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# THERMODYNAMICS

## MECHANICAL ENGINEERING

Date of Test : 22/06/2023

### ANSWER KEY ➤

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

## DETAILED EXPLANATIONS

1. (b)

Linear interpolation,

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

For  $x = y$ 

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

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

$^\circ\text{C}$	$^\circ\text{F}$
50	100
200	50
$x$	$y$

2. (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.

3. (d)

$$c_{\text{poly}} = c_v \left( \frac{\gamma - n}{1 - n} \right)$$

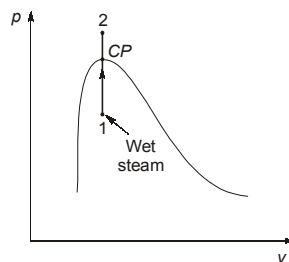
4. (b)

For irreversible system, Clausius inequality

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

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

5. (a)



Constant volume heat addition process passing through critical point.

6. (d)

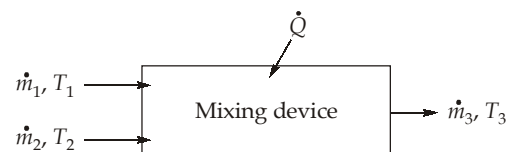
Mixing takes place at constant pressure.

From steady flow energy equation

$$\dot{m}_1(h_1) + \dot{m}_2(h_2) + \dot{Q} = \dot{m}_3(h_3) + W$$

$$\dot{m}_3(c_p T_3) = \dot{m}_1(c_p T_1) + \dot{m}_2(c_p T_2) + \dot{Q}$$

$$T_3 = \frac{\dot{m}_1}{\dot{m}_3}(T_1) + \frac{\dot{m}_2}{\dot{m}_3}(T_2) + \frac{\dot{Q}}{\dot{m}_3 c_p}$$



7. (c)

To understand the significance of the term independent property, consider the saturated-liquid and saturated-vapor states of a pure substance. These two states have the same pressure and the same temperature, but they are definitely not the same state. In a saturation state, therefore, pressure and temperature are not independent properties. Two independent properties, such as pressure and specific volume or pressure and quality, are required to specify a saturation state of a pure substance.

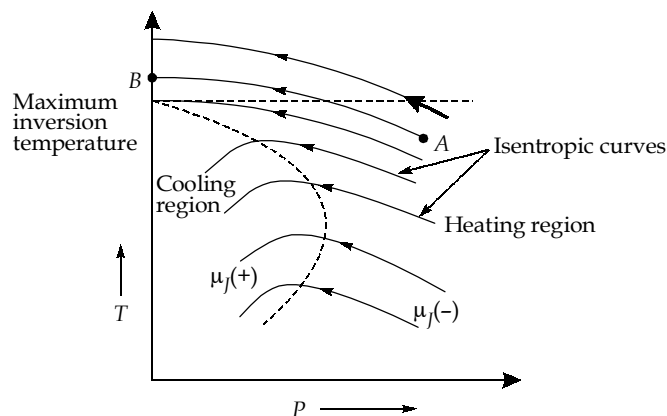
8. (b)

The change in availability of closed system is not equal to change in Helmholtz function at given room temperature.

The change in availability of closed system

$$\phi_1 - \phi_2 = (u_1 + P_o V_1 - T_o S_1) - (u_2 + P_o V_2 - T_o S_2)$$

9. (c)



As gas is throttled above maximum inversion temperature (curve AB and above) then the temperature of gas keeps on increasing.

10. (b)

Real gases deviate from the ideal gas behaviour and this deviation at given temperature and pressure can be accurately accounted by introducing a correct factor called the compressibility factor ( $z$ ),

$$z = \frac{V_{actual}}{V_{ideal}}$$

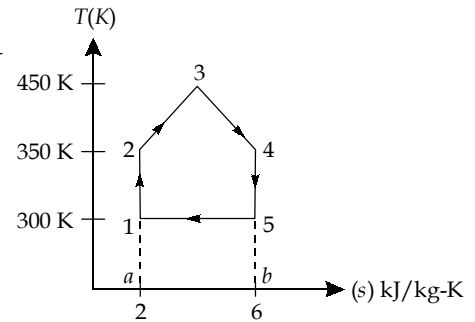
11. (b)

For steady flow through an insulated horizontal constant diameter pipe, enthalpy remains constant but not for varying diameter.

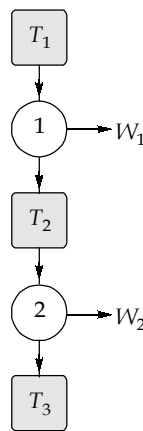
Because when diameter of pipe change corresponding to that pressure will also change for same mass flow rate and hence flow work changes.

12. (b)

$$\begin{aligned}
 \eta &= \frac{\text{Work}}{Q_{\text{supply}}} = \frac{ar(1-2-3-4-5-1)}{ar(a-2-3-4-b-a)} \\
 &= \frac{\frac{1}{2} \times 100 \times 4 + 50 \times 4}{\frac{1}{2} \times 100 \times 4 + 350 \times 4} \\
 &= \frac{400}{1600} = \frac{1}{4} = 25\%
 \end{aligned}$$



13. (d)



For series combination with same efficiency,

$$\begin{aligned}
 T_2^2 &= T_1 \times T_3 \\
 (327 + 273)^2 &= T_1 \times 500 \\
 T_1 &= \frac{600^2}{500} = 720 \text{ K}
 \end{aligned}$$

14. (b)

$$\dot{m} = 0.5 \text{ kg/s}, T_1 = 25^\circ\text{C}, T_2 = 175^\circ\text{C}, V_1 = 5 \text{ m/s}, V_2 = 2 \text{ m/s}$$

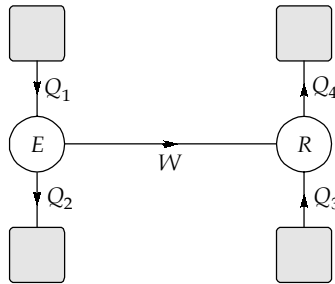
Considering compressor as system,

From first law,

$$\dot{E}_{in} - \dot{E}_{out} = \left( \frac{dE}{dt} \right)_{\text{system}}^0 \quad (\because \text{Steady flow})$$

$$\begin{aligned}
 \text{Work input, } \dot{W} &= \dot{m}(h_2 - h_1) + \frac{\dot{m}}{2000}(V_2^2 - V_1^2) + \dot{Q} \\
 &= 0.5(1.005)(175 - 25) + \frac{0.5}{2000}(2^2 - 5^2) + 10 \\
 &= 85.36 \text{ kJ}
 \end{aligned}$$

15. (a)



Given:  $\eta_E = 0.5$

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

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

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

$$\Rightarrow Q_4 = 2Q_1 - Q_2 = 1.5Q_1$$

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

16. (b)

- A gas cools upon expansion, when its Joule-Thomson coefficient is positive in the temperature range of expansion.
- For achieving the effect of cooling by Joule-Kelvin expansion, the initial temperature of the gas must be below the point where the inversion curve intersect the temperature axis, i.e. below the maximum inversion temperature.

17. (c)

$$\bullet \quad du = c_v dT + \left[ T \left( \frac{\partial P}{\partial T} \right)_v - P \right] dv$$

$$\bullet \quad dh = c_p dT + \left[ v - T \left( \frac{dv}{dT} \right)_p \right] dP$$

$$\bullet \quad c_p - c_v = -T \left( \frac{\partial v}{\partial T} \right)_p^2 \left( \frac{\partial v}{\partial T} \right)_T = \frac{T v \beta^2}{k_t}$$

$$\bullet \quad \mu = \left( \frac{\partial T}{\partial P} \right)_h = \frac{1}{c_p} \left[ T \left( \frac{\partial v}{\partial T} \right)_p - v \right]$$

18. (c)

Given data:

$$\text{Cycle efficiency} = \eta = 0.7$$

$$\text{Heat rejected} = Q_R = 1200 \text{ kJ/kg}$$

$$\text{Heat added} = Q_A$$

$$\eta = \frac{Q_A - Q_R}{Q_A} = 1 - \frac{Q_R}{Q_A}$$

$$\Rightarrow 0.7 = 1 - \frac{1200}{Q_A}$$

$$\Rightarrow \frac{1200}{Q_A} = 0.3$$

$$\Rightarrow Q_A = 4000 \text{ kJ/kg}$$

$$W = Q_A - Q_R = 2800 \text{ kJ/kg}$$

From the scale given

$$1 \text{ cm}^2 = 200 \times 0.2 = 40 \text{ kJ/kg}$$

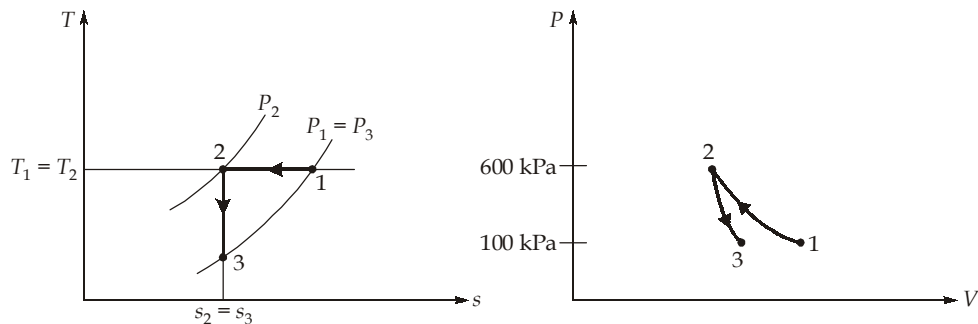
$$\text{Area of circle} \times 1 \text{ cm}^2 = W$$

$$\Rightarrow \text{Area of circle} = \frac{2800}{40} = 70 \text{ cm}^2$$

$$\frac{\pi}{4} d^2 = 70 \text{ cm}^2$$

$$d = 9.44 \text{ cm}$$

19. (c)

The adiabatic reversible expansion of ideal gas and constant specific heat, ( $k = 1.66$ )

$$\begin{aligned} T_3 &= T_2 \left( \frac{P_3}{P_2} \right)^{\frac{k-1}{k}} \\ &= 293 \left( \frac{100}{600} \right)^{0.4} = 143.089 \text{ K} \end{aligned}$$

The isothermal process has work done on the system.

$$W_{12} = -RT_1 \ln \left( \frac{P_2}{P_1} \right) = -\frac{8.314}{4} \times 293 \times \ln \left( \frac{600}{100} \right) = -1091.18 \text{ kJ/kg}$$

For process 2-3,

$$\begin{aligned} Q &= \Delta U + W \\ W_{23} &= -(U_3 - U_2) = (U_2 - U_3) ; Q_{23} = 0 \text{ [adiabatic]} \end{aligned}$$

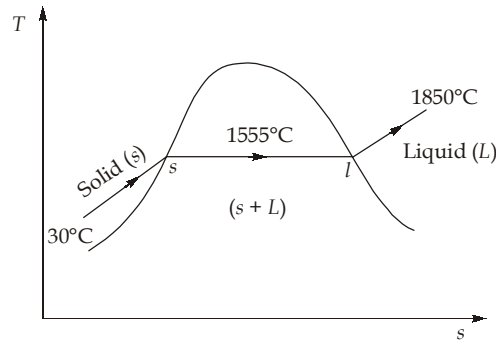
$$c_v = \frac{R}{(\gamma - 1)} = \frac{\left(\frac{8.315}{4}\right)}{(1.66 - 1)} = 3.149$$

$$W_{23} = c_v (T_2 - T_3) = 3.149(293 - 143) = 472.35 \text{ kJ/kg}$$

The net work is,

$$W_{\text{NET}} = -1091.18 + 472.35 = -618.83 \text{ kJ/kg}$$

20. (d)



$$\text{Heat required, } q = (c_p)_s (T_m - T_i) + \text{Latent heat} + (c_p)_l (T_f - T_m)$$

$$= 0.50 \times (1555 - 30) + 295 + 0.51(1850 - 1555) = 1207.95 \text{ kJ/kg}$$

$$\therefore \text{furnace rating} = \frac{\dot{m}q}{\eta} = \frac{2.1 \times 1207.95}{0.90} = 2818.55 \text{ kW} = 2.818 \text{ MW}$$

21. (b)

For a constant temperature process,

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

$$W = \int_{V_1}^{V_2} P dV = \int_{V_1}^{V_2} \frac{mRT}{V - b} dV - \int_{V_1}^{V_2} \frac{a}{V^2} dV$$

$$W = mRT \ln \left( \frac{V_2 - b}{V_1 - b} \right) + a \left( \frac{1}{V_2} - \frac{1}{V_1} \right)$$

Putting the values of  $m = 10 \text{ kg}$ ,  $R = 0.287 \text{ kJ/kgK}$

$T = 293 \text{ K}$ ,  $V_2 = 10 \text{ m}^3$ ,  $V_1 = 1 \text{ m}^3$ ,  $a = 155 \text{ kNm}^4$  and  $b = 0.0098 \text{ m}^3$ , we get

$$\begin{aligned} W &= 10 \times 0.287 \times 293 \ln \left( \frac{10 - 0.0098}{1 - 0.0098} \right) + 155 \left( \frac{1}{10} - \frac{1}{1} \right) \\ &= 1804.22 \text{ kJ} \end{aligned}$$

22. (c)

Applying steady flow energy equation,

$$m \left( h_1 + \frac{v_1^2}{2} + gz_1 \right) + Q = m \left( h_2 + \frac{v_2^2}{2} + gz_2 \right) + W$$

For adiabatic flow,  $Q = 0$ ,

$$\Rightarrow m \left( h_1 + \frac{v_1^2}{2000} + \frac{gz_1}{1000} \right) = m \left( h_2 + \frac{v_2^2}{2000} + \frac{gz_2}{1000} \right) + W$$

$$\Rightarrow m \left( h_1 - h_2 + \frac{v_1^2 - v_2^2}{2000} + \frac{g(z_1 - z_2)}{1000} \right) = 70000$$

$$\Rightarrow m \left( 3700 - 2000 + \frac{150^2 - 150^2}{2000} + \frac{9.81}{1000}(15 - 2) \right) = 70000$$

$$\Rightarrow m = 41.2 \text{ kg/s}$$

**23. (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,  $\Sigma \Delta S = 0$

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

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

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

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

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

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

**24. (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,

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

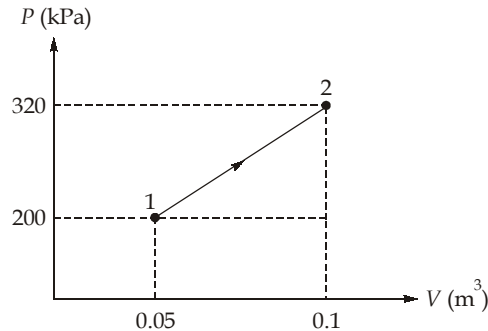
Additional pressure applied by spring,

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



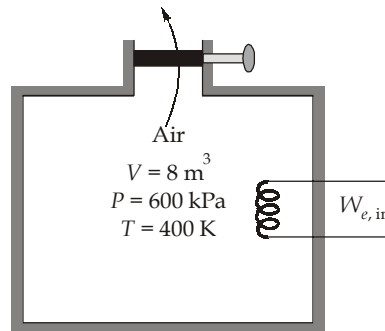
Without the spring, pressure of gas would remain constant at 200 kPa but under the effect of spring, pressure rises linearly from 200 kPa to  $(200 + 120) = 320$  kPa.

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



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

25. (b)



$$m_1 = \frac{P_1 V_1}{R T_1} = \frac{600 \times 8}{0.287 \times 400} = 41.81 \text{ kg}$$

$$m_2 = \frac{P_2 V_2}{R T_2} = \frac{200 \times 8}{0.287 \times 400} = 13.94 \text{ kg}$$

At 400 K,

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

**Mass balance:**

$$m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{system}}$$

$\Rightarrow$

$$m_e = m_1 - m_2 = 41.81 - 13.94 = 27.87 \text{ kg}$$

**Energy balance:**

$$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$$

$$W_{e,\text{in}} - m_e h_e = m_2 u_2 - m_1 u_1$$

(Since  $Q \cong \text{KE} \cong \text{PE} \cong 0$ )

$$m_e h_e + m_2 u_2 - m_1 u_1 = W_{e,\text{in}}$$

$$W_{e,\text{in}} = m_e h_e + u(m_2 - m_1)$$

( $\because u = u_1 = u_2$ )

$$= m_e h_e + u(-m_e)$$

$$W_{e,\text{in}} = m_e (h_e - u)$$

$$= 27.87 \times (400.98 - 286.16) \text{ kJ}$$

$$= 27.87 \times 114.82 \text{ kJ}$$

$$= 3200.03 \text{ kJ}$$

$$= 0.889 \text{ kWh}$$

[ $\because 1 \text{ kWh} = 3600 \text{ kJ}$ ]

26. (a)

$$\begin{aligned}\text{Work potential} &= \text{Exergy (non-flow)} = \phi_1 - \phi_0 \\ &= [(u_1 - u_0) + P_0(V_1 - V_0) - T_0(S_1 - S_0)]\end{aligned}$$

Here,

$$u_1 = u_0 \text{ as } T_1 = T_0$$

and,

$$P_0(V_1 - V_0) = P_0 \left( \frac{RT_1}{P_1} - \frac{RT_0}{P_0} \right) = RT_0 \left( \frac{P_0}{P_1} - 1 \right)$$

and,

$$T_0(S_1 - S_0) = T_0 \left( c_p \ln \left( \frac{T_1}{T_0} \right) - R \ln \left( \frac{P_1}{P_0} \right) \right) = -RT_0 \ln \left( \frac{P_1}{P_0} \right)$$

 $\Rightarrow$ 

$$\phi = RT_0 \left[ \ln \left( \frac{P_1}{P_0} \right) + \frac{P_0}{P_1} - 1 \right]$$

27. (d)

$$T_0 = 25 + 273 = 298, T_1 = 50^\circ\text{C} = 273 + 50 = 323 \text{ K}, P_1 = 800 \text{ kPa}, m = 0.5 \text{ kg/s}, P_2 = 200 \text{ kPa}$$

Assuming air as ideal gas and for throttling,

$$h_1 = h_2$$

 $\Rightarrow$ 

$$T_1 = T_2$$

So,

$$\begin{aligned}\Delta S &= c_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} \\ &= 0 - 0.287 \ln \left( \frac{1}{4} \right) = 0.287 \ln 4 = 0.287 \times 2 \times 0.693\end{aligned}$$

$$\begin{aligned}\text{Power wasted, } I &= mT_0\Delta S = 0.5 \times 298 \times 0.287 \times 2 \times 0.693 \\ &= 59.28 \text{ kW}\end{aligned}$$

28. (d)

$$W = (\Delta h)_{\text{air}} + (\Delta h)_{\text{water}} + Q$$

$$90 = 30 + 40 + Q$$

$$Q = 20 \text{ kJ/kg}$$

29. (a)

A reversible adiabatic process is the one where entropy (which is a property) of a system remains constant.

30. (d)

The state of a pure substance of given mass can be fixed by specifying two independent intensive properties, provided the system is in equilibrium. There may be any number of independent intensive properties for defining non-equilibrium system.

