[\frac{T_f}{T}\right]$$

But $(c_p)_{water} = (c_v)_{water} = c = 4.18$ kJ/kgK

∴ Entropy change for constant volume process come out similar to constant pressure process.

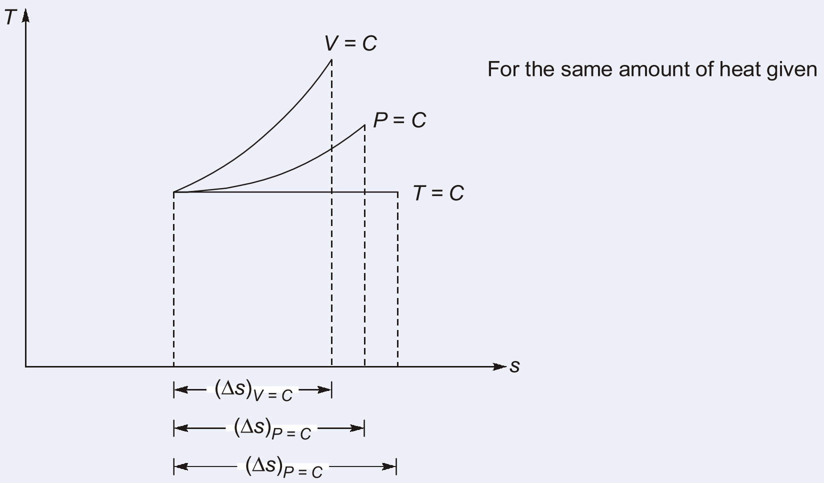
i.e. $(\Delta s)_{V=C} = (\Delta s)_{P=C} = 0.1253$ kJ/kgK

But for better understanding plot the T-s diagram for the same.

For the same amount of heat given to all the process the area under the curves are different and also it is seen that the entropy change for the various process follow the order.

$$(\Delta s)_{T=C} = (\Delta s)_{P=C} > (\Delta s)_{V=C}$$

As the slope of constant volume in steeper than the slope at constant pressure process.



2.

Entropy of a substance can change during a reversible process through heat exchange at a defined temperature. According to the second law of thermodynamics, this change $\left(\Delta S = \frac{Q_{rev}}{T}\right)$ does not violate the law, as the process is quasi-static and reversible.

While the system's entropy may change, the total entropy of the system and surroundings remains constant, preserving thermodynamic balance.

End of Solution

Q.4 (a) A cooling tower cools water from 45 °C to 25 °C. Water enters the tower at a rate of 100000 kg/hr. Air enters the tower is at 20 °C with a relative humidity of 50%; the air leaving is at 40 °C with a relative humidity of 95%. The air enters at the bottom and leaves at the top. The barometric pressure is 92 kPa. Determine-

(i) the required flow rate of atmospheric air in kg/hr;

(ii) the amount of water lost by evaporation per hour.

Saturated water—Temperature table

Temp., T °C	Sat. press., P_{sat}, kPa	Specific volume, m³/kg — Sat. liquid, v_f	Sat. vapor, v_g	Internal energy, kJ/kg — Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Enthalpy, kJ/kg — Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Entropy, kJ/kg·K — Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249
10	1.2281	0.001000	106.32	42.020	2346.6	2388.7	42.022	2477.2	2519.2	0.1511	8.7488	8.8999
15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3	0.2245	8.5559	8.7803
20	2.3392	0.001002	57.762	83.913	2318.4	2402.3	83.915	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.1698	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.2469	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.6291	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.3851	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.5953	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.352	0.001012	12.026	209.33	2233.4	2442.7	209.34	2382.0	2591.3	0.7038	7.3710	8.0748
55	15.763	0.001015	9.5639	230.24	2219.1	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898
60	19.947	0.001017	7.6670	251.16	2204.7	2455.9	251.18	2357.7	2608.8	0.8313	7.0769	7.9082
65	25.043	0.001020	6.1935	272.09	2190.3	2462.4	272.12	2345.4	2617.5	0.8937	6.9360	7.8296
70	31.202	0.001023	5.0396	293.04	2175.8	2468.9	293.07	2333.0	2626.1	0.9551	6.7989	7.7540
75	38.597	0.001026	4.1291	313.99	2161.3	2475.3	314.03	2320.6	2634.6	1.0158	6.6655	7.6812
80	47.416	0.001029	3.4053	334.97	2146.6	2481.6	335.02	2308.0	2643.0	1.0756	6.5355	7.6111
85	57.868	0.001032	2.8261	355.96	2131.9	2487.8	356.02	2295.3	2651.4	1.1346	6.4089	7.5435
90	70.183	0.001036	2.3593	376.97	2117.0	2494.0	377.04	2282.5	2659.6	1.1929	6.2853	7.4782
95	84.609	0.001040	1.9808	398.00	2102.0	2500.1	398.09	2269.6	2667.6	1.2504	6.1647	7.4151
100	101.42	0.001043	1.6720	419.06	2087.0	2506.0	419.17	2256.4	2675.6	1.3072	6.0470	7.3542
105	120.90	0.001047	1.4186	440.15	2071.8	2511.9	440.28	2243.1	2683.4	1.3634	5.9319	7.2952
110	143.38	0.001052	1.2094	461.27	2056.4	2517.7	461.42	2229.7	2691.1	1.4188	5.8193	7.2382
115	169.18	0.001056	1.0360	482.42	2040.9	2523.3	482.59	2216.0	2698.6	1.4737	5.7092	7.1829
120	198.67	0.001060	0.89133	503.60	2025.3	2528.9	503.81	2202.1	2706.0	1.5279	5.6013	7.1292
125	232.23	0.001065	0.77012	524.83	2009.5	2534.3	525.07	2188.1	2713.1	1.5816	5.4956	7.0771
130	270.28	0.001070	0.66808	546.10	1993.4	2539.5	546.38	2173.7	2720.1	1.6346	5.3919	7.0265
135	313.22	0.001075	0.58179	567.41	1977.3	2544.7	567.75	2159.1	2726.9	1.6872	5.2901	6.9773
140	361.53	0.001080	0.50850	588.77	1960.9	2549.6	589.16	2144.3	2733.5	1.7392	5.1901	6.9294
145	415.68	0.001085	0.44600	610.19	1944.2	2554.4	610.64	2129.2	2739.8	1.7908	5.0919	6.8827

[20 marks : 2025]

Solution:

Given : $\dot{m}_w$ = 100000 kg/hr; t_{w_1} = 45°C; t_{w_2} = 25°C; t_{db_1} = 20°C; ϕ_1 = 50%; t_{db_2} = 40°C; ϕ_2 = 95%; P_{atm} = 92 kPa

(i)

At 20°C and 50% RH

$$(P_{vs})_1 = 2.3392 \text{ kPa}$$

$$P_{v1} = \phi_1 \times (P_{vs})_1$$

$$P_{v1} = 0.5 \times 2.3392$$

$$P_{v1} = 1.1696 \text{ kPa}$$

$$\omega_1 = 0.622 \times \frac{P_{v_1}}{P_{atm} - P_{v_1}}$$

$$= 0.622 \times \frac{1.1696}{92 - 1.1696} = 8 \times 10^{-3} \text{ kg/kgd.a.}$$

$$h_1 = 1.005 \times t_{db_1} + \omega_1\left[2500 + 1.88 t_{db_1}\right]$$

$$= 1.005 \times 20 + 8 \times 10^{-3}\,[2500 + 1.88 \times 20]$$

$$h_1 = 40.40 \text{ kJ/kg}$$

At 40°C and 95% RH,

$$(P_{vs})_2 = 7.3851 \text{ kPa}$$

$$P_{v_2} = \phi_2 \times (P_{vs})_2 = 0.95 \times 7.3851$$

$$P_{v_2} = 7.0158 \text{ kPa}$$

$$\omega_2 = \frac{0.622 \times P_{v_2}}{P_{atm} - P_{v_2}} = \frac{0.622 \times 7.0158}{92 - 7.0158}$$

$$\omega_2 = 0.05135 \text{ kg/kg.d.a.}$$

$$h_2 = 1.005\, t_{db_2} + \omega_2[2500 + 1.88 \times 40]$$

$$h_2 = 172.436 \text{ kJ/kg}$$

By energy balance,

$$\dot{m}_w \times c_{p_w} \times \left(t_{\omega_1} - t_{\omega_2}\right) = \dot{m}_a\left(h_2 - h_1\right)$$

$$100000 \times 4.19 \times (45 - 25) = \dot{m}_a(172.436 - 40.40)$$

$$\dot{m}_a = 63467.54 \text{ kg/hr}$$

(ii) Amount of water lost by evaporation per hour

$$= \dot{m}_a(\omega_2 - \omega_1) = 63467.54 \times (0.05135 - 8 \times 10^{-3})$$

$$= 2751.32 \text{ kJ/hr}$$

End of Solution

Q.4 (b) For the velocity profile of laminar boundary layer

$$\frac{u}{U_\alpha} = \sin\left(\frac{\pi}{2} \cdot \frac{y}{\delta}\right)$$

Find the expressions for

(i) boundary layer thickness;

(ii) shear stress;

(iii) average coefficient of drag.

[20 marks : 2025]

Solution:

For velocity profile,
$$\frac{U}{U_\alpha} = \sin\left(\frac{\pi}{2} \cdot \frac{y}{\delta}\right)$$

Using momentum integral equation, we have

$$\tau_0 = \rho U_\alpha^2 \frac{\partial \theta}{\partial x}$$

$$\Rightarrow \qquad \tau_0 = \rho U_\alpha^2 \frac{\partial}{\partial x}\left[\int_0^\delta \left(1-\frac{U}{U_\alpha}\right)\frac{U}{U_\alpha}dy\right]$$

$$\Rightarrow \qquad \tau_0 = \rho U_\alpha^2 \frac{\partial}{\partial x}\left[\int_0^\delta \left[1-\sin\left(\frac{\pi}{2}\frac{y}{\delta}\right)\right]\sin\left(\frac{\pi}{2}\frac{y}{\delta}\right)dy\right]$$

$$\Rightarrow \qquad \tau_0 = \rho U_\alpha^2 \frac{\partial}{\partial x}\left[\int_0^\delta \sin\left(\frac{\pi y}{2\delta}\right)dy - \int_0^\delta \sin^2\left(\frac{\pi y}{2\delta}\right)dy\right]$$

Making the substitution

$$\sin^2\theta = \frac{1-\cos 2\theta}{2}, \text{ we get}$$

$$\tau_0 = \rho U_\alpha^2 \frac{\partial}{\partial x}\left[\int_0^\delta \sin\left(\frac{\pi}{2}\frac{y}{\delta}\right)dy - \frac{1}{2}\int_0^\delta\left\{1-\left(\cos\frac{\pi y}{\delta}\right)\right\}dy\right]$$

$$\tau_0 = \rho U_\alpha^2 \frac{\partial}{\partial x}\left[\left\{\frac{-2\delta}{\pi}\cos\left(\frac{\pi}{2}\frac{y}{\delta}\right)\right\}_0^\delta - \frac{1}{2}\left\{y-\frac{\delta}{\pi}\sin\frac{\pi y}{\delta}\right\}_0^\delta\right]$$

$$\tau_0 = \rho U_\alpha^2 \frac{\partial}{\partial x}\left[\frac{2\delta}{\pi} - \frac{\pi}{2}\right]$$

$$\tau_0 = 0.137\rho U_\alpha^2 \frac{\partial \delta}{\partial x} \qquad \textbf{Ans. (ii)} \qquad ...(i)$$

At the solid surface, Newton's law of viscosity gives:

$$\tau_0 = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0} = \mu\frac{\partial}{\partial y}\left\{U_\alpha \sin\left(\frac{\pi y}{2\delta}\right)\right\}_{y=0}$$

$$= 1.57\frac{\mu U_\alpha}{\delta} \qquad ...(ii)$$

Equating the expression (i) and (ii) for wall shear stress,

$$0.137\rho U_\alpha^2 \frac{\partial \delta}{\partial x} = 1.57\frac{\mu U_\alpha}{\delta}$$

and this can be written in the differential form as

$$\delta\partial\delta = 11.46\frac{\mu}{\rho U_\alpha}\partial x$$

Since δ is a function of x only, integration yields

$$\frac{\delta^2}{2} = 11.46\frac{\mu x}{\rho U_\alpha} + C$$

The integration constant is obtained from the boundary condition : $\delta = 0$ at $x = 0$, and that gives $C = 0$. Therefore,

$$\frac{\delta^2}{2} = 11.46\frac{\mu x}{\rho U_\alpha}$$

or $$\delta^2 = 22.92\frac{\mu x}{\rho U_\alpha}$$

This can be expressed in the non-dimensional form as

$$\frac{\delta}{x} = \sqrt{22.92}\sqrt{\frac{\mu}{x\rho U_\alpha}}$$

$$\delta = \frac{4.79}{\sqrt{R_{ex}}}$$ Ans. (i)

where, $R_{ex} = \frac{x\rho U_\alpha}{\mu}$ is the Reynolds number based on distance x from the leading edge.

(iii)

The total drag on one side of the plate with width b and length l is given by

$$\text{Total drag force, } F_D = \int_0^l \tau_0 b dx = \int_0^l \frac{\rho U_\alpha^2}{2}\times\frac{0.655}{\sqrt{R_{ex}}}\times bdx$$

$$= \frac{\rho U_\alpha^2}{2}\times\frac{0.655}{\sqrt{\frac{\rho U_\alpha}{\mu}}} b\int_0^l \frac{dx}{\sqrt{x}} = \frac{\rho U_\alpha^2}{2}\times\frac{1.31}{\sqrt{\frac{\rho U_\alpha l}{\mu}}} bl$$

$$= \frac{\rho U_\alpha^2}{2}\times\frac{1.31}{\sqrt{\frac{\rho U_\alpha l}{\mu}}} bl$$

where $R_{el} = \sqrt{\frac{\rho U_\alpha l}{\mu}}$ is the Reynolds number based on total length l of the plate.

The total drag force F_D can be expressed in terms of drag coefficient C_D, dynamic head of undisturbed flow stream $\frac{\rho U_\alpha^2}{2}$ and the area of plate.

$$F_D = C_D\times\frac{\rho U_0^2}{2}\times \text{Area}$$

For the flow configuration under investigation,

$$A = bl$$

$\therefore$ $$C_D = \frac{1.31}{\sqrt{R_{el}}}$$ Ans. (iii)

End of Solution

Q.4 (c) (i) A 4-cylinder, 4-stroke engine has cylinder diameter 10.0 cm and stroke length 10.0 cm. The engine is connected to an eddy current dynamometer, and 80.0 kW of power is dissipated by the dynamometer. Assuming engine mechanical efficiency as 85% at 4500 r.p.m. and the dynamometer efficiency as 95%, calculate

(1) the frictional power lost;
(2) the brake mean effective pressure;
(3) the engine torque at 1500 r.p.m.;
(4) the engine specific volume.

(ii) A single-cylinder SI engine is operated with gasoline of calorific value 44 MJ/kg and density 780 kg/m^3. During each combustion cycle when the flame reaches up to a height of 2 cm, combustion reaction stops due to closeness of the wall and dampens out all fluid motion while conducts heat anyway. The boundary layer of unburnt charge is formed in the combustion chamber of 4 cm diameter and fuel is distributed equally throughout the combustion chamber having unburnt charge layer of approximately 0.1 mm thickness. Find the fraction of the unburnt fuel and resulting heat loss.

[10 + 10 marks : 2025]

Solution:

(i)

1. The dynamometer measures the brake power (BP) of the engine, but the dynamometer itself has an efficiency of 95%. Thus, the actual brake power output from the engine is:

$$\text{BP}_{\text{engine}} = \frac{BP_{\text{dynamometer}}}{\eta_d} = \frac{80.0}{0.95} = 84.211 \text{ kW}$$

The mechanical efficiency relates the brake power (BP) to the indicated power (IP) of the engines as

$$\eta_m = \frac{BP}{IP}$$

$$\text{IP} = \frac{BP}{\eta_m} = \frac{84.211}{0.85} = 99.071 \text{ kW}$$

The frictional power (FP) lost is the difference between the indicated power and brake power:

$$\text{FP} = \text{IP} - \text{BP} = 99.072 - 84.211 = 14.861 \text{ kW}$$

2.
$$\text{BP} = \frac{P_{mb} \times V \times k \times n}{60 \times 1000}$$

$$= \frac{P_{mb} \times \frac{\pi}{4} \times (0.1)^2 \times (0.1) \times 4 \times \frac{4500}{2}}{60 \times 1000}$$

$$\text{BP} = P_{mb} \times 1.178 \times 10^{-4}$$

$$P_{mb} = \frac{84.211}{1.178 \times 10^{-4}} = 714805.169 \text{ Pa} = 714.805 \text{ kPa}$$

3. Torque (T), is related to brake power by:

$$\text{BP} = \frac{2\pi NT}{60 \times 1000}$$

where,

- BP is in kW,
- N is in rpm,
- T is in Nm.

Rearranging for torque:

$$T = \frac{BP \times 60 \times 1000}{2\pi N}$$

However, the brake power at 1500 rpm is not directly given. Assuming the engine's brake mean effective pressure remains approximately constant (a common assumption for torque calculations at different speeds unless specified), we can estimate the brake power at 1500 rpm using the P_{mb} from step (2).

$$\text{BP} = \frac{P_{mb} \times \frac{\pi}{4} \times (0.1)^2 \times (0.1) \times 4 \times \frac{1500}{2}}{60 \times 1000}$$

$$= \frac{714805.169 \times \frac{\pi}{4} \times (0.1)^3 \times 4 \times 1500}{120 \times 1000} = 28.07 \text{ kW}$$

Now, calculate torque at 1500 rpm:

$$T = \frac{BP \times 60 \times 1000}{2\pi N} = \frac{28.07 \times 60000}{2\pi \times 1500}$$

$$= 178.169 \text{ Nm}$$

4. Specific volume is typically defined as the volume per unit power output, often expressed as litres per kW (Displacement divided by brake power):

$$\text{Specific volume} = \frac{V_{swept}}{BP} = \frac{4 \times \text{Volume of cylinder}}{(\text{BP})_{\text{at 4500 rpm}}}$$

$$= \frac{4 \times \frac{\pi}{4} \times (0.1)^2 \times 0.1}{84.211} = 0.03731 \text{ litres/kW}$$

(ii)

Volume of fuel charge in a combustion cycle:

$$V_f = \frac{\pi}{4} D^2 \times L = \frac{\pi}{4} \times 0.04^2 \times 0.02$$

$$= 2.513 \times 10^{-5} \text{ m}^3$$

It is given that fuel is distributed equally throughout the combustion chamber and unburnt layer of 0.1 mm thickness gets formed. We have to calculate volume of this unburnt layer.

$$V_{\text{unburnt}} = \left(2 \times \frac{\pi}{4} D^2 + \pi DL\right) t$$

$$= \left(\frac{\pi}{4} \times 0.04^2 + \pi \times 0.04 \times 0.02\right) \times 0.1 \times 10^{-3}$$

$$= (2.513 \times 10^{-3} + 2.513 \times 10^{-3}) \times 0.1 \times 10^{-3}$$
$$= 5.0265 \times 10^{-7}\ m^3$$

$$\text{Fraction of unburnt fuel} = \frac{5.0265 \times 10^{-7}}{2.513 \times 10^{-5}} = 0.02 \quad \textbf{Ans.}$$

$$\text{Heat loss} = V_{unburnt} \times \rho \times CV$$
$$= 5.0265 \times 10^{-7} \times 780 \times 44 \times 10^6$$
$$= 17.25 \times 10^3\ J = 17.25\ kJ \quad \textbf{Ans.}$$

End of Solution

SECTION : B

Q.5 (a) Enumerate the advantages of using steam condenser in a steam power plant. Explain the significance of vacuum efficiency and condenser efficiency.

[12 marks : 2025]

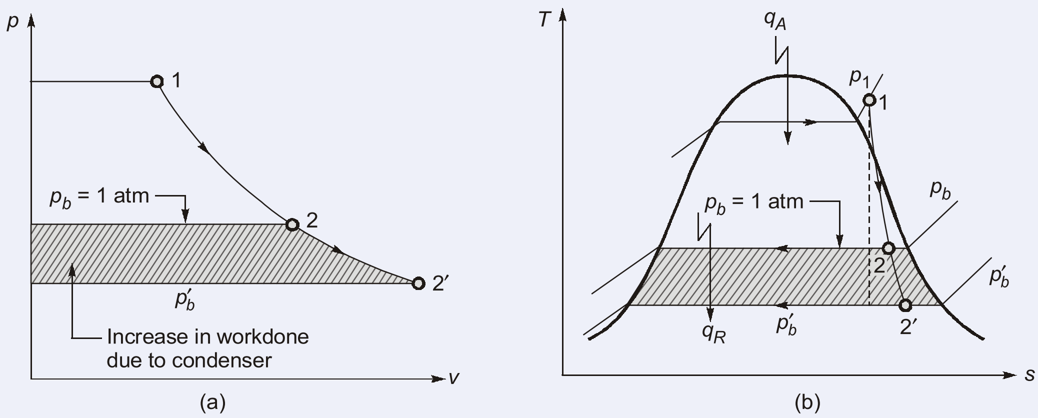
Solution:

The advantages of using steam condenser incorporated in steam power plant are:

(i) Improved workdone and efficiency due to low pressure (vacuum) of condenser.

(ii) Recovery of the condensate to be fed to the boiler as a high quality feed water for reuse.

(iii) Reduced steam consumption for the same power output due to increased workdone.



Effect of Condenser Pressure on p-v and T-s diagrams

(iv) Reduced thermal stresses due to high temperature of feed water entering to boiler.

(v) Economy in water softening plant as only make-up water is to be treated instead of full feed water.

Vacuum Efficiency (η_{vac}) : Vacuum efficiency is a measure of how close the vacuum achieved in a condenser is to the ideal (maximum possible) vacuum.

$$\eta_{vac} = \frac{\text{Actual Vacuum}}{\text{Ideal Vacuum}}$$

Significance:

- Indicates effectiveness of air removal from the condenser.
- High vacuum efficiency → Less air leakage → Better turbine performance.
- Poor vacuum reduces the pressure drop across the turbine → Reduced efficiency of the plant.

Condenser Efficiency (η_{cond}) : Condenser efficiency indicates how effectively the condenser removes heat from exhaust steam using the cooling water.

$$\eta_{cond} = \frac{\text{Rise in cooling water temperature}}{\text{Temperature difference between exhaust steam and inlet water}}$$

Significance:

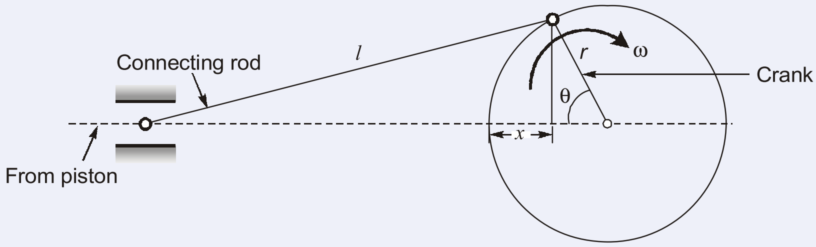
- Measures heat transfer effectiveness in the condenser.
- Higher condenser efficiency → Better heat extraction → Improved condensation → Maintains vacuum.
- Low efficiency → Higher back pressure on turbine → Lower thermal efficiency of the cycle.

End of Solution

Q.5 (b) Derive an expression for acceleration head impressed on the flow in case of a reciprocating pump. Assume that the piston has simple harmonic motion.
[12 marks : 2025]

Solution:

The schematics of piston, crank and connecting rod mechanism of a reciprocating pump has been illustrated in the figure.



Piston, crank and connecting rod mechanism

Let the crank turn through an angle θ (from inner dead centre) during time interval t when rotating with an angular velocity of ω radian/second. Then

$$\theta = \omega t = \frac{2\pi N}{60} \times t$$

where N is the rotational speed in revolutions per minute

The corresponding distance x travelled by the piston is

$$x = r - r\cos\theta = r(1 - \cos\theta)$$
$$= r(1 - \cos\omega t)$$

Velocity of the piston, $V_p = \frac{dx}{dt} = \omega r \sin \omega t$

Acceleration of the piston, $a_p = \frac{dV_p}{dt} = \omega^2 r \cos \omega t$

During suction stroke, volume of liquid flowing from the suction pipe equals the volume of liquid into the cylinder. Then from continuity considerations,

Velocity of liquid in suction pipe = Velocity of piston × $\frac{\text{Area of piston}}{\text{Area of suction pipe}}$

$$V_s = V_p \times \frac{A_p}{A_s} = \frac{A_p}{A_s} \omega r \sin \omega t$$

Acceleration of liquid in suction pipe,

$$= \frac{d}{dt}(V_s) = \frac{d}{dt}\left(\frac{A_p}{A_s} \omega r \sin \omega t\right)$$

$$= \frac{A_p}{A_s} \omega^2 r \cos \omega t$$

If l_s denotes the length of suction pipe, then mass of liquid influenced by acceleration is

= Density × Volume of liquid in pipe

$$= \rho A_s l_s = \frac{w A_s l_s}{g}$$

Invoking Newton's second law of motion, the force required to accelerate the liquid in the pipe is

= Mass × Acceleration

$$= \frac{w A_s l_s}{g} \frac{A_p}{A_s} \omega^2 r \cos \omega t$$

∴ Intensity of pressure due to acceleration = $\frac{\text{Force required to accelerate the liquid}}{\text{Area of suction pipe}}$

$$= \left(\frac{w A_s l_s}{g} \times \frac{A_p}{A_s} \omega^2 r \cos \omega t\right) \times \frac{1}{A_s}$$

$$= \frac{w l_s}{g} \times \frac{A_p}{A_s} \omega^2 r \cos \theta \qquad (\because \ \theta = \omega t)$$

∴ Pressure head due to acceleration = $\frac{\text{Intensity of pressure}}{\text{Specific weight of liquid}}$

$$= \left(\frac{w l_s}{g} \frac{A_p}{A_s} \omega^2 r \cos \theta\right) \times \frac{1}{w}$$

$$h_{as} = \frac{l_s}{g} \frac{A_p}{A_s} \omega^2 r \cos \theta$$

Hence, this is the required expression for the acceleration head.

End of Solution

Q.5 (c) What is the need of mine ventilation? Explain, with a sketch, the working of mine air-conditioning system. Also mention the various heat sources in mines.

[12 marks : 2025]

Solution:

Temperature-humidity control, one of the three functions of total mine air conditioning, is essentially heat control. It consists of those processes that are designed to regulate the sensible- and/or latent-heat content of the air: heating, cooling, humidification, and dehumidification. Temperature humidity control is akin to quality control, in that it pertains to the physical quality of the air, whereas quality control pertains to the chemical quality of the air.

The usual reason for employing air conditioning in mines is for comfort rather than product or process purposes. The heat content of the mine air is maintained within limits prescribed for the comfort, safety, and working efficiency of human beings. Occasionally, product air conditioning is employed, as in coal mines where slaking of the roof in warm, moist, summer air, or in salt mines where excessive absorption of moisture by the mineral product may constitute environmental problems.

Mine air conditioning for temperature-humidity control becomes necessary when ventilation alone is inadequate to maintain acceptable atmospheric-heat standards. If required, this aspect of total air conditioning supplements rather than replaces ventilation and quality control. The number of mines and mining districts finding it necessary to condition air, although still small, has risen sharply in the last few decades. Air conditioning can be expected to play an increasingly important role in mining under the increasingly hostile environmental conditions now being encountered under-ground.

Mine Air-conditioning System

In deep mines, natural ventilation becomes inadequate due to high geothermal gradients and machine heat. An air-conditioning system is installed to reduce heat stress and maintain a conducive working environment.

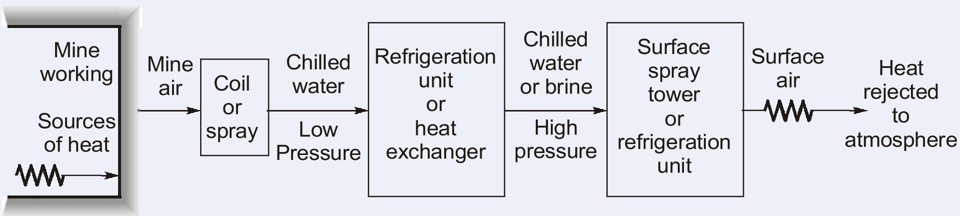
Working Principle:

Fresh air from the surface is passed through cooling towers or spray chambers, where water cools the air.

In hot mines, chilled water circulation or refrigeration plants are used, where compressors, condensers, and evaporators lower air temperature.

The conditioned air is then distributed through ducts or ventilation shafts to working areas.

The return air carries heat and contaminants back to surface exhaust fans.



Schematic of heat-transfer circuits utilized in a conventional mine air conditioning system

Sources of heat in mines :

Because cooling and dehumidification are the most critical needs in mine air conditioning, underground heat sources have to be identified and quantified. There are nine potential sources of heat in mines, the first four of which are considered major and capable of creating intolerable environmental conditions:

1. Autocompression
2. Wall rock
3. Underground water
4. Machinery and lights
5. Human metabolism
6. Oxidation
7. Blasting
8. Rock movement
9. Pipelines

End of Solution

Q.5 (d) Briefly discuss the impact of the following variables on the performance of a concentrating solar collector:

(i) Fluid inlet temperature
(ii) Mass flow rate of fluid
(iii) Concentration ratio
(iv) Type of absorber surface

[12 marks : 2025]

Solution:

Impact of Variables on Performance of a Concentrating Solar Collector

(i) Fluid Inlet Temperature: The inlet temperature of the working fluid directly affects the receiver's average temperature. As the inlet temperature rises, the receiver operates at a higher thermal level, which enhances both convective and radiative losses to the surroundings. Since radiative losses grow steeply with temperature ($\times T^4$), the overall thermal efficiency decreases with higher inlet temperatures. However, the higher outlet fluid temperature obtained is advantageous for industrial applications such as process heating and power generation, showing a trade-off between efficiency and usable output temperature.

(ii) Mass Flow Rate of Fluid: The mass flow rate governs the rate at which heat is extracted from the receiver. Increasing the flow rate reduces the temperature rise per pass, keeping the absorber surface cooler and thereby lowering thermal losses. This improves the heat removal factor and enhances the efficiency of the collector. Yet, beyond an optimum level, very high flow rates lead to excessive pumping power consumption and reduced outlet temperatures, which diminish the effective gain. Thus, system design requires a balance between efficiency, outlet temperature, and parasitic energy losses.

(iii) Concentration Ratio: The concentration ratio, defined as the ratio of aperture area to receiver area, plays a decisive role in determining collector performance. A higher concentration ratio reduces the relative receiver area, thereby lowering heat loss per unit aperture and permitting operation at higher temperatures. This raises both the thermal efficiency and the quality of output energy. In practice, however, increasing concentration also magnifies optical losses due to mirror imperfections, tracking errors, and cosine effects. At very high receiver temperatures, radiative losses may again offset the gains. Hence, an optimum concentration ratio must be chosen to maximize net performance.

(iv) Type of Absorber Surface: The absorber surface is critical in defining the balance between energy absorption and energy loss. Surfaces with high solar absorptivity and low thermal emissivity-termed selective surfaces-are ideal, as they maximize the absorption of incident solar radiation while minimizing radiative losses at elevated temperatures. Advanced coatings such as cermet-based or black chrome layers provide durability and performance stability. When combined with vacuum insulation around the receiver, these surfaces significantly reduce convective and radiative heat losses, thereby ensuring sustained efficiency and long-term reliability of concentrating solar collectors.

End of Solution

Q.5 (e) (i) Mention any four advantages of a high-pressure boiler.
(ii) Briefly explain, with the aid of an illustrative sketch, the working principle of LaMont boiler.

[4 + 8 marks : 2025]

Solution:

(i)

In all modern power plants, high pressure boilers (> 100 bar) are universally used as they offer the following advantages.

1. The efficiency and the capacity of the plant can be increased as reduced quantity of steam is required for the same power generation if high pressure steam is used.
2. The forced circulation of water through boiler tubes provides freedom in the arrangement of furnace and water walls, in addition to the reduction in the heat exchange area.
3. The tendency of scale formation is reduced due to high velocity of water.
4. The danger of overheating is reduced as all the parts are uniformly heated.

(ii)

A forced circulation boiler was first introduced in 1925 by La Mont. The arrangement of water circulation and different components are shown in figure below.

The feed water from hot well is supplied to a storage and separating drum (boiler) through the economizer. Most of the sensible heat is supplied to the feed water passing through the economizer. A pump circulates the water at a rate 8 to 10 times the mass of steam evaporated. This water is circulated through the evaporator tubes and the part of the vapour is separated in the separator drum. The large quantity of water circulated (10 times that of evaporation) prevents the tubes from being overheated.

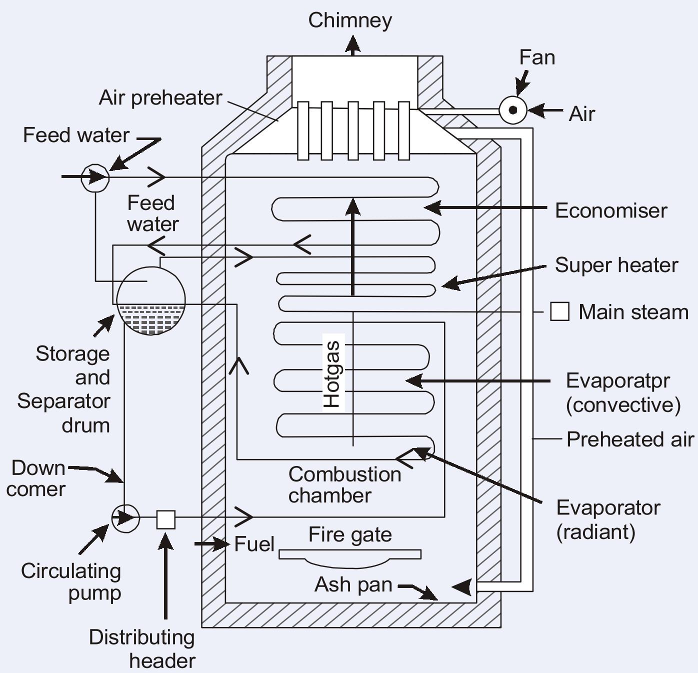


Figure : La Mont Boiler

The centrifugal pump delivers the water to the headers at a pressure of 2.5 bar above the drum pressure. The distribution headers distribute the water through the nozzle into the evaporator.

The steam separated in the boiler is further passed through the super-heater.

Secure a uniform flow of feed water through each of the parallel boiler circuits a choke is fitted entrance to each circuit.

These boilers have been built to generate 45 to 50 tonnes of superheated steam at a pressure of 120 bar and temperature of 500°C.

End of Solution

Q.6. (a) In a vapour compression refrigeration cycle based ice plant of 20 TR capacity using NH_3 as refrigerant, the following data are used for the calculations:

The temperatures of water entering and leaving the condenser are 20°C and 27°C and the temperature of brine in the evaporator is –15°C. Before entering the expansion valve, ammonia is cooled to 20°C and ammonia enters the compressor dry saturated.

Calculate

(i) the compressor power required;

(ii) the flow rate of cooling water circulated in the condenser;

(iii) the COP of the plant for 1 TR capacity.

Show the cycle on t-s and p-h diagrams. Use the properties given in the table:

Saturation Temp. (°C)	Entropy kJ/kg-K		Enthalpy (kJ/kg)		Specific heat (kJ/kg-K)	
	Liquid	Vapour	Liquid	Vapour	Liquid	Vapour
–15	0.4572	5.5490	112.34	1426.54	4.396	2.303
25	1.1242	5.0391	298.90	1465.84	4.606	2.805

[20 marks : 2025]

Solution:

Given : Q = 20 TR; T_{w_2} = 20°C = 20 + 273 = 293 K;

T_{w_1} = 27°C = 27 + 273 = 300 K; $T_{2'} = T_{3'} = 25°C = 25 + 273 = 298$ K;

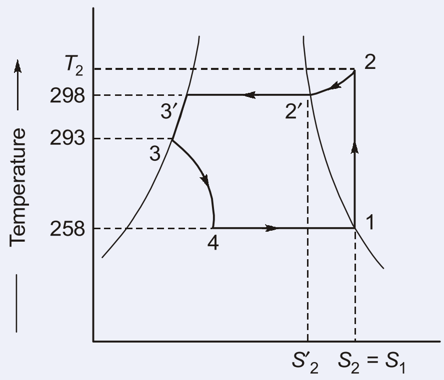
$T_1 = T_4$ = –15°C = –15 + 273 = 258 K; T_3 = 20°C = 20 + 273 = 293 K

$h_{f3'}$ = 298.90 kJ/kg; h_1 = 1426.54 kJ/kg; $h_{2'}$ = 1465.84 kJ/kg; $s_1 = s_2$ = 5.5490 kJ/kgK;

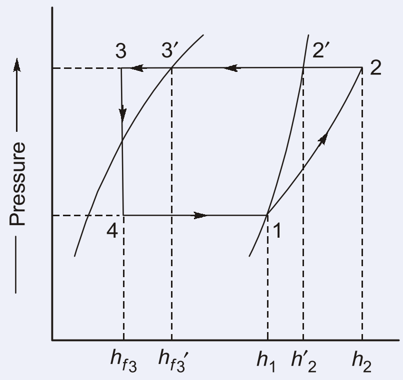
$s_{2'}$ = 5.0391 kJ/kgK; c_{pl3} = 4.606 kJ/kgK; $c_{pv2'}$ = 2.805 kJ/kgK

(i)

The T-s and p-h diagrams are shown in figure (a) and (b) respectively. First of all, let us find the temperature of refrigerant at point 2 (T_2).



(a) T-s diagram



(b) p-h diagram

$$s_2 = s_{2'} + c_{pv2'} \ln\left(\frac{T_2}{T_{2'}}\right)$$

$$5.5490 = 5.0391 + 2.805 \ln\left(\frac{T_2}{298}\right)$$

$$\ln\left(\frac{T_2}{298}\right) = \frac{5.5490 - 5.0391}{2.805} = 0.18178$$

$$\frac{T_2}{298} = 1.199 \qquad \text{...(Taking antilog of 0.079)}$$

or $$T_2 = 1.199 \times 298 = 357.302 \text{ K or } 84.302°\text{C}$$

∴ Enthalpy at point 2, $h_2 = h_{2'} + c_{pv2'}(T_2 - T_{2'})$

$$= 1465.84 + 2.805(357.302 - 298) = 1632.18 \text{ kJ/kg}$$

and enthalpy of liquid refrigerant at point 3,

$$h_{f_3} = h_{f3'} - c_{pl3} \times \text{Degree of undercooling}$$

$$= h_{f3'} - c_{pl3}(T_{3'} - T_3)$$

$$= 298.9 - 4.606(298 - 293) = 275.87 \text{ kJ/kg}$$

We know that heat extracted or refrigerating effect produced per kg of the refrigerant,

$$R_E = h_1 - h_{f3} = 1426.54 - 275.87 = 1150.67 \text{ kJ/kg}$$

and capacity of the ice plant, $Q = 20 \text{ TR} = 20 \times 210 = 4200$ kJ/min

∴ Mass flow of the refrigerant,

$$\dot{m}_R = \frac{\dot{Q}}{R_E} = \frac{4200}{1150.67} = 3.65 \text{ kg/min}$$

Work done by the compressor per minute

$$= \dot{m}_R(h_2 - h_1) = 3.65(1632.18 - 1426.54)$$

$$= 750.586 \text{ kJ/min or } 12.51 \text{ kW}$$ **Ans.**

Hence, power required by the compressor is 750.586 kJ/min or 12.51 kW.

(ii)

Let $\dot{m}_w$ = Flow rate of cooling water in the condenser

We know that heat given out by the refrigerant in the condenser

$$= \dot{m}_R(h_2 - h_{f3})$$

$$= 3.65(1632.18 - 275.87) = 4950.53 \text{ kJ/min} \quad \text{...(i)}$$

Since the specific heat of water, C_w = 4.187 kJ/kgK, therefore heat taken by water in the condenser

$$= m_w \times c_w (T_{w_1} - T_{w_2})$$

$$= m_w \times 4.187(300 - 293)$$

$$= 29.31\, m_w \text{ kJ/min} \quad \text{...(ii)}$$

Since the heat given by the refrigerant in the condenser is equal to the heat taken by water in the condenser, therefore equating equation (i) and (ii),

$$29.31\, \dot{m}_w = 4950.53$$

or $\dot{m}_w$ = 168.9 kg/min or 2.82 kg/s **Ans.**

(iii) Power expended per TR $= \dfrac{750.586}{60 \times 20} = 0.625$ kW/TR **Ans.**

COP of the plant for 1 TR capacity $= \dfrac{1}{0.625}$ TR/kW

$$= \frac{3.5}{0.625} = 5.6$$ **Ans.**

End of Solution

Q.6 (b) For a hot and humid summer condition, an air-conditioning system needs to be designed for meeting an industrial demand and the following data are used:

Outside conditions: 32°C DBT and 65% RH

Required inlet air conditions: 25°C DBT and 60% RH

Amount of free air circulated is 250 m^3/m in coil dew point temperature is 13°C. The required condition is achieved by cooling and dehumidification initially and then by heating.

Calculate the following:

(i) The cooling capacity of the cooling coil and its by-pass factor

(ii) The heating capacity of the heating coil in kW and surface temperature of the heating coil if the by-pass factor is 0.3.

(iii) The mass of water vapour removed per hour

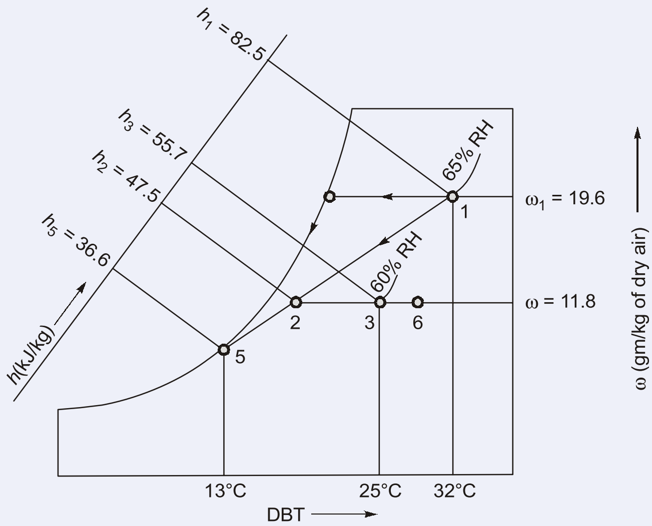
Show the psychrometric processes involved on Psychrometric Chart.

[Psychrometric Chart is given at the end of the paper]

[20 marks : 2025]

Solution:

Refer to figure,



- Locate the points '1' (32°C DBT, 65% RH), '5' (13°C) and '3' (25°C DBT, 60% RH) as shown on psychrometric chart.
- Join the line 1 - 5.
- Draw constant specific humidity line through '3' which cuts the line 1 - 5 at point '2'. The point '2' is located in this way.

From Psychrometric chart,

h_1 = 82.5 kJ/kg; h_2 = 47.5 kJ/kg; h_3 = 55.7 kJ/kg; h_5 = 36.6 kJ/kg;

ω_1 = 19.6 gm/kg; ω_3 = 11.8 gm/kg; $t_{db_2} = 17.6°C$; v_1 = 0.892 m^3/kg

The mass of air supplied per minute,

$$m_a = \frac{250}{0.892} = 280.26 \text{ kg/min}$$

(i) The capacity of the cooling coil

$$= \frac{m_a(h_1 - h_2)\times 60}{14000} = \frac{280.26(82.5-47.5)\times 60}{14000}$$

$$= 42.04 \text{ TR}$$

The by pass factor of the cooling coil is given by

$$BF = \frac{h_2 - h_5}{h_1 - h_5} = \frac{47.5-36.6}{82.5-36.6} = 0.237$$

(ii) The heating capacity of the heating coil

$$= m_a(h_3 - h_2) = 280.26(55.7 - 47.5)$$

$$= 2298.13 \text{ kJ/min} = \frac{2298.13}{60}\text{kJ/s}$$

$$= 38.3 \text{ kW}$$

The by pass factor of the heating coil is given by

$$BF = \frac{t_{db_6} - t_{db_3}}{t_{db_6} - t_{db_2}}$$

$$0.3 = \frac{t_{db_6} - 25}{t_{db_6} - 17.6}$$

$$t_{db_6} = 28.2^\circ\text{C}$$

Hence, surface temperature of heating coil = 28.2°C

(iii) The mass of water vapour removed per hour

$$= \frac{280.26(\omega_1 - \omega_3)\times 60}{1000} = \frac{280.26(19.6-11.8)\times 60}{1000}$$

$$= 131.16 \text{ kg/h}$$

End of Solution

Q.6 (c) (i) Draw and explain in detail each of the constant head characteristics of Pelton, Francis and Kaplan turbines.

(ii) A Francis turbine was installed in a power plant system. For first few years of operation, it gave noise or vibration frequency around 15 Hz. But after 10 years of operation, the noise/frequency coming out of it is around 100 Hz. Can you explain the different causes of this increase in noise or vibration and suggest the remedies for it? Can you also suggest the places where the errors are located?

(iii) Describe the significance of specific speed in turbine sizing, if any.

[20 marks : 2025]

Solution:

(i)

1. Constant Head Characteristic Curves: In order to obtain these curves the tests are performed on the turbine by maintaining a constant head and a constant gate

opening and the speed is varied by changing the load on the turbine. A series of values of N are thus obtained and corresponding to each value of N, discharge Q and the output power Pare measured. A series of such tests are performed by varying the gate opening, the head being maintained constant at the previous value. From the data of the tests the values of Q_u, P_u, N_u, and η_0 are computed for each gate opening. Then with N_u, as abscissa the values of Q_u, P_u, and η_0 for each gate opening are plotted. The curves thus obtained for Pelton wheel and the reaction turbines for four different gate openings are shown in figure.

For Pelton wheels since Q_u depends only on the gate opening and is independent of N_u, the $Q_u\ v/sN_u$, plots are horizontal straight lines. However, for low specific speed Francis turbines $Q_u v\ /sN_u$ are drooping curves, thereby indicating that as the speed increases the discharge through the turbine decreases. This is so because in these turbines a centrifugal head is developed which retards the flow. Since the centrifugal head increases with the speed, the flow through the turbine is reduced as the speed increases. On the other hand, for high specific speed Francis turbines as well as Kaplan turbines, since the flow is axial there is no such centrifugal head developed which may cause the retardation of the flow.

The curves of $P_u v/sN_u$ and $\eta_0 v/sN_u$ are parabolic in shape for the different turbines as shown in figure. It will be observed that for a Pelton wheel, for each gate opening the maximum value of η_0 is attained at almost the same value of N which corresponds to $0.46\left[K_u = \frac{(N_u \pi D)}{60\sqrt{2g}}\right]$. However, in case of reaction turbines for each gate opening the maximum value of η_0 is attained at different values of N.

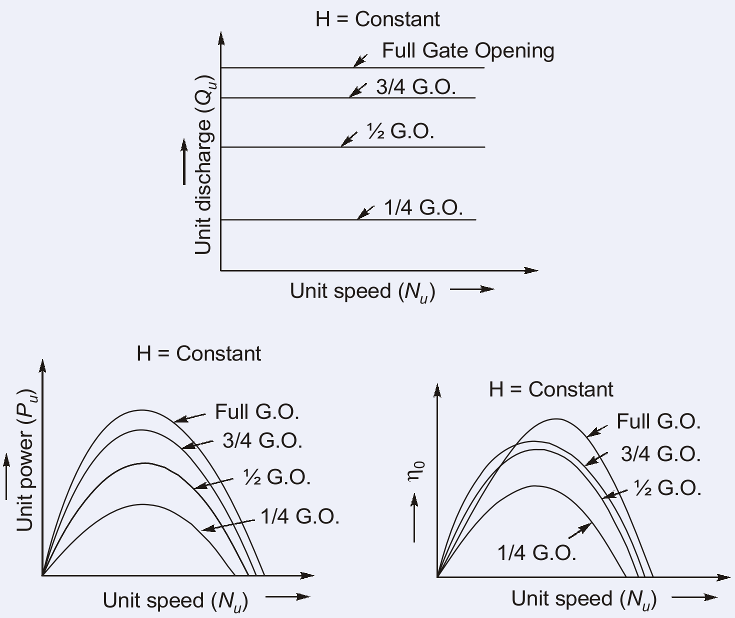


Fig. Constant head characteristic curves for a Pelton wheel

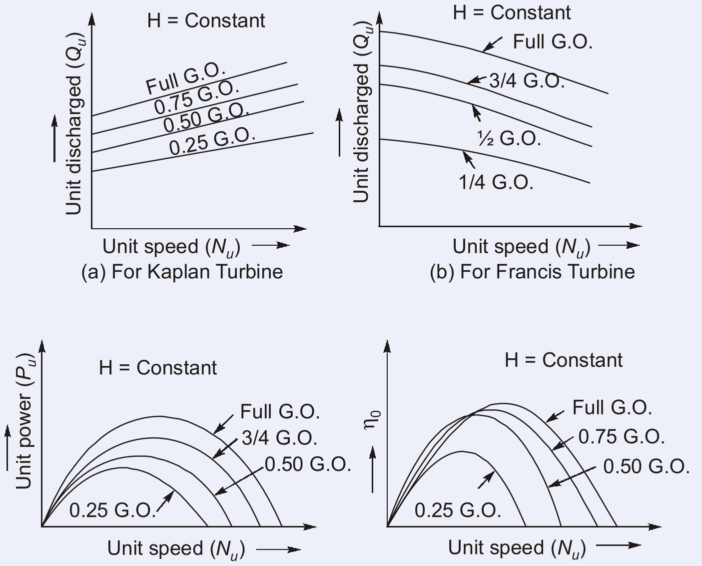


Fig. Constant head characteristic curves for Francis & Kaplan turbine

(ii)

The increase in vibration frequency from 15 Hz to 100 Hz in a Francis turbine after 10 years of operation may be attributed to factors like cavitation damage, erosion of runner blades, imbalance due to material loss, misalignment of rotating components, or bearing wear.

Aging components and silt erosion in high sediment load areas can also cause changes in flow dynamics, leading to high-frequency vibrations. Common error locations include runner blades, guide vanes, shaft, bearings, and draft tube. Remedies include regular inspection, dynamic balancing, realignment, replacement of worn parts, and ensuring clean, sediment-free water. Implementing condition monitoring systems (like vibration analysis) can help in early fault detection and maintenance planning, thus improving the turbine's longevity and operational safety.

(iii)

Significance of specific speed. Specific speed does not indicate the speed of the machine. It can be considered to indicate the flow area and shape of the runner. When the head is large, the velocity when potential energy is converted to kinetic energy will be high. The flow area required will be just the nozzle diameter. This cannot be arranged in a fully flowing type of turbine. Hence the best suited will be the impulse turbine. When the flow increases, still the area required will be unsuitable for a reaction turbine. So multi jet unit is chosen in such a case. As the head reduces and flow increases purely radial flow reaction turbines of smaller diameter can be chosen. As the head decreases still further and the flow increases, wider rotors with mixed flow are found suitable. The diameter can be reduced further and the speed increased up to the limit set by mechanical design. As the head drops further for the same power, the flow rate has to be higher. Hence axial flow units are found suitable in this situation. Keeping the power constant, the specific speed increases with N and decreases with head. The speed variation is not as high as the head variation. Hence specific speed value increases with the drop in available head. This can be easily seen from the values listed in table.

Dimensionless specific speed range	Dimensional specific speed in SI system	Type of turbine having the best efficiency at these values
0.015-0.053	8-29	Single jet Pelton turbine
0.047-0.072	26-40	Twin jet Pelton turbine
0.72-0.122	40-67	Multiple jet Pelton turbine
0.122-0.819	67-450	Radial flow turbine Francis type (H < 350m)
0.663-1.66	364-910	Axial flow Kaplan turbine. (H < 60m)

Best specific Speed Range for Different Type of Hydraulic Turbines

End of Solution

Q.7 (a) Compare running costs of winter heating system of a conference hall for which 50000 kJ/hr of heating is required using the following three methods of heating:

(i) Vapour compression cycle based heating.

(ii) Direct heating using fuel

(iii) Electric heating

Take the following data for calculation:

COP of VCRC system = 3.0

Fuel charges for light diesel oil = 64/L

Specific gravity of oil = 0.87

Heating value of fuel = 42 MJ/kg

Combustion efficiency = 0.80

Electricity charges = 8.5/unit

Now-a-days in winter season, which is the most common system being used and why?

[20 marks : 2025]

Solution:

Given : Q = 50000 kJ/hr; $(COP)_{VCRC}$ = 3; C_{diesel} = ₹64 per litre; S_{oil} = 0.87; $(C.V.)_{fuel}$ = 42 MJ/kg; η_{comb} = 0.8; $C_{electricity}$ = ₹8.5 per unit

(i) VCRC based heating :

$$(COP)_{VCRH} = 1 + (COP)_{VCRC}$$

$$= 1 + 3$$

$$(COP)_{VCRH} = 4$$

Also,

$$(COP)_{VCRH} = \frac{\text{Desired effect}}{\text{Work input}}$$

$$\text{Work input} = \frac{Q}{(COP)_{VCRH}} = \frac{50000}{4} = 12500 \text{ kJ/hr}$$

Work input in one hour is 12500 kJ.

$\therefore$ Electricity units consumed in one hour = $\dfrac{12500}{3600} = 3.4722$ units

Cost of electricity consumed = ₹8.5 × 3.4722 = ₹29.51

(ii) Direct heating using fuel:

Heat produced in one hour = 50000 kJ

Also, $Q \times \rho_{fuel} \times \eta_{comb} \times CV = 500000$

$Q \times 1000 \times 0.87 \times 0.8 \times 42 \times 1000 = 50000$

$Q = 1.7104 \times 10^{-3}\ m^3$

or $Q = 1.7104$ litre

Cost of Fuel consumption per hour = $Q \times C_{diesel} = 1.704 \times 64$

= ₹109.47

(iii) Electrical heating:

Heating produced in one hour = 50000 kJ

$\therefore$ Electricity units consumed in one hour = $\dfrac{50000}{3600} = 13.89$ units

Cost of electricity consumed = ₹8.5 × 13.89 = ₹118.07

For producing the same amount of heat, the cost of operation is lowest with a VCRC-based heating system compared to a fuel-burning heater and an electric heating. The reason lies in the high coefficient of performance (COP) of heat pumps, which transfer about 3-4 units of heat per unit of electricity consumed, unlike resistance heaters (COP $\simeq$ 1) or fuel systems limited by combustion efficiency. Thus, VCRC heat pumps are most economical and sustainable, making them the preferred option in winters.

End of Solution

Q.7 (b) Air enters a turbojet engine at 10 × 10⁴ kg / hr at 25°C and 1.03 bar, and is compressed adiabatically to 192°C and four times the pressure. Products of combustion enter the turbine at 815°C and leave the compressor at 650°C to enter the nozzle. Calculate the isentropic efficiency of the compressor, the power required to drive the compressor, the exit speed of gases, and the thrust developed when flying at 900 km/hr. Assume that isentropic efficiency of turbine is same as that of compressor and the nozzle efficiency is 90%.
Assume for air γ_a = 1.4, C_p = 1.005 kJ / kg-K and for gases assume γ_g = 1.3 and R = 1.147kJ / kg-K

[20 marks : 2025]

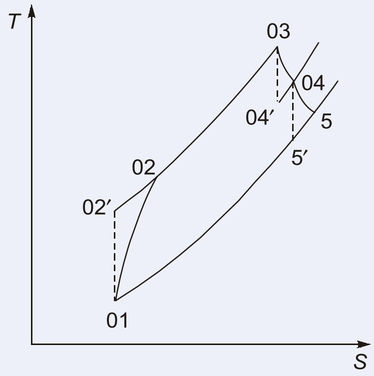
Solution:

Given : $T_{02} = 192°C = 192 + 273 = 465K$, $T_{01} = 25 + 273 = 298$ K, $\gamma_a = 1.4$

$c_p = 1.005$ kJ/kgK, $\gamma_g = 1.3$, $R = 1.147$ kJ/kgK, $\eta_n = 0.9$,

$T_{03} = 815 + 273 = 1088$ K; $T_{04} = 640 + 273 = 923$ K; $\gamma_c = 4$,

$c_i = 900$ km/h = 250 m/s, $\dot{m}_a = 10^5$ kg/h = 27.78 kg/s



$$T_{02} - T_{01} = \frac{T_{01}}{\eta_c}\left[r_c^{\left(\frac{\gamma_a-1}{\gamma_a}\right)} - 1\right]$$

$$465 - 298 = \frac{298}{\eta_c}\times\left(4^{0.286} - 1\right)$$

$$\eta_C = 86.827\% = \eta_T$$ **Ans.**

$$\text{Compressor work, } W_C = \dot{m}_a C_p (T_{02} - T_{01}) = 27.78\times 1.005\times(465-298)$$

$$= 4662.46 \text{ kW}$$ **Ans.**

Also,

$$T_{03} - T_{04} = \eta_T T_{03}\left(1 - \frac{1}{(r_t)^{\left(\frac{\gamma_g-1}{\gamma_g}\right)}}\right)$$

$$1088 - 923 = 1088\times 0.8683\times\left(1 - \frac{1}{(r_t)^{0.231}}\right)$$

$$r_t = 2.296$$

$$p_{04} = \frac{p_{03}}{r_t} = \frac{4.12}{2.296} = 1.7944 \text{ bar}$$

$$\frac{p_{04}}{p_a} = \frac{1.7944}{1.06} = 1.742$$

$$\frac{p_{04}}{p_c} = \frac{1}{\left[1 - \frac{1}{\eta_n}\left(\frac{\gamma_g - 1}{\gamma_g + 1}\right)\right]^{\frac{\gamma_g}{\gamma_g - 1}}}$$

$$= \frac{1}{\left[1 - \frac{1}{0.9}\left(\frac{0.3}{2.30}\right)\right]^{4.333}} = 1.971$$

Nozzle will not choke,

$$\therefore \qquad \frac{T_{5'}}{T_{04}} = \left(\frac{p_5}{p_{04}}\right)^{\frac{\gamma_g - 1}{\gamma_g}}$$

$$T_{5'} = 923 \times \left(\frac{1.03}{1.7944}\right)^{\frac{0.3}{1.3}} = 812.02 \text{ K}$$

$$\eta_n = \frac{T_{04} - T_5}{T_{04} - T_{5'}}$$

$$T_5 = T_{04} - \eta_n \left(T_{04} - T_{5'}\right)$$

$$= 923 - 0.9 \times (923 - 812.02) = 823.12 \text{ K}$$

$$c_j = \sqrt{2 \times 1147 \times (923 - 823.12)} = 478.67 \text{ m/s} \qquad \textbf{Ans.}$$

$$F = \dot{m}_a \left(c_j - c_i\right) = 27.78 \times (478.67 - 250)$$

$$= 6352.45 \text{ N} \qquad \textbf{Ans.}$$

End of Solution

Q.7 (c) (i) A small rural village having 40 houses with 5 members each is located remotely. Design a solar photovoltaic system to meet the daily energy needs, considering 24 × 7 energy requirements. Assume the following data for solar panel:

Peak power = 80 W
Voltage at peak power = 17.6 V
Current at peak power = 4.55 A
Operating factor = 0.8
Mismatch factor = 0.85
Sunshine hours = 5 hr/day
State clearly, if any assumptions are made.

(ii) What are the important factors affecting the solar cell performance? Discuss in brief.

[10 + 10 marks : 2025]

Solution:

(i)

Given : Peak power = 80 W; operating factor = 0.8, mismatch factor = 0.85, sunshine hours = 5 hr/day

Assumptions (per house)

2 LED lamps (9 W each, 5 hr/day) = 90 Wh/day

1 Fan (60 W, 8 hr/day) = 480 Wh/day

TV/Radio (60W, 4 hr/day) = 240 Wh/day

Phone charging (10W, 5 hr/day) = 50 Wh/day

Total daily energy per hour = 860 Wh/day or 0.86 kWh/day

$$\text{Daily power output per panel} = \text{Peak power} \times \text{Sunshine hours} \times \text{Operating factor} \times \text{Mismatch factor}$$
$$= 80 \times 5 \times 0.8 \times 0.85$$
$$= 272 \text{ Wh/day}$$
$$= 0.272 \text{ kWh/day}$$

$$\text{Number of panels required} = \frac{\text{Total daily energy usage in village}}{\text{Daily power output per panel}}$$
$$= \frac{40 \times 0.86}{0.272} = 126.5 \simeq 127 \text{ panels}$$

(ii)

The important factors affecting the solar cell performance are:

1. **Weather Change :** Lot of us assumes that high temperature leads to high solar panel efficiency, but it is just a myth. As heat exposure can prematurely degrade solar cells as for daily production, high temperatures lead to a drop in voltage and a drop in overall power. Solar cells perform better in the cold rather than in hot climates, such as if solar panels are exposed to 25°C, which can be significantly different from the real outdoor situation. Hence whatever single temperature rises above 25°C the solar panel output decays by about 0.25% for amorphous cells and about 0.4-0.5% for crystalline cells. Thus, in hot summer days, panel temperature can easily reach 70°C or more where the panels will put out up to 25% less power compared to what they rate for at 25°C. Therefore in most of India when the temperature is High about 45°C and high demand for electricity in April/May/June, a 100 W panel will produce only 75 W.
2. **Shading :** Shading is same as a clog in the pipe of running water, as it restricts the water in same pipe way solar cell is shaded, when the shadow falls on even a small part of the solar panel the current through the entire string is reduced. The cells within a panel are mostly connected wired in series, and the shaded cells affect the current flow of the whole solar power system. But in real life, there will befall of shadow some or the other day; hence partial shading should be considered while planning the installation. If the affected panel is wired in series (in a string) with other panels, then the output of all those panels will be affected by the partial shading of one panel. In such a situation, an obvious solution is to avoid wiring panels in series if possible.
3. **Roof Orientation :** The positioning of the solar panel must be facing a south direction for those living in the Northern Hemisphere and the sun is always along the southern part of the sky. Hence it is generally the best practice to position solar panels facing south to capture the maximum amount of sunlight overall.

   The south-facing solar panels should be tilted between a 30 and 40 degree angle so that behind this angle specificity is to ensure sunlight hits panels at a perpendicular angle, which produces the most energy. An edge along these lines also helps snow to slide off of solar panels more quickly during winter in the northern latitudes.

   The angle of inclination of the solar panels should be actively adjusted according to changes in seasons, latitude and longitude and sunshine hours.

4. **Cleanliness of Solar Panel Surface :** The cleanliness of the solar panel surface is directly connected to photoelectric power conversion. Due to polluted environment, rainfall, snow, dust, sandstorms are few factors can play a role in reducing the efficiency of solar module hence ensure cleaning frequency of the solar panels according to the local labour cost.

   In most places, there's more pollution in the winter; hence spring is the best time to do an annual cleaning. While once solar panels are cleaned once or twice a year they will produce 3.5% and 5.1% more electricity compared to uncleaned.

5. **Location :** Not all places have the same abundance of annual sunshine. To decide the amount of solar radiation received in your home isolation is a tough job in designing a cost-effective solar array for your usage.

   Insolation is identified by elements such as local weather, the time of year, and most importantly, the latitude of your home or company.

   Depending upon the season there will be a different climate in different locations; hence your solar panel's production numbers will be different according to the season remember to consider annual production.

End of Solution

Q.8 (a) (i) A blast furnace gas has the following volumetric compositions:

CO_2 = 10%
CO = 30%
H_2 = 1.5%
N_2 = 58.5%

Determine the theoretical volume of air required for the complete combustion of 1 m^3 of the gas. Also determine the percentage composition of dry flue gases by volume. Consider that air contains 21% of O_2 and 79% of N_2 by volume.

(ii) How does ash in the coal affect power plant economics?

[14+6 marks : 2025]

Solution:

(i)

Volumetric composition of gas

CO_2 = 10%
CO = 30%
H_2 = 1.5%
N_2 = 58.5%

Name of gas	Volume per cubic metre of gas	O_2 required per cubic meter of constituent	O_2 required per cubic meter of gas
CO_2	0.1	—	—
CO	0.3	0.5	0.15
H_2	0.015	0.5	7.5×10^{-3}
N_2	0.585	—	—

Total oxygen required = 0.15 + 7.5 × 10^{-3} = 0.1575

Theoretical volume of air required for complete combustion

$$= 0.1575 \times \frac{100}{21} = 0.75 \text{ m}^3 \text{ of air/m}^3 \text{ of gas}$$

Total volume of CO_2 in exhaust = CO_2 in fuel + CO_2 due to CO in fuel

= 0.1 + 0.3 = 0.4 m^3

Total volume of N_2 in exhaust = N_2 in fuel + N_2 in supplied air

= 0.585 + 0.79 × 0.75 = 1.178 m^3

Total volume of dry flue gas = $V_{CO_2} + V_{N_2}$ = 0.4 + 1.178 = 1.578 m^3

%Composition of CO_2 in dry flue gases by volume = $\frac{0.4}{1.578} \times 100 = 25.35\%$

%Composition of N_2 in dry flue gases by volume = $\frac{1.178}{1.578} \times 100 = 74.65\%$

(ii)

Coal used in Indian thermal power plants typically contains 30-45% ash, much higher than imported coal. High ash content directly impacts the economics of power generation. First, it lowers the calorific value, requiring more coal for the same power output, which raises fuel handling and transport costs. Since transport charges are based on weight rather than energy content, a large portion of expenditure goes into carrying non-combustible material. Second, ash necessitates over-designed boilers, frequent maintenance of tubes and mills, and extensive ash-handling systems, increasing both capital and operating costs. Third, disposal of large ash volumes demands land, water, and investment in ash ponds, while stricter emission norms require costly pollution control devices. High ash also reduces plant efficiency through higher auxiliary power use.

Thus, excessive ash reduces efficiency, increases costs, and complicates environmental management, undermining the competitiveness of coal power and highlighting the need for coal washing and cleaner technologies.

End of Solution

Q.8 (b) (i) What is the need of alternative fuels for transportation? Compare the utility of bio-diesel and bio-alcohol in Indian context.

(ii) A wind turbine is operating at wind speed of 7.0 m/s to pump water at a rate of 5 m^3 / hr with a lift of 6.0 m. Calculate the radius of the rotor and the tip speed ratio.

Assume: Water density = 1000 kg/m^3
Water pump efficiency = 45%
Efficiency of rotor to pump = 80%
Power coefficient = 0.25
Air density = 1.2 kg/m^3
Angular velocity of the rotor = 60 r.p.m.

[10 + 10 marks : 2025]

Solution:

(i)

The road transport sector, one of the major energy consumers in the country, has been growing at a steady pace and India is moving towards becoming the world's 3rd largest automobile market in the next few years, which will put pressure on India's energy requirements to fuel this growth. At the same time this will also have an impact on the contribution of transport sector towards the CO_2 emitted.

Further, the emission standards for automobile industry are being made stringent to mitigate the air pollution and its adverse impact on the environment and human health.

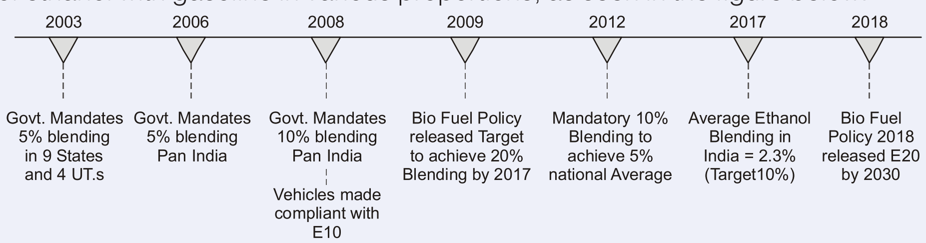
India is taking multi-pronged measures to expand the domestic energy production in terms of oil, gas, coal, nuclear and hydropower in the coming decade. Despite several options and opportunities, alternative fuels are struggling to occupy a significant energy space. India in 2016 achieved its highest ever ethanol market penetration, a gasoline blend rate of 3.3% but dropped to 2.3% in 2017 on average across the country.

The alternative fuels provide the best option to replace the traditional fossils and provide opportunities for reducing the import of oil bill, mitigation of pollution, and can be produced sustainably. Moreover, India with plentiful natural renewable energy resources can exploit them for achieving the economic and social development in an environmentally compatible manner.

The alternative fuels are in focus across the world due to their inherent benefits in terms of economy, high quality of energy, environmental compatibility and renewability. Therefore, several countries like USA, Brazil, Canada, Australia, China, Thailand and most European countries are in the process of transition to move over to higher share of alternative fuels to avoid the economic and environmental crisis which may to emanate from depleting fossil fuels and their fluctuating prices. Off late, the Government is emphasizing on the need of a comprehensive and inclusive policy on the alternative fuels focusing on low hanging fruits like CNG, LPG/LNG, bio-diesel and biofuels with a clear road map for enhancing the production of alternative fuels and commensurately reducing the reliance on the fossils fuels.

1. Bio-Alcohol : The most common biofuel, bio-alcohol, is produced from biomass containing sugar-based components, like sugar cane, sugar beet, sweet sorghum. It is also produced from starch containing materials such as corn, cassava, algae including cellulosic materials viz. bagasse, wood waste, agricultural and forestry residues or other renewable resources like industrial waste. However, in India 98% ethanol is produced from sugarcane molasses.

   Government of India announced various policies from time to time regarding blending of ethanol with gasoline in various proportions, as seen in the figure below:



Government policies on biofuel blending

2. **Bio-Diesel :** Bio-diesel is a methyl or ethyl ester of fatty acids (fatty acid methyl ester, FAME) produced from non-edible vegetable oils, acid oil, used cooking oil or animal fat and bio-oil. Government of India notified policies for blending bio-diesel.

The Government of India had initiated a Bio-Diesel Purchase Policy in October 2005 and permitted the sale of bio-diesel (B100) by private manufacturers to bulk consumers. Retailing of bio-diesel blended diesel by Public Sector Oil Marketing Companies (OMCs) has started on 10th August 2015 for blending with High Speed Diesel (HSD) to the extent of 5% at identified 20 purchase centers across the country.

(ii)

Given : $V = 7$ m/s; $Q = 5$ m^3/hr; $H = 6$ m; $\eta_p = 0.45$; $C = 0.25$; $\eta_r = 0.8$; $\rho_{air} = 1.2$ kg/m^3; $N = 60$ rpm

As we know, power required to lift the water

$$P = \frac{\rho g Q H}{\eta_p \times \eta_r} = \frac{1000 \times 9.81 \times 5 \times 6}{0.45 \times 0.8 \times 3600}$$

$$P = 227.08 \text{ W}$$

Also, area swept by the rotor,

$$A = \frac{P}{0.5 \times \rho_{air} \times C \times V^3} = \frac{227.08}{0.5 \times 1.2 \times 0.25 \times (7)^3}$$

$$A = 4.414 \text{ m}^2$$

$$\pi R^2 = 4.414 \text{ m}^2$$

$$R^2 = \frac{4.414}{\pi}$$

$$R = 1.185 \text{ m}$$

$$\text{Tip speed ratio, } \lambda = \frac{R \times \omega}{V} = \frac{1.185 \times 2 \times \pi \times 60}{7 \times 60}$$

$$\lambda = 1.064$$

End of Solution

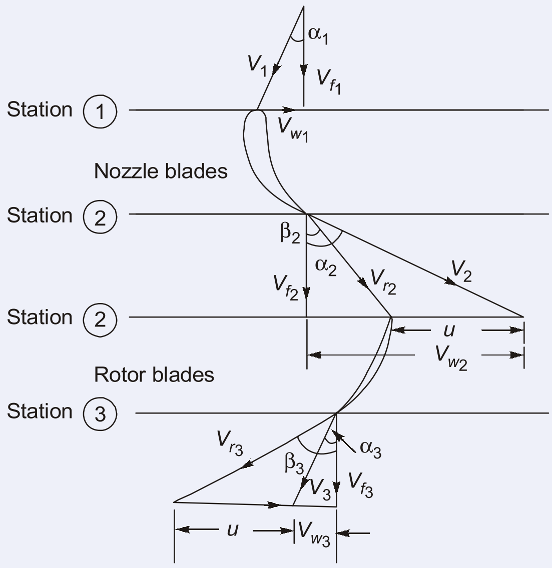
Q.8 (c) Gas at 8 bar and 300°C expands to 4 bar in an impulse turbine stage. The nozzle angle is 65° with reference to the exit direction. The rotor blades have equal inlet and outlet angles, and the stage operates with optimum blade speed ratio. Assuming that the isentropic efficiency of the nozzle is 0.9 and velocity at entry to the stage is negligible, deduce the blade angle used and the mass flow required for this stage to produce 75 kW.

[Given, $C_p = 1.15$ kJ/kg-K, $\gamma = 1.333$]

[20 marks : 2025]

Solution:

Given : T_{01} = 573 K; η_n = 0.9 C_p = 1150 J/kg-K, γ = 1.333; α_2 = 65°



Velocity triangles for a turbine stage

Let the suffix 1, 2 and 3 represent the entry to the nozzle blade, exit from the nozzle blade (entry to rotor blade) and exit from the rotor blade respectively.

Let $T_{02'}$ be the isentropic temperature after expansion in the nozzle.

$$\frac{T_{02'}}{T_{01}} = \left(\frac{P_{02}}{P_{01}}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4}{8}\right)^{\frac{0.333}{1.333}} = 0.841$$

$$T_{02'} = 573 \times 0.841 = 481.89 \text{ K}$$

$$T_{02} = T_{01} - \eta_n \times (T_{01} - T_{02'})$$

$$= 573 - 0.9 \times (573 - 481.89) = 491 \text{ K}$$

$$V_2 = \sqrt{2C_p \Delta T}$$

$$= \sqrt{2 \times 1150 \times (573 - 491)} = 434.28 \text{ m/s}$$

For optimum blade speed ratio

$$\frac{u}{V_2} = \frac{1}{2}\sin\alpha_2$$

$$u = \frac{434.28 \times \sin 65}{2} = 196.79 \text{ m/s}$$

$$\tan\beta_2 = \frac{V_{w_2} - u}{V_{f_2}} = \frac{V_2 \sin\alpha_2 - u}{V_2 \cos\alpha_2}$$

$$= \frac{434.28 \times \sin 65 - 196.79}{434.28 \times \cos 65} = 1.0723$$

$$\beta_2 = 46.997°$$

Also,

$$V_{w_2} = V_2 \sin\alpha_2 = 434.28 \times \sin 65$$

$$= 393.59 \text{ m/s}$$

$$V_{f_2} = V_{r_2} \cos\beta_2 = V_2 \cos\alpha_2$$

$$V_{r_2} = \frac{V_2 \cos\alpha_2}{\cos\beta_2} = \frac{434.28 \times \cos 65}{\cos 46.997}$$

$$= 269.09 \text{ m/s}$$

Also,

$$V_{r_2} = V_{r_3} = 269.09 \text{ m/s}$$

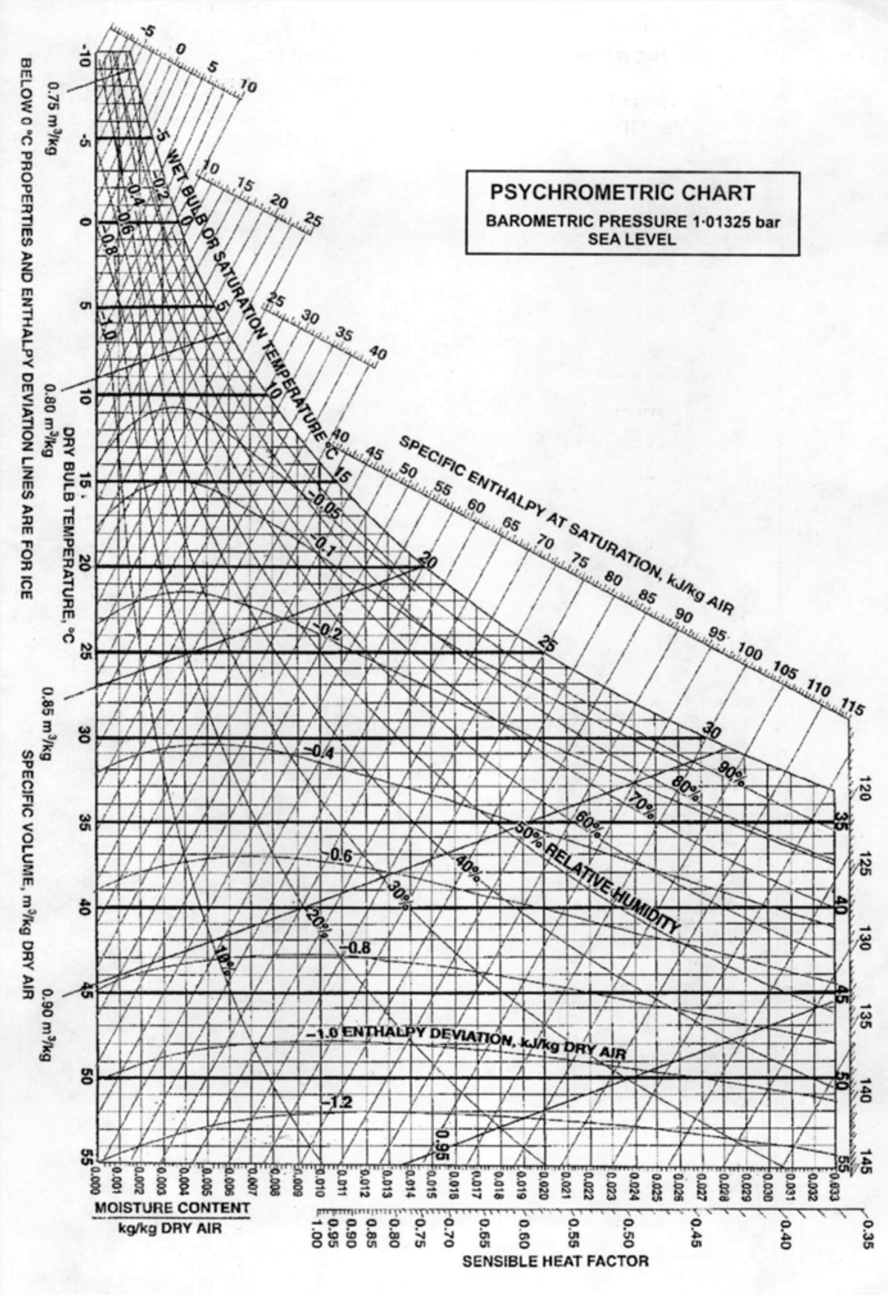
$$V_{w_3} = V_{r_3} \sin\beta_3 - u = 269.09 \times \sin 46.997 - 196.79$$

$$= 3.58 \times 10^{-4} \text{ m/s}$$

$$W_T = \frac{\dot{m}u}{1000}(V_{w_2} + V_{w_3})$$

$$\dot{m} = \frac{75 \times 1000}{196.79 \times (393.59 + 3.58 \times 10^{-4})} = 0.968 \text{ kg/s}$$

End of Solution


PSYCHROMETRIC CHART
BAROMETRIC PRESSURE 1·01325 bar
SEA LEVEL
WET BULB OR SATURATION TEMPERATURE °C
SPECIFIC ENTHALPY AT SATURATION, kJ/kg AIR
RELATIVE HUMIDITY
ENTHALPY DEVIATION, kJ/kg DRY AIR
DRY BULB TEMPERATURE, °C
SPECIFIC VOLUME, m³/kg DRY AIR
BELOW 0 °C PROPERTIES AND ENTHALPY DEVIATION LINES ARE FOR ICE
MOISTURE CONTENT
kg/kg DRY AIR
SENSIBLE HEAT FACTOR

OOOO