2020

RANK Improvement WORKBOOK

Answer key and Hint of Objective & Conventional *Questions*

Mechanical Engineering

Power Plant Engineering

MADE EASY Publications

1 Boilers, Condensors and Accessories

LEVEL 1 Objective Questions

1.	(d)
2.	(c)
3.	(b)
4.	(b)
5.	(a)
6.	(a)
7.	(d)
8.	(a)
9.	(b)
10.	(b)
11.	(b)
12.	(c)
13.	(b)
14.	(c)
15.	(c)
16.	(c)
17.	(c)
18.	(c)
19.	(d)
20.	(d)
21.	(a)
22.	(a)
23.	(c)
24.	(c)
25.	(d)
26.	(b)

LEVEL 2 Objective Questions

27.	(b)
28.	(a)
29.	(b)
30.	(c)
31.	(d)
32.	(c)
33.	(c)
34.	(b)
35.	(d)
36.	(b)
37.	(a)

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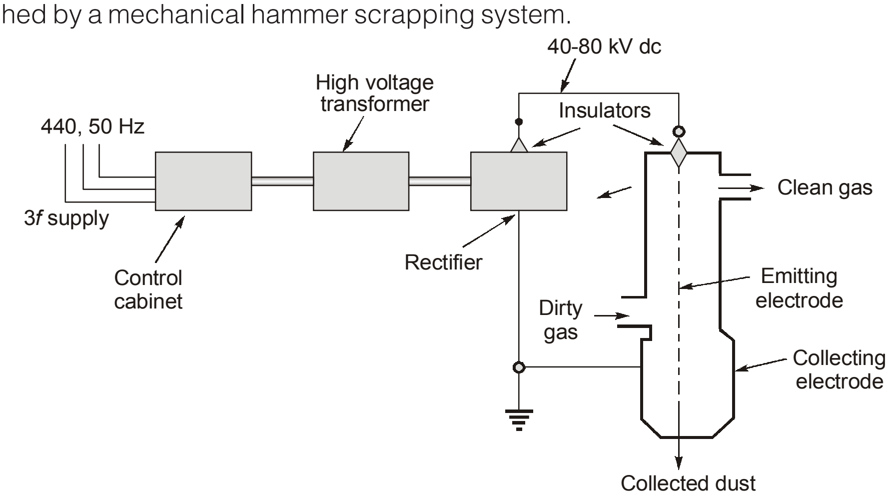
LEVEL 3 Conventional Questions

Solution : 38

Electrostatic Precipitator

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 current from an external dc source. The applied high voltage generates a unidirectional, non-uniform electrical field. 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 positive gas ions.

The positive ions travel to the negatively charged wire electrodes. The electrons follows the electrical field toward the grounded electrodes but their velocity decreases toward the plates. Gas molecules capture the low velocity electrons and become negative ions. As these ions move to the collecting electrode, the 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. 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.



An electrostatic precipitator like a cyclone separator, has an overall collection efficiency, η_o is defined by

$$\eta_o = \frac{\text{mass of all particles retained by collector (ESP)}}{\text{mass of all particles entering collector}}$$

$$= 1 - \exp\left(-\frac{AV_{mo}}{Q}\right)$$

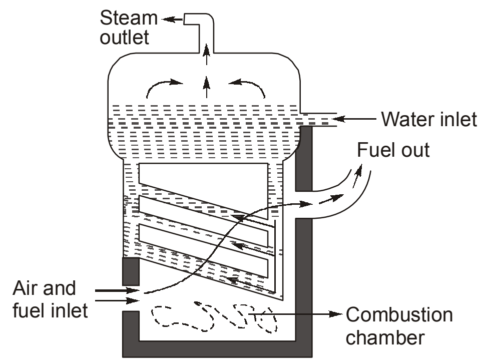
where A = Area of collector plate (m^2)

V_{mo} = effective migration velocity of particles (m/sec)

Q = Flue gas volume flow rate for each plate (m^3/sec)

(i) With increase in collector area, collection efficiency increases.
(ii) With increase in migration velocity, collection efficiency increases.
(iii) With decrease in mass flow rate, collection efficiency increases.

Solution : 39



Fire Tube Boilers	Water Tube Boilers
(i) Hot gases inside the tubes and water outside the tubes	(i) Water inside the tubes and hot gases outside the tubes
(ii) Generally internally fired	(ii) Externally fired
(iii) Operating pressure limited to 16 bar	(iii) Can work under as high pressure as 100 bar
(iv) Lower steam production rate	(iv) Higher rate of steam production
(v) Various parts not so easily accessible for cleaning, repair and inspection	(v) Various parts are more accessible
(vi) Difficult in construction	(vi) Simple in construction

Solution : 40

Essentials of a good steam boiler:

1. It should produce maximum weight of steam of the desired quality at minimum expenses.
2. Steam production rate should be as per requirements.
3. It should have high reliability.
4. It should be light in weight and occupy minimum space.
5. It should be capable of easy starting.
6. There should be an easy access to the various parts of the boiler for maintenance, repair and inspection.
7. The boiler components should be transportable without difficulty.
8. Easy installation.
9. The tubes of the boiler should not accumulate soot or water deposits.
10. The tube material should have better wear and corrosion resistant.
11. The water and gas circuits should be such as to allow minimum fluid velocity (for low frictional losses).

Factors considered while selecting a boiler.

1. Working pressure and steam quality
2. Steam generation rate
3. Floor area available
4. Accessibility for repair and inspection
5. Comparative initial cost
6. Erection facilities

7. Plant load factor
8. Availability of fuel and water
9. Operation and maintenance cost

Solution : 41

Fire-tube boilers are relatively inexpensive. They have large water storage capacity and can thus meet relatively large and sudden load demands with only small pressure changes. Reduction in pressure leaves the stored water superheated and causes part of it to flash into steam. However, the large water storage increases the explosion hazard of the unit, and also because of it, a longer period of time is required to bring the unit of steaming from a cold condition.

The major shortcoming of a fire-tube boiler is that define size and pressure limitations are inherent in its basic design, i.e., the maximum size of the unit and the maximum operating pressure are limited. The tensile stress on the drum wall is a function of the drum diameter and the internal pressure given by

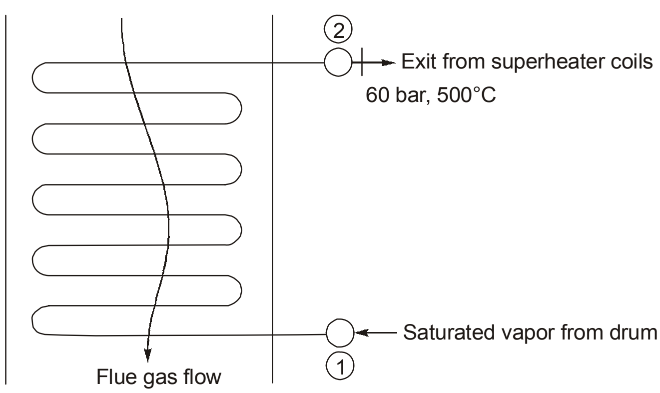
$$\sigma = pd/2t$$

The growing needs for increased quantities of steam at higher and higher pressures could not be met by fire-tube boilers, for as high pressures and large diameters lead to prohibitively thick shells, and the thicker the shell, the higher the cost.

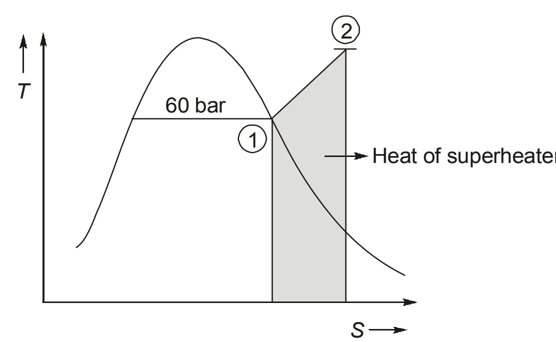
Water is adequately treated prior to feeding it to the boiler as make up water. Still, it has some impurities in the form of total dissolved solids (TDS). These solids are expressed in ppm (parts per million). Saturated water from the economiser is continuously entering the drum. Steam is separated in the drum and is taken to the superheater. So the solid content of water (TDS) in the drum goes on increasing. To maintain a certain ppm in the drum, blowdown is necessary to settledown. Trisodium phosphate is injected into the drum periodically in suitable doses to help precipitate salts to settledown at the drum bottom.

Solution : 42

Given: Heat flux $\dot{q}$ = 150 KW/m^2, d_i = 50 mm = 0.05 m, velocity V = 10 m/s, $\dot{m}_s$ = 90 kg/s



Schematic of Superheater coils



Process on T-s coordinate

As given, $h_1 = h_g$ = 2784.3 kJ/kg, h_2 = 3422.2 kJ/kg and specific volume, v_2 = 0.05665 m^3/kg

Heat absorption rate in superheater coils = $\dot{m}_s(h_2 - h_1)$ = 90(3422.2 – 2784.3) = 57411 kW = $\dot{Q}$

$$\text{Surface area required} = \frac{57411}{150} = 382.74 \text{ m}^2 \quad [\text{As, } \dot{Q} = \dot{q} \times A]$$

$$\text{From continuity equation, } \dot{m}_s = \rho_1 A_1 V_1 = \rho_2 A_2 V_2 = \left(n\frac{\pi}{4}d_i^2\right)\frac{V_2}{v_2} = 90 \text{ kg/s}$$

[where 'n' is the number of superheater coils]

$$n = \frac{4 \times 90 \times 0.05665}{\pi \times (0.05)^2 \times 10} = 259.66 \text{ or } 260$$

Number of superheater coils, n = 260

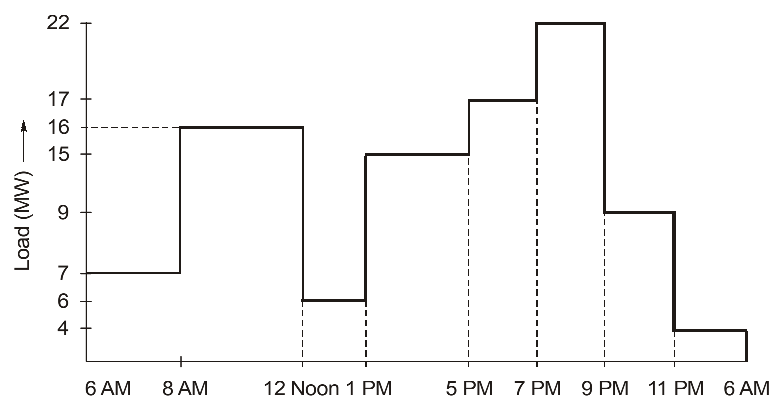
As, Surface area, $A_0 = 382.74 = n \pi d_0 l$

d_0 = outer diameter = 50 + 2 × 5 = 60 mm

[As thickness is 5 mm]

$$\text{Length of one coil} = \frac{382.74}{260 \times \pi \times 0.06} = 7.81 \text{ m}$$

Solution : 43

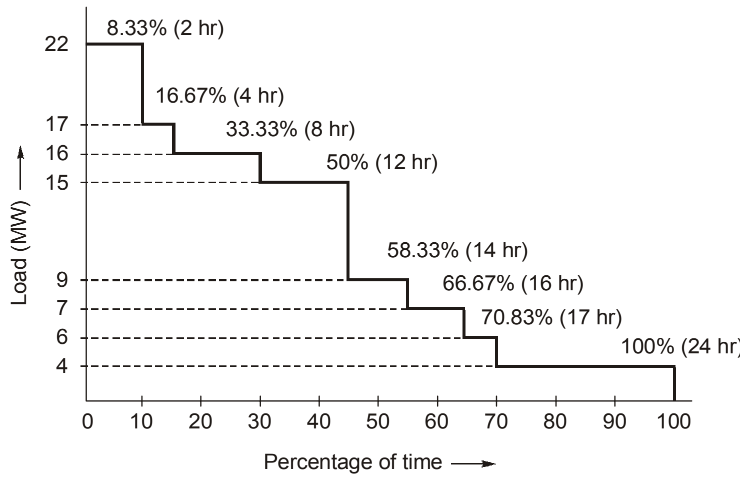


Load Curve

Load	Hours in a day	%time
22 MW	2	8.33
17 MW	2 + 2 = 4	16.67
16 MW	2 + 2 + 4 = 8	33.33
15 MW	2 + 2 + 4 + 4 = 12	50
9 MW	2 + 2 + 4 + 4 + 2 = 14	58.33
7 MW	2 + 2 + 4 + 4 + 2 + 2 = 16	66.67
6 MW	2 + 2 + 4 + 4 + 2 + 2 + 1 = 17	70.83
4 MW	2 + 2 + 4 + 4 + 2 + 2 + 1 + 7 = 24	100

Units generated during 24 hours = 2 × 7 + 4 × 16 + 1 × 6 + 4 × 15 + 2 × 17 + 2 × 22 + 2 × 9 + 7 × 4

= 268 MW.hr



Load Duration Curve

From the load variation over the 24 hours (starting from 6 AM) it can be seen that units, each of 5 MW will suffice. Since we want continuity of supply, a reserve capacity equivalent to the largest unit will be taken.

Total capacity of the plant $= 5\text{ MW} \times 5 = \mathbf{25\text{ MW}}$

Operation Schedule

11 PM to 6 AM	One unit of 5 MW
6 AM to 8 AM	Two unit of 5 MW
8 AM to 12 Noon	Four unit of 5 MW
12 Noon to 1 PM	Two unit of 5 MW
1 PM to 5 PM	Three unit of 5 MW
5 PM to 7 PM	Four unit of 5 MW
7 PM to 9 PM	Five unit of 5 MW
9 PM to 11 PM	Two unit of 5 MW

Number of units $= 5$

Load factor $= \dfrac{268}{24 \times 22} = 0.5076$

Plant capacity factor $= \dfrac{268}{25 \times 24} = 0.4466$

With the operation schedule listed above, the energy that could have been generated, by the capacity of the plant actually running for the scheduled time will be

$$= 7 \times 5 + 2 \times 10 + 4 \times 20 + 1 \times 10 + 4 \times 15 + 2 \times 20 + 2 \times 25 + 2 \times 10$$

$$= 35 + 20 + 80 + 10 + 60 + 40 + 50 + 20 = 315\text{ MW}$$

Plant use factor $= \dfrac{268}{315} = 0.8508$ or **85.08%**

Solution : 44

$$\text{Annual load factor} = \frac{\text{Average load}}{\text{Peak load}}$$

$$\text{Average} = 0.65 \times 160 = 104 \text{ MW}$$

$$\text{Energy generated per year} = 104 \times 24 \times 365 = 911040 \text{ MWh} = 911040 \times 10^3 \text{ kWh}$$

$$\text{Coal required per year} = 911040 \times 10^3 \text{ kg} = 911040 \text{ tonnes}$$

$$\text{Cost of coal} = ₹800 \text{ per ton}$$

$$\text{Cost of coal per year} = 911040 \times 800 = ₹728.832 \times 10^6$$

$$\text{Cost of energy sold} = ₹1.5 \times 911040 \times 10^3 = ₹1366.56 \times 10^6$$

(i) Revenue earned by the power plant per year = cost of energy sold – cost of coal

$$= ₹1366.56 \times 10^6 - ₹728.832 \times 10^6 = ₹637.728 \times 10^6$$

$$= ₹\,\mathbf{63.773 \text{ crore}}$$

(ii) $$\text{Capacity factor} = \frac{\text{Average load}}{\text{Capacity of the plant}} = \frac{104}{200} = \mathbf{0.52}$$

Solution : 45

$$\frac{\text{Load factor}}{\text{Capacity factor}} = \frac{\text{Average load}}{\text{Maximum demand}} \times \frac{\text{Capacity of the plant}}{\text{Average load}}$$

$$\frac{0.60}{0.54} = \frac{210 \text{ MW}}{\text{Maximum demand}}$$

$$\text{Maximum demand} = \frac{210 \times 0.54}{0.60} = 189 \text{ MW}$$

$$\text{Reserve capacity} = 210 - 189 = \mathbf{21 \text{ MW}}$$

$$\text{Average load} = \text{Load factor} \times \text{Maximum demand} = 0.6 \times 189 = 113.4 \text{ MW}$$

$$\text{Energy produced per year} = 113.4 \times 10^3 \times 8760 = 993.384 \times 10^6 \text{ kWh}$$

$$\text{Net energy delivered} = 0.94 \times 993.384 \times 10^6 = 933.781 \times 10^6 \text{ kWh}$$

Annual interest and depreciation (fixed cost)

$$= 0.12 \times 4 \times 10^7 \times 210 = ₹100.8 \times 10^7$$

$$\text{Total annual cost} = \text{Fixed cost} + \text{Running cost}$$

$$= ₹100.8 \times 10^7 + ₹400 \times 10^6 = ₹140.8 \times 10^7$$

$$\text{Cost of power generation} = \frac{`140.8 \times 10^7}{933.781 \times 10^6} = `\ 1.5/\text{KWh}$$

Solution : 46

(i) $$\text{Load factor} = \frac{\text{Average load}}{\text{Peak load}}$$

$$\text{Average load} = 0.6 \times 15 = 9 \text{ MW}$$

$$\text{Annual energy production} = 9000 \times 8760 = \mathbf{78.84 \times 10^6 \text{ kWh}}$$

(ii) $$\textbf{Capacity factor} = \frac{\text{Average load}}{\text{Plant capacity}}$$

$$\text{Plant capacity} = \frac{9\text{ MW}}{0.4} = 22.5\text{ MW}$$

Reserve capacity over and above the peak load = 22.5 – 15 = **7.5 MW**

(iii)
$$\text{Use factor} = \frac{\text{Energ generator per year}}{\text{Plant capacity} \times \text{hours in operation}}$$

$$\text{Hours in operation} = \frac{78.84 \times 10^6}{22.5 \times 0.45 \times 10^3} = \textbf{7786.67 hours}$$

Hours not in service in a year = 8760 – 7786.67 = **973.33 hours**

Solution : 47

$$\begin{aligned}
\text{Mass of steam used, } m_s &= 5.4\text{ kg/kWh} \\
\text{Pressure of steam, } P &= 50\text{ bar} \\
\eta_{\text{Boiler}} &= 82\% \\
\text{Feed water temperature, } t_f &= 150°\text{C} \\
\text{CV of coal} &= 28100\text{ kJ} \\
\text{cost of coal/tonne} &= ₹\ 50000 \\
h_{f@150°\text{C}} &= mC_p\Delta T \\
h_{f1} &= 1 \times 4.18(150 - 0) \\
h_{f1} &= 627\text{ kJ/kg} \\
\eta_{\text{boiler}} &= \frac{m_s(h - h_f)}{m_f \times CV} \\
m_f &= \frac{m_s(h - h_f)}{\eta_b \times CV} = \frac{5.4(3068.4 - 627)}{0.82 \times 28100} \\
m_f &= 0.572\text{ kg/kWh}
\end{aligned}$$

Ans. (i)

$$\begin{aligned}
\text{The cost of fuel (coal)/kWh} &= m_f\text{ in tonnes/kWh} \times \text{cost/tonne} \\
&= \frac{0.572}{1000} \times 50000 = ₹\ 28.6\text{/kWh}
\end{aligned}$$

Solution : 48

Corresponding to 35°C, the partial pressure of steam from steam table = 0.05622 bar.

$$\text{Absolute pressure of mixture in condenser} = (76 - 70) \times \frac{1013}{76} = 0.07997\text{ bar}$$

Since $p = p_s + p_a$

So, $p_a = p - p_s = 0.07997 - 0.05622 = 0.02375$ bar

(a)
$$\text{Mass of air} = m_1 = \frac{p_a \times 10^5 \times v}{R_a T_a} = \frac{0.02375 \times 10^5 \times 1}{287(273 + 35)}$$

$$= \mathbf{0.02686\ kg/m^3}$$

(b) Heat absorbed by circulating water = $m_w c_{pw}(t_{w2} - t_{w1})$

$= 4550 \times 4.18(31 - 16.5) = 2757755$ kJ/h

Heat rejected by steam in condensing at 35°C and in being undercooled from 35°C to 29°C

$$= m_c\,(h_{f1} + x h_{fg1} - h_c)$$
$$= 1200(146.56 + 2418x - 121.48)$$
$$= 1200(25.08 + 2418x)$$

Equating the heat absorbed by heat rejected, we have

$$x = \frac{2757757 - 25.08 \times 1200}{1200 \times 2418} = \mathbf{0.94}$$

(c) Vacum efficiency $= \dfrac{\text{Actual Vacuum}}{\text{Ideal Vacuum}} = \dfrac{70}{70 - 0.05622 \times \left(\dfrac{76}{1.013}\right)} \times 100$

$$= \mathbf{97.51\%}$$

(d) Undercooling of condensate = 35 – 29 = **6°C**

(e) Condensate efficiency $= \dfrac{\text{Actual temperature rise of water}}{\text{Maximum permissible temperature rise}}$

$$= \frac{(31 - 16.5)}{(35 - 16.5)} \times 100 = \mathbf{78.37\%}$$

Solution : 49

As shown in below figure

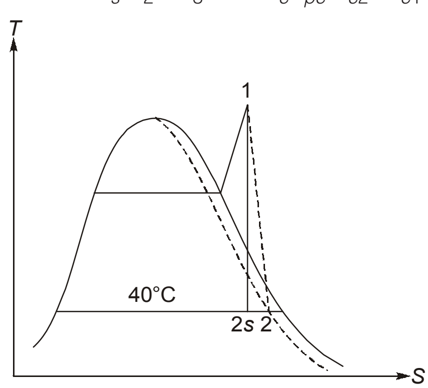
$$x_2 = 0.88,$$
$$h_2 = h_f + 0.88\,h_{fg},\ h_3 = h_f$$

At 40°C, $h_{fg} = 2407$ kJ/kg

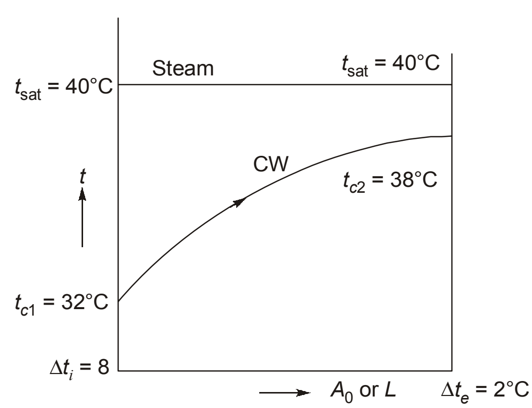
$$h_2 - h_3 = 0.88\,h_{fg} = 0.88 \times 2407 = 2118.16 \text{ kJ/kg}$$

By energy balance,

$$\omega_s(h_2 - h_3) = \omega_c c_{pc}\,(t_{c2} - t_{c1})$$



(a)



(b)

$$\frac{250 \times 1000}{3600} \times 2118.16 = \omega_c \times 4.187(38 - 32)$$

$$\omega_c = 5855.2 \text{ kg/s}$$

At 40°C $p_{sat} = 0.07375$ bar

$$p = p_{sat} + p_{air} = 0.078 \text{ bar}$$
$$p_{air} = 0.078 - 0.07375 = 0.00425 \text{ bar} = 0.425 \text{ kN/m}^2$$

$$v_2 = v_f + x_2 v_{fg} = 0.001008 + 0.88 \times 19.544 = 17.2 \text{ m}^3/\text{kg}$$

Now,
$$p_{air}\,\omega_s v_2 = \omega_{air} R_{air} T_{sh}$$

$$0.425 \times \frac{250 \times 1000}{3600} \times 17.2 = \omega_{air} \times 0.287 \times 313$$

$$\omega_{air} = 5.651 \text{ kg/s}$$

$$\Delta t_{1.m} = \frac{\Delta t_i - \Delta t_e}{\ln\left(\frac{\Delta t_i}{\Delta t_e}\right)} = \frac{8-2}{\ln\frac{8}{2}} = 4.33° \text{ C}$$

$$Q = U_0 A_0 \Delta_{t1.m} = \omega_s (h_2 - h_3)$$

$$2.6 \times A_0 \times 4.33 = \frac{250 \times 1000}{3600} \times 2118.16$$

$$A_0 = 13066 \text{ m}^2$$

$$\omega_c = \left(n\frac{\pi}{4} d_i^2\right)\rho V = 5855.2 \text{ kg/s}$$

$$n\frac{\pi}{4}(25.4 - 2.5)^2 \times 10^{-6} \times 1000 \times 1.8 = 5855.2$$

$$n = \frac{5.8552 \times 4 \times 10^6}{524.41 \times \pi \times 1.8} = 7898$$

Again,
$$A_0 = n\pi d_0 l = 13066 \text{ m}^2$$

$$l = \frac{13066}{7898 \times \pi \times 25.4 \times 10^{-3}} = 20.73 \text{ m}$$

Solution : 50

Saturation pressure of steam at 35°C = 0.5622 bar and vg = 25.24 m^3/kg

$$\text{1std. atm. pr} = 76 \text{ cm Hg} = 1.013 \text{ bar.}$$

$$\therefore \quad p_{sat} = 0.05622 \text{ bar} = 4.2717 \text{ cm Hg}$$

$$P_{abs} = 75.5 - 70 = 5.5 \text{ cm Hg}$$

Vacuum gauge corrected to standard atmosphere

$$= 76 - 5.5 = 70.5 \text{ cm Hg}$$

$$\therefore \quad \text{Vacuum efficiency} = \frac{70.5}{76 - 4.2717} = 0.9829 \text{ or } 98.29\%$$

Absolute pressure inside the condenser = 5.5 cm Hg

Partial pressure of steam at 35°C = 4.2717 cm Hg

$$\therefore \quad \text{Partial pressure of air} = 5.5 - 4.2717 = 1.2283 \text{ cm Hg}$$

∴ Mass of air associated with 1 kg steam

$$= \frac{pv}{Rt} = \frac{1.2283}{76} \times \frac{1.013 \times 10^5 \times 25.24}{287 \times (273 + 35)}$$

$$= 0.467 \text{ kg air/kg steam}$$

Solution : 51

At 0.13 barm, $t_{sat} = 51.06°C$

$$h_2 = h_f + x_2 h_{fg} = 213 + 0.9 \times 2380.3 = 2355.97 \text{ kJ/kg}$$

$$h_f \text{ at } 45°C = 188.35 \text{ kJ/kg}$$

By energy balance,

$$\dot{m}_w c_{pw}(t_{w2} - t_{w1}) = \dot{m}_s(h_2 - h_3)$$

$$\frac{\dot{m}_w}{\dot{m}_s} = \frac{2355.97 - 188.35}{4.182 \times (40 - 30)} - 51.77 \text{ kg water/kg steam}$$

$$\text{Condenser efficiency} = \frac{40 - 30}{51.06 - 30} = 0.475 \text{ or } 47.5\%$$

Solution : 52

Absolute pressure inside the condenser = 76 – 69 = 7 cm Hg. = 0.0933 bar

$$p_{sat} \text{ at } 35°C = 0.05622 \text{ bar}$$

$$\therefore \text{ Partial pressure of air, } p_a = 0.0933 - 0.05622$$

$$= 0.03708 \text{ bar}$$

$$\therefore \text{ Mass of air present, } m_a = \frac{pv}{RT}$$

or

$$m_a = \frac{0.03708 \times 10^5 \times 1}{287 \times (273 + 35)} = 0.042 \text{ kg/m}^3$$

Let x be the quality of steam at condenser inlet

$$\dot{m}_s\left[x h_{fg} + c_p(t_{sat} - 30)\right] = \dot{m}_w(t_{w2} - t_{w1})$$

$$16 \times 60[x \times 2418.8 + 4.182\,(35 - 30)] = 37500 \times 4.182 \times (32.5 - 20)$$

$$= 1.96 \times 10^6$$

$$x = 0.835$$

$$\text{Vacuum efficiency} = \frac{\text{Actual vacuum}}{\text{Ideal vacuum}} = \frac{69}{76} \times 100 = 90.7\%$$

$$\text{Condensing effeciency5} = \left(\frac{32.5 - 20}{35 - 20}\right) \times 100 = 83.33\%$$

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2 Rankine Cycle

LEVEL 1 Objective Questions

1. (c)
2. (b)
3. (a)
4. (c)
5. (d)
6. (b)
7. (b)
8. (d)
9. (c)
10. (a)
11. (d)
12. (a)

LEVEL 2 Objective Questions

13. (a)
14. (c)
15. (d)
16. (3.6)
17. (2.83)
18. (a)
19. (b)
20. (a)
21. (c)
22. (26)
23. (b)
24. (b)
25. (b)
26. (c)
27. (c)
28. (c)
29. (b)
30. (d)
31. (b)
32. (a)
33. (b)
34. (c)
35. (a)

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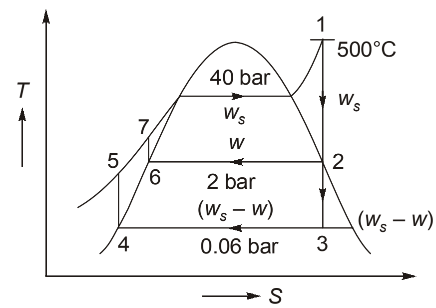
LEVEL 3 Conventional Questions

Solution : 36

Given: h_1 = 3445.3 kJ/kg, $S_1 = 7.0901 = S_2 = S_3$

$$S_1 = 7.0901 = S_2 = 1.5706 + x_2(7.0878 - 1.5706)$$
$$x_2 \approx 1$$
$$h_2 = h_g = 2712.1 \text{ kJ/kg}$$
$$h_2 - h_6 = h_{fg} = h_g - h_f = 2712.1 - 520.72$$
$$h_2 - h_6 = 2191.38 \text{ kJ/kg}$$

Let the rate of steam extraction for process heating be w.



$$w(h_2 - h_6) = 1.163 \times 10^3$$
$$w = \frac{1.163 \times 10^3}{2191.38} = 0.5307 \text{ kg/sec or } 1910.58 \text{ kg/hr}$$

As, $$S_1 = 7.0901 = S_f + x_3\, S_{fg} = 0.520 + x_3\,(8.335 - 0.520)$$
$$x_3 = 0.84$$
$$h_3 = 149.79 + 0.84(2565.79 - 149.79) = 2179.23 \text{ kJ/kg}$$

Total work output $$w_T = w_s(h_1 - h_2) + (w_s - w)(h_2 - h_3)$$
$$w_T = 5.6 \times 10^3 = w_s\,(3445.53 - 2712.1) + \{(w_s - 0.53) \times (2712.1 - 2179.23)\}$$
$$5.6 \times 10^3 = 733.2\, w_s + (w_s - 0.53)\,(532.87) = 1266.07\, w_s - 282.42$$
$$\Rightarrow \quad w_s = 4.646 \text{ kg/sec or } 16726.3 \text{ kg/hr}$$

(i) $$h_7 = 520.72 + 0.00106(40 - 2) \times 10^2$$
$$h_7 = 524.748 \text{ kJ/kg}$$

Similarly, $$h_5 = 149.79 + 0.00101 \times (40 - 0.06) \times 10^2 = 153.8 \text{ kJ/kg}$$
$$Q_1 = (w_s - w)(h_1 - h_5) + w(h_1 - h_7)$$
$$= (4.646 - 0.53)\,(3445.3 - 153.8) + 0.53(3445.3 - 524.748) = 15095.706 \text{ kJ/s}$$

(ii) $$Q_1 = 15.1 \text{ mW}$$
$$\eta_{boiler} = 0.88 = \frac{Q_1}{\dot{m}_f \times CV} = \frac{15.1}{\dot{m}_f \times 25}$$
$$\dot{m}_f = 0.687 \text{ kg/sec} = 2473.2 \text{ kg/h}$$

(iii) $$\dot{m}_f = 2473.2 \text{ kg/hr} = 2.473 \text{ t/h}$$
$$Q_2 = (w_s - w)(h_3 - h_4) = (4.646 - 0.53)\,(2179.23 - 149.79)$$

(iv) $$Q_2 = 8.353 \text{ MW}$$

Let the water flow rate in condenser be w_c,

$$Q_2 = w_c C_P(T_2 - T_1)$$

(v) $$w_c = \frac{8353}{4.187 \times 6} = 332.5 \text{ kg/sec}$$

Solution : 37

Given : $\dot{m}_s = 25$ kg/sec, $T_1 = 600°C$, $h_1 = 3682$ kJ/kg,

$S_1 = 7.50$ kJ/kgK $= S_2$, $h_3 = h_{x=0}^{45°C} = 188.4$ kJ/kg-K, $v_3 = 0.001$ m^3/kg

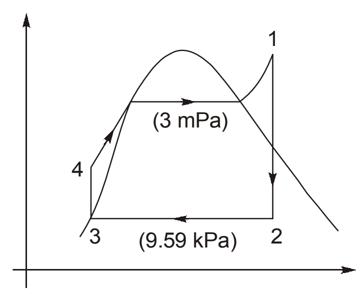
$$W_P = \text{Pump work} = vdp$$

$$W_p = 0.001 \times [3 \times 10^6 - (9.59 \times 10^3)] \times 10^{-3} = 3 \text{ kJ/kg}$$

$$h_4 - h_3 = W_P = 3 \text{ kJ/kg}$$

$$h_4 = h_3 + 3 \Rightarrow 188.4 + 3 = 191.4 \text{ kJ/kg}$$

Heat added, $$Q_1 = h_1 - h_4 = 3682 - 191.4 = 3490.6 \text{ kJ/kg}$$



$$S_1 = S_2 = 7.50 = S_F + x_2 S_{fg}$$

$$7.50 = 0.6386 + x_2(7.5261)$$

$$x_2 = 0.91168$$

$$h_2 = h_f + x_2 h_{fg}$$

$$h_2 = 188.42 + 0.91168\,(2394.8) = 2371.7 \text{ kJ/kg}$$

$$W_T = (h_1 - h_2) = 3682 - 2371.7 = 1310.3 \text{ kJ/kg}$$

$$W_{net} = W_T - W_P = (1310.3 - 3) \text{ kJ/kg}$$

$$= 1307.3 \text{ kJ/kg}$$

(i) Power output, $$W_{net} = 25 \times 1307.3 = 32.68 \text{ MW}$$

(ii) Let the required mass of ocean water be $\dot{m}_w$.

$$Q_R \Rightarrow 25 \times (2371.7 - 188.4) = 54.582 \text{ MW}$$

Also, $$Q_R = \dot{m}_w C_P(\Delta T)$$

$$54.582 \times 10^6 = \dot{m}_w \times 4.18 \times 10^3 \times (15 - 12)$$

$$\dot{m}_w = 4352.63 \text{ kg/s}$$

Solution : 38

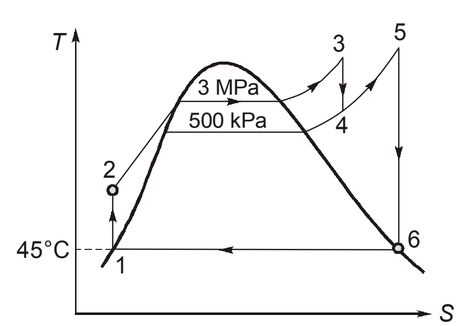
From the given table,

At 1 : 45°C,

$$x = 0, \quad h_1 = 188.42 \text{ kJ/kg}$$

$$v_1 = 0.00101 \text{ m}^3\text{/kg}$$

$$P_{sat} = 9.59 \text{ kPa}$$



At state 3, 3 MPa, 600°C

$$h_3 = 3682.34 \text{ kJ/kg}$$

$$s_3 = 7.5084 \text{ kJ/kgK}$$

At state 6, 45°C

$$x = 1, \quad h_6 = 2583.19 \text{ kJ/kg}$$

$$s_6 = 8.1647 \text{ kJ/kgK}$$

$$h_2 = h_1 + w_{pump} = 188.42 + v_1(p_2 - p_1) = 188.42 + 0.00101\,(3000 - 9.59)$$
$$= 191.44 \text{ kJ/kg}$$

For process $3 \rightarrow 4$, $s_3 = s_4$ (for HP turbine)

Properties at 500 kPa: (state 4)

$$T_{sat} = 151.83°\text{C} = 424.83 \text{ K}$$
$$h_l = 640.21 \text{ kJ/kg}, \quad h_v = 2748.7 \text{ kJ/kg}$$
$$s_l = 1.8606 \text{ kJ/kgK}, \quad s_v = 6.8212 \text{ kJ/kgK},$$
$$c_p = 2.41267 \text{ kJ/kgK}$$

3-4 is isentropic

$$s_3 = s_4$$
$$s_3 = s_1 + x\,(s_v - s_l)$$
$$7.5084 = 1.8606 + x\,(6.8212 - 1.8606)$$
$$x = 1.1385$$

$\therefore$ point 4 is in superheated state

$$\therefore \quad s_3 = s_v + c_{pv} \ln\left(\frac{T_4}{T_{sat}}\right)$$

$$7.5084 = 6.8212 + 2.4126 \ln\left(\frac{T_4}{424.83}\right)$$

$$T_4 = 564.83 \text{ K}$$
$$h_4 = h_{4v} + c_p\,(T_4 - T_{sat})$$
$$= 2748.7 + 2.4126\,(564.83 - 424.83)$$
$$h_4 = 3086.494 \text{ kJ/kg}$$

5-6 isentropic process

$$\therefore \quad s_5 = s_6$$

$$\therefore \quad s_6 = s_{5v} + c_p \ln\left(\frac{T_5}{T_{sat}}\right)$$

$$8.1647 = 6.8212 + 2.4126 \ln\left(\frac{T_5}{424.83}\right)$$

$$T_5 = 741.4 \text{ K}$$
$$h_5 = h_{5v} + c_p\,(T_5 - T_{sat})$$
$$h_5 = 2748.7 + 2.4126\,(741.4 - 424.83)$$
$$h_5 = 3512.5 \text{ kJ/kg}$$

Heat rejected in condenser 10 MW

$$\therefore \quad \dot{m}(h_6 - h_1) = 10 \times 10^3$$

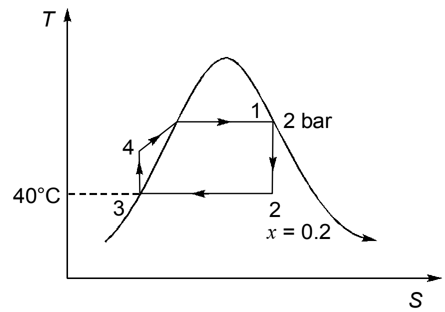
$$\dot{m} = \frac{10 \times 10^3}{(2583.19 - 188.42)} = 4.175 \text{ kg/s}$$

$$\therefore \quad \text{power output} = \dot{m}[(h_3 - h_4) + (h_5 - h_6)] = 4.175\,(3682.34 - 3086.474 + 3512.5 - 2583.19)$$

$$\text{power} = 6367.61 \text{ kW}$$

$$\text{Heat supplied in boiler} = \dot{m}[h_3 - h_2] = 4.175\,(3682.34 - 191.44)$$
$$= 14574.50 \text{ kW}$$
$$\text{Heat supplied in boiler} = 14.574 \text{ MW}$$

Solution : 39



$$h_1 = 270.3 \text{ kJ/kg}$$

$$h_3 = h_{f3} = 167.53 \text{ kJ/kg}$$

Neglecting pump work, $h_4 \approx h_3 = 167.53$ kJ/kg

$$h_2 = h_{f2} + x_2(h_{g2} - h_{f2})$$

$$= 167.53 + 0.9\,(2405.97) = 2332.90 \text{ kJ/kg}$$

$$\dot{m} = 150 \text{ kg/hr} = \frac{150}{3600} = 0.0416 \text{ kg/s}$$

Heat supplied, $Q_s = \dot{m}(h_1 - h_4) = 0.0416(2706.3 - 167.53) = 105.78$ kW

Calculating area required,

$$A = \frac{105.78}{0.58} = 182.38 \text{ m}^2 \text{ Area}$$

Calculating dryness fraction when isentropic expansion occurs in turbine.

$$s_{g1} = s_{f2} + x(s_{fg})_2$$

$$7.127 = 0.572 + x[7.686]$$

$$x_s = 0.852$$

$\therefore$ $h_2' = h_{f2} + x_2(h_{fg})_2 = 167.53 + 0.852(2405.97) = 2219.45$ kJ/kg

$\therefore$ $\eta_{\text{isentropic}} = \dfrac{2706.3 - 2332.90}{2706.3 - 2219.45} = 0.7669$ or 76.69%

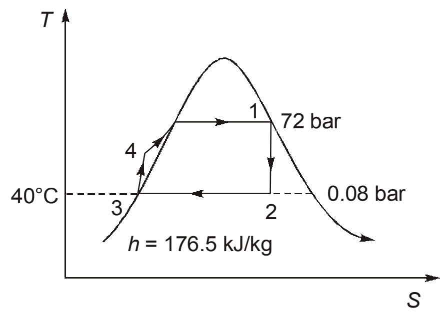
$$\text{Network output} = \dot{m}\,(h_1 - h_2)_{\text{ACTUAL}}$$

$$= \dot{m}\,(2706.3 - 2332.90) = 0.0416 \times 373.4 \text{ kW} = 15.53 \text{ kW}$$

$$\text{cycle } \eta = \frac{\text{O/P}}{I/P} = \frac{373.4}{2706.3 - 167.53} = 0.147 = 14.7\%$$

Solution : 40

Given: $\eta_t = 0.7$; Power = 750 MW; h_{g1} = 2770.9 kJ/kg; s_{g1} = 5.8019 kJ/kgK; h_f = 173.9; h_{fg} = 2403.2; s_f = 0.5926; s_{fg} = 7.6370; $s_1 = s_2$



$\Rightarrow$ $$s_{g1} = s_{f2} + x \cdot s_{fg2}$$

$\Rightarrow$ $$5.8019 = 0.5926 + x \times 7.6370$$

$\Rightarrow$ $$x = 0.6821$$

$$h_2 = h_f + xh_{fg} = 173.9 + 0.6821 \times 2403.2 = 1813.15 \text{ kJ/kg}$$

$$w_t = (h_1 - h_2) \times \eta_t = (2770.9 - 1813.15) \times 0.7 = 670.4 \text{ kJ/kg}$$

Mass flow rate of steam $$= \frac{750000}{670.4} = 1118.7 \text{ kg/s}$$

$$h_4 = h_3 = 176.5 \quad \text{(Neglecting pump work)}$$

Heat generated, $$Q_{gen} = m(h_1 - h_4) = 1118.7 \times (2770.9 - 176.5) = 2902.33 \times 10^3 \text{ kJ/s}$$

$$= \mathbf{2902.33\ MW}$$

Solution : 41

Given: P = 20 kPa; $\dot{m}_s = 20 \times 10^3$ kg/h = 5.55 kg/sec; $(\Delta T)_w$ = 10°C

Let inlet conditions to the condenser are represented as

$$x_1 = 0.95$$

$$h_1 = h_f + x_1 h_{fg} = 251.4 + 0.95 \times 2358.3 = 2491.785 \text{ kJ/kg}$$

Outlet condition, $$h_2 = h_f = 251.4 \text{ kJ/kg}$$

Let mass flow rate of cooling water $= \dot{m}_w$

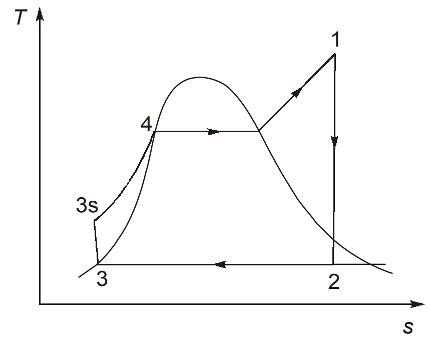
Energy balance in condenser will give,

$$\dot{m}_w c_{pw} (\Delta T)_w = \dot{m}_s (h_1 - h_2)$$

$$\dot{m}_w \times 4.18 \times 10 = 5.55 \times (2491.785 - 251.4)$$

$$\dot{m}_w = 297.46 \text{ kg/sec}$$

Solution : 42



$$W_P = v_f(P_2 - P_1)$$
$$W_P = 0.001037(3000 - 75)$$
$$W_P = 3.03 \text{ kJ/kg}$$
$$h_{3s} = h_3 + W_P$$
$$= 384.44 + 3.03$$
$$= 387.47 \text{ kJ/kg}$$
$$S_1 = S_2 \text{ (for isentropic process)}$$
$$s_1 = s_f + xs_{fg}$$
$$x_2 = \frac{s_1 - s_f}{s_{fg}} = \frac{6.7428 - 1.213}{6.2434} = 0.8857$$
$$h_2 = h_{f2} + x_2 h_{fg2} = 384.44 + 0.8857(2278.6)$$
$$h_2 = 2402.6 \text{ kJ/kg}$$
$$Q_{in} = h_1 - h_{3s} = 3115.3 - 387.47 = 2727.83 \text{ kJ/kg}$$
$$Q_{out} = h_2 - h_3 = 2402.6 - 384.44 = 2018.16 \text{ kJ/kg}$$
$$\eta_{thermal} = 1 - \frac{Q_{out}}{Q_{in}}$$
$$= 1 - \frac{2018.16}{2727.83} = 0.26 \text{ or } 26\%$$

■■■■

3 Gas Power Plant

LEVEL 1 Objective Questions

1. (a)
2. (b)
3. (b)
4. (c)
5. (b)
6. (c)
7. (b)
8. (b)
9. (b)
10. (c)
11. (d)
12. (d)
13. (236.794)
14. (402)
15. (a)
16. (725)
17. (1.74)
18. (c)
19. (d)
20. (38.18)
21. (c)
22. (4.26)
23. (b)
24. (d)

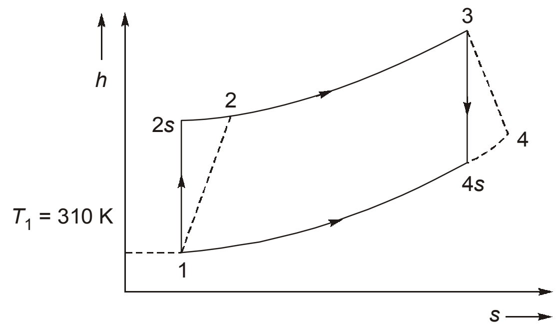
LEVEL 2 Objective Questions

25. (97.3)
26. (361.48)
27. (c)
28. (d)
29. (c)
30. (322.566)
31. (0.5445)
32. (b)
33. (a)

■■■■

LEVEL 3 Conventional Questions

Solution : 34



$$\frac{T_{2s}}{T_1} = (r_p)^{\frac{r-1}{r}}$$

$$\Rightarrow \quad T_{2s} = 490.98 \text{ K}$$

$$\eta_c = \frac{T_{2s}-T_1}{T_2-T_1}$$

$$\Rightarrow \quad 0.8 = \frac{490.98-310}{T_2-310}$$

$$\Rightarrow \quad T_2 = 536.23 \text{ K}$$

$$\text{Back Work Ratio} = r_{bw} = \frac{W_C}{W_T} = \frac{(T_{2s}-T_1)/(\eta_c)}{(T_3-T_{4s})\times\eta_T}$$

$$\Rightarrow \quad r_{bw} = 0.4 = \frac{T_1\left[\frac{T_{2s}}{T_1}-1\right]}{\eta_c\eta_T T_3\left[1-\frac{T_{4s}}{T_3}\right]}$$

$$\Rightarrow \quad r_{bw} = \frac{T_1\left[(r_p)^{\frac{r-1}{r}}-1\right]}{\eta_c\eta_T T_3\left[1-\frac{1}{(r_p)^{\frac{r-1}{r}}}\right]}$$

$$r_{bw} = \frac{T_1}{T_3}\frac{(r_p)^{\frac{r-1}{r}}}{\eta_c\eta_T}$$

$$\Rightarrow \quad 0.4 = \frac{310}{T_3}\times\frac{(5)^{\frac{0.4}{1.4}}}{0.8\times0.9}$$

$$\Rightarrow \quad T_3 = \text{Maximum temperature in cycle} = 1704.81 \text{ K}$$

Thermal efficiency, $$\eta = \frac{W_T - W_C}{Q_S} = \frac{(T_3 - T_{4s}) \times \eta_T - \frac{(T_{2s} - T_1)}{\eta_c}}{T_3 - T_2}$$

$$T_{4s} = \frac{T_3}{(r_p)^{\frac{\gamma-1}{\gamma}}} = 1076.39 \text{ K}$$

Thermal efficiency, $$\eta = \frac{565.58 - 226.23}{1704.81 - 536.23} = 29.04\%$$

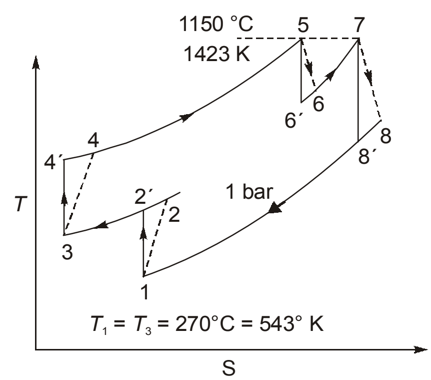
Solution : 35

Given, $T_1 = T_3 = 270°\text{C}$, $r_{p_1} = 1$ bar, $T_5 = T_7 = 1150°\text{C}$, $\eta_c = 85\%$, $\eta_T = 90\%$, $\gamma = 1.24$

As pressure ratio for second stage is not given, so assuming it equal to first stage for maximum work output.

$$\therefore \quad T_2' = T_1 (r_c)^{\frac{\gamma-1}{\gamma}} = 543\ (6)^{\frac{0.24}{1.24}} = 768 \text{ K}$$

$$T_2 = T_1 + \frac{(T_2' - T_1)}{\eta_c} = 543 + \frac{(7.68 - 543)}{0.85} = 807.8 \text{ K}$$



$\because\ T_3 = 543$ K, $\because\ T_4 = 807.8$ K

$$T_6 = \frac{T_5}{(r_p)^{r-1/r}} = \frac{1423}{(6)^{0.4/1.24}} = 1006 \text{ K}$$

$$T_6 = 1423 - 0.9\,(1423 - 1006)$$

$$T_6 = 1047.7 \text{ K}$$

Similarly since pressure ratio is same, T_7 is same. So T_8 will also be same, $T_8 = 1047.7$ K.

$$\frac{T_7^{1.24}}{P_7^{0.24}} = \frac{T_{8'}^{1.24}}{P_8^{0.24}}$$

$$T_8' = \frac{T_7}{6^{\frac{0.24}{1.24}}} = 1006 \text{ K}$$

$$\therefore \quad T_8 = 1047.7 \text{ K}$$

$$\because \quad \text{Heat input} = \dot{m}\, C_P (T_5 - T_4) + m\, C_P (T_7 - T_6)$$

$$= \dot{m} \times \frac{\gamma R}{\gamma - 1} [(1423 - 807.8) + (1423 - 1047.7)] = \dot{m} \times \frac{1.24}{0.24} \times 10.05\, [990.5]$$

$$Q = 51431.7\, \dot{m} \text{ kW}$$

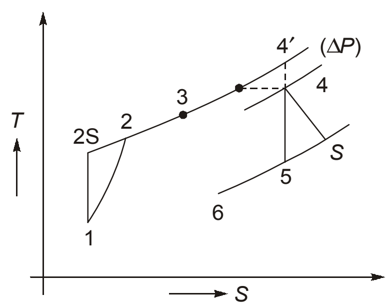
$$\text{Work Out put, } W = W_{t\text{-total}} - W_{c\text{-total}}$$

$$= 2\,[\dot{m}\, C_P (T_5 - T_6) - \dot{m}\, C_P (T_2 - T_1)] = 11475.425\, \dot{m} \text{ kW}$$

$$\eta_{th} = \frac{W}{Q} = 22.31\%$$

Solution : 36

Given : P_1 = 1 bar, T_1 = 288 k, P_2 = 2 bar, T_4 = 1700 K, η_C = 0.87, η_T = 0.88, $\eta_{comb.} = \eta_{HE}$ = 0.97



$$(\Delta P)_{\text{combuster}} = 0.4 \text{ bar}$$

$$P_4 = 2 - 0.4 = 1.6 \text{ bar}$$

$$P_5 = 1 \text{ bar}$$

$$(W_T) = 350 \text{ MW}$$

$$CV = \text{calorific value} = 42 \text{ MJ/kg}$$

$$(C_P)_{\text{air}} = (C_P)_{\text{gas}} = 1.005 \text{ kJ/kgk}, \gamma = 1.4$$

$$\frac{T_{2S}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{2}{1}\right)^{\frac{1.4-1}{1.4}} = 1.219$$

$$\Rightarrow \quad T_{2s} = 351 \text{ K [As } T_1 = 288 \text{ K}$$

$$\eta_C = 0.87 = \frac{T_{2S} - T_1}{T_2 - T_1}$$

$$(T_2 - T_1) = \left(\frac{351 - 288}{0.87}\right) = 72.5$$

$$T_2 = 360.5 \text{ K}$$

$$\frac{T_4}{T_{5S}} = \left(\frac{P_4}{P_5}\right)^{\frac{\gamma_g - 1}{\gamma_g}} = \left(\frac{1.6}{1}\right)^{\frac{1.4-1}{1.4}} \left(\gamma_g = \gamma = 1.4\right) = 1.143$$

$$T_{5S} = \frac{T_4}{1.143} = \frac{1700}{1.143} = 1486.38\text{ K}$$

$$\eta_T = 0.88 = \frac{T_4 - T_5}{T_4 - T_{5S}}$$

$$(T_4 - T_5) = 0.88\,(1700 - 1486.38)$$

$$T_5 = 1512\text{ k}$$

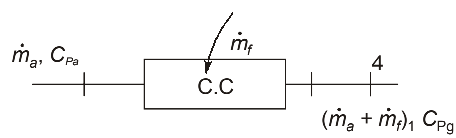
$$\eta_{\text{H.E.}} = 0.97 = \frac{T_3 - T_2}{T_5 - T_2}$$

$$T_3 - T_2 = 0.97(1512 - 360.5)$$

$$\Rightarrow \quad T_3 = 1477.5\text{ K}$$

$$\text{Power developed by turbine} = (\dot{m}_a + \dot{m}_f)C_{pg}(T_4 - T_5)$$

$$(\dot{m}_a + \dot{m}_f) \times 1.005 \times (1700 - 1512) = 350 \times 10^3$$



$$\dot{m}_a + \dot{m}_f = 1852.45\text{ kg/s}$$

$$\text{Heat released} = \text{Enthalpy rise of gas}$$

$$\dot{m}_f \times C.V. \times \eta_{\text{comb}} = (\dot{m}_a + \dot{m}_f)C_{pg}T_4 - \dot{m}_a C_{pa} T_3$$

$$\dot{m}_f(C.V. \times \eta_{\text{comb}} - C_{pa}T_4) = \dot{m}_a C_{pa}(T_4 - T_3)$$

$$\dot{m}_f\left[42 \times 10^3 \times 0.97 - 1.005 \times 1700\right] = \dot{m}_a \times 1.005 \times (1700 - 1477.5)$$

$$\Rightarrow \quad \frac{\dot{m}_a}{\dot{m}_f} = 174.55\text{ kg/s}$$

As,
$$\begin{pmatrix} \dot{m}_f = 10.55\ \text{kg/sec} \\ \dot{m}_a = 1841.9\ \text{kg/sec} \end{pmatrix}$$

$$\text{Compressor Power Input} = \dot{m}_a C_{pa}(T_2 - T_1)$$

$$= 1841.9 \times 1.005 \times (360.5 - 288) = 134.20\text{ MW}$$

$$\dot{W}_{net} = W_T - W_C = 350 - 134.20 = 215.8\text{ MW}$$

$$\text{Work ratio} = \frac{W_{\text{net}}}{W_T} = \frac{215.8}{350} = 0.616$$

$$Q_1\text{ (Heat added)} = \dot{m}_f \times C.V. \times \eta_{\text{comb.}}$$

$$Q_1 = 10.55 \times 42 \times 0.97 = Q_1 = 429.8\text{ MW})$$

$$\eta_{\text{thermal}} = \frac{W_{\text{net}}}{Q_1} = \frac{215.8}{429.8} = 0.502\text{ or }50.2\%$$

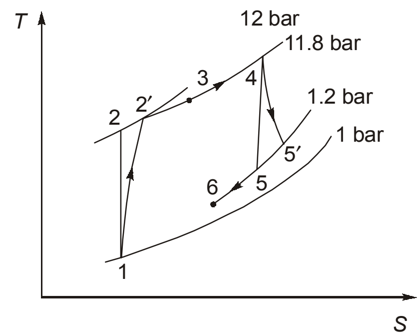
$$\text{Specific fuel consumption} = \frac{\dot{m}_f}{W_{\text{net}}} = \frac{10.55}{215.8 \times 10^3} \times 3600\text{ kg/kw.h} = 0.176\text{ kg/kw-hr}$$

Solution : 37

Given data: $T_1 = 10°\text{C} = 283$ K; $P_1 = 1$ bar; $P_2 = 12$ bar; $P_3 = 12 - 0.2 = 11.8$ bar; $P_4 = 1 + 0.2 = 1.2$ bar; $T_3 = 1400°\text{C} = 1673$ K; $\eta_c = 0.8$; $\eta_t = 0.85$, $\in = 0.75$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma}$$

$$T_2 = 283\left(\frac{12}{1}\right)^{0.4/1.4} = 575.6 \text{ K}$$



$$\eta_c = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.8 = \frac{575.6 - 283}{T_2' - 283}$$

$$T_2' = 648.75 \text{ K}$$

$$\frac{T_4}{T_5} = \left(\frac{P_4}{P_5}\right)^{\gamma-1/\gamma}$$

$$\frac{1673}{T_5} = \left(\frac{11.8}{1.2}\right)^{0.4/1.4}$$

$$T_5 = 870.69 \text{ K}$$

$$\eta_t = \frac{T_4 - T_5'}{T_4 - T_5}$$

$$0.85 = \frac{1673 - T_5'}{1673 - 870.69}$$

$$T_5' = 991.042 \text{ K}$$

$$\in = \frac{T_3 - T_2'}{T_5' - T_2'}$$

$$0.75 = \frac{T_3 - 648.75}{991.04 - 648.75}$$

$$T_3 = 905.47 \text{ K}$$

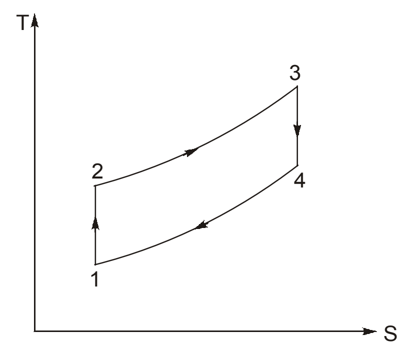
$$W_{net} = W_T - W_C = c_p[(T_4 - T_5') - (T_2' - T_1)]$$
$$= 1.005[(1673 - 991.04) - (648.75 - 283)] = 317.79 \text{ kJ/kg}$$

Heat supplied, $$Q_s = c_p(T_4 - T_3) = 1.005(1673 - 905.47)$$
$$= 771.3676 \text{ kJ/kg}$$

$\therefore$ $$\eta = \frac{W_{net}}{Q_s} = \frac{317.79}{771.3676} = 0.4119 = 41.19\%$$

Solution : 38

$$T_1 = 303 \text{ K}$$
$$T_3 = 1073 \text{ K}$$
$$T_2 = T_4 = \sqrt{T_1 T_3}$$
$$= \sqrt{303 \times 1073} = 570.19 \text{ K}$$



As there is no need for regenerator

It is operating at critical pressure ratio.

$$W = \dot{m}_a C_{pa}\left[\sqrt{T_3} - \sqrt{T_1}\right]^2$$
$$100 = \dot{m}_a \times 1.00\left[\sqrt{1073} - \sqrt{303}\right]^2 = \dot{m}_a \times 1.00[32.756 - 17.406]^2$$
$$\dot{m}_a = 0.4244 \text{ kg/s}$$
$$\Rightarrow \quad \dot{m}_a C_{pa}(T_3 - T_2) = m_f CV$$
$$\Rightarrow \quad 0.4244 \times 1(1073 - 570.19) = m_f \times 45000$$
$$\Rightarrow \quad m_f = 4.74 \times 10^{-3} \text{ kg/sec} = 17.07 \text{ kg/hr}$$

Solution : 39

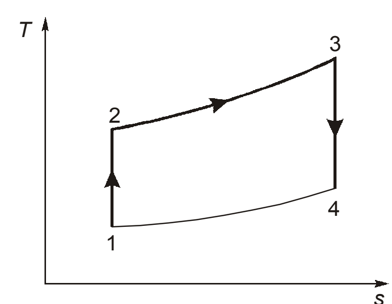
Given data: $r_p = 10$, $p_1 = 100$ kPa, $T_1 = 20°C = 293$ K; $m = 11$ kg/s; and $T_3 = 1222$ K

(i) $$\eta_T = \eta_C = 100\% = 1$$

For process 1–2,

$$\frac{T_2}{T_1} = (r_p)^{\frac{1.4-1}{1.4}} = 1.93$$

or $$T_2 = 1.93 \times 293 = 565.49 \text{ K}$$



For process 3–4,

$$\frac{T_3}{T_4} = (r_p)^{\frac{\gamma-1}{\gamma}}$$
$$\frac{1222}{T_4} = (10)^{\frac{1.4-1}{1.4}} = 1.93$$

or $$T_4 = 633.16 \text{ K}$$

Compressor work: $$W_{1-2} = mc_p(T_2 - T_1)$$
$$= 11 \times 1.005(565.49 - 293) = 3012.37 \text{ kW}$$

Turbine work: $$W_{3-4} = mc_p(T_3 - T_4)$$
$$= 11 \times 1.005(1222 - 633.16) = 6509.62 \text{ kW}$$

Net power produced: $W_{net} = W_{3-4} - W_{1-2}$

$= 6509.62 - 3012.37 =$ **3497.25 kW**

Heat supplied: $Q_{2-3} = mc_p(T_3 - T_2) = 11 \times 1.005(1222 - 565.49) = 7257.718$ kW

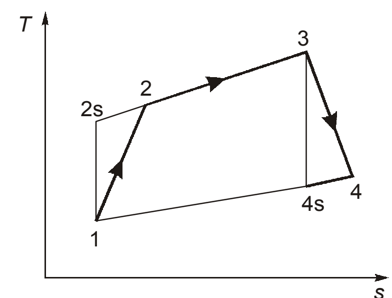
Thermal efficiency: $\eta_{th} = \dfrac{W_{net}}{Q_{2-3}} = \dfrac{3497.25}{7257.718} = 0.4818 = 48.18\%$

or $\eta_{th} = 1 - \dfrac{1}{r_p^{(\gamma-1)/\gamma}}$

$= 1 - \dfrac{1}{(10)^{(1.4-1)/1.4}} = 1 - \dfrac{1}{1.93} = 1 - 0.5181 = 0.4819 = \mathbf{48.19\%}$

(ii) $\eta_T = 88\% = 0.88$

$\eta_C = 84\% = 0.84$



For reference isentropic process 1–2s,

$$\frac{T_{2s}}{T_1} = (r_p)^{(\gamma-1)/\gamma}$$

$$\frac{T_{2s}}{293} = (10)^{(1.4-1)/1.4} = 1.93$$

or $T_{2s} = 1.93 \times 293 = 565.49$ K

$$\eta_C = \frac{T_{2s} - T_1}{T_2 - T_1}$$

$$0.84 = \frac{565.49 - 293}{T_2 - 293} = \frac{273.49}{T_2 - 293}$$

or $T_2 - 293 = \dfrac{273.49}{0.84} = 324.39$

or $T_2 = 617.39$ K

For reference isentropic process 3–4s,

$$\frac{T_3}{T_{4s}} = (r_p)^{\frac{\gamma-1}{\gamma}} = (10)^{(1.4-1)/1.4} = 1.93$$

$$\frac{1222}{T_{4s}} = 1.93$$

or $T_{4s} = 633.16$K

$$\eta_T = \frac{T_3 - T_4}{T_3 - T_{4s}}$$

$$0.88 = \frac{1222 - T_4}{1222 - 633.16} = \frac{1222 - T_4}{588.84}$$

or $0.88 \times 588.84 = 1222 - T_4$

or $T_4 = 703.82$K

Compressor work: $W_{1-2} = mc_p(T_2 - T_1)$

$$= 11 \times 1.005(617.39 - 293) = 3586.13 \text{ kW}$$

$$\text{Turbine work : } W_{3-4} = mc_p(T_3 - T_4)$$
$$= 11 \times 1.005 \times (1222 - 703.82) = 5728.47 \text{ kW}$$

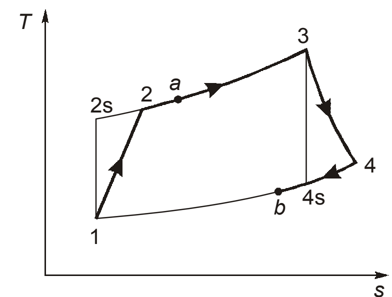
$$\text{Net power output: } W_{net} = W_{3-4} - W_{1-2} = 5728.47 - 3586.13 = \mathbf{2142.34\ kW}$$

$$\text{Heat supplied : } Q_{2-3} = mc_p(T_3 - T_2)$$
$$= 11 \times 1.005 \times (1222 - 617.39) = 6683.96 \text{ kW}$$

$$\text{Thermal efficiency : } \eta_{th} = \frac{W_{net}}{Q_{2-3}} = \frac{2142.34}{6683.96} = 0.3205 = \mathbf{32.05\%}$$

(iii)

$$\eta_T = 88\% = 0.88$$
$$\eta_C = 84\% = 0.84$$
$$\in = 80\% = 0.80$$



$$T_2 = 617.39 \text{ K}$$
$$T_4 = 703.82 \text{ K}$$
$$\in = \frac{T_a - T_2}{T_4 - T_2}$$

$$0.80 = \frac{T_a - 617.39}{703.82 - 617.39} = \frac{T_a - 617.39}{86.42}$$

or $0.80 \times 86.42 = T_a - 617.39$

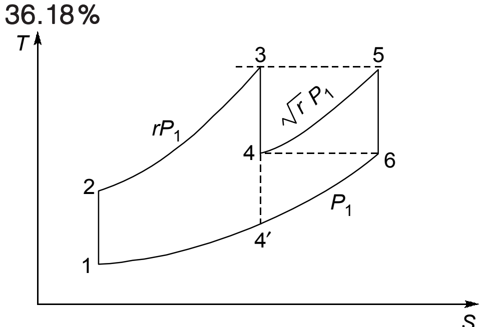
or $T_a = 686.52 \text{ K}$

$$\text{Net power developed: } W_{net} = 2142.34 \text{ kW}$$

$$\text{Heat supplied: } Q_{a-3} = mc_p(T_3 - T_a)$$
$$= 11 \times 1.005(1222 - 686.52) = 5919.73 \text{ kW}$$

$$\text{Thermal efficiency: } \eta_{th} = \frac{W_{net}}{Q_{a-3}} = \frac{2142.34}{5919.73} = 0.3618 = \mathbf{36.18\%}$$

Solution : 40



$$\frac{T_2}{T_1} = \left(\frac{rP_1}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = r^a = C$$

$$\frac{T_3}{T_4} = \frac{T_5}{T_6}$$

$$\frac{T_3}{T_4} = r_a^{\frac{\gamma-1}{\gamma}}, \frac{T_5}{T_6} = r_a^{\frac{\gamma-1}{\gamma}}$$

$r \rightarrow$ compression ratio

$r_a \rightarrow$ expansion ratio

$$\frac{T_3}{T_4} = \frac{T_5}{T_6} = (\sqrt{r})^a = \sqrt{C}$$

$$W_T = C_P(T_3 - T_4) + C_P(T_5 - T_6) = C_P(T_3 - T_4) + C_P(T_3 - T_6)$$

or $W_T = 2C_P(T_3 - T_4)$

or $W_T = 2C_P T_3\left(1 - \frac{1}{\sqrt{C}}\right)$

$$W_C = C_P(T_2 - T_1) = C_P T_1\left(\frac{T_2}{T_1} - 1\right) = C_P T_1 (C - 1)$$

Net work output, $$W_N = W_T - W_C = 2C_P T_3\left(1 - \frac{1}{\sqrt{C}}\right) - C_P T_1 (C-1)$$

$$W_N = \left\{2\frac{T_3}{T_1}\left(1 - \frac{1}{\sqrt{C}}\right) - (C-1)\right\} C_P T_1$$

$\therefore$ $$\frac{W_N}{C_P T_1} = 2\frac{T_3}{T_1}\left(1 - \frac{1}{\sqrt{C}}\right) - (C-1) = 2t(1 - C^{-1/2}) - (C-1) \quad ...(i)$$

Here c is the variable, for maximum work output, $\frac{d}{dc}\left(\frac{W_N}{C_P T_1}\right) = 0$

$$2t\left[-1 \times \frac{-1}{2} \times C^{-3/2}\right] - 1 = 0$$

or $$t\,C^{-3/2} = 1$$

$$C = (t^{-1})^{-2/3} = t^{2/3}$$

as $$C = r^a = t^{2/3}$$

or $\boxed{r = t^{(2/3a)}}$ Proved

■■■■

4 Turbine

LEVEL 1 Objective Questions

1.	(c)
2.	(c)
3.	(d)
4.	(b)
5.	(a)
6.	(d)
7.	(d)
8.	(b)
9.	(b)
10.	(c)
11.	(d)
12.	(c)
13.	(c)
14.	(d)
15.	(d)
16.	(a)
17.	(a)

LEVEL 2 Objective Questions

18.	(c)
19.	(c)
20.	(a)
21.	(1.72)
22.	(a)
23.	(d)
24.	(b)
25.	(c)
26.	(b)
27.	(3.43)
28.	(86.35)
29.	(c)
30.	(d)

■■■■

LEVEL 3 Conventional Questions

Solution : 31

Given: $V_1 = 1000$ m/s, $V_b = 400$ m/s, $\alpha = 20°$, $\beta_1 = \beta_2$ (for asymmetric blade), $\dot{m}_s = 0.75$ kg/s, $k_b = 0$

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

$$V_{r2}\cos\beta_1 = V_1\cos\alpha - V_b$$

$$\beta_1 = \tan^{-1}\left[\frac{V_1\sin\alpha}{V_1\cos\alpha - V_b}\right]$$

$$\left[\text{As } V_{r_2} = V_1\cos\alpha - V_b\right]$$

$$= \tan^{-1}\left[\frac{1000\times\sin 20°}{1000\cos 20° - 400}\right] = \tan^{-1}\left[\frac{342}{940-400}\right] = 32.35° = \beta_2$$

Blade angles, $\beta_1 = \beta_2 = \mathbf{32.35°}$

$$V_{r1}\sin 32.35° = 342$$

$$V_{r1} = \frac{342}{\sin 32.35°} = 639.25 \text{ m/s} = V_{r2}$$

$$\Delta V_w = V_{r1}\cos\beta_1 + V_{r2}\cos\beta_2 = 2V_{r1}\cos\beta_1 = 2\times 639.25\times\cos 32.35° = 1080.07 \text{ m/s}$$

$$\Delta V_a = V_{r1}\sin\beta_1 - V_{r2}\sin\beta_2 = 0$$

Tangential thrust, $= \dot{m}_s\Delta V_\omega = 0.75\times 1080.07 = \mathbf{810.05\ N}$

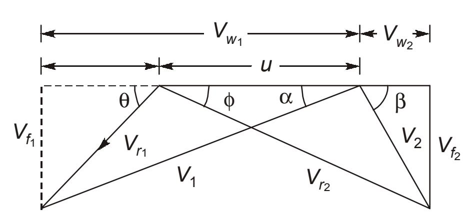
Diagram power, W_D = Tangential thrust × Blade velocity = 810.05 × 400 = **324.02 kW**

Diagram efficiency, $\eta_D = \dfrac{324.02}{\frac{1}{2}\times 0.75\times(1000)^2\times 10^{-3}} = \mathbf{0.864 \text{ or } 86.4\%}$

Axial thrust $= \dot{m}_s\Delta V_a = 0$

Solution : 32

Given : At a stage in Reaction Turbine



$v_g = 4.65$ m³/kg, $x = 0.95$, $\dot{m} = 36000$ kg/hr , Power = 950 kW,

$N = 3600$ rpm, $V_f = 0.72\,u$, $\alpha = \phi = 20°$

$$\dot{m} = 10 \text{ kg/sec}$$

$$\text{Power} = \dot{m}(V_{w_1} + V_{w_2})u$$

$$\tan\alpha = \frac{V_{f_1}}{V_{w_1}} \Rightarrow \left(V_{w_1} = \frac{V_{f_1}}{\tan 20°} = 2.75\,V_{f_1}\right)$$

Also, $V_{w_2} = V_{f_2}\cot\phi - u = V_{f_1}\cot 20° - u$ (As $V_{f_1} = V_{f_2}$)

$$V_{w_2} = V_{f_1}(2.75) - u = (2.75V_{f_1} - u)$$

$$\text{Power} = \dot{m}\left[(2.75v_{f_1}) + (2.75v_{f_1} - u)\right]u$$

$$= \dot{m}\left[5.5v_{f_i} - u\right]u = \dot{m}[(5.5)(0.72u) - u] = \dot{m}[3.96u - u]u = 2.96\dot{m}u^2$$

$$\text{Power} = 950 \times 10^3 = (10 \times 2.96)\, u^2$$

$$u = 179.15 \text{ m/sec}$$

Also,
$$u = \frac{\pi D_m N}{60}$$

$$D_m = \frac{60 \times 179.15}{\pi(3600)} = 0.95 \text{ m}$$

Mean rotor diameter is 0.95 m

$$\text{Flow Velocity, } v_f = 0.72 \times u = 0.72 \times 179.15 = 128.9 \text{ m/sec}$$

$$\text{Volume flow of steam} = m x\, v_g = 10 \times 0.95 \times 4.65$$

$$v_1 = 44.175 \text{ m}^3\text{/sec}$$

$$(\dot{m} \times v_1) = (\pi D_m H_b) V_{f_1}$$

$$(10 \times 4.4175) = (\pi \times 0.95 \times H_b) \times 128.9$$

$$H_b = 0.115 \text{ m}$$

$$\text{Height of blades } H_b = 0.115 \text{ m}$$

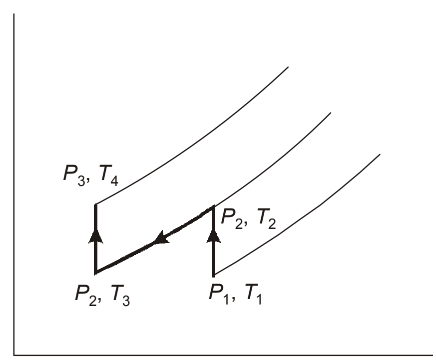
Solution : 33

Given:
$$\dot{m} = 10 \text{ kg/s}$$

$$\frac{P_2}{P_1} = 2.5, \quad \frac{P_3}{P_2} = 2.1$$

$$P_1 = 101.3 \text{ kPa}, \quad T_1 = 293 \text{ K}$$

$$T_2 - T_3 = 60°\text{C and } \eta_{\text{isent.}} = 0.9$$



For isentropic compression

$$T_{2s} = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} 293(2.5)^{0.4/1.4}$$

or
$$T_{2s} = 380.68 \text{ K}$$

$$\frac{T_{2s} - T_1}{T_2 - T_1} = \frac{0.9}{1}$$

$$T_2 = 390.43 \text{ K}$$

$$T_3 = (390.43 - 60) = 330.43 \text{ K}$$

$$T_{4s} = T_3\left(\frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}} = 408.45 \text{ K}; \quad \frac{T_{4s} - T_3}{T_4 - T_3} = \frac{0.9}{1}$$

$$T_4 = 417.12 \text{ K}$$

$$\text{Compressor power} = \dot{m}c_p\left[(T_2 - T_1) + (T_4 - T_3)\right] = 10 \times 1.005[390.43 - 293 + 417.12 - 330.43]$$

$$= 1850.385 \text{ kW}$$

Solution : 34

Given: Mean blade speed, u = 180 m/s, Nozzle angle: α = 17°, Mass flow rate,

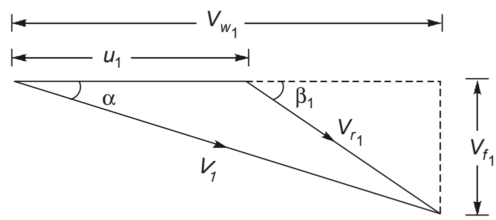
m = 3300 kg/hr = 0.9167 kg/s

Absolute inlet velocity of steam : V_1 = 550 m/s (C_{ai})

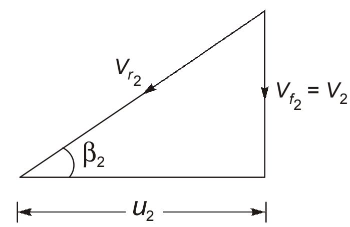
Mean blade speed, u = 180 m/s, Nozzle angle, α = 17°

Axial outlet condition.

(i) Inlet velocity triangle



Outlet velocity triangle



where β_1 and β_2 are Inlet and outlet blade angles.

From Inlet velocity triangle, we have

$$V_{w_1} = V_1 \cos\alpha = 550 \cos 17° = 525.96 \text{ m/s}$$

$$V_{f_1} = V_1 \sin\alpha = 550 \sin 17° = 160.80 \text{ m/s}$$

$$\tan\beta_1 = \frac{V_{f_1}}{V_{w_1} - u_1} = \frac{160.80}{525.96 - 180}$$

$$\beta_1 = 24.92°$$

$$\tan\beta_2 = \frac{Vf_2}{u_2} = \frac{Vf_1}{u_1} = \frac{160.80}{180}$$

$$\beta_2 = 41.77°$$

(ii) Power output,

$$P = m\left(V_{w_1} + V_{w_2}\right)u$$

$$V_{w_1} = V_1 \cos 17° = 525.96 \text{ m/s} = \frac{0.9167}{1000}(525.96 + 0) \times 180$$

$\because V_{w_2} = 0$ (Due to axial outlet condition)

$$= 86.78 \text{ kW}$$

(iii) Diagram efficiency,

$$\eta_D = \frac{2\left(V_{w_1} + V_{w_2}\right)u}{V_1^2} \times 100 = \frac{2(525.96 + 0) \times 180}{(550)^2} \times 100 = 62.59\ \%$$

Solution : 35

V_1 = 1000 m/sec, $\alpha_1 = 20°$, u = 400 m/sec. Symmetrical Blades, $\beta_1 = \beta_2 = \beta$

m_s = 0.75 kg/sec

$$FD = V_{r_1} \cos\beta_2 = V_1 \cos\alpha_1 - u$$
$$= 1000 \cos 20° - 400$$
$$= 539.7 \text{ m/sec}$$
$$AF = V_{r_2} \sin\beta_2 = V_1 \sin\alpha_1 = 1000 \sin 20 = 342.02 \text{ m/sec}$$

$$V_{r_1} = \sqrt{FC^2 + AF^2} = \sqrt{539.7^2 + 342.02^2}$$
$$V_{r_1} = 638.95 \text{ m/sec} = V_{r_2}, \text{ no friction}$$
$$\tan\beta_1 = \frac{AF}{FC} = \frac{342.02}{539.7}$$
$$\beta_1 = \beta_2 = \beta = 32.36°$$
$$\therefore \quad V_{f_1} = V_{f_2}$$

BE = $V_{r_2} \cos\beta_2 - u = V_{r_1} \cos\beta_1 - u = 638.95 \cos 32.36 - 400 = 139.7$

(i) tangential force on the blades = $m\Delta V_w$

$$= 0.75 \times (539.7 + 400 + 139.7)$$
$$= m(FC + u + BE) = 809.55 \text{ N}$$

$$\text{Diagram power} = \text{Tangential force} \times \text{Blade speed}$$
$$= 809.55 \times 400 = 323.82 \text{ kW}$$

$$\text{Axial trust} = m\left(V_{f_1} - V_{f_2}\right) = 0$$

$$\text{Diagram efficiency} = \frac{2u\,V_w}{V_1^2} = \frac{2 \times 400 \times 1079.4}{1000^2} = 0.86352 = 86.352\%$$

Solution : 36

u = 140 m/sec, $\beta_2 = \alpha_1 = 20°$, $\beta_2 = 30° = \alpha_2\ \eta_s = 80\%$

Enthalpy drop in stage $= \Delta h_m + \eta_{fix} = \frac{1}{2}m\left[\left(V_{r_2}{}^2 - V_{r_1}{}^2\right) + V_1^2\right]$

$\therefore\ \alpha_1 = \beta_2 = 20°,\ \beta_1 = \alpha_2 = 30°$

$$V_{r_1} \sin\beta_1 = V_1 \sin\alpha_1$$

$$V_1 = V_{r_1}\cdot\frac{\sin\beta_1}{\sin\alpha_1} = V_{r_1}\frac{\sin 30}{\sin 20}$$

$$V_1 = 1.462\ V_{r_1}$$

$$V_1\cos\alpha_1 - V_{r_1}\cos\beta_1 = u$$

$$V_{r_1}[1.462\cos 20 - \cos 30] = 140$$

$$V_{r_1} = 275.75\text{ m/sec}$$

$$V_1 = 1.462 \times 275.75$$

$$V_1 = 403.07\text{ m/sec}$$

$$V_f = V_1 \sin 20 = 137.86\text{ m/sec}$$

$$\because\quad V_1 = V_{r_2},\ V_2 = V_{r_1}$$

$$\text{enthalpy drop per kg} = \frac{1}{2}\left[V_1^2 + V_{r_2}{}^2 - V_{r_1}{}^2\right]$$

$$= \frac{1}{2} \times [2 \times 403.07^2 - 275.7^2]$$

$$= 124.46\text{ kJ/kg}$$

density of steam at this stage

$$\rho = \frac{P}{RT} = \frac{20\times 10^5}{461.9 \times 523} = 8.28\text{ kg/m}^3$$

Mass flow rate $m = \rho_1 A.V_f = 8.28 \times \pi D_m h \times 137.9$

$\because$ $h = \dfrac{D_m}{12}$

$$120 = 8.28\,\pi \times 12h^2 \times 137.9$$

$$h^2 = 2.79 \times 10^{-3}$$

$\Rightarrow$ $h = 5.28$ cm

Drum diameter, $D_m = 5.28 \times 12 = 63.36$ cm

% age increase in relative velocity in blade passage

$$= \frac{V_{r_2} - V_{r_1}}{V_{r_1}} = \frac{403.07}{275.7} - 1 = 46.2\%$$

Solution : 37

(i) Single stage impulse turbine

Ideal condition $\rightarrow \dfrac{u}{V_1} = \dfrac{\cos\alpha}{2} = \dfrac{\cos 18}{2} = 0.47553$

$$V_1 = \sqrt{2000 \times 12000} = 1549.2 \text{ m/sec}$$

$$u = 0.47553 \times V_1 = 736.687 \text{ m/sec}$$

$$\frac{\pi D_m N}{60} = 736.687$$

$$D_m = 3.5174 \text{ meter}$$

(ii) Stage – 50% reaction turbine

$\because$ $\dfrac{u}{V_1} = \cos\alpha = \cos 18 = 0.951$

$\because$ enthalpy drop in nozzle $= \dfrac{1200}{2} = 600$ kJ/kg

$\because$ $V_1 = \sqrt{2000 \times 600} = 1095.445$ m/sec

$$u = 0.951 \times 1095.445 = 1041.77 \text{ m/sec}$$

$$\frac{\pi D_m N}{60} = 1041.77$$

$$D_m = 4.974 \text{ meter}$$

(iii) One two row-curtis stage for ideal condition

$\dfrac{u}{V_1} = \dfrac{\cos\alpha}{2.z} = \dfrac{\cos\alpha}{4}$ $\because$ $z = 2$ – No. of stages

$$\frac{u}{V_1} = \frac{\cos 18}{4} = 0.23776$$

$$V_1 = \sqrt{2000 \times 1200} = 1549.2 \text{ m/sec}$$
$$u = 0.23776\, V_1 = 368.34 \text{ m/sec}$$
$$\frac{\pi D_m N}{60} = 368.34$$
$$D_m = 1.7586 \text{ meter}$$

(iv) Ten 50% reaction stage

enthalpy drop in one stage $\Delta h_s = \dfrac{1200}{10} = 120$ kJ/kg

$\because$ enthalpy drop in nozzle/fixed blade $= \dfrac{\Delta h_s}{2} = 60$ kJ/kg

$$\because \quad V_1 = \sqrt{2000 \times \frac{\Delta h_s}{2}} = \sqrt{2000 \times 60} = 346.4 \text{ m/sec}$$

$\because$ 50% reaction

$$\frac{u}{V_1} = \cos\alpha = \cos 18 = 0.951$$
$$u = 0.951 . V_1 = 329.446 \text{ m/sec}$$
$$\frac{\pi D_m N}{60} = 329.446$$
$$D_m = 1.573 \text{ meter}$$

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5 Compressor

LEVEL 1 Objective Questions

1.	(c)
2.	(b)
3.	(a)
4.	(c)
5.	(155.59)
6.	(c)
7.	(c)
8.	(b)
9	(d)
10.	(a)
11.	(b)
12.	(c)
13.	(d)
14.	(b)
15.	(d)
16.	(b)
17.	(c)

LEVEL 2 Objective Questions

18.	(300)
19.	(b)
20.	(c)
21.	(a)
22.	(d)
23.	(b)
24.	(a)
25.	(c)
26.	(c)
27.	(c)
28.	(b)

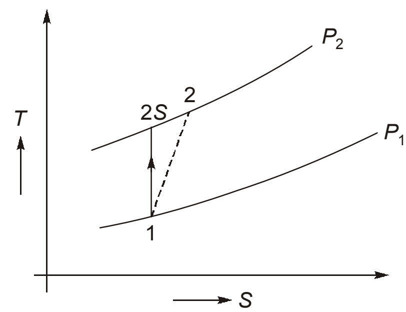
■■■■

LEVEL 3 Conventional Questions

Solution : 29

Given: For a centrifugal compressor

$N = 16000$ rpm, $r_p = 4$, $\eta = 82\%$, $\phi_s = 0.85$, $T_1 = 17°C = 290$ K



$$\frac{T_{2S}}{T_1} = (r_P)^{\frac{\gamma-1}{\gamma}} = (4)^{\frac{1.4-1}{1.4}} = 1.486$$

$$T_{2S} = 290 \times 1.487 = 430.9 \text{ K}$$

$$w_c = (h_2 - h_1) = mc_p(T_2 - T_1)$$

$$w_c = mc_p\left(\frac{T_{2s} - T_1}{\eta_{isent}}\right)$$

$$w_c = 1 \times 1.005 \times \left(\frac{430.9 - 290}{0.82}\right)$$

$$w_c = \text{power input per kg} = 172.68 \text{ kJ/kg}$$

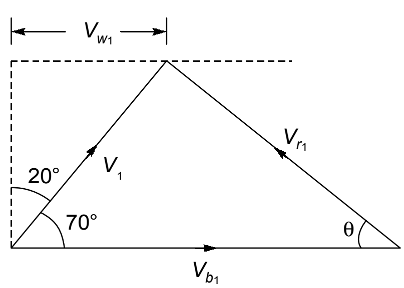
Absolute velocity at inlet, $v_1 = 120$ m/sec

$$v_{b1} = \text{blade velocity} = \frac{\pi D_1 N}{60} = \frac{\pi \times 0.2 \times 16000}{60}$$

$$v_{b1} = 167.55 \text{ m/sec}$$

Velocity Triangle at inlet

Pre-whirl Angle = 20°



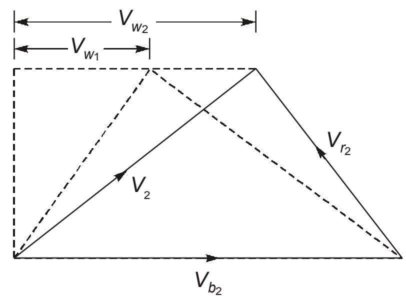
$$V_{W_1} = v_1 \sin 20° = 120 \sin 20° = 41.04 \text{ m/sec}$$

At exit of vanes

$$V_{W_2} = V_{b_2} \quad \text{[Radially inclined]}$$

$$\text{slip factor } \phi_s = \frac{V'_{W_2}}{V_{b_2}} = 0.85$$

$$V'_{W_2} = 0.85 V_{b_2}$$



$$\text{Power input per kg} = V_{b_2} V'_{w_2} - V_{b_1} V_{w_1}$$

$$172.81 \times 10^3 = v_{b_2} \times (0.85\, v_{b_2}) - 167.55 \times 41.05 = 0.85 v_{b_2}^2 - 6877.93$$

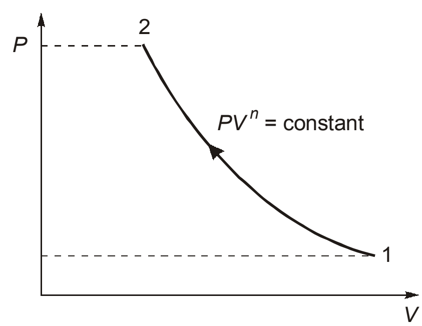
$$v_{b_2} = 459.78 \text{ m/s} = \frac{\pi D_2 \times 16000}{60}$$

$$\text{Tip diameter } (D_2) = 548.8 \text{ mm}$$

Solution : 30

Work done during polytropic compression is given by,

$$W = \int_1^2 pdV$$



We have,

$$PV^n = C$$

$$P = \frac{C}{V^n} = CV^{-n}$$

$$W = \int_1^2 V^{-n} dV = C\left(\frac{V^{-n+1}}{-n+1}\right)\Bigg|_1^2$$

$$W = \left| PV^n \frac{V^{1-n}}{1-n} \right|_1^2 = \frac{(PV)}{1-n}\Bigg|_1^2 = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{R(T_2 - T_1)}{1-n} \quad \text{... (i)}$$

Heat transfer for a polytropic process is given by

$$dQ = du + PdV = C_V(T_2 - T_1) + \frac{R(T_2 - T_1)}{1-n}$$

$$= C_V(T_2 - T_1) - \frac{C_V(\gamma - 1)(T_2 - T_1)}{1-n} = C_V(T_2 - T_1)\left[1 - \frac{\gamma - 1}{n-1}\right]$$

$$Q = C_V \frac{n-\gamma}{n-1}(T_2 - T_1) \quad \ldots \text{(ii)}$$

As given, $\frac{Q}{W} = \frac{1}{4}$

From equation (i) and (ii),

$$C_V \frac{n-\gamma}{n-1}(T_2 - T_1) = \frac{R}{4} \times \frac{(\gamma-1)C_V}{4}$$

$$\gamma - n = \frac{\gamma-1}{4}$$

$$4\gamma - 4n = \gamma - 1$$

$$4\gamma - \gamma + 1 = 4n$$

$$\frac{C_V(n-\gamma)}{(n-1)}(T_2 - T_1) = \frac{R(T_2 - T_1)}{4(1-n)}$$

$$\frac{C_V(n-\gamma)}{(n-1)} = \frac{C_V(\gamma-1)}{4(1-n)}$$

$$4n - 4\gamma = 1 - \gamma$$

$$\frac{(4n-1)}{3} = r$$

$$n = \frac{3\gamma+1}{4}$$

$$n = \frac{1+3\gamma}{4} = \frac{1+4.2}{4} = \frac{5.2}{4} = 1.3$$

Work done, $W = \frac{P_1V_1 - P_2V_2}{n-1} = \frac{R(T_1 - T_2)}{n-1}$

As work done during compression process is negative,

$$-W = 200 \text{ kJ/kg} = \frac{R\Delta T}{n-1}$$

$$\Delta T = \frac{200(n-1)}{(\gamma-1)C_V} = \frac{200(1.3-1)}{0.75(1.4-1)} = \mathbf{200\ K}$$

Solution : 31

Given: $T_1 = 300$ K, $\eta_C = 90\%$, $\dot{m} = 3.5$ Kg/s, u = mean blade speed = 200 m/s, $C_a = C_{a_1} = C_{a_2} = 120$ m/s

As the temperature change is same in each stage, the power input may be obtained by considering the overall conditions.

$$\frac{T_{2'}}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

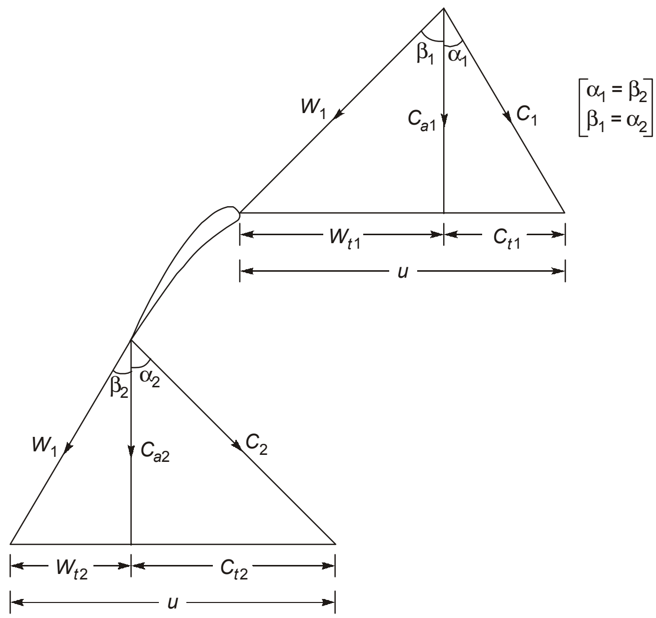
$$T_{2'} = (6)^{0.286} \times 300 = 500.55 \text{ K}$$

Isentropic efficiency, $\eta_c = \frac{T_{2'} - T_1}{T_2 - T_1}$

$$T_2 = \frac{T_{2'} - T_1}{\eta_c} + T_1 = \frac{500.8 - 300}{0.9} + 300 = 522.83 \text{ K}$$

Power given to the air, $W = \dot{m}C_p\Delta T$

$$= 3.5 \times 1.005(522.83 - 300) = \mathbf{783.82 \text{ kW}}$$



Entry to and exit from rotor : Velocity Diagram

Temperature change per stage, $\Delta T_s = \frac{\Delta T}{10} = \frac{522.83 - 300}{10} = 22.283 \text{ K}$

Work done/kg of air second $= u\Delta C_t = 200\ \Delta C_t$

Also work done/per kg of air per second $= C_p\Delta T_s = 200\ \Delta C_t$

$$\Delta C_t = \frac{1005 \times 22.312}{200} = 112.47 \text{ m/s}$$

For symmetrical stages, $\Delta C_t = C_a(\tan\beta_1 - \tan\beta_2)$

$$112.118 = 120(\tan\beta_1 - \tan\beta_2)$$

$$\tan\beta_1 - \tan\beta_2 = \frac{112.118}{120} = 0.9343 \quad \text{...(i)}$$

Degree of reaction, $R = \frac{C_a}{2u}(\tan\beta_1 + \tan\beta_2)$

$$\tan\beta_1 + \tan\beta_2 = \frac{2Ru}{C_a} = \frac{2 \times 0.5 \times 200}{120} = 1.67 \quad \text{...(ii)}$$

Solving (i) and (iii) $\tan\beta_1 = \frac{0.9343 + 1.67}{2} = 1.30215 = 52.47°$

$\Rightarrow$ $\tan\beta_1 = 1.30215 \Rightarrow \beta_1 = 52.47°$

Now from equation (ii)

As, $\tan\beta_1 + \tan\beta_2 = 1.67$

$$\Rightarrow \quad \tan\beta_2 = 1.67 - \tan\beta_1 = 1.67 - 1.30215$$

$$\beta_2 = 20.19°$$

Solution : 32

Given: $Q = 20\ m^3/sec$, $P_1 = 1$ bar, $T_1 = 15°C$ or 288 K, $r_p = 1.5$, $PV^{1.5}$ = constant, $V_{f_1} = V_{f_2} = 60$ m/sec, $D_1 = 0.6$ m, $D_2 = 1.2$ m, $N = 5000$ rpm

$$\frac{T_2}{T_1} = (r_p)^{0.5/1.5} = (1.5)^{0.5/1.5}$$

$$T_2 = 329.67 \text{ K}$$

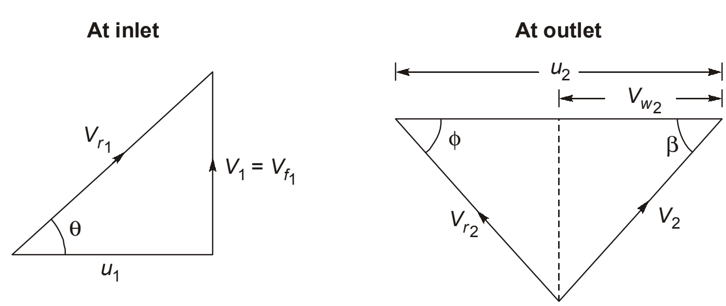
$$u_1 = \frac{\pi D_1 N}{60} = \frac{\pi \times 0.6 \times 5000}{60} = 157 \text{ m/sec}$$

$$u_2 = \frac{\pi D_2 N}{60} = \frac{\pi \times 1.2 \times 5000}{60} = 314 \text{ m/sec}$$

Blade angle at inlet, $\tan\theta = \dfrac{V_{f_1}}{u_1}$

$$\theta = \tan^{-1}\left(\frac{60}{157}\right) = 20.92°$$

Velocity triangle



$$\text{Power input to compressor} = h_2 - h_1$$

$$= \dot{m}C_p(T_2 - T_1)$$

Also $\dot{m}C_p(T_2 - T_1) = \dot{m}V_{w_2}u_2$

$$1.005 \times 10^3 \times (329.67 - 288) = V_{w_2} \times 314$$

$$V_{w_2} = 133.37 \text{ m/sec}$$

$$\tan\beta = \frac{V_{f_2}}{V_{w_2}} = \frac{60}{133.37}$$

$$\beta = 24.22°$$

The angle at which air from the impeller enters the casing ($\beta = 24.22°$)

Blade angle at outlet (ϕ) $\quad \tan\phi = \dfrac{V_{f_2}}{u_2 - V_{w_2}} = \left(\dfrac{60}{314 - 133.37}\right)$

$$\phi = 18.37°$$

Since, $\quad Q = \pi D_1 B_1 V_{f_1}$

$$20 = \pi(0.6)B_1 \times 60$$

$$B_1 = 0.176 \text{ m}$$

Breadth of impeller blade at inlet $= 0.176$ m

and $\quad Q = \pi D_2 B_2 V_{f_2}$

$$20 = \pi \times (1.2) \times B_2 \times 60$$

$$B_2 = 0.088 \text{ m}$$

Breadth of impeller blade at outlet $= 0.088$ m

Solution : 33

$$M_0 = \frac{1800}{60} = 30 \text{ kg/sec}, \mu = 0.9, \text{Pif} = 1.1$$

Power given to comp. $= m\, P_{if}\, \mu . u_2^2$

Tip-impeller velocity $u_2 = \dfrac{\pi DN}{60} = \dfrac{\pi \times 0.7 \times 1600}{60} = 58.643$ m/sec

Power of comp. $= m\, P_{if}\, \mu\, u_2^2 = 30 \times 1.1 \times 0.9 \times (58.643)^2 = 102.14$ kw

Change in temperature during comp. $\Delta T = \dfrac{P_{if} . \mu . u_2^2}{C_P} = \dfrac{1.1 \times 0.9 \times 58.643^2}{1005} = 3.388$

$$\Delta T \approx 3.39 \text{ K}$$

$\because \quad T_2 - T_1 = 3.39$

$$T_2 = 290 + 3.39 = 293.39 \text{ K}$$

Compressors efficiency

$\because \quad 0.85 = \left(\dfrac{T_2' - T_2}{T_2 - T_1}\right)$

$$T_2^1 = T_1 + 0.85 \times 3.39$$

$$T_2 = 292.88 \text{ K}$$

Pressure coefficient, $\quad \Psi_P = \dfrac{\text{Adiabatic Work } (1-2')}{\text{Max. Passible Work } (= mu_2^2)}$

$$= \eta_C . P_{if} . \mu . = 0.8415$$

Assuming absolute velocity at inlet and out let same.

$$\therefore \quad \frac{T_1^{\gamma}}{P_1^{\gamma-1}} = \frac{T_2^{\gamma}}{P_2^{\gamma-1}}$$

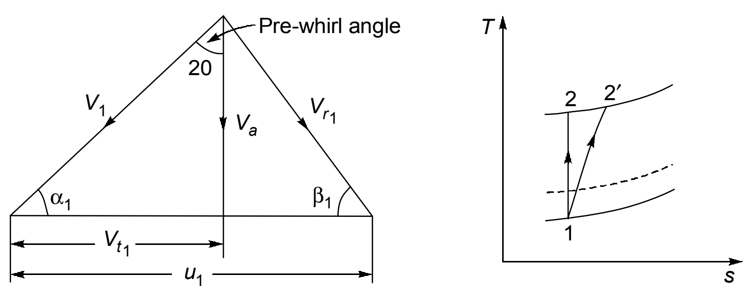
$$\frac{290^{1.4}}{1^{0.4}} = \frac{292.88^{1.4}}{P_2^{0.4}}$$

$$\frac{P_2}{1} = \left(\frac{292.88}{290}\right)^{3.5}$$

$$P_2 = 1.0352 \text{ bar}$$

Solution : 34

$N = 18000$ rpm, $\eta_c = 80\%$, $D_1 = 225$ mm, $V_1 = 130$ m/sec, $u_1 = \dfrac{\pi D_1 N}{60} = 212.06$ m/sec.



$$V_{t1} = V_1 \sin 20° = 44.463 \text{ m/sec}$$

Static condition at input $\quad T_1 = 298$ K (= 25° C) & 1 bar

$$T_2 = T_1 (r)^{(\gamma-1)/\gamma} = 298 \times 4^{(0.4)/1.4}$$

$$T_2 = 442.83 \text{ K}$$

$$P_2 = 4 \text{ bar}$$

$$T_2' = T_1 + \frac{(T_2 - T_1)}{\eta_c} = 298 + \frac{(442.83 - 298)}{0.8}$$

$$T_2' = 479.033 \text{ K}$$

Work input to comp. (unit flow) $= 1\,(u_2 V_{t2} - u_1 V_{t1})$

$$\because \quad \mu\text{-slip factor} = \frac{V_{t2}}{u_2}$$

$$= 1\left[\mu\, u_2^2 - u_1 V_{t1}\right] \quad \text{... (i)}$$

from thermodynamic relation $= C_P (T_2' - T_1) \quad$ ... (ii)

$$\because \quad C_P (T_2' - T_1) = (\mu\, u_2^2 - u_1 V_{t1})$$

$$1005 \times (479.033 - 298) = 0.9\, u_2^2 - 212.06 \times 44.463$$

$$u_2 = 461.12 \text{ m/sec}$$

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

$$461.12 = \frac{\pi \times D_2 \times 18000}{60}$$

$$D_2 = 48.93 \text{ cm} = 489.3 \text{ mm}$$

Solution : 35

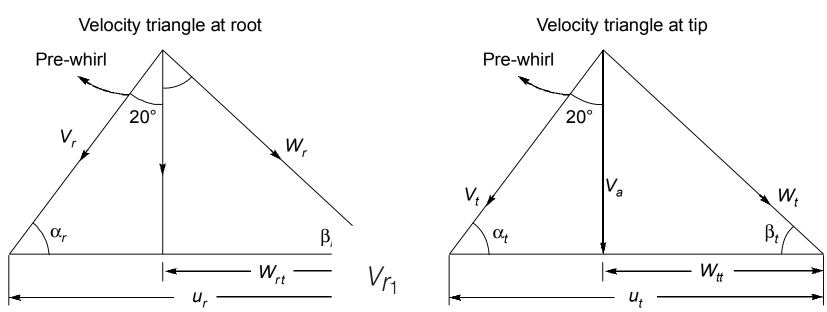
D_r = 18 cm, D_t = 30 cm, m = 16 kg/sec, N = 16000 rpm.; V_{a_t} = 150 m/sec

$$u_r = \frac{\pi D_r.N}{60} = 150.8 \text{ m/sec}$$

$$u_t = \frac{\pi D_t N}{60} = 251.33 \text{ m/sec}$$

$$W_{rt} = u_r - V_a \tan 20 = 150.8 - 54.6 = 96.2 \text{ m/sec}$$

$$W_{tt} = u_t - V_a \tan 20 = 251.33 - 54.6 = 196.73 \text{ m/sec}$$



At root $\quad \tan \beta_r = \frac{V_a}{W_{rt}} = \frac{150}{96.2} \Rightarrow \beta_r = 57.33°$

At tip $\quad \tan \beta_t = \frac{V_a}{W_{tt}} = \frac{150}{196.73} \Rightarrow \beta_t = 37.32°$

Absolute velocity at tip. $V_t = \frac{V_a}{\cos 20} = V_r = 159.63$ m/sec

Max. mach No. at tip

$$W_t = \sqrt{V_a^2 + W_{tt}^2} = 247.4 \text{ m/sec}$$

$$M_t = \frac{W_t}{C_2} \quad \text{...(i)}$$

$$\because \quad C_P T_{01} = C_P T_t + \frac{V_2^2}{2}$$

$$T_t = 288 - \frac{159.63^2}{2 \times 1005} = 275.323 \text{ m/sec}$$

$$C_2 = \sqrt{\gamma R T_t} = \sqrt{1.4 \times 287 \times 275.33} = 332.6 \text{ m/sec}$$

$$M_t = \frac{247.4}{332.6} = 0.744$$

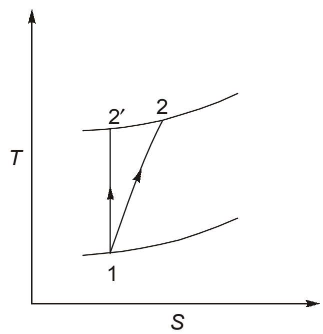
Solution : 36

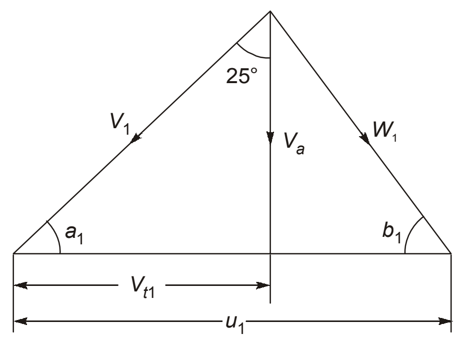
$$\because \quad T_2' = T_1 (4)^{\frac{\gamma-1}{\gamma}} = 293\,(4)^{\frac{0.4}{1.4}} = 435.4\ \text{K}$$

$$\therefore \quad (T_2 - T_1) = \frac{(435.4 - 293)}{0.8} = 178\ \text{K} \Rightarrow T_2 = 293 + 178 = 471\ \text{K}$$

$$V_1 = 150\ \text{m/sec}$$

$$u_1 = \frac{\pi\, D.N}{60} = \frac{\pi \times 0.25 \times 15000}{60}$$





$V_{t_1} = V_1 \sin 25 = 150 \sin 25 = 63.4$ m/sec

$$u_1 = 196.35\ \text{m/sec}$$

from energy balance

$$m\,C_P(\Delta T) = m(u_2\, Vt_2 - u_1\, Vt_1)$$

$$\because \quad \mu = \frac{Vt_2}{u_2}$$

$$C_P(T_2 - T_1) = (\mu\, u_2^{\,2} - u_1\, Vt_1)$$

$$\because \quad u_2 = \frac{\pi\, D_2 N}{60} = \frac{\pi \times 0.6 \times 15000}{60}$$

$$u_2 = 471.24\ \text{m/sec}$$

$$\therefore \quad 1005 \times 178 = \mu \times 471.24^2 - 196.35 \times 63.4$$

$$\mu = 0.86$$

Solution : 37

50% Reaction $\therefore\ \alpha_1 = \beta_2,\ \beta_1 = \alpha_2$

$\therefore\ \beta_1 = \alpha_2 = 45°,\ \alpha_1 = \beta_2 = 15°$

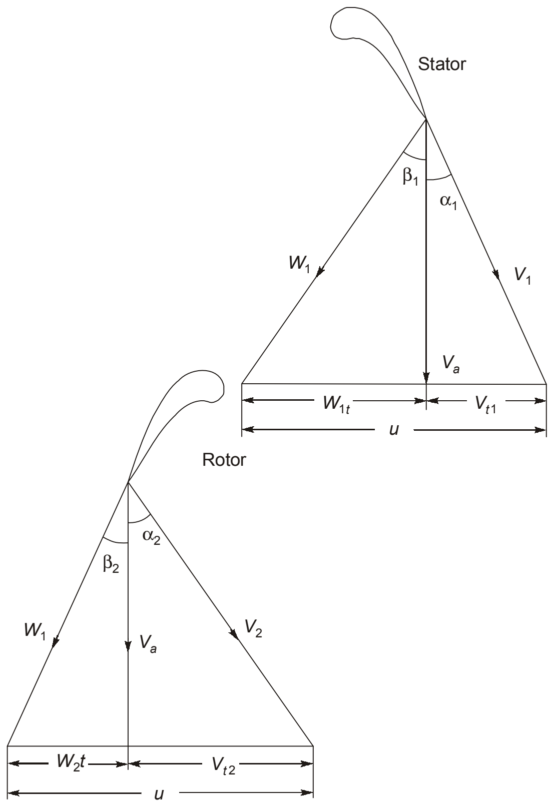
$u = 180$ m/sec. $\Omega = 0.84$

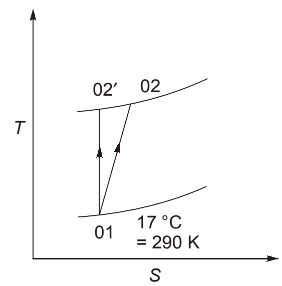
from inlet velocity triangle

$$u = w_{1t} + V_{t1} = V_a \tan\beta_1 + V_a \tan\alpha_1 = V_a(\tan\beta_1 + \tan\alpha_1)$$

$$180 = V_a[\tan 45° + \tan 15°] = V_a \times 1.268$$

$$V_a = \frac{180}{1.268} \approx 142 \text{ m/sec ... (flow velocity)}$$





Work input per stage

$$C_P \Delta T_S = \Omega u \left(V_{t2} - V_{t1}\right)$$

$$\Delta T_S = \frac{\Omega u \left(V_{t2} - V_{t1}\right)}{C_P} = \frac{0.84 \times 180 \times (142 - 38.05)}{1005}$$

$$\Delta T_S = 15.64 \text{ K per stage}$$

$$\because \quad T_2' = T_{01}\, r^{\left(\frac{\gamma - 1}{\gamma}\right)} = 290\,(4)^{0.4/1.4} = 430.94 \text{ K}$$

$$T_{02} = T_{01} + \frac{T_{02}' - T_{01}}{\eta_C} = 290 + \frac{(430.94 - 290)}{0.82}$$

$$T_{02} = 461.88 \text{ K}$$

Total change in temp across the comp $= T_{02} - T_{01} = 461.88 - 290 = 171.88$ K

$$\text{No. of stages } n = \frac{171.88}{15.64} = 10.9895 \approx 11$$

Solution : 38

$\because$ $$T_2 - T_1 = 125$$

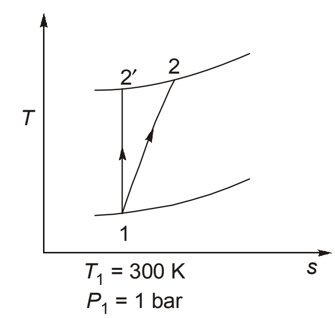
$$T_2 = 125 + 300 = 425\text{ K}$$

$\because$ $$P_2 = 3\,P_1 = 3\text{ bar}$$

$\because$ Process 1 – 2′ $$\frac{T_1^{\gamma}}{P_1^{\gamma-1}} = \frac{T_2^{\gamma}}{P_2^{\gamma-1}}$$

$$\frac{300^{1.4}}{1^{0.4}} = \frac{T_2^{1.4}}{3^{0.4}}$$

$$T_2' = 300\,(3)^{\frac{0.4}{1.4}} = 410.62\text{ K}$$



efficiency of compressor $\eta_c = \dfrac{(T_2' - T_1)}{(T_2 - T_1)} = \dfrac{(410.62 - 300)}{(425 - 300)}$

$$\eta_c = 88.5\%$$

Power conversion equation

$$\dot{m}_a\,C_P(\Delta T) = P \times \eta_m$$

$$\dot{m}_a \times 1.005 \times 125 = 2000 \times 0.95$$

$$\dot{m}_a = \frac{2000 \times 0.95}{1.005 \times 125} = 15.1244\text{ kg/sec.}$$

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6 Jet Propulsion

LEVEL 1 Objective Questions

1.	(a)
2.	(a)
3.	(b)
4.	(a)
5.	(b)
6.	(c)
7.	(a)
8.	(d)
9.	(c)
10.	(a)
11.	(c)
12.	(d)
13.	(b)
14.	(d)

LEVEL 2 Objective Questions

15.	(d)
16.	(b)
17.	(d)
18.	(d)
19.	(b)
20.	(c)
21.	(b)
22.	(a)
23.	(b)
24.	(c)
25.	(d)
26.	(a)
27.	(b)
28.	(b)

■■■■

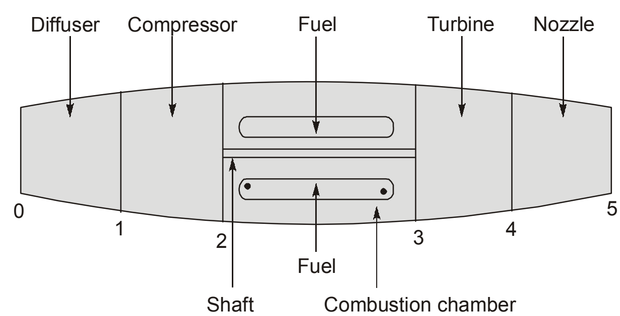
LEVEL 3 Conventional Questions

Solution : 29

The turbojet engines are most common type air breathing engine.

The engine consists of the following components:

1. A diffuser
2. A mechanical compressor
3. A combustion chamber
4. A mechanical turbine and
5. An exhaust nozzle



The turbojet engine

The function of the diffuser is to convert the kinetic energy of the entering air into a static pressure rise which is achieved by the ram effect. After this air enters the mechanical compressor.

The compressor used in a turbojet can be either centrifugal type or axial flow type. The use of a particular type of compressor gives the turbojet typical characteristics. The centrifugal compressor produces a high pressure ratio of about 4 : 1 to 5 : 1 in a single stage and usually a double sided rotor is used to reduce the engine diameter. The turbojet using a centrifugal compressor has a short and sturdy appearance. The advantages of centrifugal compressor are high durability, ease of manufacture and low cost, and good operation under adverse circumstances such as icing and when sand and small foreign particles are inhaled in inlet duct.

The axial flow compressor is more efficient than the centrifugal type and gives the turbojet a long, slim, streamlined appearance. The engine diameter is reduced which results in low aircraft drag. A multistage axial flow compressor can develop a pressure ratio as high as 6 : 1 or more. The air handled by it is more than that handled by a centrifugal compressor of the same diameter.

After the compressor air enters to the combustion chamber, the fuel nozzles feed fuel continuously and continuous combustion takes place at constant pressure. The high pressure, high temperature gases then enter the turbine, where they expand to provide enough power output from the turbine.

The turbine is directly connected to the compressor and all the power developed by the turbine is absorbed by the compressor and the auxiliaries. The main function of the turbine is to provide power, to drive the compressor. After the gases leaves the turbine they expand further in the exhaust nozzle, and are ejected into the atmosphere with a velocity greater than the flight velocity thereby producing thrust for propulsion.

Current turbojet engines operate with compressor pressure ratios between 6 and 16, and with turbine inlet temperatures of the order of 1200 K. The corresponding speed of the exhaust jet when propelling an aircraft at 900 km per hour (250 m/s) is of the order of 500 m/s.

Solution : 30

$$\text{Velocity of aircraft} = V_0 = \frac{850 \times 1000}{3600} = 236.11 \text{ m/s}$$

$$\text{AFR} = 80$$

$$\dot{m}_f = \frac{50}{80} = 0.625 \text{ kg/s}$$

Velocity of gases at exit from nozzle

$$= V_e = \sqrt{2C_p(\Delta h)\eta_n}$$

$$= \sqrt{2 \times 1005 \times 200 \times 0.9} = 601.5 \text{ m/s}$$

$$\text{Thrust} = T = \dot{m}_g V_e - \dot{m}_a V_0$$

$$= 50.625 \times 601.5 - 50 \times 236.11 = 18.645 \text{ KN}$$

$$\therefore \quad \text{Thrust Power } (TD) = TV_0 = 18.645 \times 236.11 = 4402.37 \text{ kW}$$

$$\text{Propulsive Power} = PP = \frac{1}{2}(\dot{m}_a + \dot{m}_f)V_e^2 - \frac{1}{2}\dot{m}_a V_0^2$$

$$= \frac{1}{2}(50.625) \times (601.5)^2 - \frac{1}{2} \times 50 \times (236.11)^2$$

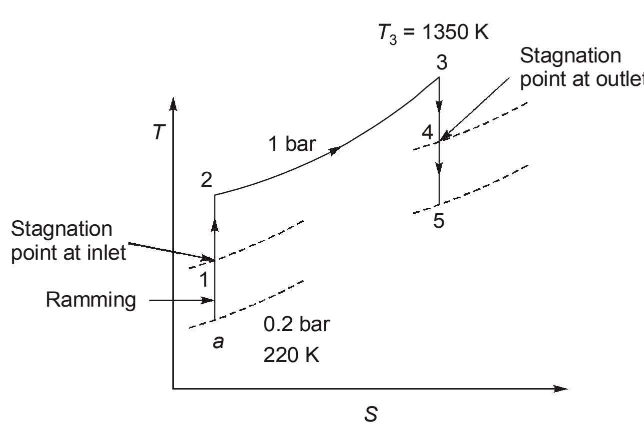
$$= 7.764 \text{ MW}$$

$$\text{Propulsive efficiency } h_p = \frac{TP}{PP} = \frac{4.402}{7.764} = 0.567 = 56.7\%$$

$$\text{Thermal efficiency} = \frac{PP}{\dot{m}_f \times CV} = \frac{7.72}{0.625 \times 40} = 0.31 = 31\%$$

$$\text{Overall efficiency} = \eta_{th} \times \eta_p = 0.176 = 17.6\%$$

Solution : 31



$$V_i = \text{flying speed} = 268 \text{ m/sec}$$

$$\therefore \quad T_1 = T_a + \frac{V_1^2}{2C_P} = 220 + \frac{268^2}{2 \times 1005}$$

$$T_1 = 255.73 \text{ K}$$

$$P_1 = P_a\left(\frac{T_1}{T_a}\right)^{\frac{\gamma}{\gamma-1}} = 0.2\left(\frac{255.73}{220}\right)^{\frac{1.4}{0.4}}$$

$$P_1 = 0.3387 \text{ bar}$$

$$\therefore \quad P_2 = P_3 = 1 \text{ bar}$$

$$\frac{T_2^{1.4}}{P_2^{0.4}} = \frac{T_4^{1.4}}{P_1^{0.4}}$$

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{0.4}{1.4}} = 255.73\left(\frac{1}{0.3387}\right)^{2/7}$$

$$T_2 = 348.436 \text{ K}$$

Compressor is run by turbine

$$m_a\, C_P\,(T_2 - T_1) = C_{P_g}\ m_a\,(1+f)\,(T_3 - T_4)$$

$$1.005(348.436 - 255.73) = 1.102\,(1+f)\,(1350 - T_4)$$

$$(1+f)\,(1350 - T_4) = 84.546 \qquad \text{...(ii)}$$

Heat added to the system

$$(1+f)\ m_a\ C_{P_g}\ T_3 - m_a\ C_{P_a}\ T_2 = m_a\, f\, C_V$$

$$(1+f)\ 1.104 \times 1350 - 1.005 \times 348.436 = f \times 43000$$

$$1490.4 + 1490.4\ f - 350.18 = 43000\ f$$

$$f = \frac{1140.22}{41509.6} = 0.02747 \text{ kg of fuel/kg of air}$$

Put f in equation (i) and get T_4

$$T_4 = 1267.7 \text{ K}$$

Thrust $\quad F = m_a\,(1+f)\,V_j - m_a\,V_i$

$$\text{Specific Thrust} = F/m_a = (1+f)\ V_j - V_i$$

$$= 1.02747 \times V_j - 268 \qquad \text{...(ii)}$$

Nozzle expansion $\quad \dfrac{T_3^{1.33}}{P_3^{0.33}} = \dfrac{T_4^{1.33}}{P_4^{0.33}}$

$$P_4 = 1\left(\frac{T_4}{T_3}\right)^{\frac{1.33}{0.33}} = 1\left(\frac{1267.7}{1350}\right)^{\frac{133}{33}} = 0.776 \text{ bar}$$

$$\therefore \quad P_5 = 0.2 \text{ bar}$$

$$\frac{P_4}{P_5} = \frac{0.776}{0.2} = 3.88$$

At critical ratio $\quad \dfrac{P_c}{P_4} = \left(\dfrac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} = 0.5404$

Hence nozzle is choked

$\therefore$ Critical pressure $\quad P_c = P_4 \times 0.5404$

$P_c = 0.41935$ bar

Critical temp. $\quad T_c = \left(\dfrac{2}{\gamma+1}\right) . T_4 = 1088.154$ K

get velocity $\quad V_j = \sqrt{\gamma R T_c} = \sqrt{1.33 \times 274 \times 1088.154} = 629.63$ m/sec

$$\left\{R = \frac{\gamma-1}{\gamma} \times C_{pg} = \frac{0.33}{1.33} \times 1102 = 273.43 \approx 274\right\}$$

Specific thrust from (ii) $= 1.02747 \times 629.63 - 268 = 378.93$ m/sec

Propulsive efficiency $= \dfrac{\left[m_a(1+f)V_j - V_i\right]V_i}{\frac{1}{2}\left[m_a(1+f)V_j^2 - m_a V_i^2\right]} = \dfrac{2V_i\left[(1+f)V_j - V_i\right]}{(1+f)V_j^2 - V_1^2}$

$$= \frac{2 \times 268\,(1.02707 \times 629.63 - 268)}{1.02747 \times 629.63^2 - 268^2} = 0.6054 = 60.54\%$$

■■■■