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ESE 2022

Main Exam Detailed Solutions

Mechanical Engineering

PAPER-I

EXAM DATE : 26-06-2022 | 9:00 AM to 12:00 PM

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ANALYSIS

Mechanical Engineering Paper-I
ESE 2022 Main Examination

Sl.	Subjects	Marks
1.	Fluid Mechanics	32
2.	Thermodynamics	72
3.	Heat Transfer	52
4.	IC Engines	32
5.	Refrigeration and Air-Conditioning	64
6.	Turbo Machinery	32
7.	Power Plant	136
8.	Renewable Sources of Energy	60
		Total 480

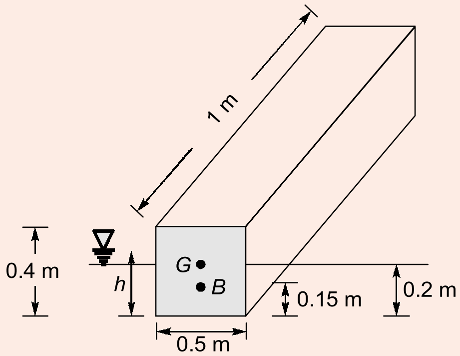
Scroll down for detailed solutions

Section-A

Q.1 (a) A wooden block of specific gravity 0.75 floats in water. If the size of the block is 1 mt × 0.5 mt × 0.4 mt, find its metacentric height.

[12 marks : 2022]

Solution:



Force analysis,

$$M_b \cdot g = F_B$$

$$\left(0.75 \times 10^3\right) \cdot \forall \cdot g = \left(10^3\right) \cdot \forall_{Dis} \cdot g$$

$$(0.75)(1 \times 0.5 \times 0.4) = (1 \times 0.5 \times h)$$

$$h = 0.3 \text{ m}$$

$$\text{B.G.} = 0.2 - 0.15$$

$$= 0.05 \text{ m}$$

$$\text{Metacentric height (GM)} = \frac{I}{\forall_{Dis}} - BG$$

$$= \frac{\frac{(1)(0.5)^3}{12}}{1 \times 0.5 \times 0.3} - 0.05$$

$$= \frac{(0.5)^2}{12 \times 0.3} - 0.05 = 0.0694 - 0.05$$

$$= 0.01944 \text{ m}$$

$$= 1.94 \text{ cm}$$

End of Solution

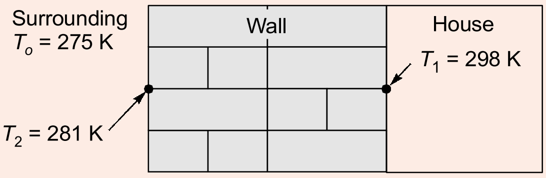
Q.1 (b) In a cold winter night with an outside ambient temperature of 2°C, a wall of house steadily loses 30 kJ per minute. If the inner and outer surface temperatures of the wall are maintained at 25°C and 8°C, respectively, determine the rate of energy destruction within the wall in Watts.

[12 marks : 2022]

Solution:

Given : Ambient temperature, T_o = 275 K; Heat loss by house, Q = 30 kJ/min = 500 W

Inner temperature of wall, T_1 = 25°C = 298 K; Outer temperature of wall, T_2 = 8°C = 281 K



Entropy generation within wall,

$$s_{gen} = \frac{Q}{T_2} - \frac{Q}{T_1}$$

$$= \frac{500}{281} - \frac{500}{298}$$

$$= 0.1015 \text{ W/K}$$

$$\text{Energy destruction} = T_o s_{gen}$$

$$= 275 \times 0.1015$$

$$= 27.91 \text{ W}$$

End of Solution

Q.1 (c) What are the physical assumptions necessary for a lumped capacity unsteady state heat transfer analysis to be applied?

[12 marks : 2022]

Solution:

Assumptions for lumped parameter analysis

(a) Lumped body (uniform temperature body)

For heat conducting bodies, temperature is a function of space and time.

$$\nabla^2 T + \frac{\dot{q}_g}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}_g}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

$$T = f(x, y, z, t)$$

When conduction resistance of body is negligible with respect to convection resistance, then the variation of temperature with space becomes negligible with respect to convection medium and body is said to be uniform temperature body i.e. lump body.

The Biot number (Bi) = $\frac{hL_c}{k_s}$ for this body should be less than 0.1, where

$$s = \left(\frac{V}{A}\right) = \frac{\text{Volume of body}}{\text{Surface area}}$$

(b) The body must be small in size.

(c) The thermal conductivity of the body should be high.

(d) The convective heat transfer coefficient should be low i.e.

Internal conductive resistance << External convective resistance

(e) Properties like density (ρ) specific heat capacity (c_p) are functions of temperature. So, their variation with temperature should be neglected.

End of Solution

Q.1 (d) The brake fuel conversion efficiency of an engine is 30%. The mechanical and combustion efficiencies are 80% and 94%, respectively. The heat losses to the oil and coolant are 60 kW. The chemical energy of the fuel entering the engine is 190 kW. What percentage of this energy becomes (a) brake power; (b) friction power; (c) heat losses; (d) exhaust chemical energy; (e) exhaust sensible energy?

[12 marks : 2022]

Solution:

$$\eta_{bth} = 30\% = 0.3$$

$$\eta_m = 80\% = 0.8$$

$$\eta_{comb} = 94\% = 0.94$$

$$\text{Heat losses} = 60 \text{ kW}$$

$$\text{Chemical energy of the fuel} = 190 \text{ kW} = \dot{m}_f \times C.V.$$

(a)
$$\eta_{bth} = \frac{B.P.}{\dot{m}_f \times C.V.}$$

$$\Rightarrow \quad 0.3 = \frac{B.P.}{190 \text{ kW}}$$

$$\Rightarrow \quad \text{B.P.} = 57 \text{ kW}$$

$$\Rightarrow \quad \text{B.P.} = \frac{57}{190} = 0.3 = 30\%$$

(b)
$$\eta_m = \frac{B.P.}{I.P.}$$

$$0.8 = \frac{57}{I.P.}$$

$$\Rightarrow \quad \text{I.P.} = 71.25 \text{ kW}$$

$$\text{F.P.} = \text{I.P.} - \text{B.P.}$$

$$= 71.25 - 57$$

$$= 14.25 \text{ kW}$$

$$\%\ \text{F.P.} = \frac{14.25}{190} = 0.075 = 7.5\%$$

(c)
$$\text{Heat losses} = 60 \text{ W}$$

$$\%\ \text{Heat losses} = \frac{60}{190} = 0.3158 = 31.58\%$$

(d) Exhaust chemical energy $= (1-\eta_{comb}) \times 190$

$= (1 - 0.94) \times 190$

$= 11.4$ kW

% Exhaust chemical energy $= \dfrac{11.4}{190} = 0.06 = 6\%$

(e) Exhaust sensible energy = 190 – I.P. – Heat losses – Exhaust chemical energy

$= 190 - 71.25 - 60 - 11.4$

$= 47.35$ kW

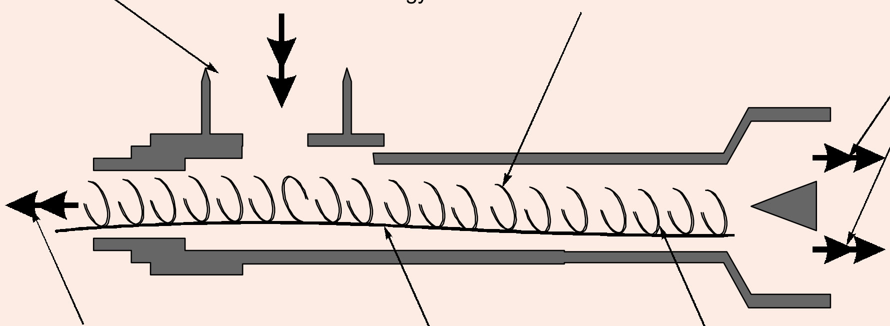
% Exhaust sensible energy $= \dfrac{47.35}{190} = 0.2492 = 24.92\%$

End of Solution

Q.1 (e) Briefly explain the working principle of a vortex tube refrigeration system.

[12 marks : 2022]

Solution:



Working : Compressed air is passed through the nozzle. Here, air expands and acquires high velocity due to particular shape of the nozzle. A vortex flow is created in the chamber and air travels in spiral like motion along the periphery of the hot side. This flow is restricted by the valve. When the pressure of the air near valve is made more than outside by partly closing the valve, a reversed axial flow through the core of the hot side starts from high pressure region to low pressure region. During this process, heat transfer takes place between reversed stream and forward steam. Therefore, air stream through the core gets cooled below the inlet temperature of the air in the vortex tube, while air stream in forward direction gets heated up. The cold stream is escaped through the diaphragm hole into the cold side, while hot stream is passed through the opening of the valve. By controlling the opening of the valve, the quantity of the cold air and its temperature can be varied.

Advantages :

1. It uses air as refrigerant, so ther is no leakage problem.
2. Vortex tube is simple in design and it avoids control systems.
3. There are no moving parts in vortex tube.
4. It is light in weight and requires less space.
5. Initial cost is low and its working expenses are also less, where compressed air is readily available.
6. Maintenance is simple and no skilled labours are required.

Disadvantages :

Its low COP, limited capacity and only small portion of the compressed air appearing as the cold as limits its wise use in practice.

Applications:

1. Vortex tubes are extremely small and as it produce hot as well as cold air. It may be of use industries where both are simultaneously required.
2. Temperature as low as –50°C can be obtained without any difficulty, so it is very much useful in industries for spot cooling of electronic components.
3. It is commonly used for body cooling of the workers in mines.

End of Solution

Q.2 (a) The diameter of the horizontal pipe which is 300 mm is suddenly enlarged to 600 mm. The rate of flow of water through this pipe is 0.4 m^3/sec. If the intensity of pressure in the smaller pipe is 125 kN/m^2, determine

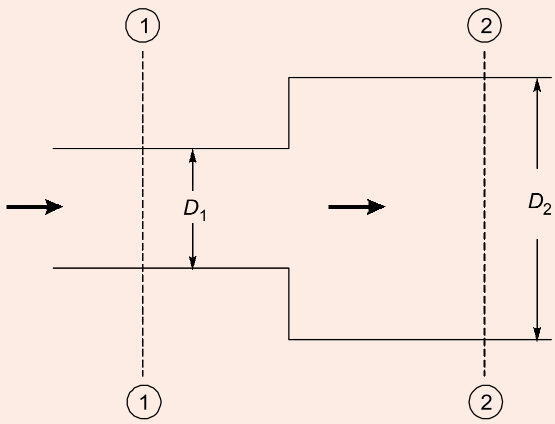
(i) loss of head, due to sudden enlargement.

(ii) intensity of pressure in the larger pipe.

(iii) power lost due to enlargement.

[20 marks : 2022]

Solution:



$D_1 = 0.3$ m; $D_2 = 0.6$ m; $\rho_w = 10^3$ kg/m^3; $Q = 0.4$ m^3/s; $P_1 = 125$ kN/m^2

Determine:

(i) $h_{L_{\text{expansion}}}$

(ii) P_2

(iii) Power loss due to sudden expansion

$$V_1 = \frac{Q}{A_1} = \frac{0.4}{\frac{\pi}{4}(0.3)^2} = 5.659 \text{ m/s}$$

$$V_2 = \frac{Q}{A_2} = \frac{0.4}{\frac{\pi}{4}(0.6)^2} = 1.415 \text{ m/s}$$

(i) $$h_{L_{\text{expansion}}} = \frac{(V_1 - V_2)^2}{2g} = \frac{(5.659 - 1.415)^2}{2(9.81)} = 0.918 \text{ m}$$ Ans.

(ii) Apply energy equation between section (i) - (i) and section (2) - (2)

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + h_{L_{\text{expansion}}}$$

$$\frac{P_2}{\rho g} = \frac{P_1}{\rho g} + \frac{V_1^2}{2g} - \frac{V_2^2}{2g} - 0.918$$

$$\frac{P_2}{\rho g} = \frac{125 \times 10^3}{1000 \times 9.81} + \frac{5.659^2}{2 \times 9.81} - \frac{1.415^2}{2 \times 9.81} - 0.918$$

$$\frac{P_2}{\rho g} = 12.74 + 1.63 - 0.10 - 0.918$$

$$P_2 = 13.352 \times 103 \times 9.81$$

$$= 130.98 \text{ kN/m}^2$$

(iii) Power loss due to sudden expansion

$$= (10^3)(0.4)(9.81)(0.918)$$

$$= 3.6022 \text{ kW}$$ Ans.

End of Solution

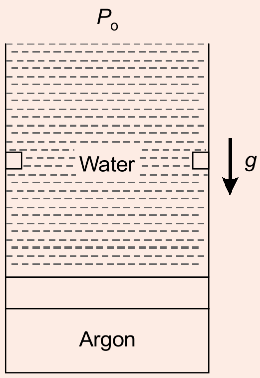
Q.2 (b) Argon at 39.85°C with a volume of 0.5 m^3 is initially contained in a piston cylinder (cross sectional area 0.7 m^2 and height 5.7 m) system with a massless piston loaded with water at 20°C and outside atmosphere (atmospheric pressure, P_0 = 101.203 kPa) as shown in figure. If the piston just touches the stops, the volume of argon would be 0.8 m^3. Heat is now added until the temperature of argon reaches 251.85°C. Plot the entire process on P-v diagram. Assume piston to be adiabatic, determine

(i) the final pressure inside the cylinder

(ii) work done (in kJ) and

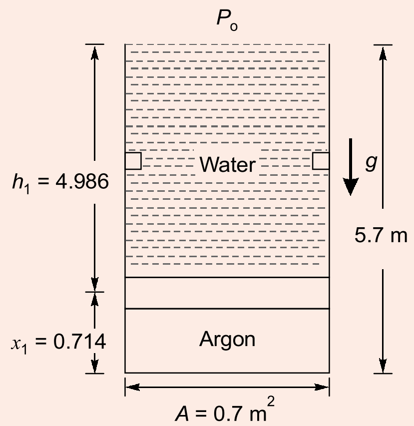
(iii) heat transfer during the process (in kJ)

Neglect the volume occupied by the piston and stops.
Take g = 9.807 m/s^2, specific volume of water = 0.001002 m^3/kg
R for argon = 0.2081 kJ/kgK
C_V for argon = 0.312 kJ/kgK



[20 marks : 2022]

Solution:



Given : For Argon
$$T_1 = 39.85°C = 312.85\text{ K}$$
$$V_1 = 0.5\text{ m}^3$$
$$A = 0.7\text{ m}^2$$

Since,
$$Ax_1 = V_1$$
$$0.7x_1 = 0.5$$
$$x_1 = 0.714\text{ m}$$

$\Rightarrow$
$$\rho_w = \frac{1}{v_w} = \frac{1}{0.001002} = 998\text{ kg/m}^3$$

By balancing forces on piston,

$$P_1 A = (P_o + \rho g h_1) A$$

$$P_1 = [101.203 + 998 \times 9.81 \times 4.986 \times 10^{-3}] \text{ kPa}$$

$$P_1 = 101.203 + 48.814$$

$$= 150.017 \text{ kPa}$$

Now let us check the pressure and temperature of gas when the piston will touch the stopper. (defined with s)

Volume when piston just touches stopper = $V_s = 0.8 \text{ m}^3$

$$\therefore \quad x_s \times A = V_s$$

$$x_s = \frac{V_s}{A} = \frac{0.8}{0.7} = 1.143 \text{ m}$$

$$\therefore \quad h_s = 5.7 - x_s$$

$$= 4.557 \text{ m}$$

Now when the piston just touches the stopper, balancing forces gives

$$P_s \times A = (P_o + \rho g h_s) A$$

$$P_s = 101.203 + 998 \times 9.81 \times 4.557 \times 10^{-3}$$

$$= 145.818 \text{ kPa}$$

For $1 \rightarrow s$, using $\quad PV = mRT$

$$\frac{P_1 V_1}{T_1} = \frac{P_s V_s}{T_s}$$

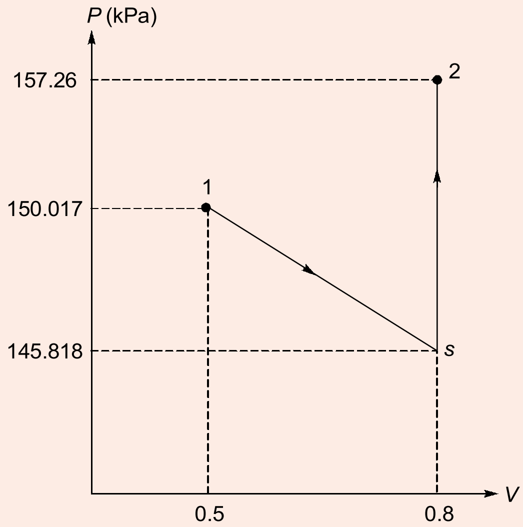
$$\frac{150.017 \times 0.5}{312.85} = \frac{145.818 \times 0.8}{T_s}$$

$$T_s = 486.55 \text{ K}$$

$$t_s = 213.55°\text{C}$$

But final temperature (T_2) is 251.85°C which is more than t_s

$\therefore$ Heat addition does not stop when the piston reaches the stopper and some further heat is added.



(i) Now, for $s \rightarrow 2$

$$Pr = mRT$$

$$P \propto T$$

$$\frac{P_2}{P_s} = \frac{T_2}{T_s}$$

$$\frac{P_2}{145.818} = \frac{273+251.85}{486.55}$$

$$P_2 = 157.26 \text{ kPa}$$

(ii)

$$W = W_{1s} + \cancelto{0}{W_{s2}}$$

$$= W_{1s}$$

$$= \frac{1}{2}(150.017+145.818)\times(0.8-0.5)$$

$$= 44.375 \text{ kJ}$$

(iii)

$$Q = \Delta U + W$$

$$\Delta U = mC_V dT$$

$$m = \frac{P_1V_1}{RT_1} = \frac{150.017\times 0.5}{0.2081\times 312.85} = 1.152 \text{ kg}$$

$$C_V = \frac{R}{\gamma-1} = \frac{0.2081}{1.667-1} = 0.31199 = 0.312 \text{ kJ/kgK}$$

$$\Delta U = 1.152\times 0.312\times(251.85-39.85)$$

$$= 76.198 \text{ kJ}$$

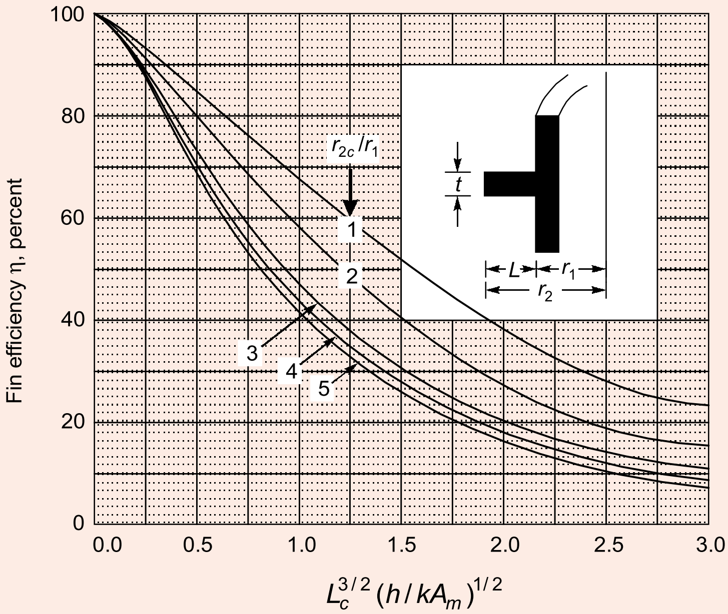
$\therefore$

$$Q = \Delta U + W$$

$$= 120.572 \text{ kJ}$$

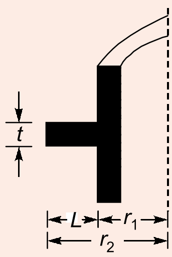
End of Solution

Q.2 (c) Aluminium fins 1.5 cm wide and 1.0 mm thick are placed on a 2.5 cm diameter tube to dissipate the heat. The tube surface temperature is 170°C and the ambient fluid temperature is 25°C. Calculate the heat loss per fin for h = 130 W/m^2°C. Assume k = 200 W/m°C for aluminium. Use the fin-efficiency curves given below:



[20 marks : 2022]

Solution:



$$r_1 = \frac{2.5}{2} = 1.25 \text{ cm} = 1.25 \times 10^{-2} \text{ m}$$

$$r_2 = r_1 + L = 1.25 + 1.5$$

$$r_2 = 2.75 \text{ cm}$$

$$= 2.75 \times 10^{-2 \text{ m}}$$

$$L = 1.5 \text{ cm} = 1.5 \times 10^{-2} \text{ m}$$

$$t = 1 \text{ mm} = 0.1 \text{ cm}$$

$$L_C = L + \frac{t}{2} = 1.5 + \frac{0.1}{2} = 1.55 \text{ cm}$$

$$L_C = 1.55 \times 10^{-2} \text{ m}$$

$$r_{2c} = r_2 + \frac{t}{2} = 2.75 + \frac{0.1}{2} = 2.8 \text{ cm}$$

$$r_{2c} = 2.8 \times 10^{-2} \text{ m}$$

$$A_m = L_C \times t = \left(1.55 \times \frac{1}{10}\right) \text{cm}^2$$

$$= 0.155 \text{ cm} = 0.155 \times 10^{-4} \text{ m}^2$$

Calculating the value of the parameter, $L_C^{3/2}\left(\frac{h}{kA_m}\right)^{1/2}$

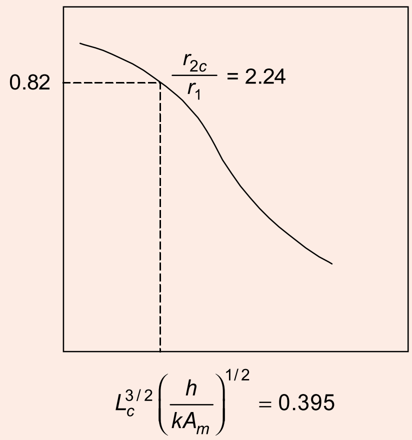
$$L_C^{3/2}\left(\frac{h}{kA_m}\right)^{1/2} = \left(1.55 \times 10^{-2}\right)^{3/2}\left(\frac{130}{200 \times 0.155 \times 10^{-4}}\right)^{1/2}$$

$$= 1.93 \times 10^{-3} \times 204.78$$

$$= 0.395$$

$$\frac{r_{2c}}{r_1} = \frac{2.8}{1.29} = 2.24$$

Calculating the value of efficiency from the given curve



$$\eta_{fin} = \frac{q_{act}}{q_{max,possible}}$$

$$q_{act} = \eta_{fin} \times q_{max,\ possible}$$

$$= 0.82 \times h \times A_{fin} \times (T_o - T_\infty)$$

$$= 0.82 \times 130 \times 2\pi\left[r_{2c}^2 - r_1^2\right][T_o - T_\infty]$$

$$= 0.82 \times 130 \times 2\pi[(2.8)^2 - (1.25)^2] \times 10^{-4} \times (170 - 25)$$

$$= 60.97 \text{ Watt}$$

End of Solution

Q.3 (a) A four cylinder SI engine has a stroke of 90 mm and a bore of 60 mm, with rated speed of 2800 rpm. The engine is tested at the rated speed against a brake which has a torque arm of 0.356 m. The brake load is 155 N and the fuel consumption is 6.74 *l*/hr. The specific gravity of the petrol used is 0.735. The net heating value of the petrol used is 44200 kJ/kg. A Morse test is carried out the cylinders are cut out in the order 1, 2, 3, 4 with corresponding brake load of 111 N, 106.5 N, 104.2 N and 111 N, respectively. Calculate for this speed, the engine torque, the bmep, the brake thermal efficiency, the specific fuel consumption, the mechanical efficiency and the indicated mean effective pressure.

[20 marks : 2022]

Solution:

Given : L = 90 mm; D = 60 mm; N = 2800 rpm; k = 4 cylinder; Brake arm (l) = 0.356 m; Brake load = 155 N; $\dot{m}_f$ = 6.74 *l*/hr; Specific gravity = 0.735; C.V. = 44200 kJ/kg

$$\text{Specific gravity} = \frac{\rho_f}{\rho_w}$$

$$\rho_f = 0.735 \times 1 = 0.735 \text{ kg/litre}$$

$$\text{BP} = T_b \times \omega$$

$$= F_b \times l \times \omega$$

$$= 155 \times 10^{-3} \times 0.356 \times \frac{2\pi \times 2800}{60}$$

$$= 16.1796 \text{ kW}$$

(i) Brake torque, $T_b = F_b \times l$

$$= 155 \times 0.356$$

$$= 55.18 \text{ Nm}$$

(ii)

$$\text{BP} = \frac{P_{bmep} \times LANK}{60n}$$

$$16.1796 = \frac{P_{bmep} \times (90 \times 10^{-3}) \times \frac{\pi}{4}(60 \times 10^{-3}) \times 2800 \times 4}{60 \times 2}$$

[n = 2 assuming 4 stroke]

$$P_{mep} = 681.233 \text{ kPa}$$

$$= 6.81 \text{ bar}$$

(iii)

$$\eta_{bth} = \frac{BP}{\dot{m}_f \times CV} = \frac{16.1796}{\frac{6.74}{3600} l/s \times 0.735 \text{ kg}/l \times 44200}$$

$$\eta_{bth} = 0.266 = 26.6\%$$

(iv)

$$\text{bsfc} = \frac{\dot{m}_f \text{ (kg/hr)}}{BP(\text{kW})} = \frac{6.74 l/\text{hr} \times 0.735 \text{ kg/hr}}{16.1796 \text{ kW}}$$

$$= 0.30618 \text{ kg/kWH}$$

When all cylinders are firing,

$$I_{1234} = BP_{1234} + FP \quad \text{...(A)}$$

When one cylinder is cut off

Cut off cylinder					
1	I_{234}	=	BP_{234}	+	FP
2	I_{134}	=	BP_{134}	+	FP
3	I_{124}	=	BP_{124}	+	FP
4	I_{123}	=	BP_{123}	+	FP
Adding	$3I_{1234}$	=	ΣBP	+	$4FP$ ...(B)

Now, $4 \times A - B$

$$\Rightarrow \quad 4I_{1234} = 4BP_{1234} + 4FP$$
$$3I_{1234} = \Sigma BP + 4FP$$
$$- \quad - \quad -$$

$$I_{1234} = 4BP_{1234} - \Sigma BP$$
$$= 4 \times 155 - (111 + 106.5 + 104.2 + 111)$$
$$= 187.3 \text{ N}$$

$\therefore$ Converting force to power $= 187.3 \times 10^{-3}$ kN $\times 0.356$ m $\times \omega$

$$= 187.3 \times 10^{-3} \times 0.356 \times \frac{2\pi \times 2800}{60}$$
$$= 19.55 \text{ kW}$$

(v)
$$\eta_m = \frac{B.P.}{I.P.} \times 100$$
$$= \frac{16.1796}{19.55} \times 100$$
$$= 82.76\%$$

(vi)
$$\text{I.P.} = \frac{P_{imep} \times LANK}{60n}$$
$$19.55 = \frac{P_{imep} \times 90 \times 10^{-3} \times \frac{\pi}{4}(60 \times 10^{-3})^2 \times 2800 \times 4}{60 \times 2}$$
$$P_{imep} = 823.14 \text{ kPa}$$
$$= 8.23 \text{ bar}$$

End of Solution

Q.3 (b) Describe the working of steam jet-ejector refrigeration system with the help of a neat sketch. Also state the important relations for normal shock in the steam jet refrigeration system.

[20 marks : 2022]

Solution:

Steam jet or Ejector refrigeration system uses water as refrigerant. It uses the basic principle of boiling of liquid at lower temperature by reducing pressure on its surface.

This system employs a steam ejector or booster instead of mechanical compressor. The main components as shown in figure are flash chamber or evaporator, steam nozzles, ejector and condenser.

The flash chamber is heavily insulated and is fitted with perforated pipes which spray warm water coming out of refrigerated space. Some of this water is converted into vapours after absorbing latent heat from the rest of the water, thereby cooling it. Loss of water through vapours is made up from make-up water line.

High pressure steam from boiler is passed through steam nozzle thereby increasing its velocity. This entrains water vapours from flash chamber and results in further formation of vapours. The mixture of steam and water vapour passes through venturi-tube of ejector and gets compressed. This leads to rise in temperature and pressure of the mixture and then it is fed to the water cooled condenser. The condensate is again fed to boiler as feed water.

Steam jet refrigeration system is widely used in paper mills, breweries, food processing plants, gas plants etc. Since water is the refrigerant, it cannot be used for applications below 0°C.

Advantages:

1. It is simple in construction and rigidly designed.
2. It is a vibration-free system as pumps are the only moving parts.
3. It has low maintenance cost, low production cost and high reliability.
4. It has relatively less plant mass (kg/TR). Hence, there are now a number of air-conditioning applications ranging up to 300 TR in capacity as well as many industrial applications of even larger size.
5. It uses water as a refrigerant. Water is very safe to use as it is non-poisonous and non-inflammable.
6. This system has an ability to adjust quickly to load variations.
7. The running cost of this system is quite low.

Disadvantages:

1. The system is not suitable for water temperature below 4°C.
2. For proper functioning of this system, maintenance of high vacuum in the evaporator is necessary. This is done by direct vaporization to produce chilled water which is usually limited as tremendous volume of vapour is to be handled.

The important relations for normal shock in the steam jet refrigeration system are:

Continuity : $$m_3 = \frac{c_{3a}A}{v_{3a}} = \frac{c_{3b}A}{v_{3b}} \qquad ...(i)$$

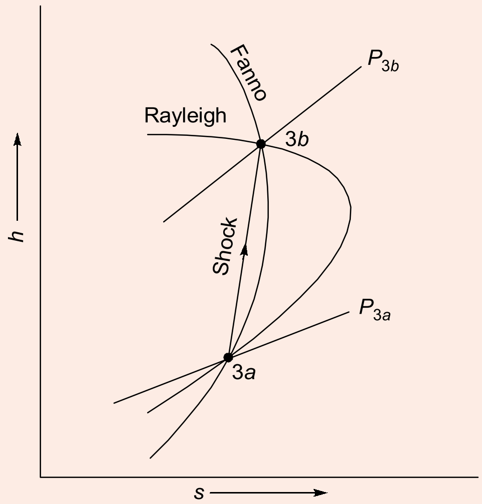
where, v is the specific volume

Momentum : $$(p_{3b} - p_{3a})A = (C_{3a} - C_{3b})m_3 \qquad ...(ii)$$

Energy : $$h_{3a} + \frac{C_{3a}^2}{2} = h_{3b} + \frac{C_{3b}^2}{2} \qquad ...(iii)$$

Equation of state : Steam property tables may be used. ...(iv)

The solution of the above four equations for the shock may be obtained by drawing two curves as shown in figure below.

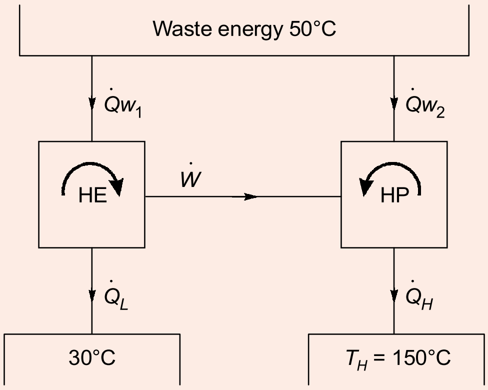


Process in shock diffuser

The solution of equation (i), (iii) and (iv) is represented by a Rayleigh line.

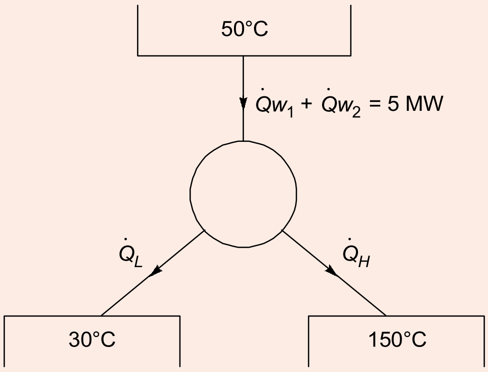
End of Solution

Q.3 (c) A combination of a heat engine driving a heat pump as shown in figure, takes waste energy at 50°C as a source $\dot{Q}w_1$, to the heat engine rejecting heat at 30°C. The remainder $\dot{Q}w_2$ goes into the heat pump that delivers a $\dot{Q}_H$ at 150°C. If the total waste energy is 5 MW, find the rate of energy delivered at the higher temperature.



[20 marks : 2022]

Solution:



Considering both devices as system

$\Rightarrow$ Conversation of energy

$$\Rightarrow \quad \dot{Q}_{W_1} + \dot{Q}_{W_2} = \dot{Q}_L + \dot{Q}_H$$

$$s = \dot{Q}_L + \dot{Q}_H \quad \text{...(i)}$$

$$\Rightarrow \quad \int \frac{\delta Q}{T} = 0 \text{ for reversible}$$

$$\frac{\dot{Q}_{W_1} + \dot{Q}_{W_2}}{50+273} - \frac{\dot{Q}_L}{273+30} - \frac{\dot{Q}_H}{273+150} = 0$$

$$\frac{5}{323} - \frac{(5-\dot{Q}_H)}{303} - \frac{\dot{Q}_H}{423} = 0$$

$$\frac{\dot{Q}_H}{303} - \frac{\dot{Q}_H}{423} = \frac{s}{303} - \frac{s}{323}$$

$$\frac{423\dot{Q}_H - 303\dot{Q}_H}{303 \times 423} = s\left(\frac{323-303}{303 \times 323}\right)$$

$$\frac{\dot{Q}_H \times 120}{423} = \frac{s \times 20}{323}$$

$$\dot{Q}_H = 1.0913 \text{ MW}$$

End of Solution

Q.4 (a) A room with dimensions as 3.5 m wide, 3 m high and 6 m deep, is required to be air conditioned. One of the walls (3.5 × 3 m) faces west and contains a double glazed glass window of size 2 m by 1.5 m. There are no heat gains through the rest of the walls. Calculate the sensible, latent and total heat gains. Also, calculate the room sensible heat factor and the required cooling capacity with the following data:

Inside conditions : 25° DBT, 50% RH
Outside conditions : 45° DBT, 24°C WBT
U_{wall} : 1.78 W/m²K
U_{roof} : 1.316 W/m²K
Effective Temperature Difference for wall : 25°C
Effective Temperature Difference for roof : 30°C
U_{glass} : 3.12 W/m²K
solar Heat gain of glass : 300 W/m²K
Internal shading coefficient of glass : 0.86
Occupancy : 4 persons (90 W sensible heat per person)
(40 W latent heat per person)
Lighting load : 33 W/m² of floor area
Appliance load : 600 W (sensible) + 300 W (latent)
Infiltration : 0.5 Air changes per hour
State assumptions, if any.

[20 marks : 2022]

Solution:

From Psychrometric chart,

Inside conditions : 25° DBT, 50% RH

$$\omega_i = 0.0099 \text{ kg/kgd.a.}$$

Outside conditions : 45° DBT, 24°C WBT

$$\omega_o = 0.0102 \text{ kg/kg.d.a.}, \ \rho_a = 1.087 \text{ kg/m}^3$$

External loads:

(i) Heat transfer through the walls $= U_{wall} \times A_{wall} \times$ Effective temperature difference

$$= 1.78 \times (3.5 \times 3 - 2 \times 1.5) \times 25$$

$$= 333.75 \text{ W} \quad \text{[Sensible]}$$

(ii) Heat transfer through roof $= U_{roof} \times A_{roof} \times$ Effective temperature difference

$$= 1.316 \times (6 \times 3.5) \times 30$$

$= 829.08\text{ W}$ [Sensible]

(iii) Heat transfer through glass $= U_{glass} \times A_{glass} \times (T_o - T_i) + (SHG)_{glass} \times A_{glass} \times S.C$

$= 3.12 \times 2 \times 1.5 \times (45 - 25) + 300 \times 2 \times 1.5 \times 0.86$

$= 961.2$ [Sensible]

(iv) Heat transfer due to infiltration:

$$\text{Mass of the infiltrated air} = \frac{\rho_a \times \text{Air changed per hour} \times \text{Volume of room}}{3600}$$

$$= \frac{1.087 \times 0.5 \times 3.5 \times 3 \times 6}{3600}$$

$= 9.511 \times 10^{-3}$ kg/s

$$\therefore \quad (Q_s)_{inf} = \dot{m}_{inf} \times c_{p_m} \times (T_o - T_i)$$

$$= 9.511 \times 10^{-3} \times 1020 \times (45 - 25)$$

[Assuming c_{p_m} = 1020 J/kgK]

$= 194.03\text{ W}$ [Sensible]

$$(Q_l)_{inf} = \dot{m}_{inf} \times h_{f_g} \times (\omega_o - \omega_i)$$

$$= 9.511 \times 10^{-3} \times 2500 \times (0.0102 - 0.0099) \times 1000$$

[Assume h_{f_g} = 2500 kJ/kg]

$= 7.133\text{ W}$ [Latent]

Internal loads:

(i) Occupants load:

Sensible

Q_s = Number of occupants × SHG

$= 4 \times 90 = 360\text{ W}$ [Sensible]

Latent

$Q_L = 4 \times 40 = 160\text{ W}$ [Latent]

(ii) Load due to lighting:

$Q = 33 \times$ Floor area

$= 33 \times 3.5 \times 6 = 693\text{ W}$ [Sensible]

(iii) Load due to appliance:

$Q_s = 600\text{ W}$ [Sensible]

$Q_L = 300\text{ W}$ [Latent]

Total sensible heat $= 333.75 + 829.08 + 961.2 + 194.03 + 360 + 693 + 600$

$= 3971.06\text{ W}$ **Ans.**

Total latent heat $= 7.133 + 160 + 300$

$= 467.133\text{ W}$ **Ans.**

$$\text{Total heat gain} = 3971.06 + 467.133$$
$$= 4438.193 \text{ W} \quad \text{Ans.}$$

$$\text{Room sensible heat factor, RSHF} = \frac{3971.06}{4438.193}$$
$$= 0.894 \text{ W} \quad \text{Ans.}$$
$$\text{Required cooling capacity} = 4438.193 \times 1.25 \quad \text{[Assume safety factor = 1.25]}$$
$$= 5547.74 \text{ W} \quad \text{Ans.}$$

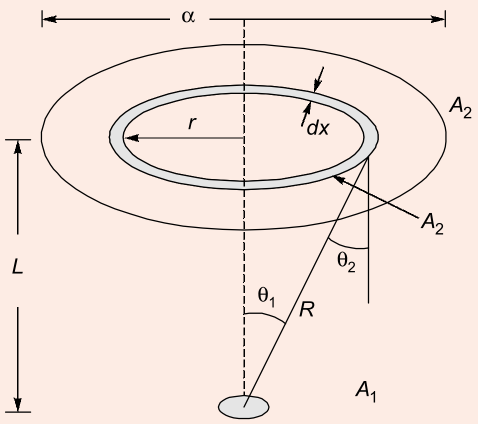
End of Solution

Q.4 (b) Determine the geometric shape factor for a very small disk A_1 and a large parallel disk A_2 located co-axially at a distance L directly above the smaller one. The radius of the large disk may be taken as α.

[20 marks : 2022]

Solution:

Let us assume that the two bodies are black and the medium is nonparticipating in the energy exchange.



Given, a very small disk A_1 and a large disk A_2 of radius α located co-axially at a distance L from each other.

Total rate at which radiation leaves surface 1 and is intercepted by surface 2 may be obtained by

$$q_{1\to 2} = J_I \int_{A_1}\int_{A_2} \frac{\cos\theta_1 \cos\theta_2 dA_1 dA_2}{\pi R^2}$$

From the definition of view factor,

$$F_{12} = \frac{q_{1\to 2}}{A_1 J_1}$$

$$\therefore \quad F_{12} = \frac{1}{A_1}\int_{A_1}\int_{A_2} \frac{\cos\theta_1 \cos\theta_2}{\theta R_2} dA_1 dA_2$$

Now using this equation for our given configuration and recognizing that θ_1, θ_2 and R are approximately independent of position of A_1, the compression reduces to

$$F_{12} = \int_{A_2} \frac{\cos\theta_1 \cos\theta_2}{\pi R^2} dA_2$$

or with $$\theta_1 \simeq \theta_2 \simeq \theta$$

$$F_{12} = \int_{A_2} \frac{\cos^2\theta}{\pi R^2} dA_2$$

and R is given as, $$R^2 = r^2 + L^2$$

$$\cos\theta = \frac{L}{R} \text{ and } dA_2 = 2\pi r dr, \text{ it follows that}$$

$$F_{12} = 2L^2 \int_0^{\alpha} \frac{rdr}{\left(r^2 + L^2\right)^2}$$

$$= \frac{(2\alpha)^2}{(2\alpha)^2 + 4L^2}$$ Ans.

End of Solution

Q.4 (c) An insulated 0.75 kg copper container containing 0.2 kg water, both in equilibrium at a temperature of 20°C. An experimeter now places 0.05 kg of ice at 0°C in the container. The specific heat of copper is 0.418 kJ/kgK and latent heat of fusion of ice at 0°C is 333 kJ/kg.

(i) What will be the temperature (T_f) at the equilibrium condition when all the ice has melted?

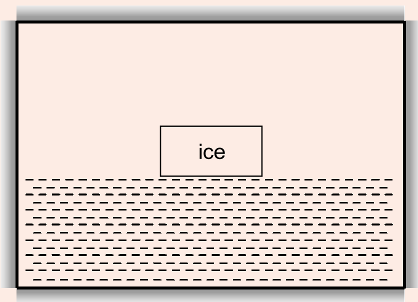
(ii) Compute the entropy generation during the process (J/K).

(iii) What will be the minimum work needed by a stirrer to bring back the temperature of water at 20°C in kJ?

Take specific heat of water as 4.187 kJ/kgK.

[20 marks : 2022]

Solution:



If the container and water reaches zero degree, the heat rejected will be

$$= m_{Cu} \times C_{Cu} \times 20 + m_w \times C_w \times 20$$
$$= 0.75 \times 0.418 \times 20 + 0.2 \times 4.187 \times 20$$
$$= 23.018 \text{ kJ}$$

Heat absorbed by ice if it melts completely $= m \times LH$

$$= 0.05 \times 333 = 16.65 \text{ kJ}$$

Hence, the net energy which will remain in system = 23.018 – 16.65 = 6.368 kJ

Therefore, the final temperature can be obtained if we give this energy back to system to change from 0°C to a final temperature T_f.

$$m_{Cu} \times C_{Cu} \times \Delta T + m_w \times C_w \times \Delta T = 6.368$$
$$0.75 \times 0.418 \times \Delta T + (0.2 + 0.05) \times 4.187 \times \Delta T = 6.368$$
$$\Delta T = 4.6815$$
$$t_f - 0 = 4.6815$$
$$t_f = 4.6815°C$$
$$T_f = 277.68 \text{ K}$$

(ii)
$$s_{gen} = \Delta s_{Cu} + \Delta s_w + \Delta s_{ice}$$
$$\Delta s_{Cu} = mc \ln\frac{T_f}{T_i} = 0.75 \times 0.418 \ln\frac{277.68}{293}$$
$$= -0.01683 \text{ kJ/K}$$
$$\Delta s_w = mc \ln\frac{T_f}{T_i} = 0.2 \times 0.418 \ln\frac{277.68}{293}$$
$$= -0.04497 \text{ kJ/K}$$
$$\Delta s_{ice} = \frac{m \times LH}{273} + m \times c \ln\frac{T_f}{T_i}$$

0°C ice ⟶ 0°C Water ⟶ 4.6815°C Water

$$= \frac{0.05 \times 333}{273} + 0.05 \times 4.187 \ln\frac{277.68}{273}$$
$$= 0.06099 + 0.003558$$
$$= 0.06455 \text{ kJ/K}$$

∴
$$s_{gen} = \Delta s_{Cu} + \Delta s_w + \Delta s_{ice}$$
$$= 0.00275 \text{ kJ/K}$$

(iii) Stirrer work needed = Energy required to raise temperature to 20°C

$$= (mC)_{Cu} \times \Delta T + (mC)_w \times \Delta T$$
$$= 0.75 \times 0.418 \times (20 - 4.6815) + (0.2 + 0.05) \times 4.187 \times (20 - 4.6815)$$
$$= 20.837 \text{ kJ}$$

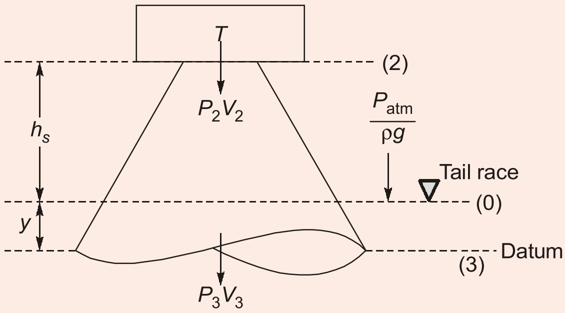
End of Solution

Section-B

Q.5 (a) Explain how the use of a draft tube at the exit of a Francis turbine will increase its efficiency but may initiate the problem of cavitation.

[12 marks : 2022]

Solution:



Apply energy equation (2) - (3)

$$\frac{P_2}{\rho g} + \frac{V_2^2}{2g} + h_s + y = \frac{P_3}{\rho g} + \frac{V_3^2}{2g} + 0 + h_f$$

$$\therefore \quad \frac{P_3}{\rho g} = \frac{P_{atm}}{\rho g} + y$$

$$\frac{P_2}{\rho g} + \frac{V_2^2}{2g} + h_s + y = \frac{P_{atm}}{\rho g} + y + \frac{V_3^2}{2g} + h_f$$

$$\frac{P_2}{\rho g} = \frac{P_{atm}}{\rho g} + \frac{V_3^2}{2g} - \frac{V_2^2}{2g} - h_s + h_f \qquad (V_3 < V_2)$$

$$\frac{P_2}{\rho g} = \frac{P_{atm}}{\rho g} - \left[\frac{V_2^2}{2g} - \frac{V_3^2}{2g} - h_f + h_s\right]$$

$$\therefore \quad \frac{P_2}{\rho g} < \frac{P_{atm}}{\rho g}$$

With the help of draft tube pressure at exit of runner can be kept below atmospheric pressure which increases the pressure energy contribution into runner, which increases the runner power. Therefore, the efficiency of turbine increases.

But if P_2 becomes either equal or below vapour pressure then there is a chance of cavitation.

Therefore to avoid the possibility of cavitation, we keep pressure P_2 above vapour pressure.

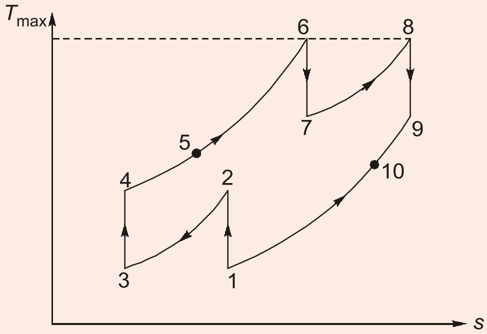
End of Solution

Q.5 (b) There is a limitation on maximum temperature in gas turbine as its blades have material constraints. While the usual two-wheeler internal combustion engine doesn't have any such constraints; why? Explain. How are such issues with gas turbine blades resolved? Explain with a neat sketch.

[12 marks : 2022]

Solution:

Blades of gas turbines rotate at very high speeds, so they are continuously subjected to very high centrifugal forces, simultaneously being crossed over by high temperature flue gases. There is a high chance of creep failure in rotary machines subjected to high temperature, so the maximum temperature in a gas turbine is limited by metallurgical limit. Whereas in internal combustion engines air enters at a low temperature, attains a maximum temperature after combustion and then again get replaced by fresh cooler air. So, the temperature of the cylinder doesn't reach the maximum temperature after combustion. Due to the metallurgical limit, gas turbine power plants operate below a certain maximum temperature. This limits the obtainable efficiency and work output. To improve efficiency and work output within the temperature limit regeneration along with intercooling and reheating is used.



Due to this,

- Compressor work is reduced by intercooling.
- Turbine work is increased by reheating.
- Regeneration increases the efficiency.

End of Solution

Q.5 (c) What is fusible plug? Where it is used and how it works? Explain with a neat sketch.

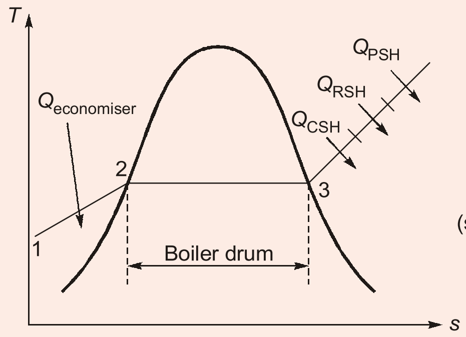
[12 marks : 2022]

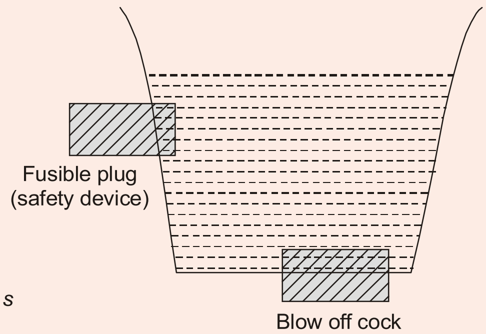
Solution:

A fusible plug is a threaded metal cylinder, often made from bronze, brass or gunmetal, which has a tapered hole drilled completely through its length.

The function of a fusible plug is to protect the boiler against damage due to overheating for low water level. It is fitted on the fire box crown plate or over the combustion chamber at its appropriate place.

Under normal condition when the water level in the boiler shell is normal, the fusible plug is fully submerged under water. In this case the heat from the fusible plug is being conducted to water which keeps the fusible metal at an almost constant temperature and below its melting point. But when the water level falls below the fusible plug, it gets uncovered from water and is exposed to steam. The heat conduction from the fusible plug to steam is very little compared with that to water. Hence fusible plug becomes overheated and it melts with the result that the hollow gun metal plug falls down making a hole. The steam and water being under pressure immediately rush to fire box and extinguish the fire.





End of Solution

Q.5 (d) Explain the working principle of electrostatic precipitator. How can its efficiency be improved?

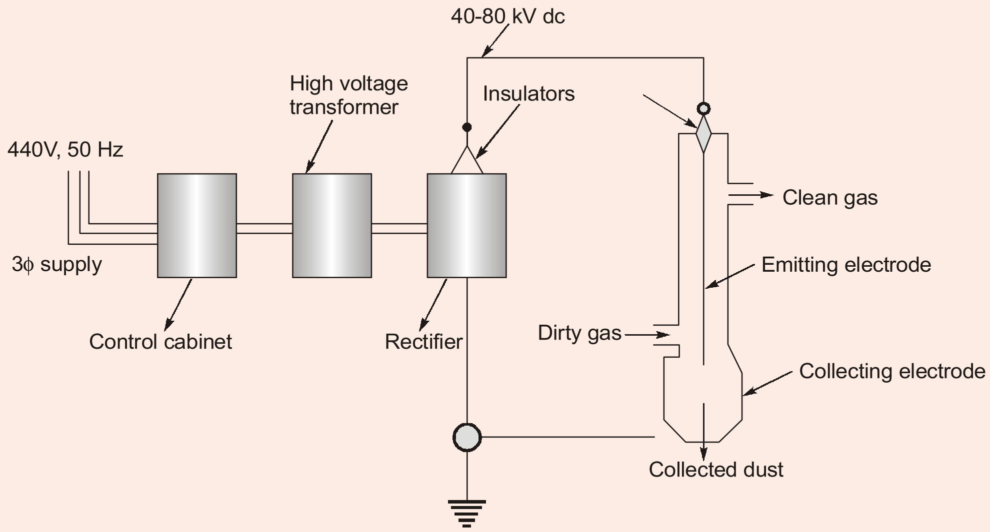
[12 marks : 2022]

Solution:

The principal components of an electrostatic precipitator (ESP) are two sets of electrodes insulated from each other. The first set is composed of rows of electrically grounded vertical parallel plates, called the collection electrodes, between which the dust-laden gas flows. The second set of electrodes consists of wires, called the discharge or emitting electrodes that are centrally located between each pair of parallel plates. The wires carry a unidirectional negatively charged high-voltage (between 20 and 100 kV) from an external dc source. The applied high voltage generates a unidirectional, non-uniform electrical field whose magnitude is greatest near the discharge electrodes. When that voltage is high enough, a blue luminous glow, called a corona, is produced around them. Electrical forces in the corona accelerate the free electrons present in the gas so that they ionize the gas molecules, thus forming more electrons and ions. The new electrons create again more free electrons and ions, which result in a chain reaction.

The positive ions travel to the negatively charged wire electrodes. The electrons follow the electrical field toward the grounded electrodes, but their velocity decreases as they move away from the corona region around the wire electrodes toward the grounded plates. Gas molecules capture the low velocity electrons and become negative ions. As these ions move to the collecting electrode, they collide with the fly ash particles in the gas stream and give them negative charge. The negatively charged fly ash particles are

driven to the collecting plate by the force which is proportional to the product of this charge and the strength of the electric field.



Basic elements of an electrostatic precipitator

The particles to the plates and makes removal more difficult. This can be rectified either by operating at high gas temperatures (before APH) or by superimposing a high voltage pulse on the base voltage to enhance ESP performance during operation under high-resistivity conditions.

Collected particulate matter must be removed from the collecting plates on a regular schedule to ensure efficient collector operation. Removal is usually accomplished by a mechanical hammer scrapping system. The vibration knocks the particulate matter off the collecting plates and into a hopper at the bottom of the precipitator.

The efficiency of Electrostatic precipitator can be improved by:

(i) increasing the collector area

(ii) increasing the migration velocity

(iii) decreasing the mass flow rate

End of Solution

Q.5 (e) Describe the working of Solar thermal vapour absorption air conditioning system. Also, list the advantages and limitations of LiBr-H_2O and NH_3-H_2O systems.

[12 marks : 2022]

Solution:

Lithium Bromide-Water Absorption System: The combination called aqua-ammonia was used in absorption systems years before Li-Br water combination became popular. The absorption system was the predecessor of the vapour compression system in the nineteenth century and aqua-ammonia system enjoyed wide application in domestic refrigerators and large industrial installations in the chemical and process industries. The LiBr-water system was commercialised in the middle of the twentieth century as water chillers for large buildings air conditioning. In the LiBr-water system, water is the refrigerant. This imposed restriction on its use for applications requiring temperatures below 0°C. And the LiBr being a salt has a re-crystallisation zone when it becomes solid and hence imposed flow restrictions. The vapour absorption system particularly LiBr-water system has bounced back with the use of solar energy and the recent emphasis on cogeneration which makes available, the otherwise waste heat, for external direct heating source in vapour absorption system.

In order to perform thermal calculation on the LiBr-water absorption refrigerating cycle, enthalpy data must be available for working substances at all crucial position in the cycle. The water in liquid and vapour form flows in and out of condenser and evaporator. Therefore enthalpies at these points can be determined from tables of the properties of water. These are available and appended at the end (datum 0°C, h = 0 kJ/kg). In the generator and absorber, LiBr-water solutions exist for which the enthalpy is a function of both temperature of the solution and the concentration. A chart of enthalpy concentration (h-x) is appended which presents the enthalpy data for LiBr-water solutions. The appended chart is applicable to saturated and subcooled solutions and are based on zero enthalpy water at 0°C, and zero enthalpy of solid LiBr at some other temperature. In fact, the enthalpy of pures LiBr (solid) is of no consequence as it is never achieved. Since the zero enthalpy of water in the solution is the same as that of the tables of the properties of water, the water property tables can be used for greater accuracy in conjunction with the chart.

End of Solution

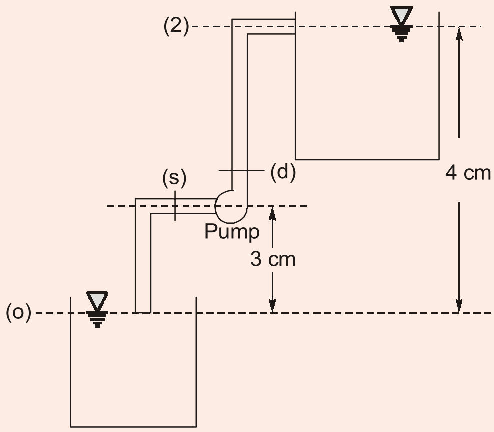
Q.6 (a) A centrifugal pump lifts water from a sump to an overhead reservoir. The static lift is 40 m out of which 3 m is suction lift. The suction and delivery pipes are both of 30 cm diameter. The friction loss in suction pipe is 2.5 m and in delivery pipe it is 7.5 m. The impeller is 0.5 m in diameter and has a width of 3 cm at the outlet. The speed of the pump is 1200 rpm. The exit blade angle is 20°. If the manometric efficiency is 86%, determine the absolute pressures at the suction and delivery ends of the pump. Assume that the inlet and outlet of the pump are at the same elevation. Take atmospheric pressure as 10.10 m of water.

[20 marks : 2022]

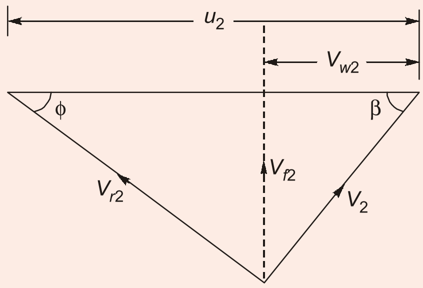
Solution:

Given: $h_{static} = 40$ m; $\dfrac{P_{atm}}{\rho g} = 10.10\,\text{m}$, $h_s = 3$ m, $d_s = d_d = 30$ cm, $h_{fs} = 2.5$ m,

$h_{fd} = 7.5$ m, $D_2 = 0.5$ m, $B_2 = 3$ cm, $N = 1200$ rpm, $\phi = 20°$, $\eta_m = 86\%$



$$u_2 = \frac{\pi DN}{60} = \frac{\pi \times 0.5 \times 1200}{60} = 10\pi \text{ m/sec}$$



Outlet velocity triangle

$$H_m = H_s + H_f$$

$$= H_s + (H_{fs} + H_{fd})$$

$$H_m = 40 + 2.5 + 75 = 50$$

$$\eta_m = 0.86 = \frac{gH_m}{V_{w2}u_2} = \frac{9.81 \times 50}{V_{w2} \times 10\pi}$$

$\Rightarrow$
$$\tan\phi = \frac{V_{f2}}{u_2 - V_{w2}} = \frac{V_{f2}}{10\pi - 18.15^4}$$

$$V_{f2} = 4.826 \text{ m/s}$$

$$Q_{pump} = \pi D_2 B_2 \times V_{f2} = \pi \times 0.5 \times 0.03 \times 4.826$$

$$Q_p = 0.22746 \text{ m}^3\text{/s}$$

$$Q_p = Q_{suction} = Q_{discharge} = 0.22746$$

$$\frac{\pi}{4}(0.3)^2 V_s = 0.22746$$

$\Rightarrow$ $V_s = V_d = 3.2179$ m/s

Applying energy equation between (o) and (s)

$$\frac{P_{atm}}{\rho g} + \frac{V_o^2}{2g} + Z_o = \frac{P_s}{\rho g} + \frac{V_s^2}{2g} + h_s + h_{fs}$$

$$10.10 + 0 + 0 = \frac{P_s}{\rho g} + \frac{(3.2179)^2}{2 \times 9.81} + 3 + 2.5$$

$$\frac{P_s}{\rho g} = 4.072 \text{ m}$$

$$P_s = 39.948 \text{ kPa} = 0.399 \text{ bar}$$

(Absolute pressure at suction side)

We know that, $$H_m = \frac{P_d - P_s}{\rho g} + \frac{V_d^2 - V_s^2}{2g}$$

$\because$ $V_s = V_s$

$\Rightarrow$ $$H_m = \frac{P_d - P_s}{\rho g}$$

$\Rightarrow$ $$50 = \frac{P_d - 0.39948}{1000 \times 9.81}$$

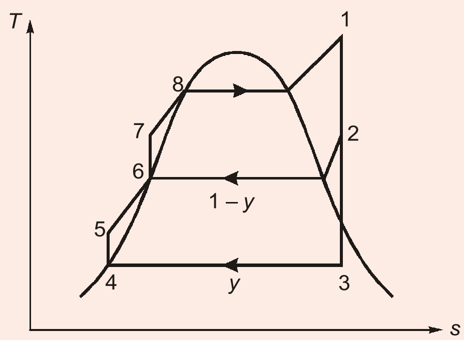
$$P_d = 530.448 \text{ kPa or } P_d = 5.30 \text{ bar}$$

End of Solution

Q.6 (b) A steam power plant has high and low pressure of 20 MPa and 10 kPa and one open feed water heater operating at 1 MPa with the exit as saturated liquid. The maximum temperature is 800°C and the turbine has a total power output of 5 MW. Find the fraction of the flow for extraction to the feedwater and the total condenser heat transfer rate.

[20 marks : 2022]

Solution:



$$h_1 = 4069.8 \text{ kJ/kg}$$

$$S_1 = 7.0544 \text{ kJ/kgK}$$

$$S_1 = S_2 = S_3$$

$$7.0544 = 0.6492 + x \times 7.5010 = S_3$$

$$x = 0.8539$$

$$h_3 = h_4 + xh_{fg}$$

$$h_3 = 191.81 + 0.8539 \times 2392.82$$

$$h_3 = 2235.07 \text{ kJ/kg}$$

C_P of steam can be calculated as,

$$C_P = \frac{h_1 - h_g(20\text{ MPa})}{T_1 - T_{sat}(20\text{ MPa})} = \frac{4069.8 - 2409.74}{800 - 365.81} = 3.82 \text{ kJ/kgK}$$

$$S_3 = 6.5864 + C_P \ln\left(\frac{T_2}{179.91 + 273}\right) = S_1 = 7.0544$$

$$T_2 = 511.94 \text{ K}$$

$$h_2 = 2778.08 + C_P(511.94 - 452.91)$$

$$= 3003.57 \text{ kJ/kg}$$

$$h_5 - h_4 = W_{pump} = V(P_5 - P_4)$$

$$h_5 = 191.81 + 0.001010(1000 - 10)$$

$$= 192.81 \text{ kJ/kg}$$

Let y fraction goes in LP turbine and remaining in OFWH. By energy conservation in OFWH.

$$(1 - y)h_2 + yh_5 = h_6$$

$$(1 - y) \times 3003.57 + y \times 192.81 = 762.79$$

$$y = 0.7972$$

Fraction to be extracted for feedwater heater = $1 - y = 0.2027$

Turbine power output = 5×10^3 kW

$$\dot{m}(h_1 - h_2) + y\dot{m}(h_2 - h_3) = 5 \times 10^3$$

$$\dot{m} = \frac{5 \times 10^3}{h_1 - h_2 + y(h_2 - h_3)} = 2.978 \text{ kg/s}$$

Total condenser heat transfer rate = $\dot{m}(h_3 - h_4) = 2.978(2235.07 - 191.81)$

$$= 6084.83 \text{ kW}$$

End of Solution

Q.6 (c) (i) A propeller-type horizontal axis wind turbine has following operating conditions:

Wind speed = 10 m/s

Air density = 1.226 kg/m^3

Rotor diameter = 120 m

Rotor speed = 50 RPM

Coefficient of performance = 40%

Calculate:

(a) Total power density in wind system in W/m^2.

(b) Total wind power in kW.

(c) Maximum extractable power in kW.

(d) Maximum torque in kN.

(ii) Explain the various features of wind-diesel hybrid power generation systems. Also describe the types of operational scheduling for diesel unit.

[10+10 marks : 2022]

Solution:

(i) Given: u_o = 10 m/s, P = 1.226 kg/m^3, D = 120 m, N = 50 RPM, C_P = 40% = 0.40

$$\text{Area of the rotor, } A = \frac{\pi D^2}{4} = 11309.7335 \text{ m}^2$$

$$\text{Speed of the rotor, } \omega = \frac{2\pi N}{60} = 5.236 \text{ rad/s}$$

(a) Power available density in wind system:

$$\Rightarrow \quad \frac{P_o}{A} = \frac{1}{2}\rho u_o^3 = 613 \text{ W/m}^2$$

(b) Total wind power, $P_o = \frac{1}{2}\rho A u_o^3 = 6932.86 \text{ kW}$

(c) Maximum extractable power, $P_\tau = C_P P_o$

$= 0.4 \times 6932.86$

$= 2773.146$ kW

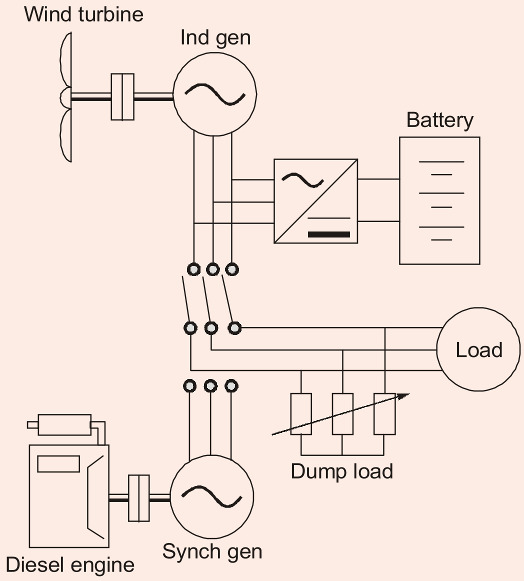
(d) Maximum torque, $T_m = \frac{P_o}{u_o} r = \frac{6932.86}{10} \times 60$

$= 41597.16$ kN-m

(ii)

Wind-Diesel Hybrid System: There are many remote and isolated areas in the world where utility power grid has no access due to techno-economic reasons. Power to such places is supplied by small locally installed diesel generator unit. In such places wind electricity may be very economical if favourable wind is available. Unfortunately, wind is a highly fluctuating power source and the raw output at the terminals of a wind turbine is incompatible with the demand of a normal domestic or commercial user. In such places isolated wind turbines can be installed in conjunction with diesel generating units for backup.

This hybrid system, popularly known as wind-diesel system, is shown in figure. For economic viability, the savings in fuel cost should cover the additional investment cost due to wind generator, controller, dump load, storage unit, converter and other auxiliary equipment.



Two types of operational schedule is possible for diesel unit:

1. **Continuous Diesel Unit Operation:** The simplest way to incorporate the wind turbine into the standard diesel powered system. without increasing the risk of loss of load, is to operate wind turbine in parallel with a continuously running diesel generator. In this mode, wind power acts as negative load, reducing the average load of the diesel unit. The diesel generator can be allowed to operate at very low loading or even at negative load. This system performs well without the need of any supervisory control.
2. **Intermittent Diesel Unit Operation:** In this mode diesel unit is switched off during periods when the output of wind turbine is sufficiently high to meet the demand without any backup. The saving in fuel is more in this case. However, due to variation in wind power, which is much more significant than that of the load, frequent starts/stops of diesel unit may be required. Frequent startups hasten the wear of diesel engine and starter. Also owing to inertia, comparatively lengthy time interval is necessary to start and stop the unit. The system may collapse during diesel generator startup if wind power drops within startup interval. Some kind of energy storage (battery, flywheel or pumped storage) may reduce diesel start/stop operations within the acceptable rate of system cycling. However, this also increases the cost of the system.

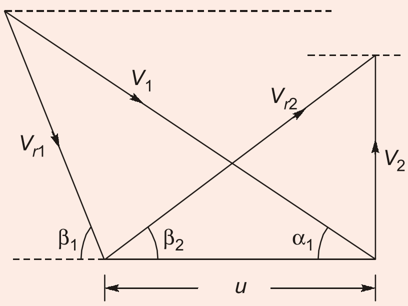
   In some hybrids, batteries meet the daily load fluctuations, and the diesel generator takes care of the long-term fluctuations. For example the diesel generator is used in the worst-case weather conditions, such as extended windless days or weeks.

End of Solution

Q.7 (a) A single row impulse steam turbine with a blade speed of 200 m/s and mass flow rate of 4 kg/s develops 300 kW of power. Steam leaves the nozzles at 500 m/s, and the blade velocity coefficient is 0.92. If the steam leaves the turbine blade at such an angle that the absolute velocity at exit is kept minimum, determine nozzle angles, blade angles and diagram efficiency. Draw compound velocity triangles.

[20 marks : 2022]

Solution:



Steam should exit axially to keep absolute velocity at exit as minimum. So,

$$V_{w2} = 0, \ \alpha_2 = 0$$

$$\text{Power} = 300 \text{ kW}$$

$$\dot{m}V_{w1}u = 300 \text{ kW}$$

$$\dot{m}V_1 \cos\alpha_1 u = 300 \text{ kW}$$

$$\cos\alpha_1 = \frac{300 \times 10^3}{4 \times 500 \times 200} = 0.75$$

$$\alpha_1 = 41.409°$$

$$V_{r1}\cos\beta_1 = V_1\cos\alpha_1 - u$$

$$V_{r1}\sin\beta_1 = V_1\sin\alpha_1$$

$$\tan\beta_1 = \frac{V_1 \sin\alpha_1}{V_1\cos\alpha_1 - u} = 1.889$$

$$\beta_1 = \tan^{-1}(1.889) = 62.11°$$

$$\therefore \quad V_{r1} = \frac{V_1 \sin\alpha_1}{\sin\beta_1} = 374.17 \text{ m/s}$$

$$\frac{V_{r2}}{V_{r1}} = 0.92$$

$$V_{r2} = 344.24 \text{ m/s}$$

$$\beta_2 = \cos^{-1}\left(\frac{u}{V_{r2}}\right) = 54.48°$$

$$\text{Diagram efficiency, } \eta_D = \frac{2V_{w1}u}{V_1^2} = \frac{2 \times 500 \times \cos(41.409) \times 200}{(500)^2}$$

$$= 0.60 = 60\%$$

End of Solution

Q.7 (b) An average flow rate of industrial waste water is 1000 m^3/day and 4000 mg/litre of an organic substance with the composition as: $C_{50}H_{75}O_{20}N_5S$. The organic waste is processed in a mesophilic anaerobic digester at 35°C for biogas production with biodegradation efficiency of 95%. Determine the methane production rate.

[20 marks : 2022]

Solution:

The decomposition in an anaerobic digester can be understood by Buswell equation as follows:

$$C_cH_h\,O_o\,N_n\,S_s + \frac{1}{4}(4c - h - 2o + 3n + 2s)H_2O$$

$$\frac{1}{8}(4c - h - 2o + 3n + 2s)CO_2 + \frac{1}{8}(4c + h - 2o - 3n - 2s)CH_4 + nNH_3 + sH_2S$$

Given: compound is $C_{50}H_{75}O_{20}N_5S$.

Thus, $c = 50$, $h = 75$, $o = 20$, $n = 5$, $s = 1$

The quantity of methane produced is

$$= \frac{1}{8}(4c + h - 2o - 3n - 2s) \times 16g$$

$$= \frac{1}{8}(4\times50 + 75 - 20\times2 - 3\times5 - 2\times1)\times16g$$

$$= 436g$$

436 g of CH_4 is produced from a formula mass ($C_{50}H_{75}O_{20}N_5S$) of 1097g

Now, daily quantity of organic substance in the industrial waste water is

$$= \frac{1000\,m^3/d \times 10^3\,l/m^3 \times 4000\,mg/l}{10^6\,mg/kg}$$

$$= 4000 \text{ kg/day}$$

Now, given biodegradation efficiency = 95%

Thus, quantity of organic matter degraded in the digester

$$= 4000 \times 0.95 = 3800 \text{ kg/day}$$

Thus, Methane produced $= 3800 \text{ kg/day} \times \frac{436g}{1097g} = 1510.3 \text{ kg/day}$

End of Solution

Q.7 (c) (i) What are once through boilers? How do they differ from drum boiler?

(ii) Why are downcomers fewer in number and bigger in diameter, while risers are more in number and smaller in diameter?

[10+10 marks : 2022]

Solution:

(i)

Once through boilers are the super critical boilers in which only one tube almost about 2 km long is used and there is no steam drum. Such boilers operate above 221.2 bar pressure as there is no latent heat of vapourization involved and the water on heating directly flashes into vapour and steam and is further heated to desired temperature in superheater. Following are the differences between once through boiler and drum boilers:

1. Once through boiler does not require centrifugal pumps and drums where as in drum boilers both pumps and drums are necessary.
2. In once through boilers extremely pure water is required since all the solids present are deposited in tubes or carried along with steam to turbines whereas in drum boilers the limitation of extremely pure water is less severe since there is some blow down of boiler water.
3. The erosion is very less in once through boiler as compared to drum boiler since it uses highly pure water.
4. The once through boilers are easy to operate and can generate peak load compared to drum boilers.
5. Once through boilers have higher thermal efficiency compared to drum boilers.
6. Once through boilers have large heat transfer coefficient compared to drum boilers.

(ii)

Downcomers are fewer in number and bigger in diameter whereas risers are more in number and smaller in diameter. Downcomers are meant to move the water fall by gravity. Bigger the diameter, lesser the pressure drop due to friction, since pressure drop is inversely proportional to the tube diameter,

$$\Delta p = \frac{\rho f L V^2}{2D}$$

So, the downcomers are made bigger in diameter, which may vary from 150 to 200 mm or even higher.

Riser absorbs heat from the furnace for the same total cross sectional area, the smaller the diameter, larger the surface area exposed to hot gas for heat transfer. Therefore, the risers are of smaller diameter 62.5 to 76.5 mm and larger in numbers compared to down comes.

End of Solution

Q.8 (a) **How is the degree of reaction of a centrifugal compressor stage defined? Explain analytically how the degree of reaction varies with flow coefficient for different values of impeller exit air angle. Assume zero swirl at the entry.**

[20 marks : 2022]

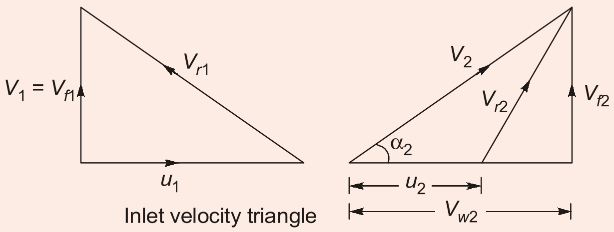
Solution:

Degree of reaction for a centrifugal compressor stage is defined as the ratio of enthalpy rise in the impeller to the total enthalpy rise in the stage.

$$R_D = \frac{\Delta h_{\text{impeller}}}{\Delta h_{\text{stage}}}$$

$$\Delta h_{\text{impeller}} = \frac{1}{2}\left(u_2^2 - u_1^2\right) + \frac{1}{2}\left(V_{r1}^2 - V_{r2}^2\right)$$

$$\Delta h_{\text{stage}} = V_{w2}u_2 - V_{w1}u_1$$



Inlet velocity triangle

Outlet velocity triangle

$$R_D = \frac{\left(V_{w2}u_2 - V_{w1}u_1\right) - \left(\dfrac{V_2^2 - V_1^2}{2}\right)}{\left(V_{w2}u_2 - V_{w1}u_1\right)}$$

$$= 1 - \frac{V_2^2 - V_1^2}{2\left(V_{w2}u_2 - V_{w1}u_1\right)}$$

$$V_{w1} = 0$$

$$V_2^2 = V_{w2}^2 + V_{f2}^2$$

$$R_D = 1 - \frac{V_2^2 - V_{f1}^2}{2\left(V_{w2}u_2\right)} = 1 - \frac{V_{w2}^2 + V_{f2}^2 - V_{f1}^2}{2V_{w2}u_2}$$

Assuming $V_{f1} = V_{f2}$

$$R_D = 1 - \frac{V_{w2}^2}{2V_{w2}u_2} = 1 - \frac{V_{w2}}{2u_2}$$

$$= 1 - \frac{1}{2} \times \frac{V_{w2}}{u_2} \times \frac{V_{f2}}{V_{f2}}$$

$$= 1 - \frac{1}{2} \times \frac{V_{f2}}{u_2} \times \frac{V_{w2}}{V_{f2}}$$

$$R_D = 1 - \frac{1}{2}\phi_2 \times \cot\alpha_2$$

where, ϕ_2 = Flow coefficient

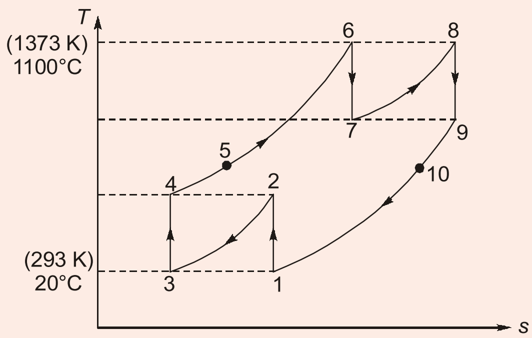
α_2 = Impeller exit air angle

End of Solution

Q.8 (b) Consider a gas turbine cycle with two stages of compression and two stages of expansion. The pressure ratio across each compressor stage and each turbine stage is 8 to 1. The pressure at the entrance of the first compressor is 100 kPa, the temperature entering each compressor is 20°C, the temperature entering each turbine is 1100°C. A regenerator is also incorporated into the cycle and it has an efficiency of 70%. Determine the compressor work, the turbine work and the thermal efficiency of the cycle. Take C_{po} as 1.004 kJ/kgK ratio of specific heats as 1.4.

[20 marks : 2022]

Solution:



$$\frac{P_2}{P_1} = \frac{P_4}{P_3} = \frac{P_6}{P_7} = \frac{P_8}{P_9} = 8$$

For isentropic processes: 1-2, 3-4, 6-7, and 8-9

$$\frac{T_2}{T_1} = \frac{T_4}{T_3} = \frac{T_6}{T_7} = \frac{T_8}{T_9} = 8^{\frac{\gamma-1}{\gamma}}$$

$$T_2 = T_4 = 530.75 \text{ K}$$

$$T_7 = T_9 = 757.96 \text{ K}$$

Efficiency of regeneration = 0.7

$$\frac{T_5 - T_4}{T_9 - T_4} = 0.7$$

$$T_5 = 689.80 \text{ K}$$

$$W_C = C_P(T_4 - T_3) + C_P(T_2 - T_1)$$

$$= 2 \times 1.004 \times (530.75 - 293)$$

$$= 477.4 \text{ kJ/kg}$$

$$W_T = C_P(T_6 - T_7) + C_P(T_8 - T_9)$$

$$= 2 \times 1.004 \times (1373 - 757.96)$$

$$= 1235 \text{ kJ/kg}$$

Thermal efficiency of the cycle,

$$\eta_{th} = \frac{W_T - W_C}{C_P(T_6 - T_5) + C_P(T_8 - T_7)}$$

$$= \frac{1235 - 477.4}{1.004(1373 - 689.80) + 1.004(1373 - 757.96)}$$

$$= 0.5812 = 58.12\%$$

End of Solution

Q.8 (c) The border region of Chattisgarh and Maharashtra has many rice mills as this region is suitable for rice crop. Suppose there is a village in this region which has many rice mills, barren land and jungle around. To meet the energy requirements of the rice mills and the village, which types of renewable energy systems would you like to propose? Justify your proposal.

[20 marks : 2022]

Solution:

Region village includes are: Jungle, Barren land and many rice mills

Resources available are:

1. Fuel wood can be taken from woods of trees.
2. Rice husk from rice mill.
3. Wind available in barren land.

Renewable energy systems that can be installed for running rice mills are:

1. **Wind Mill:** It can be installed in barren land as barren land has good enough wind available in range of 5-15 m/s.
2. **Producer gas plant:** Rice husk can be used as raw material for gasifier to produce producer gas (CO, H_2, CH_4, CO_2, N_2)
3. **Pellets and Briquettes:** It can be made by rice husk, these are solid lumps made by pressing woody waste with very high pressure.
4. **Solar PV-cells:** As the location Maharastra, Chattisgarh border receive very good amount of solar radiation.

End of Solution

■■■■