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# THERMODYNAMICS

## MECHANICAL ENGINEERING

**Date of Test : 24/09/2024****ANSWER KEY >**

- |        |         |         |         |         |
|--------|---------|---------|---------|---------|
| 1. (a) | 7. (b)  | 13. (b) | 19. (d) | 25. (b) |
| 2. (a) | 8. (c)  | 14. (b) | 20. (b) | 26. (b) |
| 3. (b) | 9. (d)  | 15. (d) | 21. (a) | 27. (d) |
| 4. (b) | 10. (d) | 16. (c) | 22. (b) | 28. (a) |
| 5. (a) | 11. (a) | 17. (a) | 23. (d) | 29. (a) |
| 6. (b) | 12. (c) | 18. (d) | 24. (c) | 30. (c) |

**DETAILED EXPLANATIONS**

1. (a)

2. (a)

3. (b)

For a heat reversible engine,

$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2}$$

$$\frac{W + Q_2}{Q_2} = \frac{T}{200}$$

$$\therefore \frac{40 + (1000/60)}{1000/60} = \frac{T}{200}$$

$$\Rightarrow T = 680 \text{ K}$$

4. (b)

$$\eta_{\text{Carnot}} = 1 - \frac{T_L}{T_H} = \frac{\dot{W}_{\text{rev}}}{\dot{Q}_H}$$

$$\begin{aligned} \therefore \dot{W}_{\text{rev}} &= \left(1 - \frac{300}{1200}\right) \times 500 \\ &= 375 \text{ kW} \end{aligned}$$

Irreversibility rate

$$\dot{i} = \text{Reversible power} - \text{Useful power}$$

$$\therefore \dot{i} = 375 \text{ kW} - 180 \text{ kW}$$

$$\dot{i} = 195 \text{ kW}$$

5. (a)

$$\frac{W_x}{m} = h_1 - h_2 + \frac{V_1^2 - V_2^2}{2 \times 1000}$$

$$\therefore \frac{W_x}{m} = (3230 - 2660) + \frac{160^2 - 100^2}{2 \times 1000}$$

$$\therefore \frac{W_x}{m} = 577.8 \text{ kJ/kg}$$

6. (b)

Linear interpolation,

$$\frac{x - 200}{50 - 200} = \frac{y - 50}{100 - 50}$$

For  $x = y$

$$\frac{x - 200}{-150} = \frac{x - 50}{50}$$

$$\Rightarrow x = 87.5^\circ\text{C}$$

$^{\circ}x$	$^{\circ}y$
50	100
200	50
$x$	$y$

7. (b)

For irreversible system, Clausius inequality

$$\oint \frac{\delta Q}{T} < 0$$

and refrigerator  $\oint \delta Q < 0$ .

8. (c)

An intensive property is a property of matter that depends only on the type of matter in a sample and independent of mass of matter. Example : Temperature, density, solubility, conductivity, viscosity, pressure, etc.

9. (d)

$$(P_1)_{\text{abs}} = 220 + 95 = 315 \text{ kPa}$$

$$(P_2)_{\text{abs}} = 235 + 95 = 330 \text{ kPa}$$

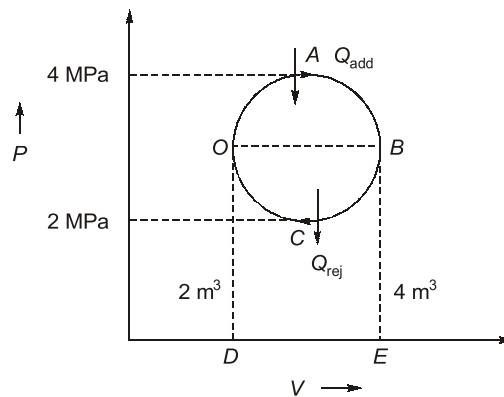
If volume is assumed constant then

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

$$\Rightarrow T_2 = \frac{P_2}{P_1} T_1 = \frac{330}{315} \times 298 = 312.19 \text{ K}$$

$$T_2 = 39.19^\circ\text{C}$$

10. (d)

In cycle  $Q_{\text{net}} = W_{\text{net}} = \text{Area enclosed by cycle.}$ 

$$= \frac{\pi}{4} \times (4 - 2) \times (4000 - 2000)$$

$$= 3141.59 \text{ kJ}$$

11. (a)

$$P_{N_2} = 400 \text{ kPa,}$$

$$P_{CO_2} = 200 \text{ kPa,}$$

$$P_{\text{mix}} = 250 \text{ kPa}$$

$$n_{N_2} = 3 \text{ Kmol,}$$

$$n_{CO_2} = 7 \text{ Kmol,}$$

$$M_{N_2} = 28 \text{ kg/Kmol}$$

$$M_{CO_2} = 44 \text{ kg/Kmol}$$

$$n_{\text{mix}} = n_{\text{N}_2} + n_{\text{CO}_2} = 10 \text{ Kmol}$$

$$y_{\text{N}_2} = \frac{n_{\text{N}_2}}{n_{\text{mix}}} = 0.3$$

$$y_{\text{CO}_2} = 0.7$$

$$\therefore P_{\text{N}_2} = y_{\text{N}_2} \times P_{\text{mix}} = 0.3 \times 250 \text{ kPa} = 75 \text{ kPa}$$

12. (c)

Availability for a flow process,

$$\begin{aligned} &= (h_1 - h_2) - T_0(S_1 - S_2) = (400 - 100) - 300 \times (1.1 - 0.7) \\ &= 300 - [300 \times (1.1 - 0.7)] \\ &= 300 - 120 \\ &= 180 \text{ kJ/kg} \end{aligned}$$

13. (b)

$$P \propto \frac{1}{V^2}$$

$$\therefore P_1 = \frac{k}{V_1^2}$$

$$\therefore P_1 V_1^2 = P_2 V_2^2$$

$$\Rightarrow 1000 \times 0.1^2 = 200 \times V_2^2$$

$$\therefore V_2 = 0.223 \text{ m}^3$$

$$\therefore W = \int_1^2 P dv = \int_1^2 \frac{k}{V^2} dV = k \left[ \frac{1}{V_1} - \frac{1}{V_2} \right]$$

$$= P_1 V_1^2 \left[ \frac{1}{V_1} - \frac{1}{V_2} \right]$$

$$= 1000 \times 0.1^2 \left[ \frac{1}{0.1} - \frac{1}{0.223} \right]$$

$$W = 55.15 \text{ kJ}$$

14. (b)

We know by 1<sup>st</sup> law of thermodynamics,

$$\Delta Q = \Delta U + \Delta W$$

$$(40 - 8) = \Delta U + \frac{-500}{1000}$$

$$\therefore 32 = \Delta U - 0.5$$

$$\Delta U = 32.5$$

$$U_2 - U_1 = 32.5$$

$$U_2 - 10 = 32.5$$

$$\therefore U_2 = 32.5 + 10$$

$$\therefore U_2 = 42.5 \text{ kJ}$$

15. (d)

$$\begin{aligned} \dot{Q}_H &= \dot{W}_{\text{net}} + \dot{Q}_L \\ &= 6000 + 3500 \end{aligned}$$

$$= 9500 \text{ kJ/min}$$

Also,  $\dot{Q}_A + \dot{Q}_B = \dot{Q}_H$

$$\dot{Q}_A + \dot{Q}_B = 9500 \text{ kJ/min} \quad \dots(1)$$

Also,  $\frac{\dot{Q}_A}{T_A} + \frac{\dot{Q}_B}{T_B} = \frac{3500}{200}$

$\therefore \dot{Q}_A + 2\dot{Q}_B = 14000 \quad \dots(2)$

Solving (1) and (2),  $\dot{Q}_A = 5000 \text{ kJ/min}$

$$\dot{Q}_B = 4500 \text{ kJ/min}$$

16. (c)

$$R_e = \frac{\Sigma mR}{\Sigma m}$$

$$\Rightarrow R_e = 0.77 \times \frac{8.314}{32} + 0.23 \times \frac{8.314}{28}$$

$$\Rightarrow R_e = 0.268 \text{ kJ/kgK}$$

$$[C_{v}]_e = \frac{R_e}{\gamma - 1} = \frac{0.268}{0.4} = 0.671 \text{ kJ/kg-K}$$

Constant volume process

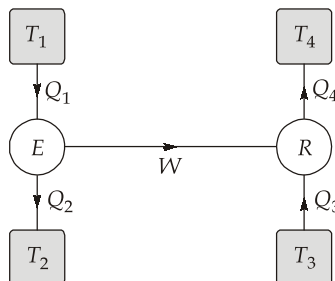
$$\frac{P_2}{P_1} = \frac{T_2}{T_1}$$

$$\Rightarrow T_2 = 2T_1$$

$$\Rightarrow T_2 = 596 \text{ K}$$

$$\begin{aligned} \text{Heat supplied} &= m(C_v)_e \Delta T \\ &= 2 \times 0.671 \times 298 = 399.916 \text{ kJ} \\ &\simeq 400 \text{ kJ} \end{aligned}$$

17. (a)



Given:  $\eta_E = 0.5$

Also  $Q_1 = \frac{1}{2}(Q_2 + Q_4)$

$$W = \eta Q_1 = 0.5 Q_1$$

$$\Rightarrow Q_2 = Q_1 - W = 0.5 Q_1$$

$$\begin{aligned} \Rightarrow Q_4 &= 2Q_1 - Q_2 = 1.5Q_1 \\ (\text{COP})_R &= \frac{Q_3}{Q_4 - Q_3} = \frac{Q_4 - W}{W} \\ &= \frac{Q_4}{W} - 1 = \frac{1.5Q_1}{0.5Q_1} - 1 = 3 - 1 = 2 \end{aligned}$$

**18. (d)**

Let the final common temperature of 3 reservoirs be  $T_f$

Given:  $U = CT$

$$\Rightarrow dU = CdT$$

Now,  $dS = \frac{CdT}{T}$

$$\Rightarrow \Delta S = C \ln \frac{T_f}{T_i}$$

$T_i$  = Initial temperature

For maximum work,  $\sum \Delta S = 0$

$$\Rightarrow \Delta S_1 + \Delta S_2 + \Delta S_3 = 0$$

$$\Rightarrow C \ln \frac{T_f}{200} + C \ln \frac{T_f}{250} + C \ln \frac{T_f}{540} = 0$$

$$\Rightarrow T_f^3 = 200 \times 250 \times 540$$

$$\Rightarrow T_f = 300 \text{ K}$$

$$\begin{aligned} W_{\max} &= -[\Delta U_1 + \Delta U_2 + \Delta U_3] = -[C[T_f - T_1] + C[T_f - T_2] + C[T_f - T_3]] \\ &= -[8.4(300 - 200) + 8.4(300 - 250) + 8.4(300 - 540)] \end{aligned}$$

$$\Rightarrow W_{\max} = 756 \text{ kJ}$$

**19. (d)**

Given:  $V_1 = 0.05 \text{ m}^3$

Now, enclosed volume at final state is

$$V_2 = 2V_1 = 0.1 \text{ m}^3$$

$$\therefore \text{Displacement of piston, } x = \frac{\Delta V}{A} = \frac{0.05}{0.25} = 0.2 \text{ m}$$

Force applied by linear spring at final state,

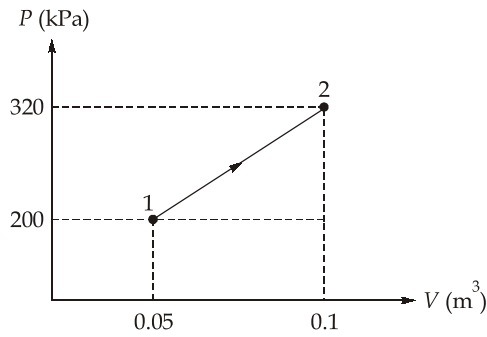
$$F_{\text{spring}} = kx = 150 \times 0.2 = 30 \text{ kN}$$

Additional pressure applied by spring,

$$P = \frac{F_{\text{spring}}}{A} = \frac{30}{0.25} = 120 \text{ kPa}$$

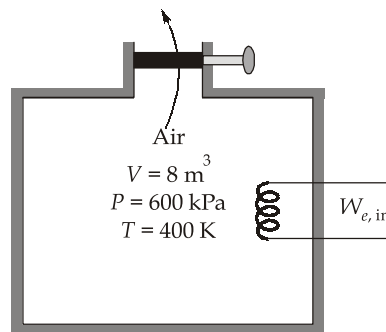
Without the spring, pressure of gas would remain constant at 200 kPa but under the effect of spring, pressure rises linearly from 200 kPa to  $(200 + 120) = 320 \text{ kPa}$ .

Now, total work done by gas = Area under the process (1-2)



$$W = \text{Area} = \left( \frac{200 + 320}{2} \right) (0.1 - 0.05) \text{ kJ} = 13 \text{ kJ}$$

20. (b)



$$m_1 = \frac{P_1 V_1}{RT_1} = \frac{600 \times 8}{0.287 \times 400} = 41.81 \text{ kg}$$

$$m_2 = \frac{P_2 V_2}{RT_2} = \frac{200 \times 8}{0.287 \times 400} = 13.94 \text{ kg}$$

At 400 K,

$$h_e = 400.98 \text{ kJ/kg and } u_1 = u_2 = 286.16 \text{ kJ/kg (Given)}$$

**Mass balance:**

$$\begin{aligned} m_{in} - m_{out} &= \Delta m_{\text{system}} \\ \Rightarrow m_e &= m_1 - m_2 = 41.81 - 13.94 = 27.87 \text{ kg} \end{aligned}$$

**Energy balance:**

$$\begin{aligned} E_{in} - E_{out} &= \Delta E_{\text{system}} \\ W_{e,in} - m_e h_e &= m_2 u_2 - m_1 u_1 \quad (\text{Since } Q \cong \text{KE} \cong \text{PE} \cong 0) \\ m_e h_e + m_2 u_2 - m_1 u_1 &= W_{e,in} \\ W_{e,in} &= m_e h_e + u(m_2 - m_1) \quad (\because u = u_1 = u_2) \\ &= m_e h_e + u(-m_e) \\ W_{e,in} &= m_e (h_e - u) \\ &= 27.87 \times (400.98 - 286.16) \text{ kJ} \\ &= 27.87 \times 114.82 \text{ kJ} \\ &= 3200.03 \text{ kJ} \\ &= 0.889 \text{ kWh} \quad [\because 1 \text{ kWh} = 3600 \text{ kJ}] \end{aligned}$$

21. (a)

22. (b)

Heat transferred in the boiler/kg of fluid,

$$Q_1 = (h_1 - h_4) = 2800 - 700 = 2100 \text{ kJ}$$

Heat transferred from the condenser per kg of fluid,

$$Q_2 = (h_3 - h_2) = 550 - 2450 = -1900 \text{ kJ}$$

$$\sum \frac{\delta Q}{T} = \frac{Q_1}{T_1} + \frac{Q_2}{T_2} = \frac{2100}{(220+273)} + \frac{-1900}{(51+273)}$$

$$= -1.6 \text{ kJ/kgK} < 0$$

Hence the cycle will be irreversible.

23. (d)

$$\text{Mean temperature of mixture} = \frac{T_1 + T_2}{2} \quad (\Delta U = 0)$$

$$\begin{aligned} \text{Change in entropy, } \Delta s &= C \int_{T_1}^{\frac{T_1+T_2}{2}} \frac{dT}{T} + \int_{\frac{T_1+T_2}{2}}^{T_2} \frac{dT}{T} \\ &= C \ln \frac{T_1+T_2}{2T_1} + C \ln \frac{T_1+T_2}{2T_2} \\ &= C \ln \frac{(T_1+T_2)^2}{4T_1T_2} = 2C \ln \frac{T_1+T_2}{2\sqrt{T_1T_2}} \\ &= 2C \ln \frac{\frac{T_1+T_2}{2}}{\sqrt{T_1T_2}} = 2C \ln \left( \frac{\text{A.M.}}{\text{G.M.}} \right) \end{aligned}$$

Since arithmetic mean  $\left( \frac{T_1+T_2}{2} \right) >$  geometric mean  $\sqrt{T_1T_2}$  therefore  $\ln \frac{\frac{T_1+T_2}{2}}{\sqrt{T_1T_2}}$  is positive.

24. (c)

$$m_1 = \frac{P_1 V_1}{RT_1} = \frac{10 \times 10^5 \times 2}{287 \times 373} = 18.68 \text{ kg.}$$

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

$$\Rightarrow T_2 = 373 \times \left( \frac{1}{10} \right)^{0.4} = 193.19 \text{ k}$$

$$m_2 = \left( \frac{P_2 V_2}{RT_2} \right) = \frac{1 \times 10^5 \times 2}{287 \times 193.19} = 3.6 \text{ kg.}$$

$$\begin{aligned} \text{K.E., } (m_1 - m_2) \frac{C^2}{2} &= (m_1 u_1 - m_2 u_2) - (m_1 - m_2)h \\ &= m_1 C_V T_1 - m_2 C_V T_2 - (m_1 - m_2) C_P T_2 \\ &= 18.68 \times 0.718 \times 373 - 3.6 \times 0.718 \times 193.19 \\ &\quad - (18.68 - 3.6) \times 1.005 \times 193.19 \\ &= 1575.5 \text{ kJ} \end{aligned}$$

25. (b)

The paddle wheel does work on the system (the gas) due to the 100 kg mass dropping 3 m. That work is negative

$$W_1 = -F \times d = -100 \times 9.81 \times 3 = -2943 \text{ J}$$

The work done by the system on this friction piston is positive,



$$W_2 = (PA)(h) = PV = (100 + 100) \times 0.002$$

$$= 0.4 \text{ kJ} = 400 \text{ J}$$

$$\therefore W_{\text{net}} = -2943 + 400 = -2543 \text{ J}$$

26. (b)

$$T_1 = 21^\circ\text{C} = 294 \text{ K}$$

$$T_2 = 6^\circ\text{C} = 279 \text{ K}$$

$$\dot{Q} = kA \frac{\Delta T}{L}$$

Here,

$$k = 0.71 \text{ W/mK}$$

$$A = 35 \text{ m}^2$$

$$\Delta T = 15 \text{ K}$$

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

$$\Rightarrow \dot{Q} = \frac{0.71 \times 35 \times 15}{0.3} = 1242.5 \text{ W}$$

Taking the wall as a system, the entropy balance.

$$\frac{dS_{\text{wall}}}{dt} = \dot{S}_{\text{transfer}} + \dot{S}_{\text{gen wall}}$$

$$\Rightarrow 0 = \sum \frac{\dot{Q}}{T} + \dot{S}_{\text{gen}} \quad (\because \frac{dS_{\text{wall}}}{dt} = 0 \text{ for steady flow})$$

$$\Rightarrow 0 = \frac{Q}{T_1} - \frac{Q}{T_2} + \dot{S}_{\text{gen}}$$

$$\Rightarrow 0 = \frac{1242.5}{294} - \frac{1242.5}{279} + \dot{S}_{\text{gen}}$$

$$\Rightarrow \dot{S}_{\text{gen}} = 0.227 \text{ W/K}$$

27. (d)

For polytropic process,

$$PV^n = c$$

$$\Rightarrow P_1 V_1^n = P_2 V_2^n$$

$$\Rightarrow n = \frac{\log_e(P_1/P_2)}{\log_e(V_2/V_1)}$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\Rightarrow V_2 = \frac{P_1 T_2}{P_2 T_1} V_1 = \frac{125}{100} \times \frac{373}{393} \times 0.08 = 0.0949 \text{ m}^3$$

$$\Rightarrow n = \frac{\log_e\left(\frac{125}{100}\right)}{\log_e\left(\frac{0.0949}{0.08}\right)} = 1.3065$$

$$\text{Work done, } W = \frac{P_1 V_1 - P_2 V_2}{n-1} = \frac{(125 \times 0.08 - 100 \times 0.0949) \times 10^3}{1.3065 - 1} = 1663.94 \approx 1664 \text{ J}$$

28. (a)

Given;  $P = 200 \text{ kN/m}^2$ ;  $W_1 = -150 \text{ kJ}$ ;  $Q = 50 \text{ kJ}$

We know,  $H = U + PV$

$$H_1 = U_1 + P_1V_1$$

$$H_2 = U_2 + P_2V_2$$

$\therefore$  Change in enthalpy  $\Delta H = H_2 - H_1 = (U_2 - U_1) + P(V_2 - V_1)$

Work done by the system,

$$W_2 = P(V_2 - V_1) = 200 \times (5 - 2) = 600 \text{ kJ}$$

From 1st law of thermodynamics,

$$\Delta Q = \Delta U + \Delta W$$

$$\Delta U = \Delta Q - \Delta W = 50 - (-150 + 600) = 50 - 450 = -400 \text{ kJ}$$

So,  $\Delta H = \Delta U + P(V_2 - V_1)$

$\therefore \Delta H = -400 + 200(5 - 2) = -400 + 600 = 200 \text{ kJ}$

29. (a)

Heat required to melt 1 kg of iron at  $15^\circ\text{C}$  to molten metal at  $1650^\circ\text{C}$  = Heat required to raise temperature from  $15^\circ\text{C}$  to  $1535^\circ\text{C}$  + Latent heat + Heat required to raise the temperature from  $1535^\circ\text{C}$  to  $1650^\circ\text{C}$ .

$$= 0.502 \times [1535 - 15] + 270 + 0.534 [1650 - 1535]$$

$$= 1094.45 \text{ kJ/kg}$$

$$\text{Melting rate} = 5 \times 10^3 \text{ kg/hr}$$

Rate of heat supply required =  $1094.45 \times 5 \times 10^3 \text{ kJ/hr}$

$$\text{kW rating of furnace required} = \frac{\text{Heat Rate}}{\text{Furnace Efficiency}} = \frac{1094.45 \times 5 \times 10^3}{0.7} \text{ kJ/hr}$$

$$= \frac{1094.45 \times 5 \times 10^3}{0.7 \times 3600} \text{ kJ/s}$$

$$= 2171.5 \text{ kW} = 2.17 \text{ MW}$$

30. (c)

Maximum work obtainable from a body and TER,

$$W_{\max} = m \left[ c_p (T - T_0) + T_0 c_p \ln \left( \frac{T_0}{T} \right) \right]$$

$$= 2 \left[ 1 \times (600 - 300) + 300 \times 1 \times \ln \left( \frac{300}{600} \right) \right]$$

$$= 184.1 \text{ kJ}$$

