ACE

GATE | PSUs

MECHANICAL ENGINEERING

Thermal Engineering

Text Book: Theory with worked out Examples and Practice Questions

Thermal Engineering

(Solutions for Text Book Practice Questions)

Chapter 1 Basic Concepts

01. Ans: (d)

Sol: $$\frac{dT}{T} - \frac{V}{T}dP$$

$$= \frac{1}{T}dT - \frac{V}{T}dP \qquad \left(PV = RT, \frac{V}{T} = \frac{R}{P}\right)$$

$$= \frac{1}{T}dT - \frac{R}{P}dP$$

$$= MdT + NdP$$

$$M = \frac{1}{T}; N = -\frac{R}{P}$$

$$\frac{\partial M}{\partial P} = 0; \frac{\partial N}{\partial T} = 0$$

$$\therefore \frac{\partial M}{\partial P} = \frac{\partial N}{\partial T} \text{ hence it is a property}$$

02. Ans: (a)

Sol: Volume → Extensive property

Density → Intensive Property

Pressure → Point function

Work → Path function

Energy → Point function

03. Ans: (b)

Sol: A real gas obeys perfect gas law at very high temperature and low pressure.

04. Ans: (b)

Sol: $F + P = C + 2$

No. of components, $C = 2$

No. of phases, $P = 2$

$\therefore F + 2 = 2 + 2$

$\Rightarrow F = 2$

05. Ans: (d)

Sol: When molecular momentum of system becomes zero, the pressure reaches its absolute zero values.

06. Ans: (b)

Sol: Final equilibrium temperature can be calculated by using conservation of energy i.e., first law of thermodynamics.

07. Ans: (b)

Sol: Mole fraction of $N_2 = \frac{n_{N_2}}{\text{Total no. of moles}}$

$$0.3 = \frac{n_{N_2}}{1}$$

$$n_{N_2} = 0.3$$

$$m_{N_2} = n_{N_2} \times \text{molecular weight}$$

$$= 0.3 \times 28 = 8.4 \text{ kg}$$

Mass fraction of $N_2 = \frac{m_{N_2}}{\text{Total mass}}$

$$= \frac{8.4}{36} = 0.233$$

08. Ans: (d)

Sol: $m_{N_2} = n_{N_2} \times \text{(molar weight)} = 2 \times 28$

$= 56 \text{ kg}$

$m_{Co_2} = n_{Co_2} \times \text{(molecular weight)} = 6 \times 44$

$= 264 \text{ kg}$

$m_{N_2} + m_{Co_2} = 320 \text{ kg}$

$$\text{Mass fraction} = \frac{m_{Co_2}}{m_{Co_2} + m_{N_2}}$$

$$= \frac{264}{320} = 0.825$$

09. Ans: (a)

Sol: $m_{N_2} = n_{N_2} \times \text{(molar weight)}$

$= 2 \times 28 = 56 \text{ kg}$

$m_{CO_2} = n_{Co_2} \times \text{(molecular weight)}$

$= 4 \times 44 = 176 \text{ kg}$

$$R_{N_2} = \frac{\overline{R}}{\text{Molecular weight}} = \frac{8.314}{28}$$

$= 0.2969 \text{ kJ/kg.K}$

$$R_{CO_2} = \frac{\overline{R}}{\text{molecular weight}} = \frac{8.31}{44}$$

$= 0.1889 \text{ Kj/kg.K}$

$$R_{\text{mixure}} = \frac{m_{N_2} \times R_{N_2} + m_{CO_2} \times R_{CO_2}}{m_{N_2} + m_{CO_2}}$$

$$= \frac{56 \times 0.2969 + 176 \times 0.1889}{56 + 176}$$

$= 0.215 \text{ kJ/kg.K}$

10. Ans: (b)

Sol:

For N_2	**For CO_2**
$n_1 = 3$	$n_2 = 7$
$P_1 = 600 \text{ kPa}$	$P_2 = 200 \text{ kPa}$

$n = n_1 + n_2 = 10$

$P_f = 300 \text{ kPa}$

$$P_{N_2} = \left(\frac{n_1}{n_1 + n_2}\right) P_f = \left(\frac{3}{10}\right) \times 300$$

$= 90 \text{ kPa}$

11. Ans: (d)

Sol: $V = 80 \text{ L}$

$n = n_{N_2} + n_{CO_2}$

$$= \frac{5}{28} + \frac{5}{44}$$

$PV = n\overline{R}\,T$

$$\frac{P}{\overline{R}T} = \frac{n}{V} = \frac{\left(\frac{5}{28} + \frac{5}{44}\right)}{80}$$

$P_1V_1 = n_1 \overline{R}\,T$

$$\frac{P}{\overline{R}\,T} = \frac{n_1}{V_1} = \frac{\left(\frac{5}{28}\right)}{V_1} = \frac{\left(\frac{5}{28} + \frac{5}{44}\right)}{80}$$

$\Rightarrow V_1 = 48.88 \text{ L}$

12. Ans: (b)

Sol: For Argon:

$m = 3 \text{ kgs}$

Molar weight = 40

$\gamma = \frac{5}{3}$ (monoatomic)

$$(C_V)_{Ar} = \frac{\overline{R}}{M(\gamma-1)} = \frac{8.314}{40\left(\frac{5}{3}-1\right)}$$

$$= 0.311 \text{ kJ/kg.K}$$

For CO_2:

$m = 6$ kgs, Molar weight = 44 , $\gamma = \frac{4}{3}$

$$(C_V)_{CO_2} = \frac{\overline{R}}{M(\gamma-1)} = \frac{8.314}{44\left(\frac{4}{3}-1\right)}$$

$$= 0.566 \text{ kJ/ kg.K}$$

$$(C_V)_{mix} = \frac{m_{Ar} \times (C_V)_{Ar} + m_{CO_2} \times (C_V)_{CO_2}}{m_{Ar} + m_{CO_2}}$$

$$= \frac{(3 \times 0.31) + (6 \times 0.566)}{3+6}$$

$$= 0.4806 \text{ kJ/kgK}$$

$$Q_S = m \times (C_V)_{mix} \times (\Delta T)$$

$$= (3 + 6) \times 0.4806 \times (350 - 250)$$

$$= 432.6 \text{ kJ}$$

13. Ans: (b)

Sol: $P_1 = 1.2$ MPa, $P_2 = 0.2$ MPa

He = 30%, Ar = 70%

Adiabatic process, $\gamma = \frac{5}{3}$ (monatomic)

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

$$T_2 = 673 \times \left(\frac{0.2}{1.2}\right)^{\frac{\frac{5}{3}-1}{\frac{5}{3}}} = 328.7 \text{ K} = 55.7^0 \text{ C}$$

14. Ans: (d)

Sol: For He: $n_1 = 3$, $\gamma = \frac{5}{3}$

$$(C_P)_{He} = \frac{\gamma\overline{R}}{(\gamma-1)} = \frac{\frac{5}{3}\times 8.314}{\left(\frac{5}{3}-1\right)} = 20.78 \text{ kJ/kg.K}$$

For Ar:

$n_2 = 7$, $\gamma = \frac{5}{3}$

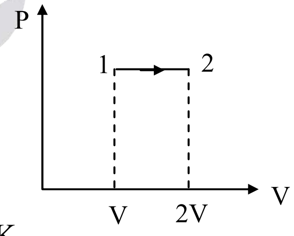
$$(C_P)_{Ar} = \frac{\gamma\overline{R}}{(\gamma-1)} = \frac{\frac{5}{3}\times 8.314}{\left(\frac{5}{3}-1\right)} = 20.78 \text{ kJ/kg.K}$$

$$(C_P)_{Mix} = \frac{n_{He}(C_P)_{He} + m_{Ar}(C_P)_{Ar}}{n_{He} + n_{Ar}}$$

$$= \frac{3 \times 20.79 + 7 \times 20.79}{3+7}$$

$$= 20.79 \text{ kJ/kg.K}$$

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$



$$T_2 = \frac{V_2}{V_1} \times T_1$$

$$= 2 \times 323 = 646 \text{ K}$$

$$Q_S = n \times (C_P)_{mix} \times (\Delta T)$$

$$= (3+7) \times 20.79 \times (646 - 323) = 67 \text{ MJ}$$

15. Ans: 2.67 cm of Hg

Sol: At ground

Balloon volume, $V_1 = \frac{4}{3}\pi r^3$

$P_1 = 72$ cm of Hg.

In the air, R = 3r

Balloon volume, $V_2 = 27\times\frac{4}{3}\pi r^3$

Temperature constant ⇒ Isothermal

$\Rightarrow$ **Process $P_1V_1 = P_2V_2$**

$\Rightarrow P_2 = 72\,r^3/27r^3 = 2.67$ cm of Hg

16. Ans: $P_1 > P_2$

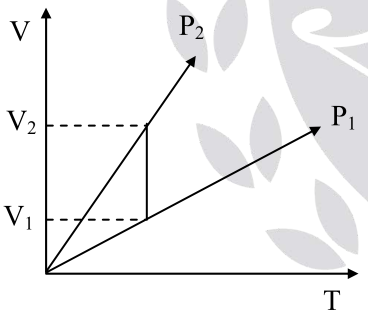
Sol: For isothermal process: T = c

$\Rightarrow P_1V_1 = P_2V_2$

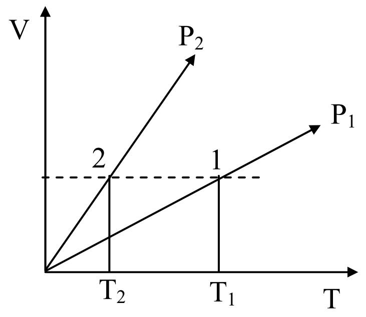
$$P_2 = P_1\left(\frac{V_1}{V_2}\right)$$

As per fig we can say $T_1 > T_2$

$\Rightarrow P_1 > P_2 ....\left(\frac{V_1}{V_2} < 1\right)$



(2) **For isochoric** : V = C



$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

$T_1 > T_2$

$$\therefore P_2 = \left(\frac{T_2}{T_1}\right)P_1$$

$\therefore P_2 < P_1$

17. Ans: (d)

Sol: LFP = Lower fixed point

UFP = upper fixed point

$$\frac{C - LFP}{UFP - LFP} = \frac{0-300}{100-300}$$

$$\frac{C-0}{100-0} = \frac{0-300}{100-300}$$

C = 150°C

18. Ans: 26.77°C

Sol: $t_A = a + bt_B + ct_B^2$

$t_A = 0°C$; $t_B = 0°C$

$t_A = 100°C$; $t_B = 100°C$

$t_A = 51°C$; $t_B = 50°C$

$0 = a + b\times 0 + c \times 0$

$\therefore$ a = 0

$$100 = 100b + 10^4\,c \times 1$$

$$\underline{51 = 50\,b + 2500\,c \times 2}$$

$$102 = 100\,b + 5000\,c$$

$$\underline{\_100 = \_\,100b + 10000\,c}$$

$$-5000\,c = 2$$

$$c = \frac{-2}{5000} = -4\times10^{-4}$$

$50\,b + 2500\,c = 51$

$50b + 2500 \times (-4\times10^{-4}) = 51$

$50\,b = 51 + 1$

$b = \frac{52}{50} = 1.04$

$\therefore\ t_A = 1.04\,t_B - 4\times10^{-4} t_B^2$

$t_B = 26°C$

$t_A = 1.04\times26 - 4\times10^{-4}\times26^2$

$= 27.04 - 0.2704$

$= 26.77°C$

Unless the constructional features of thermometer are given it is difficult to say which thermometer is correct.

19. Ans: 21.6°C

Sol: Given relation $t = a\,ln(K) + b$

K is 1.83 at ice point $\Rightarrow t = 0°C$

K is 6.78 at steam point $\Rightarrow t = 100°C$

As per given relation, $t = a\,ln(K) + b$

By condition 1 $\Rightarrow 0 = a\,ln\,(1.83) + b$

$0 = 0.60\,a + b$

By condition 2 $\Rightarrow 100 = a\,ln\,(6.78) + b$

$100 = a\,1.914 + b \Rightarrow a = 76.10$

$b = -45.66$

$\Rightarrow$ By putting value of a & b

$t = 76.10\,ln\,K - 45.66$

(K = 2.42 given)

$\Rightarrow t = 21.6°C$

20. Ans: 550°N, –50°C

Sol: Freezing point of ice = 0°C = 100° N

Boiling point = 100°C = 400°N

Let new scale be given as

$N = a\,t + b$

$100 = a\,(0) + b$

$\therefore\ b = 100$

$400 = 100\,a + b$

$\therefore\ a = 3$

when t = 150°C

$N = 3(150) + 100$

$N = 550°\,N$

The new scale N and Celsius will be same if

$t = 3\,t + 100$

$-2t = 100$

$\therefore\ t = -50°C$

21. Ans: (b, d)

Sol: Any gas can have like ideal gas under low pressure and high temperature.

22. Ans: (a, b, d)

Sol: Mdx + Ndy

If $\frac{\partial M}{\partial y} = \frac{\partial N}{\partial x}$ then the function is property

(a) $M = \frac{1}{T},\quad N = \frac{P}{T} = \frac{R}{v}$

$\frac{\partial M}{\partial v} = \frac{\partial N}{\partial T} = 0$ hence it is property.

(b) $M = \frac{1}{T}, \quad N = \frac{T}{P} = \frac{v}{R}$

$\frac{\partial M}{\partial v} = \frac{\partial N}{\partial T} = 0$ hence it is property.

(c) $M = \frac{1}{P}, \quad N = \frac{v}{T} = \frac{R}{P}$

$\frac{\partial M}{\partial v} \neq \frac{\partial N}{\partial P}$ hence it is not property.

(d) $M = \frac{1}{P}, \quad N = \frac{R}{v}$

$\frac{\partial M}{\partial v} = \frac{\partial N}{\partial P} = 0$ hence it is property.

23. Ans: (b, c, d)

Sol: Specific enthalpy, pressure and density are independent of mass hence they are intensive properties.

24. Ans: (b, c)

Sol: Mass fraction of $O_2 = \frac{3}{3+5+12} = 0.15$

Moles of $O_2 = \frac{3000}{32} = 93.75$

Moles of $N_2 = \frac{5000}{28} = 178.57$

Moles of $CH_4 = \frac{12000}{16} = 750$

$\therefore$ Mole fraction of O_2

$= \frac{93.75}{93.75 + 178.57 + 750}$

$= 0.092$

25. Ans: (a, b, d)

Sol: The correct statement for concept of continuum

- A continuum is a body that can be continually subdivided into infinitesimal elements with properties being those of the bulk material.
- concept of continuum losses its validity when mean free path of molecules approaches dimension of vessels
- In high rarefied gases, concept of continuum losses its validity.
- For gases continuum is not always valid

26. Ans: (a, b, c)

Sol: The classification of pressure thermometers are

- vapour pressure thermometer
- liquid filled thermometer
- gas filled thermometer

27. Ans: (a, b, d)

Sol: Boiling temperature, Molality and Refractive index are independent of mass hence they are intensive properties.

Chapter 2

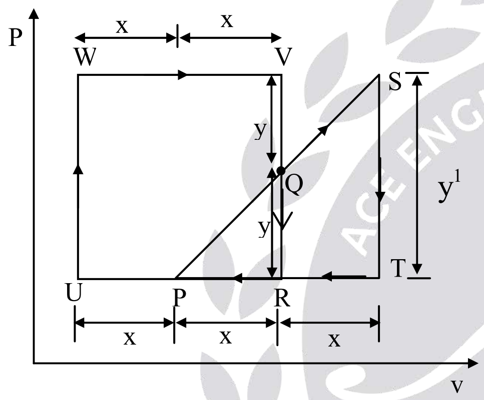
Work and Heat

01. Ans: (c)

Sol: Heat engine cycles as shown in fig

VQ = QR, PQ = QS,

UP = PR = RT



Work interaction for ‘WVUR’= 48Nm

Area WVUR = 2x ×2y = 48

$\Rightarrow xy = 12$

From similar Δ^{les} PQR and PST

$$\frac{QR}{PR} = \frac{ST}{PT}$$

$$\frac{y}{x} = \frac{y^1}{2x} \Rightarrow y^1 = 2y$$

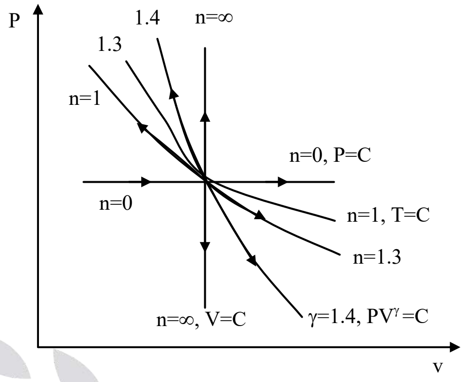
Work interaction for Δ^{le} ‘PST’

$$\frac{1}{2}(2x)y^1 = \frac{1}{2}(2x)(2y) = 2xy$$

$$= 2 \times 12 = 24 \text{ Nm}$$

02. Ans: (d)

Sol:



03. Ans: (b)

Sol:

Process	**1**	**2**	**3**	**4**
dQ(kJ)	300	0	–100	0
dW(kJ)	300	250	–100	–250

Heat supplied Q_S = 300 kJ

Work of expansion, $W_E = 300 + 250 = 550$ kJ

Work of compression, $W_C = 100+250 = 350$ kJ

$W_{net} = W_E - W_C = 550 - 350 = 200$ kJ

$$\eta_{thermal} = \frac{W_{net}}{\text{Heat supplied}} = 0.67$$

$$\text{Work ratio} = \frac{W_{net}}{W_E} = \frac{200}{550} = 0.36$$

04. Ans: (c)

Sol: (a) W.D in polytropic process

$$= \frac{(P_1V_1 - P_2V_2)}{(n-1)}$$

(b) W.D in steady flow process $= -\int v\,dP$

(c) Heat transfer in reversible adiabatic process = zero

(d) W.D in an isentropic process

$$= \frac{P_1V_1 - P_2V_2}{(\gamma - 1)}$$

05. Ans: (d)

Sol: Given

For isothermal process

$$P_1V_1 = P_2V_2$$

$$\Rightarrow P_1V_1 = \frac{P_1}{10} \times 0.55$$

$$\Rightarrow V_1 = 0.055 \text{ m}^3$$

For adiabatic process

$$P_1 V_1^{\gamma} = P_2 V_2^{\gamma}$$

$$\Rightarrow P_1 V_1^{1.4} = \frac{P_1}{10} \times V_2^{1.4}$$

$$\Rightarrow V_2^{1.4} = 10 \times (0.055)^{1.4} \Rightarrow V_2 = 0.284 \text{ m}^3$$

06. Ans: (b)

Sol:

- Adiabatic → $n = \frac{c_p}{c_v}$
- Isothermal → $n = 1$
- Constant pressure → $n = 0$
- Constant volume → $n = \infty$

07. Ans: (d)

Sol: No. of degrees of freedom in diatomic molecule = 5

No. of degrees of freedom in monoatomic molecule = 3

No. of degrees of freedom in Triatomic molecule = 6 or 7

08. Ans: (a)

Sol: The slope of log P – log V graph for a gas for isothermal change is m_1 & for adiabatic changes are m_2 if gas is diatomic gas

For isothermal process, PV = C

$$\log(P) + \log(V) = \log(C)$$

$$\log(P) = \log(C) - \log(V)$$

Compare it with y = C + mx

$$m_1 = -1$$

For adiabatic process

$$PV^{\gamma} = C$$

$$\Rightarrow \log P + \gamma \log V = \log C$$

$$\Rightarrow \log(V) = \log C - \gamma \log V$$

Compare with y = C + mx

$$m_2 = -\gamma$$

$$\Rightarrow m_1 < m_2$$

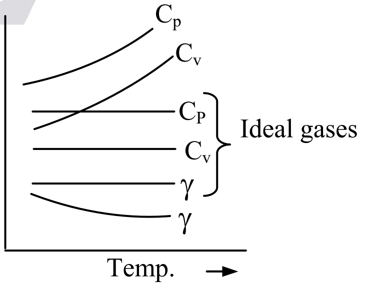
09. Ans: (d)

Sol: The ratio of C_p/C_v for a gas with n degrees of freedom is equal to $1 + \frac{2}{n}$

10. Ans: (c)

Sol: C_p ; C_V ; γ ; values are constant for ideal gases

C_p ; C_v values increase with temperature for Real gases.



Where as "γ" value decreases with temperature.

11. Ans: (b)

Sol: P = 320W

In 30 days the refrigeration runs is

$$= 30 \times \frac{1}{4} = 7.5 \text{ days}$$

So total consumption of a month in Watt-hr is

$$= 320 \times 7.5 \times 24 = 57600 \text{ W-hr}$$

$$= 57.6 \text{ kWhr}$$

So the electricity cost per month

$$= 57.6 \times 0.09 = \text{Rs. } 5.184$$

12. Ans: (d)

Sol: Work done = Area enclosed in Pv diagram

W = Area of ΔADC + Area of ΔABC

$$\text{Area of } \Delta ADC = \frac{1}{2} \times (6-2) \times (4-1)$$

$$= 6 \text{ bar–m}^3 = 600 \text{ kN-m}$$

$$\text{Area of } \Delta ABC = \frac{1}{2} \times (6-2) \times (6-4)$$

$$= 400 \text{ kN-m}$$

$\therefore$ W = (600 + 400) kN-m = 1000 kN-m

13. Ans: (d) &

14. Ans: (c)

Sol: $P_1 = 100 + 101.325 = 201.325$ kPa

$T_1 = 288$ K ,

$V_1 = 2500$ C.C

$$m = \frac{P_1 V_1}{R\ T_1} = \frac{201.325 \times 10^3 \times 2500 \times 10^{-6}}{287 \times 288}$$

$$= 6.089 \times 10^{-3}\ kg$$

As volume is constant, dW = 0

$\therefore$ dQ = dU = m C_V dT

$$= 6.089 \times 10^{-3} \times 0.718 \times 10^3 (15-5)$$

$$= 43.7 \text{ J}$$

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

P_2 = Pressure on day of play $= P_1 \times \frac{T_2}{T_1}$

$$= 201.325 \times \frac{278}{288}$$

= 194.33 kPa (absolute)

Gauge pressure on day of play

= 194.33 – 101.325

= 93 kPa = 0.93 bar

P_1 = Pressure to which it must be inflated

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

$$\frac{P_1}{288} = \frac{201.325}{278}$$

$$P_1 = 201.325 \times \frac{288}{278} = 208.56 \text{ kPa.}$$

Gauge pressure to which it must be inflated on previous day

= 208.56 – 101.3

= 107.24 kPa = 1.07 bar

15. Ans: (a)

Sol: Work done in isothermal process

$$= P_1 V_1 \ell n \frac{V_2}{V_1}$$

$$= 500 \times 0.8 \times \ell n \left(\frac{0.1}{0.8} \right) = -831.77 \text{ kJ}$$

16. Ans: 251.62 kJ

Sol: $m = 1.5$ kg, $P_1 = 0.1$ MPa,

$\rho_1 = 1.16$ kg/m^3, $P_2 = 0.7$ MPa

$$W = P_1V_1\ \ell n\left(\frac{V_2}{V_1}\right) = P_1V_1\ell n\left(\frac{P_2}{P_1}\right)$$

$$V_1 = \frac{m}{\rho_1} = 1.293\,m^3$$

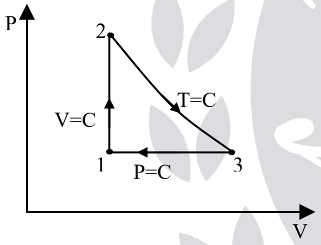
$$W = 0.1\times1000\times1.293\times\ell n\left(\frac{0.1}{0.7}\right)$$

$$= -251.62\text{ kJ}$$

∴ Work done by piston is 251.62 kJ

17. Ans: 130.16 kJ/kg

Sol:



1 – 2 Process

$T_1 = 350$ K

$$\frac{T_2}{T_1} = 3 = \frac{P_2}{P_1}$$

$T_2 = 3 \times 350 = 1050$ K

${}_1w_2 = 0$

2 – 3 Process

$${}_2Q_3 = {}_2w_3 = RT_2\ell n\frac{P_2}{P_3}$$

$$= RT_2\ell n3$$

$$= R(1050\ell n3) = 1153.54R\frac{kJ}{kg}$$

1 – 3 Process

$P = C$

$$\frac{V_3}{T_3} = \frac{V_1}{T_1}; \frac{V_3}{V_1} = \frac{T_3}{T_1} = \frac{T_2}{T_1} = 3$$

As $T_3 = T_2$

$${}_3w_3 = P(V_1 - V_3) = RT_3\left(\frac{T_1}{T_3} - 1\right)$$

$$= 1050R\left(\frac{1}{3} - 1\right)$$

$$= -700\text{ R kJ/kg}$$

$w_{net} = {}_1w_2 + {}_2w_3 + {}_3w_1$

$= 0 + 1153.54\text{ R} - 700\text{ R}$

$= 453.54$ R kJ/kg

$= 453.54 \times 0.287 = 130.16$ kJ/kg

18. Ans: 2356.2 kJ/kg

Sol: $(1\text{cm})_x = 300$ kPa

$(1\text{ cm})_y = 0.1$ m^3/kg

1 cm^2 Area = $(1\text{cm})_x \times (1\text{cm})_y$

$= 300 \times 0.1 = 30$ kJ/kg

Area on P-V diagram = $A = \frac{\pi}{4}D^2$

$$= \frac{\pi}{4}\times10^2$$

$= 78.5$ cm^2

Net work = 78.5 cm^2

$= 78.5 \times 30 = 2355$ kJ/kg

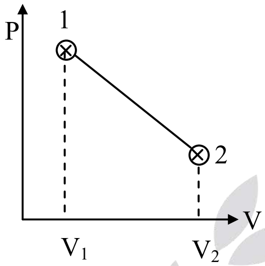
19. Ans: 29.7 kJ

Sol: $A = 0.12\ m^2$

$P_1 = 1.5\ MPa = 1500\ kPa$

$P_2 = 0.15\ MPa = 150\ kPa$

$l = 0.3\ m$



$${}_1W_2 = \frac{1}{2}(P_1 + P_2)V_s,\ V_s = V_2 - V_1$$

$$\Rightarrow {}_1W_2 = \frac{1}{2} \times (1500 + 150) \times (0.036)$$

$$(\because V_s = Al = 0.12 \times 0.3 = 0.036\ m^3)$$

$$\Rightarrow {}_1W_2 = 29.7\ kJ$$

20. Ans: 1742 kJ

Sol: Given $\left[P + \frac{a}{V^2}\right](V - b) = mRT$

$$P + \frac{a}{V^2} = \frac{mRT}{(V - b)}$$

$$P = \frac{mRT}{(V - b)} - \frac{a}{V^2}$$

$$W.D = \int_{V_1}^{V_2} P\,dV = \int_{V_1}^{V_2} \left[\frac{mRT}{(V - b)} - \frac{a}{V^2}\right] dV$$

$$W.D = mRT\,\ell n[V - b]_{V_1}^{V_2} - a\left[\frac{V^{-2+1}}{-2+1}\right]_{V_1}^{V_2}$$

$$W.D = mRT\ell n\left(\frac{V_2 - b}{V_1 - b}\right) + a\left[\frac{1}{V_2} - \frac{1}{V_1}\right]$$

$m = 10\ kg$, $V_1 = 1\ m^3$,

$V_2 = 10\ m^3$, $T = 293\ K$,

$a = 15.7 \times 10^4\ Nm^4 = 157\ kNm^4$

$b = 1.07 \times 10^{-2}$, $R = 0.278\ kJ/kg.K$

$$W.D = (10)(0.278)(293)$$

$$ln\left(\frac{10 - (1.07 \times 10^{-2})}{1 - (1.07 \times 10^{-2})}\right) + 157\left[\frac{1}{10} - 1\right]$$

$$W.D = 1742.14\ kJ$$

21. Ans: 686.62 kJ

Sol: $P \propto D^2$

$P_1 = KD_1^2$

$P_2 = KD_2^2$

$P_1 = 100\ kPa$, $D_1 = 1\ m$

$\therefore K = 100\ kPa/m^2$

$P_2 = 350\ kPa$,

$D_2 = ?$

$$\frac{P_1}{P_2} = \frac{D_1^2}{D_2^2}$$

$$D_2 = D_1\sqrt{\frac{P_2}{P_1}}$$

$$= 1\sqrt{\frac{350}{100}} = 1.8708\,m$$

Volume of balloon

$$V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi \times \left(\frac{D}{2}\right)^3$$

$$= \frac{4}{3} \times \pi \times \frac{D^3}{8}$$

$$V = \frac{\pi}{6}D^3$$

$$dV = 3\times\frac{\pi}{6}D^2 dD$$

$$= \frac{\pi}{2}D^2 dD$$

$${}_1W_2 = \int_{D_1}^{D_2} PdV = \int_{D_1}^{D_2} KD^2 \times \frac{\pi}{2}D^2 dD$$

$$= \int_{D_1}^{D_2} \frac{K}{2}\pi D^4 dD$$

$$= \int_{1}^{1.8708} \frac{100}{2}\times\pi\times D^4 dD$$

$$= 50\pi \left.\frac{D^5}{5}\right|_1^{1.8708}$$

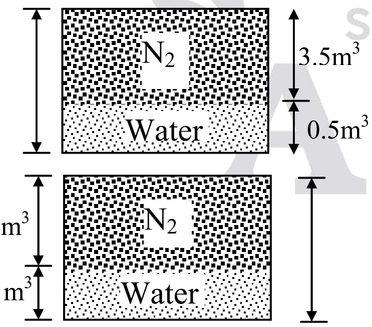
$${}_1w_2 = 10\pi\left[1.8708^5 - 1^5\right]$$

$$= 10\pi\left[22.9159 - 1\right] = 688.16\,\text{kJ}$$

22. Ans: 116.67 kPa, 54.42 kJ

Sol: Given, $m_w = 500$ kg

Total tank volume, V= 4 m^3



$P_1 = 100$ kPa

$m_w = 500$ kg, $\rho_w = 1000$ kg/m^3

For state-1, $V = \frac{500}{1000} = 0.5m^3$

For state-2, $m_w = 1000$ kg, V = 1 m^3

For state 1 'N_2':

$P_1 = 100$ kPa

V_1 = Total volume – vol. of water

$= 4 - 0.5 = 3.5\ m^3$

For state 2 ('N_2'):

V_2 = Total volume – vol. of water

$= 4 - 1 = 3\ m^3$

Condition: Isothermal process

⇒ From eq^n $P_1V_1 = P_2V_2$

$$\Rightarrow P_2 = \frac{P_1V_1}{V_2} = \frac{100\times3.5}{3}$$

$$\Rightarrow P_2 = 116.67\ \text{kPa}$$

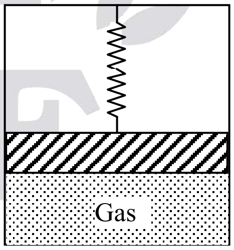
$${}_1W_2 = P_1V_1 ln\left(\frac{V_2}{V_1}\right) = 100\times3.53\times ln\left(\frac{3}{3.5}\right)$$

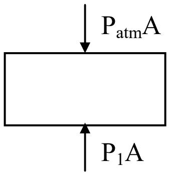
$$\Rightarrow W = -54.42\ \text{kJ}$$

Here '–ve' sign indicates compression of N_2 so system volume decreases

23. Ans: 320 kPa, 13 kJ

Sol:





$V_1 = 0.05\ m^3$,

$P_1 = 200$ kPa,

$A_p = 0.25\ m^2$,

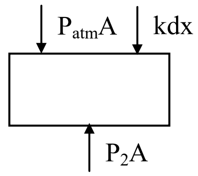
Spring constant, k = 150 kN/m

$V_2 = 2V_1 = 2\times0.05 = 0.1\ m^3$

$$dx = \frac{V_2 - V_1}{A} = \frac{0.1 - 0.05}{0.25} = 0.2\,\text{m}$$

$P_1A = P_{atm}A$

$P_1 = P_{atm}$



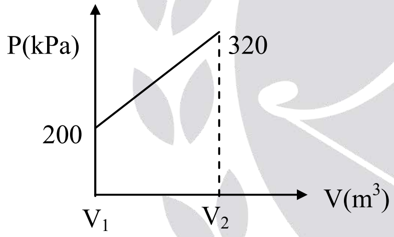
Final force = Initial force + spring force

$P_2A = P_1A + kdx$

$$P_2 = P_1 + k.\frac{dx}{A}$$

$$= 200 + 150 \times \frac{(0.2)}{0.25}$$

$= 200 + 120 = 320$ kPa



$$\text{Work done} = \frac{1}{2}(320 + 200) \times 0.05 = 13\text{kJ}$$

24. Ans: 2.5 kJ

Sol: Given $P_a = 0.1$ MPa $= 100$ kPa

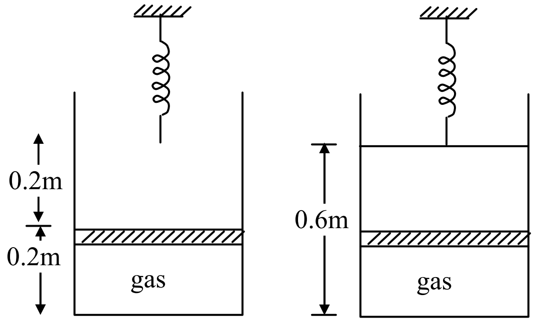
$V_1 = 0.01\text{m}^3$;

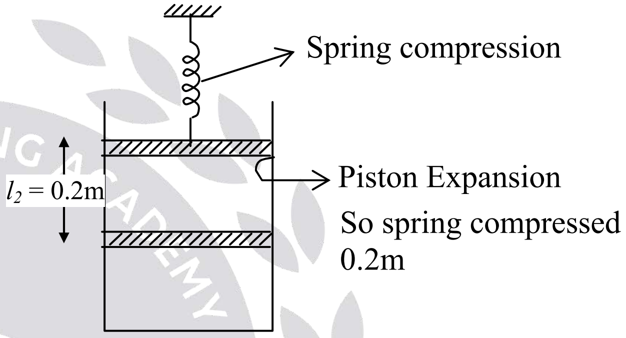
$A_1 = 0.05\text{ m}^3$

$$\Rightarrow l_1 = \frac{V_1}{A_1} = \frac{0.01}{0.05}$$

$\Rightarrow l_1 = 0.2$ m

$V_2 = 3V_1$





Find: Total W.D

Here rigid cylinder so area will be same

$Al_2 = 3\ Al_1$

$l_2 = 3l_1$

$\Rightarrow \quad l_2 = 0.6$ m

$\Rightarrow \quad V_2 = 0.03\text{ m}^3$

Total work = [work of gas + (work of spring due to expansion by heating)]

(Due to expansion of piston, spring is compressed)

$$= PdV + \frac{1}{2}Kx^2$$

$$= P(V_2 - V_1) + \frac{1}{2}(25)(0.2)^2$$

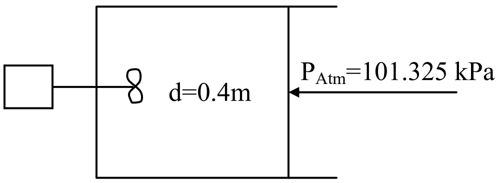
[$\because$ constant pressure process]

$$= 100\,(0.03 - 0.01) + \frac{1}{2}(0.2)^2(25)$$

Total work = 2.5 kJ

25. Ans: 0.079 N-m, 6.95 W

Sol:



$d = 0.4$ m , $N = 840$ rpm

time = 600 sec

$W = 2$ kJ , $l = 0.485$ m,

W_{Net} = Piston expansion work – $W_{Stirrer}$

$$2 = PdV - W_s$$

$$2 = (101.325)\,Al - W_S$$

$$2 = (101.325)\left(\frac{\pi}{4}(0.4)^2 \times 0.485\right) - W_S$$

$$W_S = 4.175 \text{ kJ}$$

$$\Rightarrow \text{Power} = \frac{W_S}{\text{Time}} = \frac{4.175}{600}$$

$$= 6.95 \times 10^{-3} \text{ kW} = 6.95 \text{ W}$$

$$\text{Now, } P_S = \frac{2\pi NT}{60}$$

$$\Rightarrow T = \frac{60P_S}{2\pi N} = \frac{60(6.95)}{2\times 3.14\times 840} = 0.079 \text{ Nm}$$

26. Ans: (a, c)

Sol: Work done $= nRT\,\ell n\left(\frac{V_2}{V_1}\right)$

$$= 3\times 8.314\times 300\ \ell n\left(\frac{1}{2}\right)$$

$$= -5186.54 \approx -5188 \text{ kJ}$$

For isothermal process,

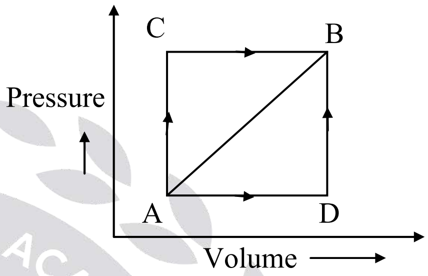
$Q = W$

$Q = -5188$ kJ

Chapter 3 First Law of Thermodynamics

01. Ans: (c)

Sol:



Along A – B – C:

$Q_{A-B} - W_{A-B} = U_{A-B}$

$180 - 130 = U_B - U_A$

$U_B - U_A = 50$ kJ

Along A – D – B:

$Q_{A-B} - W_{A-B} = U_{A-B}$

$Q_{A-B} = 50 + 40 = 90$ kJ

02. Ans: –200 kJ

Sol: For 1–2 process

${}_1Q_2 - {}_1W_2 = {}_1U_2$

$\Rightarrow 100 - 100 = U_2 - U_1$

$\Rightarrow U_2 = U_1$

For 2–3 process

${}_2Q_3 - {}_2W_3 = {}_2U_3$

$\Rightarrow -150 - {}_2W_3 = U_3 - U_2 = U_3 - U_1 = 200$

${}_2W_3 = -350$ kJ

For 3 – 4 process

$_3Q_4 - {}_3W_4 = {}_3U_4$

$_3U_4 = (U_4 - U_3) = (U_4 - U_1) - (U_3 - U_1)$

$= -(U_1 - U_4) - (U_3 - U_1)$

$= -50 - 200 = -250$

$_3Q_4 = {}_3U_4 - 250$ ……… (1)

For 4 – 1 Process

$_4Q_1 - {}_4W_1 = {}_4U_1 = U_1 - U_4$

$_4Q_1 - 300 = 50$

$_4Q_1 = 350$ kJ

$\Sigma Q = {}_1Q_2 + {}_2Q_3 - {}_3Q_4 + {}_4Q_1$

$= 100 - 150 - 500 + 350 = -200$ kJ

$(\because \Sigma Q = \Sigma W)$

$\Sigma W = 100 - 350 - 250 + 300 = -200$ kJ

03. Ans: (c)

Sol: (a) $dW = 0$ (Rigid)

$dQ = -ve$

$dU = -ve$

$dQ - dW = dU$

$dU = -ve$

(b) $dQ = 0$ (Insulated)

$dW = +ve$ (Expansion)

$\therefore dQ - dW = dU$

$0 - dW = dU$

$dU = -ve$

(c) $dW = 0$ (Free expansion)

$dQ = 0$ (Insulated)

$\Rightarrow dU = 0$

(d) $dW = -ve$

$dQ = 0$ (Adiabatic)

$dU = +ve$

04. Ans: (e)

Sol: m = 60 kg , P = 200 kPa

T = 25°C , $\dfrac{dQ}{dt} = 0.8$ kW

t = 30 min = 1800 sec

Well sealed = control mass

(Non flow process)

$dQ - dW = dU$

$\dfrac{dQ}{dt} \times t - \dfrac{dW}{dt} \times t = mC_v dT$

$1800[0.8 - (-0.12)] = 60(0.718)(T - 25)$

$T = 63.4^0C$

05. Ans (d)

Sol: Q = 2000 W

t = 15 min = 900 sec

m = 75 kg

Well sealed = control mass (Non flow process)

$dQ - dW = dU$

$\dfrac{dQ}{dt} \times t - \dfrac{dW}{dt} \times t = mC_v dT$

$t\left(\dfrac{dQ}{dt} - \dfrac{dW}{dt}\right) = mC_V dT$

$900\,[0 - (-2)] = 75(0.718)dT$

$dT = 33.42°C$

06. Ans: (c)

Sol: $P_1 = -0.25$ kW (– ve sign indicates it is a power consuming device)

$P_2 = -\ 0.12$ kW

$P_3 = -1$ kW

$P_4 = -\ 0.05$ kW

Temperature = constant

(Isothermal process)

$dQ = dW \quad (\because dU = 0)$

$dQ = -(0.25 + 0.12 + 1 + 0.05) \times 3600$

$= -5112$ kJ/hr

07. (i) Ans: (b), (ii) Ans: (c)

Sol:

(ii) Ideal gas stored in Rigid insulated Tank.

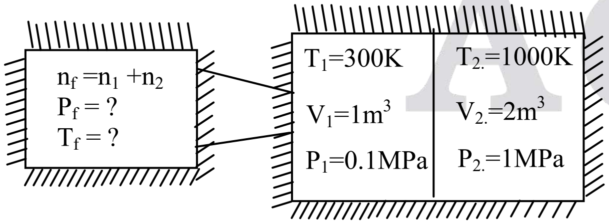
Total volume of Tank $V_f = 3m^3$

State : 1

Tank has two compartments.

State : 2

Partition between two compartments Ruptured



$$PV = mRT$$

$$\Rightarrow PV = m\frac{\overline{R}T}{M}\left(\because R = \overline{R}/M\right)$$

$$\Rightarrow PV = n\overline{R}T\left(\because n = \frac{m}{M}\right)$$

By equation $PV = n\overline{R}T$

$$= P_1V_1 = n_1\overline{R}T_1$$

$$\Rightarrow n_1 = \frac{P_1V_1}{\overline{R}T_1} = \frac{0.1\text{MPa}\times 1\text{m}^3}{8.314\times 300\text{K}}$$

$$= \frac{0.1\times 10^3\,\text{kPa}\times 1\text{m}^3}{8.314\times 300}$$

$$\Rightarrow n_1 = 0.040 \text{ moles}$$

$$\text{For } n_2 = \frac{P_2V_2}{\overline{R}T_2} = \frac{1\times 10^3\times 2}{8.314\times 1000}$$

$= 0.24$ Moles

$n_f = n_1 + n_2 = 0.04 + 0.24 = 0.28$ Moles

$V_f = V_1 + V_2 = 3m^3$

Here rigid & Insulated tank given

$\Rightarrow dQ = 0, \quad dW = 0$

$(\because \text{Rigid} \Rightarrow V = C \Rightarrow dW = 0)$

$\Rightarrow$ By 1st law

$dQ - dW = dU = C_VdT = 0$

Here $dU_1 + dU_2 = 0$

$$\Rightarrow n_1C_VdT + n_2C_VdT = 0$$

$$\Rightarrow n_1C_V(T_f - T_1) + n_2C_v(T_f - T_2) = 0$$

$$0.040C_V(T_f - 300) + 0.24C_V(T_f - 1000) = 0$$

$$\Rightarrow C_V(0.28T_f - 241.2) = 0$$

$\Rightarrow T_f \approx 900$K

Again

$\Rightarrow \quad P_fV_f = n_f\overline{R}\,T_f$

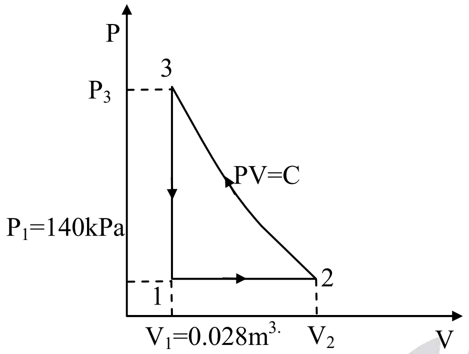
$$\Rightarrow \quad P_f = \frac{n_f\overline{R}T_f}{V_f} = \frac{0.28(8.314)(900)}{3}$$

$= 700$ kPa

$\Rightarrow \quad P_f = 0.7$MPa

08. (i) Ans: (c) , (ii) Ans: (b) , (iii) Ans: (b)

Sol:



Given

Process 1→ 2: (P = C),

$P_1 = 1.4$ bar,

$V_1 = 0.028\ m^3$,

$W_{1-2} = 10.5kJ$

Process 2 – 3: (PV = C),

$U_3 = U_2$

Process 3 – 1: (V = C),

$U_1 - U_3 = -26.4$ kJ

Process 1 – 2: (Constant pressure)

$\Rightarrow\ Q_{1-2} - W_{1-2} = U_{1-2}$

Given $\ {}_1W_2 = 10.5kJ = P(V_2 - V_1)$

$W_{1-2} = P_1(V_2 - V_1)$

$\Rightarrow\ 10.5 = 140(V_2 - 0.028)$

$\Rightarrow\ V_2 = 0.103m^3$

$U_3 = U_2\ \&\ U_1 - U_3 = -26.4kJ$

$\Rightarrow\ U_1 - U_2 = -26.4kJ$

$\Rightarrow\ U_2 - U_1 = 26.4$ kJ.

$\Rightarrow\ {}_1Q_2 = {}_1U_2 + {}_1W_2$

$\Rightarrow\ {}_1Q_2 = 26.4 + 10.5$

$\Rightarrow\ {}_1Q_2 = 36.9$ kJ

Process 2 – 3:(Isothermal Process)

$\Rightarrow\ Q_{2\text{-}3} - W_{2\text{-}3} = U_{2\text{-}3}$

Hence $T = C \Rightarrow {}_2U_3 = 0$

$$\Rightarrow Q_{2\text{-}3} = W_{2\text{-}3} = P_2V_2\ln\frac{V_3}{V_2}$$

$$= 140\times0.103\ln\left(\frac{0.028}{0.103}\right)$$

$\Rightarrow\ {}_2W_3 = -18.79$ kJ

Process 3 – 1:(constant volume)

${}_3W_1 = 0$

$\Rightarrow\ dQ - dW = dU$

$\Rightarrow\ {}_3Q_1 = {}_3U_1 = -26.4$

$\Rightarrow\ {}_3Q_1 = -26.4$ kJ

For checking answer

$\Sigma Q = {}_1Q_2 + {}_2Q_2 + {}_3Q_1$

$\Sigma Q = -8.28$ kJ

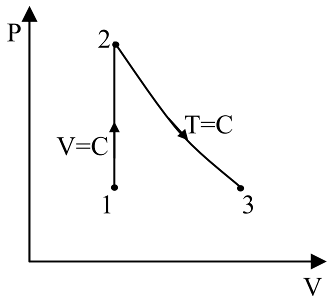
$\Sigma W = {}_1W_2 + {}_2W_3 + {}_3W_1$

$\Rightarrow\ \Sigma W = -8.28kJ$

$\Rightarrow\ \Sigma Q = \Sigma W$ (First law proved)

09. Ans: 69.3 kJ, 131.831 kJ

Sol:



Air :

$P_1 = 100$ kPa

$T_1 = 300$ K

$V_1 = 0.75\ m^3$

$T_2 = 400$ K

1 – 2 Process V = C

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

$$P_2 = \frac{T_2}{T_1} \times P_1 = \frac{400}{300} \times 100 = 133.33\text{kPa}$$

$T_3 = 400\ K = T_2$

$V_3 = 1.5\ m^3$

${}_1W_2 = 0\ (\because\ V = C)$

$$m = \frac{P_1V_1}{RT_1} = \frac{100 \times 0.75}{0.287 \times 300} = 0.871\text{kg}$$

${}_1Q_2 = mc_v(T_2 – T_1)$

$= 0.871 \times 0.718\ (400–300) = 62.54$ kJ

2 – 3 Process T = C

$P_2V_2 = P_3V_3$

$$P_3 = P_2 \times \frac{V_2}{V_3} = 133.33 \times \frac{0.75}{1.5} = 66.67\,\text{kPa}$$

$${}_2W_3 = {}_2Q_3 = P_2V_2 \ell n \frac{V_3}{V_2}$$

$$= 133.33 \times 0.75 \ell n \frac{1.5}{0.75} = 69.313\,\text{kJ}$$

${}_1W_3 = {}_1W_2 + {}_2W_3 = 0 + 69.313 = 69.313$ kJ

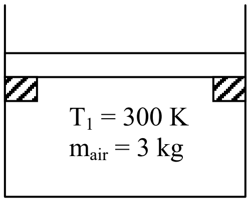
${}_1Q_3 = {}_1Q_2 + {}_2Q_3$

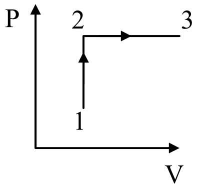
$= 62.54 + 69.313 = 131.853$ kJ

10. Ans: 516 kJ, 2454.6 kJ

Sol: $m_{air} = 3$ kg, $P_1 = 200$ kPa,

$T_1 = 27°C = 300$ K, $P_2 = 400$ kPa





1 – 2 (V = C)

$$\frac{200}{300} = \frac{400}{T_2}$$

$T_2 = 600$ K

$P_1V_1 = mRT_1$

$$V_1 = \frac{3 \times 0.287 \times 300}{200} = 1.2915\,m^3$$

$V_1 = V_2 = 1.2915\ m^3$,

$V_3 = 2V_2 = 2.583\ m^3$

2 – 3 (P = C)

$$\frac{V_3}{V_2} = \frac{T_3}{T_2}$$

$$2 = \frac{T_3}{600}$$

$T_3 = 1200$ K

Work done = 0 + P × $(V_3 – V_2)$

= 400 × 1.2915 = 516.6 kJ

${}_1Q_2 = mc_v\ (T_2 – T_1)$

= 3 × 0.717 × (600–30)

= 645.3 kJ

${}_2Q_3 = {}_2W_3 + {}_2U_3 = m\ c_p(T_3 – T_2)$

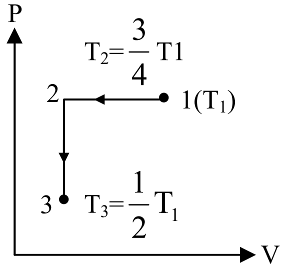
= 3 × 1.005 (1200–600)

= 1809 kJ

Total heat transfer = 645.3 + 1809 = 2454.3

11. (i) Ans: (d) , (ii) Ans: (a) , (iii) Ans: (d)

Sol:



Process 1 – 2: (P = C)

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

$$\therefore \frac{V_2}{V_1} = \frac{T_2}{T_1} = \frac{\frac{3}{4}T_1}{T_1} = \frac{3}{4} = 0.75$$

$${}_1Q_2 - {}_1W_2 = {}_1U_2$$

$${}_1Q_2 - P(V_2 - V_1) = (U_2 - U_1)$$

$$\therefore {}_1Q_2 = C_V(T_2 - T_1) + P(V_2 - V_1)$$

$$= C_VT_1\left(\frac{T_2}{T_1} - 1\right) + PV_1\left(\frac{V_2}{V_1} - 1\right)$$

$$= C_VT_1\left(\frac{3}{4} - 1\right) + PV_1\left(\frac{3}{4} - 1\right)$$

$$= -\frac{1}{4}\left(C_VT_1 + PV_1\right)$$

$$= -\frac{1}{4}\left(C_VT_1 + RT_1\right)$$

$$= \frac{-1}{4}T_1(R + C_V) = \frac{-1}{4}T_1C_P = \frac{C_PT_1}{4}$$

Process 1 – 2:

$${}_1W_2 = P(V_2 - V_1)$$

$$= PV_1\left(\frac{V_2}{V_1} - 1\right) = \frac{-RT_1}{4}$$

Process 2 – 3: (V = Constant)

$${}_2W_3 = 0$$

$${}_2Q_3 = {}_2U_3 = U_3 - U_2$$

$$= C_V(T_3 - T_2)$$

$$= C_V\left(\frac{T_1}{2} - \frac{3T_1}{4}\right)$$

$$= -C_VT_1\left(\frac{1}{4}\right)$$

$$= \frac{-C_VT_1}{4}$$

$${}_1Q_3 = {}_1Q_2 + {}_2Q_3$$

$$= \frac{-C_PT_1}{4} + \frac{-C_VT_1}{4}$$

$$= \frac{-T_1}{4}\left(C_P + C_V\right) = (C_V + C_P)\frac{T_1}{4}$$

12. (i) Ans: (c), (ii) Ans: (c), (iii) Ans: (b)

Sol:

$m = 1.5$ kg

$P_1 = 1000$ kPa

$P_2 = 200$ kPa

$V_1 = 0.2\text{m}^3$

$V_2 = 1.2\text{ m}^3$

$P = a + bV$

$u = 1.5Pv - 85$

$1000 = a + 0.2b$ ……… (i)

$200 = a + 1.2b$ …….. (ii)

By solving

$b = -800$

$a = 1160$

$P = 1160 - 800V$

(ii) $${}_1W_2 = \int_{V_1}^{V_2} PdV = \int_{v_1}^{v_2}(1160-800V)dV$$

$$= \int_{0.2}^{1.2}(1160-800V)dV$$

$$= 1160(1.2–0.2)–400(1.2^2 - 0.2^2)$$

$$= 600 \text{ kJ}$$

(iii) $u = (1.5\,Pv - 85)$ kJ/kg

$$= (1.5P\frac{V}{m} - 85) \text{ kJ/kg}$$

$$= 1.5P\frac{V}{m} - 85$$

$$= 1.5P\frac{V}{1.5} - 85$$

$$= (Pv - 85) \text{ kJ/kg}$$

$u_1 = P_1V_1 - 85 \quad = 1000 \times 0.2 - 85$

$= 115$ kJ/kg

$u_2 = P_2V_2 - 85 \quad = 200 \times 1.2 - 85$

$= 155$ kJ/kg

$u_2 - u_1 = 40$ kJ/kg

$dU = m(u_2 - u_1)$

$= 1.5 \times 40 = 60$ kJ

$dQ - dW = dU$

$dQ = 60 + 600 = 660$ kJ

$u = Pv - 85$

$= (a + bv)v - 85$

$= av + bv^2 - 85 = f(v)$

For Maximum internal energy

$$\frac{du}{dv} = 0$$

$\Rightarrow a + 2bV = 0$

$$\Rightarrow V = \frac{-a}{2b} = \frac{-1160}{-2\times800}\,m^3 = 0.725m^3$$

$u_{max} = (1160\times0.725) - (800 \times 0.725^2) - 85$

$= 335.5$ kJ/kg

$U_{max} = \dot{m} \times u_{max}$

$= 1.5 \times 335.5$

$= 503.25$ kJ

13. Ans: (b)

Sol: For process 1 – 2 : (P = C)

$\Rightarrow {}_1W_2 = P_1(V_2 - V_1)$

$\Rightarrow {}_1W_2 = 100 \times(0.3 - 0.003)$

$\Rightarrow {}_1W_2 = 29.7$kJ

By Ist law

${}_1Q_2 - {}^1W_2 = E_2 - E_1$

$\Rightarrow \quad 0 - 29.7 = E_2 - E_1$

$(\because \ {}_1Q_2 = 0)$

$-29.7 = E_2 - 0$

$E_2 = -29.7$ kJ

By Process 2 – 3

${}_2Q_3 - {}_2W_3 = {}_2E_3 = E_3 - E_2$

${}_2Q_3 - P(V_3 - V_2) = E_3 - E_2$

$-105 - 100(0.06–0.3) = E_3 - (-29.7)$

$E_3 = -110.7$ kJ

14. (i) Ans: (a) , (ii) Ans: (b)

Sol: $C_P = 2.093 + \dfrac{41.87}{t+100} J/^0C$

P = 1 atm

$V_1 = 2000\ cm^3$; $T_1 = 0°C$

$V_2 = 2400\ cm^3$; $T_2 = 100°C$

Here, C_P = J/°C form it should always in J/kg °C form

So $C_P \times kg = J/°C$

⇒ Sp. Heat × mass = Heat capacity

$$dQ = \int_{T1}^{T2} C_P dt = \int_{0^0C}^{100^0C}\left[2.093 + \frac{41.87}{t+100}\right]dt$$

$$= [2.093t]_0^{100} + 41.87\, ln[t+100]_0^{100}$$

$= [2.093(100)] + [41.87\ ln(200) - 41.87\ ln(100)]$

$= 209.3 + [2218 - 192.81]$

(i) dQ = 238.32J

Here constant pressure is given

$\Rightarrow {}_1W_2 = P_1(V_2 - V_1) = P_{atm}(V_2 - V_1)$

$= 101325(2400 - 2000)\times 10^{-6}$

${}_1W_2 = 40.53J$

$\Rightarrow dQ - dW = dU$

$\Rightarrow dU = 238.32 - 40.53$

$dU = 197.79J$

15. (i) Ans: (a), (ii) Ans: (b) , (iii) Ans: (a)

Sol: $h_1 = 3000$ kJ/kg ,

$h_2 = 2762$ kJ/kg

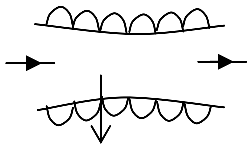
$V_1 = 60$ m/s ,

V_2 = ?

$A_1 = 0.1\ m^2$,

$v_2 = 0.498\ m^3/kg$

$v_1 = 0.187\ m^3/kg$



$$\frac{dQ}{dt} = 0$$

Applying steady flow energy equation

$$h_1 + \frac{V_1^2}{2000} + \frac{dQ}{dt} = h_2 + \frac{V_2^2}{2000} + \frac{dW}{dt}$$

$$\Rightarrow 3000 + \frac{(60)^2}{2000} = (2762) + \frac{V_2^2}{2000}$$

$\Rightarrow V_2 = 692.5$ m./s

$$\Rightarrow \dot{m} = \frac{A_1V_1}{v_1} = \frac{A_2V_2}{v_2}$$

$$\Rightarrow \dot{m} = \frac{(0.1)(60)}{0.187} \Rightarrow m = 32.08\frac{kg}{sec}$$

Find, A_2 = ?

$$\Rightarrow \dot{m} = \frac{A_2V_2}{v_2} \Rightarrow A_2 = \frac{mV_2}{v_2}$$

$$\Rightarrow A_2 = \frac{32.08\times(0.498)}{692.5}$$

$\Rightarrow A_2 = 0.023\ m^2$

16. Ans: (a)

Sol: Given:

$P_1 = 1.2$ MPa, $P_2 = 20$ kPa , $T_1 = 188°C$,

$h_1 = 2785$ kJ/kg,

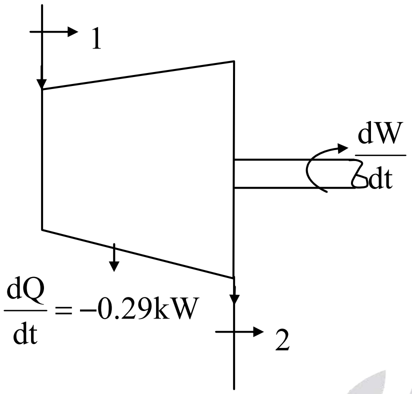
$h_2 = 2512$ kJ/kg

$V_1 = 33.33$ m/s,

$V_2 = 100$ m/sec.

$Z_2 = 0$ m , $Z_1 = 3$ m ,

$\dot{m} = 0.42$ kg/sec



Applying steady flow energy equations

$$\dot{m}\left[h_1+\frac{Z_1 g}{1000}+\frac{V_1^2}{2000}\right]+\frac{dQ}{dt}$$

$$=\dot{m}\left[h_2+\frac{V_2^2}{2000}+\frac{Z_2 g}{1000}\right]+\frac{dW}{dt}$$

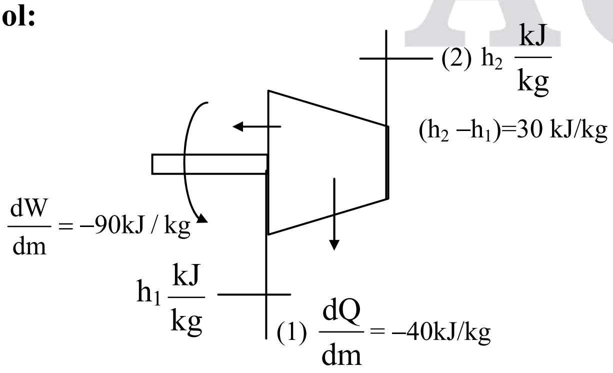
$$\Rightarrow 0.42\left[2785+\frac{3(9.81)}{1000}+\frac{(33.33)^2}{2000}\right]-0.29$$

$$=0.42\left[2512+\frac{(100)^2}{2000}+0\right]+\frac{dW}{dt}$$

$$\Rightarrow \frac{dW}{dt}=112.51\ kW$$

17. Ans: (a)

Sol:



dW = −90 kN.m/kg = −90 kJ/kg

(h_2-h_1) = 30 kJ/kg.

$$\frac{dQ}{dm}=-\ 40 kJ/kg$$

Heat rejected ⇒ dQ = '−Ve'

According to Steady flow energy equation,

$$h_1+\left(\frac{dQ}{dm}\right)_{air}+\left(\frac{dQ}{dm}\right)_{w}=h_2+\left(\frac{dW}{dm}\right)$$

$$\left(\frac{dQ}{dm}\right)_{air}=(h_2-h_1)+\frac{dW}{dm}-\left(\frac{dQ}{dm}\right)_{w}$$

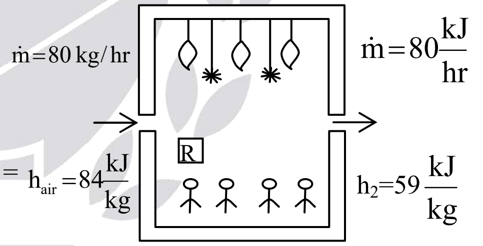
$$= 30 - 90 - (-40)$$

$$= -\ 20 kJ$$

(−ve sign indicates heat is rejected from the system)

18. Ans: (b)

Sol:



$$\left(\frac{dW}{dt}\right)_{fans} = 0.18\times 2 = -0.36\ kW$$

$$\left(\frac{dW}{dt}\right)_{Bulb} = 3\times 0.1 = -0.3\ kW$$

$$\left(\frac{dW}{dt}\right)_{Total} = -\ 0.36 + (-\ 0.3) = -0.66\ kW$$

$\dot{m}_{air\ enter}$ = 80 kg/hr.

h_1 = 84 kJ/kg

h_2 = 59 kJ/kg

$$\left(\frac{dQ}{dt}\right)_{person} = 630 \times 4 = 2520 kJ/hr$$

$$\left(\frac{dQ}{dT}\right)_{R\ cooler} = ?$$

By steady flow energy equation

$$\dot{m}_1 h_1 + \left(\frac{dQ}{dt}\right)_{person} + \left(\frac{dQ}{dt}\right)_{RCooler}$$

$$= \dot{m}_2 h_2 + \left(\frac{dW}{dt}\right)_{fan} + \left(\frac{dW}{dt}\right)_{bulb}$$

$$\frac{80\times84}{3600} + \frac{2520}{3600} + \left(\frac{dQ}{dt}\right)_{RCooler}$$

$$= \frac{80\times59}{3600} + (-0.66)$$

$$\Rightarrow \left(\frac{dQ}{dt}\right)_{RC} = -1.91 kW$$

Heat is removed from a cooler is 1.91 kW

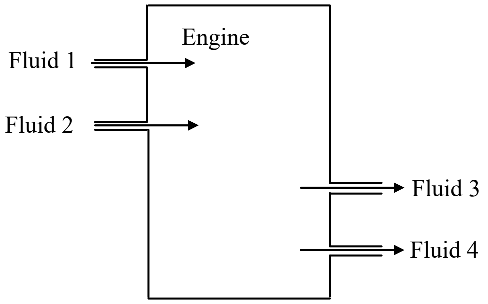
19. (i) Ans: (a), (ii) Ans: (a)

Sol: $\dot{m}_1 = 0.01 kg/sec$ $h_1 = 2952$ kJ/kg

$\dot{m}_2 = 0.1 kg/sec$ $h_2 = 2569$ kJ/kg.K

$\dot{m}_3 = 0.001 kg/sec$ $h_3 = 420$ kJ/kg

$V_1 = 20 m/sec$ $V_2 = 120 m/sec$



(1) Mass balance

Mass entering/sec = mass leaving/sec

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 + \dot{m}_4$$

$$\Rightarrow \quad \dot{m}_4 = 0.109 \text{ kg/sec}$$

(2) Energy balance

$$\dot{m}_1\left[h_1 + \frac{V_1^2}{2000}\right] + \dot{m}_2\left[h_2 + \frac{V_2^2}{2000}\right] + \frac{dQ}{dt}$$

$$= \dot{m}_3 h_3 + \dot{m}_4 h_4 + \frac{dW}{dt}$$

Here $\frac{dQ}{dt} = 0$

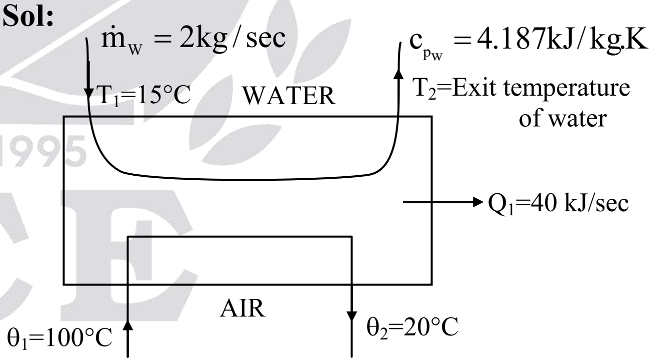
$$0.01\left[2952 + \frac{(20)^2}{2000}\right] + 0.1\left[2569 + \frac{(120)^2}{2000}\right]$$

$$= (0.001 \times 420) + (0.109 \times h_4) + 25$$

$$\Rightarrow h_4 = 2401 \text{ kJ/kg}$$

20. Ans: (c)

Sol:



$\dot{m}_a = 3 kg/sec$, $c_{p_a} = 1.005 kJ/kg.K$

Heat lost to surrounding = Q_1 = 40 kW

Heat lost by air = Heat gained by water + heat lost to surroundings

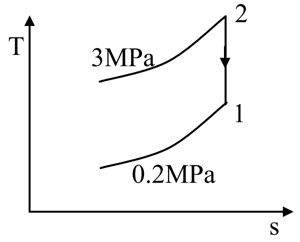
$$\dot{m}_a c_{p_a}(\theta_1 - \theta_2) = \dot{m}_w c_{p_w}(T_2 - T_1) + \theta_1$$

$$3\times1.005[100-20] = 2 \times 4.187(T_2 - 15) + 40$$

$$T_2 = 15 + \frac{241.2 - 40}{2 \times 4.187} = 39.02°C$$

21. Ans: (d)

Sol:



$T_1 = 1023$ K

Argon is a monoatomic gas, $\gamma_{Ar} = \frac{5}{3}$

Molecular weight of Argon, M = 40

$$C_{P_{Ar}} = \frac{\gamma \overline{R}}{M(\gamma - 1)}$$

$$= \frac{\frac{5}{3} \times (8.314)}{40 \times \left(\frac{5}{3} - 1\right)} = 0.5196 \text{ kJ/kg.K}$$

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = 1023 \left(\frac{0.2}{3}\right)^{0.4}$$

$= 346.28$ K $= 73.28°C$

Power (kW) = $\dot{m} C_{P_{Ar}} (T_1 - T_2)$

$= 5 \times 0.5196 \times (1023 - 346.28)$

$= \frac{1758.1}{1000} = 1.758$ MW

22. Ans: (b)

Sol: 'He' is monoatomic gas, $\gamma = \frac{5}{3}$, M = 4,

$$(C_P)_{Ar} = \frac{\gamma \overline{R}}{M(\gamma - 1)} = \frac{\frac{5}{3} \times (8.314)}{40 \times \left(\frac{5}{3} - 1\right)} = 0.5196 \text{ kJ/kgK}$$

$$(C_P)_{He} = \frac{\gamma \overline{R}}{M(\gamma - 1)} = \frac{\frac{5}{3} \times (8.314)}{4 \times \left(\frac{5}{3} - 1\right)} = 5.196 \text{ kJ/kgK}$$

$$\gamma_{mixture} = \frac{5}{3}$$

$C_{P\,mix} = 0.5(C_P)_{He} + 0.5(C_P)_{Ar}$

$= 0.5 \times 0.519 + 0.5 \times 5.19 = 2.857$ kJ/kg.K

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

$$= 1200 \left(\frac{100}{1000}\right)^{0.4} = 477.72 \text{ K}$$

Power (kW) = $\dot{m}_a \times C_{P\,mix} \times (T_1 - T_2)$

$= 0.3 \times 2.857 \times (1200 - 477.72)$

$= 619.05$ kW

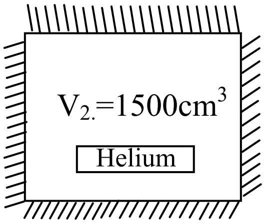
23. Ans: (a)

Sol: $V_c = V_1 = 15$ cm^3

$V_{CO} = V_2 = 1500$ cm^3

$P_1 = P_{He} = 20$ atm

$T_1 = 40°C$



$\Rightarrow dW = 0$ (Free expansion)

$dQ = 0$ (due to insulation)

By 1st law $dU = dQ - dW$

$\Rightarrow dU = 0 = C_V dT = 0$

$\Rightarrow dT = 0 \Rightarrow$ T= constant

Temperature = constant (Isothermal)

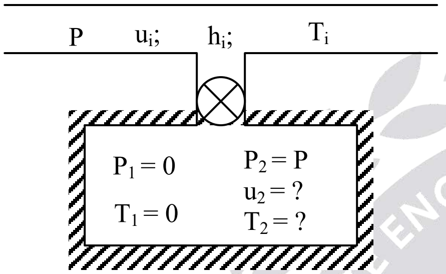
$$\Rightarrow P_1V_1 = P_2V_2$$

$$\Rightarrow 20\times 15 = P_2\times 1500$$

$$\Rightarrow P_2 = 0.2\,\text{atm}$$

24.

Sol:



Insulated Q = 0

Evacuated $m_1 = 0$

$$Q = m_2u_2 - m_1u_1 - (m_2 - m_1)h$$

$$m_2u_2 = m_2h_i$$

Final internal energy = $u_2 = h_i$

$$c_v T_2 = c_p T_i$$

Final temperature = $T_2 = \frac{c_p}{c_v}T_i = \gamma T_i$

25. Ans: (a, b, c)

Sol: Steady flow occurs when

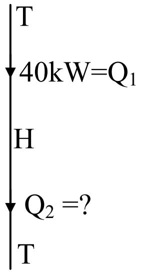
- Behaviour of the system are unchanging with time.
- For a properties 'P' of the system, $\partial P/\partial t = 0$.
- The first difference in each property is zero ($P_t - P_{t-1} = 0$)

Chapter 4 Second Law of Thermodynamics

01. Ans: (b)

02. Ans: (c)

Sol: Given: H.E



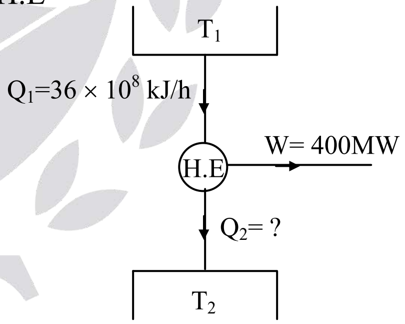
$$\eta_{H.E} = \frac{T_1 - T_2}{T_1} = \frac{Q_1 - Q_2}{Q_1}$$

$$\Rightarrow \frac{1200-300}{1200} = \frac{40-Q_2}{40}$$

$$\Rightarrow Q_2 = 10\text{ kW}$$

03. Ans: (c)

Sol: *Given:* Electric power generating station means H.E



$$\eta_{H.E} = \frac{Q_1 - Q_2}{Q_1} = \frac{W}{Q_1}$$

$$\Rightarrow Q_2 = Q_1 - W$$

$$Q_2 = 36\times 10^8\frac{KJ}{h} - 400MW$$

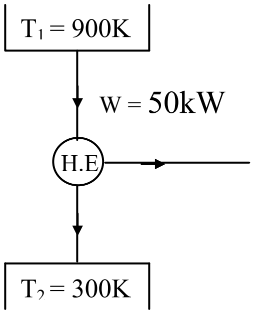
$$= \frac{36\times 10^8}{1000\times 3600}(MW) - 400MW$$

$$= 1000\,MW - 400MW$$

$$Q_2 = 600MW$$

04. Ans: (b)

Sol:



$$\eta = \frac{\text{Power}(\text{kW})}{Q_S(\text{kW})} = \frac{W(\text{kW})}{\dot{m}_f\left(\frac{\text{kg}}{\text{sec}}\right)\times C.V\left(\frac{\text{kJ}}{\text{kg}}\right)}$$

$$= \frac{50}{\frac{3}{3600}\times 75000} = 0.8$$

$$\eta_C = \frac{T_1 - T_2}{T_1} = \frac{627-27}{900} = 0.67$$

$\eta > \eta_c \Rightarrow$ Not possible

05. Ans: (b)

Sol: $(\text{COP})_R = \frac{1-\eta_E}{\eta_E} = \frac{1-0.75}{0.75} = 0.33$

06. Ans: (a)

Sol: Assertion is true

Reason is true and reason is the correct explanation.

07. Ans: (a)

Sol: PMM I → A machine which can supply mechanical work continuously without consumption of any energy. So, statement (2) is wrong.

After eliminating statement (2) only one option is available i.e., option (a).

08. Ans: (c)

Sol: ${}_1Q_2 = {}_1W_2 + {}_1U_2$

$$= \frac{P_1V_1 - P_2V_2}{n-1} + C_V\left[T_2 - T_1\right]$$

$$= \frac{R}{n-1}[T_1 - T_2] + \frac{R}{\gamma-1}[T_2 - T_1]$$

$$= \frac{R}{n-1}[T_1 - T_2] - \frac{R}{\gamma-1}[T_1 - T_2]$$

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

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

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

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

$$= \left(\frac{\gamma-n}{(\gamma-1)}\right)(W)$$

= Heat transfer for polytropic process

09. Ans: (a)

Sol: $\text{COP} = \frac{\text{NRE}(\text{kW})}{W_C(\text{kW})}$

$$3.1 = \frac{10}{3600}\times\frac{4.187\times10^3\times(23-6)}{W_C}$$

$W_C = 197$ W

10. Ans: (a)

Sol: COP = 3.2 ,

m = 1200 kg ,

P = 5 kW

$$\text{COP} = \frac{\text{NRE(kW)}}{W_C(\text{kW})}$$

$$= \frac{m_a \times C_{va} \times (\Delta T)_a}{W_C(\text{kJ})}$$

$$\Rightarrow 3.2 = \frac{1200(0.718)(22-7)}{W_C}$$

$$W_C = 4169\text{kJ}$$

$$\Rightarrow \text{Time} = \frac{W_C(\text{kJ})}{W_C(\text{kW})}$$

$$= \frac{4169(\text{kJ})}{5(\text{kJ/sec})} = \frac{834}{60} = 13.5\,\text{min}$$

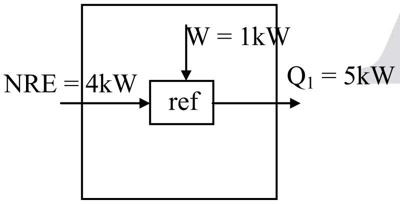
11. Ans: (d)

Sol: $\text{COP} = \frac{\text{NRE}}{W_C} = \frac{\text{NRE}}{680\text{kWhr}} = \frac{\text{NRE}}{680 \times 3600}$

$\Rightarrow$ NRE = 680 × 3600 × 1.4 = 3427 MJ/yr

12. Ans: (d)

Sol:



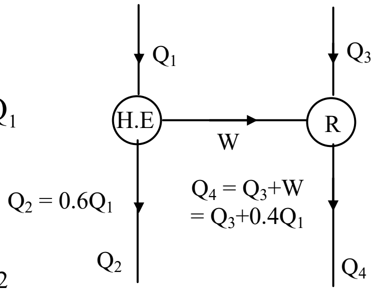
$Q_2 = Q_1 - W = 1\text{kW}$

Net effect = $Q_1 - Q_2$

= 5 – 4 = 1 kW (heating)

13. Ans: (d)

Sol: Given



$$\eta_E = 0.4$$

$$Q_2 + Q_4 = 3Q_1$$

$$\eta_E = \frac{Q_1 - Q_2}{Q_1}$$

$$\Rightarrow 0.4Q_1 = Q_1 - Q_2 = W$$

$$\Rightarrow Q_2 = 0.6Q_1$$

$$Q_2 + Q_4 = 3Q_1$$

$$\Rightarrow 0.6Q_1 + Q_4 = 3Q_1$$

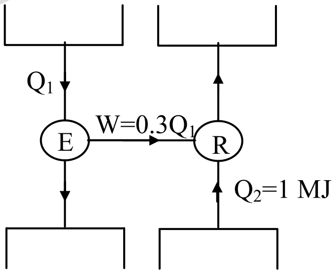
$$\Rightarrow Q_4 = 2.4Q_1$$

$$Q_3 = Q_4 - W = 2.4Q_1 - 0.4Q_1 = 2Q_1$$

$$(\text{COP})_R = \frac{Q_3}{W} = \frac{2Q_1}{0.4Q_1} = 5$$

14. Ans: 0.667 MJ

Sol:



$$\eta = \frac{W}{Q_1}$$

$$0.3 = \frac{W}{Q_1}$$

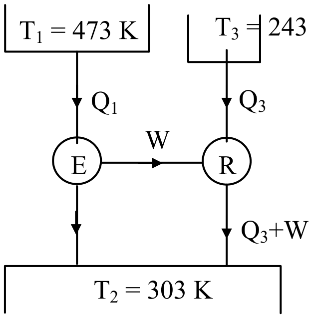
$$W = 0.3Q_1$$

$$(\text{COP})_R = 5 = \frac{Q_2}{W}$$

$$\Rightarrow Q_1 = \frac{1\,\text{MJ}}{5 \times 0.3} = 0.667\,\text{MJ}$$

15. Ans: 0.68

Sol:



$$\eta_E = \frac{T_1 - T_2}{T_1} = \frac{W}{Q_1}$$

$$\frac{473-303}{473} = \frac{W}{Q_1} \Rightarrow W = 0.359Q_1$$

$$(COP)_R = \frac{T_3}{T_2 - T_3} = \frac{Q_3}{W}$$

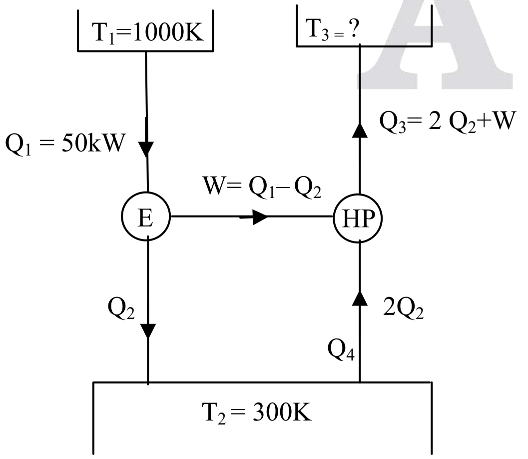
$$\frac{243}{303-243} = \frac{Q_3}{0.359Q_1}$$

$$\Rightarrow \frac{Q_3}{Q_1} = 1.45$$

$$\frac{Q_1}{Q_3} = 0.68$$

16. Ans: 86 kW

Sol:



$$\eta_E = 0.4 \times \eta_{Carnot}$$

$$0.4 \times \frac{T_1 - T_2}{T_1} = \frac{W}{Q_1}$$

$$0.4 \times \frac{(1000-300)}{1000} = \frac{W}{Q_1}$$

$\therefore$ $W = 0.28Q_1$

$Q_2 = Q_1 - W$

$= Q_1 - 0.28Q_1 = 0.72Q_1$

$Q_2 = 0.72Q_1$

$Q_3 = 2Q_2 + W$

$= 1.44Q_1 + 0.28Q_1$

$Q_3 = 1.72Q_1$

$$\frac{1.72Q_1}{0.28Q_1} = 0.5\left(\frac{T_3}{T_3 - 300}\right)$$

$T_3 = 326$ K

If $Q_1 = 50$ kW

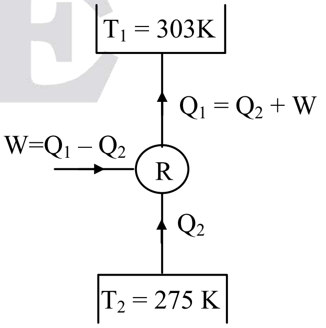
$Q_3 = 2Q_2 + W$

$= 2 \times 0.72Q_1 + 0.28Q_1$

$= 1.72 \times 50 = 86$ kW

17. Ans: 15.168

Sol:



$Q_2 = 20 \times 420 = 8400$ kJ/day

$$(COP)_{actual} = 0.15(COP)_{max}$$

$$=0.15\times\frac{T_2}{T_1-T_2}=\frac{Q_2}{W}$$

$$\Rightarrow 0.15\times\frac{275}{303-275}=\frac{8400}{W}$$

$$\Rightarrow W = 5701\text{ kJ}$$

$$1\text{ kW hr} = 3600\text{ kJ} = \frac{5701}{3600} = 1.58\text{ kW hr / day}$$

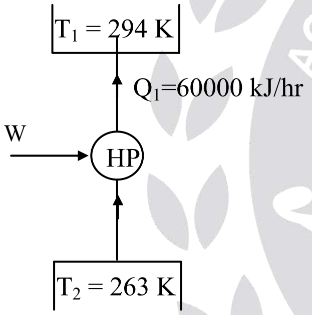
Electricity bill

= No. of unit/day × No. of days × cost/kWhr

= 1.58 × 30 × 0.32 = 15.168/-

18. Ans: 6326.5 kJ/hr

Sol:



$$(COP)_{H.P}=\frac{Q_1}{W}=\frac{T_1}{T_1-T_2}$$

$$\Rightarrow\frac{60{,}000}{W}=\frac{294}{294-263}$$

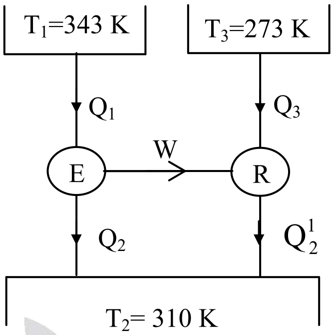
$$W = 6326.5\text{ kJ/hr}$$

$$\frac{W_{HP}}{W_{EH}}=\frac{6326.5}{60{,}000}=0.1054$$

With heat pump, initial investment is high but running cost is less. With electrical heater the initial investment is less but running cost is high.

19.

Sol: (a)



$$\dot{m}=\frac{1000}{3600}=0.277\text{ kg / s}$$

$$Q_3=\dot{m}\times\text{latent heat}=0.277\times333.43$$

$$= 92.36\text{ kW}$$

$$\eta_E=\frac{W}{Q_1}=\frac{T_1-T_2}{T_1}$$

$$\because W=\left(\frac{343-310}{343}\right)Q_1$$

$$\therefore\ W = 0.096\,Q_1\text{ -----(1)}$$

$$(COP)_R=\frac{Q_3}{W}=\frac{T_3}{T_2-T_3}$$

$$\frac{333.43\times10^3}{W}=\frac{273}{310-273}$$

$$\therefore\ W = 45190.147\text{ kJ}$$

$$\dot{W}=\frac{45190.147}{3600}=12.55\text{ kW}$$

From (1)

Q_1 = 130.759 kW

Q_2 = Q_1–W

Q_2 = 118.20 kW

$$Q_4=Q_3+W=\frac{333.43\times10^3}{3600}+W$$

$$= 92.62 + 12.55 = 105.17\text{ kW}$$

$$\frac{Q_3}{Q_1} = \frac{92.62}{130.75} = 0.708$$

Total heat rejected to lower temperature reservoir = $Q_2 + Q_{ref}$

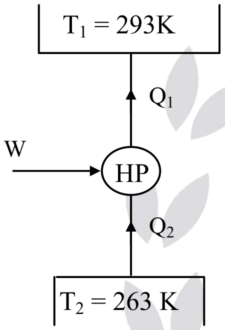
$$= 118.2 + 105.17 = 223.37 \text{ kW}$$

$$\frac{\text{Energy of freezing water}}{\text{Energy of heat engine}} = \frac{92.62}{130.759} = 0.706$$

20. Ans: 2 kW, 50°C

Sol:

(a)



$$Q_1 = 0.65(T_1 - T_2) = 0.65(293 - 263)$$

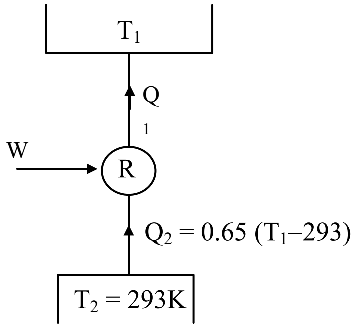
$$= 19.5 \text{ kW}$$

$$(COP)_{HP} = \frac{T_1}{T_1 - T_2} = \frac{Q_1}{W}$$

$$= \frac{293}{293 - 263} = \frac{19.5}{W}$$

$$\dot{W} = 1.99 \approx 2 \text{ kW}$$

(b)



$$Q_2 = 0.65(T_1 - T_2) = 0.65(T_1 - 293)$$

$$(COP)_R = \frac{Q_2}{W} = \frac{T_2}{T_1 - T_2}$$

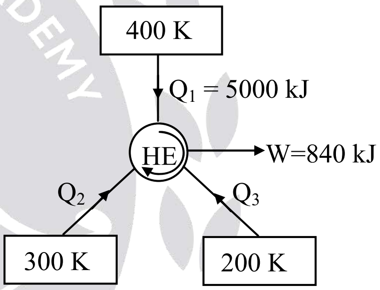
$$\Longrightarrow \frac{0.65(T_1 - 293)}{1.99} = \frac{293}{T_1 - 293}$$

$$T_1 = 323 \text{ K} = 50°\text{C}$$

Up to 50°C outside temperature, the temperature of room can be maintained 20^0 C.

21.

Sol: Initial diagram:



For reversible heat engine,

$$\oint \frac{dQ}{T} = 0$$

$$\frac{5000}{400} + \frac{Q_2}{300} + \frac{Q_3}{200} = 0$$

$$\Rightarrow \frac{Q_2}{300} + \frac{Q_3}{200} = -\frac{50}{4}$$

$$\frac{2Q_2 + 3Q_3}{600} = -\frac{50}{4}$$

$$2Q_2 + 3Q_3 = -\frac{50}{4} \times 600$$

$$2Q_2 + 3Q_3 = -7500 \text{ ------(i)}$$

Energy balance

$5000 + Q_2 + Q_3 = W$

$Q_2 + Q_3 = 840 - 5000$

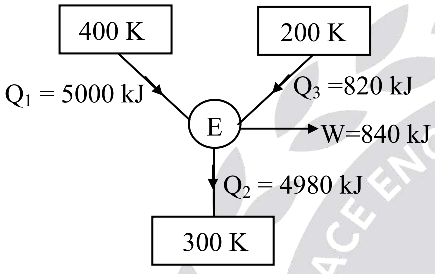
$Q_2 + Q_3 = -4160$ ------- (ii)

from eq.(i)

$Q_2 = -4980$ kJ,

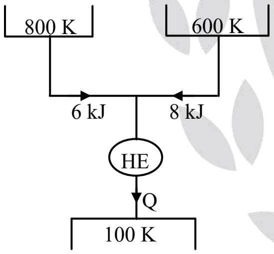
$Q_3 = 820$ kJ

Final diagram



22. Ans: (d)

Sol:



For reversible engine,

$s_{gen} = 0$

dS(reservoir at 800 K) + dS(reservoir at 600K) + dS(reservoir at 100K) + dS(working fluid) = 0

$$-\frac{6}{800}-\frac{8}{600}+\frac{Q}{100}+0=0$$

$\Rightarrow Q = 2.083$ kJ

$W_{net} = 8 + 6 - 2.083 = 11.917$

$$\eta_{th}=\frac{11.917}{8+6}=85\%$$

Chapter 5 Entropy

01. Ans: (c)

Sol: $C_p = \left(\frac{dh}{dT}\right)_p$

Tds = dh – vdp

As P = c , dp = 0

So, Tds = dh

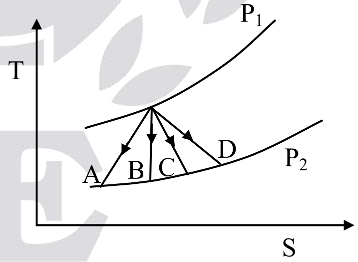
$$C_p = \left(\frac{Tds}{dT}\right)_p$$

$$C_p = T.\left(\frac{\partial s}{\partial T}\right)_p$$

02. Ans: (b)

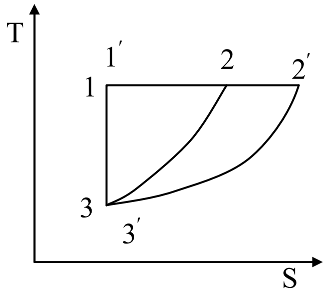
03. Ans: (a)

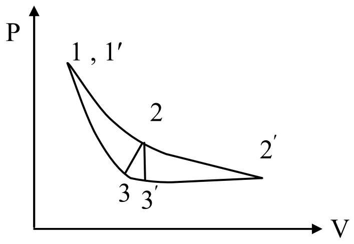
Sol:



04. Ans: (b)

Sol:





1–2, 1′–2′ → constant temperature

2 – 3 → constant volume

$2^1 - 3^1$ → constant pressure

3– 1, 3^1–1^1 → Entropy constant

05. Ans: (c)

06. Ans: (c)

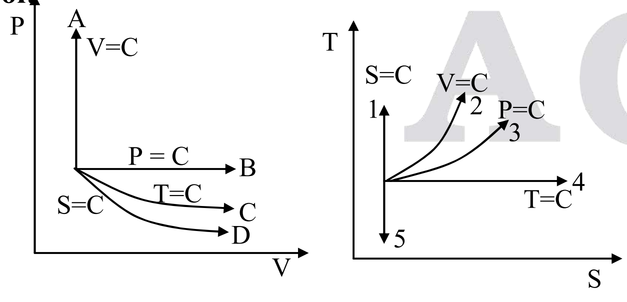
Sol: i) Temperature measurement is due to Zeroth law of thermodynamics.

ii) Entropy is due to Second law of thermodynamics

iii) Internal Energy is due to first law of thermodynamics

07. Ans: (b)

Sol:



Slope of constant volume curve is more than that of constant pressure curve in T-S diagram. Similarly slope of adiabatic curve is more than that of isothermal curve in P-V diagram.

08. Ans: (c)

Sol: $(dS)_{system} = 0$

$(dS)_{surr} = 0$

$(dS)_{univ} = 0$

09. Ans: (c)

Sol: Tds = du + Pdv.

This process is valid for any process, reversible (or) irreversible, undergone by a closed system.

10. Ans: (c)

Sol: Area on T-S graph gives amount of heat supplied.

11. Ans: (b)

Sol: Clausius inequality $\oint \frac{dQ}{T} \le 0$

$$\Rightarrow \oint \frac{dQ}{T} = \frac{Q_1}{T_1} - \frac{Q_2}{T_2} = \frac{600}{1000} - \frac{450}{300}$$

$$\oint \frac{dQ}{T} = -0.9\,\text{kJ/K} < 0$$

⇒ Irreversible cycle

$$\Rightarrow \eta = \frac{Q_1 - Q_2}{Q_1} = \frac{600 - 450}{600} = 0.25 = 25\%$$

12. Ans: (d)

Sol: Find the cycle of thermodynamic.

$T_1 = 285 + 273 = 558$ K

$T_2 = 5 + 273 = 278$ K

$$\oint \frac{dQ}{T} = \frac{Q_1}{T_1} - \frac{Q_2}{T_2}$$

$$= \frac{1000}{558} - \frac{492}{278} = 1.79 - 1.76$$

$$\oint \frac{dQ}{T} = 0.022 > 0$$

∴ It is an impossible cycle.

13. Ans: (c)

Sol: Motor power = 5 kW.

$T = 20°C = 293$ K

Due to friction, there is heat between brake and shoe and heat is transferred to surroundings.

$$(dS)_{sur} = \frac{Q}{T} = \frac{\text{Power} \times \text{Time}}{T} = \frac{5 \times 3600}{293}$$

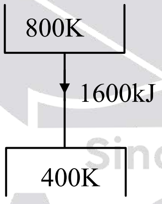
$$dS = 61.4 \text{ kJ/K}$$

14. Ans: (c)

Sol: $S_{gen} = (S_2 - S_1) - \int \frac{dQ}{T}$

$$= \frac{Q}{T_2} - \frac{Q}{T_1} = \left(\frac{1600}{400} - \frac{1600}{800}\right)$$

$$= 2 \text{ kJ/K}$$



15. Ans: (b)

Sol: $m_s = 100\text{kg}$

$$(dS)_{system} = m(s_2 - s_1) = 100(0.1) = 10 \frac{\text{kJ}}{\text{K}}$$

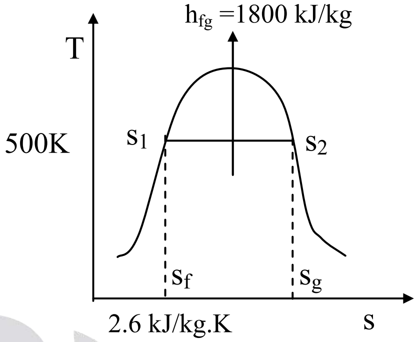
$$(dS)_{surrounding} = (S_2 - S_1) = -5 \frac{\text{kJ}}{\text{K}}$$

$$(dS)_{universe} = (dS)_{sys} - (dS)_{surr} = 10 - 5$$

$(dS)_{uni.} = 5$ kJ/K > 0 ⇒ irreversible process

16. Ans: (b)

Sol:



$$s_g - s_f = \frac{h_{fg}}{T_{sat}}$$

$$s_g - 2.6 = \frac{1800}{500}$$

$$s_g = 6.2 \text{ kJ/kg.K}$$

17. Ans: (b)

Sol: $T = 273 + 30 = 303$ K

$$d\dot{Q} = -55 \times 10^6 \text{ W}$$

As heat is removed at constant temperature,

$$dS = \frac{d\dot{Q}}{T} = \frac{-55}{303} = -0.18 \text{ MW/K}$$

18. Ans: (c)

19. Ans: (c)

Sol: $(dS)_{Isothermal} = mR\ln\left(\frac{V_2}{V_1}\right)$

$$= mR\ln\left(\frac{P_1}{P_2}\right)$$

20. Ans: (d)

21. Ans: (d)

Sol: $Q = \alpha T + \beta T^2$

$$dS = \int \frac{\delta Q}{T} = \int \frac{\delta\left(\alpha T + \beta T^2\right)}{T}$$

$$= \alpha \ln \frac{T_2}{T_1} + 2\beta\left(T_2 - T_1\right)$$

22. Ans: (a)

Sol: $S_{gen} = (S_2 - S_1) - \int \frac{dQ}{T} = \frac{Q}{T_2} - \frac{Q}{T_1}$

$$= \frac{600}{278} - \frac{600}{293} = 0.11\,\text{W/K}$$

23. Ans: (a)

Sol: $T_1 = 273+15 = 288$ K ,

$T_2 = 288.2$ K

$$(S_2 - S_1) - \int \frac{dQ}{T} = S_{gen}$$

Here $dQ = 0$

$$\therefore\ S_2 - S1 = dS = mC_p \ln\left(\frac{T_2}{T_1}\right)$$

$$= 8 \times 4200 \times \ln\left(\frac{288.2}{288}\right) = 23\ \text{W/K}$$

24. Ans: 6.68 kJ/K

Sol: H_2O $T_1 = 0°C = 273K$

$\downarrow$

H_2O $T_2 = 164.97°C = 437.97K$

$\downarrow$

Steam $T_3 = 164.97°C = 437.97K$

$$(dS)_1 = \int_{T_1}^{T_2} \frac{dQ}{T} = mC_{pw}\,ln\left(\frac{T_2}{T_1}\right)$$

$$= 1 \times (4.187)\ ln\left(\frac{437.97}{273}\right)$$

$(dS)_1 = 1.97$ kJ/kg.K

$$(dS)_2 = \frac{Q}{T} = \frac{m \times L.H}{T} = \frac{1 \times (2066.3)}{437.97}$$

$\Rightarrow (dS)_2 = 4.71$ kJ/kg.K

$(dS)_{Universe} = (dS)_1 + (dS)_2$

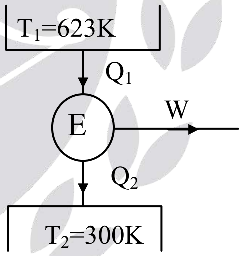
$\Rightarrow (dS)_{Universe} = 6.68$ kJ/kg.K

25.

Sol:

(a): Given Carnot cycle

$ds = 1.44$ kJ/kgK



$$\eta_{Carnot} = \frac{T_1 - T_2}{T_1} = \frac{623 - 300}{623} = 0.518$$

$$\eta = \frac{W}{Q_1}$$

$W = Q_1 \times \eta = T_1 dS \times \eta$

$W = 623 \times 1.44 \times 0.518 = 464.7$ kJ

(b) Given

Power = 20 kW

$$\text{Power (kW)} = \dot{m}_s\left(\frac{\text{kg}}{\text{sec}}\right)\times W\left(\frac{\text{kJ}}{\text{kg}}\right)$$

$$\Rightarrow \dot{m}_s = 0.043\,\text{kg/sec}$$

$$= 0.043\times 3600\ \text{kg/hr}$$

$$\dot{m}_s = 154.8\,\text{kg/hr}$$

26. Ans: –16.01 J/K

Sol: Water $T_1 = 20°C = 293$ K

↓

Water $T_2 = 0°C = 273$ K

↓

Ice $T_2 = 0°C = 273K$

↓

Ice $T_3 = -10^oC = 263K$

m = 10 g, $C_P = 4.2$ J/gK

$$dS_1 = mC_P\ell n\frac{T_2}{T_1} = 10\times 4.2\times \ell n\left(\frac{273}{293}\right)$$

$$= -2.96\ \text{J/K}$$

$$dS_2 = \frac{-m_iL_{ice}}{T_2} = \frac{-10\times 335}{273} = -12.27\,\text{J/K}$$

$$dS_3 = mC_{P_{ice}}\ell n\frac{T_3}{T_2} = 10\times 2.1\ell n\left(\frac{263}{273}\right)$$

$$= -0.78\text{J}$$

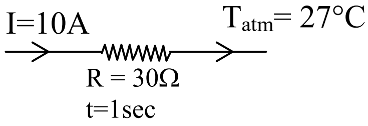
$$(dS)_{system} = dS_1 + dS_2 + dS_3$$

$$= -2.96 - 12.27 - 0.78$$

$$= -16.01\ \text{J/K}$$

27.

Sol:



$m_w = 10$ gm, $C_{pw} = 0.9\times 10^3$

With work transfer there is no entropy change so entropy change of resistor is equal to zero.

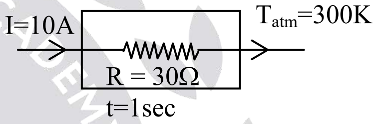
$$(dS)_{Resister} = 0$$

$$(ds)_{surrounding} = \frac{Q}{T_{atm}} = \frac{I^2Rt}{T_{atm}} = \frac{10^2\times 30\times 1}{300} = 10\,\text{J/K}$$

$(dS)_{universe} = (dS)_{resistor} + (dS)_{surrounding}$

= 10 J/K

When it is insulated:



Heat gained by wire = work done = I^2Rt

$m_w\times C_{pw}\times(T_2 - T_{atm}) = I^2Rt$

$10\times 10^{-3}(0.9\times 10^3)(T_2 - 300) = 10^2\times 30\times 1$

$T_2 = 633$ K

$$(dS)_{wire} = \frac{dQ}{T} = m_{wire}\times C_{Pwire}\times \ell n\frac{T_2}{T_1}$$

$$= \left(10\times 10^{-3}\right)\times\left(0.9\times 10^3\right)\times \ell n\left(\frac{633}{300}\right)$$

$$= 6.720\,\text{J/K}$$

$(dS)_{surrounding} = 0$

$(dS)_{universe} = 6.720 + 0 = 6.72$ J/K

28.

Sol: Case - 1:

Copper block

m = 600 g, C_P= 150 J/k, $T_1 = 100°C$

Lake Temperature = 8°C = T_2

Find: $(dS)_{Universe}$

If C_P is in J/K means mass is included and it is known as heat capacity.)

$$(dS)_{Cu\ block} = mC_P\, ln\frac{T_2}{T_1} = 150\, ln\left(\frac{281}{373}\right)$$

$$\Rightarrow (dS)_{Cu\ block} = -42.48\ J/K$$

$$(dS)_{H_2O} = \frac{mC_P(T_2-T_1)}{T_2}$$

$$= 150\frac{(373-281)}{281} = 49.11\ J/K$$

$$\Rightarrow (dS)_{Universe} = (dS)_{Cu\ block} + (dS)_{H_20}$$

$$= -42.48 + 49.11$$

$$(dS)_{Universe} = 6.626\ J/K$$

Case – 2 :

Same block, $T_2 = 8°C = 281$ K

As it is dropped from certain height, so there is change in potential energy. Work is done by the block

Change in entropy due to work interaction = 0

$$\Rightarrow (dS)_{block} = 0$$

$$(dS)_{H_2O} = \frac{Q}{T_2} = \frac{mgh}{T_2} = \frac{0.6\times 9.81\times 100}{281}$$

$$= 2.09\ J/K$$

$$\Rightarrow (dS)_{Uni} = 2.09\ J/K$$

Case - 3

Now by joining two blocks find $(dS)_{uni}$

$T_1 = 100°C$, $T_2 = 0°C$

Heat lost by block -1 = Heat gained by block -2

$$C(T_1 - T_f) = C(T_f - T_2)$$

$$T_f = \frac{T_1 + T_2}{2} = 50^o C$$

$$\Rightarrow (dS)_{block\,1} = C\ ln\left(\frac{T_f}{T_1}\right)$$

$$= 150\ell n\left(\frac{50+273}{373}\right) = -21.58\ J/K$$

$$\Rightarrow (dS)_{Block\,2} = C\,\ell n\left(\frac{T_f}{T_2}\right)$$

$$= 150\, ln\left(\frac{50+273}{273}\right) = +25.22\ J/K$$

$$\Rightarrow (dS)_{Uni} = -21.58 + 25.22$$

$$\Rightarrow (dS)_{Uni} = 3.64\ J/K$$

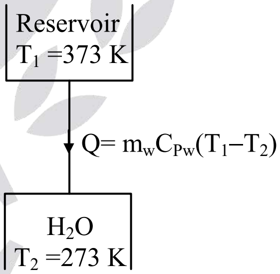
$$(dS)_{Universe} > 0$$

So it is an irreversible process.

29.

Sol:

(a)



m=1kg water

$$(dS)_{H_2O} = \int_{T_2}^{T_1}\frac{dQ}{T} = \int_{T_2}^{T_1} m_w C_{Pw}\frac{dT}{T}$$

$$= mC_P\, ln\left(\frac{T_1}{T_2}\right)$$

$$(dS)_{Reservoir} = -\frac{Q}{T_1} = \frac{-m_w C_{Pw}\times(T_1 - T_2)}{T_1}$$

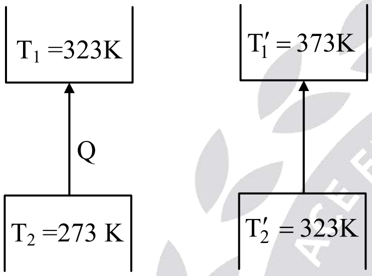
$$(dS)_{Universe} = (dS)_{H_2O} + (dS)_{surr}$$

$$= m_w C_{Pw}\left[\ln\left(\frac{T_1}{T_2}\right) - \left(\frac{T_1 - T_2}{T_1}\right)\right]$$

$$= 1(4.187) \times \left[\ln\left(\frac{373}{273}\right) - \left(\frac{373 - 273}{373}\right)\right]$$

$(dS)_{universe} = 0.183$ kJ/kg.K

(b)



By providing one more reservoir at 323 K

1st stage, $(dS)_{universe,1st}$

$$\Rightarrow (ds)_{universe1} = m_w C_{Pw}\left[\ln\frac{T_1}{T_2} - \left(\frac{T_1 - T_2}{T_1}\right)\right]$$

$$(dS)_{univ,1st\,stage} = 1 \times 4.18\left[\ln\left(\frac{323}{273}\right) - \left(\frac{323 - 273}{323}\right)\right]$$

$$= 0.056 \text{ kJ/kg.K}$$

$$\Rightarrow (ds)_{univ,2nd\,stage}$$

$$= 1 \times 4187\left[\ln\left(\frac{373}{323}\right) - \left(\frac{373 - 323}{373}\right)\right]$$

$$= 0.041 \text{ kJ/kg.K}$$

$$(dS)_{universe} = (dS)_{univ,2nd\,stage} + (dS)_{univ,1st\,stage}$$

$$= 0.041 + 0.056 = 0.097 \text{ kJ/kgK}$$

$(dS)_{uni} = 0.097$ kJ/kg.K

(c) From above problem, when compared to singe stage heating in a two stage heating entropy is halved. As the no. of stages of heating goes on increasing, entropy change of universe are decreasing. This way we can heat the fluid with almost no change in entropy of universe.

30.

Sol: Given $C_P = a + bT$.

$$Q = \int_1^2 dQ = \int_{T_1}^{T_2} mC_p dT = \int_{T_1}^{T_2} m(a + bT)\,dT$$

$$= \int_{T_1}^{T_2} ma\,dT + mbT\,dT$$

$$Q = a\{T_2 - T_1\} + \frac{b}{2}\left[T_2^2 - T_1^2\right]$$

$$\int_{S_1}^{S_2} dS = \int_{T_1}^{T_2} mC_P \frac{dT}{T}$$

$$\Rightarrow dS = (S_2 - S_1) = \int_{T_1}^{T_2} m(a + bT)\frac{dT}{T}$$

$$\Rightarrow (S_2 - S_1) = am\,ln\left[\frac{T_2}{T_1}\right] + bm[T_2 - T_1]$$

$C_P = a + bT$

$25.2 \times 10^3 = a + b \times 500$ ……….. (1)

$30.1 \times 10^3 = a + b \times 1200$ ……….. (2)

By solving

$a = 21700, \qquad b = 7$

$$Q = 21{,}700(1200 - 500) + \frac{7}{2}(1200^2 - 500^2)$$

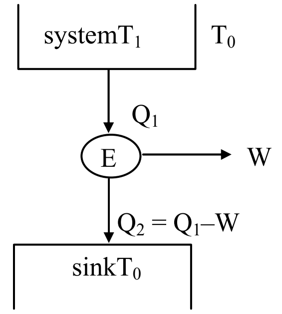
$$= 19355 \text{ J}$$

$$dS = 21700\left(\frac{1200}{500}\right) + 7(1200 - 500)$$

$$= 2897.6716 \text{ J/K}$$

31.

Sol:



For maximum work done condition the engine has to be reversible and for the condition of reversibility entropy change of universe is zero.

$$(dS)_{system} = \int_{T_1}^{T_0} \frac{dQ}{T}$$

$$\int_{T_1}^{T_0} \frac{C_v dT}{T} = C_v \ell n\left(\frac{T_0}{T_1}\right)$$

$$(dS)_{surrounding} = \frac{Q_1 - W}{T_0} = \frac{C_v(T_1 - T_0) - W}{T_0}$$

$$(dS)_{univ} = (dS)_{system} + (dS)_{sink} = 0$$

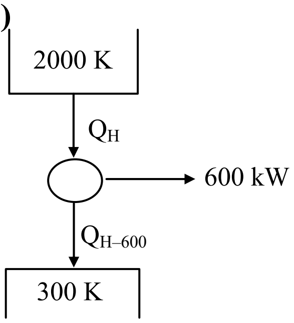
$$C_v \ell n\left(\frac{T_0}{T_1}\right) + \frac{C_v(T_1 - T_0) - W}{T_0} = 0$$

$$W = C_v(T_1 - T_0) + T_0\, C_v\, \ell n\left(\frac{T_0}{T_1}\right)$$

$$= C_v\left((T_1 - T_0) + T_0\, \ell n\left(\frac{T_0}{T_1}\right)\right)$$

32. Ans: (c)

Sol:



$$W_{output} = \left(\frac{T_H - T_L}{T_H}\right) \times Q_H$$

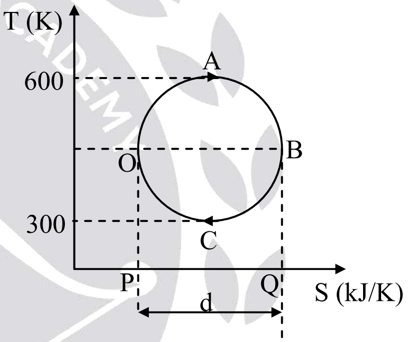
$$\left(\frac{2000 - 300}{2000}\right) \times Q_H = 600$$

$Q_H = 705.89$

Entropy change of working fluid during heat addition process = $\frac{705.89}{2000} = 0.353$ kW/K

33. Ans: (b)

Sol:



W_{net} = Area of cycle OABC

$$= \frac{\pi}{4} \times 300 \times d = 75\pi d$$

Heat supplied,

Q_s = Area of semicircle OAB + Area of rectangle OBQP

$$= \frac{\frac{\pi}{4} \times 300 \times d}{2} + 450 \times d$$

$$= (37.5\,\pi + 450)d$$

$$\eta_{th} = \frac{W_{net}}{Q_s}$$

$$= \frac{75\pi d}{(37.5\pi + 450)d} = 41.5\%$$

34. Ans: 25%

Sol: Net work, W_{net} = Area of ΔABC

$$= \frac{1}{2} \times (400) \times (5-1)$$

$$= 800 \text{ kJ}$$

Heat supplied,

Q_s = Area of rectangle enclosed by line BC

$= 800 \times (5 - 1) = 3200$ kJ

$$\eta = \frac{W_{net}}{Q_s} = \frac{800}{3200} = 25\%$$

35. Ans: (a, b)

Sol:

- The entropy of universe is continually on the increase.
- The increase in entropy is obtained from a given quantity of heat transfer at low temperature.
- The entropy of system reaches the maximum value when it is a state of equilibrium with its surrounding.

36. Ans: (a, b)

Sol: $2.5 \times 4.18\,(T - 30) = 5 \times 4.18 \times (100 - T)$

$\Rightarrow T = 77°C$

$$\Delta s = 2.5 \times 4.18 \times \ell n\left(\frac{350}{303}\right) + 5 \times 4.18 \times \ell n\left(\frac{350}{373}\right)$$

$= 1.507 - 1.33 = 0.177$ kJ/K

37. Ans: (b, c, d)

Sol: Option figures (b, c, d) represents throttling process of real gas across the orifice.

38. Ans: (a, b, d)

Sol: When air is compressed to half of volume at constant pressure entropy change is negative.

39. Ans: (a, c, d)

Sol:

- Two reversible adiabatic path cannot intersect each other.
- Through one point, only one reversible adiabatic can pass
- The path of forward and reversible process coincide for an internally reversible process
- Heat transfer between a reservoir and a system is an irreversible process

40. Ans: (a, b, d)

Sol: For a isentropic process

- A process where ΔS = 0
- An isentropic process can serve as an appropriate model for actual processes.
- Isentropic process help us to define efficiencies for processes to compare the actual performance.

41. Ans: (a, b, d)

Sol: Example of ideal reversible process are

- Frictionless adiabatic expansion
- Condensation and boiling of liquids
- Frictionless isothermal compression

42. Ans: (a, b, c, d)

Sol: For a cycle to be reversible,

- The pressure and temperature of working substance must not differ, appreciably from those of the surrounding at any stage in the process
- All process must be extremely slow
- There should be no loss of energy
- Working parts of engine must be friction free

Chapter 6 Availability

01. Ans: (b)

Sol: Whenever certain quantity of heat transferred from a system available energy decrease

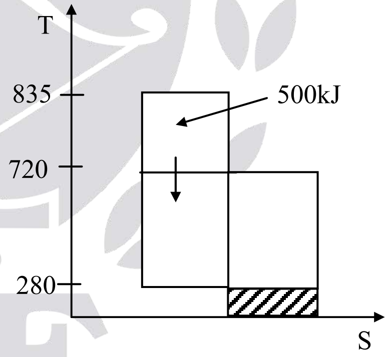
02. Ans: (d)

Sol: Irreversibility is zero in the case of Reversible process

03. Ans: (b)

04. Ans: 26.77 kJ

Sol:



Loss in A.E $= T_0 S_{gen}$

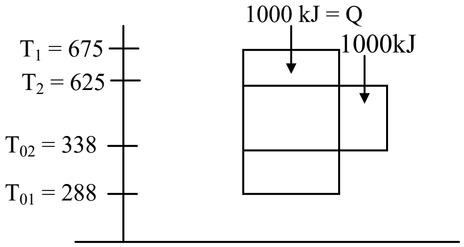
$$= 280\left(\frac{Q}{T_2} - \frac{Q}{T_1}\right)$$

$$= 280\left[\frac{500}{720} - \frac{500}{835}\right]$$

Loss in A.E $= 26.77$ kJ

05. Ans: 11.2 kJ, 5.25 kJ

Sol:

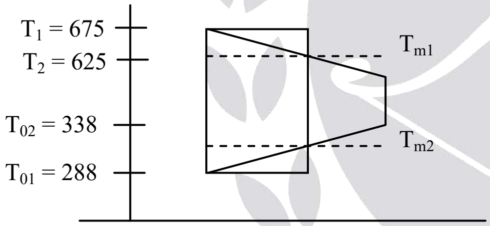


$$AE = Q\left(1-\frac{T_0}{T}\right) = 100\left(1-\frac{288}{675}\right) = 57.33\text{ kJ}$$

$$AE_I = Q\left(1-\frac{T_{02}}{T_2}\right) = 100\left(1-\frac{338}{625}\right) = 45.92\text{ kJ}$$

Loss of available energy = 57.33 – 45.92

= 11.41 kJ



$$T_{m1} = \frac{T_1+T_2}{2} = \frac{675+625}{2} = 650\text{K}$$

$$T_{m2} = \frac{T_{01}+T_{02}}{2} = \frac{288+338}{2} = 313\text{ K}$$

$$AE_{II} = Q\left(1-\frac{T_{m2}}{T_{m1}}\right)$$

$$= 100\left(1-\frac{333}{650}\right) = 51.84\text{ kJ}$$

Loss in AE = $AE_I - AE_{II}$

= 57.33 – 51.84 = 5.49kJ

06. Ans: 5743 kJ

Sol: Given Ideal gas , n = 1 k mol

$P_1 = 1$ MPa, $P_2 = 0.1$ MPa ,

$T_1 = 300$ K $T_f = T_1$

T = constant ⇒ isothermal process

For isothermal process,

$$s_2 - s_1 = mR\, ln\left(\frac{p_1}{p_2}\right)$$

$$= n\overline{R}\ \ln\left(\frac{p_1}{p_2}\right)$$

For Non-flow process

$W_{max} = (u_1 - u_2) - T_0(s_1 - s_2)$

$W_{max} = -T_0(s_1 - s_2)$ (∵ T = constant)

$$W_{max} = T_0\, n\overline{R}\ln\left(\frac{p_1}{p_2}\right) = -T_0(s_1 - s_2)$$

$$= T_0(s_2 - s_1)$$

$$= 300\ (1)\ (8.314)\ ln\left(\frac{1}{0.1}\right)$$

$\therefore W_{max} = 5743$ kJ

07. Ans: 222.7 kJ

Sol: $P_1 = 1.4$ MPa =1400 kPa

$T_1 = 175 + 273 = 448$ K;

$V = 1\ m^3$

$$m = \frac{P_1V}{RT_1} = \frac{1400\times1}{0.287\times448} = 10.88\text{ kg}$$

$T_2 = 25°C = 298$ K

$T_0 = 25°C = 298$ K

V = constant

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

$$\frac{1400}{448}=\frac{P_2}{298}$$

$P_2 = 931.25$ kPa

Non flow process:

Availability at state I

$AE_1 = (u_1 - u_0) - T_0\,(s_1 – s_0)$

$$= C_v\left(T_1 - T_0\right) - T_0\left(C_p \ln\frac{T_1}{T_0} - R\ln\frac{P_1}{P_0}\right)$$

$$= 0.718\,(448 - 298) - 298$$

$$\left(1.005\ln\frac{448}{298} - 0.287\ln\frac{1400}{100}\right)$$

$= 211.3$ kJ/kg

Availability at state 2

$AE_{II} = (u_2 - u_0) - T_0\,(s_2 – s_0)$

$$= C_v\left(T_2 - T_0\right) - T_0\left(c_p \ln\frac{T_2}{T_0} - R\ln\frac{P_2}{P_0}\right)$$

$$= 0.718\,(298 - 298) - 298$$

$$\left(1.005\ln\frac{298}{298} - 0.287\ln\frac{931.15}{100}\right)$$

$= 190.82$ kJ

Loss in AE = 20.47 kJ/kg

Total Irreversibility

I = m × loss in AE = 222.7 kJ

08. Ans: 25.83 kJ

Sol: Loss in available Energy in pipe

$$(\Delta E)_{lost} = mRT_0\left(\frac{\Delta p}{p_1}\right)$$

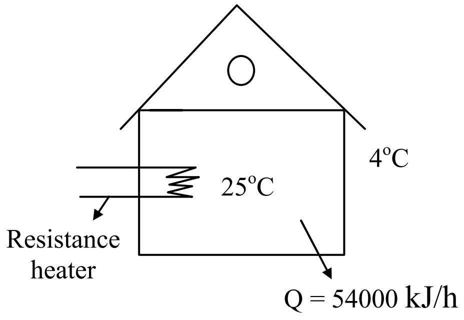
$$= 3 \times 0.287 \times 300\left(\frac{0.1 p_1}{p_1}\right)$$

$$= 3 \times 0.287 \times 300\,(0.1)$$

$(\Delta E)_{Lost} = 25.83$ kJ

09. Ans: 7.04 %

Sol:



Second law efficiency,

$$\eta_{II} = \frac{W_{rev}}{W_{act}} \text{ or } \frac{(Cop)_{act}}{(Cop)_{rev}}$$

$$(Cop)_{rev} = \frac{T_H}{T_H - T_L} = \frac{298}{21}$$

$(Cop)_{act} = 14.19$

$$(Cop)_{act} = \frac{\text{Heating effect}}{\text{Work input}}$$

For resistance heater, the entire work in heating is lost as heat

$$\therefore (COP)_{act} = \frac{54000}{54000} = 1$$

$$\eta_{II} = \frac{1}{14.19}$$

$\eta_{II} = 7.04$ %

10. Ans: 0.962

Sol: $\eta_{II} = \dfrac{\eta_{actual}}{\eta_{reversible}}$

$$\eta_{actual} = \frac{(1000-20)-(300+20)}{(1000-20)} = 0.6734$$

$$\eta_{reversible} = \frac{(1000-300)}{1000} = 0.7$$

$$\eta_{II} = \frac{0.6734}{0.7} = 0.962$$

11. Ans: 214.8 MJ

Sol: Available energy

$$= mc_p(T_1 - T_2) - T_o\left(m c_p \,\ell n\left(\frac{T_1}{T_2}\right)\right)$$

where, $T_1 = 1200$ K, $T_2 = 400$ K, $T_o = 300$ K

$$= 1000\times 0.5\times(1200-400) - 300\left[1000\times 0.5\times \ell n\left(\frac{1200}{400}\right)\right]$$

$$= 235.2 \text{ MJ}$$

Total energy available with steel

$$= mc_p(T_1 - T_o)$$

$$= 1000\times 0.5\times(1200-300) = 450 \text{ MJ}$$

Unavailable energy = 450 – 235.2

= 214.8 MJ

12. Ans: 61.9 %

Sol: $$W_{max} = (h_1 - h_2) - T_o(S_1 - S_2) + \frac{V_1^2 - V_2^2}{2000}$$

$$= c_p(T_1 - T_2) - T_o\left[c_p \ell n\left(\frac{T_1}{T_2}\right) - R\ell n\left(\frac{P_1}{P_2}\right)\right] + \frac{V_1^2 - V_2^2}{2000}$$

where,

$T_1 = 150°C$, $T_2 = 35°C$, $T_o = 25°C$

$P_1 = 1000$ kPa, $P_2 = 140$ kPa

$V_1 = 100$ m/s and $V_2 = 50$ m/s

$$= 1.005\times(150-35) - 298\left[1.005\ell n\left(\frac{273+150}{273+35}\right) - 0.287\ell n\left(\frac{1000}{140}\right)\right] + \frac{100^2 - 50^2}{2000}$$

$$= 192.633 \text{ kJ/kg}$$

W_{act} can be calculated using S.F.E.E

$$h_1 + \frac{V_1^2}{2000} + \frac{dQ}{dm} = h_2 + \frac{V_2^2}{2000} + \frac{dW}{dm}$$

$$1.005\times 150 + \frac{100^2}{2000} + 0 = 1.005\times 35 + \frac{50^2}{2000} + \frac{dW}{dm}$$

$$\frac{dW}{dm} = W_{act} = 119.325 \text{ kJ/kg}$$

$$\eta_{II} = \frac{W_{act}}{W_{max}} = \frac{119.325}{192.633} = 0.619 \approx 61.9\%$$

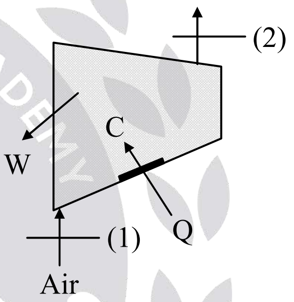
13. Ans: 85.3 %

Sol: SFEE for the compressor gives

$$\dot W = \dot Q + \dot m(h_1 - h_2)$$

$$= -100 + 1 \times 1.005(25 - 160)$$

$$= -235.7 \text{ kW}$$



Exergy balance for the compressor gives

$$\dot m a_{f1} + \dot Q\left(1 - \frac{T_o}{T}\right) - \dot W - \dot m a_{f_2} = \dot I$$

$$-\dot W = \dot m(a_{f2} - a_{f1}) - \dot Q\left(1 - \frac{T_o}{T}\right) + \dot I$$

$$\eta_{II} = \frac{\dot m(a_{f2} - a_{f1})}{\dot W}$$

$$a_{f2} - a_{f1} = h_2 - h_1 - T_o(s_2 - s_1)$$

$$= c_p(T_2 - T_1) - T_o\left(c_p \ln\frac{T_2}{T_1} - R\ln\frac{p_2}{p_1}\right)$$

$$= 1.005(160 - 25) - 298\left(1.005\ell n\left(\frac{433}{298}\right) - 0.287\ell n(8)\right)$$

$$= 200.95 \text{ kJ/kg}$$

$$\eta_{II} = \frac{200.95}{235.7} = 0.853 \text{ or } 85.3\%$$

Chapter 7 Properties of Pure Substances

01. Ans: (b)

02.

Sol: Given Non flow process & adiabatic system

$m = 1\text{kg at } P_1 = 700 \text{ kPa}, \; T_1 = 300^0 \text{C},$

$v_1 = 0.371 \text{ m}^3/\text{kg}, \qquad h_1 = 3059 \text{ kJ/kg}$

Due to Paddle work

$T_2 = 400°\text{C}, \quad v_2 = 0.44\text{m}^3/\text{kg},$

$P_2 = 700 \text{ kPa}, \quad h_2 = 3269 \text{ kJ/kg}$

At $P_1 = 700$ kPa from pressure Table

$T_{sat} = 164.95^0\text{C}$

$\Rightarrow T_1 > T_{sat}$ so it is in super heated state.

$$u_1 = h_1 - P_1v_1 = 3059 - (700 \times 0.371)$$
$$= 2799.3 \text{ kJ/kg}$$

$$u_2 = h_2 - P_2v_2 = 3269 - 700 \times 0.44$$
$$= 2961 \text{ kJ/kg}$$

It is a non flow process

$P = C$

$${}_1W_2 = P(v_2 - v_1) = 700(0.44 - 0.371)$$

$$W_s = {}_1W_2 = 48.3\text{kJ/kg}$$

For non flow process

$$u_1 + Q = u_2 + W$$

$$W = W_S + W_P = Q + (u_1 - u_2)$$

$$W_p = Q + (u_1 - u_2) - W_S$$
$$= 0 + (2800 - 2961) - 48.3$$
$$= -209.3 \text{ kJ/kg}$$

03.

Sol: Given Non flow constant volume process

$P_1 = 1.5\text{MPa} \qquad x_1 = 0.9$

$V = 0.03\text{m}^3 \qquad P_2 = 500\text{kPa}$

$$v_1 = x_1v_g = 0.9 \times 0.132 = 0.1188 \text{ m}^3/\text{kg}$$

$$h_1 = h_f + x_1h_{fg} = 845 + 0.9 \times 1947 = 2597.3\text{kJ/kg}$$

$$u_1 = h_1 - P_1v_1 = 2597.3 - (1500 \times 0.1188)$$

$$u_1 = 2419.1 \text{ kJ/kg}, \quad V = 0.03 \text{ m}^3$$

(i) Mass of wet steam $= \dfrac{V}{v_1} = \dfrac{0.03}{0.1188} = 0.253\text{kg}$

$V = C$ (Rigid vessel)

$$v_1 = v_2 = x_2v_{g2}$$

$$0.1188 = x_2(0.375)$$

(ii) $x_2 = 0.317$

$$h_2 = h_{f_2} + xh_{fg_2} = 640 + 0.317 \times 2109$$

$$h_2 = 1308.55 \text{ kJ/kg}$$

$$u_2 = h_2 - P_2v_2 = 1308.55 - 500 \times 0.1188$$
$$= 1249.15 \text{ kJ/kg}$$

(iii) $\Delta H = m(h_2 - h_1) = -1288.75 \times 0.253$
$$= -326.054 \text{ kJ}$$

$$\Delta U = m(u_2 - u_1) = 0.253(1249.15 - 2419.1)$$

$$\Delta U = -295.997 \text{ kJ}$$

For constant volume $dV = 0, {}_1W_2 = 0$

(iv) ${}_1Q_2 = m(u_2 - u_1) = \Delta U$

$$\Delta U = -295.997 \text{ kJ}$$

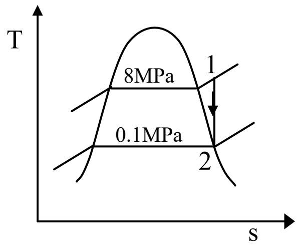
04. Ans: (d)

Sol: At P = 1 atm, $h_{fg} = 2256.5$ kJ/kg

$$\text{Power} = \frac{\dot{m}_w \times h_{fg}}{\text{time}} = \frac{0.5 \times 2256.5}{18 \times 60}$$
$$= 1.05 \text{ kW}$$

05. Ans: (a)

Sol:



$\dot{m} = 3$ kg/sec

By applying steady flow energy equation to turbine

$$\dot{m}h_1 + \dot{Q} = \dot{m}_2h_2 + \dot{W}$$

$\dot{Q} = 0$ (For adiabatic)

$$\dot{W} = \dot{m}(h_1 - h_2)$$

At 8 MPa & 500^0 C, $h_1 = 3399.5$ kJ/kg

At 0.1 MPa, $h_2 = h_{g_2} = 2675$ kJ/kg

$$\dot{W} = 3\times(3399.5 - 2675) = 2173.5 \text{ kW}$$

06. Ans: (a)

Sol: At 200 kPa,

$v_f = 0.001061$ m^3/kg, $v_g = 0.8857$ m^3/kg

$v = 300$ m^3, $P = 200$ kPa

$m_f + m_v = m$

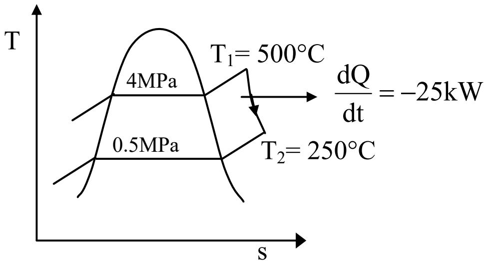
$v_f + v_v = v$

$(0.25\times m\times 0.001061)+(0.75\times m\times 0.8857) = 300$

$\Rightarrow$ $m = 451.44$ kg

07. Ans: (a)

Sol:



From tables:

$h_1 = 3446$ kJ/kg, $h_2 = 2961$ kJ/kg,

$\dot{m} = 1350$ kg/hr

Applying first law

$$\dot{m}h_1 + \frac{dQ}{dt} = \dot{m}h_2 + \frac{dW}{dt}$$

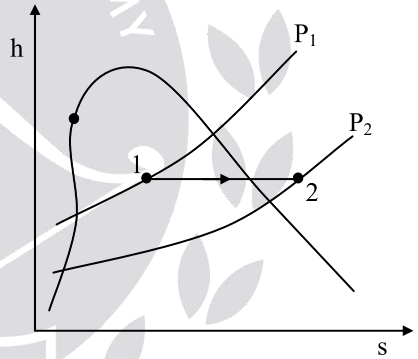
$$\frac{dW}{dt} = \dot{m}(h_1 - h_2) + \frac{dQ}{dt}$$

$$= \frac{1350}{3600}[3446 - 2961] - 25$$

$$= 156.875 \text{ kW}$$

08. Ans: 0.95

Sol:



$P_1 = 3$ MPa = 30 bar,

$h_{f_1} = 1008.41$ kJ/kg, $h_{fg} = 1795.7$ kJ/kg

$P_2 = 0.1$ MPa, $T_2 = 120°C$

From steam tables

At $P_2 = 0.1$ MPa,

$T_{sat} = 99.61°C$ and $T_2 = 100°C$,

$T_2 > T_{sat}$ (superheated)

$h = 2676.2$ kJ/kg

At $P_2 = 0.1$ MPa and $T_2 = 150°C$

$h = 2776.4$ kJ/kg

At $P_2 = 0.1$ MPa and $T_2 = 120°C$,

$h_2 = ?$

150°C → 2776.6 kJ/kg

100°C → 2675.8 kJ/kg

$dT = 50°C \rightarrow dh = 100.8$ kJ/kg

$dT' = 30°C \rightarrow x = 60.48$ kJ/kg

$\therefore h_2 = 2716.12$ kJ/kg $= h_1$

(For throttling process)

$\therefore$ If dryness fraction is x

$\therefore\ h_1 = h_{f_1} + xh_{fg_1}$

$1008.41 + x(1795.7) = 2716.12$

$\therefore\ x = 0.95$

09. Ans: 0.8488

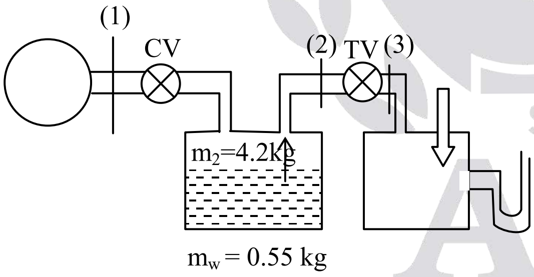
Sol: Given separating & throttling calorimeter

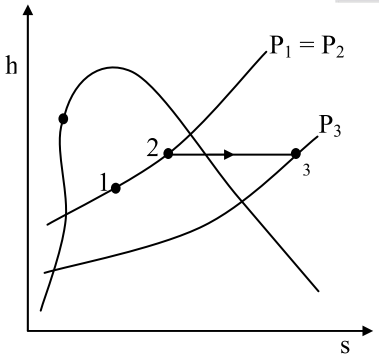
$P_1 = 15$ bar $= P_2$, $m_1 = 0.55$ kg

$T_1 = 198.3^0$ C $= T_2$, $m_2 = 4.2$ kg

$P_3 = 1$ bar, $T_3 = 120^0$ C

$\therefore h_3 = 2716.3$ kJ/kg





(Dryness fraction)$_{\text{separator}}$, $x_1 = \dfrac{m_2}{m_1 + m_2}$

$$= \frac{4.2}{4.2 + 0.55} = 0.88$$

For throttling: $h_2 = h_3$

$$h_{f_2} + x_2 h_{fg_2} = h_3$$

$844.55 + x_2(1946.4) = 2716.2$

$\Rightarrow\ x_2 = 0.9616$

Mass of vapour $= m_v = x_2 m_2 = 0.96 \times 4.2$

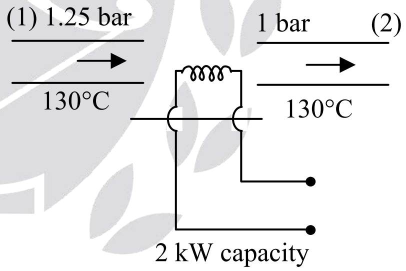
$= 4.032$ kg

(Dryness fraction)$_{\text{Boiler}} = x = \dfrac{m_v}{m_{\text{total}}} = 0.8488$

As quality of steam at boiler is < 90% so only throttling calorimeter can not be used.

10. Ans: 0.94

Sol:



From steam tables

At 1 bar, 150°C, h = 2675.8 kJ/kg

At 1 bar, 100°C, h = 2776.6 kJ/kg

A 1 bar, 130°C, $h_2 = ?$

$P_2 = 100$ kPa, $T_{sat} = 99.61°C$

$T_2 > T_{sat}$ (Superheated state)

100°C → 2776.6 kJ/kg

130°C → $h_3 = ?$

150°C → 2675.8 kJ/kg

$dT = 50°C \rightarrow 100.8$ kJ/kg

$dT' = 20°C \rightarrow x$

$$x = \frac{100.8\times 20}{50} = 40.32\,kJ/kg$$

$h_2 = 2776.6 - 40.32 = 2736.28$ kJ/kg

$$\dot{m} = \frac{3.4\,kg}{5\,min} = \frac{3.4}{300} = 0.0113\,kg/s$$

By steady flow energy equation

$$\dot{m}h_1 + \dot{Q} = \dot{m}h_2 - \dot{W}$$

$$h_1 = h_2 - \frac{\dot{Q}}{m}$$

$$= 2736.28 - \frac{2}{0.0113} = 2559.28\,kJ/kg$$

$$h_1 = h_{f_1} + xh_{fg_1} = 444.36 + x\times 2240.6$$

$x = 0.9439$

11. Ans: (a)

Sol: v_1 = specific volume $= \frac{0.025}{10} = 0.0025\frac{m^3}{kg}$

$v_1 < v_c$ (critical volume) after heating at constant volume it goes into liquid region hence level of liquid in the vessel rises.

12. Ans: (a, b, c, d)

Sol:

- Surface represent the fundamental properties of substance
- It provide a tool to study TD properties
- Each point on this surface represent an equilibrium state
- Line on the surface represent a process

Chapter 8 Air Cycles

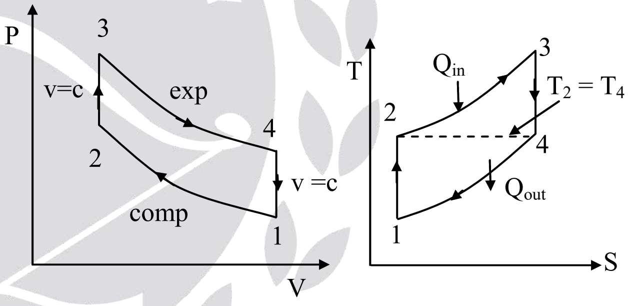
01. Ans: (a)

Sol: 1–2 → Isothermal

3–1 → Adiabatic process

02. Ans: (d)

Sol: For Maximum specific output in case of Otto cycle, the temperature of working fluid at the end of compression and expansion should be equal



03. Ans: (c)

04. Ans: (c)

Sol: $\eta_{Carnot} > \eta_{Stirling}$

(If 100% effectiveness of heat exchanger is given then carnot efficiency equals to stirling efficiency)

05. Ans: (d)

Sol: For equal r_k & heat rejected

$$\eta_{otto} > \eta_{Dual} > \eta_{Diesel}$$

06. Ans: (a)

Sol: For same maximum pressure in Otto & Diesel cycle

$$\eta_{Diesel} > \eta_{Otto}$$

And $r_{k\,Diesel} > r_{k\,Otto}$

07. Ans: (c)

08.

Sol: $Q_s = 1500$ kJ/kg,

$P_1 = 100$ kPa,

$T_1 = 27°C = 300$ K

$$r_k = 8 = \frac{V_1}{V_2} = \frac{8}{1} = \frac{V_4}{V_3}$$

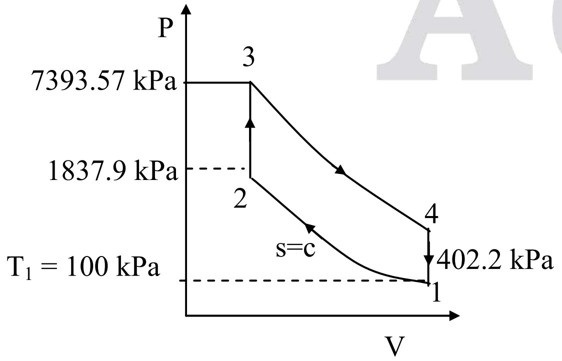
$(C_v)_{air} = 0.72$ kJ/kgK

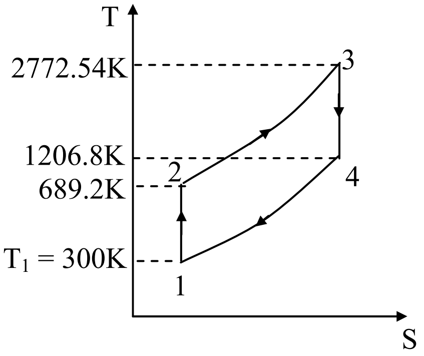
For process 1- 2

$$P_1 V_1^{\gamma} = P_2 V_2^{\gamma}$$

$$\Rightarrow \quad P_2 = P_1\left(\frac{V_1}{V_2}\right)^{\gamma} = 100 \times 8^{1.4}$$

$$= 1837.9 \text{ kPa}$$





$$T_2 = T_1\left(\frac{P_1}{P_2}\right)^{\frac{1-\gamma}{\gamma}} = 300 \times \left(\frac{100}{1837.9}\right)^{\frac{1-1.4}{1.4}}$$

$$= 689.2\text{K}$$

$$Q_S = C_v (T_3 - T_2) = 1500 \text{ kJ/kg}$$

$$\Rightarrow 0.72 \times (T_3 - 689.21) = 1500$$

$$T_3 = 2772.54 \text{ K}$$

Process 2 – 3

$$\Rightarrow \frac{P_2}{T_2} = \frac{P_3}{T_3}$$

$$\Rightarrow \; P_3 = P_2 \times \frac{T_3}{T_2} = 1837.9 \times \frac{2772.54}{689.2}$$

$$P_3 = 7393.57 \text{ kPa}$$

Process 3 – 4

$$\Rightarrow P_3 \; V_3^{\gamma} = P_4 \; V_4^{\gamma}$$

$$\Rightarrow P_4 = P_3 \times \left(\frac{V_3}{V_4}\right)^{\gamma} = 7393.47 \times \left(\frac{1}{8}\right)^{1.4}$$

$$\Rightarrow \; P_4 = 402.2\text{kPa}$$

$$T_3 \; V_3^{\gamma-1} = T_4 \; V_4^{\gamma-1}$$

$$\Rightarrow \; T_4 = 1206.8\text{K}$$

$$\eta_{Otto} = 1 - \frac{1}{(r_k)^{\gamma-1}} = 1 - \frac{1}{8^{1.4-1}}$$

$$\Rightarrow \eta_{Otto} = 0.56 = \frac{W}{1500} \Rightarrow W = 847 \text{ kJ/kg}$$

09. Ans: (c)

Sol: $V_c = 0.2\ V_s$

r_k = Compression ratio

$$= \frac{V_S + V_C}{V_C} = \frac{V_S + 0.2V_S}{0.2V} = 6$$

$$\eta_{th} = 1 - \left(\frac{1}{r_k}\right)^{\gamma-1} = 1 - \left(\frac{1}{6}\right)^{1.4-1}$$

$$= 0.5116 \quad \text{or} \quad 51.16\%$$

10. Ans: 47.36 %

Sol: $V_C = 2000$ CC

$$V_S = \frac{\pi}{4}D^2L = \frac{\pi}{4} \times 15^2 \times 45 = 7948.125\text{CC}$$

Compression Ratio

$$r_k = \frac{V_S + V_C}{V_C} = \frac{7948.125 + 2000}{2000}$$

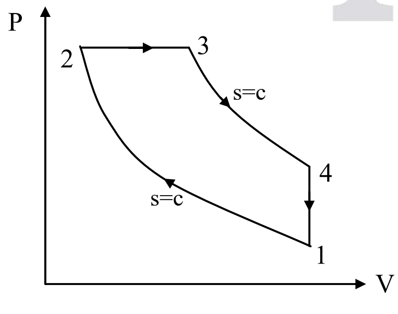
$$= 4.974$$

$$\eta_{th} = 1 - \left(\frac{1}{r_k}\right)^{\gamma-1}$$

$$= 1 - \left(\frac{1}{4.974}\right)^{1.4-1} = 0.4376 \quad \text{or} \quad 47.36\ \%$$

11. Ans: 60.8 %

Sol:



$$r_k = \frac{V_1}{V_2} = 15 \Rightarrow V_1 = 15V_2$$

$$V_3 - V_2 = \frac{6.5}{100}(V_1 - V_2)$$

$$= \frac{6.5}{100}(15V_2 - V_2)$$

$$= 0.91\ V_2$$

$$V_3 = 0.91V_2 + V_2 = 1.91V_2$$

$$r_c = \frac{V_3}{V_2} = 1.91$$

$$\eta_{th} = 1 - \frac{1}{\gamma \cdot r_k^{\gamma-1}} \cdot \frac{r_c^{\gamma} - 1}{r_c - 1}$$

$$= 1 - \frac{1}{1.4 \times 15^{0.4}} \cdot \left(\frac{1.91^{1.4} - 1}{1.91 - 1}\right) = 60.8\%$$

12. Ans: (c)

Sol: $V_1 = 3L$,

$V_2 = 0.15L$

Compression ratio

$$r_k = \frac{V_1}{V_2} = \frac{3}{0.15} = 20$$

$$r_c = \frac{V_3}{V_2} = \frac{0.30}{0.15} = 2$$

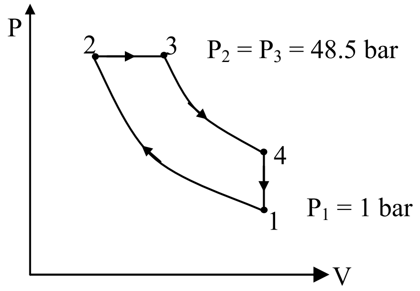
$$\eta_{Diesel} = 1 - \frac{1}{\gamma} \cdot \frac{1}{r_k^{\gamma-1}} \cdot \frac{r_c^{\gamma} - 1}{r_c - 1}$$

$$= 1 - \frac{1}{1.4} \times \frac{1}{(20)^{1.4-1}} \times \frac{2^{1.4} - 1}{(2-1)} = 0.6467$$

$$= 64.67\%$$

13. Ans: 63.44 %

Sol:



$$\text{Compression ratio} = r_k = \frac{V_1}{V_2}$$

$$\text{Expansion ratio} = r_E = \frac{V_4}{V_3} = \frac{V_1}{V_3} = 10$$

$$P_1V_1^{\gamma} = P_2V_2^{\gamma}$$

$$r_k = \frac{V_1}{V_2} = \left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}} = \left(\frac{48.5}{1}\right)^{\frac{1}{1.4}} = 16$$

$$\text{Fuel cut off ratio} = r_C = \frac{V_3}{V_2} = \frac{r_k}{r_E} = \frac{16}{10} = 1.6$$

$$\eta_{th} = 1 - \frac{1}{\gamma . r_k^{\gamma-1}}\left[\frac{r_C^{\gamma} - 1}{r_C - 1}\right]$$

$$= 1 - \frac{1}{(1.4)16^{(1.4-1)}}\left[\frac{1.6^{1.4} - 1}{1.6 - 1}\right]$$

$$= 1 - \frac{1}{1.4 \times 3.0314}\left[\frac{1.9309 - 1}{1.6 - 1}\right] = 0.6344$$

14. Ans: 235.5 kPa

Sol: $D_1 = 500 - 200 = 300$ kPa

$D_2 = 0.03 - 0.01 = 0.02\ m^3$

$${}_1W_2 = \frac{\pi}{4} \times D_1 \times D_2$$

$${}_1V_2 = V_2 - V_1 = 0.03 - 0.01 = 0.02\ m^3$$

$$\text{mep} = \frac{\text{work done}}{\text{swept volume}} = \frac{{}_1W_2}{{}_1V_2} = \frac{\frac{\pi}{4} \times D_1 \times D_2}{(V_1 - V_2)}$$

$$= \frac{\frac{\pi}{4} \times 300 \times 0.02}{0.02}$$

$$= 75\ \pi = 75 \times 3.14 = 235.5 \text{ kPa}$$

15. Ans: (b)

Sol: Swept volume = $V_s = 0.03\ m^3$

$$(\text{work})_{net} = \frac{\text{work(kW)}}{\text{N(rps)}} = \frac{1000}{\frac{2000}{60}} = 30\,\text{kJ}$$

$$\text{mep} = \frac{W_{net}(\text{kJ})}{V_s(m^3)} = \frac{30}{0.03} = 1000\text{kPa} = 1\text{MPa}$$

16. Ans: (b)

Sol: $v_1 = \frac{1}{\rho_1} = \frac{1}{1.2} = 0.833\,m^3/kg$

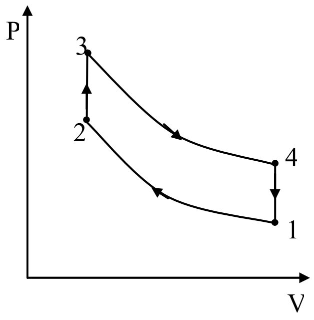
$$r_k = \frac{V_1}{V_2} = \frac{2.2}{0.26} = 8.46$$

$$V_2 = \frac{0.834}{8.46} = 0.098 m^3/kg$$

$$\text{mep} = \frac{W_{net}}{V_1 - V_2} = \frac{440}{0.833 - 0.098} = 598.8\ \text{kPa}$$

17.

Sol: $\eta = 0.54 = 1 - \left(\frac{1}{r_k}\right)^{\gamma - 1} = 1 - \left(\frac{1}{r_k}\right)^{0.4}$



$$\left(\frac{1}{r_k}\right)^{0.4} = 0.46$$

$$r_k = \frac{1}{(0.46)^{2.5}} = 6.97$$

$P_1 = 1$ bar

$T_1 = 273 + 15 = 288$ K

$P_3 = 75$ bar

$P_2 = P_1 r_k^{\gamma} = 1 \times (6.97)^{1.4}$

$= 15.154$ bar

$T_2 = T_1\, r_k^{\gamma-1} = 288(6.97)^{1.4-1} = 626.16$ K

$$T_3 = T_2 \times \frac{P_3}{P_2} = 626.16 \times \frac{75}{15.154} = 3099\text{K}$$

Heat supplied $= C_v \times (T_3 - T_2)$

$= 0.718(3099 - 626.16)$

$Q_s = 1775.5$ kJ/kg

Work done $= \eta_{th} \times Q_s$

$W = 0.54 \times 1775.5 = 958.77$ kJ/kg

Heat rejected $= Q_S - W = 1775.5 - 958.77$

$= 816.73$ kJ/kg

$$v_1 = \frac{RT_1}{P_1} = \frac{0.287 \times 288}{100} = 0.82656\frac{\text{m}^3}{\text{kg}}$$

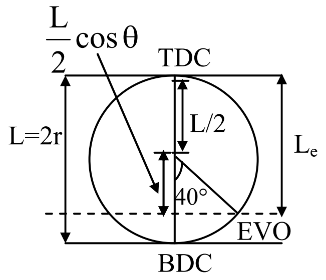
$$v_2 = \frac{RT_2}{P_2} = \frac{0.287 \times 626.16}{1515.4} = 0.1186\frac{\text{m}^3}{\text{kg}}$$

$$\text{mep} = \frac{W_{net}\left(\frac{\text{kJ}}{\text{kg}}\right)}{(v_1 - v_2)\left(\frac{\text{m}^3}{\text{kg}}\right)} = \frac{958.77}{0.82656 - 0.1186}$$

$$= \frac{958.77}{0.70796} = 1354.27\,\text{kPa}$$

18. Ans: 54 %

Sol:



L = 14 cm , θ = 40° , D = 10 cm

Effective stroke length

$$L_e = L/2 + \frac{L}{2}\cos\theta$$

$= 7+7\cos 40 = 12.36$ cm

Effective stroke volume

$$(V_s)_{eff} = \frac{\pi}{4}D^2 L_e = \frac{\pi}{4} \times 10^2 \times 12.36 = 970.75\text{cm}^3$$

$V_C = 157$ cm^3

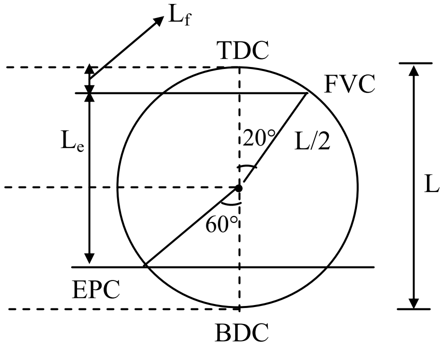
$$(r_k)_{effective} = \frac{(V_s)_{eff} + V_C}{V_C} = \frac{970.75 + 157}{157} = 7.18$$

$$\eta_{th} = 1 - \left(\frac{1}{r_k}\right)^{\gamma-1} = 1 - \left(\frac{1}{7.18}\right)^{0.4}$$

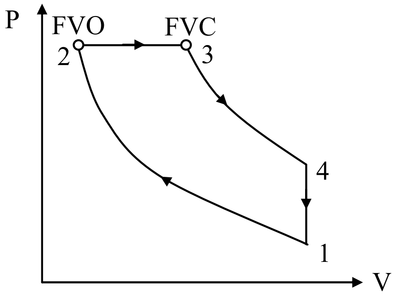
$= 0.54$ or 54%

19. Ans: 66.5 %

Sol:



D = 10 cm , L = 14 cm



$$L_e = \frac{L}{2} + \frac{L}{2}\cos\theta = 7 + 7\cos 60^\circ = 10.5 \text{ cm}$$

$$L_f = \frac{L}{2} - \frac{L}{2}\cos\theta_1$$

$$= 7 - 7\cos 20^0$$

$$= 0.42 \text{ cm}$$

$$(V_s)_{eff} = \frac{\pi}{4} D^2 L_e = \frac{\pi}{4} \times 10^2 \times 10.5$$

$$= 824.6 \text{ cm}^3$$

$$V_C = 40.2 \text{ cm}^3$$

$$(r_k)_{effective} = \frac{(V_s)_{eff} + V_C}{V_C} = 21.51$$

Volume corresponding to fuel cutoff

$$V_3 - V_2 = \frac{\pi}{4} D^2 L_f = \frac{\pi}{4} \times 10^2 \times 0.42$$

$$= 32.98 \text{ cc}$$

$$V_3 - 40.2 = 32.98.$$

$$V_3 = 73.18$$

$$r_c = \frac{V_3}{V_2} = \frac{73.18}{40.2} = 1.82$$

$$\eta_{th} = 1 - \frac{1}{\gamma r_k^{\gamma-1}} \cdot \frac{r_c^{\gamma} - 1}{r_c - 1}$$

$$= 1 - \frac{1}{1.4 \times (21.51)^{0.4}} \times \frac{1.82^{1.4} - 1}{1.82 - 1}$$

$$= 66.5\%$$

20. Ans: 503 mm^2

Sol: $IP = \dfrac{p_{mi} L A N n}{120{,}000}$

$$= \frac{\frac{A_d}{L_d} \times k \times L \times A \times N \times n}{120000}$$

$$4 = \frac{\frac{A_d}{0.1L} \times 25 \times 10^6 \times L \times \frac{\pi}{4}(0.15)^2 \times 216 \times 1}{120000}$$

$$A_d = 503 \text{ mm}^2$$

21. Ans: (a, b, d)

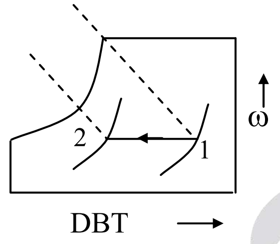
Sol:

- Diesel cycle efficiency is always more than Otto cycle
- Otto cycle is used for two stroke CI engine
- Dual cycle is used for high speed Diesel engine
- For compression ratio more than 12 efficiency of Otto cycle increases

Chapter 9 Psychrometry

01. Ans: (b)

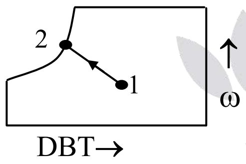
Sol:



During sensible cooling of air
DBT decreases, WBT decreases, h decreases and ω = constant,
DPT = constant, R.H increases

02. Ans: (c)

Sol:



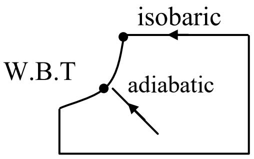
During adiabatic saturation process DBT decreases, WBT = constant, h = constant, specific humidity (ω) increases, DPT increases, relative humidity increases.

03. Ans: (b)

Sol: When warm saturated air is cooled, excess moisture condenses but relative humidity remains unchanged

04. Ans: (c)

Sol: **Case (A):** Moist air is adiabatically saturated
Case (B): Moist air is isobarically saturated



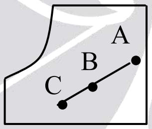
Case-(A): Adiabatically saturated → W.B.T
Case-(B): isobarically saturated → D.P.T

05. Ans (b)

Sol: For dehumidification, the coil temperature should be less than the dew point temperature of the incoming air.

06. Ans: (d)

Sol:

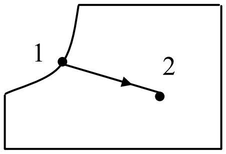


By pass factor = $\frac{BC}{AC}$

07. Ans: (b)

08. Ans: (d)

Sol:



During chemical dehumidification
Enthalpy & W.B.T remains constant, specific humidity decreases, dew point temperature decreases and relative humidity decreases.

09. Ans: (c)

10. Ans: (a)

Sol: T_{coil} is greater than dew point temperature but less than dry bulb temperature hence it is sensible cooling.

11. Ans: (c)

Sol: Temperature of water spray is greater than dew point temperature hence it is a heating process and water molecules are mixing with air hence it is humidification.

12. Ans: (b)

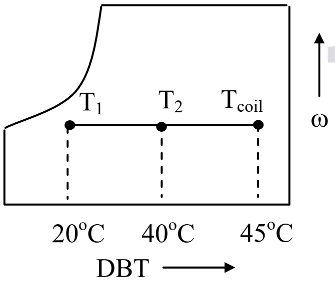
Sol: Heat is absorbed so it is absorption or chemical process in which WBT remains constant & DBT increases.

13. Ans: (a)

Sol: $$\mu = \phi \times \left(\frac{P_{atm} - P_{sat}}{P_{atm} - P_v}\right) = \frac{P_b - P_s}{P_b - P_v} \times \phi$$

14. Ans: (a)

Sol:



$$\text{By pass factor} = \frac{T_{coil} - T_2}{T_{coil} - T_1} = \frac{45-40}{45-20}$$

$$\text{BPF} = 0.2$$

15. Ans: (c)

Sol: L.H.L = 0.25 S.H.L

$$\text{S.H.F} = \frac{\text{SHL}}{\text{SHL} + \text{LHL}}$$

$$\text{S.H.F} = \frac{\text{S.H.L}}{1.25 \times \text{S.H.L}} = 0.8$$

16. Ans: (d)

Sol: $T_{sat} = 25°C \rightarrow \phi = 100\%$

$P_{sat} = 3.1698$ kPa

$P_{total} = 100$ kPa

$$\phi = \frac{P_V}{P_{sat}} = 1 \quad \Rightarrow P_V = P_{sat} = 3.1698\,\text{kPa}$$

$$\omega = 0.622\frac{P_V}{P_{atm} - P_V} = 0.622 \times \frac{3.1698}{100 - 3.1698}$$

$$= 0.0204 \times \frac{\text{kg Vap}}{\text{kg dry air}}$$

$$\omega = \frac{m_v}{m_a}$$

$$m_V = 100 \times 0.0204 = 2.04\,\text{kg}$$

17. Ans: (c)

Sol: $$\omega = \frac{m_v}{m_a} = \frac{0.6}{50} = 0.012\frac{\text{kg of Vapour}}{\text{kg of dry air}}$$

$T_{sat} = 25^0\text{C}$,

$P_{sat} = 3.1698$ kPa

$$\omega = 0.622\frac{P_v}{95 - P_v} = 0.012$$

$P_V = 1.798$ kPa

$$\phi = \frac{P_v}{P_{sat}} = \frac{1.798}{3.1698} = 0.567 = 56.7\%$$

18. Ans: (c)

Sol: $T_{sat} = 30°C \rightarrow P_{sat} = 4.2469$ kPa

$$P_{atm} = 90\text{ kPa},\quad \phi = \frac{P_V}{P_{sat}} = 75\%$$

$$P_V = 0.75 \times 4.2469 = 3.185\text{ kPa}$$

$$P_a = P_{atm} - P_v$$

$$P_{air} = 86.815\text{ kPa}$$

$$m_a = \frac{P_a V}{R_a T} = \frac{86.815 \times 40}{0.287 \times 303} = 39.93\text{ kg}$$

19.

Sol: $T_{sat} = 30°C$

$P_{atm} = 100$ kPa

$P_{sat} = 4$ kPa

$$\mu = 0.24 = \frac{P_v(P_{atm} - P_{sat})}{P_{sat}(P_{atm} - P_v)} = \frac{P_V(100-4)}{4(100-P_v)}$$

$$400 \times 0.24 - 0.24\,Pv = 100\,P_v - 4P_v$$

$$96.24\,P_v = 400 \times 0.24$$

$$P_v = \frac{400 \times 0.24}{96.24} = 0.9975\text{ kPa}$$

Relative humidity

$$\phi = \frac{P_v}{P_{sat}} = \frac{0.9975}{4} = 0.2493 \text{ or } 24.93\%$$

$$\omega = 0.622\,\frac{P_v}{P_{atm} - P_v}$$

$$= 0.622 \times \frac{0.9975}{100 - 0.9975} = 0.00627\,\frac{\text{kg.vap}}{\text{kg.d.a}}$$

20.

Sol: $P_{atm} = 101$ kPa ; $T_{sat} = 40^oC$

$P_{sat} = 7.38$ kPa

$$\phi = 0.5 = \frac{P_v}{P_{sat}} = \frac{P_v}{7.38}$$

$$P_v = 3.692$$

$$\omega = 0.622\,\frac{P_v}{P_{atm} - P_v}$$

$$= 0.622 \times \frac{3.692}{101 - 3.692}$$

$$\omega = 0.0235\,\frac{\text{kgVap}}{\text{kg da}}$$

As gas is compressed partial pressure increases in the same ratio,

$$P_v = 3.692 \times \frac{5.05}{1.01}$$

At 150^{o}C,

$P_{sat} = 475.8$ kPa

$$\phi = \frac{P_v}{P_{sat}} = \frac{18.46}{475.8} \times 100 = 3.9\ \%$$

21. Ans: 1.125 kPa

Sol: $P_1 = 100$ kPa

$P_2 = 500$ kPa

DBT = 35°C

$P_{VS} = 5.628$ kPa

$$\omega_S = 0.622 \times \frac{P_{VS}}{P_2 - P_{VS}} = 0.622 \times \frac{5.628}{500 - 5.628}$$

$$= 7.08 \times 10^{-3}\text{ kg vapour/kg dry air}$$

$$\omega_2 = \omega_{s3} = 7.08 \times 10^{-3}$$

($\because$ pressure remains constant in after cooler)

Moisture is same throughout the process i.e., in compressor no moisture is removed or added and in after cooler, the pressure is constant so the moisture content will not change.

$$\omega_1 = 0.622 \times \frac{P_V}{P_1 - P_V}$$

$$\frac{7.08\times10^{-3}}{0.622} = \frac{P_V}{(100 - P_V)}$$

$\therefore$ $P_V = 1.125$ kPa

22. Ans: (d)

Sol: $T_{sat} = 20°C$, $P_{sat} = 2.339$ kPa

$\phi = 0.5$

$$\phi = \frac{P_V}{P_{sat}} \Rightarrow P_V = 0.5 \times 2.339 = 1.169 \text{ kPa}$$

Corresponding to partial pressure of vapor whatever the saturation temperature is the temperature at which the water vapor present in air starts condensing and this beginning of this condensation is called as dew point temperature.

At 5°C $\rightarrow$ 0.8725

T_2 - ? $\rightarrow$ $P_2 = 1.169$

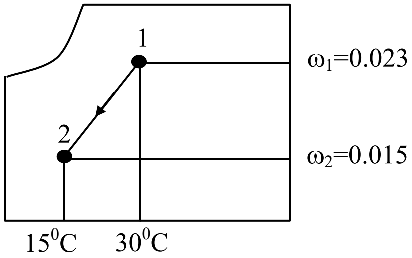
10°C $\rightarrow$1.2281

$$\frac{1.2281 - 0.8725}{1.169 - 0.8725} = \frac{10 - 5}{T_2 - 5}$$

$T_2 = 9.16$ °C

23. Ans: (d)

Sol:



Cooling load on coil h_1

$$= C_{Pa}(T_1 - 0) + \omega_1\left[(h_{fg})_{0^0C} + C_{PV}(T_1 - 0)\right]$$

$$= 1.005 \times (30 - 0) + 0.023[2500 + 1.88(30 - 0)]$$

= 88.94 kJ/kg of dry air

$$h_2 = C_{Pa}(T_2 - 0) + \omega_2\left[(h_{fg})_{0^0C} + C_{PV}(T_2 - 0)\right]$$

$$= 1.005(15 - 0) + 0.015[2500 + 1.88(15 - 0)]$$

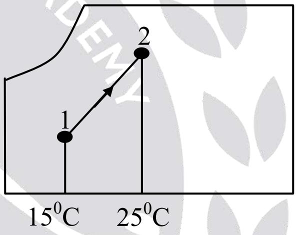
= 52.99 kJ/kg of dry air

Total heat load = m_a (h_2–h_1)

= 0.7(52.99–88.94) = –25 kW

24. Ans: (a)

Sol:



$P_{total} = 90$ kPa, $T_{sat} = 15°C$, $P_{sat} = 1.7057$ kPa

$$\phi_1 = \frac{P_{V_1}}{P_{sat_1}} = 0.75$$

$P_{V1} = 1.278$ kPa

$$\omega_1 = 0.622 \times \frac{P_{V1}}{P_{atm} - P_{V1}} = 0.622 \times \frac{1.278}{90 - 1.278}$$

$$= 0.0089 \frac{\text{kg of vapour}}{\text{kg of dry air}}$$

$T_{sat} = 25°C$, $P_{sat} = 3.1698$ kPa, $\phi = 0.75$

$$\phi = \frac{P_{V2}}{P_{sat2}} \Rightarrow P_{V2} = 2.377 \text{ kPa}$$

$$\omega_2 = 0.622 \times \frac{P_{V_2}}{P_{atm} - P_{V_2}}$$

$$= 0.622 \times \frac{2.377}{90 - 2.377} = 0.0168 \frac{\text{kg of Vap}}{\text{kg of dry air}}$$

Mass of vapour added,

$$\dot{m}_v = \dot{m}_a(\omega_2 - \omega_1)$$
$$= 4(0.0168 - 0.0089)$$
$$= 0.03\,\text{kg of vapour/sec}$$

25. Ans: 769 m

Sol: $P_{sat} = 3.166$ kPa,

$T_{sat} = 25°C = 298$ K

$$\phi = 0.74 = \frac{P_v}{P_{sat}} = \frac{P_v}{3.166}$$

$P_v = 0.74 \times 3.166 = 2.34$ kPa,

At 2.34 kPa ,

$T_{sat} = 20^0C = 293\text{ K} = \text{DPT}$

Corresponding to saturation temperature whatever the saturation pressure, the water vapor starts condensing.

$dT = 298 - 293 = 5$ K

6.5 K drops in temperature = 1000 m

$$5\text{ K drop temperature} = \frac{5}{6.5}\times 1000$$
$$= 769\text{ m}$$

26. Ans: 0.02

Sol: $m = m_a + m_{v_1}$

$$\frac{m}{m_a} = 1 + \frac{m_{v1}}{m_a}$$

$$\frac{m}{m_a} = 1 + \omega_1$$

$$\frac{10.1}{m_a} = 1.01$$

$$\dot{m}_a = \frac{10.1}{1.01} = 10\,\text{kg/sec}$$

$$\dot{m}_{v_1} = \omega_1 \times m_a = 0.01 \times 10 = 0.1\,\text{kg/sec}$$

$$\dot{m}_{v_2} = 0.1\text{ kg/sec}$$

Total mass of vapour after mixing

$$= \dot{m}_v = \dot{m}_{v_1} + \dot{m}_{v_2}$$
$$= 0.1 + 0.1$$
$$= 0.2\,\text{kg/sec}$$

Specific humidity of mixture

$$\omega = \frac{\dot{m}_v}{\dot{m}_a} = \frac{0.2\,\text{kg/sec}}{10\,\text{kg/sec}}$$

= 0.02 kgvap/kgd.a

27. Ans: (a, b, d)

Sol:

- For given total atmospheric pressure specific humidity is only function at partial pressure of vapour
- Steam spray is an example of heating and humidification
- Silica gel is used for heating and dehumidification
- Air cooler is an example of sensible cooling

Chapter 10 Rankine Cycle

01. Ans: (d)

Sol: Assertion is false and Reason is true

Steam rate or specific steam consumption

$$= \frac{1}{W_T - W_C}\frac{kg}{kW\,sec} = \frac{3600}{W_T - W_P}\frac{kg}{kW.hr}$$

For Carnot cycle as pump work is very high so specific steam consumption is very high.

For Carnot cycle the mean temperature heat addition is greater than Rankine cycle, so $\eta_C > \eta_R$

02. Ans: (d)

03. Ans: (a)

Sol: At 5 MPa,

$T_{sat} = 263.9°C$,

At 2 MPa,

$T_{sat} = 212.38°C$

$$\eta_{Carnot} = \frac{263.9 - 212.38}{263.9 + 273} = 0.095$$

Work done = 0.095 × 380 = 36.5 kW

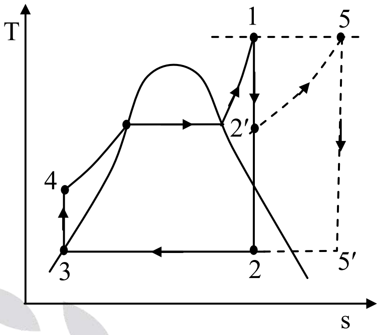
Note: Correct answer is option (a)

04. Ans: (b)

Sol: The expansion process in turbine like 1-2 is carried out in modified Rankine cycle.

05. Ans: (c)

Sol: Due to reheating in Rankine cycle :



(i) Work output of turbine increases as expansion is carried in two stages.

$W(\text{without reheat}) = h_1 - h_2$

$W(\text{with reheat}) = (h_1 - h_2') + (h_5 - h_5')$

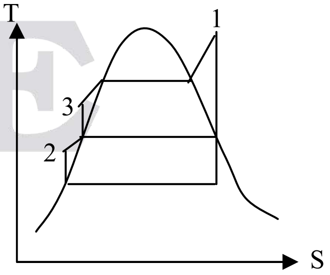
(ii) Turbine efficiency increases as mean temperature of heat addition increases.

(iii) Specific steam consumption $= \frac{3600}{W_{net}}$

As W_{net} increases so specific steam consumption decreases.

06. Ans: (b)

Sol:



$h_1 = 3514$ kJ/kg

$W_{HP} = 3$ kJ/kg

$h_2 = 613$ kJ/kg,

$W_{LP} = 1$ kJ/kg

$h_3 - h_2 = W_{HP}$

$h_3 - 613 = 3$

$h_3 = 616$ kJ/kg

$Q_S = h_1 - h_3 = 3514 - 616$

$= 2898$ kJ/kg

07. Ans: (d)

Sol: $$\eta = \frac{P_W}{\text{Power input}} = \frac{vdp}{\text{Power input}}$$

$$0.75 = \frac{\frac{0.15}{60}(5000-200)}{P_i}$$

$P_i = 16$ kW

08. Ans: 3.6

Sol: Specific steam consumption $= \dfrac{3600}{W_{net}}$

$W_T = 3103 - 2100 - 3 = 1000$ kJ/kg

Specific steam consumption $= \dfrac{3600}{1000}$

$= 3.6$ kg/kW-hr

09.

Sol: At $T_1 = 500°C$ and 7 MPa

$h_1 = 3410.3$ kJ/kg

$s_1 = 6.7975$ kJ/kgK

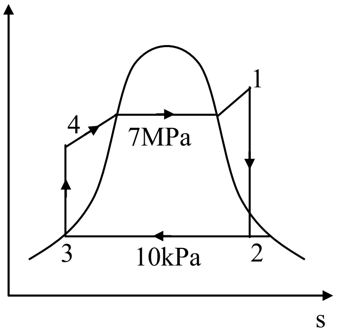
At 10 kPa

$h_3 = h_{f_3} = 191.83$ kJ/kg

$s_3 = s_{f_3} = 0.6493$ kJ/kgK

$v_3 = v_{f_3} = 1.01 \times 10^{-3}$ m^3/kg

$s_{g_2} = 8.1502$ kJ/kgK



Process (1-2)

$Q = 0, \; s = c$

$s_1 = s_2 = 6.7975 \text{ kJ/kg K} < 8.1502 \dfrac{\text{kJ}}{\text{kgK}}$

So point 2 is in wet state

$s_2 = s_{f2} + x_2 s_{fg_2}$

$6.7975 = 0.6493 + x_2 (8.1502 - 0.6493)$

$x_2 = 0.82$

$h_2 = h_{f_2} + x_2 h_{fg_2}$

$= 191.83 + 0.82 \times 2392.8$

$= 2153.92$ kJ/kg

Process (3-4)

$s_3 = s_4 = 0.6393$ kJ/kgK

$W_p = h_4 - h_3 = V_{f_3} \times (P_{boil} - P_{cond})$

$= 1.01 \times 10^{-3} (7000 - 10)$

$= 7.05$ kJ/kg

$h_4 = 7.05 + 191.83 = 198.88$ kJ/kg

$W_T = h_1 - h_2 = 3410.3 - 2153.92$

$= 1256.4$ kJ/kg

Heat supplied, $Q_S = h_1 - h_4$

$3410.3 - 198.88 = 3211.5$ kJ/kg

$W_{net} = W_T - W_P = 1256.4 - 7.05$

$= 1249.35$ kJ/kg

$$\text{Work ratio} = \frac{W_{net}}{W_T} = \frac{1249.35}{1256.4} = 0.99$$

$$\eta_{th} = \frac{W_{net}}{Q_S} = \frac{1249.35}{3211.5} = 38.9\%$$

$$\text{Steam rate} = \frac{3600}{W_{net}} = 2.8816 \text{ kg/kW-hr}$$

$$\text{Heat rate} = \frac{3600}{\eta_{th}} = 9254 \text{ kJ/kW-hr}$$

$$\text{Power} = \dot{m}_s \times W_{net} = 30 \times 10^3$$

$$\dot{m}_s = \frac{30\times10^3}{1249.35} = 24.01 \text{ kg/sec}$$

Boiler capacity is mass flow rate of steam expressed in kg/hr

$= 24.01 \times 3600$ kg/hr

$= 86436$ kg/hr

Condenser load $= \dot{m}_s (h_2 - h_3)$

$= 24.01\ (2153.92 - 191.83)$

$= 47109.7$ kW

$(\Delta T)_w$ = rise in temperature of water

Heat gained by water = condenser load

$$\dot{m}_w \times C_{pw} \times (\Delta T)_w = 47109.7$$

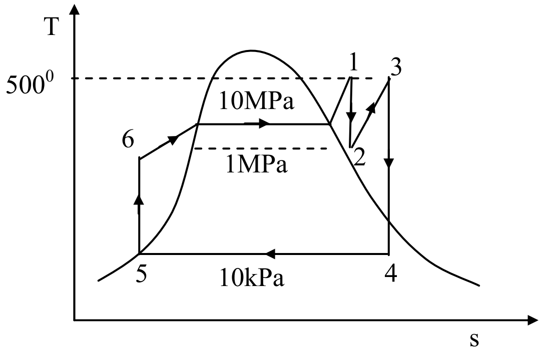
$$(\Delta T)_w = \frac{47109.7}{2000\times4.186} = 5.63°C$$

10.

Sol: State – 1

$P_1 = 10$ MPa, $T_1 = 500°C$

$h_1 = 3373.7$ kJ/kg, $s_1 = 6.5966$ kJ/kgK



State – 2

$P_2 = 1$ MPa, $T_2 = ?$

$T_{sat} = 179.91°C$, $h_2 = ?$

$s_1 = 6.5966$ kJ/kg $= s_2$

$$s_2 = s_{g_2} + C_{P_{Vapur}} \times ln\left(\frac{T_2}{T_{sat}}\right)$$

(As $s_2 > s_{g2}$ it is in superheated state)

$s_2 = 6.5966$ kJ/kgK

$$= 6.5865 + 2.1\times ln\left(\frac{T_2}{(273+179.91)}\right)$$

$T_2 = 455.09$ K

$$h_2 = h_{g_2} + C_{P_{vapour}} \times (T_2 - T_{sat})$$

$= 2778.1+2.1[455.09–(273 + 179.91)]$

$= 2782.67$ kJ/kg

State – 3

$P_3 = 1$ MPa, $T_3 = 500°C$

$h_3 = 3478.5$ kJ/kg, $s_3 = 7.7622$ kJ/kgK

State – 4

$P_4 = 10$ kPa, $T_4 = 45.81°C$, $h_4 = ?$

$s_4 = s_3 = 7.7622$ kJ/kg K

$$s_4 = s_{f_4} + x_4\left(s_{g_4} - s_{f_4}\right)$$

$= 0.6493 + x_4(8.1502 - 0.6493)$

$x_4 = 0.94 \rightarrow$ (wet state)

$h_4 = h_{f_4} + x_4\left(h_{g_4} - h_{f_4}\right)$

$= 191.83 + 0.94\ (2584.6 - 191.83)$

$= 2441.03$ kJ/kg

State – 5

$P_5 = 10$ kPa

$h_5 = (h_f)_w = 191.83$ kJ/kg

$s_5 = s_{f_5} = 0.6493$ kJ/kg K

$v_5 = 0.0010\ m^3 kg$

State – 6

$P_6 = 1$ MPa

$S_6 = 0.6493$ kJ/kg.K

$W_p = v_{f_5}\ (P_6 - P_5)$

$= 0.0010 \times (10\times10^3 - 10) = 9.99$ kJ/kg

$W_p = (h_6 - h_5)$

$h_6 = W_p + h_5$

$= 9.99 + 191.83 = 201.82$ kJ/kg

$W_T = (h_1 - h_2) + (h_3 - h_4)$

$=(3373.7 - 2782.67) + (3478.5 - 2441.03)$

$= 1628.5$ kJ/kg

$W_{net} = W_T - W_P = 1628.5 - 9.99$

$= 1618.51$ kJ/kg

$$\text{Work ratio} = \frac{W_{net}}{W_T} = \frac{1618.51}{1628.5} = 0.99$$

Heat supplied $Q_S = (h_1 - h_6) + (h_3 - h_2)$

$= (3373.7 - 201.82) + (3478.5 - 2782.67)$

$= 3867.71$ kJ/kg

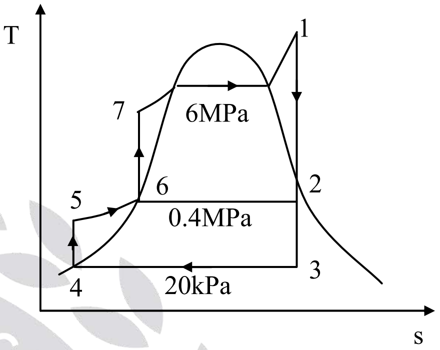
$$\eta_{th} = \frac{W_{net}}{Q_S} = \frac{1618.51}{3867.71} = 0.418 = 41.8\%$$

11.

Sol: ***State - 1:*** (super heated)

$P_1 = 6$ MPa, $T_1 = 450°C$

$h_1 = 3301.8$ kJ/kg, $s_1 = 6.7193$ kJ/kgK



State - 2: (wet state)

$P_2 = 0.4$MPa, $h_2 = ?$, $T_2 = ?$

$s_2 = 6.7193$ kJ/kg, $s_{g_2} = 6.8959$ kJ/kg K

As $s_2 < s_{g_2}$ this is in wet state

$s_2 = s_{f_2} + x_2\left(s_{g_2} - s_{f_2}\right)$

$6.7193 = 1.7766 + x_2(6.8959 - 1.7766)$

$x_2 = 0.96$

$h_2 = h_{f_2} + x_2\left(h_{g_2} - h_{f_2}\right)$

$= 604.74 + 0.96\ (2738.6 - 604.74)$

$= 2653.24$ kJ/kg

State - 3: (wet state)

$P_3 = 20$ kPa, $h_3 = ?$

$s_2 = s_3 = 6.7193$ kJ/kgK

$s_{g_3} = 7.9085$ kJ/kg K

$6.7193 = 0.8320 + x_3(7.9085 - 0.8320)$

$x_3 = 0.83$

$h_3 = h_{f_3} + x_3\left(h_{g_3} - h_{f_3}\right)$

$= 251.4 + 0.83\ (2609.7 - 251.40)$

$= 2208.8$ kJ/kg

State - 4: **(saturated)**

$P_4 = 20$ kPa

$h_4 = h_{f_4} = 251.40$ kJ/kg

State - 5: **(compressed)**

$P_5 = 0.4$ MPa

State – 6: **(saturated)**

$P_6 = 0.4$ MPa

$h_6 = h_{f_6} = 604.74$ kJ/kg

$s_6 = 1.7766$ kJ/kg.K

State – 7: **(compressed)**

$P_7 = 6$ MPa

High pressure pump work

$W_{HP} = v_{f_6}(P_7 - P_6)$

$= 1.084 \times 10^{-3}(6 \times 10^3 - 0.4 \times 10^3)$

$= 6.0704$ kJ/kg

$h_7 = h_6 + W_{HP}$

$= 604.74 + 6.0704 = 610.08$ kJ/kg

Low pressure pump work

$W_{LP} = v_{f_4}(P_5 - P_4)$

$= 1.017 \times 10^{-3}(0.4 \times 10^3 - 20)$

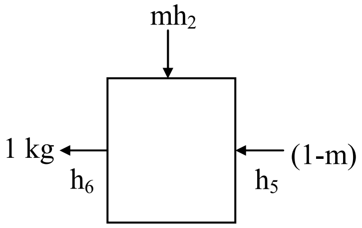
$= 0.386$ kJ/kg

$h_5 = h_4 + W_{LP}$

$= 251.40 + 0.386 = 251.786$ kJ/kg

The mass of steam m_1 extracted from turbine at 0.4 MPa

Energy balance:



Energy in = Energy out

$(1-m)\,h_5 + mh_2 = 1 \times h_6$

$\Rightarrow\ m(h_2 - h_5) = h_6 - h_5$

$$m = \frac{h_6 - h_5}{h_2 - h_5}$$

$$= \frac{604.74 - 251.786}{2653.24 - 251.786} = 0.146\,\text{kg}$$

$W_T = (h_1 - h_2) + (1-m)(h_2 - h_3)$

$= (3301.8 - 2653.24) + (1 - 0.146) \times (2653.24 - 2208.8)$

$= 1028.12$ kJ/kg

$W_P = W_{HP} + W_{LP}$

$= 6.0704 + 0.386 = 6.456$ kJ/kg

$W_{net} = W_T - W_P = 1028.12 - 6.456$

$= 1021.66$ kJ/kg

$Q_s = h_1 - h_7$

$= 3301.8 - 610.07 = 2691.73$ kJ/kg

$$\eta_{th} = \frac{W_{net}}{Q_s} = \frac{1021.66}{2691.73} = 0.379 = 37.9\%$$

12. Ans: (a, b, c, d)

Sol: Carnot cycle cannot be considered as the theoretical cycle for steam power plant because

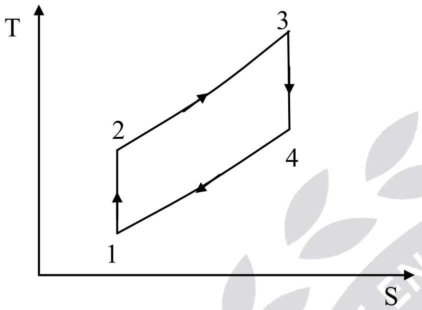
- the compression work is high
- net work is high
- superheat cannot be advantage
- compression of mixture is very difficult

Chapter 11

Gas Turbines

01.

Sol:



Given

$T_1 = 300$ K

$P_1 = 0.1$ MPa

$$\frac{P_2}{P_1} = 6.25 = \frac{P_3}{P_4}$$

$T_3 = 800 + 273 = 1073$ K

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = (6.25)^{\frac{0.4}{1.4}} \quad \{\gamma = 1.4 \text{ for air}\}$$

$T_2 = 506.4$ K

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{0.4}{1.4}} = (6.25)^{\frac{0.4}{1.4}}$$

$$\frac{1073}{T_4} = (6.25)^{\frac{0.4}{1.4}}$$

$T_4 = 635.6$ K

(a) Work done on the compressor

$W_C = m \times C_p \times (T_2 - T_1)$

$= 1 \times 1.005 \times (506.4 - 300)$

$= 207.432$ kJ/kg

(b) Work done by Turbine

$W_T = m \times C_p \times (T_3 - T_4)$

$= 1 \times 1.005 \times (1073 - 635.6)$

$= 439.587$ kJ/kg

(c) Heat supplied

$Q_S = mC_p \times (T_3 - T_2)$

$= 1 \times 1.005 \times (1073 - 506.4)$

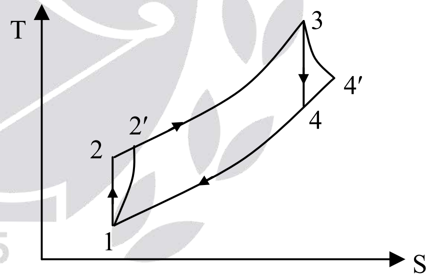
$Q_S = 569.433$ kJ/kg

(d) $$\eta_{th} = \frac{W_T - W_C}{Q_S} = \frac{439.587 - 207.432}{569.433}$$

$= 40.77\%$

02.

Sol:



Caloric value (CV) = 42000 kJ/kg

$\eta_T = 0.85$,

$\eta_c = 0.8$

$T_{max} = T_3 = 875^0C = 1148K$

$P_1 = 1$ atm

$T_1 = 300$ K

$$\frac{P_2}{P_1} = 4 = r_p$$

The temperature after isentropic compression

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

$$= 300\times 4^{\frac{1.4-1}{1.4}} = 446 \text{ K}$$

The isentropic efficiency of the compressor

$$\eta_c = \frac{W_{s=c}}{W_{actual}} = \frac{C_P(T_2-T_1)}{C_P(T_2'-T_1)}$$

$$\Rightarrow 0.8 = \frac{445.8-300}{T_2'-300}$$

$$\Rightarrow T_2' = 482.5 \text{ K}$$

T_2' = actual temperature at exit of compressor

Process 3-4: Q=0, S=C

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_4 = \frac{T_3}{(4)^{\frac{0.4}{1.4}}} = \frac{1148}{4^{\frac{0.4}{1.4}}}$$

T_4 = 773 K

$$\eta_T = \frac{W_{act}}{W_{S=C}} = \frac{C_P(T_3-T_{4'})}{C_P(T_3-T_4)}$$

$$T_{4'} = 1148 - 0.85(1148-773)$$

$$T_{4'} = 829\text{K}$$

$$W_T = C_P(T_3 - T_{4'}) = 1.005(1148-829)$$

$$= 320.32 \text{ kJ/kg}$$

$$W_C = C_P(T_2'-T_1) = 1.005(483-300) = 184 \text{ kJ/kg}$$

$$Q_S = C_P(T_3-T_2') = 1.005(1148-484)$$

$$= 668.325 \text{ kJ/kg}$$

$$W_{net} = W_T - W_C = 320.32 - 184$$

$$= 136.32 \text{ kJ/kg}$$

$$\text{Work ratio} = \frac{W_{net}}{W_T} = 0.428$$

$$\text{Back work ratio} = \frac{W_C}{W_T} = 0.571$$

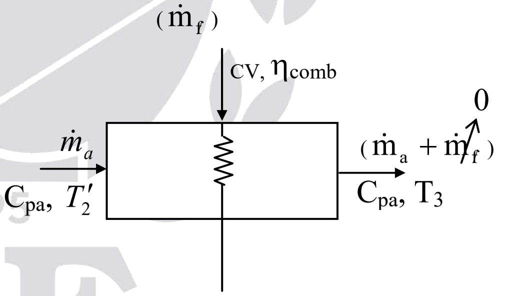
$$\eta_{th} = \frac{W_{net}}{Q_S} = 20.5\%$$

$$\text{Heat rate} = \frac{3600}{\eta_{th}} = 17560.97 \frac{\text{kJ}}{\text{kW/hr}}$$

$$\text{Air rate} = \frac{3600}{W_{net}} = 26.22 \frac{\text{kg}}{\text{kWhr}}$$

$$T_{m1} = \frac{h_3-h_{2'}}{s_3-s_{2'}} = \frac{C_P(T_3-T_{2'})}{C_P\left(\ln\frac{T_3}{T_{2'}}\right)} = 768 \text{ K}$$

$$T_{m2} = \frac{h_{4'}-h_1}{s_{4'}-s_1} = \frac{C_P(T_{4'}-T_1)}{C_P\left(\ln\frac{T_{4'}}{T_1}\right)} = 520.4 \text{ K}$$



Energy balance:

$$\dot m_a C_{Pa} T_2' + \dot m_f (CV)\eta_{comb} = \dot m_a C_{Pa} T_3$$

$$\frac{\dot m_a}{\dot m_f} C_{Pa} T_2' + \dot m_f (CV)\eta_{comb} = \frac{\dot m_a}{\dot m_f} C_{Pa} T_3$$

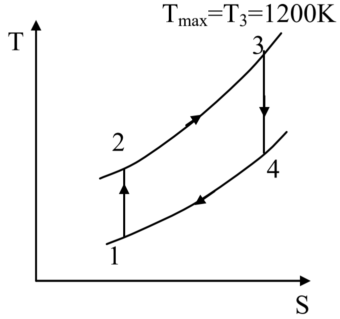
$$(AFR)C_{Pa}T_2' + (CV)\eta_{comb} = (AFR)C_{Pa}T_3$$

AFR×1×482.5+42000×0.9 = AFR×1×1148

∴ AFR = 56.56:1

03.

Sol:



$T_{max} = 1200$ K, $T_{min} = 300$ K

At $\left(r_p\right)_{opt}$, $T_2 = T_4 = \sqrt{T_1 T_3} = 600K$

$W_C = C_P (T_2 - T_1)$

$= 1.005(600 - 300) = 301.5$ kJ/kg

$W_T = C_P (T_3 - T_4) = 1.005(1200 - 600)$

$= 603$ kJ/kg

$$\eta_{th,\,(rp)opt} = 1 - \sqrt{\frac{T_{min}}{T_{max}}}$$

$$= 1 - \sqrt{\frac{300}{1200}} = 50\%$$

04. Ans: (a)

Sol:

- Due to Regeneration thermal efficiency increases as heat required in combustor is less.
- Reheating decreases thermal efficiency as mean temperature of heat rejection increases.
- When maximum temperature of the cycle is increased, thermal efficiency increases as mean temperature of heat addition increases.

05. Ans: (d)

Sol:

- There is very little gain in thermal efficiency when intercooling is used without the benefit of regeneration.
- With higher values of ‘γ’ and cp of the working fluid the net power output of Brayton cycle will increase.

06. Ans: (a)

Sol: During regeneration process, turbine work and compressor work remain unchanged and only heat supplied decreases so specific work output remains same.

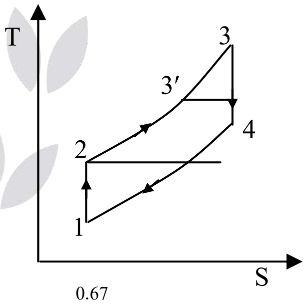
07. Ans: (d)

Sol: $P_1 = 100$ kPa,

$P_2 = 400$ kPa

$T_1 = 298$ K,

$T_3 = 1473$ K



$$r_P = \frac{400}{100} = 4$$

$$T_2 = T_1\left(r_P\right)^{\frac{\gamma-1}{\gamma}} = 298 \times 4^{\frac{0.67}{1.67}} = 519.7K$$

$$T_4 = \frac{T_3}{\left(r_P\right)^{\frac{\gamma-1}{\gamma}}} = 844.61K$$

The maximum temperature up to which we can heat the compressed air is turbine exhaust temperature and this will happen when effectiveness of the heat exchanger must be unity.

i.e. $T_3' = T_4 = 844.61K = 573^\circ C$

08.

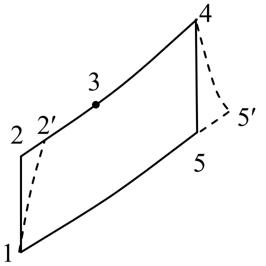
Sol: $T_1 = 300$ K, $r_p = 4$

$T_4 = 833$ K

$\eta_T = 0.85$

$\eta_c = 0.83$

$\xi = 0.75$



$$\frac{T_2}{T_1} = (r_p)^{\frac{\gamma-1}{\gamma}} \Rightarrow T_2 = 445.8\,\text{K} \ \{\gamma = 1.4 \text{ for air}\}$$

$$\eta_C = 0.83 = \frac{T_2 - T_1}{T_2' - T_1} = \frac{445.8 - 300}{T_2' - 300}$$

$$T_2' = 475.66\,\text{K}$$

$$\frac{T_4}{T_5} = (r_p)^{\frac{\gamma-1}{\gamma}} = (4)^{\frac{0.4}{1.4}} \Rightarrow T_5 = 560.56\,\text{K}$$

$$\eta_T = 0.85 = \frac{T_4 - T_5'}{T_4 - T_5} = \frac{833 - T_5'}{833 - 560.56}$$

$$T_5' = 601.43\,\text{K}$$

$$\xi = \frac{Q_{act}}{Q_{max}} = \frac{T_3 - T_2'}{T_5' - T_2'} = \frac{T_3 - 475.66}{601.43 - 475.66}$$

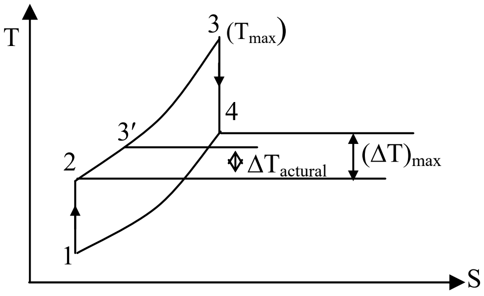
$\Rightarrow T_3 = 569.98$ K

$$\eta_{th} = \frac{W_T - W_C}{Q_S} = \frac{mc_p \times (T_4 - T_5') - mc_p \times (T_2' - T_1)}{m \times c_p \times (T_4 - T_3)}$$

$$= \frac{(833 - 601.43) - (475.66 - 300)}{833 - 569.98} = 21.26\%$$

09. Ans: (d)

Sol:



$P_1 = 80$ kPa, $P_2 = 400$ kPa,

$T_1 = 283$ K $T_3 = 1273$K

$$r_P = \frac{400}{80} = 5$$

$T_3^1 = 450 + 273 = 723$ K

$$T_4 = \frac{T_3}{(r_P)^{\frac{\gamma-1}{\gamma}}} = \frac{1273}{(5)^{\frac{0.4}{1.4}}} = 804\text{K}$$

Effectiveness of heat exchanger.

$$\in = \frac{(\Delta T)_{act}}{(\Delta T)_{max}} = \frac{T_3' - T_2}{T_4 - T_2} \times 100 = 77\%$$

10. Ans: (c)

Sol: $T_{min} = T_1 = 20 + 273 = 293$ K,

$T_{max} = T_4 = 900 + 273 = 1173$ K

$\gamma = 1.3$, $r_p = 6$

$$(\eta_B)_{\text{ideal regeneration}} = 1 - \frac{T_{min}}{T_{max}}(r_p)^{\frac{\gamma-1}{\gamma}}$$

$$= 1 - \left(\frac{293}{1173}\right) \times (6)^{\frac{1.3-1}{1.3}}$$

$$= 0.62 \text{ or } 62\%$$

11. Ans: (d)

Sol: Whenever we reheat, we reheat to the same temperature until unless mentioned in the problem. Whenever, we intercool to the same temperature, if there are infinitely large number of reheats and if there are infinitely large number of intercoolers then reversible adiabatic expansion becomes isothermal expansion and reversible adiabatic compression becomes isothermal compression and thermal efficiency of Brayton cycle becomes equal to Ericsson cycle.

$$\therefore (\eta_{th})_{Braton} = (\eta_{th})_{Ericsson}$$

Ericsson cycle is an ideal gas turbine cycle

Ideal $(\eta)_{Ericsson} = (\eta)_{Carnot}$

$$(\eta)_{Carnot} = 1 - \frac{T_{min}}{T_{max}} = 76\%$$

12. Ans: (a, c, d)

Sol:

- Regeneration always increases the efficiency
- Reheating may increase or decrease the efficiency of cycle
- Ericsson cycle is ideal regeneration cycle
- Intercooling along with regeneration increase the efficiency of the cycle

Chapter 12 Refrigeration

01.

Sol: Refrigeration effect = 1 tonne

= 210 kJ/min

= 3.5 kW

Work input = 1.5 kW

$$COP = \frac{3.5}{1.5} = 2.33$$

02.

Sol: Maximum COP = Carnot COP

$$= \frac{-30+273}{(273+32)-(273-30)}$$

$$= \frac{243}{62} = 3.92$$

Actual COP = 0.75×3.92 = 2.94

$$2.94 = \frac{5}{W_{input}}$$

$\Rightarrow W_{input} = 1.7$ kW

03.

Sol: Actual COP = 0.15 × Carnot's COP

$$= 0.15 \times \frac{273+2}{(273+30)-(273+2)}$$

$$= 1.473$$

$$R.E = \frac{8000}{24\times 60\times 60} kN = 0.093 \text{ kW}$$

$$1.473 = \frac{0.093}{W_{in}}$$

$W_{in} = 0.063$ kW

$= 0.063$ kJ/s × 3600×24 s

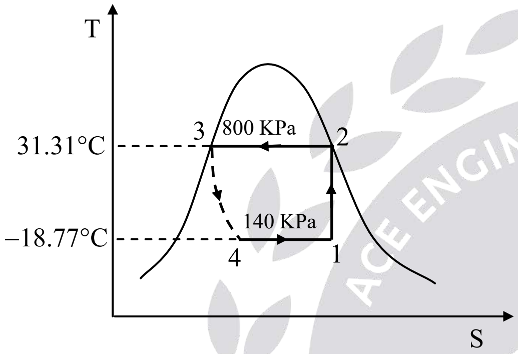
$= 5443.2$ kJ

1 kW-h = 3600 kJ

5443.2 kJ = 1.5 kW-h

04. Ans: (a)

Sol:



$P_1 = 140$ kPa, $P_2 = 800$ kPa

From steam table

$h_2 = h_g = 267.29$ kJ/kg

$h_3 = h_f = 95.49$ kJ/kg

$Q_R = h_2 - h_3$

$= 267.29 - 95.49 = 171.82$ kJ/kg

$$(\text{COP})_{HP} = \frac{Q_R}{W} = \frac{T_2}{T_2 - T_1}$$

$$\frac{171.82}{W} = \frac{273+31.31}{(273+31.31)-(273-18.77)}$$

$W = 28.54$ kJ/kg

05. Ans: (b)

Sol: For minimum required power input condition the COP has to be maximum and the maximum COP is the reversed Carnot cycle COP.

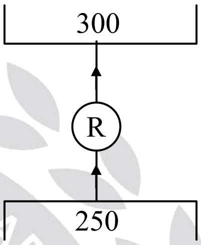
$$\left[(\text{COP})_{\text{Carnot}}\right]_{\text{Refrigerator}} = \frac{T_2}{T_1 - T_2} = \frac{Q_2}{W}$$

$$\Rightarrow \frac{268}{293-268} = \frac{0.35}{W}$$

$$\Rightarrow \quad W_{min} = 33 \text{ W}$$

06. Ans: 12 kW

Sol:



Total heat to be removed

$= 3600×2×[27–(–3)]+3600×230+3600×20×0.5$

$= 1080000$ kJ

$$\text{Rate of heat removed} = \frac{1080000}{10\times3600} = 30 \text{ kW}$$

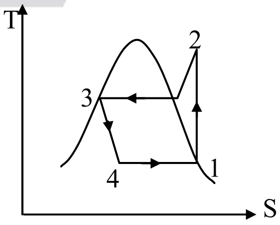
$$\text{Actual cop} = 0.5\times\frac{250}{300-250} = 2.5$$

$$2.5 = \frac{30}{\text{Power}}$$

Power input = 12 kW

07. Ans: (c)

Sol:



Ideal vapour compression means the compression starts from dry and saturated vapor line.

$P_1 = 120$ kPa, $P_2 = 800$ kPa

$h_1 = 236.97$ kJ/kg

$h_3 = h_4 = 95.47$ kJ/kg

Net refrigeration effect (NRE) = 32 kW

$= \dot{m}_r(h_1 - h_4)$

$\dot{m}_r = 0.23\,\text{kg/sec}$

08. Ans: (d)

Sol: $\dot{m}_r = 0.193\,\text{kg/sec}$

$s_1 = s_2 = 0.93$ kJ/kgK

After compression the refrigerant is in super heated state with entropy = 0.93 at a pressure 1.2 MPa

$h_1 = 251.88$ kJ/kg

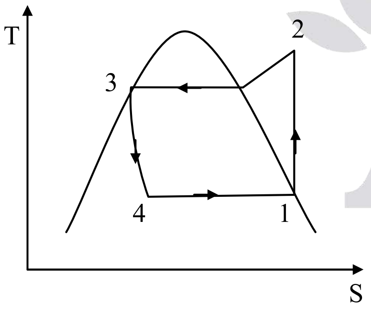
$h_2 = 278.27$ kJ/kg

$h_3 = 117.73$ kJ/kg

Heat supply = $\dot{m}_r(h_2 - h_3) = 30.98\,\text{kW}$

09.

Sol:



Refrigeration effect = 5 kW

$h_4 = 75$ kJ/kg, $h_1 = 183$ kJ/kg,

$h_2 = 210$ kJ/kg

(i) $$\text{COP} = \frac{\text{Refrigeration effect}}{\text{work input}} = \frac{h_1 - h_4}{h_2 - h_1} = 4$$

(ii) Cooling capacity = $\dot{m} \times (h_1 - h_4)$

$5 = \dot{m} \times (183 - 75)$

$\dot{m} = 0.0463\,\text{kg/s}$

Power input to the compressor

$= \dot{m} \times (h_2 - h_1)$

$= 0.0463 \times (210 - 183)$

= 1.25 kW

(iii) Heat transfer at the condenser

$= 0.0463 \times (h_2 - h_3)$

$= 0.0463 \times (210 - 75)$

= 6.25 kW

10. Ans: (b)

Sol: $h_3 = 107.32$ kJ/kg = h_4 at 1 MPa

$h_4 = h_{f_4} + x(h_{g_4} - h_{f_4})$

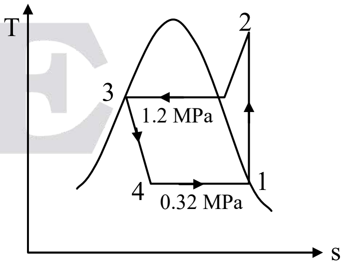
$107.32 = 22.49 + x(226.97 - 22.49)$

Dry fraction of liquid, x = 0.4

Mass fraction of liquid = 1–x = 0.6

11. Ans: (d)

Sol:



$h_3 = 117.71$ kJ/kg at 1.2 MPa

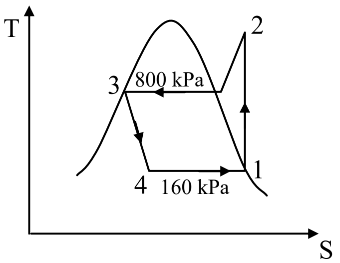
$h_1 = 251.8$ kJ/kg at 0.32 MPa

$h_2 = 278.27$ kJ/kg

$$\text{COP} = \frac{h_1 - h_4}{h_2 - h_1} = \frac{251.8 - 117.71}{278.27 - 251.8} = 5.07$$

12. Ans: (d)

Sol:



$h_1 = 241$ kJ/kg

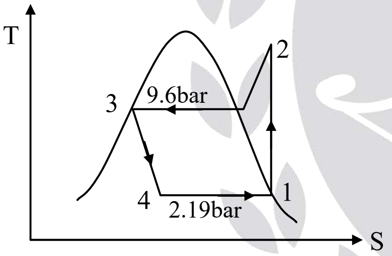
$h_2 = 286.69$ kJ/kg

$h_4 = h_3 = 95.47$ kJ/kg

$$\text{COP} = \frac{h_1 - h_4}{h_2 - h_1} = \frac{\text{NRE}}{W_C} = 3.2$$

13.

Sol:



$h_3 = h_4 = 64.6$ kJ/kg , $h_1 = 195.7$ kJ/kg

$v_1 = 0.082\ \text{m}^3/\text{kg}$

$n = 1.13$

$$\text{NRE (kW)} = 3.517 \times 15 = \dot{m}_r(h_1 - h_4)$$

$$\dot{m}_r = 0.402\ \text{Kg/sec}$$

$$W_C(\text{kJ/kg}) = \frac{n}{n-1} P_1 v_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \frac{1.13}{1.13-1} \times 219 \times 0.082 \left[\left(\frac{9.6}{2.19}\right)^{\frac{1.13-1}{1.13}} - 1\right]$$

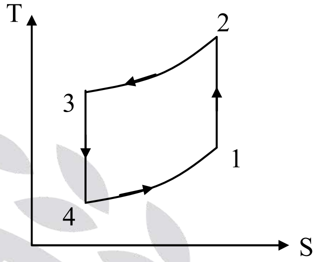
$$= 28.92\ \text{kJ/kg}$$

$W_C(\text{kW}) = 0.402 \times 28.92 = 11.62$ kW

$$\text{COP} = \frac{\text{NRE}}{W_C} = \frac{15 \times 3.517}{11.62} = 4.54$$

14. Ans: (a)

Sol:



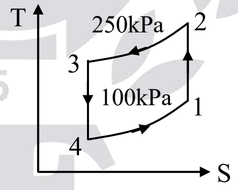
$$T_3 = 308\text{K}$$

$$T_4 = \frac{T_3}{(r_p)^{\frac{\gamma-1}{\gamma}}} = \frac{308}{\left(\frac{280}{80}\right)^{\frac{0.4}{1.4}}}$$

$T_4 = -58°\text{C}$

15. Ans: (b)

Sol:



For Helium, $\gamma = 1.67$

$\dot{m} = 0.2$ kg/sec, $T_1 = -10^0\text{C} = 263$ K

$$\text{Pressure ratio, } r_p = \frac{P_2}{P_1} = \frac{250}{100} = 2.5$$

$$T_2 = T_1 \times (r_p)^{\frac{\gamma-1}{\gamma}} = 263 \times (2.5)^{\frac{0.67}{1.67}} = 379.84\text{K}$$

$$T_4 = \frac{T_3}{(r_p)^{\frac{\gamma-1}{\gamma}}} = \frac{293}{(2.5)^{\frac{0.67}{1.67}}} = 202.87\text{ K}$$

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

$$= \dot{m}\frac{\gamma\overline{R}}{M(\gamma-1)}(T_2 - T_1)$$

$$= \frac{0.2\times1.67\times8.314}{4(1.67-1)}(379.84-263)$$

$$= 121 \text{ kW}$$

$$W_E = \dot{m}\frac{\gamma\overline{R}}{M(\gamma-1)}(T_3 - T_4)$$

$$= \frac{0.2\times1.67\times8.314}{4\times(1.67-1)}\times(293-202.87)$$

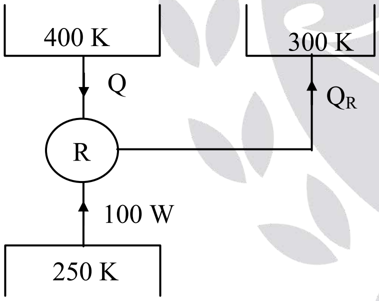
$$= 93.3 \text{ kW}$$

$$W_{net} = W_C - W_E$$

$$= 121 - 93.3 = 27.7 \text{ kW}$$

16. Ans: 80 W

Sol:



For minimum value of heat required

$S_{gen} = 0$

dS(reservoir at 400 K) + dS(reservoir at 250K) + dS(reservoir at 300K) + dS(working fluid) = 0

$$\frac{-Q}{400} - \frac{100}{250} + \frac{Q_R}{300} + 0 = 0 \text{ ……….. (i)}$$

$Q_R = 100 + Q$ ………… (ii)

Solve (i) and (ii)

$\therefore$ Q = 80 W

17. Ans: (b, c)

Sol:

- Air refrigeration system is based on reversed Brayton cycle
- Vapour refrigeration system is not based on reversed Carnot cycle
- R-32 is the most commonly used refrigerant
- Domestic refrigerator is based on vapour compression refrigeration system

Chapter 13 Thermodynamic Relations

01. Ans: (b)

Sol: Clayperon equation is given by

$$\left(\frac{dP}{dT}\right)_h = \frac{(h_g - h_f)}{T_s(v_g - v_f)}$$

$$\therefore \ (v_g - v_f) = \frac{dT_s}{dP}\frac{(h_g - h_f)}{T_s}$$

02. Ans: (a)

Sol: Joule Thomson coefficient is

$$\mu_j = \left(\frac{dT}{dP}\right)_h$$

It is the constant enthalpy line in temperature pressure curve of real gases.

03. Ans: (c)

Sol:

(a) $(c_p - c_v) = -T\left(\frac{\partial V}{\partial T}\right)_P^2\left(\frac{\partial P}{\partial V}\right)_T$

$\because \left(\frac{\partial P}{\partial V}\right)_T$ is always negative

$\therefore \ c_p - c_v > 0$

Hence, c_p is always greater than c_v .

(b) For an ideal gas

$$Pv = RT$$

$$\left(\frac{dP}{dv}\right)_T v + P = 0$$

$$\left(\frac{dP}{dv}\right)_T = -\frac{P}{V} \qquad \text{-----(1)}$$

$$\left(\frac{dv}{dT}\right)_P = \left(\frac{R}{P}\right) = \left(\frac{v}{T}\right) \qquad \text{-----(2)}$$

From (1) and (2)

$$\therefore \ c_p - c_v = -T\times\frac{v^2}{T^2}\left(-\frac{P}{v}\right) = \frac{Pv}{T} = R$$

$\therefore \ c_p - c_v = R$

(c) $\left(\frac{\partial P}{\partial v}\right)_T$ is always negative.

$\left(\frac{\partial v}{\partial P}\right)_P^2$ is always positive

(d) For water (incompressible fluid)

$\therefore \ c_p \approx c_v$

04. Ans: (a)

Sol: Gibb's energy 'G' is given by $G = H - TS$

05. Ans: (c)

Sol:

- Specific heat at constant volume $C_v \rightarrow T\left(\frac{\partial s}{\partial T}\right)_V$
- Isothermal compressibility $\kappa \rightarrow -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T$
- Volume expansivity $\beta \rightarrow \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P$
- Difference between specific heats at constant pressure and constant volume $(C_p - C_v) \rightarrow -T\left(\frac{\partial P}{\partial V}\right)_T\left(\frac{\partial V}{\partial T}\right)_P^2$

06. Ans: (c)

Sol: Helmholtz function is given by $H = U - TS$

07. Ans: (b)

Sol: Joule Thomson coefficient is

$$\mu_j = \left(\frac{\partial T}{\partial P}\right)_h = \text{slop of constant}$$

Enthalpy line in on T-P diagram

08. Ans: (b)

Sol: Joule Thomson coefficient → $(\partial T / \partial p)_h$

C_p for monoatomic gas → 5/2 R

$C_p - C_v$ for diatomic gas → R

$(\partial U / \partial T)_v \rightarrow C_v$

09. Ans: (d)

Sol:

- Irreversibility → Loss of availability
- Joule Thomson experiment → Throttling process
- Joule's experiment → Mechanical equivalent
- Reversible engines → Thermodynamic temperature scale

10. Ans: (b)

Sol: Clapeyron's equation for dry saturated steam is given by

$$(v_g - v_f) = \left(\frac{dT_s}{dP}\right)_h \frac{(h_g - h_f)}{T_s}$$

11. Ans: (c)

Sol: The internal energy of a gas obeying Vander Waals equation $(P + \frac{a}{V^2})(v\text{-}b) = RT$ depends on its temperature and specific volume.

Chapter 14

Reciprocating Air Compressors

01. Ans: (b)

Sol: $n = 2$, $P_s = 1.5$ bar, $P_d = 54$ bar

Intercooler pressure,

$$P_i = \sqrt{P_s P_d}$$

$$= \sqrt{54 \times 1.5}$$

$$\Rightarrow P_i = 9 \text{ bar}$$

02. Ans: (a)

03. Ans: (a)

Sol: $\eta_v = 1 - C\left[\left(\frac{P_d}{P_s}\right)^{\frac{1}{n}} - 1\right]$

If clearance (C) is large volumetric efficiency (η_v) decreases hence volume flow rate decreases.

04. Ans: (c)

Sol: Mass of air in clearance volume has no effect on work done per kg of air.

05. Ans: (d)

Sol: Volumetric efficiency is given by

$$\eta_v = 1 - C\left[\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}} - 1\right]$$

where,

C = clearance ratio,

P_2 = delivery pressure,

P_1 = suction pressure

n = index of expansion

06. Ans: (c)

Sol: $$\eta_v = 1 - C\left[\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}} - 1\right]$$

where,

C = clearance ratio,

P_2 = delivery pressure,

P_1 = suction pressure

07. Ans: (d)

Sol: Total work of 3-stages is given by

$$W = \frac{3n}{(n-1)} P_1 V_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{3n}} - 1\right]$$

08. Ans: (a)

Sol: $$\eta_{Vol} = 1 + C - C\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}} \quad ; \; P_1 V_1^n = P_2 V_2^n$$

$$\eta_{Vol} = 1 + C - C\left(\frac{V_1}{V_2}\right) \; ; \quad \left(\frac{V_1}{V_2}\right)^n = \frac{P_2}{P_1}$$

$$\eta_{vol} = 1 + 0.05 - 0.05\left(\frac{0.04}{0.02}\right) = 0.95 \text{ or } 95\ \%$$

09. Ans: (b)

Sol: Advantages of multi-stage compression are

- Improved overall volumetric efficiency. If all compression were done in one cylinder the gas in the clearance volume would expand to a large volume before the new intake could begin. This results in a very low volumetric efficiency. By cooling the gas between the stages a much higher efficiency can be obtained.
- A reduction in work required per stroke, and therefore the total driving power.
- Size and strength of cylinders can be adjusted to suit volume and pressure of gas.
- Multi-cylinders give more uniform torque and better mechanical balance thus needing smaller flywheel.

10. Ans: (d)

Sol: $$\eta_v = 1 - C\left[\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}} - 1\right]$$

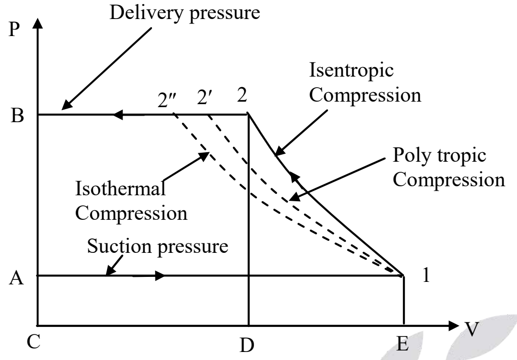
where, C = clearance ratio,

$\frac{P_2}{P_1}$ = pressure ratio

We can observe from the above expression that as C and $\frac{P_2}{P_1}$ increases η_v decreases.

11. Ans: (a)

Sol:



P-V representation of cycle in a reciprocating compressor

From the P.V. diagram we can see that work done is minimum when the compression process is isothermal.

12. Ans: (b)

13. Ans: (d)

Sol: Cooling of reciprocating compressor

1. increases volumetric efficiency
2. decreases work input

14. Ans: 3

Sol: $$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$$

$$\frac{423}{300} = \left(\frac{P_2}{1}\right)^{\frac{1.25-1}{1.25}}$$

$P_2 = 5.57$ bar

For optimum intercooling pressure ratios are same

$$\frac{P_2}{P_1} = \frac{P_3}{P_2} = \frac{P_4}{P_3} = \frac{P_{n+1}}{P_n}$$

$$\left(\frac{P_2}{P_1}\right)^n = \frac{180}{1}$$

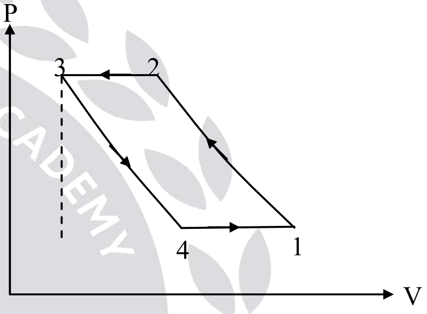
$(5.57)^n = 180$

$\Rightarrow$ $n \approx 3.023$

$\Rightarrow$ $n = 3$ stages

15.

Sol:



Swept volume, $V_S = V_1 - V_3 = \frac{\pi}{4} \times D^2 \times L$

$$= \frac{\pi}{4} \times 0.2^2 \times 0.3 = 9.42 \times 10^{-3}\, m^3$$

Clearance volume = $V_3 = 0.05 \times (V_1 - V_3)$

$= 4.71 \times 10^{-4}\, m^3$

$V_1 = V_S + V_3 = 9.89 \times 10^{-3}\, m^3$

$$\frac{V_4}{V_3} = \left(\frac{P_3}{P_4}\right)^{\frac{1}{n}} = \left(\frac{550}{97}\right)^{\frac{1}{1.3}}$$

$V_4 = 1.79 \times 10^{-3}$

Effective swept volume = $V_1 - V_4$

$= 8.1 \times 10^{-3}\, m^3$

$$\frac{P_a V_a}{T_a} = \frac{P_1 \times (V_1 - V_4)}{T_1}$$

$$= \frac{101.325 \times V_a}{288} = \frac{97 \times 8.1 \times 10^{-3}}{293}$$

(i) $\eta_v = 1 + C - C\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}$

$$= 1 + 0.05 - 0.05 \times \left(\frac{550}{97}\right)^{\frac{1}{1.3}}$$

$$= 86\%$$

(ii) Power required

$$= \frac{n}{n-1} P_1(V_1 - V_4)\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \frac{1.3}{1.3-1} \times 97 \times 8.1 \times 10^{-3} \times \left[\left(\frac{550}{97}\right)^{\frac{1.3-1}{1.3}} - 1\right]$$

$$= 1.676 \text{ kJ/cycle}$$

$$= 1.676 \times \frac{500}{60} = 13.97 \text{ kW}$$

(iii) $V_a = 7.622 \times 10^{-3}$ m^3/cycle

$V_a = 7.622 \times 10^{-3} \times 500 = 3.81$ m^3/min

Chapter 15 Steam Turbines

01. Ans: (a)

Sol:

- De laval turbine – simple impulse turbine
- Rateau Turbine – Pressure compounded steam turbine
- Curtis Turbine – velocity compounded steam turbine
- Parson – simple reaction steam turbine

02. Ans: (c)

Sol: In compounding high speeds of rotors are brought down to normal levels.

03. Ans: (c)

Sol: Blade speed , $U = \frac{\pi DN}{60}$

As power generated in the IIIrd stage is more than I and II stage

$U_3 > U_2 = U_1$

$D_3 > D_2 = D_1 \quad (\because \text{N is same for all stages})$

04. Ans: (c)

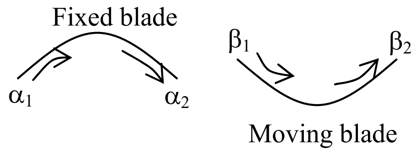
Sol: $\frac{U}{V_1} = 0.42$

$$V_1 = \frac{U}{0.42} = \frac{\frac{\pi DN}{60}}{0.42}$$

$$= \frac{\pi \times 1.2 \times 3000}{60 \times 0.42} = 450\ m/\sec$$

05. Ans: (b)

Sol:



Exit of fixed blade = Exit of moving blade

$(\alpha_2 = \beta_2)$

Inlet of fixed blade = Inlet of moving blade.

$(\alpha_1 = \beta_1)$

06. Ans: (c)

Sol:

- Parson's → Reaction
- De Laval → Simple impulse
- Rateau → Pressure compounded
- Curtis → Velocity Compounded

07. Ans: (c)

Sol: Ljungstrom turbine is steam turbine in which flow is in radial direction from inside to the outside and consists of two halves that rotate against each other.

08. Ans: (a)

Sol: $\frac{U}{V} = \cos\alpha. \Rightarrow V = \frac{320}{\cos 30} = \frac{640}{\sqrt{3}}\frac{m}{s}$

09. Ans: (a)

Sol: Impulse turbine blades are De-Laval blades which are thick at centre and thin at edges.

10. Ans: (a)

Sol: Running speeds of steam turbine can be brought down to practical limits by compounding. The types of compounding are :

- Pressure compounding.
- Velocity compounding.
- Pressure and Velocity compounding.

11. Ans: (d)

Sol: Power $= F_T \times V$

$50\ kW = F_T \times 400$

$$F_T = \frac{50 \times 1000}{400} = 125\ N$$

12. Ans: (c)

Sol:

- 50% Reaction – Parson
- Two row Velocity compounded – Curtis
- Simple impulse stage – De Laval
- Pressure compounded – Rateau

13. Ans: (a)

Sol: Change in KE of steam = Work Done

$$\frac{1}{2}m\left(V_2^2 - V_1^2\right) = \text{Work}$$

$$\Rightarrow \text{Work} = \frac{1}{2} \times 1\left(30^2 - 10^2\right) = 400\text{Nm}$$

14. Ans: (c)

Sol: $(\Delta h)_R = 2.38\ kJ/kg$

$(\Delta h)_S = 4.62\ kJ/Kg.$

$$DR = \frac{(\Delta h)_R}{(\Delta h)_R + (\Delta h)_S}$$

$$= \frac{2.38}{2.38 + 4.62} = 0.34$$

15. Ans: (d)

Sol: Given maximum blade efficiency, for 50 % reaction turbine.

$$\Rightarrow \rho = \cos\alpha = \frac{u}{V_1}$$

Work done,

$$W = V_1^2 (2\rho\cos\alpha - \rho^2)$$

$$= V_1^2\,(2\rho \times \rho - \rho^2)$$

$$= V_1^2\,(2\rho^2 - \rho^2) = V_1^2 \times \rho^2$$

$$= V_1^2 \times \left(\frac{u}{V_1}\right)^2 = U^2$$

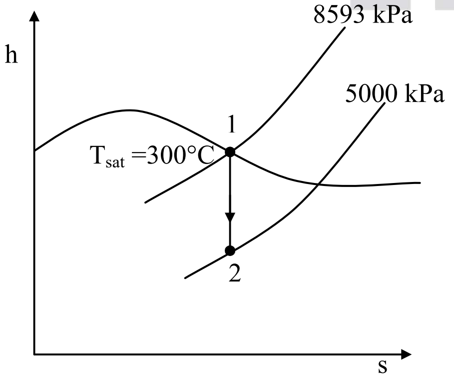
$$W = U^2$$

16. Ans: (d)

Sol: As pressure drop is gradual in both fixed and moving blades it is reaction turbine.

17. Ans: 445.97

Sol:



$s_1 = s_2$

$s_{g1} = s_{f2} + x\,(s_{g2} - s_{f2})$

$5.7081 = 2.9206 + \{x\,(5.9735 - 2.9206)\}$

$\Rightarrow \quad x = 0.913$

$C_1 = 0$

$h_1 = h_{g1} = 2751$ kJ/kg

$h_2 = h_{f2} + x\,(h_{g2} - h_{f2})$

$= 1154.5 + \{0.913\,(2794.2 - 1154.5)\}$

$= 2651.55$ kJ/kg

$$\frac{C_1^2}{2000} + h_1 = \frac{C_2^2}{2000} + h_2$$

$$C_2 = 44.72\sqrt{h_1 - h_2}$$

$$= 44.72\sqrt{(2751 - 2651.55)} = 445.97 \text{ m/s}$$

18. Ans: (a)

Sol: Given data :

$\eta_b = 0.92, \qquad \eta_T = 0.94,$

$\eta_g = 0.95, \qquad \eta_c = 0.44,$

$$\eta_{aux} = \frac{\text{Net power transmitted by the generator}}{\text{Gross power produced by the plant}}$$

$$= \frac{\text{gross power} - \text{power for auxilliaries}}{\text{gross power}}$$

$$= \frac{\text{gross power} - 6\%\text{ of gross power}}{\text{gross power}}$$

$= 1 - 0.06$

$\eta_{aux} = 0.94$

Overall efficiency

$(\eta_o) = \eta_b \times \eta_T \times \eta_g \times \eta_c \times \eta_{aux}$

$= 0.92 \times 0.94 \times 0.95 \times 0.44 \times 0.94$

$= 0.34$

$= 34$ %

19. Ans: (a)

Sol: Given data :

$u = 150$ m/s,

$$\frac{u}{V_1} = 0.5$$

$$\frac{150}{V_1} = 0.5 \Rightarrow V_1 = 300\ \text{m/s}$$

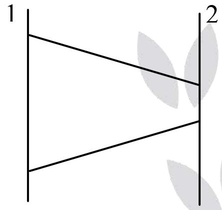
$$\eta_{\text{nozzle}} = \frac{\frac{1}{2}\times V_1^2}{\Delta h}$$

$$0.9 = \frac{300^2}{2\times\Delta h}$$

$\Rightarrow \Delta h = 50000$ J/kg $= 50$ kJ/kg

20. Ans: (b)

Sol:



$A_2 = 2.5\ \text{cm}^2 = 2.5\times10^{-4}\ \text{m}^2$

$P_1 = 10$ bar,

$P_2 = 2$ bar

$T_1 = 500$ K, $T_2 = ?$

$c_p = 1005$ J/kg.K,

$c_v = 718$ J/kg.K

$$\gamma = \frac{c_p}{c_v} = \frac{1005}{718} = 1.4$$

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = 500\times\left(\frac{2}{10}\right)^{\frac{0.4}{1.4}} = 315.7\,\text{K}$$

$$h_1 + \frac{V_1^2}{2} + Q = h_2 + \frac{V_2^2}{2g} + W$$

$Q = 0, \quad W = 0, \quad V_1 = 0$

$$\therefore\ V_2 = \sqrt{2c_p(T_1 - T_2)}$$

$$= \sqrt{2\times1005(500-315.7)}$$

$= 608.64$ m/sec

Specific volume,

$$v_2 = \frac{RT_2}{P_2}$$

$$= \frac{287\times315.7}{2\times10^5} = 0.453\ \text{m}^3/\text{kg}$$

Mass flow rate,

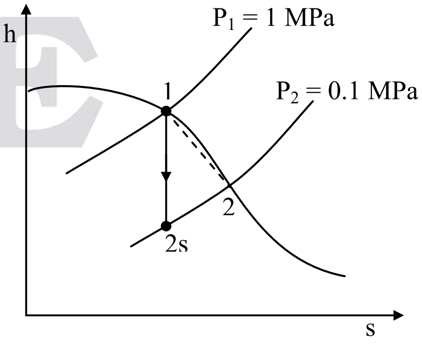
$$\dot{m} = \frac{A_2V_2}{v_2}$$

$$= \frac{2.5\times10^{-4}\times608.64}{0.453} = 0.3358\ \text{kg/sec}$$

Note: *Option (b) is correct answer.*

21. Ans: 2.319

Sol:



1-2s → isentropic expansion

1-2 → actual expansion

$$S_{gen} = S_{prod} = m\,(S_2 - S_1) - \frac{dQ}{T}$$

Adiabatic turbine, dQ = 0 and moisture at exit is negligible.

$\therefore\ S_{gen} = m\,(S_2 - S_1)$

$= 3\,(7.359 - 6.586) = 2.319$ kW/K

22. Ans: (a)

Sol: $V = 44.72\sqrt{h_1 - h_2}$

$= 44.72\sqrt{(2935 - 2584)} = 837.83$ m/s

For maximum blade efficiency in impulse turbine,

$$\frac{u}{V_1} = \frac{\cos\alpha}{2}$$

$$\frac{u}{837.83} = \frac{\cos 20^\circ}{2}$$

$\Rightarrow\quad u = 393.65$ m/s

23. Ans: (d)

Sol: $\dot{m}h_1 - Q = \dot{m}h_2 + W_T$

$W_T = \dot{m}(h_1 - h_2) - Q$

$= [0.25\,(3486 - 3175.8)] - 50$

$= 27.55$ kW

24. Ans: (b)

Sol: Work given by z- stage Curtis turbine.

z = no. of stages

Work given by last stage of Curtis turbine = $2u^2$

$W_{total} = 2u^2 \times (z^2) = 6400$

W_{total} = last stage work × $(z^2) = 6400$

No. of stages, z = 4

$\therefore$ Last stage work $= \dfrac{6400}{z^2}$

$$= \frac{6400}{4^2} = 400 \text{ kW}$$

25. Ans: (c)

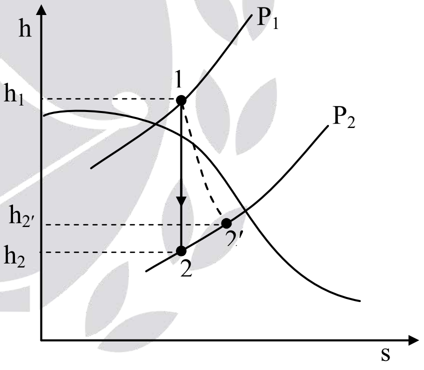
Sol: Ideal regenerative Rankine cycle efficiency is same as Carnot cycle efficiency.

$$\eta = 1 - \frac{T_2}{T_1}$$

$$= 1 - \frac{(27+273)}{(327+273)} = 1 - \frac{300}{600} = 50\ \%$$

26. Ans: (b)

Sol:



$$\eta_{Turbine} = \frac{\text{Actual enthalpy drop}}{\text{Isentropic enthalpy drop}}$$

$$= \frac{3200 - 2560}{3200 - 2400} = 0.8 = 80\%$$

27. Ans: (a)

Sol: $V_w = 60$ m/s, $u = 30$ m/s

Specific work done $= V_w \times u$

$= 60 \times 30 = 1800$ J/kg

28. Ans: (b)

Sol: Manometer reading,

$P_1 - P_2 = 45$ mm of water

$= 0.045$ m of water

Pressure at section, $P_1 = 100$ kPa (abs)

Temperature, $T_1 = 25°C$

Density of water, $\rho_w = 999\ kg/m^3$

$$P_1 - P_2 = \frac{\rho_{air} \times V_2^2}{2}$$

$$\rho_{air} = \frac{P}{RT} = \frac{100 \times 10^3}{287 \times 298} = 1.169 \approx 1.17\ kg/m^3$$

$$P_1 - P_2 = \rho_w\, g\, (\Delta h)$$

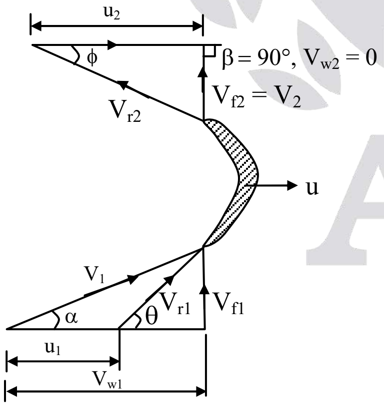
$$\Rightarrow \frac{\rho_{air} \times V_2^2}{2} = \rho_w\, g(\Delta h)$$

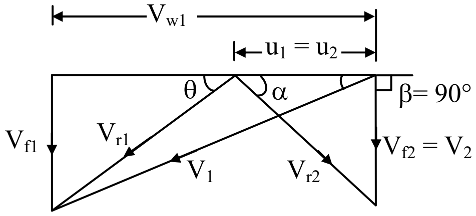
$$\frac{1.17 \times V_2^2}{2} = 999 \times 9.8 \times 0.045$$

$\therefore \quad V_2 = 27.44$ m/s

29. Ans: (b, d)

Sol:





$$\frac{u}{V_{w1}} = 0.6$$

$V_1 = 1200$ m/s , $\alpha = 20°$

$u_1 = u_2 = u$

$V_{w1} = V_1 \cos\alpha$

$= 1200 \times \cos 20° = 1127.63$ m/s

$$\frac{u}{V_{w1}} = 0.6$$

$\Rightarrow u = 0.6 \times V_{w1}$

$= 0.6 \times 1127.63 = 676.578$ m/s

Blade velocity = 676.58 m/s

Work done/s = $F_x \times u$

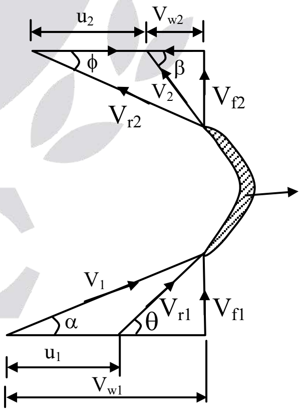
$= \dot{m}_s (V_{w1} \pm V_{w2})\, u$

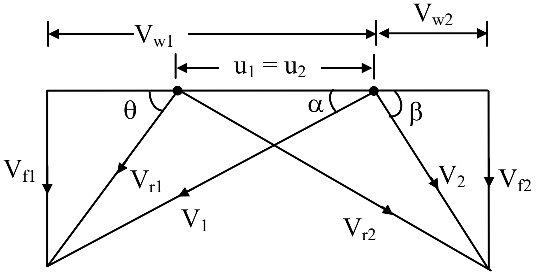
$= 1 \times (1127.63 \pm 0) \times 676.578$

$= 762929.65$ J/kg $= 762.93$ kJ/kg

30. Ans: (a, d)

Sol:





$V_1 = 400$ m/s, $\alpha = 20°$

Given, blades are operating close to maximum blading efficiency.

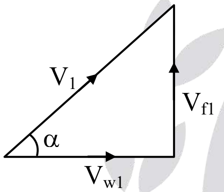
$$\Rightarrow \frac{u}{V_1} = \frac{\cos\alpha}{2}$$

$V_{r1} = V_{r2}$ (No blade friction)

$\theta = \phi$ (equiangular blades)

From, $\frac{u}{V_1} = \frac{\cos\alpha}{2}$

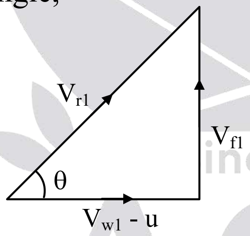
$$u = \frac{V_1\cos\alpha}{2} = \frac{400\times\cos 20^\circ}{2} = 187.94 \text{ m/s}$$



$V_{w1} = V_1 \cos\alpha = 400 \cos 20° = 375.87$ m/s

$V_{f1} = V_1 \sin\alpha = 400 \sin 20° = 136.8$ m/s

Consider inner inlet triangle,



$$\tan\theta = \frac{V_{f1}}{V_{w1} - u}$$

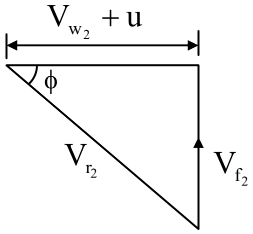
$$\theta = \tan^{-1}\left(\frac{V_{f1}}{V_{w1} - u}\right)$$

$$= \tan^{-1}\left(\frac{136.8}{375.87 - 187.94}\right) = 36.05^\circ$$

$\theta = \phi = 36.05°$

$$V_{r1} = \frac{V_{f1}}{\sin\theta} = \frac{136.8}{\sin(36.05^\circ)} = 232.45 \text{ m/s}$$

$V_{r1} = V_{r2} = 232.45$ m/s



$$\cos\phi = \frac{V_{w2} + u}{V_{r2}}$$

$V_{w2} = V_{r2} \cos\phi - u$

$= [(232.45 \times \cos 36.05°) - 187.94]$

$= 0$

$$\text{Power} = \frac{\dot{m}_s(V_{w1} \pm V_{w2})\times u}{1000}$$

$$= \frac{0.6\times(375.87 \pm 0)\times 187.94}{1000}$$

$= 42.38$ kW

Diagram efficiency

$$(\eta_{\text{blade}}) = \frac{2u\times(V_{w1} \pm V_{w2})}{V_1^2}$$

$$= \frac{2\times 187.94(375.87 \pm 0)}{(400)^2} = 88.3\ \%$$

(OR)

Maximum diagram work = $2u^2$

Maximum diagram power = $\dot{m}\times(2u^2)$

$$= 0.6\times\left(2\times\left(\frac{400}{2}\cos 20^\circ\right)^2\right) = 42.38 \text{ kW}$$

Maximum blade efficiency

$(\eta_{\text{blade max}}) = \cos^2\alpha$

$= \cos^2(20°) = 88.3$ %

NOTE: *In given options diagram power is 48 kW and diagram efficiency is 87.9%, change them to 42.38 kW and 88.3 % respectively.*

31. Ans: (b, c)

Sol:

- The supersonic velocity in the flow can be found for de-Laval turbine.
- The blade thickness is more at the centre of impulse turbine blades.
- Degree of reaction is 50% for a Parson reaction turbine.
- Both impulse and reaction turbines need compounding.

32. Ans: (a, c, d)

Sol:

- Ljunstorm turbine is outward flow reaction turbine
- Normal shock waves are developed only in the diverging portion, because, the normal shock waves are characteristics of supersonic flow.
- Mass flow rate increases with metastable flow
- Mass flow rate cannot be changed with normal shock wave.

33. Ans: (a, b, d)

Sol:

- The blades are arranged for Parson's turbine to have the converging passages.
- Chances of flow separation is less in Parson's turbine
- For the same blade speed the Parson's turbine maximum work output is not more than that of De-Laval turbine

  Maximum work of De-Laval turbine = $2u^2$

  Maximum work of Parson's turbine = u^2
- The relative velocity increases in the Parson's turbine.