MADE EASY

Leading Institute for ESE, GATE & PSUs

ESE 2025 : Mains Test Series

UPSC ENGINEERING SERVICES EXAMINATION

Mechanical Engineering

Test-9 : Full Syllabus Test (Paper-I)

Name : ....

Roll No :

Test Centres			Student's Signature
Delhi ☑	Bhopal ☐	Jaipur ☐	
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Instructions for Candidates

1. Do furnish the appropriate details in the answer sheet (viz. Name & Roll No).
2. There are Eight questions divided in TWO sections.
3. Candidate has to attempt FIVE questions in all in English only.
4. Question no. 1 and 5 are compulsory and out of the remaining THREE are to be attempted choosing at least ONE question from each section.
5. Use only black/blue pen.
6. The space limit for every part of the question is specified in this Question Cum Answer Booklet. Candidate should write the answer in the space provided.
7. Any page or portion of the page left blank in the Question Cum Answer Booklet must be clearly struck off.
8. There are few rough work sheets at the end of this booklet. Strike off these pages after completion of the examination.

FOR OFFICE USE

Question No.	Marks Obtained
Section-A	
Q.1	34+02=36
Q.2	—
Q.3	48
Q.4	41
Section-B	
Q.5	30
Q.6	—
Q.7	35
Q.8	—
Total Marks Obtained	~~[illegible]~~ → 190

Signature of Evaluator .... Cross Checked by ....

Well done! Keep it up

IMPORTANT INSTRUCTIONS

CANDIDATES SHOULD READ THE UNDERMENTIONED INSTRUCTIONS CAREFULLY. VIOLATION OF ANY OF THE INSTRUCTIONS MAY LEAD TO PENALTY.

DONT'S

1. Do not write your name or registration number anywhere inside this Question-cum-Answer Booklet (QCAB).
2. Do not write anything other than the actual answers to the questions anywhere inside your QCAB.
3. Do not tear off any leaves from your QCAB, if you find any page missing do not fail to notify the supervisor/invigilator.
4. Do not leave behind your QCAB on your table unattended, it should be handed over to the invigilator after conclusion of the exam.

DO'S

1. Read the Instructions on the cover page and strictly follow them.
2. Write your registration number and other particulars, in the space provided on the cover of QCAB.
3. Write legibly and neatly.
4. For rough notes or calculation, the last two blank pages of this booklet should be used. The rough notes should be crossed through afterwards.
5. If you wish to cancel any work, draw your pen through it or write "Cancelled" across it, otherwise it may be evaluated.
6. Handover your QCAB personally to the invigilator before leaving the examination hall.

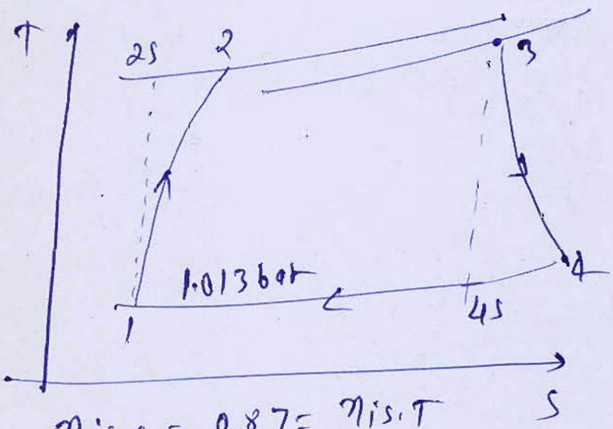
Do not write in this margin

Section : A

1 (a) A simple gas turbine admits air at atmospheric pressure (1.013 bar) and 15°C and compresses air in the compressor up to 16 bar. Then the air enters the combustion chamber and is heated to a maximum temperature of 1350°C, further it enters the turbine and expands to atmospheric pressure. The isentropic efficiency of compressor and turbine is 0.87, combustion efficiency 0.98, drop of pressure through the combustion chamber is 0.3 bar. Specific heat at constant pressure for both air and gases is 1.005 kJ/kg-K. Ratio of specific heats 1.4. Determine the flow of air for a net power of 200 MW developed.

[12 marks]

Ans: Given:



$P_1 = 1.013$ bar

$P_2 = 16$ bar

$P_3 = P_2 - 0.3 = 16 - 0.3$

$= 15.7$ bar

$P_4 = 1.013$ bar

$T_1 = 15°C = 288K$

$T_3 = 1350°C = 1623$ K

$\eta_{is,c} = 0.87 = \eta_{is,T}$

$\eta_{comb.} = 0.98$

3+2

1-2s $\quad \frac{T_{2s}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow \frac{T_{2s}}{288} = \left(\frac{16}{1.013}\right)^{.4/1.4} \Rightarrow \boxed{T_{2s} = 633.613\ K}$

$W_C \Rightarrow \frac{T_{2s} - T_1}{T_2 - T_1} = \eta_{is,c} \Rightarrow \frac{633.613 - 288}{T_2 - 288} = 0.87$

$\rightarrow \boxed{T_2 = 685.256\ K}$

3-4 $\quad \frac{T_3}{T_{4s}} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow \frac{1623}{T_{4s}} = \left(\frac{15.7}{1.013}\right)^{.4/1.4} \Rightarrow \boxed{T_{4s} = 741.712\ K}$

$\eta_{is,T} = \frac{T_3 - T_4}{T_3 - T_{4s}} \Rightarrow 0.87 = \frac{1623 - T_4}{1623 - 741.712} \Rightarrow \boxed{T_4 = 856.28\ K}$

now, <u>for compressor</u>

$W_C = \dot{m} C_p (T_2 - T_1) = \dot{m} \times 1.005 (685.256 - 288)$

$= 399.24228\ \dot{m}$ kW

for turbine

$W_T = \dot{m} C_p (T_3 - T_4) = \dot{m} \times 1.005 \times (\cancel{8}623 - 856.28)$

$= 770.5536 \, \dot{m} \text{ kW}$

$\Rightarrow$ Net power = $W_T - W_C$

$= 770.5536 \, \dot{m} - 399.2428 \, \dot{m}$

$= 371.311 \, \dot{m} \text{ kW}$

$\Rightarrow 371.311 \, \dot{m} = 200 \times 10^3$

$\boxed{\dot{m} = 538.63 \text{ kg/s}}$ Ans.

required flow of air

Q.1 (b) A cylindrical buoy, diameter 1.5 m and 1.1 m high weighing 4500 N is floating in sea water with its axis vertical. Find the maximum permissible height above the top of the buoy, of the centre of gravity of a 500 N load which is placed centrally on top of the buoy. Take specific gravity of sea water as 1.025.

[12 marks]

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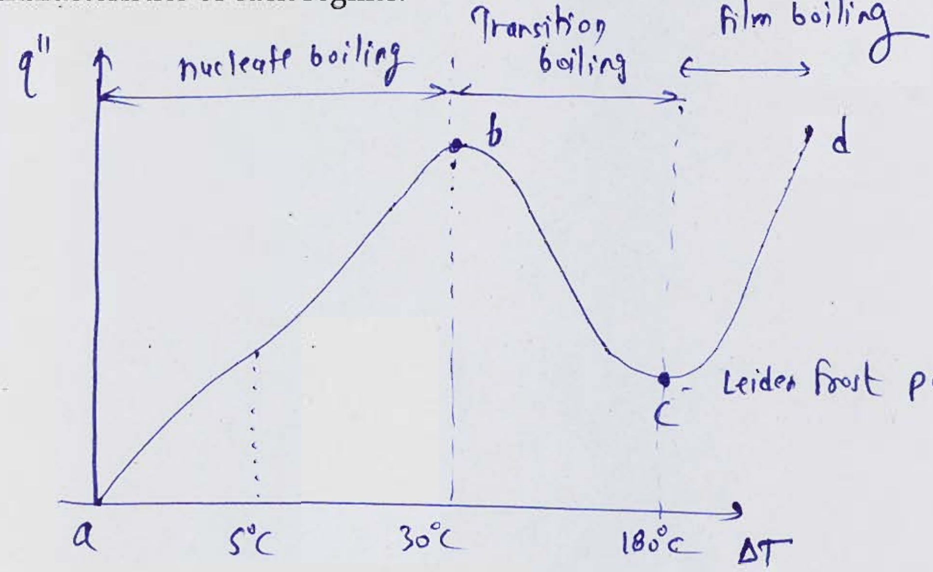
Q.1 (c) Draw the boiling curve and identify the different boiling regimes. Also, explain the characteristics of each regime. **[12 marks]**

Sol^n.



a-b nucleate boiling

→ upto ΔT = 5°C, no significant heat transfer rate is observed

→ after ~~5°C~~ ΔT = 5°C, significant heat transfer rate are observed and it reaches maximum at point b.

⇒ During this period, energy is sufficient for bubble/~~vapours~~ to reach the surface. Hence, higher heat transfer rates are observed.

b-c Transition boiling

→ as ΔT excess is increased, pockets of vapour starts forming at the solid-liquid interface. These acts as insulation to heat transfer rates and hence reduced heat transfer rates are observed.

→ In this region both convection & radiation heat transfer dominates.

→ heat transfer rate reaches its min. at point c known as Leidenfrost point.

Do not write in this margin

c-d Transition boiling

→ when ΔT_{excess} is very high, radiation heat transfer dominates and a sharp rise in heat transfer rate is observed.

→ point C (Leiden frost point) represents transition from nucleate boiling to film boiling is completed.

→ In the region, very high heat transfer rates are observed.

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(d) An inward flow turbine (reaction type with radial discharge) with an overall efficiency of 85% is required to develop 160 kW. The head is 8 m; peripheral velocity of the wheel is $0.96\sqrt{2gH}$; the radial velocity of the flow is $0.36\sqrt{2gH}$. The wheel is to make 180 rpm, and the hydraulic losses in the turbine are 25% of the available energy. Determine:

(i) the angle of the guide blade at inlet.

(ii) the wheel vane angle blade at inlet.

(iii) the diameter of the wheel.

(iv) the width of the wheel at inlet.

[12 marks]

Given: Inward flow reaction turbine

$\eta_o = 85\%$, $P_{out} = 160\ kW$, $H = 8\ m$, $U = 0.96\sqrt{2gH}$

$V_f = 0.36\sqrt{2gH}$, $N = 180$ rpm,

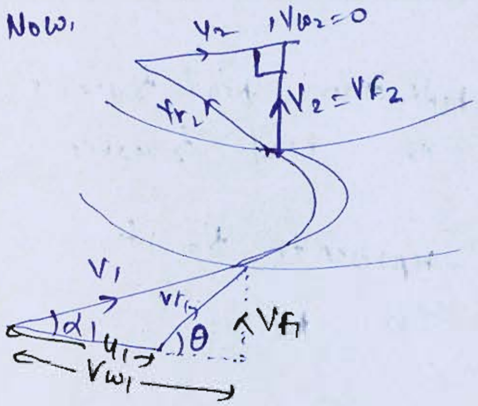
Now, $U_1 = 0.96\sqrt{2gH} = 0.96 \times \sqrt{2 \times 9.81 \times 8} = 12.027$ m/s

$V_{f_1} = 0.36\sqrt{2gH} = .36\sqrt{2 \times 9.81 \times 8} = 4.51$ m/s

$\therefore U_1 = \frac{\pi D_1 N}{60} \rightarrow 12.027 = \frac{\pi \times D_1 \times 180}{60}$

$\boxed{D_1 = 1.276\ m}$ Ans. (dia of wheel)

Now,



overall efficiency, $\eta_o = \frac{P_{out}}{\rho Q g H}$

$$0.85 = \frac{160 \times 10^3}{10^3 \times Q \times 9.81 \times 8}$$

$$\boxed{Q = 2.3985\ m^3/s}$$

$\Rightarrow$ $Q = \pi D_1 B_1 V_{f_1} = \pi \times 1.276 \times B_1 \times 4.51$

$\boxed{B_1 = 0.1326\ m}$ Ans: (width of wheel at inlet)

now, Hydraulic losses = 25 %

$\Rightarrow$ hydraulic efficiency = 75 %

$\Rightarrow$ $\frac{V_{w_1} U_1}{gH} = 0.75 \rightarrow \frac{V_{w_1} \times 12.027}{9.81 \times 8} = 0.75$

$$\boxed{V_{w_1} = 4.894\ m/s}$$

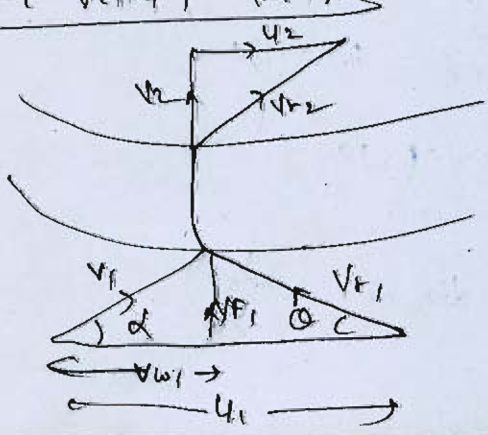
, Guide vane angle at inlet (α)

$\tan\alpha = \frac{V_{f_1}}{V_{w_1}} = \frac{4.51}{4.894} \Rightarrow \boxed{\alpha = 42.66^\circ}$ Ans:

wheel vane angle at inlet (θ) [$\because u_1 > V_{w_1}$]

$\tan\theta = \frac{V_{f_1}}{-V_{w_1}+u_1} = \frac{4.51}{12.027 - 4.894} \Rightarrow \boxed{\theta = 32.3^\circ}$ Ans:

Correct velocity triangle



1 (e) A gas of mass 1.5 kg undergoes a quasi-static expansion which follows a relationship $p = a + bV$, where a and b are constants. The initial and final pressures are 1000 kPa and 200 kPa respectively and the corresponding volumes are 0.20 m^3 and 1.20 m^3. The specific internal energy of the gas is given by the relation.

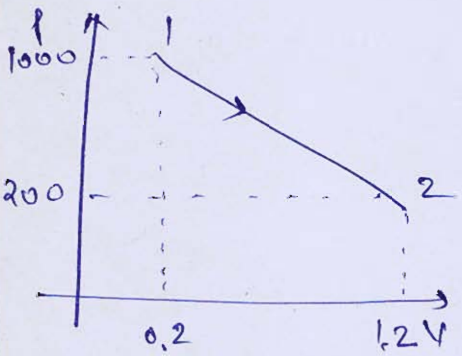
$u = 1.5\,pv - 85$ kJ/kg

Where p is in kPa and v is in m^3/kg. Calculate the net heat transfer and the maximum internal energy of the gas attained during expansion.

[Take ratio of specific heat $\gamma = 1.20$]

[12 marks]

$P = a + bV \rightarrow$ linear relationship.



work done during process

W_{1-2} = area under PV diagram

$= \frac{1}{2}(P_1+P_2)(V_2-V_1)$

$= \frac{1}{2}[1000+200][1.2-0.2]$

$\boxed{W_{1-2} = 600 \text{ kJ}}$

now, internal energy is given as

$u = 1.5PV - 85$ —— (1)

also, $\because$ $P = a + bV$

$1000 = a + 0.2 \times b$

$200 = a + 1.2 \times b$

on solving

$\boxed{a = 1160 \quad b = -800}$

6

$\Rightarrow$ $P = 1160 - 800V$

so from eqn (1)

$u = 1.5V[1160 - 800V] - 85$

$\boxed{u = 1740V - 1200V^2 - 85}$

now, ∵ internal energy is point function!

$$\Delta U_{1-2} = 1.5[u_2 - u_1] = [(1.5P_2V_2 - 85) - (1.5P_1V_1 - 85)] \times 1.5$$
$$= [1.5(P_2V_2 - P_1V_1)] \times 1.5$$
$$= [1.5[200 \times 1.2 - 0.2 \times 1000]] 1.5$$
$$= 60 \text{ kJ/kg} \times 1.5 = 90 \text{ kJ}$$

⇒ heat transfer, $Q_{1-2} = \Delta U_{1-2} + W_{1-2}$
$$= 90 + 600 = 690 \text{ kJ}$$

$\boxed{Q_{1-2} = 690 \text{ kJ}}$ Ans.

maximum internal energy

$$u = 1740V - 1200V^2 - 85$$

for this to be maximum

$$\frac{\partial u}{\partial V} = 0$$

$$\Rightarrow 1740 - 2 \times 1200V = 0$$

$$\boxed{V = 0.725 \text{ m}^3/\text{kg}}$$

$$u_{max} = 1740 \times .725 - 1200 \times .725^2 - 85$$
$$= 545.75 \text{ kJ/kg}$$

or $\boxed{U_{max} = 1.5 \times u_{max} = 818.625 \text{ kJ}}$ Ans.

2 (a) A total of 15 litres per second of oil is pumped through two pipes in parallel, one 10 cm in diameter and the 12 cm in diameter, both pipes 1000 metres long. The specific gravity of the oil is 0.95 and the kinematic viscosity 9 cm^2 per second. Calculate the flow rate through each time and the horse-power of the pump.

[20 marks]

2 (b) Explain the construction and working of turbojet engine with the help of neat sketch and derive the expression for its thermal efficiency.

[20 marks]

2 (c) The nose section of a missile is formed of a 6 mm thick stainless plate and is held initially at uniform temperature of 88°C The missile enters the denser layers of the atmosphere at very high velocity. The effective temperature of air surrounding the nose region attains the value 2200°C and the surface convective coefficient is estimated at 3400 W/m^2-K Make calculations for the maximum permissible time in these surroundings if the maximum metal temperature is not to exceed 1095°C Also workout the inside surface temperature under these conditions.

The properties for steel are: ρ = 7800 kg/m^3, k = 51 W/m-°C, C_p = 465 J/kg-K.

[Take, x/L_c = 1, outside surface from nose section]

[Use Heisler chart attached at the end]

[20 marks]

3 (a) Explain the basic function of refrigerants in a refrigeration cycle and how they are classified? Also discuss the desirable properties of refrigerants and the basic difference between primary and secondary refrigerants.

[20 marks]

Ans :

Basis function of Refrigerant

Basic function of refrigerant is to provide a refrigerating effect (ie. producing a temperature lower than that of surrounding).

They are basically classified into 2 categories

(1) Primary refrigerant
(2) secondary refrigerant

Primary refrigerant

Primary refrigerant directly takes part in the refrigeration effect and produces refrigeration effect at desired place.

secondary refrigerant

These are first cooled by primary refrigerant and then are used to desired place for providing cooling / refrigeration,

Desirable properties of Refrigerants

~~(1) Physical properties~~

I. (1) Thermodynamic properties.

(1) Conductivity (k) → High conductivity is desirable

(2) Specific heat : High specific heat of vapour & liquid refrigerant is desirable. low specific heat of

(3) Latent heat of vapourisation, Higher LH of vapourisation is desirable.

(4) Critical temperature

High critical temperature is desirable.

(5) CoP

Higher Cop is desirable

II. Chemical properties

→ should be non-toxic

→ should be non-inflammable.

→ should be non-reactive.

→ should be corrosion resistant.

III. Physical properties

→ should be ~~either~~ completely miscible or completely immiscible with oil.

→ should ~~be~~ not leak. However in case of leakage, it should be easily detectable.

→ storage should be easy.

4

Q.3 (b) The velocity components in a two-dimensional flow field for an incompressible fluid are expressed as $u = \frac{y^3}{3} + 2x - x^2y;\ v = xy^2 - 2y - \frac{x^3}{3}$

(i) Show that these functions represent a possible case of an irrotational flow.

(ii) Obtain an expression for stream function ψ.

(iii) Obtain an expression for velocity potential φ.

[20 marks]

Soln:

(i) $u = \frac{y^3}{3} + 2x - x^2y$; $v = xy^2 - 2y - \frac{x^3}{3}$

we know

$\omega_z = \frac{1}{2}\left[\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right]$

$= \frac{1}{2}\left\{\frac{\partial}{\partial x}\left[xy^2 - 2y - \frac{x^3}{3}\right] - \frac{\partial}{\partial y}\left[\frac{y^3}{3} + 2x - x^2y\right]\right\}$

$= \frac{1}{2}\left[\left(y^2 - \frac{3x^2}{3}\right) - \left(\frac{3y^2}{3} - x^2\right)\right]$

$= \frac{1}{2}\left[y^2 - x^2 - y^2 + x^2\right] = 0$

∵ $\omega_z = 0 \rightarrow$ it represents a possible case of an irrotational flow.

(ii) stream function

$u = \frac{\partial \psi}{\partial y} = \frac{y^3}{3} + 2x - x^2y$

on integrating

$\psi = \frac{y^4}{3 \times 4} + 2xy - \frac{x^2y^2}{2} + f(x)$ —(1)

differentiating w.r.t x

$\frac{\partial \psi}{\partial x} = 2y - \frac{y^2}{2}(2x) + f'(x) = 2y - xy^2 + f'(x)$

but $\frac{\partial \psi}{\partial x} = -v = -xy^2 + 2y + \frac{x^3}{3} = -xy^2 + 2y + f'(x)$

⇒ $f'(x) = \frac{x^3}{3}$ ⇒ $\boxed{f(x) = \frac{x^4}{3 \times 4}}$

⇒ $\psi = \frac{y^4}{12} + 2xy - \frac{x^2y^2}{2} + \frac{x^4}{3 \times 4}$

or $\boxed{\psi = \frac{x^4 + y^4}{12} + 2xy - \frac{x^2y^2}{2}}$ Ans.

(iii) Velocity potential function.

$u = \frac{y^3}{3} + 2x - x^2 y$, $v = xy^2 - 2y - \frac{x^3}{3}$

we know

$u = -\frac{\partial \phi}{\partial x} = \frac{y^3}{3} + 2x - x^2 y$

$\Rightarrow \frac{\partial \phi}{\partial x} = -\frac{y^3}{3} - 2x + x^2 y$

on integrating

$\phi = -\frac{y^3}{3}x - 2\frac{x^2}{2} + \frac{x^3}{3}y + f(y)$

$\phi = -\frac{xy^3}{3} - x^2 + \frac{yx^3}{3} + f(y)$ — (2)

differentiating above eqn w.r.t y

$\frac{\partial \phi}{\partial y} = -\frac{x.3y^2}{3} - 0 + \frac{x^3}{3} + f'(y)$

$= -xy^2 + \frac{x^3}{3} + f'(y)$ — (3)

but $\frac{\partial \phi}{\partial y} = -v = -xy^2 + \frac{x^3}{3} + 2y$ (4)

on comparing eqn (3) & (4)

$f'(y) = 2y$

$\Rightarrow \boxed{f(y) = y^2}$

$\Rightarrow \phi = -\frac{xy^3}{3} - x^2 + \frac{yx^3}{3} + y^2$

$\boxed{\phi = \frac{yx^3 - xy^3}{3} + y^2 - x^2}$ Ans.

2

Q.3 (c) A gasoline engine has a stroke volume of 0.0015 m^3 and a compression ratio of 6. At the end of compression stroke, the pressure is 8 bar and temperature 350°C. Ignition is set so that the pressure rises along a straight line during combustion and attains its highest value of 25 bar after the piston has travelled $\frac{1}{30}$ of the stroke. The charge consists of a gasoline-air mixture in proportion by mass 1 to 16. Take R = 287 J/kgK, Calorific value of fuel as 42 MJ/kg and C_p = 1 kJ/kgK. Calculate the heat lost per kg of charge during combustion.

[20 marks]

Given:

Gasoline engine

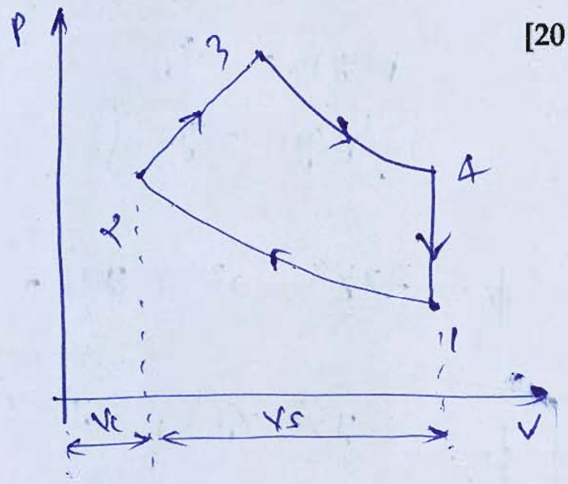
$V_s = 0.0015 \ m^3$

Compression ratio $r = 6$

$P_2 = 8$ bar

$T_2 = 350°C = 350 + 273$

$T_2 = 623 K$



$P_3 = 25$ bar

$V_3 = V_2 + \frac{V_s}{30} = V_c + \frac{V_s}{30}$

now, $r = \frac{V_1}{V_2} = \frac{V_s + V_c}{V_c} = \frac{V_s}{V_c} + 1$

$6 = \frac{0.0015}{V_c} + 1 \rightarrow \boxed{V_c = 0.0003\ m^3} = V_2$

$V_3 = V_c + \frac{V_s}{30} = 0.0003 + \frac{0.0015}{30} = 0.00035\ m^3$.

2–3 ⇒ combustion along a straight line

$W_{2-3} = \frac{1}{2}(P_2 + P_3)(V_3 - V_2)$

$= \frac{1}{2}[8 + 25] \times 100 \times [0.00035 - 0.0003] \times 1000$

$\boxed{W_{2-3} = 82.5\ J}$ (per kg of charge)

change in internal energy

$U_{2-3} = C_v(T_3 - T_2) = (C_p - R)\left[\frac{P_3 V_3}{R} - \frac{P_2 V_2}{R}\right]$

$= \frac{(1000 - 287)}{287}\left[25 \times 10^5 \times .00035 - 8 \times 10^5 \times .0003\right]$

$\boxed{U_{2-3} = 1577.543\ J/kg\ \text{of charge}}$

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~~now, given~~ by 1st law of thermodynamics

⇒ $Q_{2-3} = W_{2-3} + U_{2-3}$

$= 82.5 + 1577.543$

$\boxed{Q_{2-3} = 1660.043\ J/kg\ \text{of charge}}$

now, Heat released by fuel

$\because\ m_f/m_a = 16 \Rightarrow m_a = \frac{m_f}{16} = 0.0625\ m_f$

⇒ $Q_{released} = m_f \times CV = m_f \times 42000\ kJ/kg$

$= 42000\ kJ/kg$ of fuel

but 1 kg of fuel = (1 + .0625) kg of charge

$\Rightarrow \quad Q_{released} = \frac{42000}{1.0625} = 39529.411$ kJ / kg of charge

$\Rightarrow$ heat lost / kg of charge

$= 39529.411 - \frac{1660.43}{1000}$

$= 39527.75$ kJ / kg of charge

Ans:

Q.4 (a) In a Francis turbine, prove that hydraulic efficiency η_h of the turbine can be expressed as

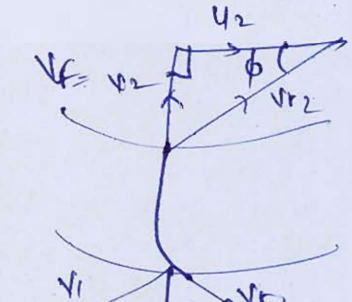
$$\eta_h = \frac{2}{2 + \dfrac{k_1 + k_2 + k_3 + k_4}{(\cot\alpha - \cot\theta)\left\{\cot\alpha\left(1+n^2\right) - n\left((\cot\phi + n\cot\theta)\right)\right\}}}$$

where k_1, k_2, k_3 and k_1 represent the fraction of the losses in the guide vanes, runner vanes, draft tube and at exit respectively expressed in terms of the velocity of flow head; α, θ and ϕ are the guide vane angle, the runner vane angle at inlet and the runner vane angle at outlet respectively and n is the ratio of the inner to outer diameter of the runner. Assume the velocity of flow to remain constant in the runner.

[20 marks]

Soln: Given: Francis turbine - radial exit

$\boxed{V_2 = 0}$



Now $n = \frac{D_1}{D_2}$

$V_{f_1} = V_{f_2} = V_f$

hyd. efficiency $\eta_h = \frac{\text{Power output}}{\text{energy input}} = \frac{P_{out}}{E_{in}}$

energy input = power output + losses

$= P_{out} + (k_1 + k_2 + k_3 + k_4)$

$$\eta_H = \frac{P_{out}}{P_{out} + k_1 + k_2 + k_3 + k_4} = \frac{1}{1 + \frac{(k_1 + k_2 + k_3 + k_4)}{P_{out}}}$$

$P_{out} = V_{w_1} u_1 - \cancel{V_{w_2}} u_2 = V_{w_1} u_1$

$u_1 = \frac{\pi D_1 N}{60} =$; $\boxed{\frac{u_1}{u_2} = \frac{D_1}{D_2} = D}$

$u_2 = \frac{\pi D_2 N}{60}$

from outlet velocity Δ. $\tan\phi = \frac{V_f}{u_2}$

$V_F = u_2 \tan\phi = \frac{u_1}{D} \tan\phi$

or $\boxed{u_1 = V_f \cdot D \cot\phi}$ —①

now, $\tan\alpha = \frac{V_f}{V_{w_1}}$

$\Rightarrow$ $\boxed{V_{w_1} = V_F \cot\alpha}$

$\tan\theta = \frac{V_f}{u_1 - V_{w_1}} = \frac{V_f}{V_f \cdot D \cot\phi - V_f \cot\alpha}$

5

4 (b) Castor oil at 25°C flows at a velocity of 0.1 m/s past a flat plate in a certain process. If the plate is 4.5 m long and is maintained at a uniform temperature of 95 °C. Calculate the following using exact solution :

(i) The hydrodynamic and thermal boundary layer thickness on one side of the plate.

(ii) The total drag force per unit width on one side of the plate.

(iii) The local heat transfer coefficient at the trailing edge, and the heat transfer rate.

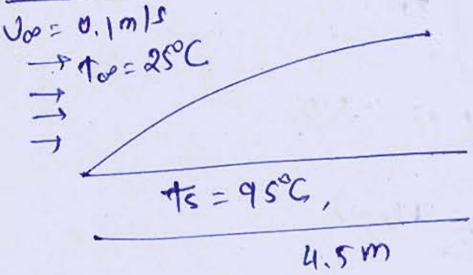
[Take $\nu = 0.65 \times 10^{-4}$ m^2/s, $\alpha = 7.2 \times 10^{-8}$ m^2/s, $k = 0.213$ W/m°C, $\rho = 956.8$ kg/m^3]

[20 marks]

Ans:

Given:

$V_\infty = 0.1 \, m/s$



$\vartheta = 0.65 \times 10^{-4} \, m^2/s$

$\alpha = 7.2 \times 10^{-8} \, m^2/s$

$K = 0.213 \, W/m°C$

$\rho = 956.8 \, kg/m^3$

Reynolds no at end of plate

$$Re = \frac{\rho V x}{\mu} = \frac{V x}{\nu} = \frac{0.1 \times 4.5}{0.65 \times 10^{-4}}$$

$$= 6923.077$$

$\therefore Re < 5 \times 10^5$

flow is laminar throught.

(ii) Now, $$P_r = \frac{\mu C_p}{K} = \frac{(\rho\vartheta).C_p}{K} \quad \cancel{956.8 \times 0.65 \times 10^{-4}} \times$$

$$= \vartheta/\alpha = \frac{0.65 \times 10^{-4}}{7.2 \times 10^{-8}} = 902.77$$

(i) By Blausius eq^n

$$\delta_H = \frac{5x}{\sqrt{Re_x}} = \frac{5 \times 4.5}{\sqrt{6923.077}} = 0.2704 \, m$$

we know

$$\frac{\delta_H}{\delta_T} = (P_r)^{1/3} = (902.77)^{1/3} = \frac{0.2704}{\delta_T}$$

$$\delta_T = 0.028 \, m$$

$$\boxed{\begin{aligned} \delta_H &= 0.2704 \, m \\ \delta_T &= 0.028 \, m \end{aligned}}$$

(ii) $C_{DL} = \frac{1.328}{\sqrt{Re_L}} = \frac{1.328}{\sqrt{6923.077}} = 0.01596$

$\Rightarrow$ Drag force $= C_{DL} \times \frac{1}{2} \rho A U_\infty^2$, $A = L \times 1 = 4.5\, m^2$

$= 0.01596 \times \frac{1}{2} \times 956.8 \times 4.5 \times 0.1^2$

$\boxed{\text{Drag force / width} = 0.3436\ N}$ Ans:

(iii) Local heat transfer coefficient at $x = 4.5m$

$Nu_x = 0.332\, Re_x^{1/2}\, Pr^{1/3}$ (laminar flow)

$\frac{h_x \times 4.5}{0.213} = 0.332 \times (6923.077)^{1/2}\, 902.77^{1/3}$

$\boxed{h_x = 12.637\ W/m^2K}$ Ans:

Heat transfer rate (from one side)

we know avg. heat transfer coefficient

$\bar{h}_L = 2h_x$ (for laminar flow)

$= 2 \times 12.637 = 25.274\ W/m^2K$

$\Rightarrow$ heat transfer $= \bar{h}_L \cdot (A) \cdot \Delta T$

$= 25.274 \times 4.5 \times 1 \times (95 - 25)$

$\boxed{q = 7961.368\ W/m}$ Ans:

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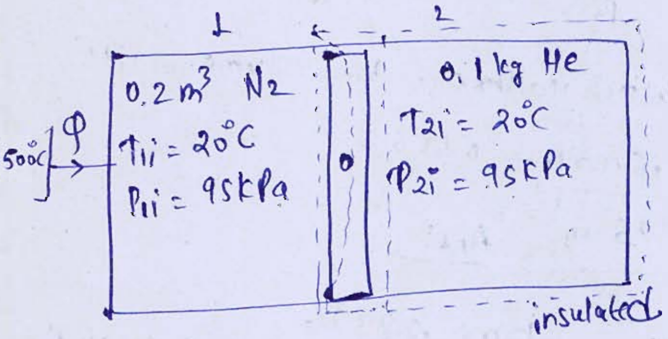
4 (c) A horizontal cylinder is separated into two compartments by an adiabatic frictionless piston. One side contains 0.2 m^3 of nitrogen and the other side contains 0.1 kg of helium, both initially at 20°C and 95 kPa. The curved surface of the cylinder and the helium end are insulated. Now heat is added to the nitrogen side from a reservoir at 500°C until the pressure of the helium rises to 120 kPa. Determine:

(a) the final temperature of the helium,
(b) the final volume of the nitrogen,
(c) the heat transferred to the nitrogen, and
(d) the entropy generation during this process.

The properties of nitrogen at room temperature are: R = 0.2968 kPa. m^3/kg.K, c_p = 1.039 kJ/kg.K, c_v = 0.743 kJ/kgK, k = 1.4. The properties for helium are R = 2.0769 kPa.m^3/kgK, c_p = 5.1926 kJ/kgK, c_v = 3.1156 kJ/kgK, k = 1.667

[20 marks]

Sol:



i & f represents initial & final conditions in ~~side~~ each side respectively.

$\Rightarrow P_{2f} = 120\,kPa$

Assuming both the gases to be ideal gas

Helium → since it undergoes adiabatic compression $\gamma_{He} = k = 1.667$

$$\Rightarrow \frac{T_{2f}}{T_{2i}} = \left(\frac{P_{2f}}{P_{2i}}\right)^{\frac{\gamma_{He}-1}{\gamma_{He}}},$$

$$\frac{T_{2f}}{20+273} = \left(\frac{120}{95}\right)^{\frac{1.667-1}{1.667}} \rightarrow \boxed{T_{2f} = 321.708\,K} \quad \text{Ans:}$$

~~change in inter~~

now, work done, $W_{He} = \dfrac{P_{2i}V_{2i} - P_{2f}V_{2f}}{\gamma_{He}-1} = \dfrac{mR[T_{2i} - T_{2f}]}{\gamma_{He}-1}$

$$= \frac{0.1 \times 2.7069\,[20+273 - 321.708]}{1.667-1} = -11.65\,kJ$$

-ve sign indicates that work is done on the helium and this work is done by N_2 from other side.

$$\Rightarrow \boxed{W_{N_2} = 11.65\,kJ}$$

entropy change of Helium

$$\Delta S_{He} = m\left[C_p \ln \frac{T_{2f}}{T_{2i}} - R \ln \frac{P_{2f}}{P_{2i}}\right] = 0 \quad \left[\begin{array}{c}\text{frictionless} \\ \text{adiabatic process}\end{array}\right]$$

Nitrogen $\quad m = \frac{P_1 V_1}{RT_1} = \frac{95 \times 0.2}{.2968 \times (20+273)} = 0.218485 \text{ kg}$

at equilibrium, pressure at both sides of piston will be same $\Rightarrow$ $P_{1F} = P_{2F} = 120 \text{ kPa}$

$\Rightarrow$ initial ~~final~~ volume of He $= \frac{mRT_1}{P_1} = \frac{0.1 \times 2.0769 \times 293}{95} = 0.64056 \text{ m}^3$

final volume of He $= \frac{mRT_2}{P_2} = \frac{0.1 \times 2.0769 \times 321.708}{120} = 0.5568 \text{ m}^3$

final volume of N_2 = total initial volume − final volume of He

$= 0.2 + .64056 - 0.5568$

$\boxed{V_{1f} = 0.28376 \text{ m}^3}$ Ans:

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final temp of N_2 $= \frac{P_{1F} V_{1F}}{mR} = \frac{120 \times .28376}{0.218485 \times .2968} = 525.106 \text{ K}$

change in internal energy of N_2

$\Delta U_{N_2} = m c_v (T_{1F} - T_{21})$

$= 0.218485 \times .743 (525.106 - 293)$

$\boxed{\Delta U_{N_2} = 37.678 \text{ kJ}}$

by First law of thermodynamics

$Q_{N_2} = \Delta U_{N_2} + W_{N_2}$

$= 37.678 + 11.65$

$\boxed{Q_{N_2} = 49.328 \text{ kJ}}$ Ans:

Entropy generation $S_{gen} = \Delta S_{N_2} = m\left[C_p \ln \frac{T_{1f}}{T_{1i}} - R \ln \frac{P_{1f}}{P_{1i}}\right]$

$= 0.218485 \left[1.039 \ln \frac{525.106}{293} - .2968 \ln \frac{120}{95}\right]$

$\boxed{S_{gen} = 0.1173 \text{ kJ/K}}$ Ans:

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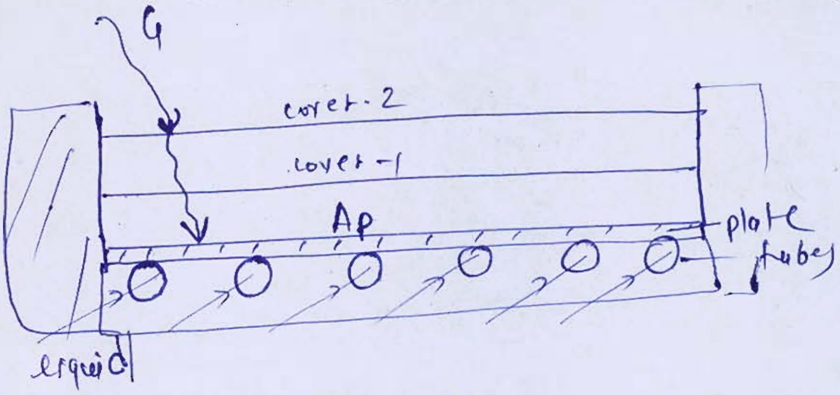
Section : B

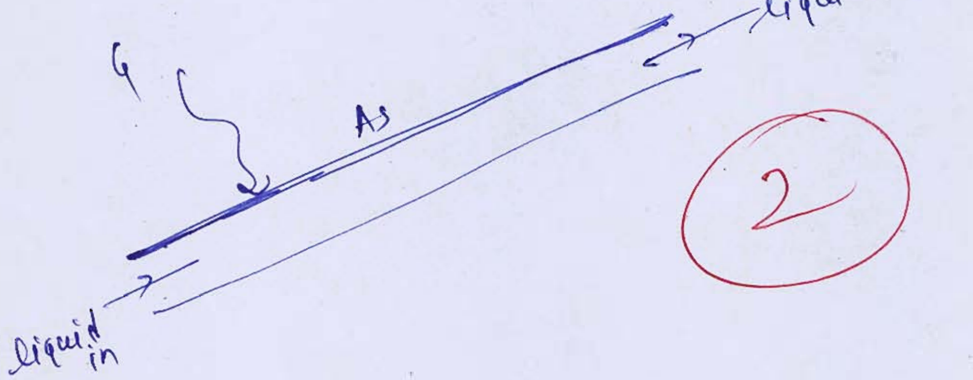
.5 (a) Explain the working of liquid flat plate collector with suitable diagrams.

[12 marks]



A_p = area of plate

G = incident light reaching the absorber plate



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5 (b) At a point in a turbulent flow field the instantaneous values of u and v velocity components measured at an interval of 0.05 seconds are listed below.

u (mm/s)	+105	+110	+84	+89	+102	+94	+111	+101	+87	+95	+89
v (mm/s)	-3	-16	+11	+25	-6	-20	-20	+4	+21	-2	+6

Determine $\overline{u}, \overline{v}, \overline{u'v'}$ and local value of Reynolds' shear stress. Take $\overline{\rho} = 1.23\ \text{kg/m}^3$.

[12 marks]

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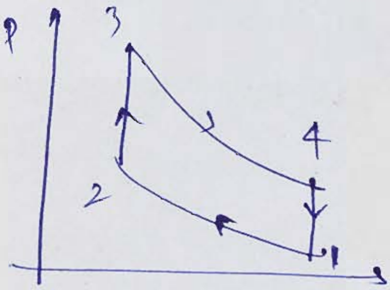
Q.5 (c) Derive the relation for the percentage variation in air standard efficiency of Otto cycle with percentage variation of c_v. Also determine percentage change in efficiency of Otto cycle if compression ratio is 8, and specific heat at constant volume increases by 2%.

[12 marks]

Soln:



r = compression ratio $= 8$

air standard efficiency

$$\eta_{air\text{-}std} = 1 - \frac{1}{r^{\gamma - 1}}, \quad \gamma = \frac{C_p}{C_V} \quad \& \quad C_V = \frac{R}{\gamma - 1}$$

$$\gamma - 1 = R/C_V$$

$$\boxed{\eta_{air\text{-}std} = 1 - \frac{1}{r^{R/C_V}}}$$ where, $R = 0.287$ kJ/kg K

let C_V changes by a % ($\uparrow$), let $\underline{R/C_V = b}$

$\Rightarrow$ changed efficiency

$$\eta_2 = 1 - \frac{1}{r^{R/(1.0a\,C_V)}}$$

% change in efficiency

$$\Rightarrow \% \Delta\eta \quad \frac{\eta_2 - \eta_1}{\eta_1} = \frac{\eta_2}{\eta_1} - 1 = \frac{1 - \frac{1}{r^{R/1.0a\,C_V}}}{1 - \frac{1}{r^{R/C_V}}} - 1$$

$$= \frac{r^{\frac{R}{1.0a\,C_V}} - 1}{r^{\frac{R}{1.0a\,C_V}}} \times \frac{r^{R/C_V}}{r^{R/C_V} - 1}$$

$$= \frac{r^{\frac{b}{1.0a}} - 1}{r^{\frac{b}{1.0a}}\, r^b - 1} \times \frac{r^b \cdot r^{\frac{b}{1.0a}}}{\cdot}$$

$$\boxed{\% \Delta\eta = \frac{r^{\frac{b}{1.0a}} - 1}{r^b - 1} \times r^{b\frac{.0a}{1.0a}} \times 100}$$ Ans:

now, $C_v \uparrow$ by 2% $\Rightarrow a = 2$

$$\%\Delta\eta = \frac{\gamma^{\frac{b}{1.0a}} - 1}{\gamma^{b} - 1} \times \gamma^{\frac{b \times .0a}{1.0a}}$$

$$b = \frac{R}{C_v} = \frac{.287}{.718} = 0.4$$

$$\%\Delta\eta = \frac{8^{\frac{.4}{1.02}} - 1}{8^{.4} - 1} \times 8^{\frac{0.4 \times .02}{1.02}} \times 100$$

$$\boxed{\%\Delta\eta = -1.267\%}$$

i.e. efficiency decreases by 1.267% when $C_v \uparrow$ by 2%.

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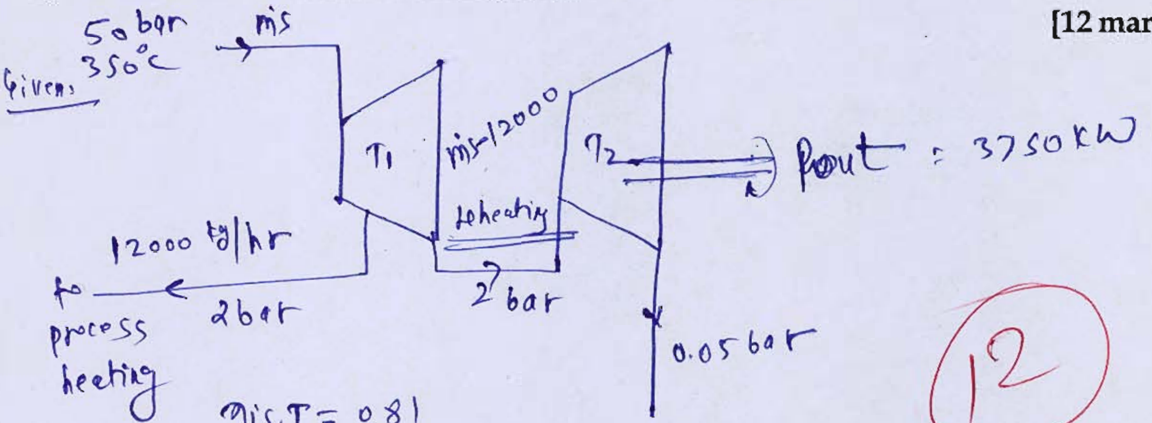
(d) A passout two stage turbine receives steam at 50 bar and 350°C. At 2.0 bar the high-pressure stage exhausts and 12000 kg of steam per hour are taken at this stage for process heating. The remainder is reheated at 2.0 bar to 250°C and then expanded through the low pressure turbine to condenser pressure of 0.05 bar. The power output from the turbine unit is 3750 kW. Take isentropic efficiency of high pressure and low pressure turbine stage as 0.81. Calculate the boiler capacity.

[12 marks]



12

As table is not provided

now, $P_{out} = 3750\ kW$

$$\frac{\dot{m}_s - 12000}{3600} \times \frac{\Delta h_2}{\eta_{is,T}} = 3750$$

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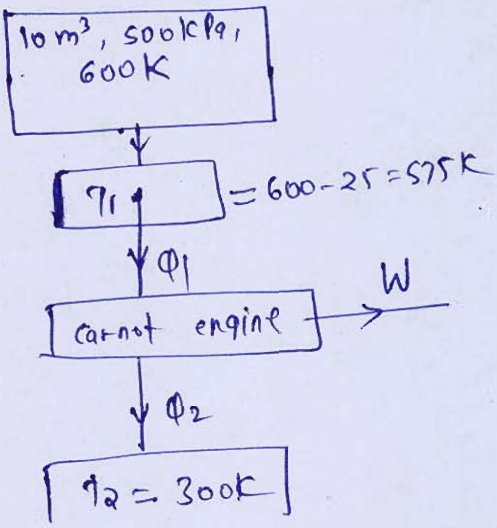
.5 (e) A 10 m^3 tank of air at 500 kPa, 600 K acts as the high temperature reservoir for a Carnot heat engine that rejects heat at 300 K. A temperature difference of 25°C between the air tank and the Carnot cycle high temperature is needed to transfer the heat. The heat engine runs until the air temperature has dropped to 400 K and then stops. Assume constant specific heat for air and find how much work is given out by the heat engine?

[12 Marks]



mass of air tank

$$m = \frac{P_i V_i}{R T_i}$$

$$= \frac{500 \times 10}{.287 \times 600}$$

$$\boxed{m = 29.036 \text{ kg}}$$

4

Q_1 = heat supplied to engine (assuming tank to be rigid).

$$= m C_v (T_i - T_F)$$

$$= 29.036 \times .718 (600 - 400)$$

$$\boxed{Q_1 = 4169.57 \text{ kJ}}$$

⇒ Carnot efficiency

$$\eta_{carnot} = 1 - \frac{T_2}{T_1} = \frac{W_{out}}{Q_1}$$

$$1 - \frac{300}{(400-25)} = \frac{W_{out}}{4169.57}$$

$$\boxed{W_{out} = 833.914 \text{ kJ}}$$ Ans.

Q.6 (a) (i) Explain the working principle of thermo electric refrigeration with schematic diagram.

(ii) A tracking mechanism for the solar heating purpose needs to be installed in Kolkata (22°N, 88°22′E), West-Bengal. Determine the sunshine hour angle on 28th of May and also determine the global radiation in (kJ/m^2 day) by using modified angstroms equation.

$$\frac{H_g}{H_o} = a + b\left(\frac{L_a}{L_m}\right); \text{ where } a = 0.28,\ b = 0.48,\ \frac{L_a}{L_m} = 0.7944$$

$$I_n = I_{sc}\left\{1 + 0.033\cos\left(\frac{360}{365} \times n\right)\right\}$$

[20 marks]

Q.6 (b) Percentage volumetric analysis of a sample of dry flue gases of a coal fired boiler gave 10.4% CO_2, and 2% of CO. Gravimetric percentage analysis of coal was 84% Carbon, 6% Hydrogen and 10% incombustible. Estimate (consider oxygen also in combustion product)

(i) Weight of dry flue gases per kg of fuel.

(ii) Weight of air supplied per kg of fuel.

(iii) Weight of water vapour formed per kg of fuel.

[20 marks]

6 (c) Air enters an air-conditioning system that use refrigerant R-134a at 30°C and 70% R.H. at a rate of 4 m^3/min. The refrigerant enters the cooling section at 700 kPa with a quality of 20% and leaves as saturated vapour. The air is cooled at 20°C and 20% RH at a pressure of 1 atm. Determine :

(a) the rate of dehumidification

(b) the rate of heat transfer

(c) the mass flow rate of the refrigerant

Assume the condensate temperature as 20°C. Use the following data for water and refrigerant R-134a.

Water :

T(°C)	P_{sat} (kPa)	Sp. Volume (m^3/kg)		Sp. Enthalpy (kJ/kg)	
		v_f	v_g	h_f	h_{fg}
20	2.3392	0.001002	57.762	83.915	2537.4
30	4.2469	0.001004	32.879	125.74	2555.6

R-134a:

T(°C)	P_{sat} (kPa)	Sp. Volume (m^3/kg)		Sp. Enthalpy (kJ/kg)	
		v_f	v_g	h_f	h_{fg}
26.72	700	0.0008328	0.0292	86.78	175.07

[20 marks]

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Q.7 (a) (i) Explain the working principle of a flooded type evaporator used in refrigeration system with the help of neat and labelled diagram.

(ii) A centrifugal compressor running at 18000 rpm takes in air at 25°C and compresses it through a pressure ratio of 4.0 with an isentropic efficiency of 80%. Guide vane at inlet, guides the air, at an angle of pre-whirl of 20° to the axial direction. The mean diameter of impeller eye is 225 mm. Absolute air velocity at inlet is 130 m/s and slip factor is 0.9. If at exit the blades are radially inclined, calculate the impeller tip diameter.

[20 marks]

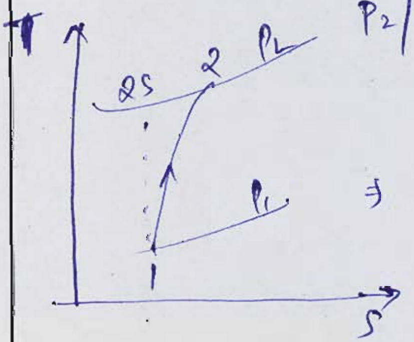
Sol^n:

(ii) Centrifugal Compressor

$N = 18000$ rpm $\rightarrow \omega = \frac{2\pi \times 18000}{60} = 1884.955$ rad/s

$P_2/P_1 = 4$, $T_1 = 25^\circ C = 25 + 273 = 298\,K$

$\eta_{is,c} = 80\%$



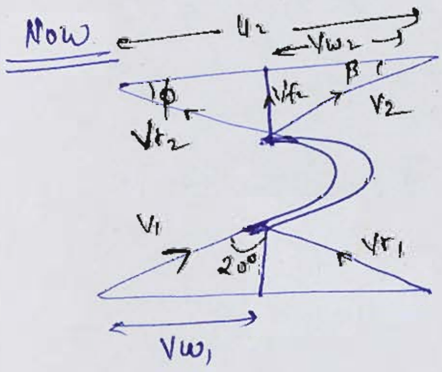
$\Rightarrow \frac{T_{2s}}{T_1} = r_p^{\frac{\gamma-1}{\gamma}}$

$\frac{T_{2s}}{298} = 4^{.4/1.4} \rightarrow T_{2s} = 442.826\,K$

$\eta_{is,c} = \frac{T_{2s} - T_1}{T_2 - T_1} \rightarrow 0.80 = \frac{442.826 - 298}{T_2 - 298}$

$\Rightarrow \boxed{T_2 = 479.033\,K}$

Now



slip factor, $\phi = \frac{V_{w2}}{u_2} = 0.9$

$V_{w2} = 0.9\,u_2$

$V_1 = 130$ m/s

$\Rightarrow V_{w1} = V_1 \sin 20^\circ = 130 \sin 20^\circ$

$\boxed{V_{w1} = 44.4626\ m/s}$

also, mean impeller eye dia, $D_1 = 225$ mm

$\Rightarrow$ blade velocity at inlet

$u_1 = \frac{\pi D_1 N}{60} = \frac{\pi \times .225 \times 18000}{60}$

$\boxed{u_1 = 212.0575\ m/s}$

Now,

Work done $= \cancel{\dot{m}} C_p(T_2 - T_1) = \cancel{\dot{m}}[V_{w2}U_2 - V_{w1}U_1]$

$C_p(T_2 - T_1) = 1005 \times (479.033 - 298) = 181938.165$ kW/kg

$\Rightarrow V_{w2}U_2 - V_{w1}U_1 = 181938.165$

$0.9 U_2 \cdot U_2 - V_{w1}U_1 = 181938.165$

$0.9 U_2^2 - 44.4626 \times 212.0575 = 181938.165$

$\Rightarrow$ on solving.

$\boxed{U_2 = 461.118 \text{ m/s}}$

10

$\because U_2 = \dfrac{\pi D_2 N}{60}$

$461.118 = \dfrac{\pi \times D_2 \times 18000}{60}$

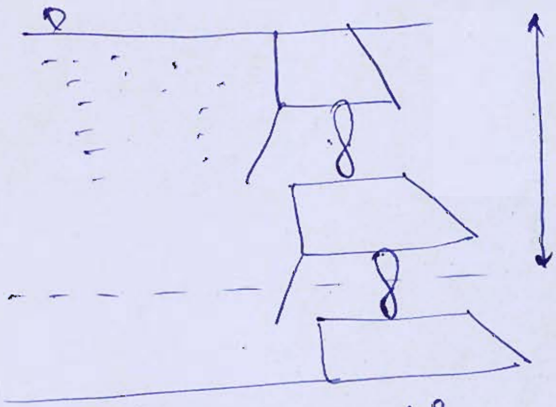
$D_2 = 0.48926$ m

or $\boxed{D_2 = 489.26 \text{ mm}}$ Ans.

(impeller tip diameter)

(b) Water is pumped rapidly from the ocean into the basin at high tide to give an increased water level of 1.2 m in a tidal power basin. If tidal range is 6 m and the efficiency of pump and generator system is only 50%. Find the energy gain due to use of pumping.

[20 marks]



R, $\eta_{gen} = 50\%$.

$R =$ range $= 6m$

now, without pumping

Energy available $= \frac{1}{2} \rho A g R^2$, where $\rho = 1025 \ kg/m^3$

Power available $= \frac{Energy}{time} = \frac{\frac{1}{2}\rho g A R^2}{22350}$.

$= 0.225 AR^2$, where A = area of basin.

⇒ net power output

$P_{out} = \eta_{gen} \times P_{available} = 0.5 \times .225 AR^2$

$P_{out} = 0.1125 AR^2$

⇒ $\boxed{\frac{P_{out}}{A} = 0.1125 R^2}$

when no pumping is done (R = 6 m)

$\frac{P_{out}}{A} = 0.1125 \times 6^2 = 4.05 \ W/m^2$ of basin area.

when pumping is done,

new Range, $R' = 6 + 1.2 = 7.2 m$

⇒ new net power output

$P' = 0.1125 \times 7.2^2 = 5.832 \ W/m^2$ of basin area energy gain due to pumping

$$= \frac{5.832 - 4.05}{4.05} \times 100$$

$$= 44\% \quad \text{Ans!}$$

Q.7 (c) In a constant speed CI engine operating on 4-stroke cycle and fitted with a band brake, the following observations were recorded:

Brake wheel diameter = 60 cm; Band thickness = 5 mm;
Speed = 450 rpm; Load on band = 210 N;
Spring balance reading = 30 N; Area of indicator diagram = 4.15 cm^2;
Length of indicator diagram = 6.25 cm; Spring constant = 11 bar/cm;
Bore = 10 cm; Stroke = 15 cm;
Specific fuel consumption = 0.3 kg/kW-hr; Calorific value of fuel = 41800 kJ/kg

Determine the brake power, indicated power, mechanical efficiency, the indicated thermal efficiency and the brake thermal efficiency.

[20 marks]

Soln: Given: 4 stroke CI engine

Brake wheel dia = 60 cm, band thickness = 5 mm = 0.5 cm

$\Rightarrow r_{eff} = \frac{60 + 2 \times 0.5}{2} = 30.5\ cm = 0.305\ m$

Load on band = 210 N, spring balance reading = 30 N

$\Rightarrow$ brake load, $F_b = 210 - 30 = 180\ N$

brake torque, $T_b = F_b \times r_{eff} = 180 \times .305 = 54.9\ N\text{-}m$

brake power, $BP = T_b \times \frac{2\pi N}{60} = \frac{54.9 \times 2 \times \pi \times 450}{60}$

$\boxed{BP = 2587.10155\ W}$ Ans!

Now, Height of indicator diagram, $h_m = \frac{\text{Area of indicator dia.}}{\text{length of indicator dia.}} = \frac{4.15}{6.25}$

$h_m = 0.664$ cm,

$\because$ spring constant = 11 bar/cm

$\Rightarrow$ indicated mean effective pressure, imep = 11 × .664

$\Rightarrow$ $\boxed{\text{imep} = 7.304 \text{ bar}}$

Now $\dot{V}_s = \frac{\pi}{4} D^2 L \times \frac{k \times N}{60 \times 2} = \frac{\pi}{4} \times \frac{0.1^2 \times 0.15 \times 1 \times 450}{60 \times 2} = 4.41786 \times 10^{-3}$ m³/s

$\Rightarrow$ indicated power, IP = imep × $\dot{V}_s$ = $4.41786 \times 10^{-3} \times 7.304 \times 10^5$

$\boxed{\text{I.P.} = 3226.88 \text{ W}}$ Ans.

(iii) mechanical efficiency

$\eta_m = \frac{BP}{IP} \times 100 = \frac{2587.10155}{3226.88} \times 100 = 80.175\%$ Ans.

(iv) Given: $sfc = \frac{\dot{m}_f}{BP} = 0.3$ kg/kW Hr

$\Rightarrow \frac{\dot{m}_f}{\left(\frac{2587.10155}{1000}\right)} = 0.3 \rightarrow \boxed{\dot{m}_f = \frac{776.13}{1000} \text{ kg/Hr}}$

$= 0.77613$ kg/hr

$\Rightarrow$ Heat supplied, $Q_{supp.} = \dot{m}_f \times CV$

$= \frac{.776.13}{3600} \times 41800 \times 10^3$

$\boxed{Q_{supp} = 9011.73 \text{ W}}$

20

indicated thermal efficiency

$\Rightarrow \eta_{ite} = \frac{IP}{Q_{supp}} \times 100 = \frac{3226.88}{9011.73} \times 100 = 35.807\%$

Brake Thermal efficiency

$\eta_{bte} = \frac{BP}{Q_{supp}} \times 100 = \frac{2587.10155}{9011.73} \times 100 = 28.708\%$

Ans:

$$\boxed{\begin{array}{l} \text{(1) } BP = 2587.10155\ W \\ \text{(2) } IP = 3226.88\ W \\ \text{(3) } \eta_m = 80.175\ \% \\ \text{(4) } \eta_{ite} = 35.807\ \% \\ \text{(5) } \eta_{bte} = 28.708\ \% \end{array}}$$

Q.8 (a) Explain thermo-chemical and bio-chemical biomass conversion technologies.

[20 marks]

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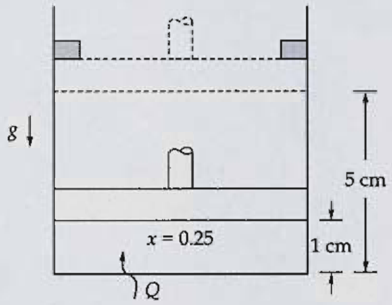
Q.8 (b) Two phase water vapour of dryness fraction equal to 0.25 is contained in a cylinder and cylinder arrangement as shown in figure. The mass of the piston is 40 kg and its diameter is 10 cm. The barometric pressure is 1 bar. The position of the piston in the initial and final stage is 1 cm and 5 cm. The water is heated with pressure maintained constant inside the cylinder till it reaches the stops. The addition of heat continues till the pressure inside the cylinder is 3 bar. Estimate the total heat transfer. Also draw p-V diagram.



The following data for steam may be used:

Saturated steam

p bar	Specific volume m^3/kg		Specific entropy kJ/kgK		Specific enthalpy kJ/kg	
	v_f	v_g	s_f	s_g	h_f	h_g
1.5	0.001053	1.1593	1.4336	7.2233	467.11	2693.6

Superheated steam

T °C	v m^3/kg	h kJ/kg	s kJ/kgK
	$p = 3$ bar (133.55°C)		
Sat.	0.6058	2725.3	6.9919
200	0.6339	2761.0	7.0778
600	1.3414	3703.2	8.5892
700	1.4957	3927.1	8.8319

[20 marks]

(c) The draft tube of a Kaplan turbine has inlet diameter 2.6 m and inlet is set at 2.9 m above the tail race. When the turbine develops 1545 kW of power under a net head of 6.5 m, it is found that the vacuum gauge fitted at inlet to draft tube indicates a negative head of 4 m. If the turbine efficiency is 85%, determine the draft tube efficiency. If the turbine output is reduced to half with the same head, speed and draft tube efficiency, what would be the reading of the vacuum gauge?
Atmospheric pressure is 10.3 m of water and specific weight is 1000 kg/m^3.

[20 marks]

Do not write in this margin

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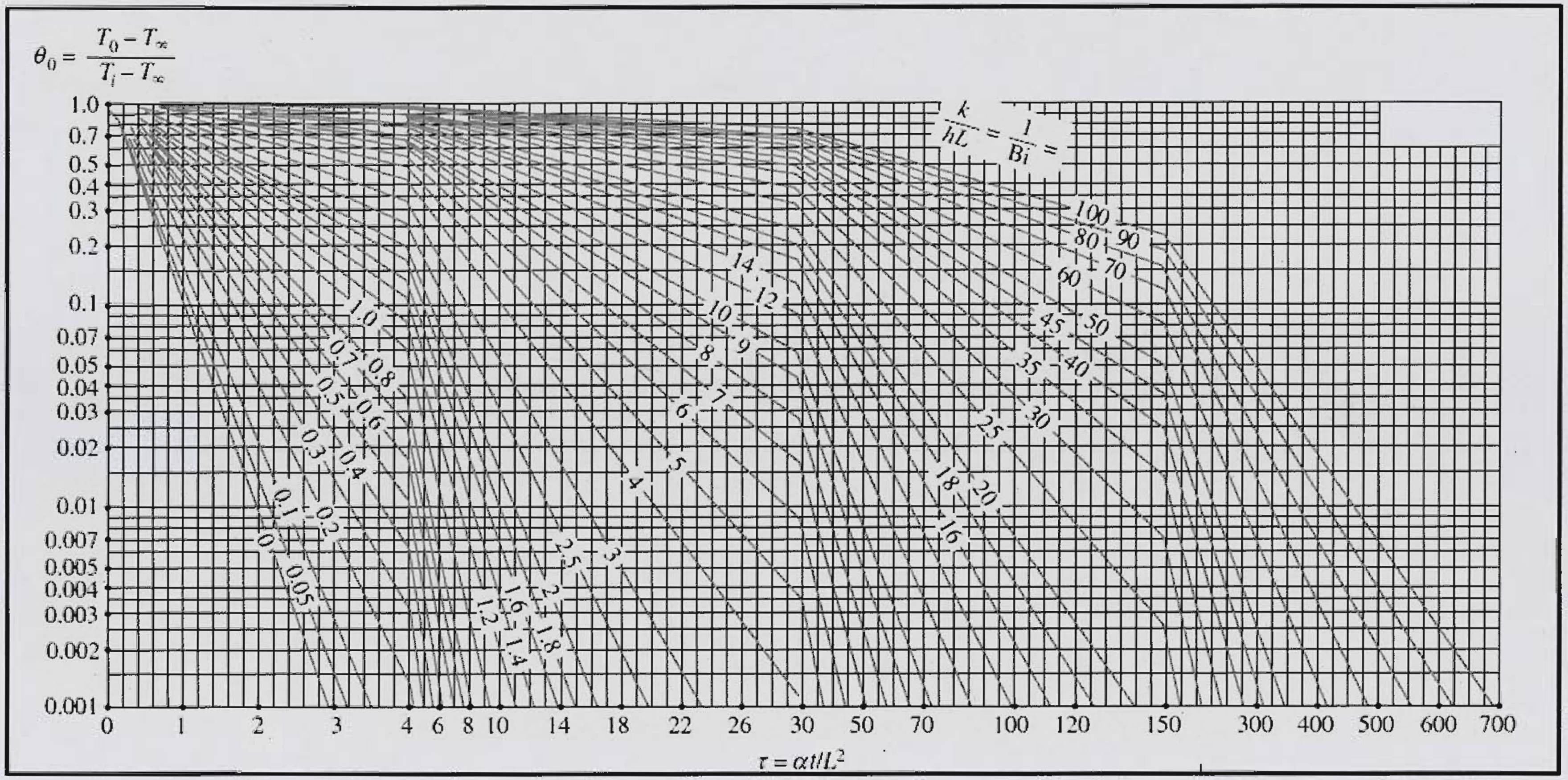
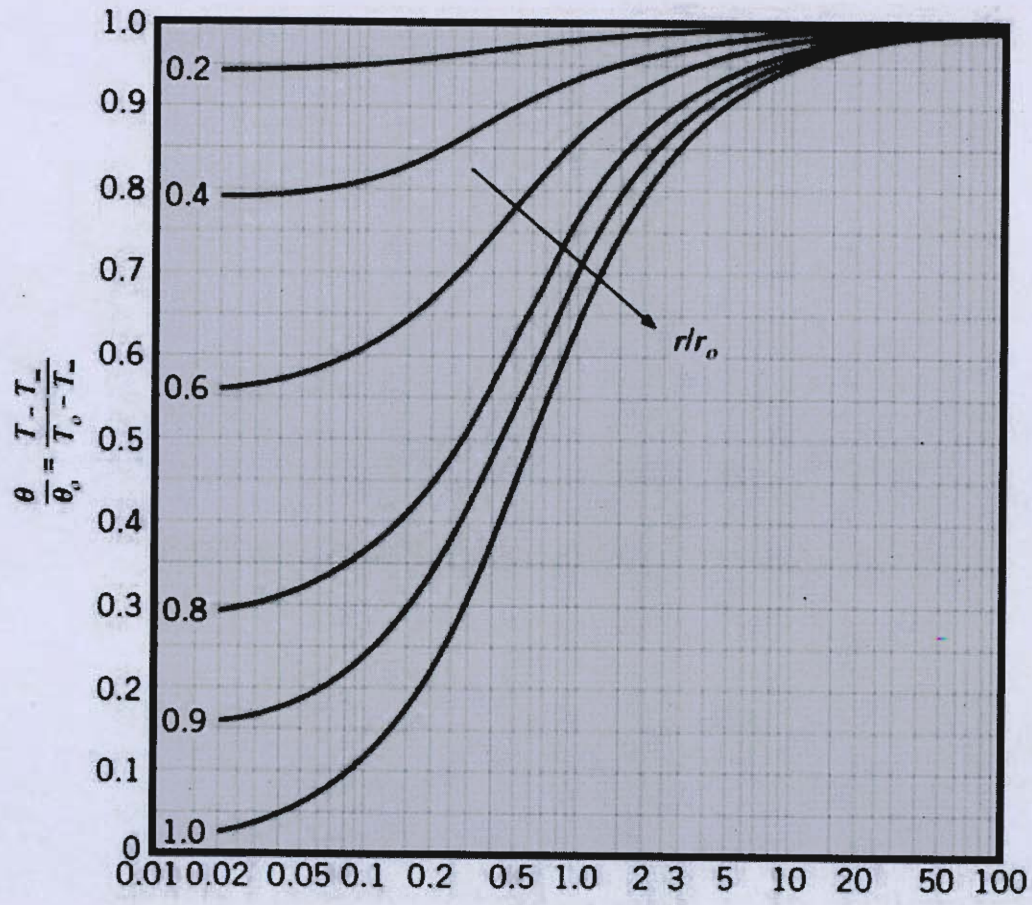


$\theta_0 = \frac{T_0 - T_\infty}{T_i - T_\infty}$
1.0
0.7
0.5
0.4
0.3
0.2
0.1
0.07
0.05
0.04
0.03
0.02
0.01
0.007
0.005
0.004
0.003
0.002
0.001
0 1 2 3 4 6 8 10 14 18 22 26 30 50 70 100 120 150 300 400 500 600 700
$\tau = \alpha t/L^2$
$\frac{k}{hL} = \frac{1}{Bi} =$
100 90 80 70 60 50 45 40 35 30 25 20 18 16 14 12 10 9 8 7 6 5 4 3 2.5 2 1.8 1.6 1.4 1.2 1.0 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.05 0



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
0.9
1.0
r/r_o
0.01 0.02 0.05 0.1 0.2 0.5 1.0 2 3 5 10 20 50 100

$(k/hr_o) = Bi^{-1}$

Space for Rough Work

Space for Rough Work

Space for Rough Work