

Q.1 Explain any FOUR of the following:

[20]

Q.1(a) State and explain Maxwell relations.

(A) Maxwell's relations

$$\left[\frac{\partial T}{\partial V} \right]_S = - \left[\frac{\partial P}{\partial S} \right]_V$$

$$\left[\frac{\partial T}{\partial P} \right]_S = \left[\frac{\partial V}{\partial S} \right]_P$$

$$\left[\frac{\partial P}{\partial T} \right]_V = \left[\frac{\partial S}{\partial V} \right]_T$$

$$\left[\frac{\partial V}{\partial T} \right]_P = - \left[\frac{\partial S}{\partial P} \right]_T$$

Maxwell relations are the equation mode of properties which must be satisfied when any system is in a state of equilibrium.

Q.1(b) Explain clausius inequality.

(A) Clausius Inequality

Let us consider a cycle ABCD (Figure). Let AB be a general process, either reversible or irreversible, while the other processes in the cycle are reversible. Let the cycle be divided into a number of elementary cycles, as shown. For one of these elementary cycles.

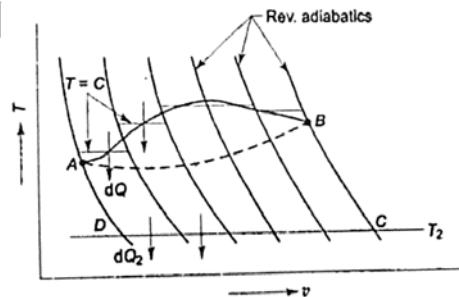


Fig. : Inequality of Clausius

$$\eta = 1 - \frac{dQ_2}{dQ}$$

where dQ is the heat supplied at T_1 and dQ_2 the heat rejected at T_2 .

Now the efficiency of a general cycle will be equal to or less than the efficiency of a reversible cycle.

$$\therefore 1 - \frac{dQ_2}{dQ} \leq \left(1 - \frac{dQ_2}{dQ} \right)_{\text{rev}}$$

$$\text{or } \frac{dQ_2}{dQ} \geq \left(\frac{dQ_2}{dQ} \right)_{\text{rev}}$$

$$\text{or } \frac{dQ}{dQ_2} \leq \left(\frac{dQ}{dQ_2} \right)_{\text{rev}}$$

$$\text{Since } \left(\frac{dQ}{dQ_2} \right)_{\text{rev}} = \frac{T}{T_2}$$

$$\therefore \frac{dQ}{dQ_2} \leq \frac{T}{T_2}$$

$$\text{or } \frac{dQ}{T} \leq \frac{dQ_2}{T_2} \quad \text{for any process AB, reversible or irreversible.}$$

For a reversible process,

$$ds = \frac{dQ_{\text{rev}}}{T} = \frac{dQ_2}{T_2}$$

Hence, for any process AB

$$\frac{dQ}{T} \leq ds$$

Then for any cycle

$$\oint \frac{dQ}{T} \leq \oint ds$$

Since entropy is a property and the cyclic integral of any property is zero

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

This equation is known as the inequality of Clausius. It provides the criterion of the reversibility of a cycle.

If $\oint \frac{dQ}{T} = 0$, the cycle is reversible

$\oint \frac{dQ}{T} < 0$, the cycle is irreversible and possible.

Q.1(c) Explain adiabatic flame temperature.

(A) In a given combustion process, that takes place adiabatically and with no work or changes in kinetic or potential energy involved, the temperature of the products is referred to as the '*adiabatic flame temperature*'. With the assumptions of no work and no changes in kinetic or potential energy, this is the maximum temperature that can be achieved for the given reactants because any heat transfer from the reacting substances and any incomplete combustion would tend to lower the temperature of the products.

The following points are worth noting:

- (i) The maximum temperature achieved through adiabatic complete combustion varies with the type of reaction and per cent of theoretical air supplied. An increase in the air-fuel ratio will effect a decrease in the maximum temperature.

- (ii) For a given fuel and given pressure and temperature of the reactants, the maximum adiabatic flame temperature that can be achieved is with a 'stoichiometric' mixture.
- (iii) The adiabatic flame temperature can be controlled by the amount of excess air that is used. This is important, for example, in gas turbines, where the maximum permissible temperature is determined by *metallurgical considerations* in the turbine, and close control of the temperature of the products is essential.

Q.1(d) Explain second law of thermodynamics.

(A) Second Law of thermodynamics provides the possibility of conversion of heat and work and is given by 2 statements:

- (i) Kelvin Planck's Statement: It is impossible to construct an engine which while operating in a cycle produces no other effect except to extract heat from a single reservoir and do equivalent amount of work.
- (ii) Clausius Statement: It is impossible for a self-acting machine working in a cyclic process unaided by any external source to convey heat from a body at a lower temperature to a body at a higher temperature.

Q.1(e) Explain Joule's experiment.

(A) Throttling process involves the passage of a higher pressure fluid through a narrow constriction. The effect is the reduction in pressure and increase in volume. This process is adiabatic as no heat flows from and to the system, but it is not reversible. It is not an isentropic process. The entropy of the fluid actually increases.

Such a process occurs in a flow through a porous plug, a partially closed valve and a very narrow orifice. The porous plug is shown in Figure.

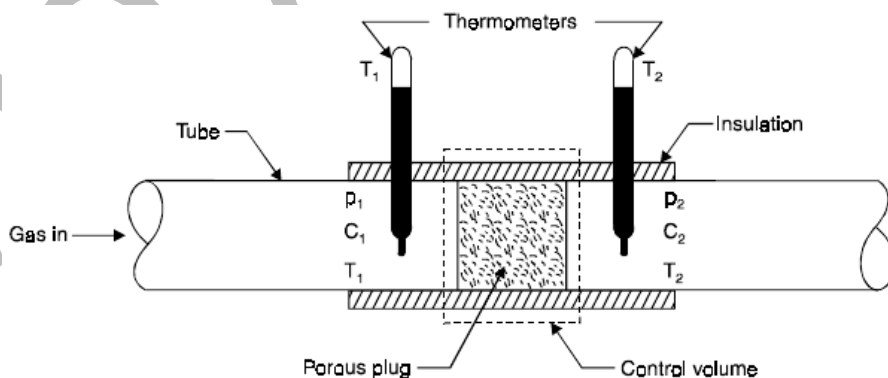


Fig. : The Joule-Thomson porous plug experiment.

Applying the energy equation to the system,

$$h_1 = h_2$$

This shows that enthalpy remains constant during adiabatic throttling process.

The throttling process is commonly used for the following purposes :

- (i) For determining the condition of steam (dryness fraction).
- (ii) For controlling the speed of the turbine.
- (iii) Used in refrigeration plant for reducing the pressure of the refrigerant before entry into the evaporator.

Q.1(f) Explain second law efficiency.

(A) Second Law Efficiency :

It is a measure of the perfectness of any component involves work interaction given by ratio of actual work and reversible work or actual efficiency to reversible efficiency.

For pump, $\eta_p = \frac{W_{rev.}}{W_{actual}}$

For turbine, $\eta_t = \frac{W_{actual}}{W_{rev.}}$

Q.2(a) State and prove Clausius Theorem.

[8]

(A) Clausius Inequality

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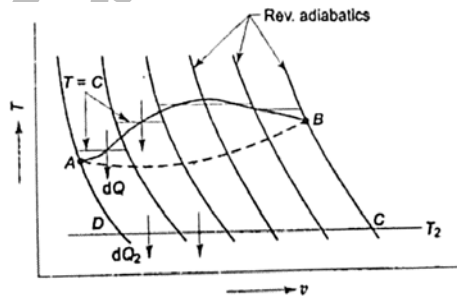


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or $\frac{dQ_2}{dQ} \geq \left(\frac{dQ_2}{dQ} \right)_{rev}$

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$$\text{or } \frac{dQ}{T} \leq \frac{dQ_2}{T_2} \quad \text{for any process AB, reversible or irreversible.}$$

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Q.2(b) A power washer is being used to clean the walls of house. Water [12] at the rate of 0.1 kg/s enters at 20°C and 1 atm, with the velocity 0.2 m/s. The jet of water exits at 23°C, 1 atm with a velocity 50 m/s at an elevation of 5 m. At steady state the magnitude of the heat transfer rate from power unit to the surrounding is 10% of the power input. Determine the power input to the motor in KW.

(A) Given :

$$m = 0.1 \text{ kg/s}$$

$$T_1 = 293\text{K}$$

$$P_1 = 101325 \text{ pa}$$

$$C_1 = 0.2 \text{ m/s}$$

$$z_2 - z_1 = 5\text{m}$$

$$Q = -0.1\text{W}$$

$$T_2 = 296\text{K}$$

$$P_2 = 101325 \text{ pa}$$

$$C_2 = 50 \text{ m/s}$$

$$P_1 = P_2, V_1 = V_2$$

$$\therefore \Delta n = \Delta u$$

Applying SFEE

$$Q - W = m \left[h_2 - h_1 + \frac{C_2^2 - C_1^2}{2} + g(z_2 - z_1) \right]$$

$$Q - W = m \left[u_2 - u_1 + \frac{C_2^2 - C_1^2}{2} + g(z_2 - z_1) \right]$$

$$-0.1W - W = 0.1 \left[4187(296 - 293) + \frac{50^2 - 0.2^2}{2} + 9.81(5) \right]$$

$$-1.1W = 1386$$

$$W = -1260 \text{ J/s}$$

$$W = 1.26 \text{ kW}$$

Q.3(a) State and derive steady flow energy equation and apply it to a boiler condenser, nozzle and turbine. [8]

(A) 1st law when applied to open system with control volume, result in

$$Q - W = \Delta E$$

$$Q - W = \Delta PE + \Delta KE + \Delta u + \Delta(PV)$$

$$Q - W = \Delta PE = \Delta KE + \Delta h$$

$$Q - W = [(mgz_2 - mgz_1) + \left(\frac{1}{2}mV_2^2 - \frac{1}{2}mV_1^2 \right) + h_2 - h_1]$$

$$Q - W = m \left[h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \right]$$

↳ = FEE

$$\therefore Q + \left[h_1 + \frac{V_1^2}{2} + gz_1 \right] = W + h_2 + \frac{V_2^2}{2} + gz_2 \quad (\text{J/Kg})$$

where ΔE : Total energy stored

ΔPE : Change in potential energy

ΔKE : Change in kinetic energy

Δu : Change in internal energy

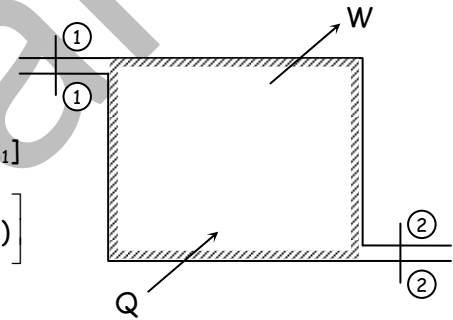
$\Delta(PV)$: Change in flow work

$\Delta h = \Delta u + \Delta(PV)$

h_1, h_2 : Enthalpy at inlet and outlet

V_1, V_2 : Velocity at inlet and outlet

z_1, z_2 : Datum head at inlet and outlet



For Boiler : Considering ideal condition

$$W = 0, \Delta KE = 0, \Delta PE = 0, z_2 = z_1$$

$$\therefore Q - W = \left[h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \right]$$

$$\therefore Q = h_2 - h_1$$

\therefore for condenser,

$$Q = h_1 - h_2$$

For Turbine : Considering ideal condition,

$$Q = 0, \Delta PE = 0, \Delta KE = 0, z_2 = z_1$$

$$\therefore Q - W = \left[h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \right]$$

$$\therefore W = h_2 - h_1$$

$$W = h_1 - h_2$$

Similarly for compressor,

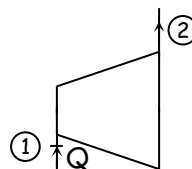
$$W = h_2 - h_1$$

For Nozzle :

$$W = 0, \Delta PE = 0, z_2 = z_1, Q = 0$$

$$Q - W = \left[h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \right]$$

$$\therefore h_2 - h_1 = \frac{V_2^2 - V_1^2}{2}$$



Q.3(b) Liquid Octane C_8H_{18} at $25^\circ C$ is used as fuel. Air used is 150% of [12] theoretical air and is supplied at $25^\circ C$. Assume a complete combustion and the product leaves the combustion chamber at 1600K. Calculate heat transfer per kg mole of fuel. use the following data :

Substance	h_f^0 (MJ/Kmole)	h_{298K} (MJ/Kmole)	h_{1500K} (MJ/Kmole)
C_8H_{18}	- 250	-	-
O_2	-	8.68	52.96
N_2	-	8.67	50.57
H_2O (gas)	-241.8	9.9	62.75
CO_2	-393.5	9.36	76.95

(A)

C_8H_{18} at $25^\circ C$

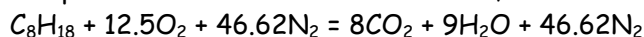
150% theoretical air at $25^\circ C$

Temperature of products = 1600K

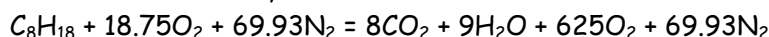
To find Q/Kg mol. of fuel

$$\text{Heat transfer} = H_p - H_R = Q$$

For complete combustion at theoretical air,



For 150% theoretical air,



Enthalpy of products,

$$\begin{aligned}
 H_P &= H_{CO_2} + H_{H_2O} + H_{O_2} + H_{N_2} \quad [\because \sum n[h_f + (h - h_{298})]] \\
 &= 8[-393.5 + (76.95 - 9.36)] + 9[-241.8 + (62.75 - 9.9)] \\
 &\quad + 6.25[0 + (52.96 - 8.68)] + 69.93[0 + (50.75 - 8.67)] \\
 &= -1088.43 \text{ MJ/K mol.}
 \end{aligned}$$

Enthalpy of reactants

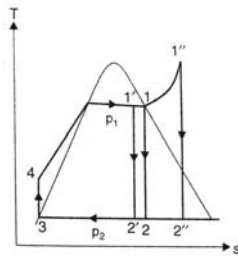
$$\begin{aligned}
 H_R &= H_{C_8H_{18}} + H_{O_2} + H_{N_2} \\
 &= 1[-250] + 12.5[8.68] + 69.93[8.67] \\
 &= 464.793 \text{ MJ/K Mol.}
 \end{aligned}$$

$$\begin{aligned}
 \text{Heat transfer} &= -1088.43 - 464.793 \\
 &= -1553.16 \text{ MJ/K mole}
 \end{aligned}$$

$$\therefore Q = -1553.16 \times 10^3 \text{ KJ/K mole}$$

Q.4(a) Plot the Rankine cycle on T-S diagram and derive an expression [8]
for thermal efficiency of the cycle. List different methods of
improving the performance of the cycle. Discuss any one method in
brief.

(A)



Process 1-2: Reversible adiabatic expansion in the turbine (or steam engine).

Process 2-3: Constant-pressure transfer of heat in the condenser.

Process 3-4: Reversible adiabatic pumping process in the feed pump.

Process 4-1: Constant-pressure transfer of heat in the boiler.

Fig. shows the Rankine cycle on p-v, T-s and h-s diagrams (when the saturated steam enters the turbine, the steam can be wet superheated also).

Considering 1kg of fluid:

Applying steady flow energy equation (S.F.E.E.) to boiler, turbine, condenser and pump:

(i) For boiler (as control volume), we get

$$h_{f_4} + Q_1 = h_1$$

$$\therefore Q_1 = h_1 - h_{f_4}$$

(ii) For turbine (as control volume), we get

$$h_1 = W_T + h_2, \text{ where } W_T = \text{turbine work}$$

$$\therefore W_T = h_1 - h_2$$

$$h_2 = Q_2 + h_{f_3}$$

$$\therefore Q_2 = h_2 - h_{f_3}$$

(iii) For the feed pump, we get

$$h_{f_3} + W_p = h_{f_4}, \text{ where } W_p = \text{Pump work}$$

$$\therefore W_p = h_{f_4} - h_{f_3}$$

Now, efficiency of Rankine cycle is given by

$$\eta_{\text{Rankine}} = \frac{W_{\text{net}}}{Q_1} = \frac{W_T - W_p}{Q_1} = \frac{(h_1 - h_2) - (h_{f_4} - h_{f_3})}{(h_1 - h_{f_4})}$$

The feed pump handles liquid water which is incompressible which means with the increase in pressure its density or specific volume undergoes a little change. Using general property relation for reversible adiabatic compression, we get

$$Tds = dh - vdp$$

$$\therefore ds = 0$$

$$\therefore dh = vdp$$

or $\Delta h = v\Delta p$... (since change in specific volume is negligible)

$$\text{or } h_{f_4} - h_{f_3} = v_3 (p_1 - p_2)$$

When p is in bar and v is in m^3/kg . We have

$$h_{f_4} - h_{f_3} = v_3 (p_1 - p_2) \times 10^5 \text{ J/kg}$$

The feed pump term $(h_{f_4} - h_{f_3})$ being a small quantity in comparison with turbine work. W_T is usually neglected, especially when the boiler pressures are low.

$$\text{Then, } \eta_{\text{Rankine}} = \frac{h_1 - h_2}{h_1 - h_{f_4}}$$

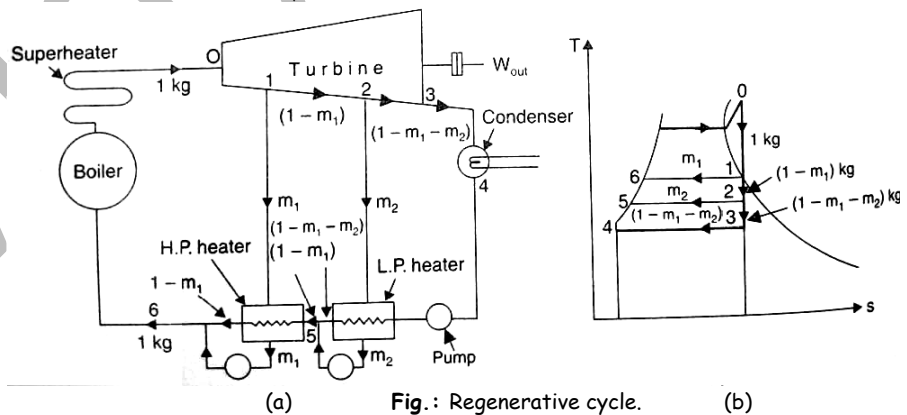


Fig.: Regenerative cycle.

Q.4(b) Water at 40° C is continuously sprayed into a pipeline carrying 5 tons of steam per hour at 5 bar, 300° C. At a section downstream where the pressure is 3 bar, the quality is to be 95%. Find the rate of water spray in kg/hr [6]

(A) Temp of water = 40°C

Mass of steam = 5 tons/hr

pre of steam = 5 bar

Temp of steam = 300°C (superheated)

Pre of mixture (wet steam) = 3 bar

Dryness fraction = 0.95

Enthalpy of water (40°C) = 167.54 KJ/kg

Enthalpy of steam (superheated) = 3064.59 KJ/kg

$$\begin{aligned} \text{Enthalpy of wet steam} &= 1h_f + xh_{fg} \\ &= 561.43 + 0.95 \times 2163.2 \\ &= 2616.47 \text{ KJ/kg} \end{aligned}$$

Enthalpy of water + Enthalpy of steam = Enthalpy of wet steam

$$m_w \times 167.54 + 50 \times 3064.59 = (m_w + 50) 2616.47$$

$$m_w = 9.14 \text{ kg/hr} \quad \dots \text{ mass flow rate of water per hr.}$$

Q.4(c) Derive an expression for ratio of Heat Capacities (γ) in terms of isothermal compressibility (k) and adiabatic compressibility (k_s). [6]

(A) From Maxwell Relation and by definitions

$$C_p = T \cdot \left(\frac{\partial s}{\partial T} \right)_p \quad \text{or,} \quad \frac{C_p}{T} = \left(\frac{\partial s}{\partial T} \right)_p$$

$$\text{and } C_v = T \cdot \left(\frac{\partial s}{\partial T} \right)_v \quad \text{or} \quad \frac{C_v}{T} = \left(\frac{\partial s}{\partial T} \right)_v$$

$$\left(\frac{\partial s}{\partial T} \right)_p \cdot \left(\frac{\partial T}{\partial p} \right)_s \cdot \left(\frac{\partial p}{\partial s} \right)_T = -1$$

$$\text{or,} \quad \left(\frac{\partial s}{\partial T} \right)_p = \frac{-1}{\left(\frac{\partial T}{\partial p} \right)_s \cdot \left(\frac{\partial p}{\partial s} \right)_T}$$

Similarly for s , T and v properties we can write using cyclic relation :

$$\left(\frac{\partial s}{\partial T} \right)_v \cdot \left(\frac{\partial T}{\partial v} \right)_s \cdot \left(\frac{\partial v}{\partial s} \right)_T = -1$$

$$\text{or} \quad \left(\frac{\partial s}{\partial T} \right)_v = \frac{-1}{\left(\frac{\partial T}{\partial v} \right)_s \cdot \left(\frac{\partial v}{\partial s} \right)_T}$$

Substituting in the relation for (C_p/T) and $\left(\frac{C_v}{T}\right)$

$$\left(\frac{C_p}{T}\right) = \frac{-1}{\left(\frac{\partial T}{\partial p}\right)_s \cdot \left(\frac{\partial p}{\partial s}\right)_T}$$

and
$$\left(\frac{C_v}{T}\right) = \frac{-1}{\left(\frac{\partial T}{\partial v}\right)_s \cdot \left(\frac{\partial p}{\partial s}\right)_T}$$

Taking ratio of two specific heats,

$$\frac{C_p}{C_v} = \frac{\left(\frac{\partial T}{\partial v}\right)_s \cdot \left(\frac{\partial v}{\partial s}\right)_T}{\left(\frac{\partial T}{\partial p}\right)_s \cdot \left(\frac{\partial p}{\partial s}\right)_T}$$

or,
$$\left(\frac{C_p}{C_v}\right) = \left(\frac{\partial T}{\partial v}\right)_s \cdot \left(\frac{\partial v}{\partial s}\right)_T \cdot \left(\frac{\partial p}{\partial T}\right)_s \cdot \left(\frac{\partial s}{\partial p}\right)_T$$

$$\left(\frac{C_p}{C_v}\right) = \left\{ \left(\frac{\partial v}{\partial s}\right)_T \cdot \left(\frac{\partial s}{\partial p}\right)_T \right\} \cdot \left\{ \left(\frac{\partial p}{\partial T}\right)_s \cdot \left(\frac{\partial T}{\partial v}\right)_s \right\}$$

By chain rule of calculus we can write,

$$\left(\frac{\partial v}{\partial p}\right)_T = \left(\frac{\partial v}{\partial s}\right)_T \cdot \left(\frac{\partial s}{\partial p}\right)_T$$

and
$$\left(\frac{\partial p}{\partial v}\right)_s = \left(\frac{\partial p}{\partial T}\right)_s \cdot \left(\frac{\partial T}{\partial v}\right)_s$$

Upon substitution in specific heat ratio we get,

$$\left(\frac{C_p}{C_v}\right) = \left(\frac{\partial v}{\partial p}\right)_T \cdot \left(\frac{\partial p}{\partial v}\right)_s$$

or,
$$= \left\{ \frac{-1}{v} \left(\frac{\partial v}{\partial p}\right)_T \right\} \cdot \left\{ \frac{1}{\frac{-1}{v} \left(\frac{\partial v}{\partial p}\right)_s} \right\}$$

$$\frac{C_p}{C_v} = \frac{\alpha}{\alpha_s} = \frac{\text{Isothermal compressibility}}{\text{Isetropic compressibility}}$$

Q.5(a) Explain: (i) Enthalpy of reaction [6]
 (ii) Enthalpy of formation
 (iii) Heating value

(A) (i) Enthalpy of Reaction

It is the amount of energy or heat absorbed in a reaction.

If the reaction is endothermic enthalpy of reaction $\rightarrow +ve$

If the reaction is exothermic enthalpy of reaction $\rightarrow -ve$

(ii) Enthalpy of formation

Enthalpy of formation is the change of enthalpy from the formation of 1 mole of the compound from its constituent elements. With all substance in their standard state at 1 atm.

(iii) Heating value

It is the energy or heat released when a compound undergoes complete combustion with oxygen under standard conditions.

Q.5(b) How much of the 1200 KJ of thermal energy at 700 K can be converted to useful work if the environment is at 25°C [4]

(A) $T_1 = 700 \text{ K}$ $T_2 = 298 \text{ K}$ $Q = 1200 \text{ kJ}$

$$\text{Change of entropy at source} = \frac{1200}{700} = 1.714$$

$$\text{Available energy at source} = (700 - 298) \times 1.714 = 689.142 \text{ kJ}$$

$\therefore 689.142 \text{ kJ}$ is the max amount of work available

Q.5(c) A turbo compressor delivers 2.33 m³/s of air at 0.276 MPa, 43° C [10]
 which is heated at this pressure to 430°C and finally expanded in turbine which delivers 860 kW. During expansion there is a heat transfer of 0.09 MJ/s to surroundings. Calculate the turbine exhaust temperature if changes in kinetic and potential energy are negligible.

(A) Given : $V_1 = 2.33 \text{ m}^3/\text{s}$

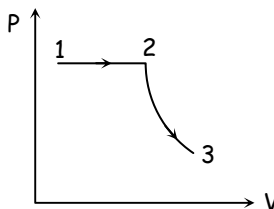
$$P_1 = 276 \text{ kPa} = 276 \times 10^3 \text{ Pa}$$

$$T_1 = 43^\circ\text{C} = 316 \text{ K}$$

$$T_2 = 430^\circ\text{C} = 703 \text{ K}$$

$$W_t = 860 \text{ kW} = 860 \times 10^3 \text{ W}$$

$$Q = 90 \text{ kJ/s} = 90 \times 10^3 \text{ W}$$



To find, T_3

$$P_1 V_1 = m R T_1$$

$$\dot{m} = \frac{276 \times 10^3 \times 2.33}{287 \times 316} = 7.09 \text{ Kg/s}$$

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

$$\therefore V_2 = 5.184 \text{ m}^3/\text{s}$$

For 2 – 3 (expansion)

$$90 \times 10^3 = -C_v (T_3 - T_2) + 860 \times 10^3$$

$$90 \times 10^3 = -718 (T_3 - 703) + 860 \times 10^3$$

$$T_3 = 369.42 \text{ K}$$

$$\therefore \text{Turbine exhaust temp} = 369.42 \text{ K}$$

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