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-: HAND WRITTEN NOTES:-

OF

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MECHANICAL ENGINEERING

-: SUBJECT:-

BASIC THERMODYNAMICS



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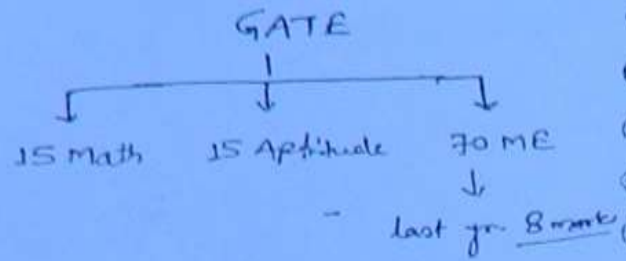
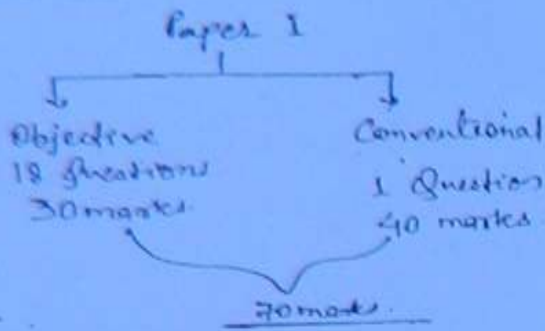
②





Thermodynamics:-

ESP



Basic Concepts

- Zeroth law of thermodynamics
- First law of thermodynamics
- First law applied to flow process
- 2nd law of thermodynamics.
- Entropy
- Availability of Energy
- Properties of pure substances

Text Books

Thermodynamics - P.K. Nag.
(Solve even unsolved questions)

(4)

BASIC CONCEPTS

Thermodynamics :- It is the science of energy transfer and its effects on properties of system.

The main aim of thermodynamics

study is to convert disorganised form of energy (heat) into organised form of energy (work) in an efficient manner.

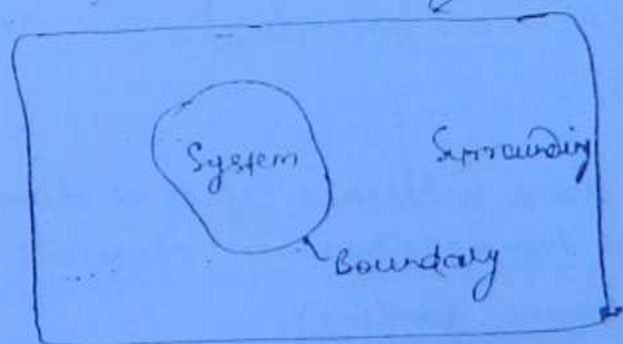
System :- It is a region in space upon which the study is focussed or concentrated.

Surroundings :- Anything external to the system is known as surroundings.

Boundary :- The separation between systems and surroundings is known as boundary.

Boundary can be either "rigid or movable" and boundary can be "real or imaginary."

Note :- Universe = System + Surrounding



** TYPES OF SYSTEM :

Types of System	Mass Transfer	Energy Transfer	Examples
Closed	X	✓	Piston cylinders without valves.
Open	✓	✓	Turbine, Comp., Pump, etc.
Isolated	X	X	Universe, Hot coffee in a well insulated flask.

* Microscopic and Macroscopic approach of Thermodynamics :-

In microscopic approach, the behaviour of individual molecules is taken into consideration. This approach is also known as statistical thermodynamics, and this approach is useful at low densities (higher altitudes).

$$\rho = \frac{m}{V} \quad \left\{ \begin{array}{l} \text{No. of molecules} \\ \text{---} \end{array} \right.$$

In macroscopic approach, the behaviour of individual molecules is not taken into consideration but the average behaviour of molecules is taken into consideration. This approach is also known as classical thermodynamics.

In our course we follow Classical Thermodynamics. 6

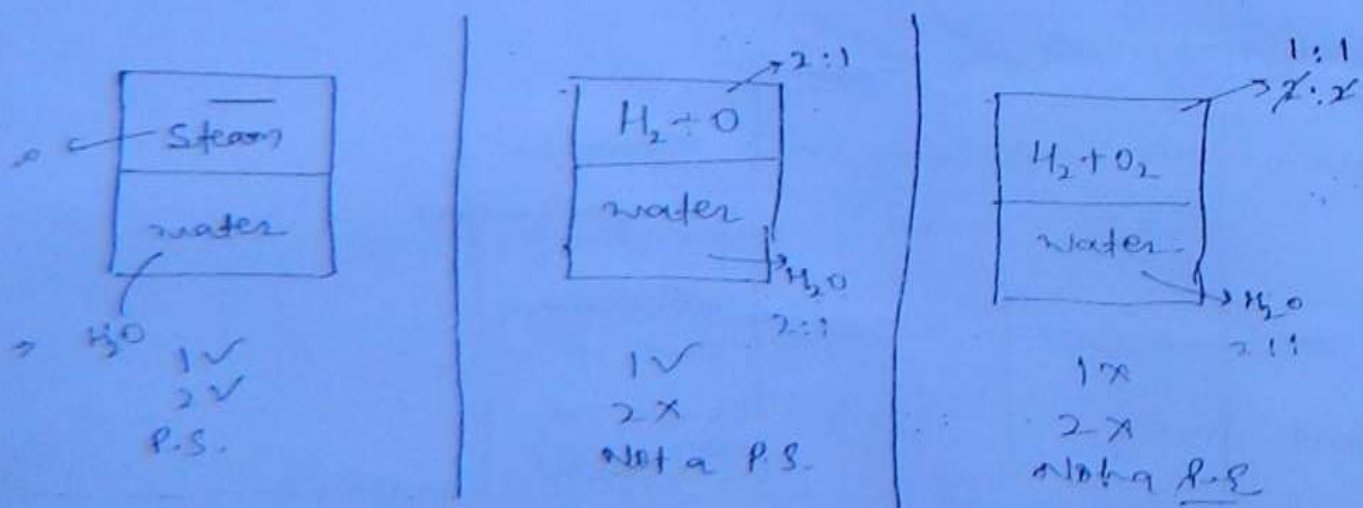
* Thermodynamic Equilibrium :-

A system is said to be in thermodynamic equilibrium, if it is in thermal equilibrium (equality of temperature), mechanical equilibrium (equality of forces or pressure) and chemical equilibrium (equality of chemical potential).

* Pure Substances :-

A substance is said to be a pure substance if it is homogeneous in chemical composition and homogeneous in chemical aggregation.

* (Aggregation means bonding).



⇒ * PROPERTIES OF A SYSTEM! - (Important).

Properties are characteristics of system. Examples Pressure, temp^o, volume, density, mass, etc. Properties are of two types:-

- ① Intensive (or intensive)
- ② Extensive (or extensive)

Intensive properties are independent of size or mass.

Examples - Pressure, temperature, density, thermal conductivity, viscosity, etc.

Extensive properties depend on size or mass of the system.

Examples - volumes, all forms of energy, etc.

Note:- Ratio of two extensive properties is an intensive property.

m
v
P
T

m/2	m/2
v/2	v/2
P	P
T	T

⑦

$f = \frac{m \rightarrow E}{v \rightarrow E}$

$m = 10 \text{ kg}$
 $v = 10 \text{ m}^3$ $f = \frac{m}{v} = 1$

m = 5	m = 5
v = 5	v = 5

$f = \frac{m}{v} = 1$

Note:- Specific properties are extensive properties per unit mass and these ~~specific~~ properties are intensive properties.

Specific properties are intensive properties.

- Example:-
- Specific volume (v)
 - Specific enthalpy (h)
 - Specific internal energy (u)
 - Specific entropy (s)

Important points with respect to properties:-

- ① Properties are point functions or state functions.
- ② Properties are independent of past history.
- ③ Properties are exact differentials.

⑧

State of a system:-

The condition of a system is known as state of a system. The condition of a system is specified by means of its properties. As long as the properties are fixed, the condition is also fixed.

Process:- A change of state is known as a process.

GIBB'S PHASE RULE:-

According to Gibb's phase rule:-

$$P + F = C + 2$$

where,

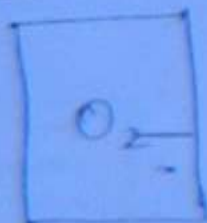
P = No. of Phases

F = Degree of freedom

or
Minimum no. of independent ^{intensive} variables required.

C = No. of components.

Expt-1



$$P = 1$$

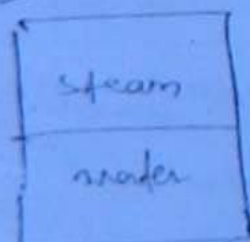
$$C = 1$$

$$P + F = C + 2$$

$$1 + F = 1 + 2$$

$$\therefore F = 2$$

Expt-2



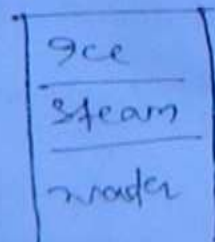
$$P = 2$$

$$C = 1$$

$$P + F = C + 2$$

$$F = 1$$

Expt-3



$$P = 3$$

$$C = 1$$

$$P + F = C + 2$$

$$F = 0$$

→* THERMODYNAMIC CYCLES:-

A system is said to have undergone a cycle if the initial and final points are same. Minimum number of processes required for a cycle are 2.

Note:- for a cycle the change in property is equal to zero. because property depend on point and for a cycle initial and final points are same.

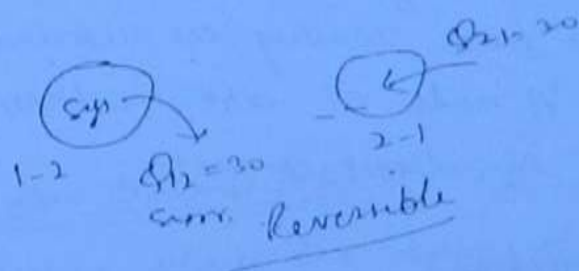
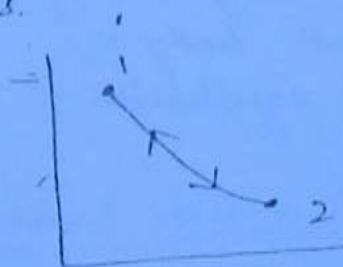
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→* REVERSIBLE AND IRREVERSIBLE PROCESSES:-

A process is said to be a reversible process, if when reversed in direction follows the same path as that of the forward-path without leaving any effect on system and surroundings.

A process which is not a reversible process is an irreversible process.

Friction is one of the reasons which makes a process irreversible. Reversible process is the most efficient process.



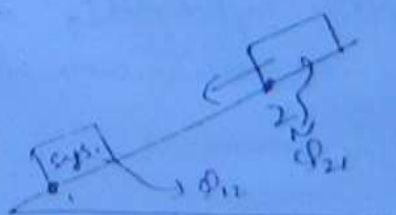
System Surroundings

$$Q_{12} = -30 \quad Q_{12} = +30$$

$$Q_{21} = +30 \quad Q_{21} = -30$$

0

0



Irreversible

Pritya

⇒ * QUASI-STATIC PROCESS :-

(almost) (rest)

A process is said to be quasi-static process, if it is carried out in a very slow manner with small gradient. Frictionless quasi-static process is a reversible process.

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⇒ * ZEROth LAW OF THERMODYNAMICS (Concept of Temperature)

statement :-

When a body 'A' is in thermal equilibrium with body 'B' and body 'B' is in thermal equilibrium with body 'C' separately, then 'A' and 'C' are in thermal equilibrium.

In zeroth law of thermodynamics 'one' body acts as thermometer. Let us assume that body 'B' is thermometer. Let us immerse thermometer 'B' in body 'A'. When the thermal equilibrium is reached, body 'B' records some temperature. Now, place the body 'B' (thermometer) in body 'C'. If the thermometer records same reading as recorded with body 'A', then we can say that 'A' and 'C' are in thermal equilibrium without bringing them in direct contact.

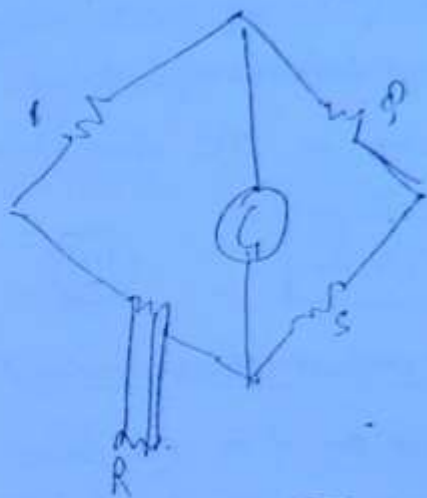
* Principle of Thermometers :-

In finding temperature, first the property which varies with temperature is found and this property is known as thermometric property and with the help of thermometric property, the unknown tempⁿ 'T' can be found.

⇒ * Types of Thermometers :-

① Resistance Thermometer (Thermistor) :-

These thermometers are based on Wheatstone bridge principle. In these thermometers, resistance plays the role of thermometric property.



$$R/S = P/Q$$

$$R = \frac{PS}{Q}$$

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$$R = R_0(1 + \alpha t + \beta t^2)$$

② Thermocouple: Thermocouples are based on Seebeck effect. According to this Seebeck effect, when two dissimilar metals are joined to form two separate junctions and if these junctions are maintained at different temp^s emf (voltage) is generated as this ~~temp~~ emf is proportional to the temperature difference.

③ Constant Volume Gas ~~thermometer~~ thermometer: In constant volume gas thermometer, pressure plays the role of thermometric property.

④ Constant Pressure Gas thermometer:-

Volume plays the role

of thermometric property.

✓ Type of thermometer

Thermometric Property

- 1) Thermistor →
- 2) Thermocouple →
- 3) Constant Vol^m Gas thermometer →
- 4) Constant Pressure " " →

Temperature Scale:-

Temperature scales are arbitrary.

In Celsius scale, ice point is taken as 0°C and steam point is taken as 100°C .

$$K = ^{\circ}\text{C} + 273.15$$

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Method used before 1954 for temperature measurement :-

This method is based on two reference temperatures i.e. ice point (0°C) and steam point (100°C):

$$t = ap + b$$

$$t_i = a p_i + b$$

$$t_s = a p_s + b$$

$$100 = a p_s + b$$

$$0 = a p_i + b$$

$$100 = a(p_s - p_i)$$

$$\therefore a = \frac{100}{(p_s - p_i)}$$

And

$$0 = a p_i + b$$

$$\therefore b = -a p_i$$

$$= -\frac{100}{(p_s - p_i)} \times p_i$$

$$\therefore t = \frac{100}{(p_s - p_i)} p - \frac{100 \cdot p_i}{(p_s - p_i)}$$

$$\therefore t = \frac{100}{(p_s - p_i)} \cdot (p - p_i)$$

By knowing the unknown property " p ", the temperature ' t ' can be found.

* Method used after 1954 for temperature measurement :-
 It is based on single fixed temperature i.e. triple point of water.

$$PV = nRT$$

let $v = c$.

$$P \propto T$$

$$P = cT$$

$$c = P/T$$

At triple point

$$c = \frac{P_{TP}}{T_{TP}}$$

$$\therefore P = \frac{P_{TP}}{T_{TP}} \times T$$

$$T = \frac{P}{P_{TP}} \cdot T_{TP}$$

$$T = 273.15 \left(\frac{P}{P_{TP}} \right)$$

The triple point of water is assigned a value of 0.01°C (273.15 K)

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At triple point,

$$T = 0.01^\circ\text{C}$$

$$K = 0.01 + 273.15$$

$$K = \underline{\underline{273.16 K}}$$

Note:- Ideal gas thermometers are independent of material of construction. \therefore All ideal gas behave same.

PROBLEM

Q. The reading t_A and t_B of 2°C thermometers 'A' & 'B' agree at ice point (0°C) and steam point (100°C) and are related by the equation, $t_A = l + m t_B + n t_B^2$. Between these temp where l , m and n are constants when both are immersed in oil 'A' reads 51°C and 'B' reads 50°C . Determine the reading on 'A', when 'B' reads 25°C . And discuss the question which thermometer is correct?

$t_A = l + m t_B + n t_B^2$

$t_A = 0^\circ\text{C} = t_B$

$0 = l + m(0) + n(0)$

$\Rightarrow \boxed{l = 0}$

$t_A = m t_B + n t_B^2$

$t_A = 100^\circ\text{C} = t_B$

$100 = m(100) + n(100)^2$

$1 = m + 100n \quad \text{--- (1)}$

$t_A = 51^\circ\text{C}, t_B = 50^\circ\text{C}$

$51 = 0 + m(50) + n(50)^2$

$\Rightarrow 51 = 50m + 2500n \quad \text{--- (2)}$

from (1) & (2)

$m = 1.04$

$n = -4 \times 10^{-4}$

$t_A = 0 + 1.04 t_B - 4 \times 10^{-4} t_B^2 \quad \text{--- (3)}$

$t_B = 25^\circ\text{C}$
 $t_A = 1.04(25) - 4 \times 10^{-4}(25)^2$

$\boxed{t_A = 25.75^\circ\text{C}}$

Though the end temperatures are same, it does not necessarily mean the intermediate point temperatures are also same.

① Assertion (A) - If alcohol and mercury thermometers read exactly at ice point and steam point, these two thermometers will also give same reading exactly at 50°C .

Reasoning (R) - Temperature scales are arbitrary.

Ans - Assertion is wrong and Reasoning is independently correct.

② Which of the following are intensive properties?

1. Kinetic Energy
2. Thermal conductivity
3. ~~Volume~~ Pressure
4. Volume.

Ans (b) (2 and 3)

③ Match the following Question:-

List I
(Type of thermometer)

List II
(Thermometric Property)

A) Mercury in Glass

1) Pressure

B) Thermocouple

2) Resistance

C) Thermistor

3) Volume or length

4) Constant Vol^m Gas Thermometer

4) Emf

Ans 3-4-2-1

④ The thermometric property x varies with tempⁿ T according to the relation $x = at + b$, where t is in $^{\circ}\text{C}$ and x is in cm. a and b are constants. At ice point (0°C) and steam point (100°C), the values of x are 5 cm and 20 cm respectively. When this thermometer is brought in contact with heated body, the value of x is recorded as 15 cm. Then the tempⁿ of heated body is?

Solⁿ:

$$0 = 25a + b \Rightarrow b = -25a \quad \text{--- (1)}$$

$$100 = 400a + b$$

$$\Rightarrow 100 = 400a - 25a \Rightarrow a = 100/375 = 0.27$$

$$\therefore b = -25 \times 0.27 = -6.75$$

$$t = 0.27(15)^2 + -6.75$$

$$a = 0.26$$

$$b = -6.66$$

$$\Rightarrow \boxed{t = 54^\circ\text{C}} \approx \boxed{53.3^\circ\text{C}} \dots$$

1.4.1

Q.5 In a new temperature scale, $^\circ\text{P}$, the boiling and freezing points of water are 100°P and 300°P respectively. Find the reading corresponding to 0°C on Celsius scale.

info let us assume a linear relation between $^\circ\text{C}$ and $^\circ\text{P}$ scale.

let it be,

$$^\circ\text{P} = a \times ^\circ\text{C} + b.$$

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Now

$$300 = a \times (0) + b$$

$$\Rightarrow \boxed{b = 300}$$

Again

$$100 = a \times 100 + 300$$

$$\Rightarrow \boxed{a = -2}$$

$$\therefore ^\circ\text{P} = -2 \times ^\circ\text{C} + 300 =$$

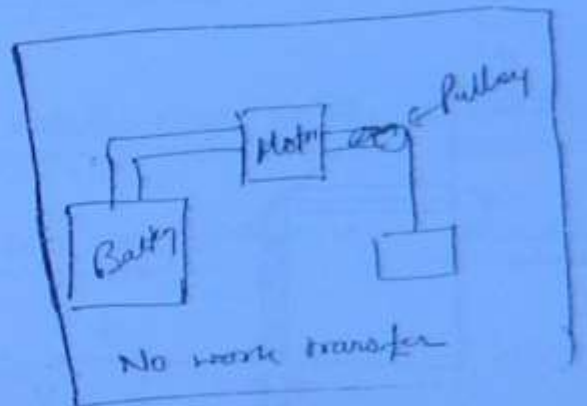
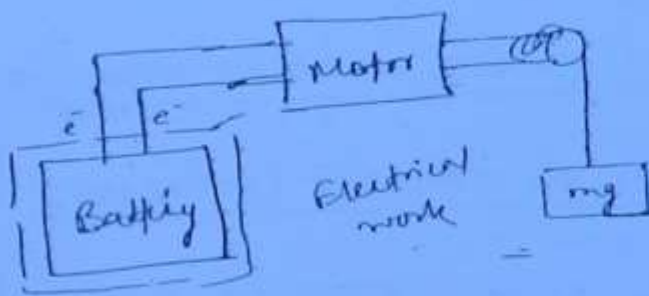
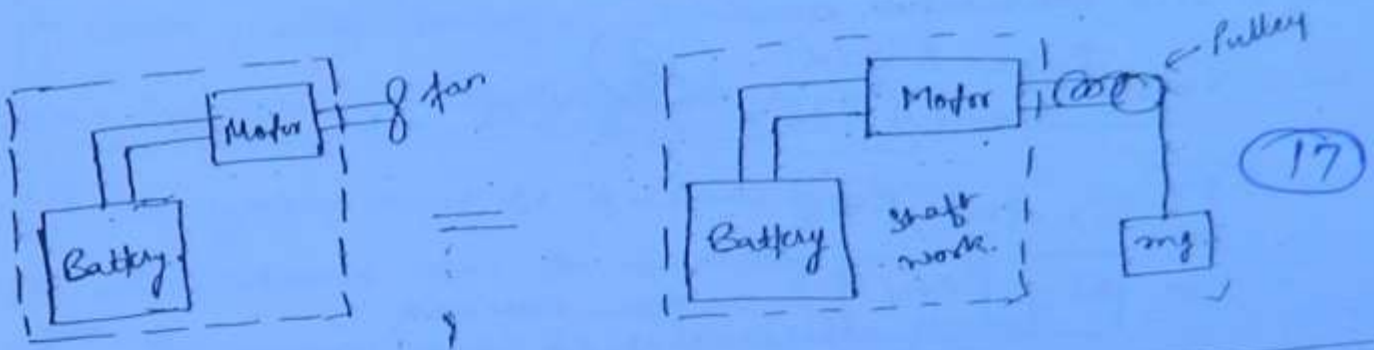
$$\text{let } 0 = -2 \times ^\circ\text{C} + 300.$$

$$\therefore \boxed{^\circ\text{C} = 150}$$

CHAPTER-2 :-

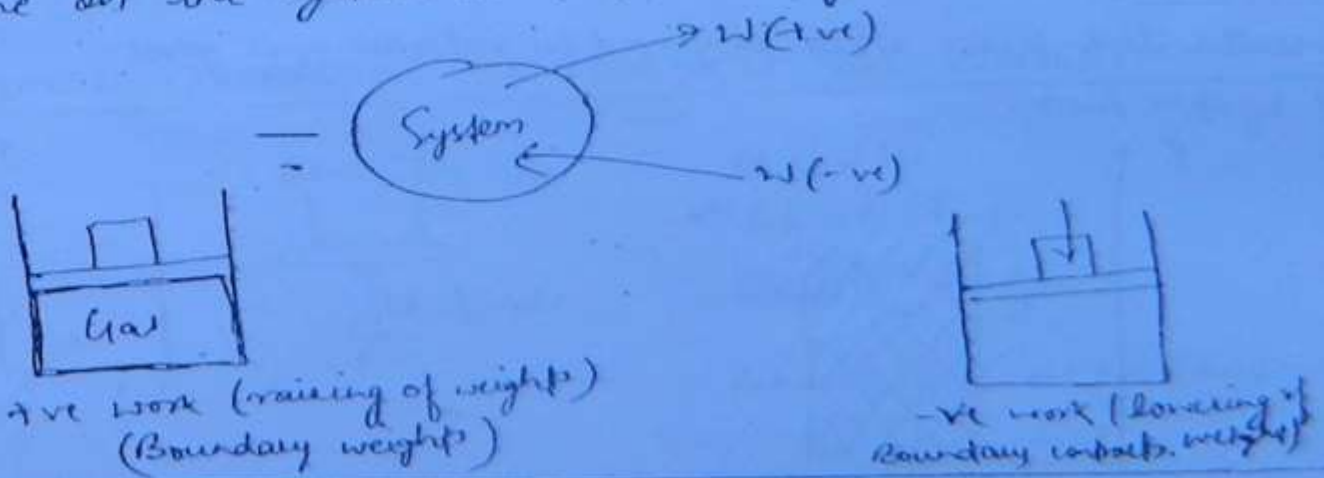
ENERGY INTERACTIONS (WORK & HEAT)

⇒ * Thermodynamic work :- Work is said to be done by the system if the sole 'effect on things' external to the system can be equated to raising of weights (weights may not be actually raised but the effect can be equated to raising of weights).

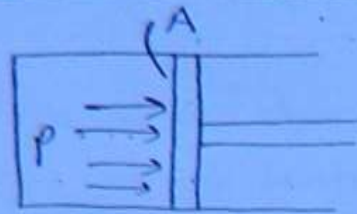


⇒ * Conventions of work transfer

Work done by the system is taken as positive and work done on the system is taken as negative.



→ * Generalised Equation for Non-flow work or closed system work!-



$$P = F/A$$

$$F = PA$$

$$W = F \times x$$

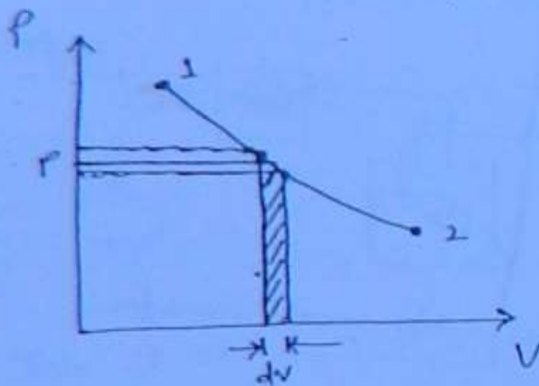
$$dW = F \times dx$$

$$= \underbrace{P \cdot A}_{(18)} \times dx$$

$$\therefore dW = P \cdot dV$$

$$\text{or } \boxed{W = \int P dV}$$

→ Non-flow work / (Closed system work).



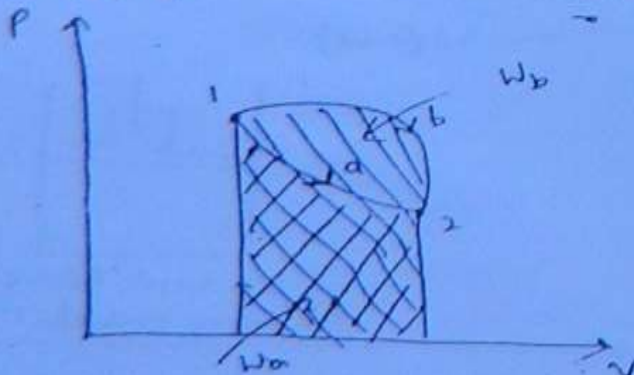
$$\text{Area} = P \cdot dV$$

$$\text{Also, work} = P dV$$

$$\therefore \boxed{\text{Area} = \text{Work}}$$

(very important sentence)

→ Area under the curve when projected on volume axis gives closed system work.



$$W_a \neq W_b$$

→ Though the end points for 'a' and 'b' are same, work transfer is not same because areas are different. Therefore, work transfer depends on path followed by the process and hence work transfer is a path function and it is not a property and it is inexact differentials (dW or δW).

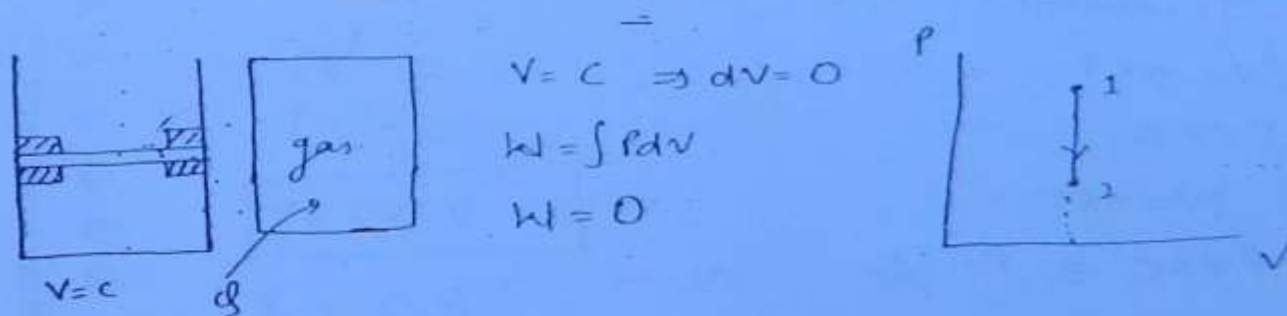
⇒* There is no work transfer when the system is in equilibrium state. Work transfer is always associated with a process.

⇒* Conditions for Applying the Equation $W = \int P dV$: →

- ① The system must be a closed system. (19)
- ② Work should cross the boundary.
- ③ The process must be a reversible process.

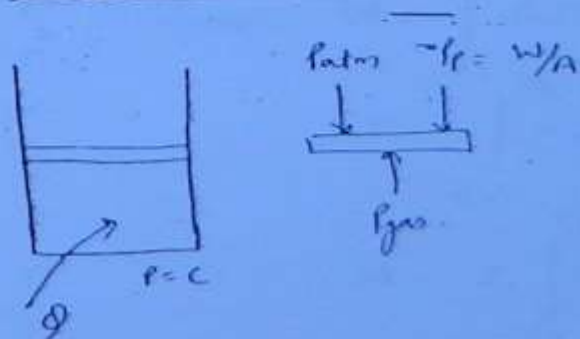
⇒* NON-FLOW OR CLOSED SYSTEM WORK FOR VARIOUS PROCESSES

① CONSTANT VOLUME OR ISOCHORIC OR ISOMETRIC PROCESS:



Constant volume closed system work = 0.

② CONSTANT PRESSURE OR ISOBARIC OR ISOPIESTIC PROCESS:



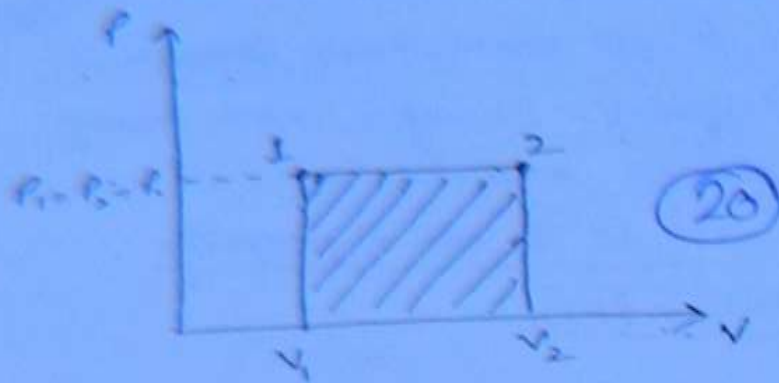
At equilibrium,

$$P_{atm} + W = P_{gas}$$

$$P_{atm} + \frac{W}{A} = P_{gas}$$

∴ P_{atm} , W & A are constants.

So, $P_{gas} = \text{constant}$.



W = Area.

$$W = P(V_2 - V_1)$$

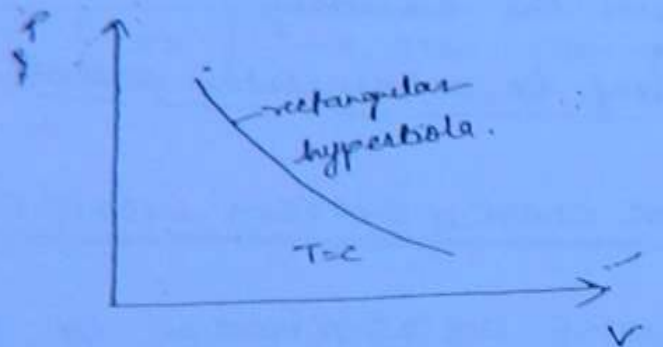
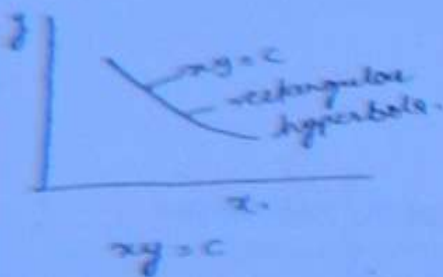
$$W = \int_{V_1}^{V_2} P \cdot dV.$$

$$W = P \int_{V_1}^{V_2} dV.$$

$$W = P(V_2 - V_1)$$



3) CONSTANT TEMPERATURE OR ISOTHERMAL PROCESS:-



T = constant.

$$PV = nRT$$

$$PV = C.$$

$$\therefore PV = nRT = C.$$

$$PV = C \Rightarrow P = \frac{C}{V}.$$

$$P_1 V_1 = P_2 V_2 = C.$$

Now,

$$W = \int_{V_1}^{V_2} P \cdot dV$$

$$W = \int_{V_1}^{V_2} \frac{C}{V} \cdot dV$$

$$\text{or, } W = C \int_{V_1}^{V_2} \frac{dV}{V}$$

$$W = C [\ln v_2 - \ln v_1]$$

$$\text{or, } W = C \ln \left(\frac{v_2}{v_1} \right)$$

$$\therefore \boxed{W = P_1 v_1 \ln \left(\frac{v_2}{v_1} \right)}$$

$$\boxed{W = mRT \ln \left(\frac{v_2}{v_1} \right)}$$

Ques

An adiabatic process can never be an isolated process

(21)

((Isothermal curves for an ideal gas are rectangular hyperbola on P-V diagram.))

(4) ADIABATIC PROCESS :- A process is said to be adiabatic process in which there is no heat transfer from the system or to the system.

For adiabatic process;

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

where, γ = adiabatic index and it is greater than 1 ($\gamma > 1$).

$$PV^\gamma = C$$

$$P = \frac{C}{V^\gamma}$$

$$\boxed{P = C \cdot V^{-\gamma}}$$

$$P_1 = C \cdot v_1^{-\gamma} \quad \text{--- (1)}$$

$$P_2 = C \cdot v_2^{-\gamma} \quad \text{--- (2)}$$

Now

$$W = \int_{v_1}^{v_2} P \, dv$$

$$W = \int_{v_1}^{v_2} C \cdot v^{-\gamma} \, dv$$

$$W = C \int_{v_1}^{v_2} v^{-\gamma} \, dv$$

$$W = C \left[\frac{V^{-\gamma+1}}{-\gamma+1} \right]_{V_1}^{V_2}$$

$$W = \frac{C}{-\gamma+1} \left[V_2^{-\gamma+1} - V_1^{-\gamma+1} \right] \quad (22)$$

$$W = \frac{1}{-\gamma+1} \left[\underbrace{C \cdot V_2^{-\gamma+1}}_{P_2 \cdot V_2} - \underbrace{C \cdot V_1^{-\gamma+1}}_{P_1 \cdot V_1} \right]$$

$$\Rightarrow W = \frac{1}{-\gamma+1} \left[P_2 \cdot V_2 - P_1 \cdot V_1 \right]$$

$$\Rightarrow W = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1}$$

$$\therefore \boxed{W = \frac{(P_1 V_1 - P_2 V_2)}{(\gamma - 1)}}$$

⑤ POLYTROPIC PROCESS :-

A process is said to be a polytropic process, if pressure & volume follows the relation $PV^n = C$, where, 'n' is known as polytropic index.

Generally,

$$\boxed{n > 1 \text{ and } n < \gamma}$$

In polytropic process, there is both heat transfer and work transfer but in adiabatic process, there is only work transfer.

Polytropic work,

$$\boxed{W = \frac{(P_1 V_1 - P_2 V_2)}{(n - 1)}}$$

Any process can be represented as $PV^k = C$. $N^k = C$

* for constant pressure process,

$$P = C$$

$$PV^k = C$$

$$k = 0$$

$$PV^0 = C$$

$$P \cdot 1 = C$$

$$\boxed{P = C}$$

(23)

* for thermal constant process,

$$T = C$$

$$PV = mRT$$

$$PV = C$$

$$PV^1 = C$$

$$\boxed{k = 1}$$

* for constant volume process,

$$V = C$$

$$PV^k = C$$

$$(PV^k)^{1/k} = C^{1/k}$$

$$P^{1/k} \cdot V = C^{1/k} \text{ (constant new)}$$

when, $k = \infty$

$$P^0 \cdot V = C$$

$$\therefore \boxed{V = C}$$

* for adiabatic process,

$$PV^\gamma = C$$

$$\boxed{k = \infty}$$

* for polytropic process,

$$PV^n = C$$

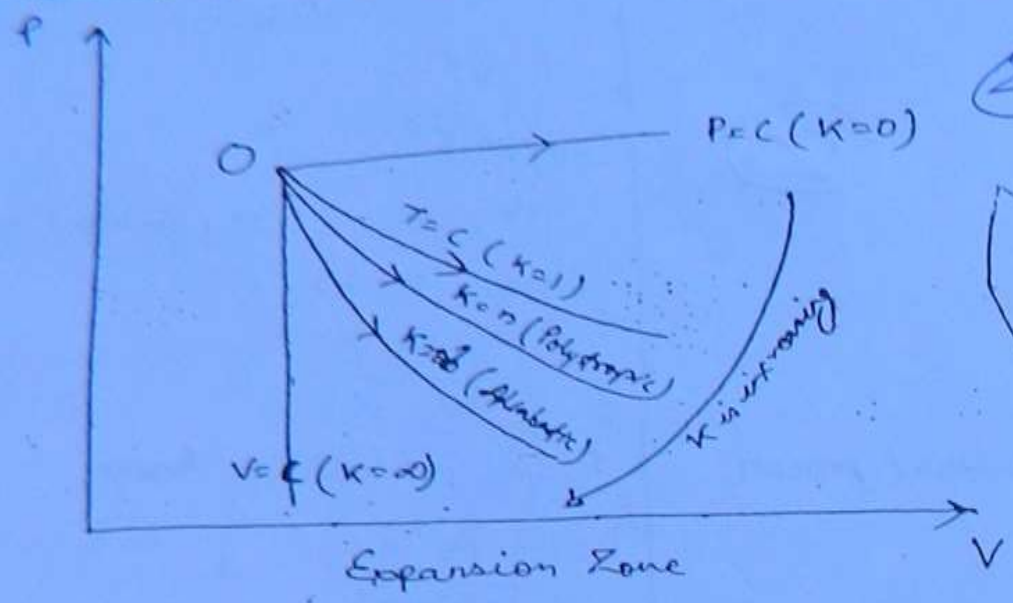
$$\boxed{k = n}$$

- | |
|------------------------------------|
| $P = C \rightarrow k = 0$ |
| $V = C \rightarrow k = \infty$ |
| $T = C \rightarrow k = 1$ |
| Adiabatic $\rightarrow k = \gamma$ |
| Polytropic $\rightarrow k = n$ |

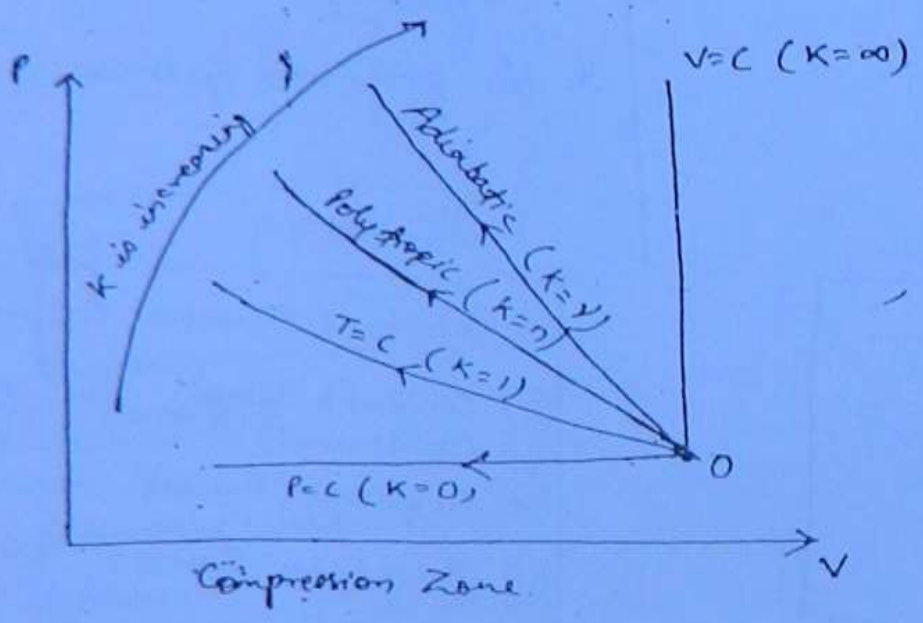
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|---------------------------------------------------------------------------|
| ① Constant pressure, $P = C, \rightarrow k = 0$ |
| ② Constant Temp ^r , $T = C, \rightarrow k = 1$
(isothermal) |
| ③ Polytropic process, $k = n$ |
| ④ Adiabatic process $k = \gamma$ |
| ⑤ Constant volume, $V = C \rightarrow k = \infty$ |

$$PV^k = C$$

⇒ * Representation of Various Process on P-V diagram :-



(24)

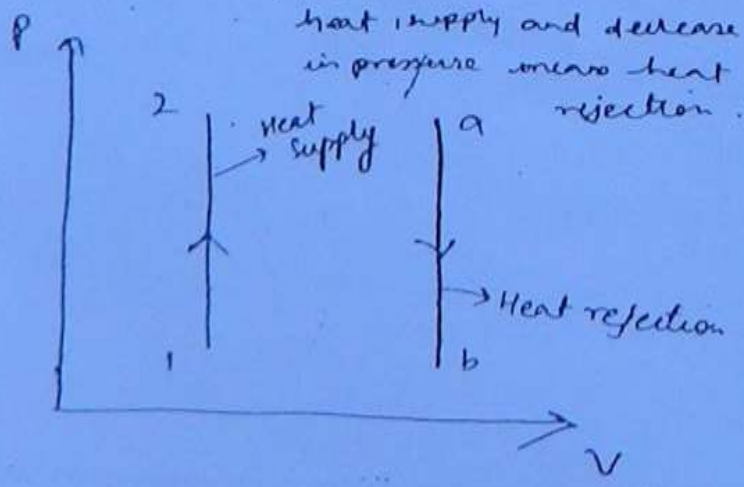


⇒ * Ideal Gas Equations for Various Processes :-

① Constant Volume Process :-

$V = C$
 $P \propto T$
 $P \propto T$
 $\frac{P_2}{P_1} = \frac{T_2}{T_1}$

Increase in pressure means heat supply and decrease in pressure means heat rejection.



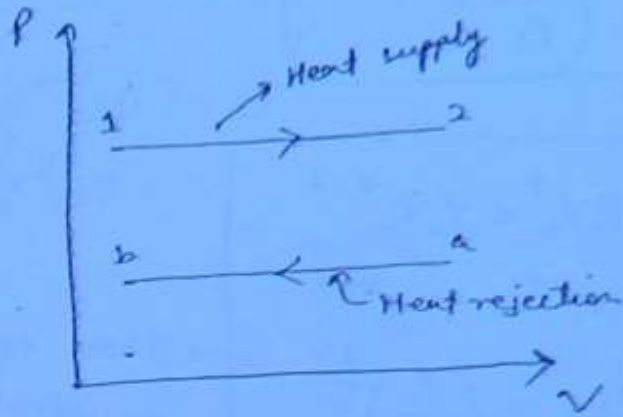
② Constant Pressure Process :-

$$P = \text{constant}$$

$$PV = mRT$$

$$V \propto T$$

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



③ Isothermal Process :-

$$T = \text{constant}$$

$$PV = mRT$$

$$PV = C$$

$$\boxed{P_1 V_1 = P_2 V_2}$$

(25)

④ Adiabatic Process :-

$$PV^\gamma = C$$

$$PV = mRT$$

$$P = \frac{mRT}{V}$$

$$\frac{mRT}{V} \cdot V^\gamma = C$$

$$\text{or, } T \cdot V^{\gamma-1} = \frac{C}{RT} = C$$

$$\text{or, } T \cdot V^{\gamma-1} = \text{const.}$$

$$\boxed{P_1 V_1^\gamma = P_2 V_2^\gamma} \quad \text{--- (1)}$$

$$\Rightarrow \left(\frac{V_1}{V_2}\right)^\gamma = \left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}}$$

$$\boxed{T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1}} \quad \text{--- (2)}$$

$$\Rightarrow \left(\frac{V_1}{V_2}\right)^{\frac{\gamma}{\gamma-1}} = \left(\frac{T_2}{T_1}\right)^{\frac{1}{\gamma-1}}$$

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

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

(26)

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

$$T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1}$$

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

→ These equations are valid for an ideal gas undergoing adiabatic process.

⑤ Polytropic process :-

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

$$T_1 V_1^{n-1} = T_2 V_2^{n-1}$$

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

→ These equations are valid for an ideal gas undergoing adiabatic polytropic process.

* SLOPE OF ISOTHERMAL CURVES ON P-V DIAGRAM :-

$T = \text{constant}$

$$PV = nRT$$

$$PV = C$$

$$Pdv + vdp = 0$$

$$Pd\tilde{v} = -v d\tilde{p}$$

$$\frac{d\tilde{p}}{d\tilde{v}} = -\frac{\tilde{p}}{\tilde{v}}$$

Slope of isothermal curves on P-V diagram = $-\frac{P}{V}$

⇒ * SLOPE OF ADIABATIC CURVES ON P-V DIAGRAM:-

$$PV^\gamma = C$$

$$P[\gamma \cdot V^{\gamma-1} \cdot dV] + V^\gamma [dP] = 0.$$

$$\gamma P \cdot \frac{V^{\gamma-1}}{V} \cdot dV = -V^\gamma dP$$

$$\Rightarrow -\frac{\gamma P}{V} = \frac{dP}{dV}$$

$$\therefore \frac{dP}{dV} = -\frac{\gamma P}{V}$$

$$\therefore \boxed{\frac{dP}{dV} = \gamma \left(-\frac{P}{V}\right)}$$

(27)

∴ Slope of adiabatic curves = γ (Slope of isothermal curves)

$$\frac{\text{Slope of adiabatic}}{\text{Slope of isothermal}} = \gamma$$

$$\because \gamma > 1.$$

$$\therefore \frac{\text{Slope of adiabatic}}{\text{Slope of isothermal}} > 1.$$

Hence,

Slope of adiabatic curves > Slope of isothermal curves

CONVENTIONAL PROBLEM

Q. A system undergoes three processes as shown in figure.

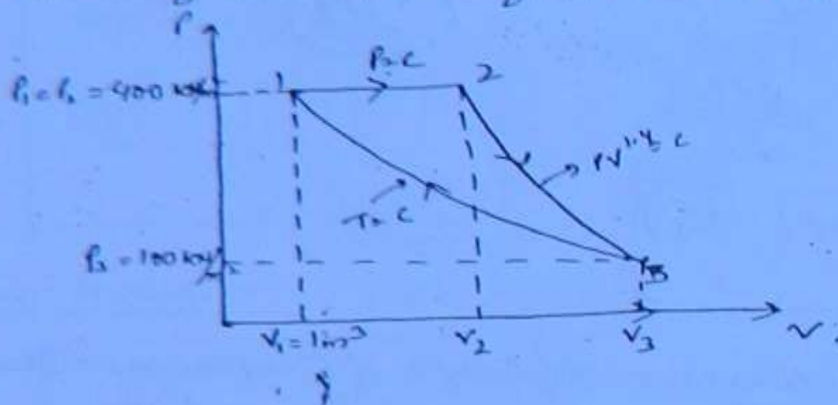
1-2 → Isobaric process

2-3 → Adiabatic process with $\gamma = 1.4$

3-1 → Isothermal process with $PV = C$.

(28)

Find the value of V_2 and also find net work transfer.



Soln.
(Process 3-1)

$$T = C.$$

$$\text{Also } PV = C$$

$$P_3 V_3 = P_1 V_1$$

$$\Rightarrow 100 \times V_3 = 400 \times 1$$

$$\therefore V_3 = 4 \text{ m}^3$$

Again

(Process 2-3)

$$PV^{1.4} = C$$

$$P_2 V_2^{1.4} = P_3 V_3^{1.4}$$

$$\Rightarrow 400 \times V_2^{1.4} = 100 \times (4)^{1.4}$$

$$\Rightarrow V_2 = 1.486 \text{ m}^3 \quad \text{(Ans)}$$

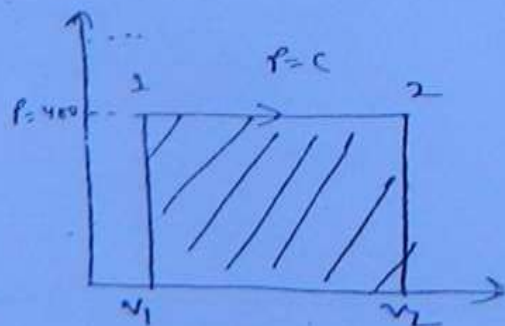
Now

$$W_{\text{net}} = W_{12} + W_{23} + W_{31}$$

$$W_{12} = P(V_2 - V_1)$$

$$= 400(1.486 - 1) \frac{\text{N}}{\text{m}^2} \times \text{m}^3$$

$$\therefore W_{12} = 194.4 \text{ kJ}$$



$$W_{23} = \frac{P_2 V_2 - P_3 V_3}{\gamma - 1}$$

$$\Rightarrow W_{23} = \frac{400 \times 1.486 - 100 \times 4}{1.4 - 1}$$

$$\Rightarrow \boxed{W_{23} = 486 \text{ kJ}}$$

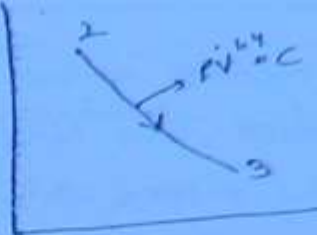
$$W_{31} = P_3 V_3 \ln \frac{V_1}{V_3}$$

$$= 100 \times 4 \ln \left(\frac{1}{4} \right)$$

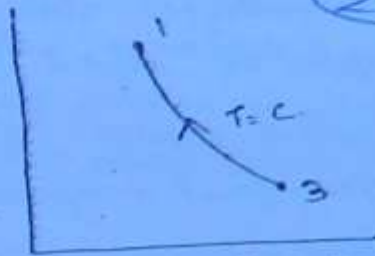
$$\boxed{W_{31} = -554.5 \text{ kJ}}$$

$$W_{\text{net}} = 194.4 + 486 + (-554.5)$$

$$\therefore \boxed{W_{\text{net}} = 125.8 \text{ kJ}}$$



(28)



$$W = P_i V_i \ln \frac{V_f}{V_i}$$

Note:-

Net work in a cycle is equal to area of the closed regions. All clockwise cycles on P-V diagram are work producing or power producing ~~for~~ cycles. All anti-clockwise cycles are power absorbing or work absorbing cycles.

Q:-

An imaginary engine receives heat and performs work on a slowly moving piston at such a rate that the cycle of operation of 1 kg of working fluid can be represented as a circle of 10 cm diameter on P-V diagram, on which 1 cm = 300 kPa and 1 cm = 0.1 m³/kg. Then, find the net work during the cycle.

$$1 \text{ cm} = 300 \text{ kPa}$$

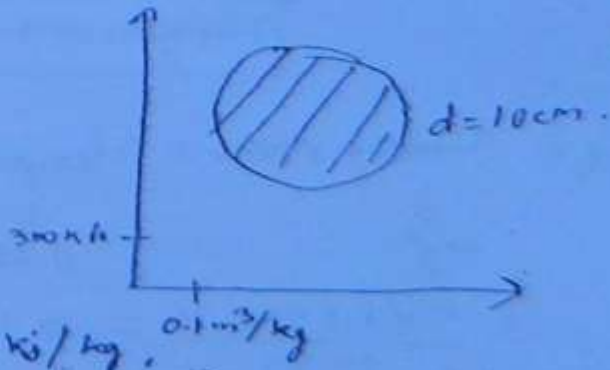
$$1 \text{ cm} = 0.1 \text{ m}^3/\text{kg}$$

$$1 \text{ cm}^2 = 300 \times 0.1 = 30 \text{ kJ/kg}$$

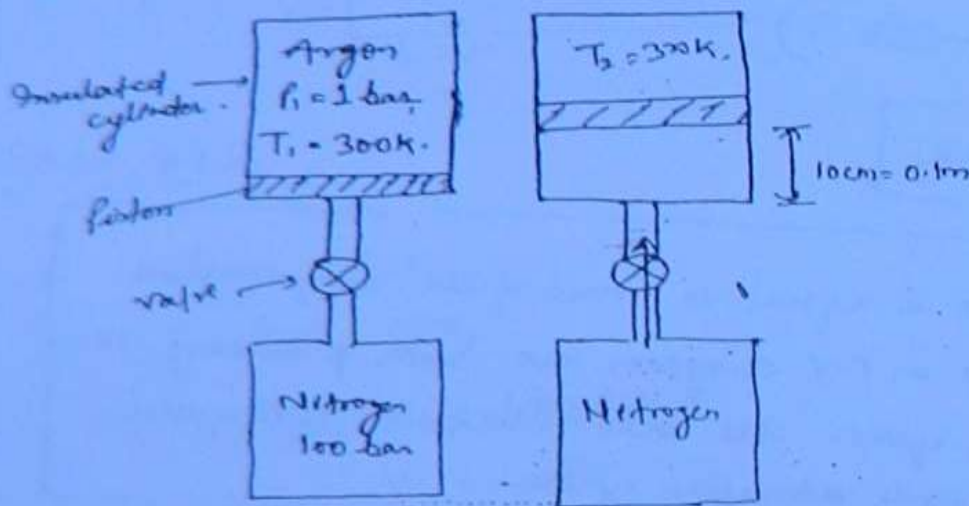
$$W_{\text{net}} = \text{Area} = \frac{\pi}{4} d^2$$

$$= \frac{\pi}{4} (10)^2 = 78.54 \text{ cm}^2$$

$$\therefore W_{\text{net}} = (78.54 \times 30) = 2356.2 \text{ kJ/kg}$$



Q An insulated vertical cylinder contains 0.1 kg of Argon gas. With the help of a frictionless non-conducting piston as shown in figure. The mass of the piston is 5 kg and it initially rests on the bottom of the cylinder. The cylinder is connected to nitrogen tank at 100 bar to a pipeline fitted with the valve. The valve is opened and nitrogen slowly enters the cylinder. During this process, the piston is lifted to a height of 10 cm by nitrogen gas. The initial pressure and temperature of argon are 300 k and 1 bar. The final temperature of argon gas is 320 K. For argon gas $k = 0.208 \text{ kJ/kg K}$ and $\gamma = 1.67$.



$$W_{\text{argon}} = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1} = \frac{m_1 R_1 T_1 - m_2 R_2 T_2}{\gamma - 1} \quad (\because m \text{ \& } R \text{ are constant})$$

$$\therefore W_{\text{argon}} = \frac{mR(T_1 - T_2)}{\gamma - 1}$$

$$= \frac{0.1 \times 0.208 (300 - 320)}{1.67 - 1}$$

$$\therefore \boxed{W_{\text{argon}} = -0.621 \text{ kJ}}$$

$$W_{N_2} = W_{\text{raising piston}} + W_{\text{compressing Argon}}$$

$$\downarrow \qquad \qquad \qquad \downarrow$$

$$\text{mgh} \qquad \qquad \qquad 0.621 \text{ kJ}$$

$$= \frac{5 \times 9.81 \times 0.1}{1000} = 4.905 \times 10^{-3} \text{ KJ}$$

$\frac{5 \times 9.81 \times 0.1}{1000}$

∴ Net work done by Nitrogen.

$$W_{N_2} = 4.905 \times 10^{-3} \text{ kJ} + 0.621 \text{ kJ}$$

$$\boxed{W_{N_2} = 0.626 \text{ kJ}} \quad (\text{Ans})$$

$$\boxed{V_s = A \times L}$$

V_s = swept vol.

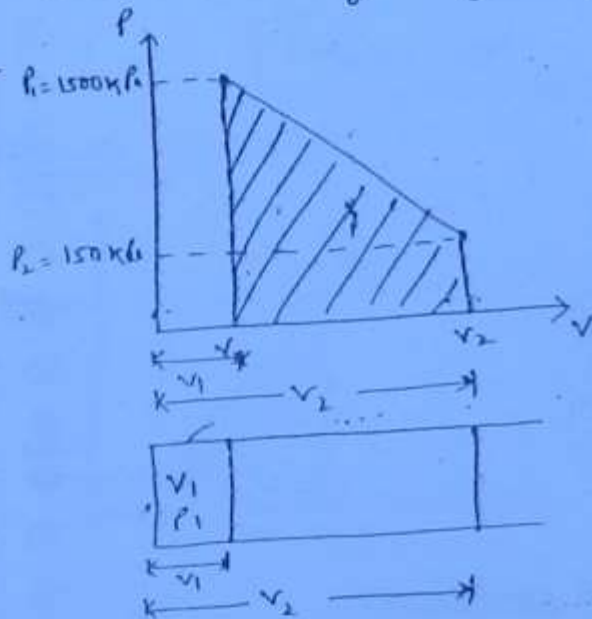
L = stroke length

A = Area of piston.

Q1.
Important

An engine cylinder has a piston area of 0.12 m^2 and contains a gas at a pressure of 1.5 MPa . The gas expands according to a process which is represented by a straight line on P - V diagram. The final pressure is 0.15 MPa . Calculate the work done by the gas if the stroke length is 0.3 m .

Soln.



Work = Area under curve

$$= \frac{1}{2} (1500 + 150) \times (V_2 - V_1)$$

But, $V_2 - V_1 = V_s = AL$.

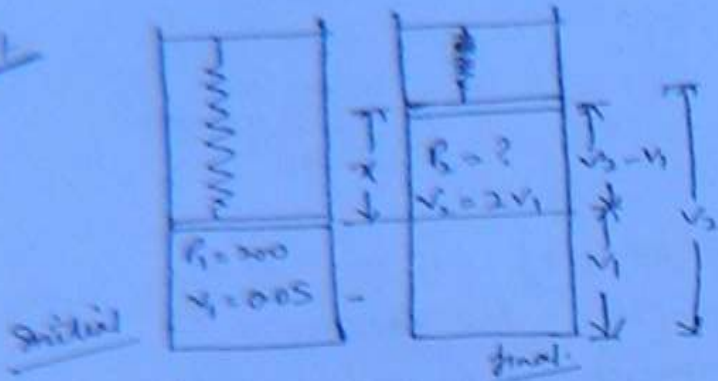
$$= \frac{1}{2} \times 1650 \times (0.12 \times 0.3)$$

$$\therefore \boxed{W = 29.7 \text{ kJ}} \quad (\text{Ans})$$

Q1.
Imp

A piston cylinder device contains 0.05 m^3 of a gas initially at 200 kPa . At this state a linear spring which has spring constant of 150 kN/m is just touching the piston but exerting no force on it. ^{Now} Heat is transferred to the gas causing the piston to rise and to compress the spring until the volume inside the cylinder doubles. If the cross-sectional area of the piston is 0.25 m^2 , find :-

- ① Final pressure inside the cylinder.
- ② Work done by the gas.



$$V_2 - V_1 = A \times x$$

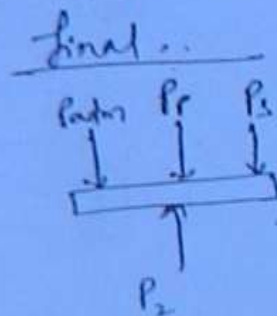
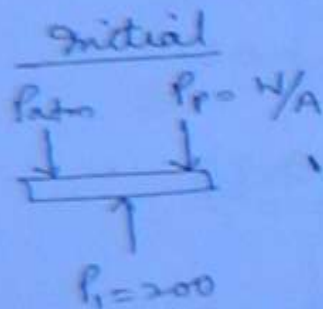
$$\Rightarrow 2V_1 - V_1 = 0.25 \times x$$

$$\Rightarrow 0.05 = 0.25x$$

$$\therefore \boxed{x = 0.2 \text{ m}}$$

(32)

Now free body diagrams.



At equilibrium.

$$P_1 + W/A = 200 \quad \text{--- (1)}$$

At equilibrium

$$P_1 + P_2 + P_3 = P_2 \quad \text{--- (2)}$$

But from eqⁿ (1), $P_1 + P_2 = 200$

$$\therefore 200 + P_3 = P_2 \quad \text{--- (3)}$$

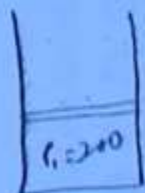
Now

$$P_3 = \frac{F_3}{A} = \frac{K \cdot x}{A}$$

$$\therefore P_3 = \frac{150 \times 0.2}{0.25} = 120 \text{ kN/m}^2 \text{ or kPa.}$$

$$\therefore \boxed{P_2 = 200 + 120 = 320 \text{ kPa}} \quad \text{--- (Ans)}$$

Work done by gas = work done in raising piston + work done in compressing spring.



(33)

$$W_{\text{piston}} = P(V_2 - V_1)$$

$$200(2V_1 - V_1)$$

$$= 200 \times (0.05) \Rightarrow W_{\text{piston}} = 10 \text{ kJ}$$

$$W_{\text{Total}} = 10 + 3 = 13 \text{ kJ} \quad (\text{Ans})$$

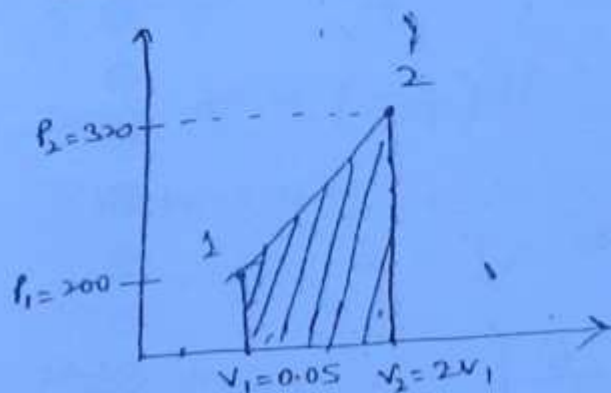
Spring Work

$$= \frac{1}{2} kx^2$$

$$= \frac{1}{2} \times 150 \times 0.2^2$$

$$= 3 \text{ kJ}$$

Alternate Method



$$P_2 = 200 + P_s$$

$$P_s = \frac{F_s}{A} = \frac{kx}{A} \quad \text{--- (1)}$$

$$\text{Also, } V_2 - V_1 = Ax$$

$$\Rightarrow x = \frac{V_2 - V_1}{A} = \frac{\Delta V}{A}$$

$$\therefore P_s = \frac{k}{A} \cdot \frac{\Delta V}{A}$$

$$\text{or } P_s = \frac{k}{A^2} \cdot \Delta V$$

$$\text{Thus, } P_2 = 200 + \frac{k}{A^2} \cdot \Delta V$$

$$W = \frac{1}{2} (200 + 320)(2V_1 - V_1)$$

$$= \frac{1}{2} \times 520 \times 0.05$$

$$\therefore W = 13 \text{ kJ} \quad (\text{Ans})$$

Chapter - 1

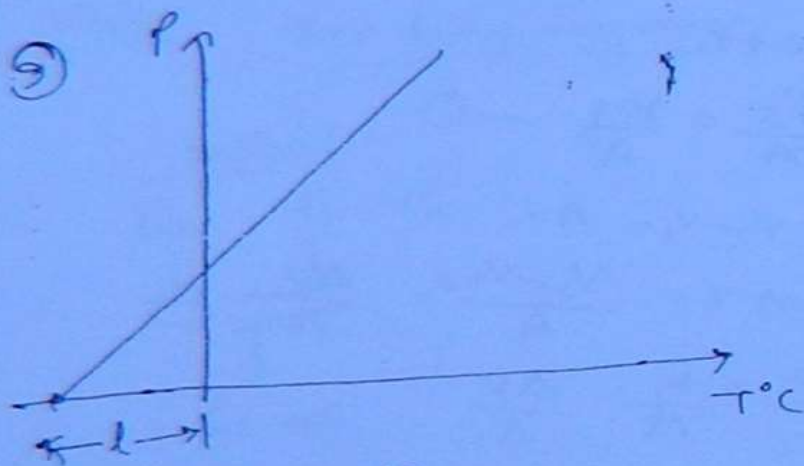
- 1 - a
- 2 - c
- 3 - b
- 4 - d
- 5 - a
- 6 - b
- 7 - c

- 8 - c
- 9 - d
- 10 - c
- 11 - b
- 12 - c
- 13 - d
- 14 - d

- 15 - d
- 16 - c
- 17 - d
- 18 - c
- 19 - d
- 20 - ~~b~~ d

334

1-2-7
3-8



$$Pv = mRT$$

$$P = \frac{mk}{v} \cdot T, \text{ Here, } m, k \text{ \& } v \text{ are constants.}$$

$$\therefore P = CT$$

$$\therefore P = 0 \quad \therefore \underline{\underline{T = 0K}}$$

convert in $^{\circ}C$

$$K = ^{\circ}C + 273.15$$

$$\therefore 0 = ^{\circ}C + 273.15$$

$$\Rightarrow ^{\circ}C = -273.15, \text{ Hence (d) is an.}$$

13

(a) $\int f dx$ & (b) $\int v df$

Both are works and work ~~is not~~ ^{is not} a property.

$$\boxed{\begin{aligned} dz &= M dx + N dy \\ \left(\frac{\partial M}{\partial y}\right)_x &= \left(\frac{\partial N}{\partial x}\right)_y \end{aligned}}$$

30

The equation $dz = M dx + N dy$ is exact, when

$$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$$

Solving option (d) 1.

$$\frac{dT}{T} - \frac{v df}{T}$$

$$\frac{1}{T} \cdot dT + \left(-\frac{v}{T}\right) df$$

$$M dx + N dy$$

$$M = \frac{x}{T}; \quad x = T; \quad N = -\frac{v}{T}; \quad y = P.$$

Now,

$$\left(\frac{\partial M}{\partial y}\right)_x = \left[\frac{\partial}{\partial P} \left(\frac{1}{T}\right)\right]_T$$

$\therefore T$ is constant

$$\left(\frac{\partial M}{\partial y}\right)_x = 0$$

Again,

$$\left(\frac{\partial N}{\partial x}\right)_y = \left[\frac{\partial}{\partial T} \left(-\frac{v}{T}\right)\right]_P$$

from ideal gas equation

$$PV = mRT \quad \therefore \frac{v}{T} = \frac{mR}{P}$$

$$\therefore \left(\frac{\partial N}{\partial x}\right)_y = \left[\frac{\partial}{\partial T} \left(-\frac{mR}{P}\right)\right]_P$$

$\therefore P$ is constant

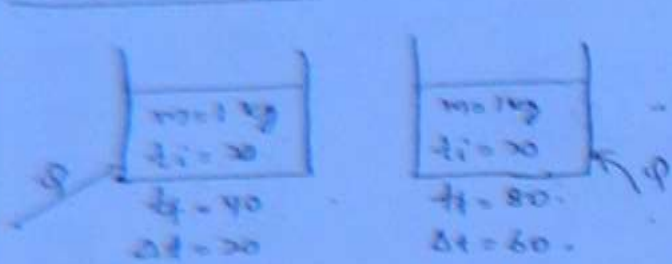
$$\therefore \left(\frac{\partial N}{\partial x}\right)_y = 0$$

$$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y = 0$$

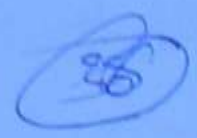
Hence, these are exact differentials. So, it is a property.

← HEAT →

The energy transfer due to temperature difference is known as heat transfer.



$$\begin{aligned} Q &\propto \Delta t \\ Q &\propto m \\ Q &\propto m(\Delta t) \end{aligned}$$



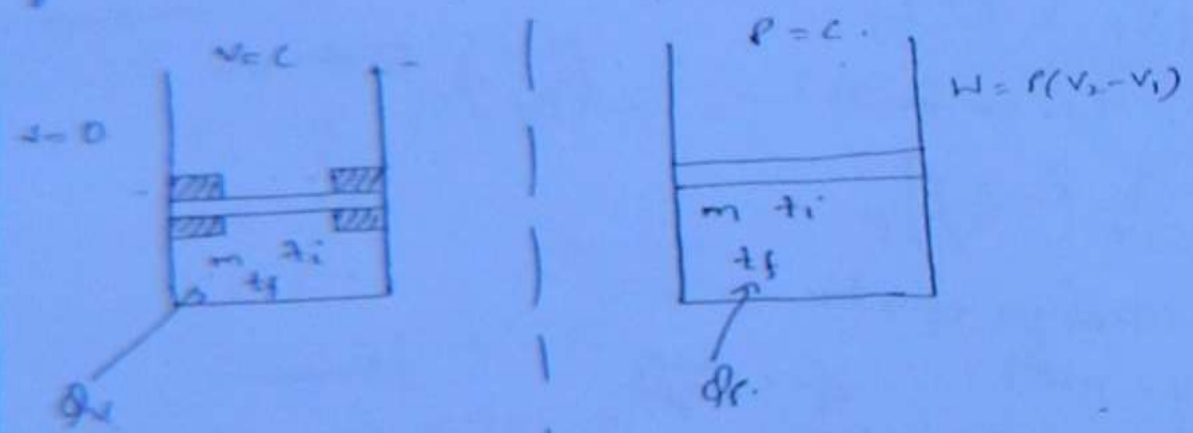
$$Q = mc(\Delta t) \quad \text{(specific heat)}$$

when $m=1$; $\Delta t=1$

$$Q = c$$

$$c = \frac{Q}{m\Delta t} \text{ units } \left(\frac{\text{kJ}}{\text{kg K}} \right)$$

Specific heat (c) is the amount of heat required to raise the temperature of unit mass of substance through unit degree temperature difference.



$$\begin{aligned} Q_1 &> Q_2 \\ \cancel{m} \cancel{c_p} \cancel{\Delta t} &> \cancel{m} \cancel{c_v} \cancel{\Delta t} \end{aligned}$$

$$\therefore c_p > c_v$$

$$\therefore \gamma = \frac{c_p}{c_v} > 1 \quad \therefore \gamma > 1$$

Specific heat at constant pressure (C_p) is greater than specific heat at constant volume (C_v) because ' C_p ' includes internal energy and external work whereas ' C_v ' includes internal energy only.

FIRST LAW OF THERMODYNAMICS \rightarrow

(39)

(Law of Conservation of Energy):-

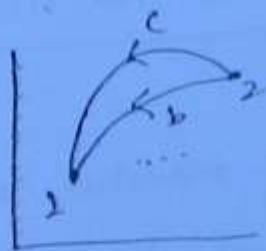
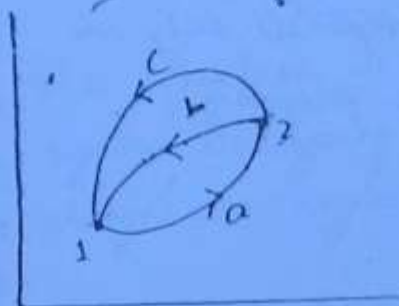
Statement:- For a closed system undergoing a cycle net heat transfer (ΣQ) is equal to net work transfer (ΣW)

$$\boxed{\Sigma Q = \Sigma W}$$

\hookrightarrow valid for a cycle...

(Results)
Consequences of first law of Thermodynamics:-

① Heat transfer is a path function.



$$\begin{aligned} \cancel{(\delta Q)_{1a2}} + (\delta Q)_{2b1} &= \cancel{(\delta Q)_{1a2}} + (\delta W)_{21} \\ (\delta Q)_{1a2} + \cancel{(\delta Q)_{2c1}} &= \cancel{(\delta W)_{1a2}} + (\delta W)_{2c} \\ \hline (\delta Q)_{2b1} - \cancel{(\delta Q)_{2c1}} &= (\delta W)_{2b1} - (\delta W)_{2c} \end{aligned}$$

$$(\delta W)_{2b1} \neq (\delta W)_{2c1}$$

$$\therefore (\delta W)_{2b1} - (\delta W)_{2c1} \neq 0$$

$$\therefore (\delta Q)_{2b1} - (\delta Q)_{2c1} \neq 0$$

$$\text{Hence, } (\delta Q)_{2b1} \neq (\delta Q)_{2c1}$$

Though, for paths 'b' and 'c', end points are same but heat transfer is not same and hence heat transfer is a path function.

* Important points with respect to heat transfer and work transfer

- 1) Both are path functions.
- 2) Both are not properties.
- 3) Both are inexact differentials.
- 4) Both are boundary phenomenon. (38)

$$(\delta Q = \delta W)$$

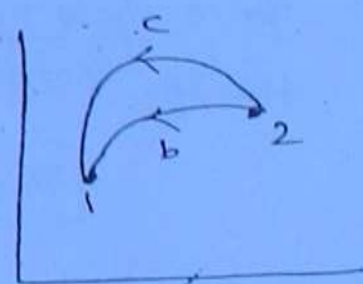
consequences continued....

→ Energy is a property.

$$dQ_{2b1} - dQ_{2c1} = (\delta W)_{2b1} - (\delta W)_{2c1}$$

$$dQ_{2b1} - \delta W_{2b1} = dQ_{2c1} - \delta W_{2c1}$$

$$\boxed{(\delta Q - \delta W)_{2b1} = (\delta Q - \delta W)_{2c1}}$$



~~quantity~~
The quantity $(\delta Q - \delta W)$ is same for paths 'b' and 'c' and hence it does not depend on path and it depends only on end points. Therefore, $(\delta Q - \delta W)$ must be a property and this property is known as energy.

$$(\delta Q - \delta W)_{2b1} = (\delta Q - \delta W)_{2c1} = dE$$

$$(\delta Q - \delta W)_{2b1} = dE$$

$$\boxed{\delta Q = dE + \delta W}$$

This is the first law of thermodynamics for a closed system undergoing a process (reversible or irreversible).

$$\boxed{\delta Q = dE + PdV}$$
 It is the first law of

thermodynamics for a closed system undergoing reversible process because ~~but~~ $W = PdV$ is valid for a reversible process.

Now,

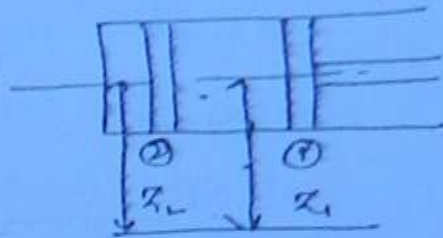
$$E = \underbrace{K.E + P.E}_{\text{Macroscopic}} + \underbrace{U}_{\text{Microscopic}}$$

(28)

$$dE = d(K.E) + d(P.E) + dU.$$

Let the system is initially ~~and~~ finally at rest, so $K.E = 0$ and again finally it is also at rest, $\therefore K.E = 0$ again.

The height is also same \therefore change in Potential Energy, $d(P.E) = 0$.



$$\therefore dE = dU.$$

Now,

$$dQ = dE + dU$$

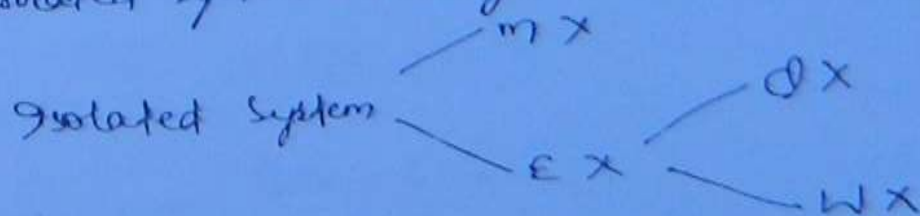
$$\therefore \boxed{dQ = dU + dW}$$

This equation is first law of thermodynamics equation for a system undergoing a process when kinetic and potential energy changes are neglected.

INTERNAL ENERGY (U) :-

It is the energy associated with molecules. It is an extensive property. and it is generally expressed in J. Specific Internal Energy = U/m and it is an intensive property. It is generally expressed in kJ/kg .

③ Energy of an isolated system is always constant.



* To show that $(C_p - C_v) = R$ for an ideal gas :-
(Meyer's Eqⁿ):

$$H = U + PV$$

(3)

$$dH = dU + d(PV)$$

$$m c_p dT = m c_v dT + d(mRT) \quad (\text{for an ideal gas})$$

$$\Rightarrow m c_p dT = m c_v dT + m R dT$$

$$\Rightarrow C_p = C_v + R.$$

$$\text{or } \boxed{C_p - C_v = R} \rightarrow \text{Meyer's Equation}$$

Now,

$$\frac{C_p}{C_v} = \gamma \Rightarrow C_p = \gamma \cdot C_v.$$

$$\therefore \gamma C_v - C_v = R$$

$$\Rightarrow \boxed{C_v = \frac{R}{\gamma - 1}} \quad \text{--- (2)}$$

$$\therefore C_p = \gamma \cdot C_v$$

$$\therefore \boxed{C_p = \frac{\gamma \cdot R}{\gamma - 1}} \quad \text{--- (3)}$$

for Air

$$\begin{aligned} C_p &= 1.005 \text{ kJ/kg K} \\ C_v &= 0.718 \text{ kJ/kg K} \\ R &= 0.287 \text{ kJ/kg K} \\ \gamma &= 1.4. \end{aligned}$$

③ Isothermal Process:-

$$dQ = dU + dW$$

for an ideal gas, $U = f(T)$.

Here, $T = \text{constant}$

$$\therefore U = \text{constant} \Rightarrow dU = 0 \quad (4)$$

$$\therefore dQ_T = 0 + dW$$

$$\Rightarrow \boxed{dQ_T = dW}$$

When an ideal gas undergoes isothermal process, heat transfer is equal to work transfer.

④ Adiabatic Process:-

$$\cancel{dQ = dU + dW} \quad Q = 0.$$

There is no heat transfer in adiabatic process.

⑤ Polytropic Process:-

$$dQ = dU + dW$$

for an ideal gas, $dU = m c_v dT$.

$$\& \text{ Polytropic work} = dW = \left(\frac{P_1 V_1 - P_2 V_2}{n-1} \right)$$

$$\therefore dQ = m c_v dT + \frac{P_1 V_1 - P_2 V_2}{(n-1)}$$

$$= m \frac{R}{\gamma-1} dT + \frac{P_1 V_1 - P_2 V_2}{n-1}$$

$$= \frac{mR}{\gamma-1} (T_2 - T_1) + \frac{P_1 V_1 - P_2 V_2}{n-1}$$

$$\therefore mRT = PV \quad \therefore mRT_2 = P_2 V_2 \quad \& \quad mRT_1 = P_1 V_1$$

$$dQ = \frac{P_2 V_2 - P_1 V_1}{\gamma-1} + \frac{P_1 V_1 - P_2 V_2}{n-1}$$

$$= \frac{P_1 V_1 - P_2 V_2}{n-1} + \frac{P_2 V_2 - P_1 V_1}{\gamma-1}$$

$$\begin{aligned} \rightarrow dQ &= P_1 V_1 - P_2 V_2 \left[\frac{1}{n-1} - \frac{1}{\gamma-1} \right] \\ &= P_1 V_1 - P_2 V_2 \left[\frac{\gamma-1 - (n-1)}{(n-1)(\gamma-1)} \right] \\ &= \frac{P_1 V_1 - P_2 V_2}{n-1} \left[\frac{\gamma-n}{\gamma-1} \right] \end{aligned}$$

(42)

$$\therefore dQ = \left(\frac{\gamma-n}{\gamma-1} \right) W_{\text{polytropic}}$$

VV1

Polytropic Specific heat (C_{poly}) :-

$$dQ_V = dU = m c_v dT \quad (\text{for ideal gas})$$

$$dQ_V = m c_v dT \quad \text{--- (1)}$$

$$dQ_P = dH = m c_p dT \quad (\text{for ideal gas})$$

$$dQ_P = m c_p dT \quad \text{--- (2)}$$

Note for polytropic process:

$$dQ_{\text{poly}} = \left(\frac{\gamma-n}{\gamma-1} \right) \times \left(\frac{P_1 V_1 - P_2 V_2}{n-1} \right)$$

$$\therefore PV = mRT$$

$$\therefore dQ_{\text{poly}} = \frac{(\gamma-n)}{(\gamma-1)} \left[\frac{mRT_1 - mRT_2}{n-1} \right]$$

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

$$= \frac{(\gamma-n)}{(\gamma-1)} \cdot \frac{mR}{(n-1)} (-dT)$$

$$\therefore (dT = T_2 - T_1) \quad \text{Also, } \frac{R}{\gamma-1} = c_v$$

$$\therefore dQ_{\text{poly}} = \frac{(\gamma-n)}{(\gamma-1)} m c_v (-dT)$$

$$\text{or } dQ_{\text{poly}} = \frac{(n-\gamma)}{(n-1)} \cdot m c_v (dT)$$

Rearranging above equation.

$$dQ_{\text{poly}} = m \left[\frac{n-\gamma}{n-1} C_v \right] dT$$

$$\therefore C_{\text{poly}} = \frac{n-\gamma}{n-1} \cdot C_v$$

(12)

for ' $n > 1$ ' and ' $n < \gamma$,' C_{poly} is negative i.e. though heat is supplied, there is a decrease in temperature. This is because in such a polytropic process, work transfer is more than heat transfer and this excess work transfer comes from internal energy of the system and as there is a decrease in internal energy the temperature also decreases.

* To show that $PV^\gamma = \text{constant}$ for adiabatic process:-

$$dQ = dU + dW$$

for reversible process,

$$dQ = dU + PdV$$

Heat gas undergoing adiabatic process.

$$dU = m c_v dT, \quad dQ = 0$$

$$\therefore 0 = m c_v dT + PdV$$

$$\text{or, } PdV = -m c_v dT \quad \text{--- (1)}$$

Now

$$H = U + PV$$

$$\rightarrow dH = dU + PdV + VdP$$

$$\therefore dH = dQ + VdP$$

for ideal gas:-

$$dH = m c_p dT$$

$$\text{adiabatic} \Rightarrow dQ = 0.$$

$$\therefore m c_p dT = 0 + V dp.$$

$$\Rightarrow m c_p dT = V dp \quad \text{--- (2)}$$

(48)

Dividing eqⁿ (1) by eqⁿ (2) :-

$$\frac{m c_p dT}{-m c_v dT} = \frac{V dp}{P dV}$$

$$\Rightarrow -\gamma = \frac{V}{dV} \cdot \frac{dP}{P}$$

$$\Rightarrow -\gamma \cdot \frac{dV}{dV} = \frac{dP}{P}$$

$$\Rightarrow \frac{dP}{P} + \gamma \frac{dV}{V} = 0.$$

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

$$\Rightarrow \ln P + \ln V^\gamma = \ln C$$

$$\Rightarrow \ln PV^\gamma = \ln C.$$

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

The equation " $PV^\gamma = C$ " is valid for an ideal gas undergoing reversible adiabatic process.

CONVENTIONAL QUESTIONS:-

IAS
40 marks

Q.1 A fluid is contained in a cylinder by spring loaded friction piston so that pressure in the fluid is a linear function of volume, i.e. $P = a + bV$, where 'a' and 'b' are constants. Internal energy of the fluid is given by $U = 34 + 3.15 PV$, where 'U' is in kJ, 'P' is in kPa and 'V' is in m^3 . If the fluid changes from initial state of $P_1 = 170$ kPa, $V_1 = 0.03$ m^3 to a final state of $P_2 = 400$ kPa, $V_2 = 0.06$ m^3 , find the magnitude and direction of heat transfer and work transfer. (45)

Soln:

$$W = \text{Area under curve}$$

$$= \frac{1}{2} \times (170 + 400) \times 0.03$$

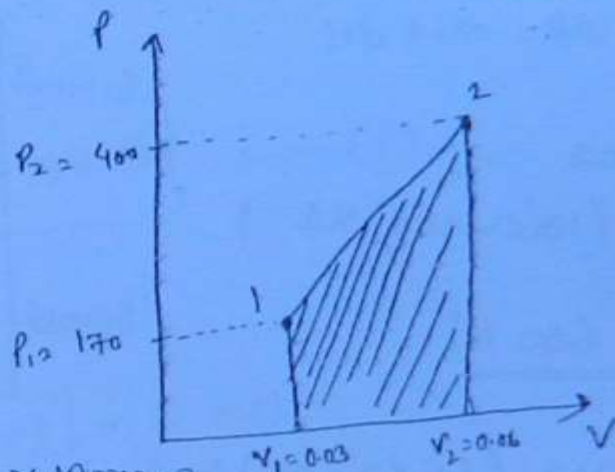
$$=$$

$$dU = U_2 - U_1 = 3.15 P_2 V_2 - 3.15 P_1 V_1$$

$$= 3.15 \times 400 \times 0.06 - 3.15 \times 170 \times 0.03$$

$$\therefore dU =$$

$$dQ = dU + dW$$

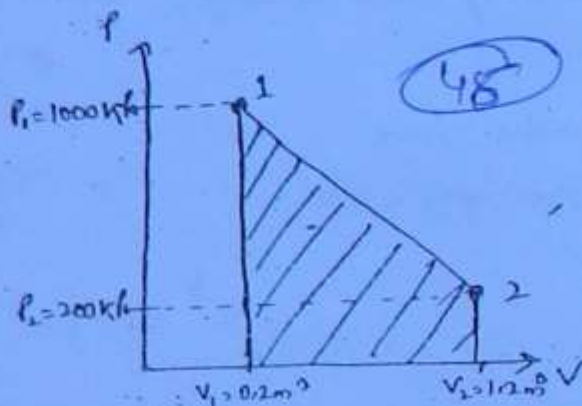


Q. 1.1) A gas of mass 1.5 kg undergoes a reversible expansion process which follows the relationship $P = a + bV$, where 'a' and 'b' are constants. The initial and final pressures are 1000 kPa and 200 kPa respectively and the corresponding volumes are $V_1 = 0.2 \text{ m}^3$ and $V_2 = 1.2 \text{ m}^3$. The specific internal energy, $u = (1.5 PV - 85) \text{ kJ/kg}$ where 'P' is in kPa and small 'v' is m^3/kg . Calculate net heat transfer and maximum internal energy of the gas.

P1 $dQ = dU + dW$

$W = \text{Area}$
 $= \frac{1}{2} (1000 + 200) \times 1$

$W = 600 \text{ kJ}$



Now $u = (1.5 PV - 85) \text{ kJ/kg}$

$u = U/m \Rightarrow U = u \times m$

$\therefore U = m [1.5 PV - 85]$
 $= [1.5 PVm - m \cdot 85]$

$u = \frac{U}{m} \Rightarrow U = u \cdot m$

$\therefore U = (1.5 PV - 1.5 \times 85)$

$\therefore (m = 1.5 \text{ kg})$

$\therefore \boxed{U = (1.5 PV - 127.5)}$

$dU = U_2 - U_1$

Now $U_2 = 1.5 P_2 V_2 - 127.5$

$U_1 = 1.5 P_1 V_1 - 127.5$

$dU = U_2 - U_1 = 1.5 (P_2 V_2 - P_1 V_1)$

$$\therefore dU = 1.5 [200 \times 1.2 - 1000 \times 0.2]$$

$$= 60 \text{ kJ.}$$

Now

$$dQ = dU + dW$$

$$= (60 + 600) \text{ kJ}$$

$$\therefore \boxed{dQ = 660 \text{ kJ}} \quad \text{(A)}$$

Now 2nd part

$$U = 1.5 PV - 127.5.$$

(18)

$$\therefore P = a + bV$$

$$\therefore U = 1.5 (a + bV)V - 127.5$$

$$\Rightarrow \boxed{U = 1.5 [aV + bV^2] - 127.5} \quad \text{--- (1)}$$

for max^m U, $\frac{dU}{dV} = 0.$

$$\frac{dU}{dV} = 1.5 [a(1) + 4(2V)] = 0 = 0$$

$$\Rightarrow 1.5 [a + 2bV] = 0.$$

$$\therefore (a + 2bV) = 0$$

$$\text{or, } a = -2bV$$

$$\Rightarrow \boxed{V = \frac{-a}{2b}}$$

$$P_1 = a + bV_1 \Rightarrow 1000 = a + b \times 0.2$$

$$P_2 = a + bV_2 \Rightarrow \frac{200 = a + b \times 1.2}{800 = -b}$$

$$\text{or } \boxed{b = -800}$$

Again

$$200 = a + 1.2b \Rightarrow \text{circled } 200 \text{ and } 1.2 \times (-800)$$

$$\Rightarrow a = 200 - 1.2(-800)$$

$$\boxed{a = 1160}$$

Now $V = \frac{-1160}{2 \times (-800)} \Rightarrow V = 0.725 \text{ m}^3$

$$U = 1.5 [1160 \times 0.725 + (-800) 0.725^2] - 127.5$$

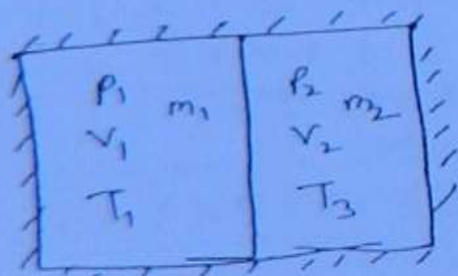
$\therefore U_{\text{max}} = 503.25 \text{ KJ.}$ (Ans) (48)

Q. 13
An insulated rigid pressure vessel is divided into two portions by a thin partition. First part of vessel is occupied by an ideal gas at a pressure P_1 , volume V_1 and temperature T_1 . The other part is occupied by the same ideal gas but at a pressure P_2 , volume V_2 and temperature T_2 . Suddenly the partition is removed and two portions mix with each other. Show that the final pressure P_3 and final temp T_3 are given by

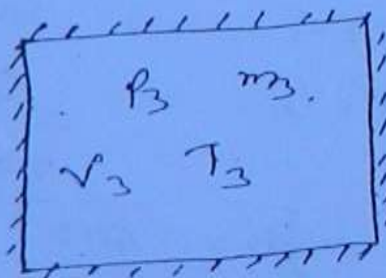
$$P_3 = \frac{P_1 V_1 + P_2 V_2}{V_1 + V_2}$$

$$T_3 = \frac{P_1 V_1 + P_2 V_2}{\frac{P_1 V_1}{T_1} + \frac{P_2 V_2}{T_2}}$$

Ans: $PV = nRT \Rightarrow m = \frac{PV}{RT}$



Initial



Final

$$m_3 = m_1 + m_2$$

$$\frac{P_3 V_3}{RT_3} = \frac{P_1 V_1}{RT_1} + \frac{P_2 V_2}{RT_2}$$

$$\frac{P_3 V_3}{T_3} = \left(\frac{P_1 V_1}{T_1} + \frac{P_2 V_2}{T_2} \right)$$

$$\Rightarrow T_3 = \frac{P_3 V_3}{\left(\frac{P_1 V_1}{T_1} + \frac{P_2 V_2}{T_2} \right)} \quad \text{--- (1)}$$

Now $dQ = dU + dW$

for constant vol^m, closed system, $dW = 0$.

Also, \therefore the system is insulated

$$\therefore dQ = 0$$

$$\therefore 0 = dU + 0$$

$$\Rightarrow dU = 0$$

$$\Rightarrow U_f - U_i = 0 \Rightarrow U_f = U_i$$

Now $U_3 = U_1 + U_2$

$$m_3 C_v T_3 = m_1 C_v T_1 + m_2 C_v T_2$$

$$\Rightarrow \frac{m_3 R T_3}{\cancel{C_v}} = \frac{m_1 R T_1}{\cancel{C_v}} + \frac{m_2 R T_2}{\cancel{C_v}}$$

$$\Rightarrow P_3 V_3 = P_1 V_1 + P_2 V_2 \quad \text{--- (2)}$$

Also, $V_3 = V_1 + V_2$

$$\therefore P_3 (V_1 + V_2) = P_1 V_1 + P_2 V_2$$

$$\Rightarrow \boxed{P_3 = \frac{P_1 V_1 + P_2 V_2}{V_1 + V_2}} \quad \text{proved}$$

$$\& \boxed{T_3 = \frac{P_1 V_1 + P_2 V_2}{\left(\frac{P_1 V_1}{T_1} + \frac{P_2 V_2}{T_2} \right)}} \quad \text{proved}$$

from eq (2)

Q: A fluid system contained in a piston-cylinder machine passes through a complete cycle of four processes. The summation of heat transfer is -340 kJ/cycle . The system completes 200 cycles per minute. Complete the following table and also find the net work transfer in kWatt.

Process	$Q \text{ (kJ/min)}$	$W \text{ (kJ/min)}$	$dU \text{ (kJ/min)}$
1-2	0	4340	-4340
2-3	42000	0	42000
3-4	-4200	69000	-73200
4-1	-105800	-141340	35540

Soln:

For Process (1-2):

$$dQ = dU + dW$$

$$0 = dU_{12} + 4340$$

$$\Rightarrow dU_{12} = -4340$$

(10)

For 2-3 (Process):

$$dQ = dU + dW$$

$$42000 = dU + 0 \Rightarrow dU_{23} = 42000$$

For 3-4 (Process):

$$dQ = dU + dW$$

$$\Rightarrow -4200 = dU_{34} + 73200$$

$$\Rightarrow dW_{34} = 69000$$

Now,

$$\Sigma Q = -340 \text{ kJ/cycle}$$

& There are 200 cycles/minute.

$$\therefore \Sigma Q = -340 \times 200 = -68000 \text{ kJ/min}$$

Also $\Sigma Q = Q_{12} + Q_{23} + Q_{34} + Q_{41}$
 $\Rightarrow -68000 = 0 + 42000 + (-4200) + Q_{41}$
 $\Rightarrow \underline{Q_{41} = -105800}$

Again $\Sigma Q = \Sigma W = -68000$

$\Sigma W = W_{12} + W_{23} + W_{34} + W_{41}$
 $\Rightarrow W_{41} = -68000 - 4340 - 0 - 69000$

$\therefore \underline{W_{41} = -141340}$

Now for process (4-1)

$dQ = dU + dW$
 $\Rightarrow dU = dQ - dW$
 $= -105800 + (-141340)$

$\Rightarrow \underline{dU_{41} = 35540}$

Now $W_{net} = \Sigma W = -68000 \text{ kJ/min}$

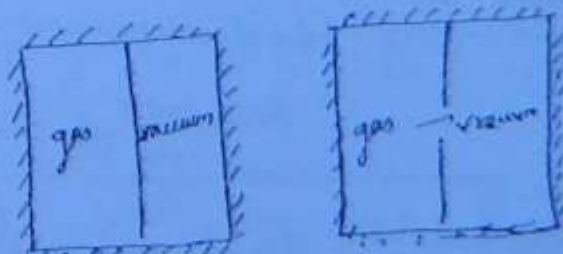
$W_{net} = -\frac{68000}{60} \text{ kJ/sec} = \text{kW}$

$W_{net} = -11333 \text{ kW}$ (Ans)

THEORY

\Rightarrow * FREE EXPANSION \rightarrow

The expansion of a gas against vacuum is known as free expansion.



Free expansion
or
Restricted expansion

Free expansion work is equal to zero because as the gas is expanding against vacuum, there is no resistance offered from

Surroundings and hence work is equal to zero.



(54)

$$dQ = dU + dW$$

$$0 = dU + 0$$

$$\Rightarrow dU = 0$$

$$U_f - U_i = 0 \Rightarrow U_f = U_i$$

If an ideal gas undergoes free expansion

$$U = f(T)$$

$$\Rightarrow U_i = U_f \Rightarrow T_i = T_f$$

Also,

$$H = U + PV$$

$$H = f(T) + mRT$$

$$\therefore H = \phi(T)$$

$$\text{As, } T_i = T_f \Rightarrow H_i = H_f$$

Note:

When an ideal gas undergoes free expansion :-

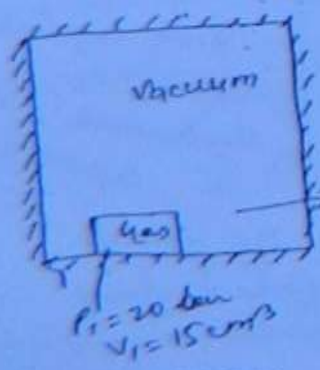
- (i) $U_i = U_f$
- (ii) $T_i = T_f$
- (iii) $H_i = H_f$

PROBLEM

Ques

An ideal gas at 20 bar and 40°C is contained in a small cylinder having a volume of 15 cm³. This cylinder is placed inside a large container having a volume of 1500 cm³. The large container is perfectly insulated and evacuated. By an appropriate means, the gas is allowed to discharge and fill the large container. Find the final pressure after the entire assembly reaches the equilibrium.

$$T_1 = T_2 \text{ (for free expansion)}$$



$$PV = mRT$$

$$m = \frac{PV}{RT}$$

from mass conservation

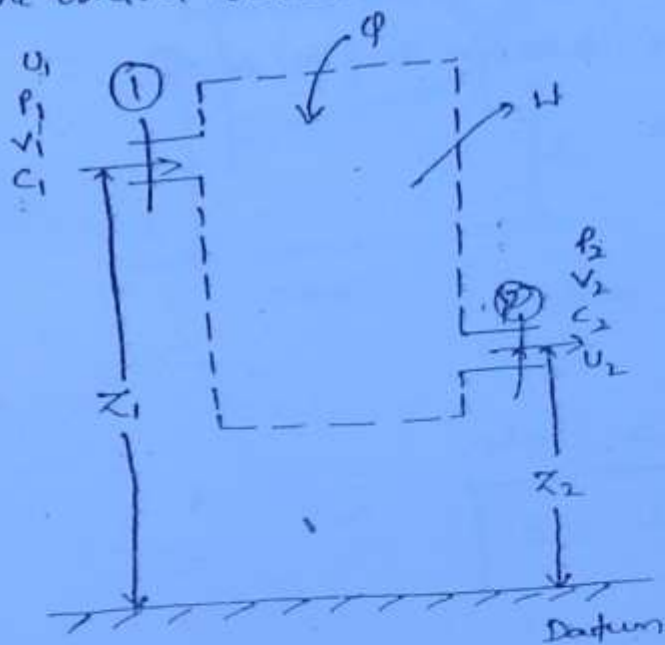
$$m_1 = m_2$$

STEADY FLOW ENERGY EQUATION (SFEE) :-

A flow is said to be steady flow if properties do not vary with respect to time at any given section.

For steady flow, there is no accumulation of mass and energy in the control volume i.e. mass entering is equal to mass leaving and energy entering = energy leaving the control volume.

(53)



$$\left. \begin{aligned} W &= W_{\text{ent flow}} + W_{\text{cv}} \\ &\quad + W_{\text{exit flow}} \\ W &= -P_1 V_1 + W_{\text{cv}} + P_2 V_2 \end{aligned} \right\}$$

For steady flow, $E_1 = E_2$.

$$\frac{1}{2} m C_1^2 + mgZ_1 + U_1 + Q = \frac{1}{2} m C_2^2 + mgZ_2 + U_2 + W$$

$$\Rightarrow \frac{1}{2} m C_1^2 + mgZ_1 + U_1 + Q = \frac{1}{2} m C_2^2 + mgZ_2 + U_2 + (-P_1 V_1) + W_{\text{cv}} + P_2 V_2$$

$$\frac{1}{2} m C_1^2 + mgZ_1 + U_1 + P_1 V_1 + Q = \frac{1}{2} m C_2^2 + mgZ_2 + U_2 + P_2 V_2 + W_{\text{cv}}$$

$$H_1 + \frac{1}{2} m C_1^2 + mgZ_1 + Q = \frac{1}{2} m C_2^2 + H_2 + mgZ_2 + W_{\text{cv}}$$

Dividing the above equation by 'm' :-

$$h_1 + \frac{C_1^2}{2} + gZ_1 + q = h_2 + \frac{C_2^2}{2} + gZ_2 + w_{\text{cv}}$$

→ 1st law of thermodynamics for steady flow open system.

Here, C_1 and C_2 are velocities at 1 and 2 respectively.

$$\frac{P_1 V_1}{RT_1} = \frac{P_2 V_2}{RT_2}$$

$$\Rightarrow P_1 V_1 = P_2 V_2$$

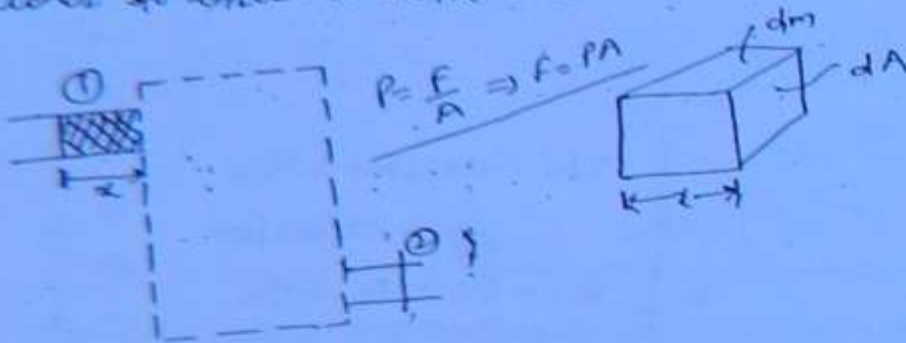
$$\Rightarrow 20 \times 15 = 100 \times V_2$$

$$\therefore \boxed{V_2 = 0.2 \text{ kgm}} \quad (\text{Ans}) \dots$$

FLOW WORK :-

(24)

It is the work transfer involved in causing the fluid element either to enter or leave the control volume to known as flow work.



$$\text{Work} = F \times x$$

$$= P \cdot dA \times x$$

$$\text{Work} = P dV$$

$$dV = dA \times x$$

$$v = \frac{dV}{dm}$$

$$\text{Work} = P dV$$

$$\frac{\text{Work}}{\text{mass}} = \frac{P dV}{dm}$$

$$\frac{\text{Work}}{\text{mass}} = P v$$

$$\text{Total Work} = P v \cdot m$$

$$\boxed{\text{Total work} = P V}$$

$$v = \frac{V}{m}$$

$$\therefore \underline{V = v \cdot m}$$

If the entry occurs at '1', then the entry flow work = $(-P_1 V_1)$

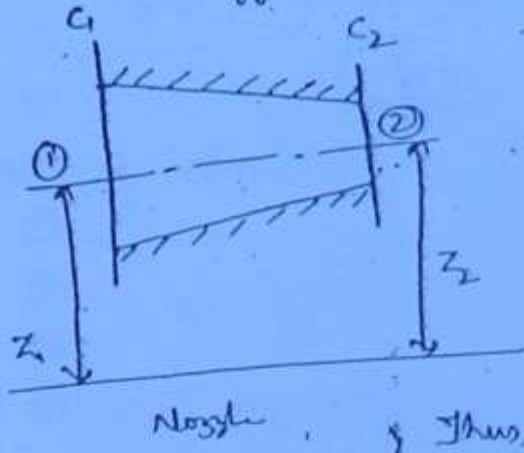
If the exit occurs at '2', then the exit flow work = $(+P_2 V_2)$.

This is the first law of thermodynamics equation for open system under steady flow conditions.

(56)

Special Cases:-

① Nozzle:- Nozzle is a device which is used for increasing kinetic energy at the expense of pressure energy.



$$h_1 + \frac{c_1^2}{2} + z_1 g + \cancel{q} = h_2 + \frac{c_2^2}{2} + z_2 g + \cancel{w}$$

\therefore Insulated, $q=0$.

for a nozzle, $w_{cv} = 0$.

Also, $z_1 = z_2 \therefore$ P.E are same

Nozzle

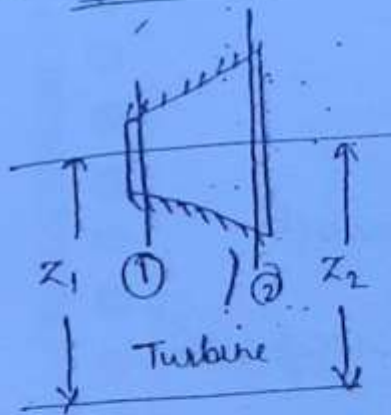
Thus,

$$\boxed{h_1 + \frac{c_1^2}{2} = h_2 + \frac{c_2^2}{2}}$$

when $c_1 \ll c_2$, then

$$\boxed{h_1 = h_2 + \frac{c_2^2}{2}}$$

② Turbine:-



$$h_1 + \frac{c_1^2}{2} + z_1 g + \cancel{q} = h_2 + \frac{c_2^2}{2} + z_2 g + w_{cv}$$

Assumptions:-

- ① Steady flow
- ② Perfectly insulated, so $\therefore q=0$.
- ③ Neglecting P.E changes.
- ④ Neglecting K.E changes.

$$h_1 = h_2 + w_{cv}$$

or, $\boxed{w_{Turbine} = h_1 - h_2}$

③ Compressor:-

Compressor work is always negative, since work is done on the system.

$$W_{\text{comp}} = h_2 - h_1$$

(Assumptions are same as in case of turbine).

$$W_{\text{Turbine}} = h_1 - h_2$$

$$W_{\text{comp}} = -W_{\text{Turbine}} = -(h_1 - h_2)$$

$$\therefore W_{\text{comp}} = h_2 - h_1$$

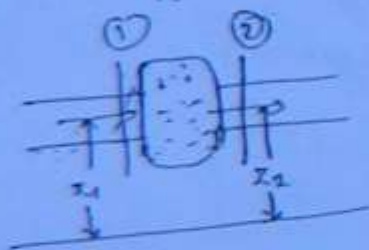
④ Throttling valve:-

Examples of throttling:-

- (i) flow through a partially opened valve.
- (ii) flow through a very small opening (orifice).
- (iii) flow through a porous plug.

Characteristics of throttling:-

- (i) No heat transfer.
- (ii) No work transfer.
- (iii) Highly irreversible process.
- (iv) Enthalpy remains constant. (It is isenthalpic process).



$$h_1 + \frac{C_1^2}{2} + z_1 g + \rho \dots = h_2 + \frac{C_2^2}{2} + z_2 g + \rho \dots$$

$$h_1 + \frac{C_1^2}{2} = h_2 + \frac{C_2^2}{2}$$

In comparison to enthalpy values, K.E changes are negligible.

$$\therefore h_1 = h_2$$

Ideal Gas ($PV = mRT$)

Perfect Gas

C_p & C_v are constants



Semi-Perfect Gas

C_p & C_v ~~are~~ vary with temp

$$\text{No. of moles } (n) = \frac{\text{mass } (m)}{\text{Molecular wt. } (M)}$$

$$n = \frac{m}{M}$$

$$\text{or } m = nM$$

\therefore Ideal gas equation

$$PV = mRT \\ = nMR$$

$$MR = \bar{R} \text{ (universal gas constant)}$$

$$PV = n\bar{R}T$$

$$\text{Isothermal work} = mRT \ln \frac{V_2}{V_1}$$

$$= (n\bar{R}T \ln \frac{V_2}{V_1})$$

$$R = \frac{\bar{R}}{M} = \frac{8.314}{M}$$

$$\bar{R} = 8.314 \text{ kJ/kg K}$$

R = characteristic gas constant

- | | | | |
|--------|--------|--------|--------|
| 1 - a | 14 - b | 27 - b | 40 - a |
| 2 - c | 15 - c | 28 - c | 41 - a |
| 3 - a | 16 - c | 29 - a | 32 - a |
| 4 - c | 17 - b | 30 - b | 33 - a |
| 5 - c | 18 - c | 31 - a | 34 - a |
| 6 - a | 19 - a | 35 - a | 35 - a |
| 7 - a | 20 - c | 36 - a | 36 - a |
| 8 - c | 21 - c | 37 - c | 37 - c |
| 9 - a | 22 - c | 38 - a | 38 - a |
| 10 - b | 23 - c | 39 - c | 39 - c |
| | 24 - a | 40 - a | 40 - a |
| | 25 - | 41 - a | 41 - a |
| | 26 - b | | |
| | 27 - a | | |
| | 28 - c | | |
| | 29 - a | | |
| | 30 - b | | |

(Assignment)
153

① T_{0C} , $n = 70$, $T = 354K$, $V_2 = 1m^3$, $W = -206 kJ$

$$W = nRT \ln \frac{V_2}{V_1}$$

$$\Rightarrow -206 = 70 \times 8.314 \times 354 \ln \left(\frac{V_2}{V_1} \right)$$

$$\Rightarrow \ln \left(\frac{V_2}{V_1} \right) = \frac{-206}{70 \times 8.314 \times 354}$$

$$\Rightarrow \left(\frac{V_2}{V_1} \right) = e^{(9.989845 \times 10^{-4})} = 1.001 \approx 1$$

$$\therefore \left(\frac{V_2}{V_1} \right) = 1 \quad \therefore V_2 = V_1$$

② ~~$dQ = dW$~~ $dQ_T = dW$

$P_i = P_o$ and $T_i = T_o$

$T = \text{const}$ (isothermal process)

$P_f = P_i$

$$PV = nRT = C$$

$$PV = C$$

$$P_i V_i = P_f V_f$$

$$\frac{V_f}{V_i} = \frac{P_i}{P_f}$$

$$W = Q = nRT \ln \frac{V_f}{V_i}$$

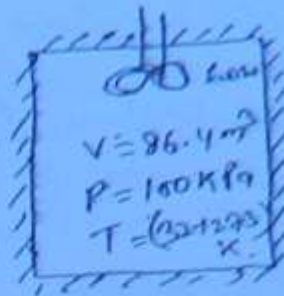
$$W = Q = nRT \ln \frac{P_i}{P_f}$$

$$Q = 1 \times R \times T_o \ln \left(\frac{P_i}{P_f} \right)$$

$$Q = RT_o \ln \left(\frac{P_o}{P_i} \right)$$

$$Q = -RT_o \ln \left(\frac{P_f}{P_o} \right)$$

③ $W = -60 \text{ W} = \frac{-60 \text{ J}}{\text{s}} = \frac{-60 \times 60 \times 60}{1000} \text{ kJ}$
 $V = 86.4 \text{ m}^3$
 $T_1 = 32^\circ\text{C}, T_2 = ?$
 $C_v = 0.718, R = 0.287 \text{ J/kg K}$
 $P_1 = 100 \text{ kPa}$
 $T_1 = (273 + 32) \text{ K} = 305 \text{ K}$



$W = -60 \text{ J/s} = \frac{-60 \times 60 \times 60 \times 4}{1000} \text{ kJ}$
 $= \underline{\underline{-864 \text{ kJ}}}$

Air can be treated as an ideal gas.

$\therefore dU = m c_v dT$

$dQ = dU + dW$

\therefore Insulated, $\therefore dQ = 0$

$\therefore 0 = m c_v dT + (-864)$

$\Rightarrow \cancel{dU} \quad m c_v dT = 864$

$\Rightarrow dT = \frac{864}{m c_v} \quad \text{--- (1)}$

Now for ideal gas $PV = mRT$

$\Rightarrow m = \frac{PV}{RT} = \frac{100 \times 86.4}{0.287 \times 305}$

$\therefore \underline{\underline{m = 98.7 \text{ kg}}}$

$\therefore dT = \frac{864}{98.7 \times 0.718} = 12.19 \approx \underline{\underline{12^\circ\text{C}}}$

⑦ $dQ = dU + dW$

$T_1 = 15^\circ\text{C}, T_2 = 45^\circ\text{C}, P = 100 \text{ kPa}$

for constant volume process, $v = c$

$dQ_v = dU = m c_v dT$

$= 1 \times 3.5107 \times 30 = \underline{\underline{105.32 \text{ kJ}}}$

$\frac{C_p}{C_v} = \gamma$
 $\Rightarrow C_v = \frac{C_p}{\gamma} = \frac{1.042}{1.34} = 3.5107$

④ Area of cycle = Area enclosed by the curve:-

$$\text{1st case, Area of } \Delta = \frac{1}{2}bh \\ = \frac{1}{2} \times 8 \times 3 = \underline{\underline{12}}$$

$$\text{2nd case, Area} = \frac{1}{2} \times 6 \times 4 = 12$$

but for clockwise dirⁿ ~~work~~ work is \oplus ve
and for anticlockwise dirⁿ work is \ominus ve,

$$\frac{C_p \cdot R}{C_p - C_v}$$

⑤ A-2, B-4, C-1, D-3.



⑥ $m = 1 \text{ kg}$, $T_1 = 15^\circ\text{C}$, $p = 100 \text{ kPa}$, $T_2 = 45^\circ\text{C}$.

$$C_p = 1.042 \text{ kJ/kg}\cdot\text{K}, \quad R = 0.2968.$$

$$Q_v = m C_v dT \\ = 1 \times 0.7452 \times 30 \\ =$$

$$\frac{C_p \cdot R}{C_p - C_v}$$

$$\frac{(C_p - C_v) \cdot R}{1.042 - 0.2968} \\ = 0.7452$$

$$(C_p - C_v) \delta = R.$$

$$(5.19 - C_v) = \frac{8.314}{4}$$

$$\therefore C_v = (5.19 - 2.0785) = \underline{\underline{3.11}}$$

$$dq = du + dw.$$

$$du = \frac{100 \times 60 \times 30}{1000} = \underline{\underline{-180 \text{ kJ}}}$$

$$dw = (-180 \text{ kJ})$$

$$du = m C_v dT \\ = 30 \times 0.7 \times dT$$

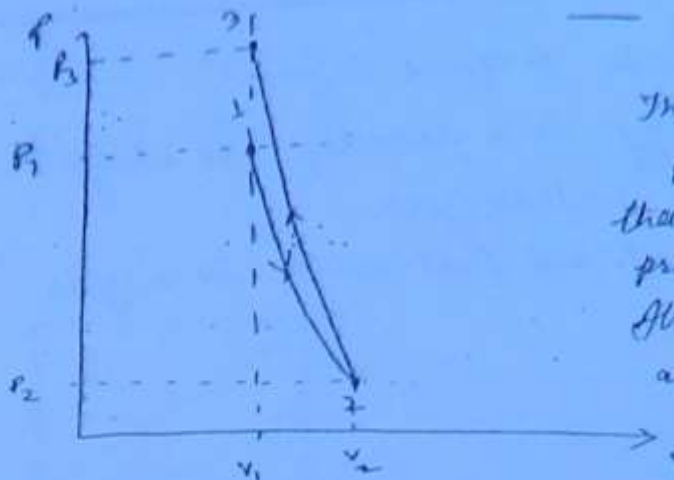
$$du = (dw)$$

$$\rightarrow 30 \times 0.7 \times dT = +180$$

$$\rightarrow dT = \underline{\underline{+8.57}}$$

$$\therefore T_2 = T_1 + dT \\ = 21 + 8.57 \\ = \underline{\underline{29.57^\circ\text{C}}}$$

16



The slope of adiabatic process is always greater than the slope of isothermal process.
 Also, expansion work is \ominus ve and compression work is \oplus ve

here is greater

60k

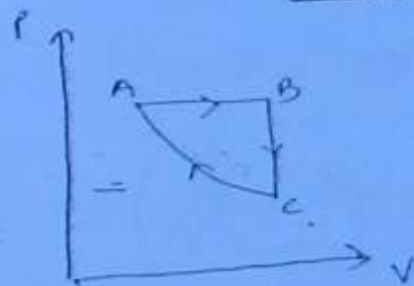
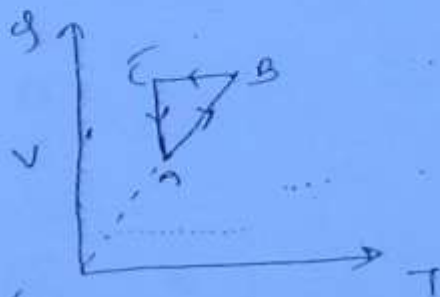
$\therefore W < 0$ (\because Win \ominus ve)

$+ P_3 \Delta V_1$

17 The total work done by the gas is $(300 \times 0.01) = 3 \text{ kJ}$
 Out of this total work, $(100 \times 0.01) = 1 \text{ kJ}$ is used in displacing atmospheric air.

Therefore the work that could be utilised = $(3 - 1) = \underline{2 \text{ kJ}}$

19



$PV = nRT$

$V = \frac{nR}{P} \cdot T$

$y = m \cdot x$

$m = \frac{nR}{P} = \text{const}$

m is const if P is constant \therefore $AB \rightarrow P = C$

$BC \rightarrow V = C$

$CA \rightarrow T = C$

$AB \rightarrow P = C$

20 For isothermal process of an ideal gas open system work is equal to closed system work because a rectangular hyperbola is symmetric about 'x' and 'y' axis and hence it gives same area.

21) Change in property for any cycle is equal to zero.

Since internal energy is a property, so change in internal energy for a cycle will be zero.

As the ~~start~~ initial and final points in a cycle are same.

Q - 2

$$\text{Q} = 300 \text{ kJ} = \frac{300 \times 60 \times 15}{1000} = 2700 \text{ kJ}$$

$$\Delta = 0$$

Q 25 - Assignment

$$P_1 = 10 \text{ bar}, V_1 = 1 \text{ m}^3, T_1 = 300 \text{ K}$$

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

$$\left(P + \frac{a}{V^2}\right)V = RT = C$$

$$\left(P_1 + \frac{a}{V_1^2}\right)V_1 = \left(P_2 + \frac{a}{V_2^2}\right)V_2$$

$$\Rightarrow \left(10 + \frac{a}{1}\right) \times 1 = \left(P_2 + \frac{a}{2^2}\right) \times 2$$

$$= (10 + a) = \frac{4P_2 + a}{2}$$

$$\Rightarrow 20 + 2a = 4P_2 + a$$

$$\Rightarrow a = \underline{4P_2 - 20}$$

$$\Rightarrow P_2 = \frac{a + 20}{4} = \frac{a}{4} + 5$$

$$\boxed{P_2 = \frac{a}{4} + 5}$$

$\because a > 0$ and also its value is

slightly greater than 0, $\therefore \frac{a}{4}$ will

be very less.

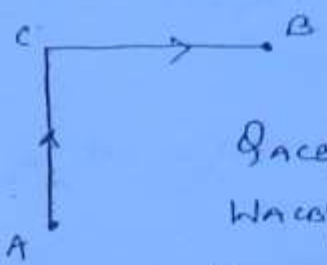
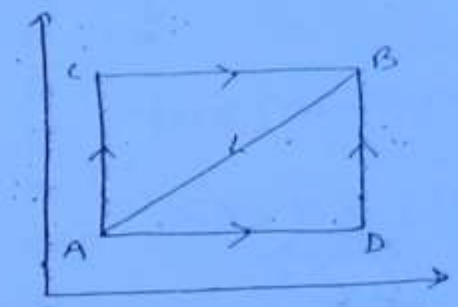
$\therefore P_2$ will be slightly more than 5 bar.

27

E-G-I-K-N
F-H-J-K-M

Boundary and transient
both are same and can be
used for both heat and work

28



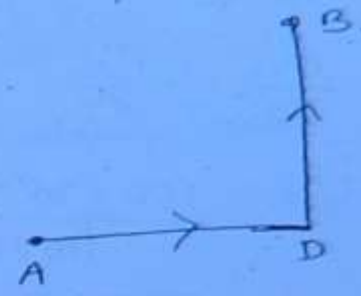
$Q_{ACB} = 180$
 $W_{ACB} = 130$

$dQ_{ACB} = dU_{ACB} + dW_{ACB}$

$\Rightarrow 180 = (U_B - U_A) + 130$

$\therefore (U_B - U_A) = 50$ — (1)

62



$Q_{ADB} = ?$

$W_{ADB} = 40 \text{ kJ}$

$dQ_{ADB} = dU_{ADB} + dW_{ADB}$

$dQ_{ADB} = 50 + 40$

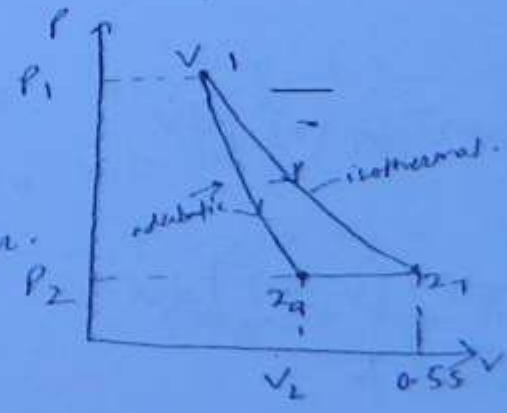
$\therefore dQ_{ADB} = 90 \text{ kJ}$ (A)

29

$P_1 V_1 = P_2 V_2$
 $P/V_1 = \frac{P}{10} \times 0.55$
 $V_1 = 0.055 \text{ m}^3$

for adiabatic $P_1 V_1^\gamma = P_2 V_2^\gamma$
 $\Rightarrow P_1 \times (0.055)^\gamma = \frac{P_1}{10} \times (V_2)^\gamma$

All values are greater
than 0.55 but only
value 0.40 is lesser.



6

$$\begin{aligned}
 T_1 &= 293 \text{ K} \\
 P_1 &= 100 \text{ kPa} \\
 V_1 &= 15 \text{ m}^3
 \end{aligned}$$

$$\begin{aligned}
 T_2 &= ? \\
 P_2 &= 150 \\
 V_2 &= 25 \text{ m}^3
 \end{aligned}$$

$$PV = nRT$$

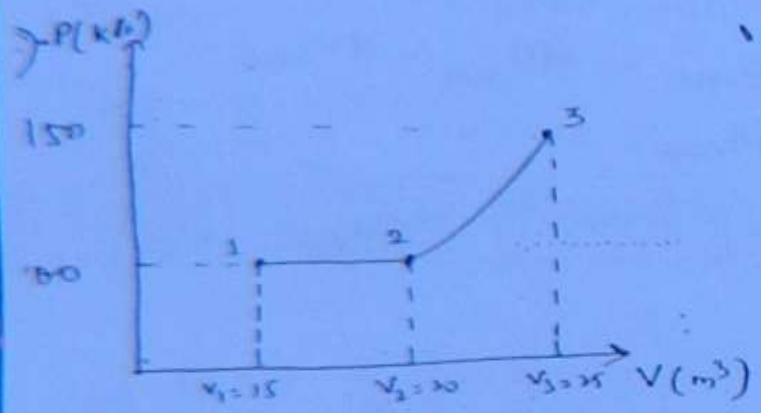
$$m = \frac{PV}{RT}$$

$$m_1 = m_2$$

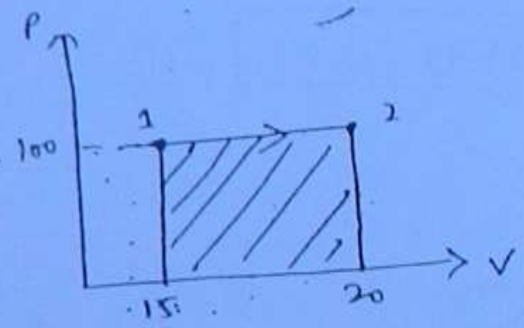
$$\frac{P_1 V_1}{RT_1} = \frac{P_2 V_2}{RT_2}$$

$$\begin{aligned}
 \Rightarrow T_2 &= \frac{150 \times 25 \times 293}{100 \times 15} \\
 &= 732.5 \approx \underline{\underline{733 \text{ K}}}
 \end{aligned}$$

64



$$P = P_0 + 2(V - V_0)^2$$



$$\begin{aligned}
 W_{12} &= P(V_2 - V_1) \\
 &= 100(20 - 15) \\
 &= \underline{\underline{500 \text{ kJ}}}
 \end{aligned}$$

Again

$$W = \int P dV$$

$$W_{23} = \int_{V_2}^{V_3} [P_0 + 2(V - V_0)^2] dV$$

$$= \int_{20}^{25} [100 + 2(V - 20)^2] dV$$

$$W_{23} = \int_{20}^{25} 100 dV + 2(V-20)^2 dV$$

$$= \int_{20}^{25} \left[100V + \frac{2}{3}(V-20)^3 \right] dV$$

$$1 \text{ bar} = 100 \text{ kPa}$$

$$= 100 \times (25-20) + \frac{2}{3} \left[(25-20)^3 - (20-20)^3 \right]$$

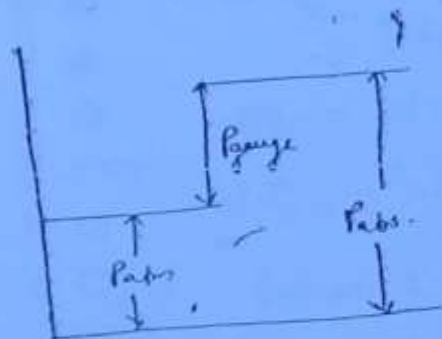
$$= 500 + \frac{2}{3} (5)^3 = 500 + 83 = 583 \text{ kJ}$$

$$\therefore W_{\text{total}} = W_{12} + W_{23}$$

$$= (500 + 583) \text{ kJ} = \underline{\underline{1083 \text{ kJ}}}$$

(65)

38) In the equation $PV = mRT$, 'P' is in absolute scale.



$$P_{\text{abs}} = P_{\text{g}} + P_{\text{atm}}$$

$$P_1 = 1 \text{ bar (gauge)}$$

$$T_1 = 288 \text{ K}$$

$$P_{\text{abs}} = P_{\text{g}} + P_{\text{atm}}$$

$$P_1 = 1 + 1.013$$

$$P_1 = 2.013 \text{ bar}$$

$$PV = mRT$$

$$\Rightarrow m = \frac{PV}{RT}$$

$$= \frac{2.013 \times 100 \times 2500}{0.287 \times 288 \times 10^{-6}}$$

$$\Rightarrow m = 6.08 \times 10^{-3} \text{ kg}$$

($\because 1 \text{ bar} = 100 \text{ kPa}$)

For a constant volume process

$$dQ = dU$$

$$dQ_v = m c_v dT = m c_v (T_2 - T_1)$$

$$= 6.08 \times 10^{-3} \times 0.718 \times (278 - 288)$$

$$\Rightarrow dQ_v = -43.7 \times 10^{-3} \text{ kJ} = -43.7 \text{ joule}$$

(Negative sign indicates rejection of heat)

$$P_1 = 2.013$$
$$T_1 = 288$$

$$P_2 = ?$$
$$T_2 = 298$$

$$PV = nRT$$

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

66

$$\Rightarrow P_2 = \frac{T_2 \times P_1}{T_1} = \frac{298 \times 2.013}{288}$$

$$\therefore P_2 = 1.943 \text{ bar}$$

$$\therefore (P_2)_{\text{gauge}} = P_2 - P_{\text{atm}}$$
$$= 1.943 - 1.013$$

$$\therefore (P_2)_{\text{gauge}} = \underline{0.93 \text{ bar}} \quad (\text{Ans.})$$

5

$$P_1 = ?$$
$$T_1 = 288$$

$$P_2 = 1 \text{ bar (gauge)}$$
$$T_2 = 298$$

$$P_2 \text{ abs} = 1 + 1.013 = \underline{2.013 \text{ bar}}$$

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

$$\Rightarrow P_1 = \frac{2.013 \times 288}{298} = 2.085 \text{ bar}$$

$$(P_1)_{\text{gauge}} = (P_1)_{\text{abs}} - P_{\text{atm}}$$
$$= 2.085 - 1.013$$

$$\therefore (P_1)_{\text{gauge}} = \underline{1.07 \text{ bar}} \quad (\text{gauge})$$

$$W_{1-3} = P(V_3 - V_1)$$

Process 1-2

$$P_1 V_1 = P_2 V_2$$

$$\Rightarrow 1 \times 1.6 = P_2 \times 0.2$$

$$\Rightarrow P_2 = \frac{1.6}{0.2} = 8 \text{ bar}$$

$$W_{2-3} = 800 (1.6 - 0.2) = 1120 \text{ kJ}$$

(67)

41) Heat transfer for constant pressure process.

$$dQ_p = dH$$
$$= d(U + PV)$$

$$dQ_p = dU + dW$$

$$dQ_{2-3} = dU_{23} + dW_{23}$$

Process 1-2 is an isothermal process.

$$\therefore U_1 = U_2$$

(\therefore Change in internal energy for isothermal process is 0).

$$dU = U_3 - U_2$$

$$U_3 - U_2 = U_3 - U_1 = 3549 \text{ kJ}$$

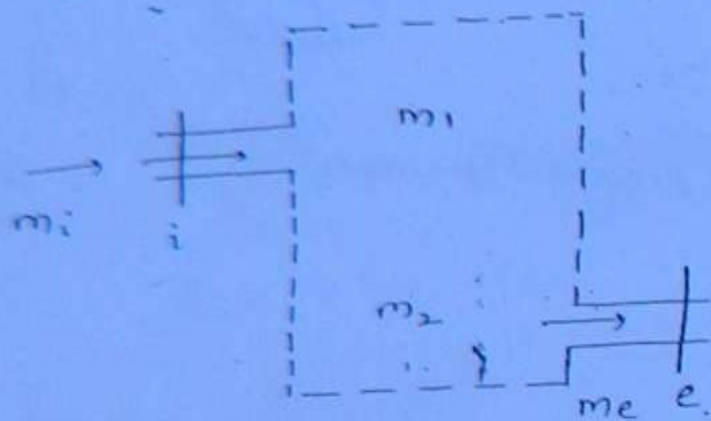
$$dQ_{23} = (3549 + 1120) \text{ kJ}$$

$$= 4669 \text{ kJ}$$

← UNSTEADY STATE FLOW →

Let m_i and m_e be the masses entering and leaving the control volume.

Let m_1 and m_2 be the masses in the control volume initially and finally respectively.



$$m \rightarrow \text{kg}$$

$$\dot{m} = \frac{m}{t} = \frac{\text{kg}}{\text{sec}}$$

conservation of mass:-

$$\left(\frac{dm}{dt}\right)_{cv} = \frac{dm_i}{dt} - \frac{dm_e}{dt}$$

$$\boxed{\left(\frac{dm}{dt}\right)_{cv} = \dot{m}_i - \dot{m}_e} \quad \text{--- (1)}$$

conservation of Energy:-

energy per unit mass = $h_i + \frac{C_i^2}{2} + z_i g + v$.

Total inlet energy, $E_i = m_i h_i + \frac{1}{2} m_i C_i^2 + m_i g z_i + \dots$

Similarly, Total energy leaving,

$$E_e = m_e h_e + \frac{1}{2} m_e C_e^2 + m_e g z_e + W_{cv}$$

Now,

$$\left(\frac{dE}{dt}\right)_{cv} = \frac{dE_i}{dt} - \frac{dE_e}{dt}$$

$$\left(\frac{dE}{dt}\right)_{cv} = \frac{d}{dt} \left(m_i h_i + \frac{1}{2} m_i c_i^2 + m_i g z_i + \Phi \right) - \frac{d}{dt} \left(m_e h_e + \frac{1}{2} m_e c_e^2 + m_e g z_e + W_{cv} \right)$$

Neglecting k.E & P.E changes, we have.

$$\left(\frac{dU}{dt}\right)_{cv} = \frac{d}{dt} (m_i h_i + \Phi) - \frac{d}{dt} (m_e h_e + W_{cv})$$

$$\left(\frac{dU}{dt}\right)_{cv} = \frac{d}{dt} m_i h_i + \dot{\Phi} - \frac{d}{dt} (m_e h_e) + \dot{W}_{cv}$$

$E = KE + PE + U$
 $\therefore dE = d(KE) + d(PE) + dU$
 If $d(KE)$ & $d(PE)$ are neglected, then $dE = dU$

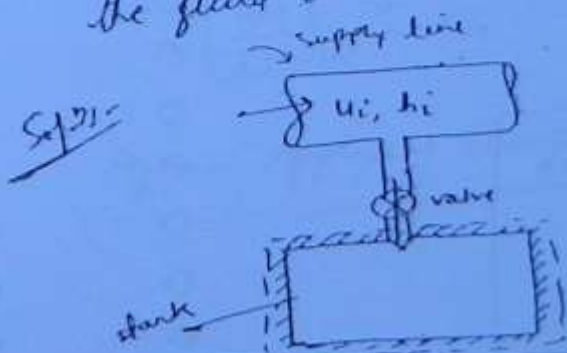
Let h_i & h_e are assumed to be constant with respect to time, then

$$\left(\frac{dU}{dt}\right)_{cv} = h_i \frac{dm_i}{dt} + \dot{\Phi} - h_e \frac{dm_e}{dt} - \dot{W}_{cv}$$

$$\text{or, } \left(\frac{dU}{dt}\right)_{cv} = \dot{m}_i h_i + \dot{\Phi} - \dot{m}_e h_e - \dot{W}_{cv} \quad \text{--- (2)}$$

PROBLEM

Q: An insulated storage tank that is initially evacuated is connected to a supply pipeline carrying a fluid at specific internal energy u_i and specific enthalpy h_i . The valve is opened and fluid flows into the tank from the supply line and reaches the pressure same as that of supply pipe line. Show that the final specific internal energy of the fluid in the tank is equal to h_i .



$m_i = 0$ (evacuated)

Applying mass conservation :-

$$\left(\frac{dm}{dt}\right)_{cv} = \dot{m}_i - \dot{m}_e$$

$\dot{m}_e = 0$ (because no mass is leaving C.V)

$$\left(\frac{dm}{dt}\right)_{cv} = \dot{m}_i \quad \text{--- (1)}$$

(70)

Now Energy conservation :-

$$\left(\frac{dU}{dt}\right)_{cv} = \dot{m}_i h_i + \cancel{\dot{Q}} - \dot{m}_e h_e - \cancel{\dot{W}} \quad \text{(No work done)}$$

(assumed) ($\because \dot{m}_e = 0$)

$$\left(\frac{dU}{dt}\right)_{cv} = \dot{m}_i h_i \quad \text{--- (2)}$$

$$\left(\frac{dU}{dt}\right)_{cv} = h_i \left(\frac{dm}{dt}\right)_{cv}$$

Integrating , we have.

$$(dU)_{cv} = h_i (dm)_{cv}$$

$$U_2 - U_1 = h_i (m_2 - m_1)$$

$$m_2 u_2 - m_1 u_1 = h_i (m_2 - m_1)$$

$$\therefore m_1 = 0$$

$$\therefore m_2 u_2 = h_i (m_2)$$

$$\therefore \boxed{u_2 = h_i} \quad \text{proved}$$

Note :-

If the fluid flowing is an ideal gas,

$$u_2 = h_i$$

$$c_v T_2 = c_p T_i$$

$$T_2 = \frac{c_p}{c_v} T_i$$

$$\therefore \boxed{T_2 = \gamma T_i}$$

Therefore T_2 will always be greater than T_i .

$$\left[\begin{array}{l} U = mc_v T \\ u = c_v T \\ h = c_p T \end{array} \right]$$

(7)

ESE-2011

Q. The Pressure-cylinder of volume 'V' contains air at a pressure 'P_i' and temperature 'T_i'. It is to be filled from a supply pipeline maintained at a constant pressure 'P_i' and temperature 'T_i'. Show that the final tempⁿ of air in the cylinder after it has been charged to the pressure same as the supply line pressure is given by $T_2 = \frac{\gamma T_i}{1 + \frac{P_i}{P_i} \left(\frac{\gamma T_i}{T_i} - 1 \right)}$. The tank is insulated.

Solⁿ: Applying mass conservation:

$$\left(\frac{dm}{dt} \right)_{cv} = \dot{m}_i - \dot{m}_e$$

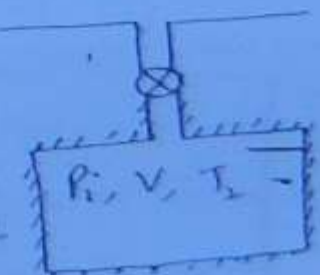
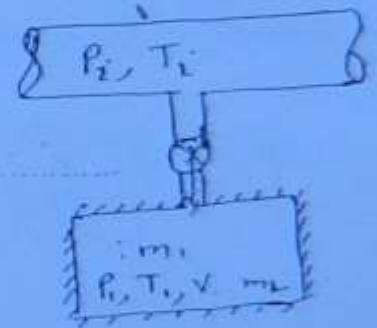
$$PV = mRT$$

$$m = \frac{PV}{RT} \quad \therefore m_2 = \frac{P_i V}{RT_2} \quad \& \quad m_1 = \frac{P_i V}{RT_i}$$

(\dot{m}_e) = 0 (because no mass is leaving control volume).

$$\therefore \left(\frac{dm}{dt} \right)_{cv} = \dot{m}_i \quad \text{--- (1)}$$

Again, Applying energy conservation:



(P. 70)

Finally we get; ϕ

$$U_2 - U_1 = (m_2 - m_1) h_i \quad (\text{as from last problem})$$

$$m_2 u_2 - m_1 u_1 = (m_2 - m_1) h_i$$

$$\Rightarrow m_2 C_v T_2 - m_1 C_v T_1 = (m_2 - m_1) C_p T_i \quad (72)$$

$$\Rightarrow C_v (m_2 T_2 - m_1 T_1) = C_p T_i (m_2 - m_1)$$

$$\Rightarrow C_v \left(\frac{P_i V}{R} - \frac{P_1 V}{R} \right) = C_p T_i \left(\frac{P_i V}{R T_2} - \frac{P_1 V}{R T_1} \right)$$

$$\Rightarrow \frac{P_i V}{R} - \frac{P_1 V}{R} = \frac{C_p}{C_v} T_i \left(\frac{P_i V}{R T_2} - \frac{P_1 V}{R T_1} \right)$$

$$\Rightarrow (P_i - P_1) = \gamma T_i \left(\frac{P_i}{T_2} - \frac{P_1}{T_1} \right)$$

$$\Rightarrow (P_i - P_1) = \frac{\gamma T_i P_i}{T_2} - \frac{\gamma T_i P_1}{T_1}$$

$$\Rightarrow \cancel{P_i} - P_1 + \frac{\gamma T_i P_1}{T_1} = \frac{\gamma T_i P_i}{T_2}$$

$$\Rightarrow T_2 = \frac{\gamma T_i P_i}{P_i - P_1 + \frac{\gamma T_i P_1}{T_1}}$$

$$T_2 = \frac{\gamma T_i P_i}{P_i \left[1 - \frac{P_1}{P_i} + \frac{\gamma T_i P_1}{P_i T_1} \right]}$$

$$\therefore T_2 = \frac{\gamma T_i}{1 + \frac{P_1}{P_i} \left(\frac{\gamma T_i}{T_1} - 1 \right)}$$

(Proved)

← : SECOND LAW OF THERMODYNAMICS : →

(Directional Law) →

(Concept of Entropy)

First law of thermodynamics simply says that energy is conserved. It does not give any direction for a particular process. It is the second law of thermodynamics which gives direction for a particular process through the concept of entropy - and hence second law is known as directional law. (73)

Work is known as high grade energy. Heat is known as low grade energy.

It is found that, for a cycle, complete conversion of low grade energy (heat) into high grade energy (work) is impossible.

* * Thermal Energy Reservoirs (TER) :-

Source :- Source is a ~~res~~ reservoir which supplies thermal energy without undergoing any temperature change.

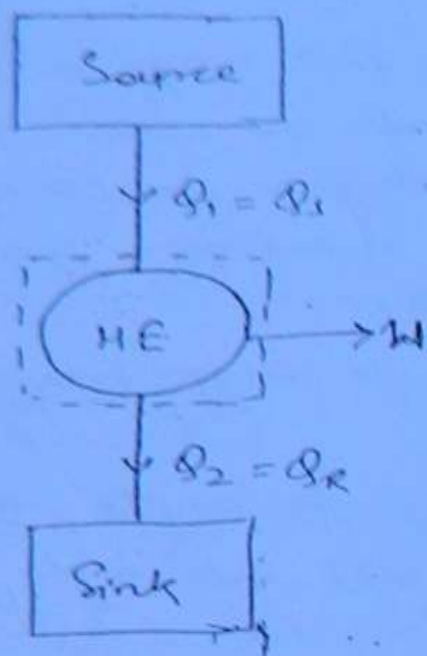
Sink :- It is a reservoir which absorbs thermal energy without undergoing any temperature change.

* * Statements of 2nd law of Thermodynamics :-

1st > KELVIN - PLANCK STATEMENT :-

It is impossible to develop a device operating on a cycle which produces work while exchanging heat with a single reservoir. This device is known as PMM-II and the efficiency of PMM-II is 100% and therefore 100% efficiency is impossible from second law of thermodynamics.

* CONCEPT OF HEAT ENGINE :-



$$Q_1 = \delta W + \delta_2$$

$$W = \delta_1 - \delta_2$$

$$\eta = \frac{Q}{I} = \frac{W}{\delta_1} \quad (54)$$

$$\eta = \frac{\delta_1 - \delta_2}{\delta_1} = 1 - \frac{\delta_2}{\delta_1}$$

$$\therefore \boxed{\eta = 1 - \frac{Q_R}{Q_S}} \quad \text{--- (1)}$$

Heat Engine is a device which converts part of heat into work and rejects remaining to sink or surrounding.

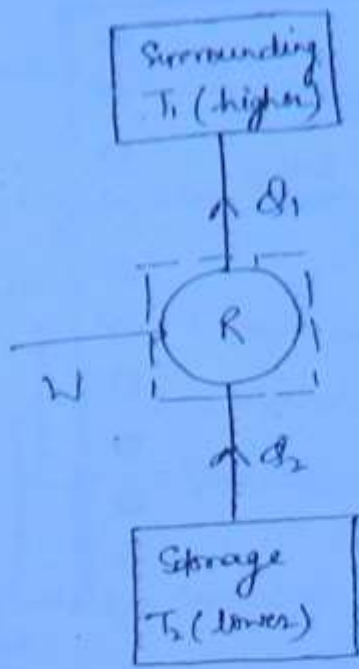
Equation (1) is valid both for reversible and irreversible cycle.

CLAUDE STATEMENT :-

It is impossible to transfer heat from lower temperature to the higher temperature without any external input.

* REFRIGERATOR :-

A refrigerator is a device which maintains lower temperature compared to surrounding. As lower temperatures are to be maintained continuously, refrigerators must operate on a cycle.



$$COP = \frac{\text{Desired Effect}}{\text{Energy Input}}$$

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

$$(COP)_R = \frac{Q_2}{Q_1 - Q_2} \quad \text{--- (2)}$$

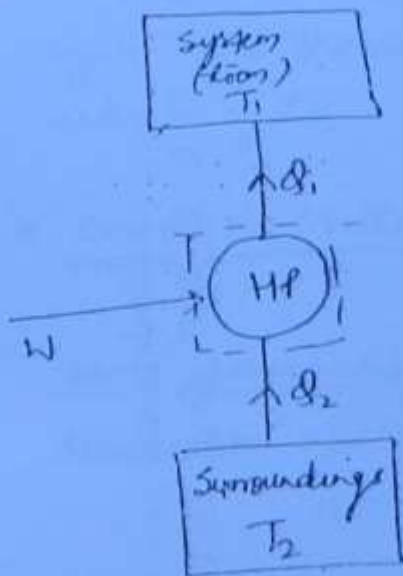
--- (2)

(TS)

$$\begin{aligned} \therefore W + Q_2 &= Q_1 \\ \therefore W &= Q_1 - Q_2 \end{aligned}$$

Equation (2) is valid for reversible and irreversible refrigerators. ?

* HEAT PUMP :- Heat pump is a device which maintains higher temperature compared to surrounding.



$$(C.O.P)_{HP} = \frac{Q_1}{W}$$

$$W + Q_2 = Q_1$$

$$W = Q_1 - Q_2$$

$$(COP) = \frac{Q_1}{Q_1 - Q_2} \quad \text{--- (3)}$$

--- (3)

This equation is valid for reversible as well as irreversible heat pump.

RELATIONSHIP BETWEEN COP OF A HEAT PUMP AND COP OF A REFRIGERATOR OPERATING BETWEEN SAME TEMPERATURES :-

$$(COP)_{HP} = \frac{Q_1}{Q_1 - Q_2}$$

$$(COP)_R = \frac{Q_2}{Q_1 - Q_2}$$

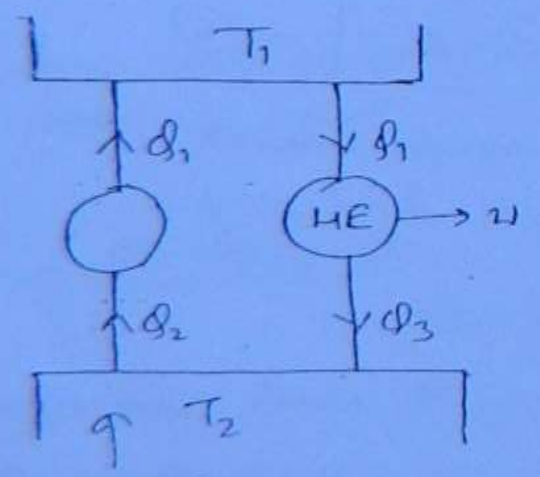
$$(COP)_{HP} - (COP)_R = \frac{Q_1}{Q_1 - Q_2} - \frac{Q_2}{Q_1 - Q_2}$$

$$(COP)_{HP} - (COP)_R = 1$$

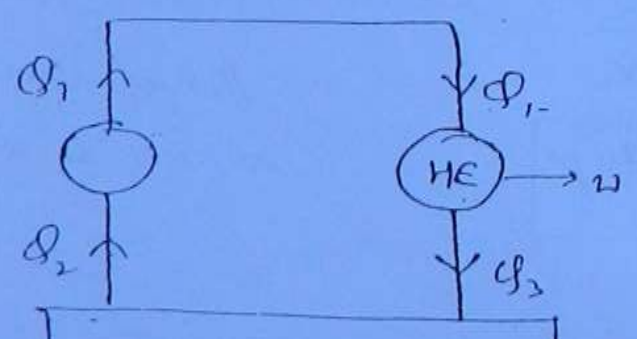
$$\text{or, } \boxed{(COP)_{HP} = 1 + (COP)_R} \quad \text{--- (4)}$$

TO SHOW THAT A KELVIN-PLANCK AND CLAUSIUS STATEMENTS ARE PARALLEL STATEMENTS OF 2ND LAW OF THERMODYNAMICS :-

ASE-33 Violation of Clausius Statement :-



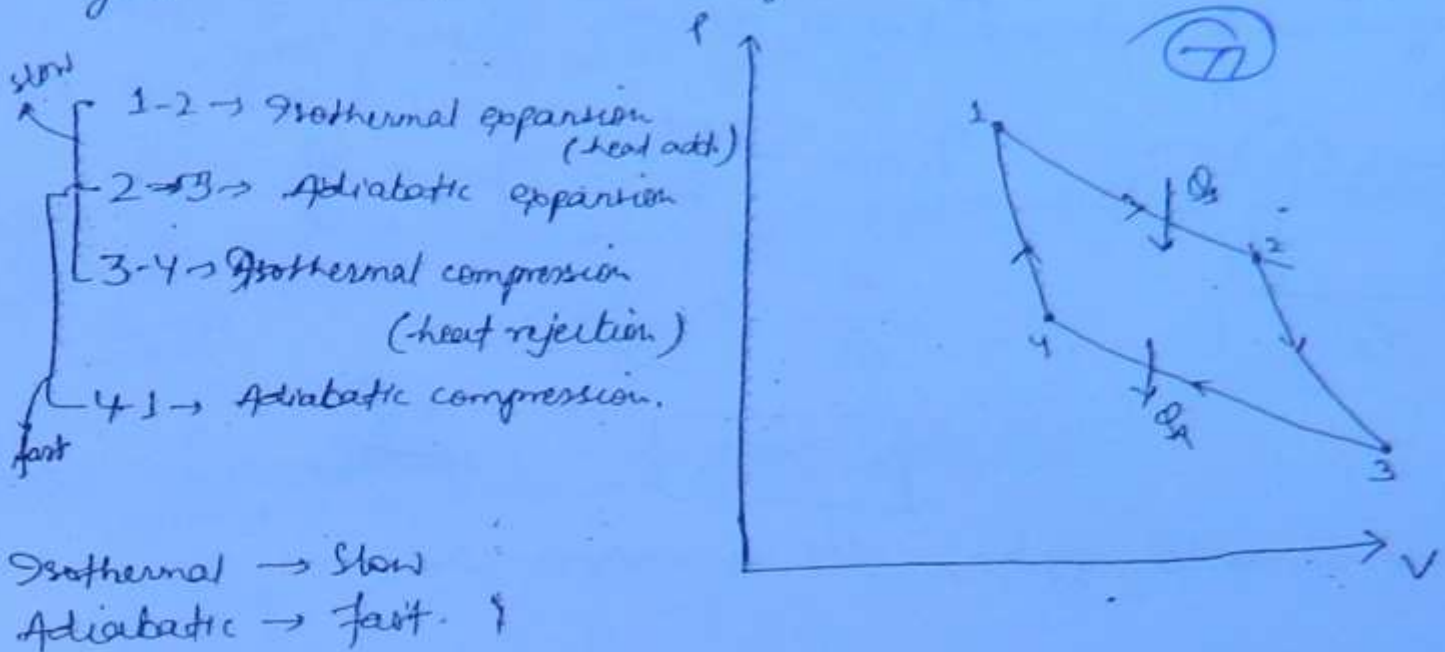
Violation of Clausius Statement



Violation of Kelvin-Planck Statement

→ * CARNOT CYCLE :- (Reversible Cycle) :-

A cycle is said to be a reversible cycle, when each process in a cycle is reversible.



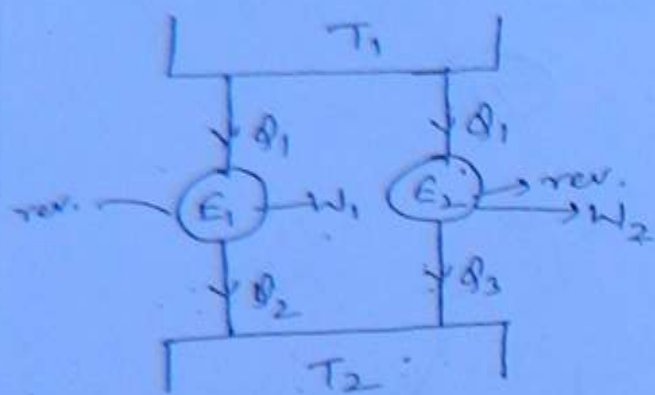
Carnot cycle consists of two isothermal processes and two adiabatic processes. Isothermal process is a slow process and adiabatic process is a fast process and hence, these two combinations in a cycle are not possible, therefore Carnot's cycle is a theoretical cycle and it is used for comparing other actual cycles.

* CARNOT'S THEOREM :-

for various cycles operating between same temperature limits, none has efficiency greater than reversible cycle efficiency

(P.T.O)

Let us consider two engines E_1 and E_2 . Let E_1 be irreversible engine and E_2 be reversible engine.



* Let us assume, $\eta_{\text{irrev}} > \eta_{\text{rev}}$.

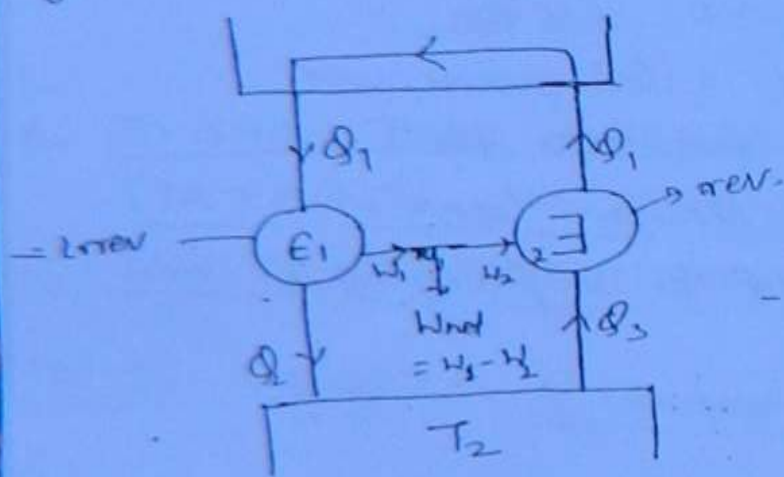
$$\eta_{\text{irrev}} = \frac{W_1}{Q_1} ; \eta_{\text{rev}} = \frac{W_2}{Q_1}$$

$$\frac{W_1}{Q_1} > \frac{W_2}{Q_1}$$

$$\therefore \boxed{W_1 > W_2}$$

(78)

As E_2 is a reversible engine, let us reverse the engine.



- Violation of K-P statement.

($\eta_{\text{irrev}} > \eta_{\text{rev}} \rightarrow \text{wrong}$)

This is the violation of Kelvin-Planck statement and hence the assumption is wrong. Similarly, if we take the efficiency of both the engines to be same, then it would lead to violation of Clausius statement. Therefore this is not possible. And hence, efficiency of a reversible engine is always greater than efficiency of irreversible engine operating between same temperature limits.

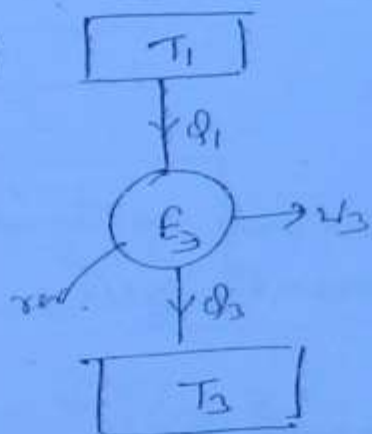
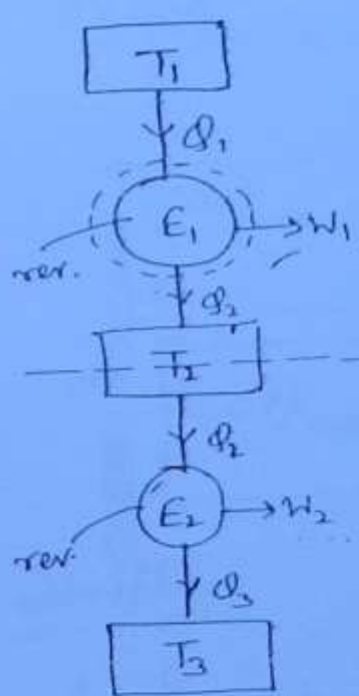
* Important Points with respect to reversible cycle.

① Efficiency of all reversible cycles is equal if they operate between same temperature limits.

② Efficiency of a reversible cycle is independent of working fluid.

③ Efficiency of a reversible cycle depends only on temperature limits.

⇒ * THERMODYNAMIC TEMPERATURE SCALE - (79)



$$\eta = 1 - \frac{Q_2}{Q_1}$$

$$\eta_1 = 1 - \frac{Q_2}{Q_1}$$

$$\eta_1 = f(T_1, T_2)$$

$$1 - \frac{Q_2}{Q_1} = f_1(T_1, T_2)$$

$$1 - f_1(T_1, T_2) = Q_2/Q_1$$

$$\frac{Q_1}{Q_2} = \frac{1}{1 - f_1(T_1, T_2)}$$

$$Q_1/Q_2 = \phi_1(T_1, T_2)$$

Similarly:-

$$\frac{Q_2}{Q_3} = \phi(T_2, T_3)$$

and $\frac{Q_1}{Q_3} = \phi(T_1, T_3)$.

$$\frac{Q_1}{Q_2} = \frac{\frac{Q_1}{Q_3}}{\frac{Q_2}{Q_3}} \quad \text{or,} \quad \frac{Q_1}{Q_2} = \frac{\phi(T_1, T_3)}{\phi(T_2, T_3)}$$

$$\frac{Q_1}{Q_2} = \frac{\psi_1(T_1)}{\psi_2(T_2)}$$

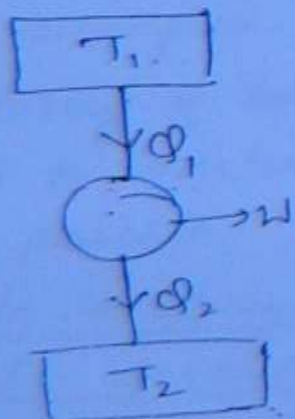
(88)

Based on kelvin's experiments.

$$\boxed{\frac{Q_1}{Q_2} = \frac{T_1}{T_2}} \rightarrow \text{This is only valid for reversible cycle.}$$

$\left(\frac{Q_1}{Q_2} = \frac{T_1}{T_2} \right)$ is valid for a reversible cycle.

* EFFICIENCY OF A REVERSIBLE ENGINE :-



$$\eta = 1 - \frac{Q_2}{Q_1}$$

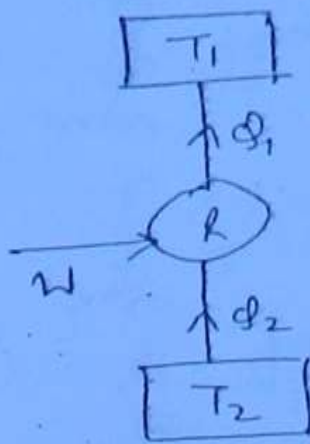
If the cycle is reversible,

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

$$\boxed{\eta_{rev} = 1 - \frac{T_2}{T_1}}$$

$$\boxed{\eta_{rev} = \eta_{max} = 1 - \frac{T_L}{T_H}}$$

⇒ * COP OF A REVERSIBLE REFRIGERATOR :-



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

$$COP_R = \frac{Q_2}{Q_2 \left[\frac{Q_1}{Q_2} - 1 \right]}$$

$$(COP)_R = \frac{1}{\frac{Q_1}{Q_2} - 1}$$

(8)

for reversible refrigerator,

$$(COP)_{rev, R} = \frac{1}{\frac{T_1}{T_2} - 1}$$

$$(COP)_{rev, R} = \frac{T_2}{T_1 - T_2}$$

$$\Rightarrow (COP)_{max, R} = (COP)_{rev, R} = \frac{T_L}{T_H - T_L}$$

Similarly,

for reversible heat pump :-

$$(COP)_{rev, HP} = \frac{T_H}{T_H - T_L}$$

CLAUJUS INEQUALITY:-

The cyclic integral of $\frac{dQ}{T}$ is less than or equal to zero.

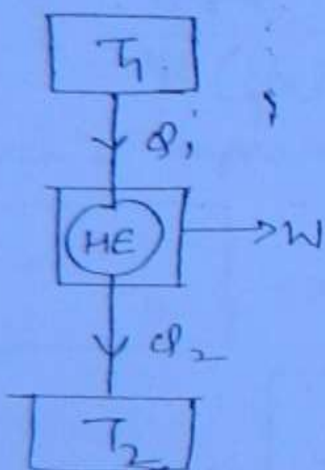
$$\oint \frac{dQ}{T} \leq 0$$

$$\oint \frac{dQ}{T} = 0 \Rightarrow \text{Cycle is reversible}$$

$$\oint \frac{dQ}{T} < 0 \Rightarrow \text{cycle is irreversible.}$$

(82)

ex 1:- Reversible Cycle:-



$$\oint_{rev} \frac{dQ}{T} = \frac{Q_1}{T_1} + \left(\frac{-Q_2}{T_2} \right) \quad \text{--- (1)}$$

we know that for a reversible process,

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

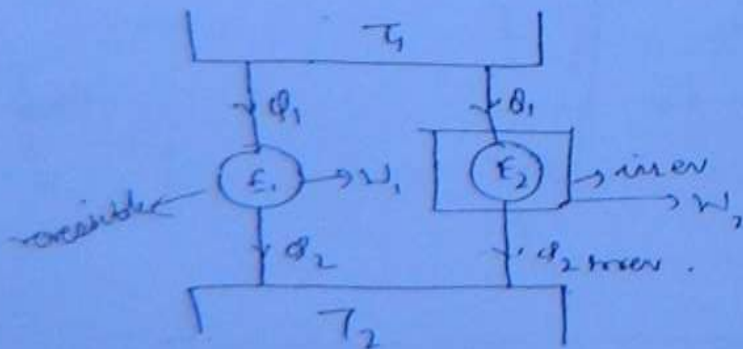
$$\text{or } \frac{Q_1}{T_1} = \frac{Q_2}{T_2} \quad \text{--- (2)}$$

substituting in eq (1), we have

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

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

- II: Irreversible Cycle:-



$$\eta_1 = \frac{W_1}{Q_1} ; \eta_2 = \frac{W_2}{Q_1}$$

$$\eta_1 > \eta_2$$

$$\frac{W_1}{Q_1} > \frac{W_2}{Q_1}$$

$$\Rightarrow W_1 > W_2$$

for reversible process

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

$$\oint_{\text{irrev.}} \frac{dQ}{T} = \int_{\text{rev.}} \frac{Q_1}{T_1} + \left(-\frac{Q_2 \text{ irrev.}}{T_2} \right)$$

$$\oint_{\text{irrev.}} \frac{dQ}{T} = \frac{Q_1}{T_1} - \frac{Q_2 \text{ irrev.}}{T_2}$$

$$\oint_{\text{irrev.}} \frac{dQ}{T} = \frac{Q_2}{T_2} - \frac{Q_2 \text{ irrev.}}{T_2}$$

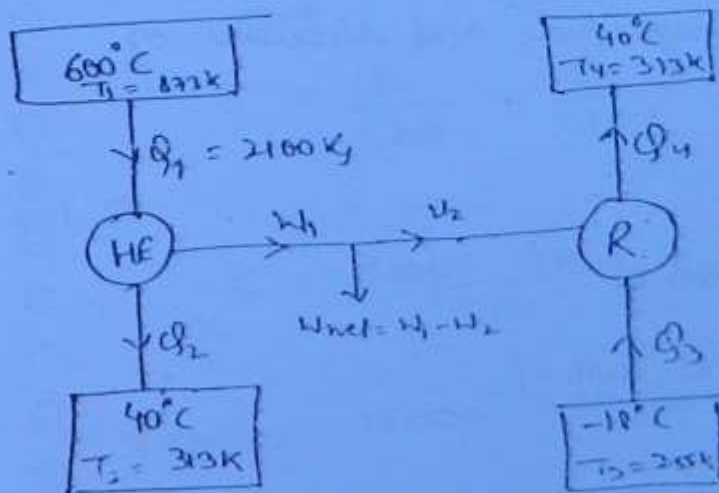
$$\oint_{\text{irrev.}} \frac{dQ}{T} = \frac{Q_2 - Q_2 \text{ irrev.}}{T_2}$$

(83)

$$\boxed{\oint \frac{dQ}{T} < 0 \text{ if } (Q_2 < Q_2 \text{ irrev.})}$$

PROBLEM

Q:- A reversible heat engine operates between 600°C and 40°C . This engine drives a reversible refrigerator operating between 40°C and -18°C . Still there is a net work output of 270kJ where the heat received by the engine is 2100kJ . Determine the cooling effect.



$$(\text{COP})_R = \frac{T_L}{T_H - T_L}$$

$$\frac{Q_3}{W_2}$$

$$(\text{COP})_R = \frac{Q_3}{W_2} = \frac{255}{313 - 255}$$

$$\therefore \frac{Q_3}{W_2} = 4.396$$

$$W_1 = Q_1 - Q_2$$

Also \therefore it is reversible cycle,

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

$$\Rightarrow Q_2 = \frac{Q_1 \times T_2}{T_1} = \frac{2100 \times 313}{823}$$

$$\therefore Q_2 = 752.9 \text{ kJ}$$

$$\therefore W_1 = (2100 - 752.9) = 1347.1 \text{ kJ}$$

(84)

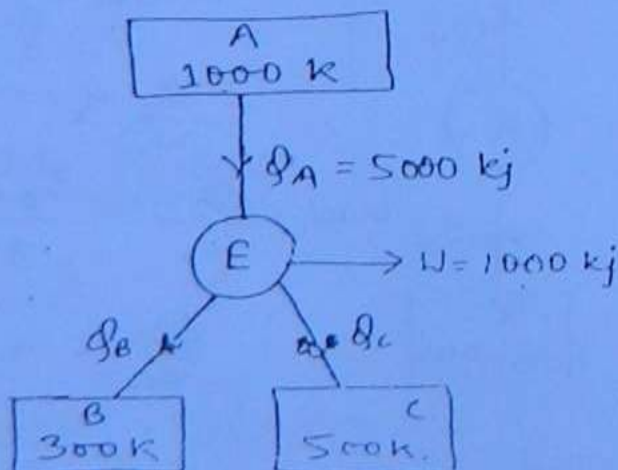
$$W_{net} = W_1 - W_2 = 370$$

$$\therefore W_2 = 977.1 \text{ kJ}$$

$$\frac{Q_3}{977.1} = 4.396$$

$$\therefore Q_3 \text{ (Cooling Effect)} = 4295.2 \text{ kJ} \quad \text{(Ans)}$$

Figure shows a reversible cycle during which, it exchanges heat with three thermal reservoirs and develops 1000 kJ of work. find the magnitude and direction of Q_B and Q_C .



Let Q_B and Q_C are the heat rejected by the system

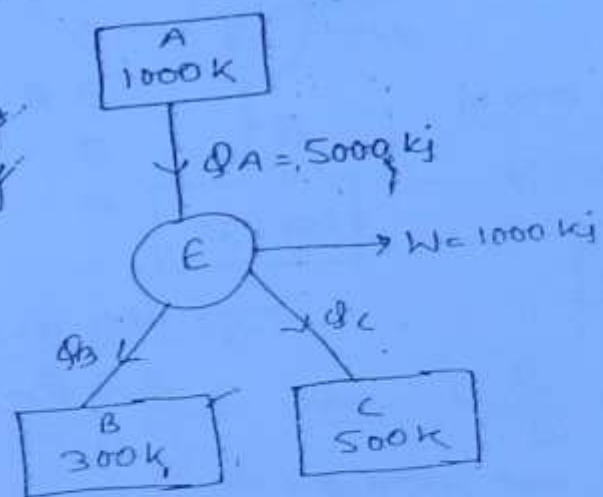
$$W = Q_A - (Q_B + Q_C) \quad \text{--- (1)}$$

$$\frac{Q_A}{T_A} = \frac{Q_B}{T_B}$$

$$\Rightarrow \frac{5000}{1000} = \frac{Q_B}{300} \Rightarrow Q_B = 1500 \text{ kJ}$$

$$\frac{Q_A}{T_A} = \frac{Q_C}{T_C} \Rightarrow Q_C = \frac{5000}{1000} \times 500 = 2500 \text{ kJ}$$

Let the direction of Q_B and Q_C are downwards.



Using energy conservation:

$$Q_A = W + Q_B + Q_C$$

$$\Rightarrow 5000 = 1000 + Q_B + Q_C$$

$$\therefore Q_B + Q_C = 4000 \quad \text{--- (1)}$$

Again, using Clausius inequality:

$$\oint_{rev} \frac{dQ}{T} = 0$$

$$\frac{5000}{1000} + \left(\frac{-Q_C}{500} \right) + \left(\frac{-Q_B}{300} \right) = 0$$

$$5 = \frac{Q_C}{500} + \frac{Q_B}{300} \quad \text{--- (2)}$$

from eq (1),

$$5 = \frac{4000 - Q_B}{500} + \frac{Q_B}{300}$$

$$7500 = 12000 - 300 Q_B + 500 Q_B$$

$$\therefore 200 Q_B = -4500$$

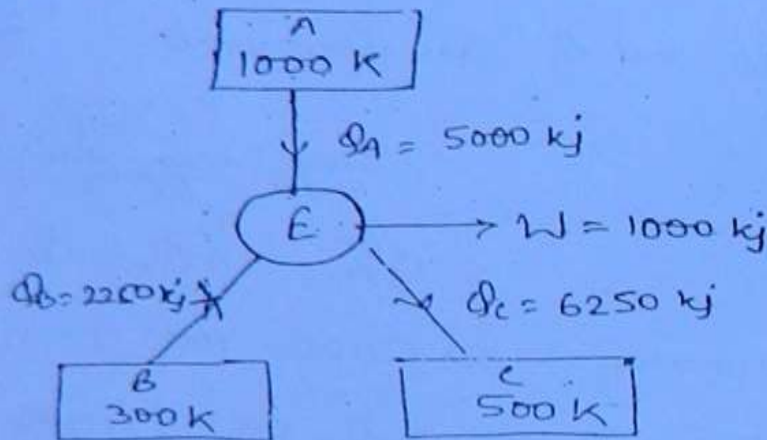
$$\therefore Q_B = -2250 \text{ kJ}$$

$$Q_B + Q_C = 4000$$

$$\Rightarrow -2250 + Q_C = 4000$$

$$\therefore Q_C = \underline{6250 \text{ kJ}}$$

\therefore The value of Q_B is negative, it means that the direction assumed by us is wrong, hence the direction of Q_B is upward.



Two reversible heat engines 'A' and 'B' are arranged in series. Heat engine 'A' rejects heat directly to 'B'. Engine 'A' receives 300 kJ of heat at a temperature of 427°C from a high temperature source while engine 'B' rejects heat to a sink at 7°C . If the work output of 'A' is 2 times that of 'B', find:-

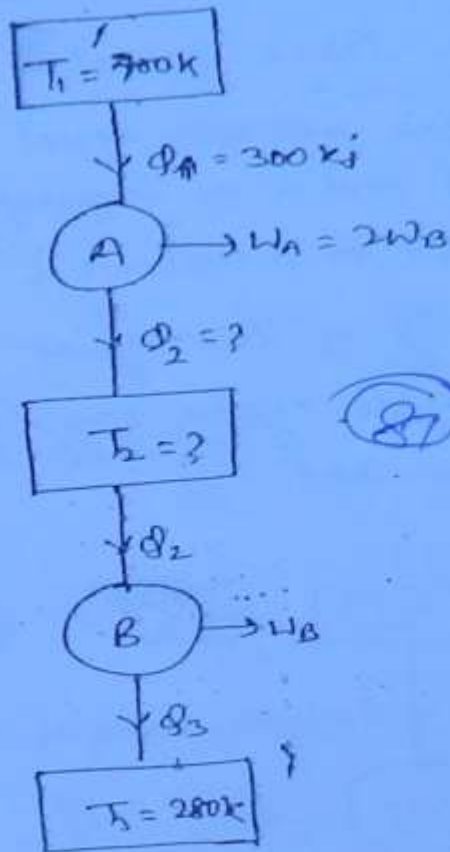
1) Intermediate temperature of 'A' and 'B'.

Efficiencies of each engine

Heat rejected by Engine 'A' i.e. heat received by Engine 'B'.

Heat rejected to sink.

Solⁿ:



(87)

$$\begin{aligned}
 W_B &= Q_2 - Q_3 \\
 2W_B &= Q_1 - Q_2 \\
 \frac{Q_1}{T_1} &= \frac{Q_2}{T_2} \\
 W_A &= 2Q_2 - 2Q_3 \\
 2Q_2 - 2Q_3 &= Q_1 - Q_2 \\
 \Rightarrow 3Q_2 &= 300 + 2Q_3 \\
 Q_2 &= 100 + \frac{2Q_3}{3} \\
 \frac{Q_2}{T_2} &= \frac{Q_3}{T_3} \\
 &= 100 + \frac{2Q_3}{3} = \frac{Q_3}{T_3} \\
 &= 300 + 2Q_3 = \frac{3Q_3}{T_3} \\
 &= 300 \times 280 + \dots
 \end{aligned}$$

for a reversible engine,

$$\frac{Q_1}{T_1} = \frac{Q_2}{T_2} \quad \text{--- (1)}$$

Also,

$$\frac{Q_2}{T_2} = \frac{Q_3}{T_3} \quad \text{--- (2)}$$

from (1) & (2)

$$\frac{Q_1}{T_1} = \frac{Q_3}{T_3} \Rightarrow Q_2 = \frac{300 \times 280}{700} = 120\text{ kJ}$$

$$W_A = 2W_B$$

$$Q_1 - Q_2 = 2Q_2 - 2Q_3$$

$$\Rightarrow 3Q_2 = Q_1 + 2Q_3$$

$$\Rightarrow Q_2 = \frac{300 + 240}{3} = 180\text{ kJ}$$

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

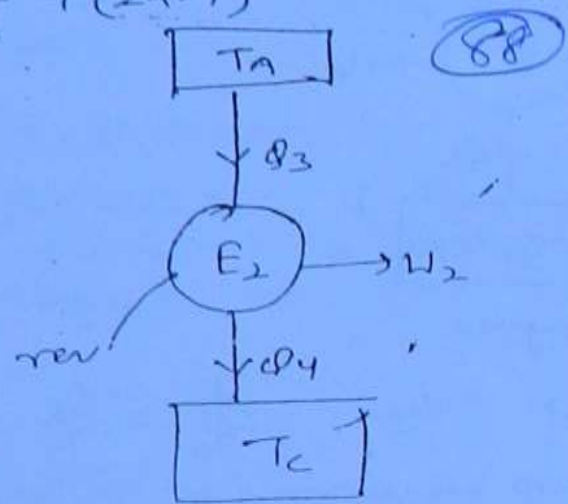
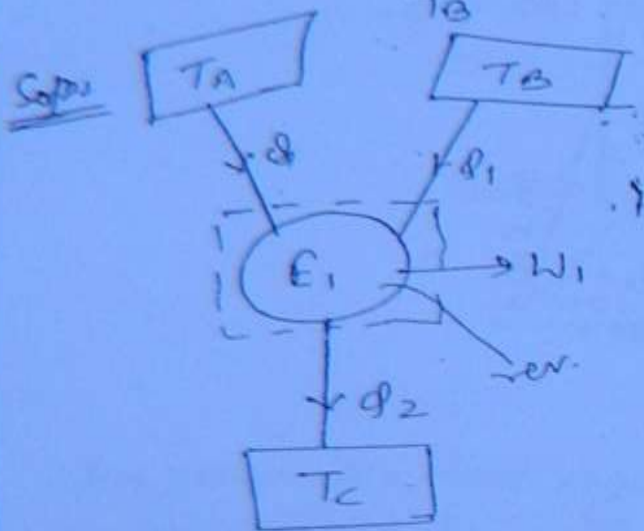
$$\Rightarrow T_2 = \frac{Q_2 \times T_1}{Q_1} = \frac{180 \times 700}{300} = 420\text{ K}$$

$$\eta_A = 1 - \frac{T_2}{T_1} = 0.4 = 40\%$$

$$\eta_B = 1 - \frac{T_3}{T_2} = 0.33 = 33.3\%$$

A reversible engine works between three thermal reservoirs 'A', 'B' and 'C'. The engine receives equal amount of heat from reservoirs 'A' and 'B' at temperatures T_A and T_B respectively, and rejects heat to a reservoir 'C' at a temperature T_C . If the efficiency of this engine is α times the efficiency of a reversible engine operating between two reservoirs 'A' and 'C', show that

$$\frac{T_A}{T_B} = 2(1-\alpha) \frac{T_A}{T_C} + (2\alpha-1)$$



$$\eta_1 = 1 - \frac{Q_3}{2Q_1} \quad \text{--- (1)}$$

$$\oint \frac{dQ}{T} = 0 \quad (\text{for rev. cycle})$$

$$\therefore \frac{Q_1}{T_A} + \frac{Q_2}{T_B} - \frac{Q_3}{T_C} = 0$$

$$Q_1 \left[\frac{1}{T_A} + \frac{1}{T_B} \right] = \frac{Q_3}{T_C}$$

$$\frac{Q_3}{Q_1} = \frac{T_C}{T_A} + \frac{T_C}{T_B}$$

$$\eta_1 = 1 - \frac{1}{2} \left(\frac{T_C}{T_A} + \frac{T_C}{T_B} \right) \quad \text{--- (2)}$$

Now

$$\eta_2 = 1 - \frac{Q_4}{Q_3} \quad \text{--- (3)}$$

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

$$\frac{Q_3}{T_A} - \frac{Q_4}{T_C} = 0 \Rightarrow \frac{Q_3}{T_A} = \frac{Q_4}{T_C}$$

$$\text{or } \frac{Q_4}{Q_3} = \frac{T_C}{T_A}$$

$$\therefore \eta_2 = 1 - \frac{T_C}{T_A} \quad \text{--- (4)}$$

(89)

But it is given that,

$$\eta_1 = \alpha \eta_2$$

$$\therefore 1 - \frac{1}{2} \left(\frac{T_C}{T_A} + \frac{T_C}{T_B} \right) = \alpha \left(1 - \frac{T_C}{T_A} \right) \quad \text{--- (5)}$$

• Multiplying both sides with T_A .

Eq: (5) becomes;

$$T_A - \frac{T_A}{2} \left(\frac{T_C}{T_A} + \frac{T_C}{T_B} \right) = \alpha T_A \left(1 - \frac{T_C}{T_A} \right)$$

$$\Rightarrow T_A - \frac{T_C}{2} - \frac{T_C}{2} \cdot \frac{T_A}{T_B} = \alpha T_A - \alpha T_C$$

$$\Rightarrow T_A - \frac{T_C}{2} - \alpha T_A + \alpha T_C = \frac{T_C}{2} \cdot \frac{T_A}{T_B}$$

$$\Rightarrow \frac{2}{T_C} \left[T_A - \frac{T_C}{2} - \alpha T_A + \alpha T_C \right] = \frac{T_A}{T_B}$$

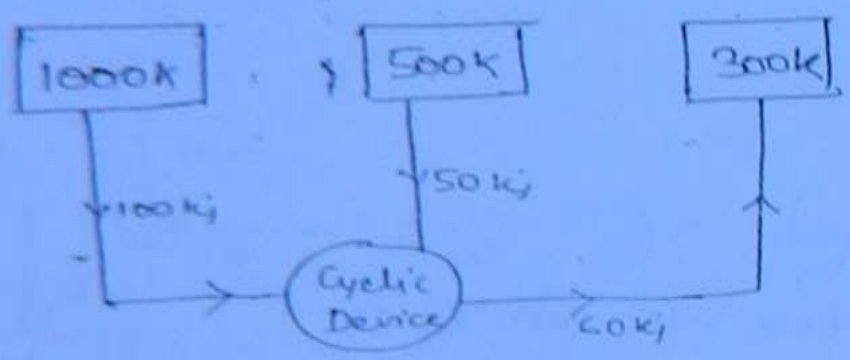
$$\Rightarrow \frac{2T_A}{T_C} - 1 - 2\alpha \frac{T_A}{T_C} + 2\alpha = \frac{T_A}{T_B}$$

$$\text{or, } \boxed{\frac{T_A}{T_B} = \frac{2T_A}{T_C} (1-\alpha) + 2\alpha - 1}$$

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14
- 15

- 16
- 17
- 18
- 19

96

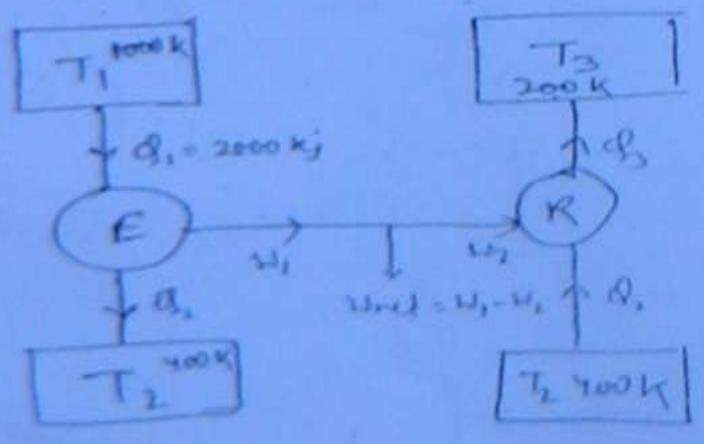


∴ Heat supplied > Heat Rejected.

∴ There will work output, & of these is work output, it is an engine.

Also, $\oint \frac{dQ}{T} = 0$.

∴ It is reversible.



Ans

$$\frac{\phi_1}{T_1} = \frac{\phi_2}{T_2}$$

$$\Rightarrow \phi_2 = \frac{\phi_1 \times T_2}{T_1} = \frac{2000 \times 400}{1000}$$

$$= 800 \text{ kJ}$$

$$W_1 = \phi_1 - \phi_2 = (2000 - 800) = 1200 \text{ kJ}$$

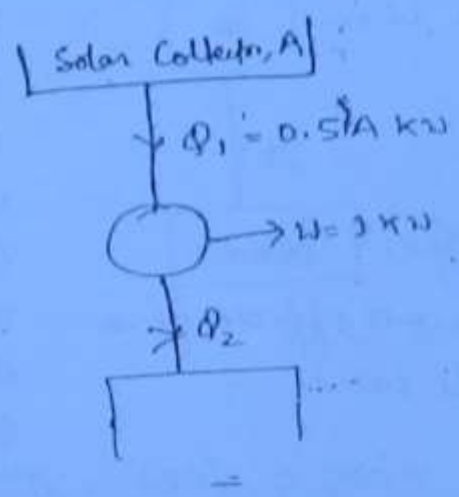
$$W_2 = \text{Heat } W_1 - W_{\text{net}} = (1200 - 300) = 900 \text{ kJ}$$

$$W_2 = \phi_2 - \phi_3$$

$$\Rightarrow \phi_3 = \phi_2 - W_2 = 80$$

(9)

(2)



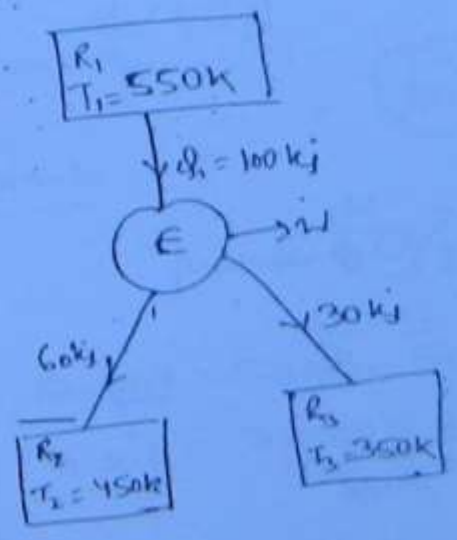
$$0.5 \text{ kW/m}^2 \times A \text{ m}^2$$

$$\eta = W / \phi_1$$

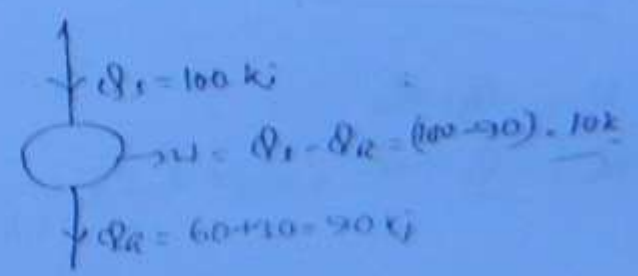
$$\Rightarrow 0.2 = \frac{1}{0.5A}$$

$$\Rightarrow A = 10$$

(4)

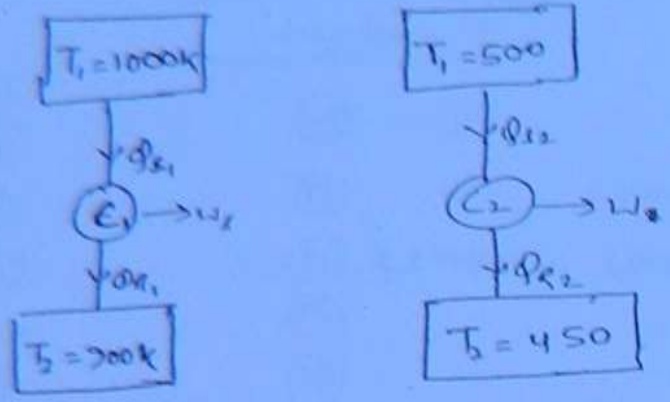


$$\eta = \frac{\text{Output}}{\text{Input}}$$



$$\eta = \frac{10}{100} = 10\%$$

6



$W_1 = W_2 = W$

$\eta_1 = 1 - \frac{T_2}{T_1} = 1 - \frac{200}{1000} = 0.8$

$\eta_1 = \frac{W}{Q_{s1}}$

$\eta_2 = 1 - \frac{450}{500} = 0.1$

$\eta_2 = \frac{W}{Q_{s2}}$

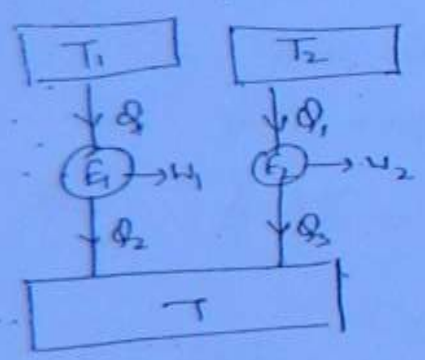
But $\eta_1 = \eta_2 \Rightarrow \frac{W}{Q_{s1}} = \frac{W}{Q_{s2}}$

$\therefore Q_{s1} = Q_{s2} \quad \therefore Q_{r1} = Q_{r2}$

\therefore Supply is same, work is same and efficiency is same, therefore rejection will also be same.

92

Q. 10



$\left(\frac{T_2}{T_1 - T_2}\right)$
 $\left(\frac{T}{2 - 1}\right) = 1$

$\eta_1 = \frac{1 - \frac{T}{T_1}}{1 - \frac{T}{T_1}}$ $\eta_2 = \frac{1 - \frac{T}{T_2}}{1 - \frac{T}{T_2}}$

$\eta_1 = 1 - \frac{T}{T_1} = \frac{W_1}{Q}$

$\eta_2 = 1 - \frac{T}{T_2} = \frac{W_2}{Q}$

$W_1 = Q_1 - Q_2$
 $W_2 = Q_2 - Q_3$

$W_1 = Q \left(1 - \frac{T}{T_1}\right)$

$W_2 = Q \left(1 - \frac{T}{T_2}\right)$

$\therefore T_2$ is less $\therefore W_2$ will be less.

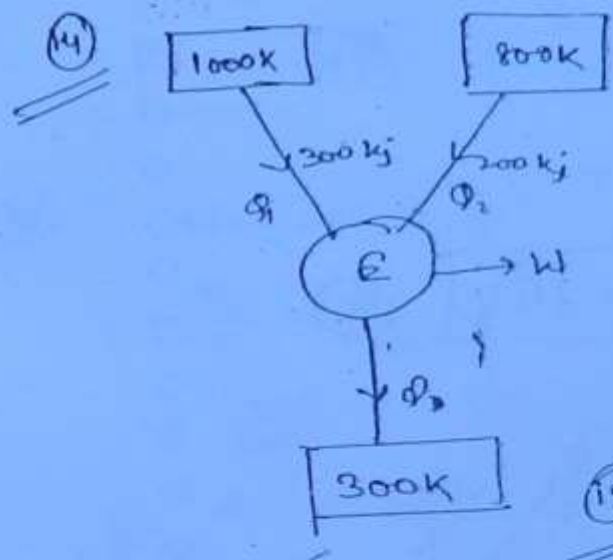
or, $W_1 > W_2$

$$(12) (\eta_{max})_E = \left(1 - \frac{T_2}{T_1}\right) \cdot \left(\frac{T_1 - T_2}{T_1}\right) = \frac{T_1}{T_1 - T_2} - 1$$

$$(\eta_{max})_R = \left(\frac{T_2}{T_1 - T_2}\right) = \frac{T_1/T_1 + T_2}{T_1 - T_2} = \left(\frac{T_2}{T_1 - T_2}\right)$$

$$(\eta_{max})_R = \frac{1}{(\eta_{max})_E} - 1$$

(93)



$$\frac{300}{1000} + \frac{200}{800} = \frac{Q}{300}$$

$$\Rightarrow 0.3 + 0.25 = \frac{Q}{300}$$

$$\therefore Q = 165 \text{ kJ} \quad (13)$$

(15) $Q_1 + Q_2 = W + Q$

$$\Rightarrow W = Q_1 + Q_2 - Q$$

$$= 500 - 165 = 335 \text{ kJ} \quad (14)$$

(13) $T_H = 629^\circ\text{C} = 900 \text{ K}$

$T_L = 27^\circ\text{C} + 273 = 300 \text{ K}$

$\eta_{max} = \eta_{rev} = 1 - \frac{300}{900} = 0.6667 = 66.67\%$

$\eta_{inverter} = ?$

$\eta_{inverter} = O/I$

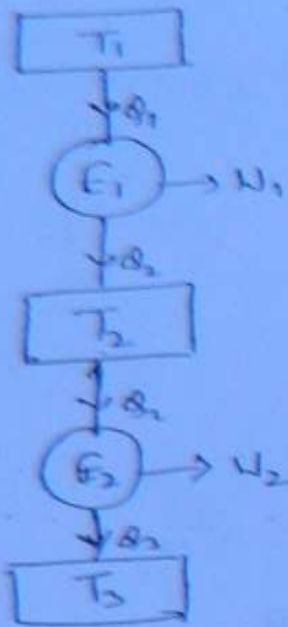
Output = 50 kW = 50 kJ/sec

Input = $\frac{75000 \times 3}{3600}$ kJ/sec = 62.5 kJ/sec

$\eta_{inverter} = \frac{50}{62.5} = 0.8 = 80\%$

\therefore reversible efficiency is max^m efficiency and $\eta_{inverter}$ is exceeding that, hence it is not possible.

16



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

$$\eta_{E1} = 1 - \frac{T_2}{T_1}$$

$$\eta_{E2} = 1 - \frac{T_3}{T_2}$$

$$\frac{T_1 - T_2}{T_1} = \frac{T_2 - T_3}{T_2}$$

(94)

$$\Rightarrow \frac{T_1 - T_2}{T_1} = \frac{T_2 - T_3}{T_2}$$

$$\Rightarrow T_1 T_3 = T_2^2 \quad \boxed{T_2 = \sqrt{T_1 T_3}} \quad (9)$$

$$W_1 = Q_1 - Q_2$$

$$W_2 = Q_2 - Q_3$$

$$W_1 = W_2 \Rightarrow Q_1 - Q_2 = Q_2 - Q_3$$

$$\Rightarrow Q_1 = 2Q_2 - Q_3$$

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

$$\frac{Q_2}{T_2} = \frac{Q_3}{T_3}$$

$$\frac{Q_1}{T_1} = \frac{Q_3}{T_3}$$

$$\eta_1 = \frac{W_1}{Q_1} \Rightarrow 1 - \frac{T_2}{T_1} = \frac{W_1}{Q_1}$$

$$\eta_2 = \frac{W_2}{Q_2} \Rightarrow 1 - \frac{T_3}{T_2} = \frac{W_2}{Q_2}$$

$$Q_1 \left(1 - \frac{T_2}{T_1}\right) = Q_2 \left(1 - \frac{T_3}{T_2}\right)$$

(17) $W_1 = W_2$ (given)

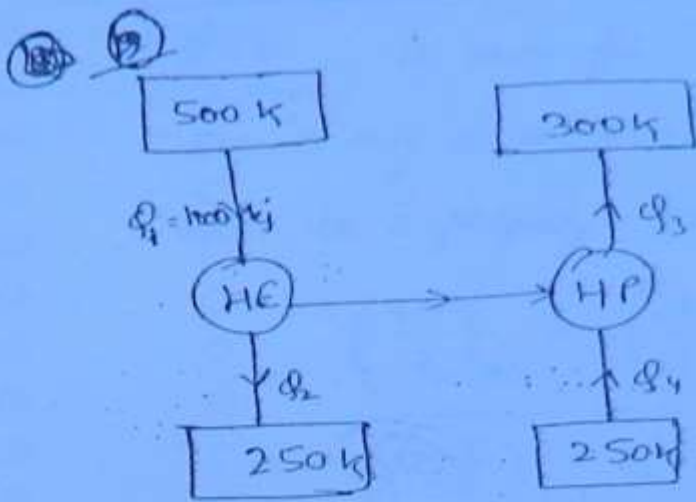
$$\Rightarrow Q_1 - Q_2 = Q_2 - Q_3 \Rightarrow Q_1 + Q_3 = 2Q_2 \quad (1)$$

$$\frac{Q_1}{T_1} = \frac{Q_2}{T_2} = \frac{Q_3}{T_3} = k \Rightarrow Q_1 = kT_1, \quad Q_2 = kT_2, \quad Q_3 = kT_3$$

$$kT_1 + kT_3 = 2kT_2$$

$$\Rightarrow T_2 = \frac{T_1 + T_3}{2}$$

(18)



$$\begin{aligned}
 (COP)_{HP} &= \frac{Q_3}{W} = \frac{T_h}{T_h - T_c} \\
 &= \frac{300}{300 - 250} = 6.
 \end{aligned}$$

(95)

(78) $W = (1000 - Q_2)$

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

$$\Rightarrow \frac{1000}{500} = \frac{Q_2}{250}$$

$$\therefore Q_2 = 500 \text{ kJ}$$

$$W = (1000 - 500) = 500 \text{ kJ}$$

$$Q_3 = W \times 6 = 500 \times 6 = 3000 \text{ kJ}$$

← : ENTROPY : →

REVERSIBLE CYCLE :-



(96)

1-a-2-b-1 → reversible cycle

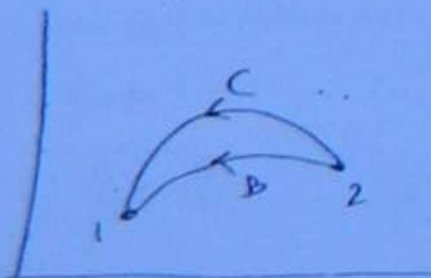
1-b-2-a-1 → reversible cycle

$$\oint_{\text{rev}} \frac{dQ}{T} = 0 \Rightarrow \left(\frac{dQ}{T} \right)_{1a2} + \left(\frac{dQ}{T} \right)_{2b1} = 0$$

$$\left(\frac{dQ}{T} \right)_{1a2} + \left(\frac{dQ}{T} \right)_{2c1} = 0$$

$$\left(\frac{dQ}{T} \right)_{2b1} - \left(\frac{dQ}{T} \right)_{2c1} = 0$$

$$\text{or, } \left(\frac{dQ}{T} \right)_{2b1} = \left(\frac{dQ}{T} \right)_{2c1} \text{ (rev.)}$$



$\left(\frac{dQ}{T}\right)_{\text{rev}}$ is same for both paths 'b' and 'c' and it depends only on end points (2 and 1), therefore $\left(\frac{dQ}{T}\right)_{\text{rev}}$ must be a property and this property is known as entropy.

$$\left(\frac{dQ}{T}\right)_{2b1} = \left(\frac{dQ}{T}\right)_{2c1} = ds.$$

$$\boxed{\left(\frac{dQ}{T}\right)_{2b1} = ds}$$

\downarrow
 rev: ***

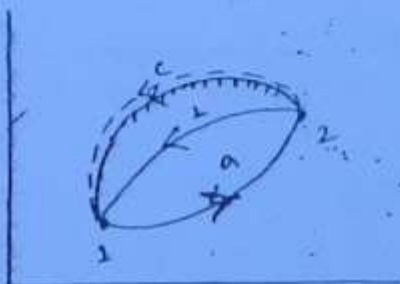
This is the second law of thermodynamics for equation for a process.

(97)

$$\boxed{ds \neq \left(\frac{dQ}{T}\right)_{\text{REV.}}}$$

CASE-II:

IRREVERSIBLE CYCLE:-



1-a-2-b-1 (reversible cycle)

1-a-2-c-1 (irreversible)

$$\oint_{\text{rev.}} \frac{dQ}{T} = 0$$

$$\left(\frac{dQ}{T}\right)_{1a2} + \left(\frac{dQ}{T}\right)_{2b1} = 0$$

$$\left(\frac{dQ}{T}\right)_{1a2} = - \left(\frac{dQ}{T}\right)_{2b1} \quad \text{--- (1)}$$

$$\oint_{\text{irrev.}} \frac{dq}{T} < 0 \quad = \left(\frac{dq}{T} \right)_{1 \rightarrow 2} + \left(\frac{dq}{T} \right)_{2 \rightarrow 1} < 0 \quad \text{--- (2)}$$

Substituting the value from eqⁿ (1) to eqⁿ (2).

$$-\left(\frac{dq}{T} \right)_{2 \rightarrow 1} + \left(\frac{dq}{T} \right)_{2 \rightarrow 1} < 0$$

$$\underbrace{\left(\frac{dq}{T} \right)_{2 \rightarrow 1}}_{\text{irrev.}} < \underbrace{\left(\frac{dq}{T} \right)_{2 \rightarrow 1}}_{\text{rev.}}$$

(98)

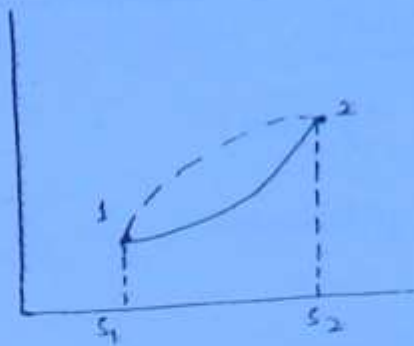
$$\left(\frac{dq}{T} \right)_{\text{irrev.}} < ds$$

$$\therefore ds > \left(\frac{dq}{T} \right)_{\text{irrev.}}$$

$$ds = \left(\frac{dq}{T} \right)_{\text{rev.}}$$

$$ds > \left(\frac{dq}{T} \right)_{\text{irrev.}}$$

$$\therefore ds \geq \left(\frac{dq}{T} \right)$$



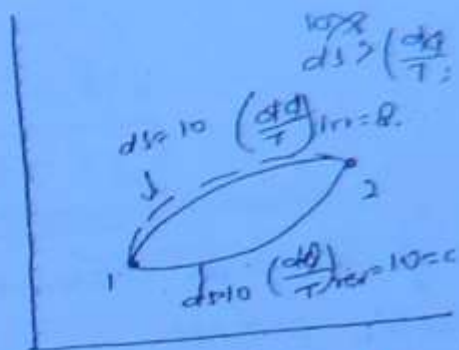
$$(dS)_{\text{irrev}} = S_2 - S_1$$

$$(dS)_{\text{rev}} = (dS)_{\text{irrev}}$$

(99)

$$(dS)_{\text{rev}} = S_2 - S_1$$

As entropy is a property, it depends only on end points and hence as long as the end points are same, the entropy change remains same for reversible as well as irreversible process.



In order to find the entropy change for irreversible process, it must be replaced by a reversible process between same end points.

-1 ENTROPY CHANGE OF SYSTEM FOR REVERSIBLE PROCESS:-

Case-1:

~~When heat is app~~
When heat is supplied to the system:-

$$dS = \left(\frac{dq}{T} \right)_{\text{rev}}$$

$$dS = +ve$$

$$dS > 0$$

The entropy of system increases when heat is supplied in a reversible process.

Case-II:

When heat is rejected from the system:-

$$ds = \frac{d\phi}{T} \quad \begin{matrix} \text{---ve} \\ \rightarrow \text{+ve} \end{matrix}$$

$$ds = -ve.$$

$$\boxed{ds < 0}$$

(100)

Entropy of a system decreases when heat is rejected in a reversible process.

Case-III:

Reversible Adiabatic Process:-

$$ds = \frac{d\phi}{T}$$

1) reversible

2) Adiabatic $\rightarrow d\phi = 0$

$$ds = \frac{0}{T}$$

$$ds = 0$$

$$S_2 - S_1 = 0$$

$$S_2 = S_1 = \text{constant}$$

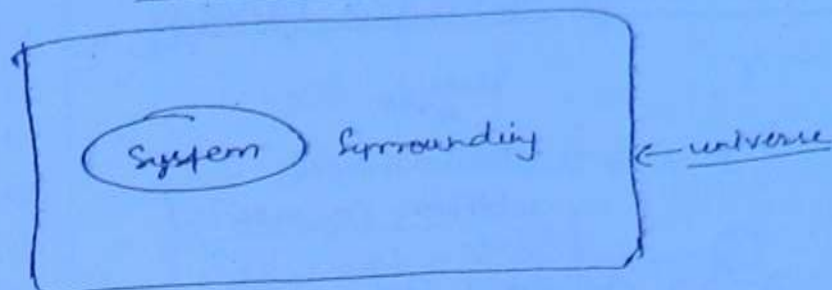
\rightarrow Iso + Entropy

Isentropic

A reversible adiabatic process is always isentropic process.

System entropy can increase, ~~decrease~~ system entropy can decrease or it can remain constant in a reversible process depending upon heat transfer.

∴ ENTROPY CHANGE OF UNIVERSE :-



(101)

$$ds \geq \frac{dq}{T}$$

$$ds_{\text{(universe)}} \geq 0$$

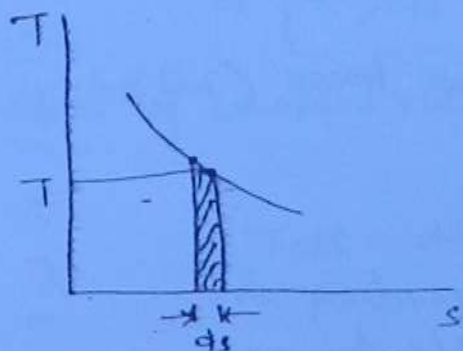
(∵ universe is isolated system ∴ $dQ=0$)

$$(ds)_{\text{system}} + (ds)_{\text{surrounding}} \geq 0.$$

Note

Entropy of system can increase, can decrease or it can remain constant. Similarly, entropy of surroundings can increase, can decrease or can remain constant but the overall change in entropy of universe can never decrease. and this is known as the principle of increase of entropy.

← T-S DIAGRAM →



$$\frac{dq}{T} = ds$$

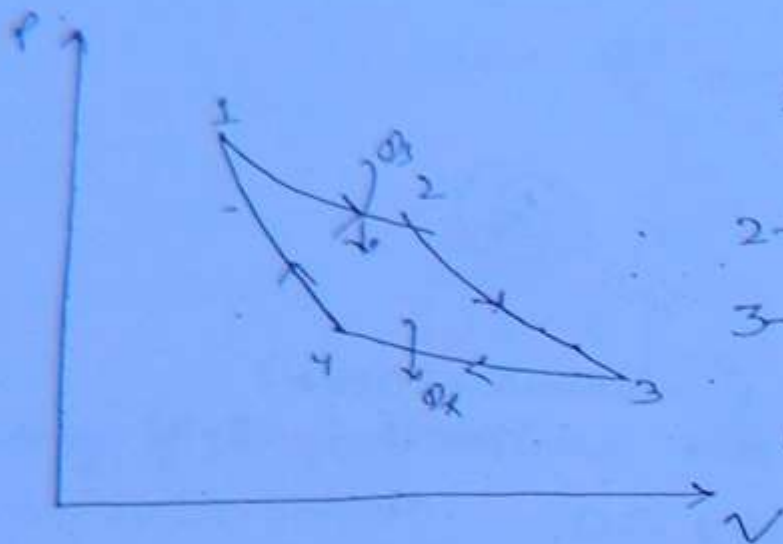
$$dq = T ds \quad \text{--- (2)}$$

$$dq = \text{Area}$$

$$\text{Area} = T ds \quad \text{--- (1)}$$

Area under the curve when projected on entropy axis gives reversible heat transfer.

REPRESENTATION OF CARNOT CYCLE ON T-S DIAGRAM.



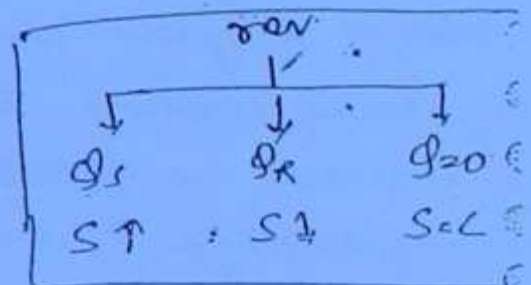
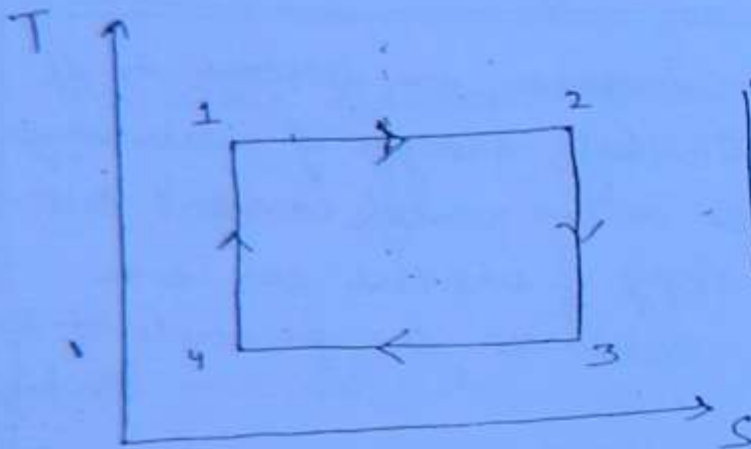
1-2 \rightarrow Isothermal heat addition (expansion)

2-3 \rightarrow Adiabatic Expansion (rev)

3-4 \rightarrow Isothermal heat rejection (rev) (compression)

4-1 \rightarrow Adiabatic comp. (rev)

(102)



COMBINED FIRST AND SECOND LAW OF THERMODYNAMICS

$$dQ = dU + PdV \rightarrow \text{rev. process (1st law)}$$

$$\frac{dQ}{T} = dS \Rightarrow dQ = TdS \rightarrow \text{rev. process (2nd law)}$$

Combining both, we have.

$$\boxed{TdS = dU + PdV}$$

\rightarrow This equation is applicable for any

process (reversible or irreversible) because it connects various properties.

$$h = u + Pv$$

$$dh = du + Pdv + vdp$$

$$dh = d\phi + vdp$$

$$dh = Tds + vdp$$

$$(\because d\phi = du + Pdv)$$

$$(\because d\phi = Tds)$$

(103)

$$\therefore \boxed{Tds = dh - vdp} \quad \text{--- (2)}$$

This equation is applicable for reversible as well as irreversible process, because it connects various properties

Equation (1) and Eq: (2) are combined first and second law equations.

⇒ * REPRESENTATION OF CONSTANT-VOLUME AND CONSTANT PRESSURE LINES ON T-S DIAGRAM! - (for ideal gas):-

$$Tds = du + Pdv$$

$$v = c \Rightarrow dv = 0$$

$$du = cvdT$$

$$Tds = cvdT + P(0)$$

$$\Rightarrow Tds = cvdT$$

$$\Rightarrow \boxed{dT/ds = T/cv}$$

Slope of constant volume lines of T-S diagram = $\underline{\underline{T/cv}}$

$$Tds = dh - vdp$$

$$P = c$$

$$dP = 0$$

$$dh = Cp dT$$

$$Tds = Cp dT - v(0)$$

$$\Rightarrow Tds = Cp dT$$

$$\Rightarrow \boxed{dT/ds = T/Cp}$$

Hence,

Slope of constant pressure lines on T-S

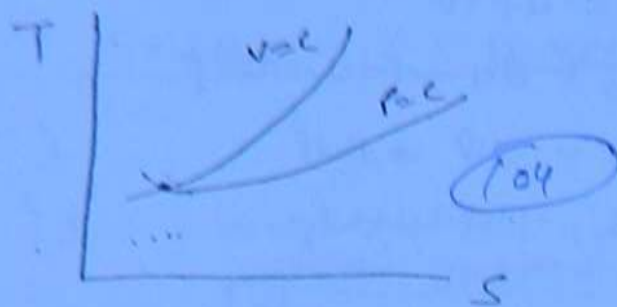
diagram = $\underline{\underline{T/Cp}}$

(P. 70)

$$P = c \rightarrow T/c_p$$

$$P = c \rightarrow T/c_v$$

$$\therefore c_p > c_v$$



As c_p is greater than c_v ($c_p > c_v$), the slope of constant volume line is greater than the slope of constant pressure lines on T-S diagram. ~~Entropy change~~

→ ENTROPY CHANGE FOR IDEAL GAS ←

$$Tds = du + PdV$$

$$ds = \frac{du}{T} + \frac{P}{T} dV$$

ideal gas

$$du = c_v dT; PV = RT$$

$$\Rightarrow \frac{P}{T} = \frac{R}{V}$$

$$\int_{s_1}^{s_2} ds = \int_{T_1}^{T_2} \frac{c_v dT}{T} + \int_{V_1}^{V_2} \frac{R}{V} dV$$

$$(s_2 - s_1) = c_v \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1}$$

①

$$Tds = dh - vdf$$

$$ds = \frac{dh}{T} - \frac{v}{T} dp$$

for ideal gas

$$dh = c_p dT; PV = RT$$

$$\Rightarrow \frac{v}{T} = \frac{R}{P}$$

$$\therefore ds = \frac{c_p dT}{T} - \frac{R}{P} dp$$

$$\int_{s_1}^{s_2} ds = \int_{T_1}^{T_2} \frac{c_p dT}{T} - \int_{P_1}^{P_2} \frac{R}{P} dp$$

$$\Rightarrow (s_2 - s_1) = c_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

②

∴ Show that for an ideal gas entropy change ~~($s_2 - s_1$)~~

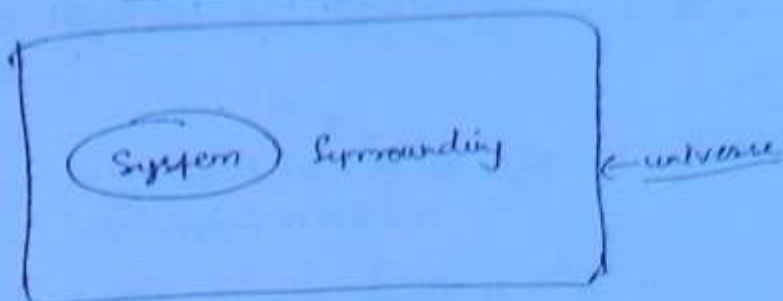
$$(s_2 - s_1) = c_p \ln \frac{V_2}{V_1} + c_p \ln \frac{P_2}{P_1}$$

$\frac{c_p}{c_v} = \gamma$

$$Tds = dh - vdf$$

$$dh = du + vdf + PdV$$

ENTROPY CHANGE OF UNIVERSE



105

$$ds \geq \frac{dq}{T}$$

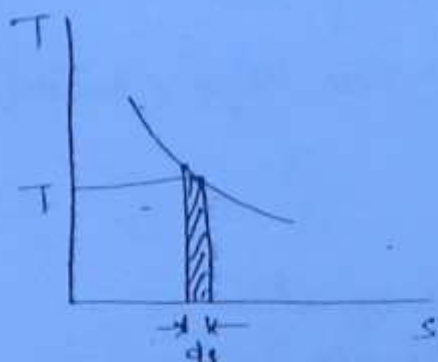
$$ds_{(universe)} \geq 0 \quad (\because \text{universe is isolated system} \therefore dq=0)$$

$$(ds)_{\text{system}} + (ds)_{\text{surrounding}} \geq 0$$

Note

Entropy of system can increase, can decrease or it can remain constant. Similarly, entropy of surroundings can increase, can decrease or can remain constant but the overall change in entropy of universe can never decrease. and this is known as the principle of increase of entropy.

← T-S DIAGRAM →



$$\frac{dq}{T} = ds$$

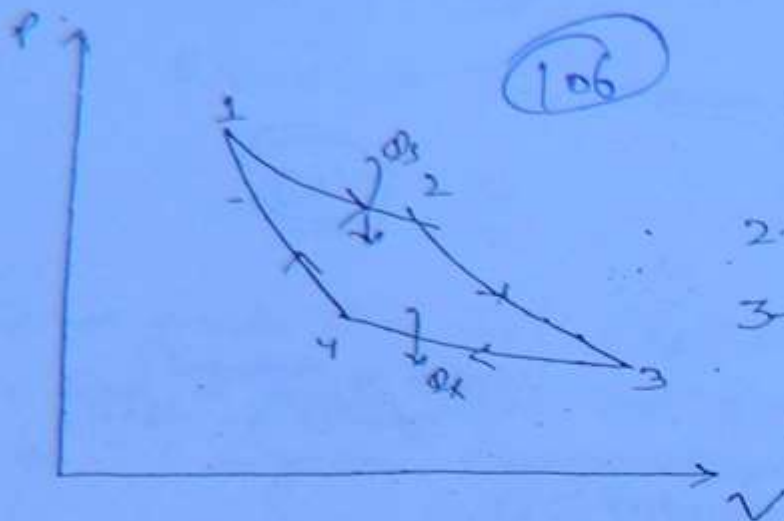
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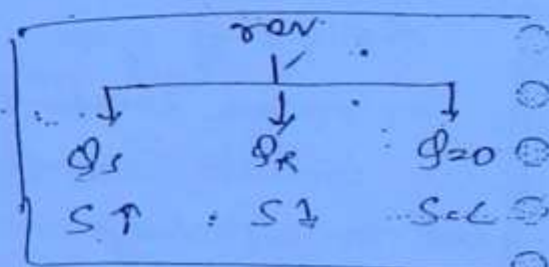
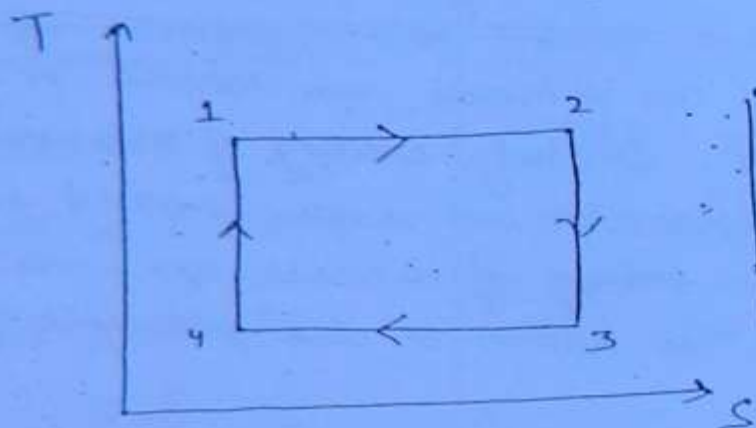


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$$dQ = dU + PdV \rightarrow \text{rev. process (1st law)}$$

$$\frac{dQ}{T} = dS \Rightarrow dQ = TdS \rightarrow \text{rev. process (2nd law)}$$

Combining both, we have.

$$\boxed{TdS = dU + PdV}$$

\rightarrow This equation is applicable for any process (reversible or irreversible) because it connects various properties.

$$(S_2 - S_1) = C_p \ln \frac{V_2}{V_1} + C_p \ln \frac{P_2}{P_1}$$

Solⁿ: $(S_2 - S_1) = C_v \ln \frac{T_2}{T_1} + R \ln \frac{P_2}{P_1}$ (107)

Also, $(S_2 - S_1) = \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$
 $\Rightarrow \frac{P_1 V_1}{P_2 V_2} = \frac{T_1}{T_2}$

$$(S_2 - S_1) = C_v \ln \frac{T_2}{T_1} + (C_p - C_v) \ln \frac{V_2}{V_1} \quad (C_p - C_v = R)$$

$$= C_v \ln \frac{T_2}{T_1} + C_p \ln \frac{V_2}{V_1} - C_v \ln \frac{V_2}{V_1}$$

$$(S_2 - S_1) = C_v \left[\ln \frac{T_2}{T_1} - \ln \frac{V_2}{V_1} \right] + C_p \ln \frac{V_2}{V_1}$$

$$(S_2 - S_1) = C_v \ln \left[\frac{T_2/T_1}{V_2/V_1} \right] + C_p \ln \frac{V_2}{V_1}$$

$$(S_2 - S_1) = C_v \ln \left(\frac{T_2}{T_1} \cdot \frac{V_1}{V_2} \right) + C_p \ln \frac{V_2}{V_1}$$

$$PV = mRT$$

$$\frac{PV}{T} = mR \Rightarrow \frac{PV}{T} = C$$

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

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

$$\therefore (S_2 - S_1) = C_v \ln \frac{P_2}{P_1} + C_p \ln \frac{V_2}{V_1}$$

$$(S_2 - S_1) = C_p \ln \frac{V_2}{V_1} + C_v \ln \frac{P_2}{P_1}$$

$$S_2 - S_1 = C_p \ln \left(\frac{T_2}{T_1} \right) + R \ln \left(\frac{V_2}{V_1} \right)$$

108

$$S_2 - S_1 = C_p \ln \left(\frac{T_2}{T_1} \right) - R \ln \left(\frac{P_2}{P_1} \right)$$

$$S_2 - S_1 = C_p \ln \left(\frac{V_2}{V_1} \right) + C_v \ln \left(\frac{P_2}{P_1} \right)$$

Work Book

Chapter - 5

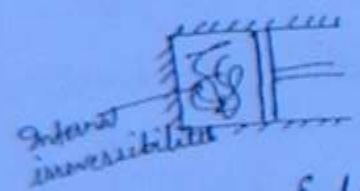
①	d	⑨	d & c	⑰	a	⑲	c	⑳	b
②	c	⑩	a & d	⑱	b	⑳	a	㉑	a
③	b	⑪	a & d	⑲	b	㉒	b	㉒	b
④	a	⑫	a & c	⑳	d	㉓	a	㉓	a
⑤	d	⑬	a	㉑	b	㉔	b	㉔	b
⑥	c	⑭	d & a	㉒	d	㉕	b	㉕	b
⑦	a	⑮	a	㉓	d	㉖	c	㉖	c
⑧	b	⑯	d & d	㉔	b	㉗	a	㉗	a

03/08/2011

*
$$dS = \left(\frac{dQ}{T} \right)_{\text{ext}} + (dS)_{\text{gen}}$$

\downarrow external \downarrow internal (irreversibilities)

$$dS = \left(\frac{dQ}{T} \right)_{\text{rev}} + 0$$



Entropy change occurs due to external interactions and internal irreversibilities. In a reversible process as there are no irreversibilities the entropy change occurs only due to external interactions.

* In an adiabatic process as there is no interaction of system with surroundings in the form of heat transfer, therefore in an adiabatic process, there is no entropy change for surroundings.

$$h = u + Pv$$

$$dh = du + Pdv + vdp$$

$$dh = d\phi + vdf$$

$$dh = Tds + vdp$$

$$(\because d\phi = du + Pdv)$$

$$(\because d\phi = Tds)$$

$$\therefore \boxed{Tds = dh - vdp} \quad \text{--- (2)}$$

(109)

This equation is applicable for reversible as well as irreversible process, because it connects various properties

Equation (1) and Eq: (2) are combined first and second law equations.

⇒ * REPRESENTATION OF CONSTANT-VOLUME AND CONSTANT PRESSURE LINES ON T-S DIAGRAM! (for ideal gas):-

$$Tds = du + Pdv$$

$$v = c \Rightarrow dv = 0$$

$$du = cvdT$$

$$Tds = cvdT + P(0)$$

$$\Rightarrow Tds = cvdT$$

$$\Rightarrow \boxed{\frac{dT}{ds} = \frac{T}{cv}}$$

Slope of constant volume lines of T-S diagram = $\frac{T}{cv}$

$$Tds = dh - vdp$$

$$P = c$$

$$dP = 0$$

$$dh = Cp dT$$

$$Tds = Cp dT - v(0)$$

$$\Rightarrow Tds = Cp dT$$

$$\Rightarrow \boxed{\frac{dT}{ds} = \frac{T}{Cp}}$$

Hence,

Slope of constant pressure lines on T-S

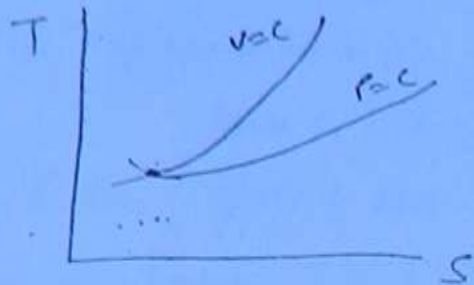
diagram = $\frac{T}{Cp}$

(P.70)

$$P = c \rightarrow T/c_p$$

$$P = c \rightarrow T/c_v$$

$$\therefore c_p > c_v$$



As ' c_p ' is greater than ' c_v ' ($c_p > c_v$), the slope of constant volume line is greater than the slope of constant pressure lines on T-S diagram. ~~Entropy change~~

→ ENTROPY CHANGE FOR IDEAL GAS ←

$$Tds = du + pdv$$

$$ds = \frac{du}{T} + \frac{p}{T} dv$$

for ideal gas,

$$du = c_v dT; \quad PV = RT$$

$$\Rightarrow \frac{p}{T} = \frac{R}{V}$$

$$\int_{S_1}^{S_2} ds = \int_{T_1}^{T_2} \frac{c_v dT}{T} + \int_{V_1}^{V_2} \frac{R}{V} dV$$

$$(S_2 - S_1) = c_v \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1}$$

①

$$Tds = dh - vdp$$

$$ds = \frac{dh}{T} - \frac{v}{T} dp$$

for ideal gas,

$$dh = c_p dT; \quad PV = RT$$

$$\Rightarrow \frac{v}{T} = \frac{R}{P}$$

$$\therefore ds = \frac{c_p dT}{T} - \frac{R}{P} dp$$

$$\int_{S_1}^{S_2} ds = \int_{T_1}^{T_2} \frac{c_p dT}{T} - \int_{P_1}^{P_2} \frac{R}{P} dp$$

$$\Rightarrow (S_2 - S_1) = c_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

②

∴ Show that for an ideal gas entropy change (~~$S_2 - S_1$~~)

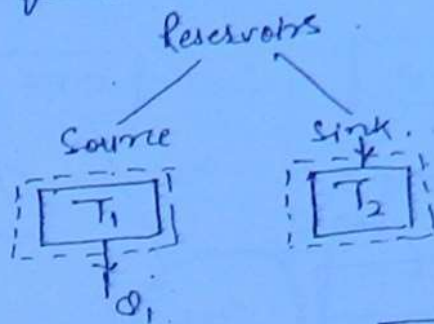
$$(S_2 - S_1) = c_p \ln \frac{V_2}{V_1} + c_p \ln \frac{P_2}{P_1}$$

$$Tds = dh - vdp$$

$$dh = du + vdp + p/dv$$

11/10/20

* Entropy change for reservoirs

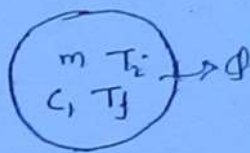


$$(\Delta S)_{\text{source}} = -\frac{Q_1}{T_1}$$

$$(\Delta S)_{\text{sink}} = \frac{Q_2}{T_2}$$

All temp must be in Kelvin.

* Entropy change for a finite body:-



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

$$\& dQ = mc dT$$

$$\int_{s_i}^{s_f} ds = \int_{T_i}^{T_f} mc \frac{dT}{T}$$

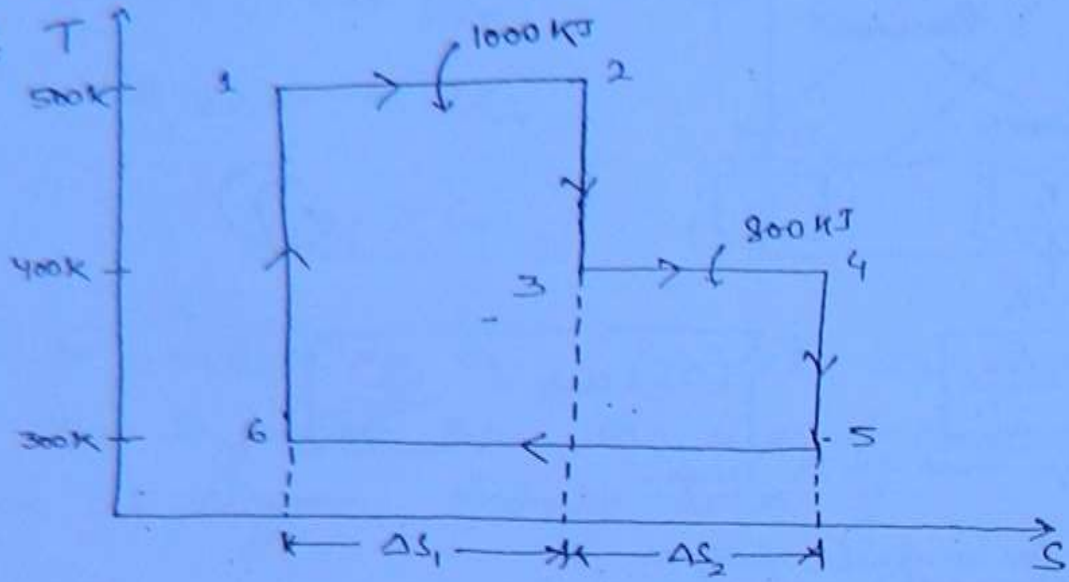
$$\Rightarrow \boxed{s_f - s_i = mc \ln \frac{T_f}{T_i}}$$

Problem 1

Q1

A closed system executes a reversible cycle 1-2-3-4-5-6-1 consisting of 6 processes. During process 1-2, 1000 kJ of heat is added at const. temp^r of 500 K. 2-3 is adiabatic expansion in which the temp decreases from 500 to 400 K. 3-4 is a constant temp^r heat rejection addition in which 800 kJ of heat is added at 400 K. 4-5 is adiabatic expansion in which the temp^r decreases from 400 K to 300 K. In 5-6, heat is rejected at a constant temp^r of 360 K. 6-1 is adiabatic compression. Represent the cycle on T-S diagram and calculate the net work transfer and efficiency of cycle.

Sol/D1

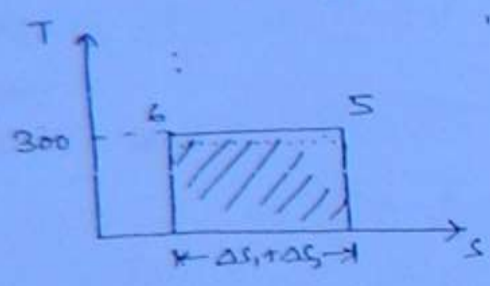


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$$\Sigma W = \Sigma Q$$

$$\Rightarrow W = Q_S - Q_R$$

$$Q_S = 1000 + 800 = 1800 \text{ kJ}$$



$$Q_R = 300 \times (\Delta S_1 + \Delta S_2)$$

$$= 300 \times (2 + 2)$$

$$= 1200$$

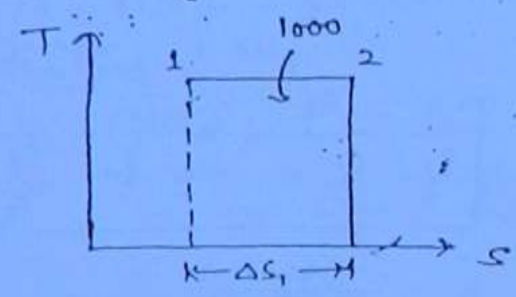
$$W = Q_S - Q_R$$

$$= 1800 - 1200$$

$$\therefore W = 600 \text{ kJ}$$

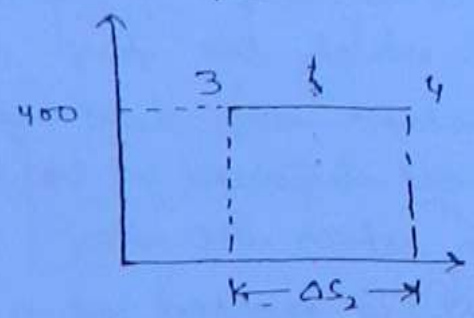
now efficiency,

$$\eta = W/Q_S = \frac{600}{1800} = 33.3\%$$



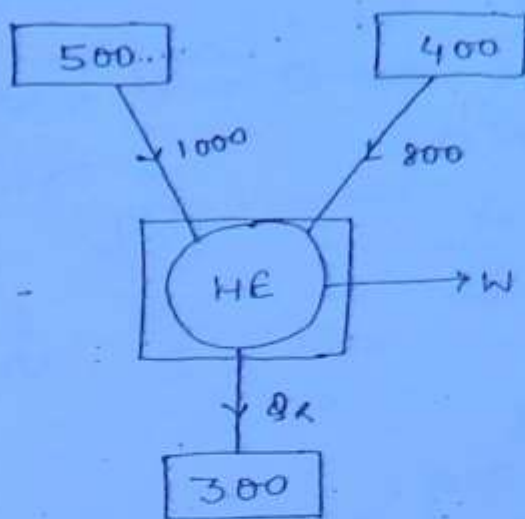
$$1000 = 500 \times \Delta S_1$$

$$\Rightarrow \Delta S_1 = 2$$



$$800 = 400 \times \Delta S_2$$

$$\therefore \Delta S_2 = 2$$



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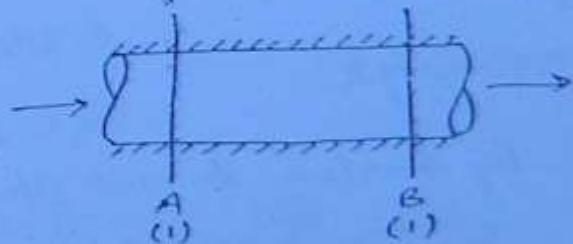
$$\oint \frac{dQ}{T} = 0 \Rightarrow \frac{1000}{500} + \frac{800}{400} - \frac{Q_R}{300} = 0.$$

$$\Rightarrow Q_R = 4 \times 300 = \underline{\underline{1200 \text{ kJ}}}$$

Q:- Air is flowing steadily in an insulated pipe, the pressure and temp^r at two stations A and B are given in table, Establish the direction of flow of air. Take $C_p = 1.005 \text{ kJ/kg} \cdot \text{K}$ and $R = 0.287 \text{ kJ/kg} \cdot \text{K}$.

	A	B
Pressure	130 kPa	100 kPa
Temp ^r	50°C	13°C

Pressure alone can never decide the direction.
It is total energy which decides the direction.



Solⁿ $(\Delta S)_{univ} \geq 0$
 $\Rightarrow (\Delta S)_{system} + (\Delta S)_{surroundings} \geq 0$

as the system is insulated

$$\Rightarrow (\Delta S)_{surroundings} = 0.$$

$$(\Delta S)_{system} \geq 0$$

Let us assume, flow from A to B

$$\begin{aligned} \text{Now, } (\Delta S)_{system} &= S_B - S_A = C_p \ln \frac{T_B}{T_A} - R \ln \frac{P_B}{P_A} \\ &= -0.0469 \text{ kJ/kg} \end{aligned}$$

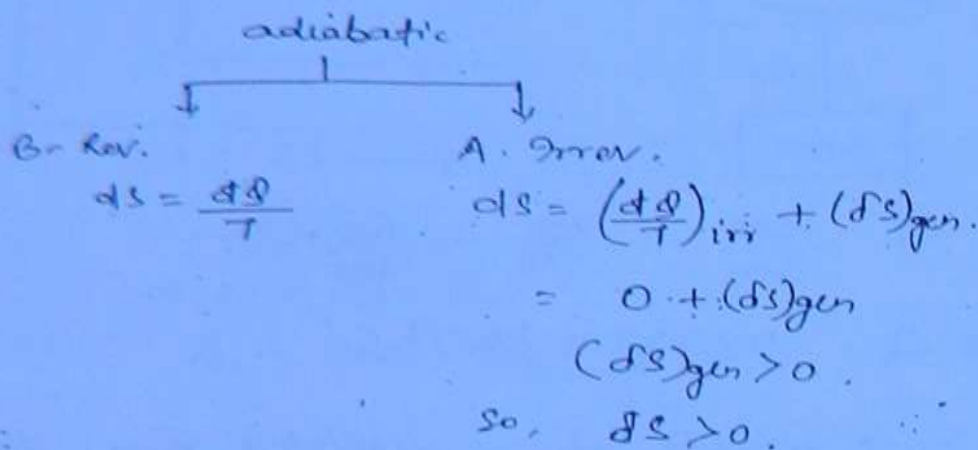
$$\Rightarrow (\Delta S)_{\text{system}} < 0.$$

As the entropy change is less than 0, so it is not possible hence direction is from B to A.

Work Book
Chapter - 5

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(1) (a)



(3) $m = 10 \text{ kg}$

$$C_v = \frac{5R}{2}$$

$$C_p - C_v = R$$

$$P_1 = 100$$

$$T_1 = 300$$

$$P_2 = 200$$

$$T_2 = 500$$

$$\Rightarrow C_p = R + \frac{5}{2}R$$

$$= \frac{7}{2}R$$

$$= \frac{7}{2} (0.287)$$

$$= 1.0045 \text{ kJ/kg K}$$

$$S_2 - S_1 = C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

$$= 1.0045 \ln \frac{500}{300} - 0.287 \ln \frac{200}{100}$$

$$= 0.314 \text{ kJ/kg K}$$

Pay Attention to unit always.

$$S_2 - S_1 = 0.314 \text{ kJ/kg K} \times 10 = 3.14 \text{ kJ/K}$$

(b)

(5) - (6)

All are properties, hence valid for all processes.

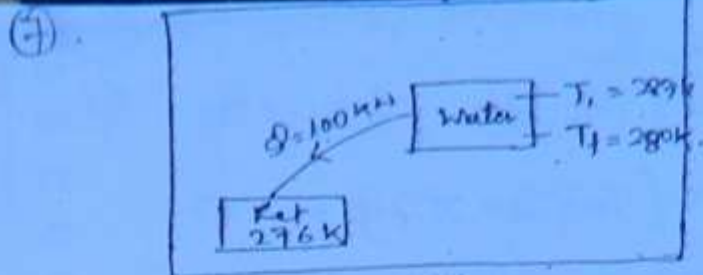
(6) - (10)

$$h = U + PV$$

$$= f(T) + mRT$$

$$h = f(T)$$

(c) as $S_2 - S_1 = C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$
hence, it is function of pressure also.



$$Q = mc\Delta T$$

$$mc = \frac{Q}{\Delta T} = \frac{100}{7}$$

$$\Delta S = (\Delta S)_{H_2O} + (\Delta S)_{ref}$$

$$(\Delta S)_{ref} = \frac{Q}{T} = \frac{100}{7} \text{ kJ/K}$$

$$(\Delta S)_{H_2O} = mc \ln \frac{T_2}{T_1} \quad (15)$$

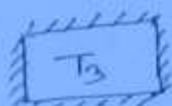
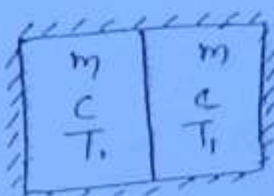
$$= \frac{100}{7} \ln \frac{280}{283}$$

$$\text{So, } (\Delta S) = (\Delta S)_{H_2O} + (\Delta S)_{ref}$$

$$= \frac{100}{7} \ln \frac{280}{283} + \frac{100}{7} \frac{\text{kJ}}{\text{K}}$$

$$= 9.55 \times 10^{-3} \text{ kJ/K} = \underline{\underline{9.55 \text{ W/K}}}$$

(8) Show that mixing is irreversible? (d)



$$\Delta S = \Delta S_1 + \Delta S_2 \text{ — as this is extensive}$$

$$\text{So, } \Delta S = mc \ln \frac{T_3}{T_1} + mc \ln \frac{T_3}{T_2}$$

$$= mc \ln \frac{T_3^2}{T_1 T_2}$$

$$= mc \ln \left(\frac{T_3}{\sqrt{T_1 T_2}} \right) \text{ — (1)}$$

Now, heat loss = heat gain

$$mc(T_1 - T_3) = mc(T_3 - T_2)$$

$$\Rightarrow T_1 - T_3 = T_3 - T_2$$

$$\Rightarrow T_3 = \frac{T_1 + T_2}{2}$$

Substituting it into (1), we get :-

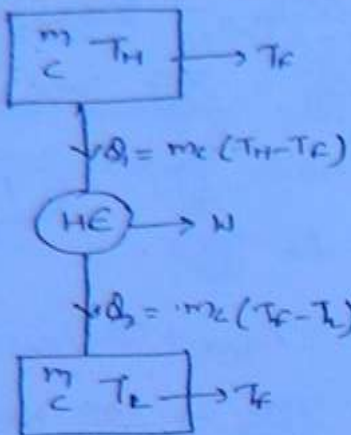
$$\Delta S = 2mc \ln \left(\frac{T_1 + T_2}{2\sqrt{T_1 T_2}} \right) \text{ — (2) } \underline{\underline{As...}}$$

We know that $AM > GM$ and hence this entropy change is > 0 but as the system is insulated the surrounding entropy change is 0 and hence $(\Delta S)_{universe} = (\Delta S)_{system}$.

Therefore in this case $(\Delta S)_{universe} > 0$ and hence mixing is an irreversible process.

$$AM = \frac{T_1 + T_2}{2} \quad GM = \sqrt{T_1 T_2}$$

9



So, $W = Q_1 - Q_2$

$$= mc [(T_H - T_F) - (T_F - T_L)]$$

$$= mc [T_H + T_L - 2T_F] \quad \text{--- (1)}$$

* As the system undergoes cycle the $(\Delta S)_{\text{system}} = 0$ because for a cycle initial and final points are same entropy being property depends only on points.

Now

$$(\Delta S)_{\text{univ}} \geq 0$$

$$(\Delta S)_{\text{univ}} = 0 \quad (\text{rev. cycle})$$

$$(\Delta S)_{\text{system}} + (\Delta S)_{\text{surrounding}} = 0$$

$$\downarrow \text{cycle} \quad \downarrow \text{surrounding}$$

$$0 + (\Delta S)_{\text{surr.}} = 0$$

$$(\Delta S)_{\text{surr.}} = 0$$

$$mc \ln \frac{T_F}{T_H} + mc \ln \frac{T_F}{T_L} = 0$$

$$\Rightarrow mc \ln \frac{T_F}{T_H} + mc \ln \frac{T_F}{T_L} = 0$$

$$\Rightarrow mc \left[\ln \frac{T_F^2}{T_H T_L} \right] = 0$$

$$\Rightarrow \ln \frac{T_F^2}{T_H T_L} = 0 = \ln 1$$

$$T_F^2 = T_H T_L$$

$$\Rightarrow T_F = \sqrt{T_H T_L}$$

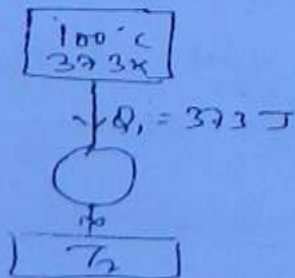
and putting it into (1), we get :-

$$W = mc [T_H + T_L - 2\sqrt{T_H T_L}]$$

(10) \rightarrow (1)

(11) \rightarrow (2)

(12) \rightarrow (3)



$$(\Delta S)_{\text{sys}} = \frac{-Q}{T}$$

$$= \frac{-373}{373}$$

$$= -1$$

(13) (a) Same as 8th problem.

(14) $ds = \frac{dq}{T}$ and $dq = mc dT$

$\Rightarrow ds = \frac{mc dT}{T}$

$\Rightarrow \int_{s_1}^{s_2} ds = \int_{T_1}^{T_2} \frac{m c dT}{T} = \int_{T_1}^{T_2} \frac{(a + bT^2)}{T} dT$

$\Rightarrow \int_{s_1}^{s_2} ds = \int_{T_1}^{T_2} \frac{a dT}{T} + \int_{T_1}^{T_2} bT dT$

(117)

$= a \ln \frac{T_2}{T_1} + b \frac{T_2^2 - T_1^2}{2}$

$= a \ln \frac{T_2}{T_1} + 0.5 b (T_2^2 - T_1^2)$

Ans to (a) 1.

(15) $T ds = dh - v dp$

$\Rightarrow T ds = dh$ as const. P.

$\Rightarrow \frac{dh}{ds} = T$

So, as $T \uparrow$ $\frac{dh}{ds} \uparrow$

(a) Ans.

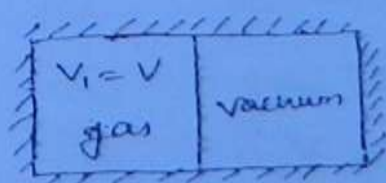
(16) \rightarrow (d)

(17) $\frac{dT}{ds} = \frac{T}{C_p} = \frac{T}{\gamma R / \gamma - 1} = \frac{(\gamma - 1) T}{\gamma R}$

(a) Ans.

(18) $m c \ln \frac{T_2}{T_1} \Rightarrow 1 \times 1 \times \ln \frac{(30 + 273)}{(600 + 273)}$
 $= -1.05 \text{ kJ/k.}$

(19) (b)



$S_2 - S_1 = C_v \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1}$

\Rightarrow Ideal gas undergoes free expansion

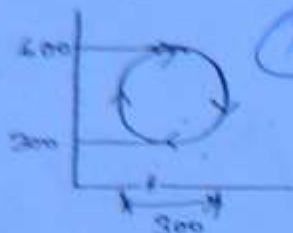
So, $T_2 = T_1$

$$\Delta S = C_v \ln 2 + R \ln \frac{2V}{V} = R \ln 2 \quad \text{as } V_2 = 2V$$

$$V_1 = V$$

(20) → (9)

$$1 - \frac{300}{600}$$

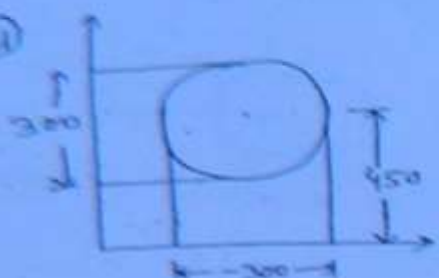


$$\pi r^2$$

$$300 \times \pi \times (150)^2 \text{ W}$$

$$\underline{\underline{\Sigma d = \Sigma W}}$$

(21)



$$W = \text{Area under curve}$$

$$= \frac{\pi}{4} d^2 = \frac{\pi}{4} \times (300)^2$$

$$\eta = W / Q_s$$

$$Q_s = \text{area under curve}$$

$$= \frac{\pi}{4} \times (300)^2 \times \frac{1}{2} + 450 \times 300$$

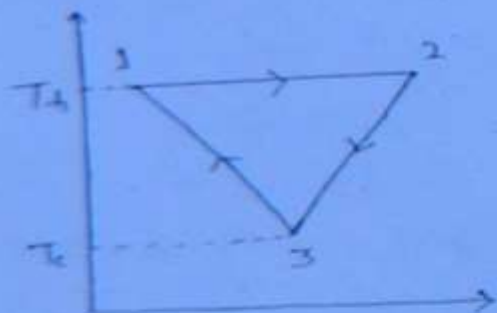
$$\eta = \frac{W}{Q_s} = \frac{\frac{\pi}{4} \times (300)^2}{\frac{\pi}{4} \times \frac{1}{2} \times (300)^2 + 450 \times 300}$$

$$\eta = 41.4\% \quad (\text{Ans})$$

(22) - (9)

(23) - (9)

(24) Increase in entropy means heat supplied. So, to find Q_s on T-S diagram take the area under curve upon which 's' is increasing.



$$\eta = W / Q_s$$

$$W = \text{Area of } \Delta$$

$$= \frac{1}{2} \times (\Delta S) (T_h - T_c)$$

$$Q_s = T_h \times \Delta S$$

(25) - (9)

(26) - (9)

$$S_2 - S_1 = C_v \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1}$$

Rigid container $V = \text{const.}$

$$S_2 - S_1 = C_v \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1}$$

$$S_2 - S_1 = cv \ln \frac{T_2}{T_1} \text{ as } T_2 < T_1$$

$(\Delta S) = -ve$. Hence A is (3).

- (27) (b) A-2 During expansion there is reduction in temperature. (119)
 B-3
 C-4
 D-5

(28) - (a) As long as end points are same, property are remain changed.

(29) - (B), (30) - (B), (31) - (C)

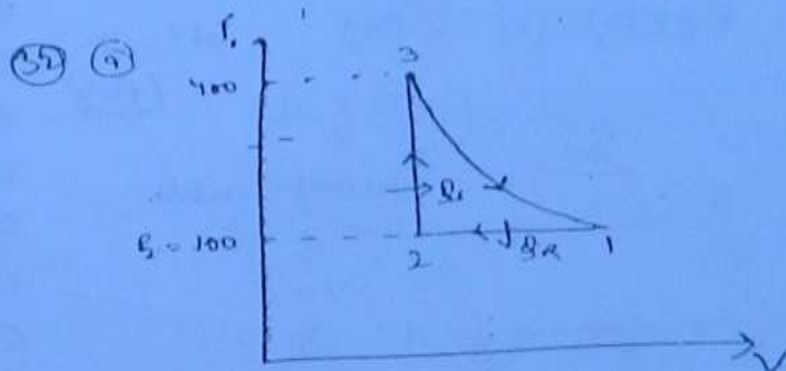
(32) $S_2 - S_1 = \frac{W}{T_1}$ $W = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1}$

$$P_1 V_1^{1.4} = P_2 V_2^{1.4}$$

$$\Rightarrow \frac{400 \times 1}{100} = P_2 V_2^{1.4}$$

$$\ln 4 = 1.4 \ln V_2 = \underline{2.69 \text{ m}^3}$$

$$W = \frac{P_1 V_1 - P_2 V_2}{1.4 - 1} = 327.5 \text{ J}$$



$$dV = dU = mc_v dT$$

$$dP = dH = mc_p dT$$

$$\eta = 1 - \frac{Q_2}{Q_1}$$

$$Q_1 = mc_v (T_3 - T_2)$$

$$Q_2 = -mc_p (T_1 - T_2)$$

$$-Q_2 = mc_p (T_1 - T_2)$$

$$Q_2 = mc_p (T_1 - T_2)$$

$$\eta = \frac{1 - \gamma(T_1 - T_2)}{\gamma(T_2 - T_1)}$$

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

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

$$= 1 - \gamma \left(\frac{V_1}{V_2} - 1 \right)$$

$$\eta = 1 - 1.4 \left(\frac{2.69}{1} - 1 \right)$$

$$\therefore \eta = 0.211 = 21.1\%$$

33) - (B)

$$P_1 = 100 \quad V_1 = 0.002$$

$$P_2 = 125 \quad V_2 = 0.003$$

$$S_2 - S_1 = C_p \ln \frac{V_1}{V_2} + C_v \ln \frac{P_2}{P_1}$$

$$= 1.005 \times \ln \frac{0.002}{0.003} + 0.718 \ln \left(\frac{125}{100} \right)$$

$$= 0.567$$

(d) Ans

9) - (d)

isentropic

↓

incompressible

↓

$f = \text{const} \Rightarrow v = \text{const}$

$f = m/v \cdot \text{rot}$

$\Rightarrow v = c$

$$Tds = dU + PdV$$

$v = \text{const}$, so $dV = 0$

$$\therefore Tds = dU$$

$s = \text{const}$ (given)

$$ds = 0$$

$$T(ds) = dU$$

$$\Rightarrow dU = 0 \rightarrow dU = C(dT)$$

$$U = \text{const} \rightarrow 0 = C(dT)$$

$$U = C(T) \quad dT = 0$$

(Ans)

So.

Incompressible

↓

$v = c$

↓

$s = c$

↓

$U = c$

↓

$T = c$

(2) → (c)

(Ans)

120

Q. Find the irreversibility associated with the expansion of air ^{from} a very small opening in a pipe from pressure and temperature of 8 bar and 600K to a pressure of 1.2 bar. Assume it to be an ideal gas and take temperature of surroundings 298K

Soln: As the fluid is flowing through a very small opening, it undergoes throttling ($h = \text{constant}$)

$$I = T_0 [(\Delta S)_{\text{system}} + (\Delta S)_{\text{surroundings}}]$$

$$I = T_0 (\Delta S)_{\text{sys.}}$$

(12)

$$(\Delta S)_{\text{sys}} = S_2 - S_1 = C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

for throttling,

$$h_1 = h_2$$

$$C_p T_1 = C_p T_2$$

$$\Rightarrow T_1 = T_2 \quad \text{or} \quad \frac{T_2}{T_1} = 1.$$

$$\ln \left(\frac{T_2}{T_1} \right) = \ln 1 = 0.$$

$$\therefore (\Delta S)_{\text{sys}} = -R \ln \frac{P_2}{P_1} = R \ln \left(\frac{P_1}{P_2} \right)$$

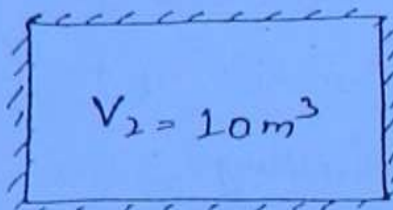
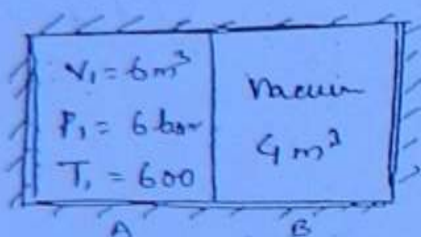
$$\therefore I = T_0 (\Delta S)_{\text{sys}}$$

$$= T_0 \left[R \ln \left(\frac{P_1}{P_2} \right) \right]$$

$$= 298 \times 0.287 \times \ln \left(\frac{8}{1.2} \right)$$

$$\Rightarrow I = 162.25 \text{ kJ/kg}$$

Q.2 An adiabatic cylinder of 10 m^3 volume is divided into two compartments 'A' and 'B', each of volume 6 m^3 and 4 m^3 by a thin sliding partition. Initially the compartment 'A' is filled with air at 6 bar, 600 K , while there is vacuum in compartment 'B'. Suddenly, the partition is removed and the fluid in compartment 'A' expands freely and fills both the compartments. Calculate the irreversibility in kJ and take atmospheric pressure as 1 bar and atmospheric temperature as 300 K .



(122)

$$I = T_0 [(\Delta S)_{\text{sys}} + (\Delta S)_{\text{surr}}]$$

\because The system is insulated, $\therefore (\Delta S)_{\text{surr}} = 0$.

$$\therefore I = T_0 [(\Delta S)_{\text{sys}}]$$

$$(\Delta S)_{\text{sys}} = S_2 - S_1 = C_v \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1}$$

$$T_1 = T_2 \quad (\text{from free expansion})$$

$$\therefore \frac{T_2}{T_1} = 1 \Rightarrow \ln \left(\frac{T_2}{T_1} \right) = \ln 1 = 0$$

$$(\Delta S)_{\text{sys}} = R \ln \frac{V_2}{V_1}$$

$$I = T_0 \left(R \ln \frac{V_2}{V_1} \right) \quad \text{K} \times \frac{\text{kJ}}{\text{kg K}} = \underline{\underline{\text{kJ/kg}}}$$

$$= 300 \times 0.287 \times \ln \left(\frac{10}{6} \right)$$

$$\therefore I = 43.98 \text{ kJ/kg}$$

$$PV = mRT$$

$$m = PV/RT = \frac{6 \times 100 \times 6}{0.287 \times 600}$$

$$\therefore m = 20.9 \text{ kg}$$

$$\therefore I = (43.98 \times 20.9) \frac{\text{kJ}}{\text{kg}} \times \frac{\text{kg}}{\cancel{\text{kg}}}$$

$$\therefore \boxed{I = 919.2 \text{ kJ}} \quad (\text{Ans})$$

(123)

Q:- A solid aluminium sphere of 0.1 m diameter and initially at 200°C is cooled to ambient temperature of 25°C . The density of aluminium is 2700 kg/m^3 and specific heat is 0.9 kJ/kgK . Find the irreversibility associated with this process in kJ.

Soln: $T_1 = 200^\circ\text{C} = 473 \text{ K}$
 $T_2 = 25^\circ\text{C} = 298 \text{ K}$

$$\text{Vol}^{\text{Area}} = \frac{4}{3} \pi r^3 = \frac{4}{3} \pi \left(\frac{0.1}{2}\right)^3 = 0.00052 \text{ m}^3$$

$$\rho = m/v \Rightarrow m = v \times \rho = 0.00052 \times 2700 = 1.414 \text{ kg}$$

$$I = T_0 [(\Delta S)_{\text{sys}} + (\Delta S)_{\text{sur}}]$$

$$I = T_0 [(\Delta S)_{\text{sys}}]$$

$$(\Delta S)_{\text{sys}} =$$

(P.T.O)

ESE-

Q: Steam flows steadily in an adiabatic turbine, the enthalpy at the entrance is 4142 kJ/kg and at the exit is 2585 kJ . The values of flow availability at the entrance and exit are 1787 kJ and 140 kJ/kg respectively. The ambient temperature is 300 K .

find :- ① actual work

② max^m work

③ change in entropy of the system. (Neglect K.E & P.E changes).

(125)

Sol: $W_{\max} = \phi_1 - \phi_2 = 1787 - 140 = 1647 \text{ kJ/kg}$.

$$h_1 = 4142 \text{ kJ/kg}, \quad h_2 = 2585 \text{ kJ/kg}$$

$$\phi_1 = 1787 \text{ kJ/kg}, \quad \phi_2 = 140 \text{ kJ/kg}$$

Steady flow equation:

$$h_1 + \frac{C_1^2}{2} + z_1 g + \phi_1 = h_2 + \frac{C_2^2}{2} + z_2 g + \phi_2 + w_{cv}$$

(adiabatic) (Neglecting K.E & P.E changes)

① $\therefore W = h_1 - h_2 = 1557 \text{ kJ/kg}$
(actual)

② $W_{\max} = \phi_1 - \phi_2$ (\because the system is open).
 $= (1787 - 140) = 1647 \text{ kJ/kg}$.

③ $W_{\max} = h_1 - h_2 - T_0(S_1 - S_2)$ [\because the system is open].

$$\Rightarrow 1647 = 4142 - 2585 - 300(S_1 - S_2)$$

$$\Rightarrow (S_1 - S_2) = \frac{1647 - 1557}{300} = 0.3 \text{ kJ/kg-K}$$

$$\therefore \Delta S = (S_2 - S_1) = -(S_1 - S_2) = 0.3 \text{ kJ/kg-K}$$

(A)

ESE-

Q:- Steam flows steadily in an adiabatic turbine, the enthalpy at the entrance is 4142 kJ/kg and at the exit is 2585 kJ . The values of flow availability at the entrance and exit are 1787 and 140 kJ/kg respectively. The ambient temperature is 300 K .

Find :- ① actual work

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③ change in entropy of the system. (Neglect K.E & P.E changes).

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Sol:- $W_{\max} = \phi_1 - \phi_2 = 1787 - 140 = 1647 \text{ kJ/kg}$

$$h_1 = 4142 \text{ kJ/kg}, \quad h_2 = 2585 \text{ kJ/kg}$$

$$\phi_1 = 1787 \text{ kJ/kg}, \quad \phi_2 = 140 \text{ kJ/kg}$$

Steady flow equation:-

$$h_1 + \frac{C_1^2}{2} + z_1 g + \phi_1 \stackrel{\text{(adiabatic)}}{=} h_2 + \frac{C_2^2}{2} + z_2 g + W_{cv} \stackrel{\text{(Neglecting K.E \& P.E changes)}}{=}$$

① $W = h_1 - h_2 = 1557 \text{ kJ/kg}$
(actual)

② $W_{\max} = \phi_1 - \phi_2$ (\because the system is open).
 $= (1787 - 140) = 1647 \text{ kJ/kg}$

③ $W_{\max} = h_1 - h_2 - T_0(S_1 - S_2)$ [\because the system is open]

$$\Rightarrow 1647 = 4142 - 2585 - 300(S_1 - S_2)$$

$$\Rightarrow (S_1 - S_2) = \cancel{0} - 0.3 \text{ kJ/kg}\cdot\text{K}$$

$$\therefore (\Delta S) = (S_2 - S_1) = - (S_1 - S_2) = 0.3 \text{ kJ/kg}\cdot\text{K}$$

(A)

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 $= (1787 - 140) = 1647 \text{ kJ/kg}$

③ $W_{max} = h_1 - h_2 - T_0(S_1 - S_2)$ [\because the system is open]

$$\Rightarrow 1647 = 4142 - 2585 - 300(S_1 - S_2)$$

$$\Rightarrow (S_1 - S_2) = \text{---} - 0.3 \text{ kJ/kg-K}$$

$$\therefore (\Delta S) = (S_2 - S_1) = - (S_1 - S_2) = 0.3 \text{ kJ/kg-K}$$

(Ans)

Find the maximum work per kg of air that can be obtained in a piston cylinder arrangement. Air expands from initial state of 9 bar, 400 K to a final state of 1.5 bar, 300 K. Assume atmospheric pressure to be 1 bar and atmospheric temperature to be 288 K. Also find maximum useful work.

(126)

$$W_{\max} = U_1 - U_2 - T_0 (S_1 - S_2) \quad [\text{for closed system}]$$

∵ Air can be treated as ideal gas,

$$\therefore U = m C_v T \quad \because m = 1 \text{ kg}$$

$$\therefore U = C_v T$$

$$\begin{aligned} \therefore W_{\max} &= C_v T_1 - C_v T_2 - T_0 (S_1 - S_2) \\ &= C_v (T_1 - T_2) - T_0 (S_1 - S_2) \end{aligned}$$

Now,

$$P_1 = 9 \text{ bar}$$

$$T_1 = 400 \text{ K}$$

$$P_2 = 1.5 \text{ bar}$$

$$T_2 = 300 \text{ K}$$

$$T_0 = 288 \text{ K}$$

$$(S_2 - S_1) = C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

$$= 1.005 \ln \left(\frac{300}{400} \right) - 0.287 \ln \left(\frac{1.5}{9} \right)$$

$$\therefore (S_2 - S_1) = 0.225 \text{ kJ/kgK}$$

$$\therefore (S_1 - S_2) = -0.225 \text{ kJ/kgK}$$

$$\therefore W_{\max} = C_v (T_1 - T_2) - T_0 (S_1 - S_2)$$

$$= 0.718 (400 - 300) - 288 (-0.225)$$

$$\Rightarrow \boxed{W_{\max} = 136.6 \text{ kJ/kg}} \quad (\text{Ans})$$

Maximum useful work,

$$W_{\max \text{ useful}} = W_{\max} - W_{\text{atm}}$$

$$W_{\text{atm}} = P_0 (V_2 - V_1)$$

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Now,

$$PV = mRT$$

$$\Rightarrow V_1 = \frac{mRT_1}{P_1} = \frac{1 \times 0.287 \times 400}{9 \times 100} = 0.1275 \text{ m}^3$$

Similarly,

$$V_2 = \frac{mRT_2}{P_2} = \frac{1 \times 0.287 \times 300}{1.5 \times 100} = 0.574 \text{ m}^3$$

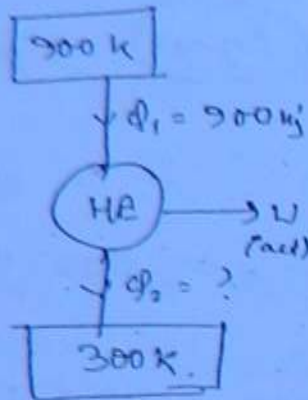
$$\begin{aligned} W_{\text{atm}} &= \cancel{1 \times 100} P_0 (V_2 - V_1) \\ &= 1 \times 100 (0.574 - 0.1275) \\ &= 44.65 \text{ kJ/kg} \end{aligned}$$

$$\begin{aligned} \therefore W_{\max \text{ useful}} &= W_{\max} - W_{\text{atm}} \\ &= (136.6 - 44.65) \text{ kJ/kg} \end{aligned}$$

$$\boxed{W_{\max \text{ useful}} = 91.95 \text{ kJ/kg}} \quad (\text{Ans})$$

A heat engine operates between two thermal reservoirs at 900 K and 300 K. The heat supplied to the engine is 900 kJ. The work output is 400 kJ. Find the irreversibility. Surrounding temp is 300 K. (128)

Soln



$$I = T_0 [(\Delta S)_{\text{sys}} + (\Delta S)_{\text{sur}}]$$

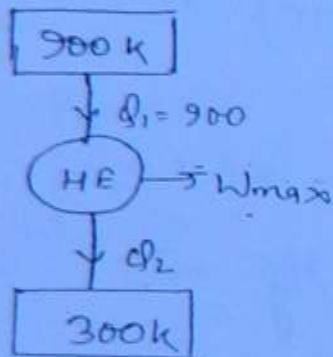
$$W = Q_1 - Q_2$$

$$\Rightarrow Q_2 = Q_1 - W = 500 \text{ kJ}$$

$$W_{\text{act}} = 400 \text{ kJ}$$

$$I = W_{\text{max}} - W_{\text{act}}$$

Let us assume the engine to be reversible.



W_{max} is only for reversible engine.

for reversible engine, --

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

$$\Rightarrow \frac{900}{900} = \frac{Q_2}{300}$$

$$\Rightarrow \underline{\underline{Q_2 = 300 \text{ kJ}}}$$

$$\therefore W_{\text{max}} = Q_1 - Q_2 = (900 - 300) = 600 \text{ kJ}$$

Now $I = W_{\text{max}} - W_{\text{act}}$

$$= 600 - 400$$

$$\therefore \boxed{I = 200 \text{ kJ}} \quad \underline{\underline{(Ans)}}$$

MIXTURE OF IDEAL GASES

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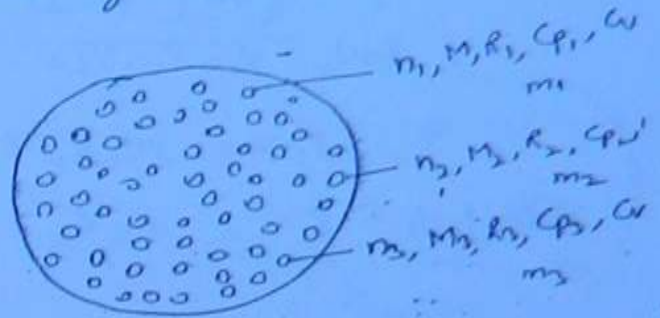
Mole fraction (x) - It is defined as the ratio of no. of moles of a gas to the total number of moles.

$$x = \frac{n}{\sum n}$$

$$x_1 = \frac{n_1}{n_1 + n_2 + \dots}$$

$$x_2 = \frac{n_2}{n_1 + n_2 + \dots}$$

$$x_1 + x_2 + \dots = 1$$



$$V_1 = V_2 = V_3 = V$$

$$T_1 = T_2 = T_3 = T$$

$$P = P_1 + P_2 + P_3$$

$$PV = nRT$$

$$PV = nRT$$

$$P_1 V_1 = n_1 R T_1$$

but $V_1 = V_2 = V_3 = V$ & $T_1 = T_2 = T_3 = T$

$$\therefore P_1 V = n_1 R T \quad \text{--- (1)}$$

$$PV = \sum n R T \quad \text{--- (2)}$$

Dividing (1) by (2) we have

$$\frac{P_1 V}{PV} = \frac{n_1 R T}{\sum n R T} \quad \therefore \frac{P_1}{P} = \frac{n_1}{\sum n}$$

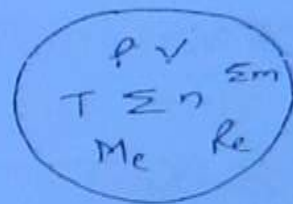
$$\text{But, } \frac{n_1}{\sum n} = x_1$$

$$\therefore \frac{P_1}{P} = x_1$$

$$\text{or } P_1 = x_1 P$$

$$\text{Similarly, } P_2 = x_2 P$$

\therefore Partial Pressure = Mole fraction \times Total Pressure



⇒ * EQUIVALENT GAS CONSTANT (R_e) :->

$$PV = mRT$$

$$P_1 V_1 = m_1 R_1 T_1$$

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But, $V_1 = V_2 = V_3 = \dots = V$ & $T_1 = T_2 = \dots = T.$

$$\therefore P_1 V = m_1 R_1 T$$

Similarly $P_2 V = m_2 R_2 T$

⋮

$$(P_1 + P_2 + \dots) V = (m_1 R_1 + m_2 R_2 + \dots) T$$

But, $(P_1 + P_2 + \dots) = P.$

$$\therefore PV = (m_1 R_1 + m_2 R_2 + \dots) T \quad \text{--- (1)}$$

But

$$PV = \sum m R_e T \quad \text{--- (2)}$$

from (1) & (2).

$$\sum m R_e T = (m_1 R_1 + m_2 R_2 + \dots) T$$

$$\therefore R_e = \frac{m_1 R_1 + m_2 R_2 + \dots}{\sum m}$$

or,
$$R_e = \frac{m_1 R_1 + m_2 R_2 + \dots}{m_1 + m_2 + \dots}$$

Similarly,

$$C_{pe} = \frac{m_1 C_{p1} + m_2 C_{p2} + \dots}{m_1 + m_2 + \dots}$$

$$C_{ve} = \frac{m_1 C_{v1} + m_2 C_{v2} + \dots}{m_1 + m_2 + \dots}$$

(131)

⇒ * EQUIVALENT MOLECULAR WEIGHT (Me) :-

$$n = \frac{m}{M}$$

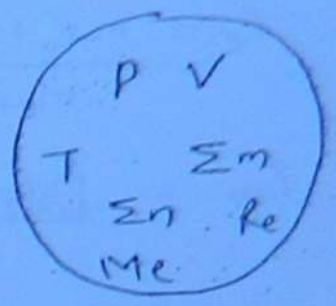
~~m = nM~~
 $m = nM$

$$m_1 = n_1 M_1$$

$$m_2 = n_2 M_2$$

$$m_1 + m_2 + \dots = n_1 M_1 + n_2 M_2 + \dots$$

$$\Rightarrow \Sigma m = (n_1 M_1 + n_2 M_2 + \dots) \quad \text{--- (1)}$$



Also, $\Sigma m = \Sigma n M_e \quad \text{--- (2)}$

from (1) & (2)

$$\Sigma n M_e = (n_1 M_1 + n_2 M_2 + \dots)$$

$$\Rightarrow M_e = \frac{(n_1 M_1 + n_2 M_2 + \dots)}{\Sigma n}$$

$$\text{or, } M_e = \frac{n_1}{\Sigma n} \cdot M_1 + \frac{n_2}{\Sigma n} \cdot M_2 + \dots$$

$$M_e = x_1 M_1 + x_2 M_2 + \dots$$

⇒ Equations to be remembered:

1. $PV = mRT$; $PV = n\bar{R}T$

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2. $x = \frac{n}{\sum n}$; 3. $p_1 = x_1 P$; $p_2 = x_2 P$ and so on

4. $R_e = \frac{m_1 R_1 + m_2 R_2 + \dots}{m_1 + m_2 + \dots}$

5. $C_{pe} = \frac{m_1 C_{p1} + m_2 C_{p2} + \dots}{m_1 + m_2 + \dots}$

6. $C_{ve} = \frac{m_1 C_{v1} + m_2 C_{v2} + \dots}{m_1 + m_2 + \dots}$

7. $M_e = x_1 M_1 + x_2 M_2 + \dots$

8. $R = \frac{\bar{R}}{M}$

Q:- A mixture of ideal gases consists of 3 kg ^{of nitrogen} and 5 kg of Carbon dioxide at a pressure of 300 kPa and temperature of 20°C. Find

- ① Mole fraction of each constituent
- ② Equivalent molecular weight of the mixture
- ③ Equivalent gas constant
- ④ Partial pressure of each constituent
- ⑤ Total volume of the mixture
- ⑥ Density of the mixture
- ⑦ C_p and C_v of the mixture
- ⑧ If this mixture is heated at constant volume to 40°C, find changes in internal energy, enthalpy and entropy of the mixture.

① If the mixture is heated at constant pressure to 40°C , find changes in internal energy, enthalpy and entropy of the mixture.

Solⁿ: Take γ for nitrogen as 1.4 & γ for CO_2 as 1.286

$$\text{H}_2 \rightarrow 1; \quad \text{CO}_2 \rightarrow 2.$$

(133)

$$m_1 = 3 \text{ kg}, \quad m_2 = 5 \text{ kg}.$$

$$M_1 = 28; \quad M_2 = 44.$$

$$n = \frac{m}{M} \quad \therefore n_1 = \frac{m_1}{M_1} = \frac{3}{28} = 0.10714$$

$$n_2 = \frac{m_2}{M_2} = \frac{5}{44} = 0.11364$$

Now,

$$\textcircled{1} \quad x = \frac{n}{\sum n}; \quad \therefore x_1 = \frac{n_1}{n_1 + n_2} = \frac{3/28}{3/28 + 5/44} =$$

$$\therefore \boxed{x_1 = 0.485}$$

$$x_2 = \frac{n_2}{n_1 + n_2} = \frac{5/44}{3/28 + 5/44} = \boxed{0.515} \quad \text{Ans}$$

$$\textcircled{2} \quad M_e = x_1 M_1 + x_2 M_2$$

$$= 0.485 \times 28 + 0.515 \times 44 =$$

$$\Rightarrow \boxed{M_e = 36.25}$$

$$\textcircled{3} \quad R_e = \frac{\bar{R}}{M_e} = \frac{8.314}{36.25}$$

$$\therefore \boxed{R_e = 0.229 \text{ kJ/kgK}}$$

$$\textcircled{4} \quad p_1 = x_1 p \Rightarrow p_1 = 0.485 \times 300$$

$$\Rightarrow \boxed{p_1 = 145.5 \text{ kPa}}$$

$$p_2 = x_2 p \Rightarrow p_2 = 0.515 \times 300 \Rightarrow \boxed{p_2 = 154.5}$$

$$\textcircled{5} \quad PV = \sum m k_e T$$

$$\Rightarrow V = \frac{8 \times 0.229 \times 293}{300}$$

$$\therefore \boxed{V = 1.789 \text{ m}^3}$$

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$$\textcircled{6} \quad \text{Density, } \rho = \frac{\sum m}{V} = \frac{8}{1.789} = 4.47 \text{ kg/m}^3$$

$$\therefore \boxed{\rho = 4.47 \text{ kg/m}^3}$$

$$\textcircled{7} \quad C_{pe} = \frac{m_1 C_{p1} + m_2 C_{p2}}{m_1 + m_2}$$

$$\cancel{C_{p1}} \quad C_{p1} = \frac{7R}{7-1}$$

$$R_1 = \frac{R}{M_1} = \frac{8.314}{28} \\ = 0.2969$$

$$\Rightarrow C_{p1} = \frac{1.4 \times 0.2969}{(1.4-1)}$$

$$\therefore C_{p1} = 1.039$$

$$\cancel{C_{p2}} \quad \cancel{R_2} \quad R_2 = \frac{8.314}{44} = 0.18895$$

$$C_{p2} = \frac{1.286 \times 0.189}{1.286-1}$$

$$\therefore C_{p2} = 0.849 \approx 0.85$$

$$\therefore C_{pe} = \frac{3 \times 1.039 + 5 \times 0.849}{8}$$

$$\boxed{C_{pe} = 0.92} \quad (\text{Ans})$$

$$C_{pe} - C_{ve} = R_e$$

$$[\because C_p - C_v = R]$$

$$\Rightarrow C_{ve} = C_{pe} - R_e \\ = (0.92 - 0.229)$$

$$\therefore \boxed{C_{ve} = 0.6916 \text{ kJ/kgK}}$$

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$$\textcircled{8} \quad T_2 = 40^\circ\text{C}, \quad T_1 = 20^\circ\text{C}$$

$$(a) \quad dU = m C_{ve} dT$$

$$= 8 \times 0.6916 \times 20 = \underline{\underline{110.656 \text{ kJ}}}$$

$$(b) \quad dH = m C_{pe} dT$$

$$= 8 \times 0.9206 \times 20 =$$

$$\underline{\underline{147.296 \text{ kJ}}}$$

$$(c) \quad dS = (S_2 - S_1) = C_v \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1}$$

$$\because \text{vol}^m \text{ is constant, } \therefore V_1 = V_2$$

$$\therefore \ln \frac{V_2}{V_1} = \ln 1 = 0$$

$$\therefore (S_2 - S_1) = C_v \ln \frac{T_2}{T_1}$$

$$= 0.6916 \ln \left(\frac{313}{293} \right)$$

$$\therefore dS = 0.0459 \text{ kJ/kgK}$$

$$\therefore \text{Total Entropy change} = (0.0459 \times 8) \text{ kJ/K}$$

$$\underline{\underline{dS = 0.364 \text{ kJ/K}}}$$

$$\textcircled{9} \quad dU = m c_v dT = 110.656 \text{ kJ}$$

$$dH = m c_p dT = 149.296 \text{ kJ}$$

Ans. $dS = (S_2 - S_1) = C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$

\therefore pressures are constant.

$$\therefore P_1 = P_2$$

$$\therefore \ln \frac{P_2}{P_1} = \ln 1 = 0 \dots$$

$$\therefore (S_2 - S_1) = C_p \ln \frac{T_2}{T_1} = 0.9106 \times \ln \left(\frac{313}{293} \right)$$

$$\therefore dS = (S_2 - S_1) = 0.0607 \text{ kJ/kg K}$$

$$\therefore \text{Total Entropy change} = 8 \times 0.0607$$

$$\boxed{dS = 0.486 \text{ kJ/K}} \quad \text{(Ans)}$$

THERMODYNAMIC RELATIONS I-

Theorem: 1 The equation $(dz = Mdx + Ndy)$ is exact

when

$$\left(\frac{\partial M}{\partial y} \right)_x = \left(\frac{\partial N}{\partial x} \right)_y$$

Theorem: 2

$$f = \phi(x, y, z)$$

$$\left(\frac{\partial x}{\partial y} \right)_f \left(\frac{\partial y}{\partial z} \right)_f \left(\frac{\partial z}{\partial x} \right)_f = 1$$

Theorem: 3

$$z = \phi(x, y)$$

$$\left(\frac{\partial x}{\partial y} \right)_z \left(\frac{\partial y}{\partial z} \right)_x \left(\frac{\partial z}{\partial x} \right)_y = -1$$

⇒ * MAXWELL'S EQUATIONS :->

(1) $Tds = du + PdV$

$du = Tds - PdV$

$dz = Mdx + Ndy$

$M = T; x = S; N = -P; y = V.$

(137)

$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$

$\therefore \left(\frac{\partial T}{\partial V}\right)_S = - \left(\frac{\partial P}{\partial S}\right)_V$

This is first Maxwell's equation.

(2) $Tds = dh - vdf$

$\Rightarrow dh = Tds + vdf$

$dz = Mdx + Ndy$

$M = T; x = S; N = v; y = P.$

$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$

$\therefore \left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial v}{\partial S}\right)_P$

This is second Maxwell's equation

(3) $G = H - TS$ (Gibb's function).

$dG = dH - (Tds + SdT)$

or, $dG = dH - Tds - SdT$

$\therefore dG = vdf - SdT$

$dz = Mdx + Ndy$

$M = v; x = P; N = -S; y = T.$

$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$

$\left[\begin{array}{l} \because Tds = dH - vdf \\ \Rightarrow dH - Tds = vdf \end{array} \right]$

$\therefore \left(\frac{\partial v}{\partial T}\right)_P = - \left(\frac{\partial S}{\partial P}\right)_T$

This is third Maxwell's equation

④ From Helmholtz's function:

$$F = U - TS$$

$$F = U - TS$$

$$dF = dU - (Tds + SdT)$$

$$\Rightarrow dF = \underbrace{dU - Tds - SdT} \dots \left[\begin{array}{l} Tds = dU + PdV \\ \Rightarrow dU - Tds = -PdV \end{array} \right]$$

$$\Rightarrow dF = -PdV - SdT$$

$$dz = Mdx + Ndy$$

$$M = -P; \quad x = V; \quad N = -S; \quad y = T.$$

$$\left(\frac{\partial M}{\partial y} \right)_x = \left(\frac{\partial N}{\partial x} \right)_y$$

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

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

This is 4th Maxwell's
equation

Maxwell's Equations:

$$\textcircled{1} \left[\left(\frac{\partial T}{\partial V} \right)_S = - \left(\frac{\partial P}{\partial S} \right)_V \right]$$

$$\textcircled{2} \left[\left(\frac{\partial T}{\partial P} \right)_S = \left(\frac{\partial V}{\partial S} \right)_P \right]$$

$$\textcircled{3} \left[\left(\frac{\partial V}{\partial T} \right)_P = - \left(\frac{\partial S}{\partial P} \right)_T \right]$$

$$\textcircled{4} \left[\left(\frac{\partial P}{\partial T} \right)_V = - \left(\frac{\partial S}{\partial V} \right)_T \right]$$

⇒* Tds Equations :-

$$S = f(T, v)$$

$$ds = \left(\frac{\partial s}{\partial T}\right)_v dT + \left(\frac{\partial s}{\partial v}\right)_T dv$$

(139)

$$Tds = T\left(\frac{\partial s}{\partial T}\right)_v dT + T\left(\frac{\partial s}{\partial v}\right)_T dv \quad \text{--- (1)}$$

Now At constant pressure, i.e. $P=C$

$$\frac{dT}{ds} = T/c_p$$

$$\left(\frac{\partial T}{\partial s}\right)_P = T/c_p$$

$$c_p = T\left(\frac{\partial s}{\partial T}\right)_P \quad \text{--- (a)}$$

Similarly, $c_v = T\left(\frac{\partial s}{\partial T}\right)_v \quad \text{--- (b)}$

Also, from Maxwell's Equation :-

$$\left(\frac{\partial s}{\partial v}\right)_T = \left(\frac{\partial P}{\partial T}\right)_v \quad \text{--- (c)}$$

$$f \left(\frac{\partial s}{\partial T}\right)_T = -\left(\frac{\partial v}{\partial T}\right)_P \quad \text{--- (d)}$$

Substituting from (a) + (c) in eq: (1), we have

$$\boxed{Tds = c_v dT + T\left(\frac{\partial P}{\partial T}\right)_v dv} \quad \text{--- (A)}$$

This is known as first Tds Equation

$$S = f(T, P)$$

$$dS = \left(\frac{\partial S}{\partial T}\right)_P dT + \left(\frac{\partial S}{\partial P}\right)_T dP \dots$$

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$$T dS = T \left(\frac{\partial S}{\partial T}\right)_P dT + T \left(\frac{\partial S}{\partial P}\right)_T dP \quad \text{--- (2)}$$

Substituting from (1) + (2) in eq: (1), we have :-

$$T dS = C_p dT - T \left(\frac{\partial V}{\partial T}\right)_P dP \quad \text{--- (3)}$$

This is known as second Tds equation.

17 Nov.

Equating both T-ds equations A + B, we have

$$T dS = C_p dT + T \left(\frac{\partial P}{\partial T}\right)_V dV = C_p dT - T \left(\frac{\partial V}{\partial T}\right)_P dP$$

$$\therefore T \left(\frac{\partial V}{\partial T}\right)_P dP + T \left(\frac{\partial P}{\partial T}\right)_V dV = (C_p - C_v) dT$$

$$\therefore dT = \left(\frac{T}{C_p - C_v}\right) \left(\frac{\partial V}{\partial T}\right)_P dP + \left(\frac{T}{C_p - C_v}\right) \left(\frac{\partial P}{\partial T}\right)_V dV \quad \text{--- (1)}$$

$$T = \phi(P, V)$$

$$dT = \left(\frac{\partial T}{\partial P}\right)_V dP + \left(\frac{\partial T}{\partial V}\right)_P dV \quad \text{--- (2)}$$

Comparing eq: (1) + (2), we have :-

$$\frac{T}{C_p - C_v} \left(\frac{\partial V}{\partial T}\right)_P = \left(\frac{\partial T}{\partial P}\right)_V$$

$$(C_p - C_v) = T \left(\frac{\partial v}{\partial T} \right)_p \left(\frac{\partial p}{\partial T} \right)_v \quad \text{--- (3)}$$

Again, $T = \phi(p, v)$

(141)

from this theorem, we have

$$\left(\frac{\partial p}{\partial v} \right)_T \left(\frac{\partial v}{\partial T} \right)_p \left(\frac{\partial T}{\partial p} \right)_v = -1$$

$$\text{or, } - \left(\frac{\partial p}{\partial v} \right)_T \left(\frac{\partial v}{\partial T} \right)_p = \left(\frac{\partial p}{\partial T} \right)_v \quad \text{--- (4)}$$

Substituting eq (4) in eq (3), we have

$$(C_p - C_v) = T \left(\frac{\partial v}{\partial T} \right)_p \left[- \left(\frac{\partial p}{\partial v} \right)_T \left(\frac{\partial v}{\partial T} \right)_p \right]$$

$$C_p - C_v = -T \left[\left(\frac{\partial v}{\partial T} \right)_p \right]^2 \left(\frac{\partial p}{\partial v} \right)_T$$

⊙
This equation has been asked 9 times.

$$C_p - C_v = -T \left[\left(\frac{\partial v}{\partial T} \right)_p \right]^2 \left(\frac{\partial p}{\partial v} \right)_T \quad \ominus \text{ve}$$

$$C_p - C_v = +ve.$$

$$\text{or } C_p - C_v > 0$$

$$C_p > C_v \quad \text{--- (D)}$$

$$\left[\frac{dv}{dv} = -1/v \right]$$

for an isothermal process $\left(\frac{\partial p}{\partial v} \right)$ is always negative
square of a quantity is always positive
Temperature can never be negative.

⇒ * CO-EFFICIENT OF VOLUME EXPANSIVITY (β): -

It shows variation of volume with respect to temperature under isobaric conditions.

$$\beta = \frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_P \quad \text{--- (E)}$$

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⇒ * ISOTHERMAL COMPRESSIBILITY (K_T): -

This shows variation of volume with respect to pressure under isothermal conditions.

$$K_T = -\frac{1}{V} \left(\frac{\partial V}{\partial P} \right)_T \quad \text{--- (F)}$$

$$K_T = -\frac{1}{V} \left(\frac{\partial V}{\partial P} \right)_T \Rightarrow \left(\frac{\partial P}{\partial V} \right)_T = -\frac{1}{K_T V}$$

Again

$$\beta = \frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_P \Rightarrow \left(\frac{\partial V}{\partial T} \right)_P = \beta V$$

Now

$$C_p - C_v = -T \left[\left(\frac{\partial V}{\partial T} \right)_P \right]^2 \left(\frac{\partial P}{\partial V} \right)_T$$

$$C_p - C_v = -T \left[\beta^2 V^2 \right] \times \frac{-1}{K_T V}$$

$$C_p - C_v = \frac{T V \beta^2}{K_T} \quad \text{--- (G)}$$

This has been asked 13 times.

⇒ ⇒ ENERGY EQUATION : →

$$TdS = dU + PdV$$

$$dU = TdS - PdV$$

$$\Rightarrow dU = C_v dT + \underbrace{T \left(\frac{\partial P}{\partial T} \right)_V}_{\text{from 1st T-ds Equation}} dV - PdV$$

(143)

$$\Rightarrow dU = C_v dT + \left[T \left(\frac{\partial P}{\partial T} \right)_V - P \right] dV \quad \text{--- (1)}$$

Now

$$U = f(T, V)$$

$$dU = \left(\frac{\partial U}{\partial T} \right)_V dT + \left(\frac{\partial U}{\partial V} \right)_T dV \quad \text{--- (2)}$$

Comparing equation (1) & (2), we have.

$$C_v = \left(\frac{\partial U}{\partial T} \right)_V ; \quad \& \quad \left(\frac{\partial U}{\partial V} \right)_T = T \left(\frac{\partial P}{\partial T} \right)_V - P$$

Now

for an ideal gas:

$$PV = mRT$$

$$P = \frac{mk}{V} \cdot T$$

for constant volume, this is of the form $y = cx$ ($\because \frac{mk}{V} = c$)

$$\therefore \frac{dy}{dx} = c$$

$$\therefore \left(\frac{\partial P}{\partial T} \right)_V = \frac{mk}{V}$$

$$\text{Also, } \frac{mk}{V} = \frac{P}{T}$$

$$\therefore \left(\frac{\partial p}{\partial T}\right)_V = \frac{mR}{V} = \frac{p}{T}$$

$$\left(\frac{\partial p}{\partial T}\right)_V = \frac{p}{T}$$

$$T \left(\frac{\partial p}{\partial T}\right)_V = p$$

$$\text{or } T \left(\frac{\partial p}{\partial T}\right)_V - p = 0 \quad \text{--- (3)}$$

Putting the value of (3) in eq. (1) :-

$$dU = C_V dT + \left[T \left(\frac{\partial p}{\partial T}\right)_V - p \right] dV \quad \text{--- (H)}$$

This is energy equation.

for ideal gas,

$$\left[T \left(\frac{\partial p}{\partial T}\right)_V - p \right] = 0.$$

$$\therefore \boxed{dU = C_V dT} \quad \text{--- (1) This is for an ideal gas.}$$

for an ideal gas :-

$$\left(\frac{\partial U}{\partial V}\right)_T = T \left(\frac{\partial p}{\partial T}\right)_V - p = 0.$$

$$\text{It means } \boxed{\left(\frac{\partial U}{\partial V}\right)_T = 0.} \quad \text{--- (2) (3)}$$

i.e. ((The internal ^{energy} ~~change~~ of an ideal gas does not change even if the volume changes.

It means internal energy is independent of volume for an ideal gas.))

With respect to β :

For an ideal gas under isothermal conditions, there is no change of internal energy with respect to volume. i.e. internal energy of an ideal gas is independent of volume.

$$U = f(T, P, V)$$

$$T = \phi(U, P, V)$$

(145)

From 2nd theorem, we have:-

$$\left(\frac{\partial U}{\partial P}\right)_T \left(\frac{\partial P}{\partial V}\right)_T \left(\frac{\partial V}{\partial U}\right)_T = 1$$

$$\left(\frac{\partial U}{\partial V}\right)_T = \left(\frac{\partial U}{\partial P}\right)_T \left(\frac{\partial P}{\partial V}\right)_T$$

$$\text{for an ideal gas, } \left(\frac{\partial U}{\partial V}\right)_T = 0.$$

$$0 = \left(\frac{\partial U}{\partial P}\right)_T \left(\frac{\partial P}{\partial V}\right)_T$$

\hookrightarrow This is always negative.

$$\boxed{\left(\frac{\partial U}{\partial P}\right)_T = 0}$$

— (B)

With respect to β :

This shows that the internal energy of an ideal gas does not vary with respect to pressure under isothermal conditions. Therefore, internal energy of an ideal gas is a function of temperature.

⇒ * JOULE THOMSON COEFFICIENT (μ) :-

Joule Thomson coefficient shows variation of temperature with respect to pressure under throttling or isenthalpic conditions.

$$\mu = \left(\frac{\partial T}{\partial P} \right)_h \quad \text{--- (J)}$$

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⇒ *

$$T ds = dh - v dp$$

$$dh = T ds + v dp$$

$$\Rightarrow dh = C_p dT - T \left(\frac{\partial v}{\partial T} \right)_P dp + v dp$$

(From 2nd Tds Equation)

$$\Rightarrow dh = C_p dT - \left[T \left(\frac{\partial v}{\partial T} \right)_P - v \right] dp \quad \text{--- (1)}$$

for an ideal gas:-

$$PV = mRT$$

$$V = \frac{mR}{P} \cdot T$$

This is of the form $y = cx$ ($\because P = c$).

$$\therefore \left(\frac{\partial v}{\partial T} \right)_P = \frac{mR}{P}$$

$$\text{But, } \frac{mR}{P} = \frac{V}{T}$$

$$\therefore \left(\frac{\partial v}{\partial T} \right)_P = \frac{mR}{P} = \frac{V}{T}$$

$$\therefore T \left(\frac{\partial v}{\partial T} \right)_P - v = 0$$

$$\therefore dh = C_p dT - \left[T \left(\frac{\partial v}{\partial T} \right)_P - v \right] dp$$

$$\Rightarrow dh = C_p dT - 0 \quad (\text{for ideal gas})$$

$$\Rightarrow \boxed{dh = C_p dT} \quad \text{--- (K)}$$

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for an ideal gas, $dh = C_p dT$.

for throttling, $h = \text{const}$, $dh = 0$.

$$\therefore 0 = C_p dT - \left[T \left(\frac{\partial v}{\partial T} \right)_P - v \right] dp$$

$$\text{or, } C_p dT = \left[T \left(\frac{\partial v}{\partial T} \right)_P - v \right] dp$$

$$\frac{dT}{dp} = \frac{1}{C_p} \left[T \left(\frac{\partial v}{\partial T} \right)_P - v \right]$$

$$\left(\frac{\partial T}{\partial p} \right)_h = \frac{1}{C_p} \left[T \left(\frac{\partial v}{\partial T} \right)_P - v \right]$$

$$\Rightarrow \mu = \frac{1}{C_p} \left[T \left(\frac{\partial v}{\partial T} \right)_P - v \right]$$

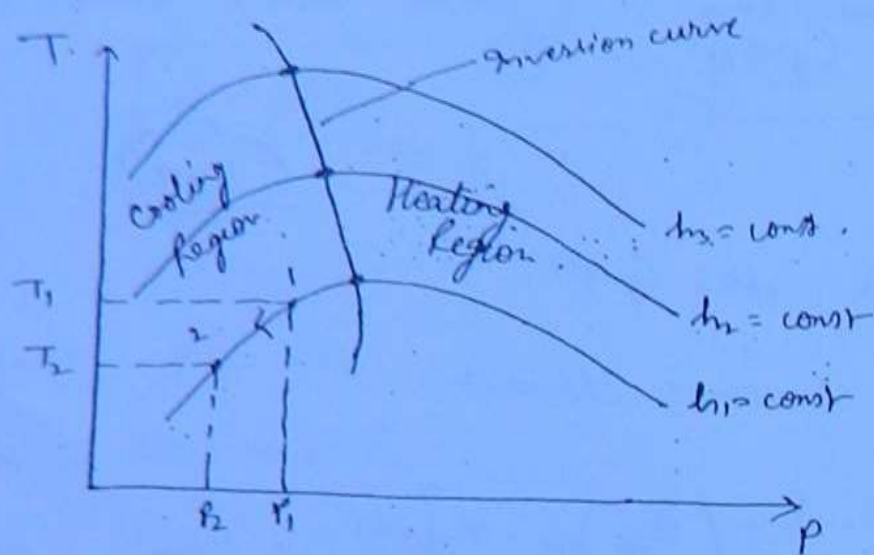
for an ideal gas,

$$T \left(\frac{\partial v}{\partial T} \right)_P - v = 0$$

$$\therefore \boxed{\mu = 0} \quad (\text{for an ideal gas}) \quad \text{--- (L)}$$

Joule-Thomson coefficient for an ideal gas is zero.

For an ideal gas, as enthalpy is a function of temperature, under throttling conditions, as enthalpy remains constant, temperature also remains constant.



$$\text{Slope} \rightarrow \left(\frac{\partial T}{\partial p} \right)_h$$

$$\mu = \left(\frac{\partial T}{\partial p} \right)_h = \text{slope of isenthalpic curves 'on } T-p \text{ diagram.}$$

for cooling region, $\mu = \oplus$ ve.

for heating region, $\mu = \ominus$ ve.

Joule Thomson co-efficient is positive or ~~negat~~ slope of isenthalpic curves on T-p diagram is positive in cooling region. Similarly Joule Thomson co-efficient or slope of isenthalpic curves is negative in heating region.

⇒ PROPERTIES OF PURE SUBSTANCES ⇒

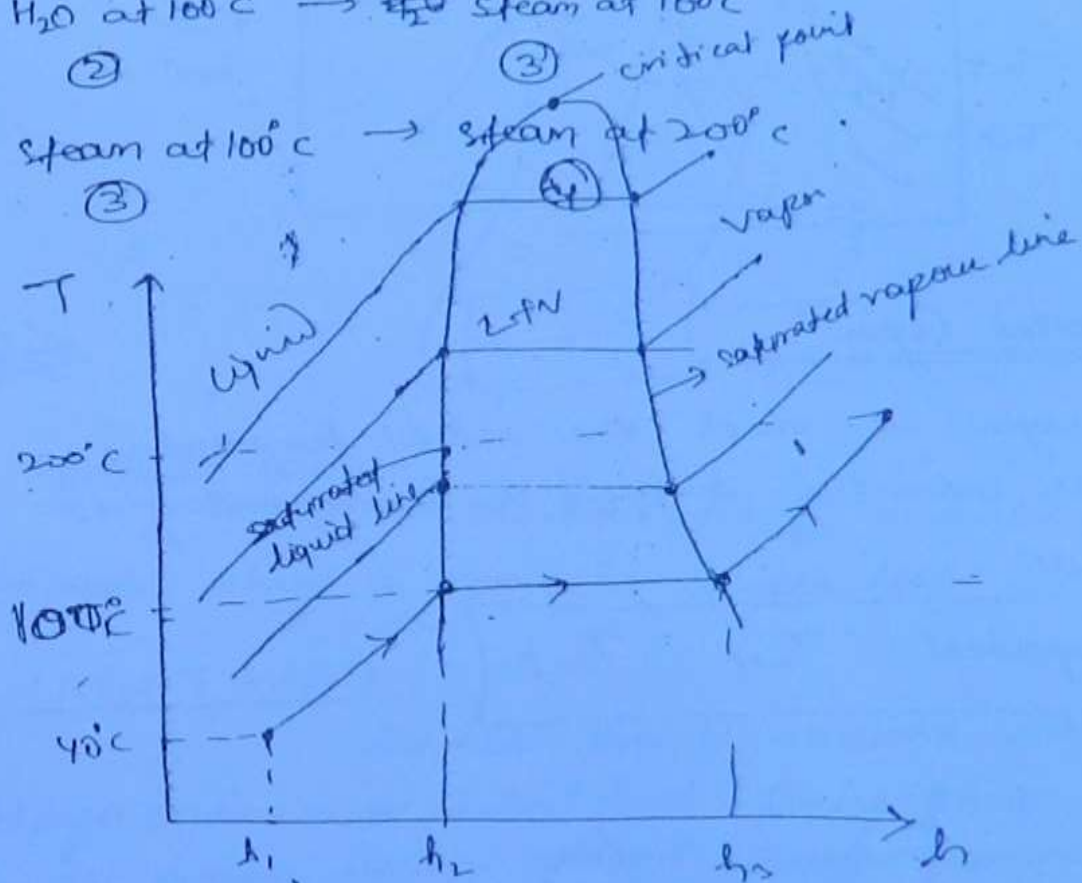
H_2O at $40^\circ C$ → steam at $200^\circ C$
 when pressure is atmospheric.

(149)

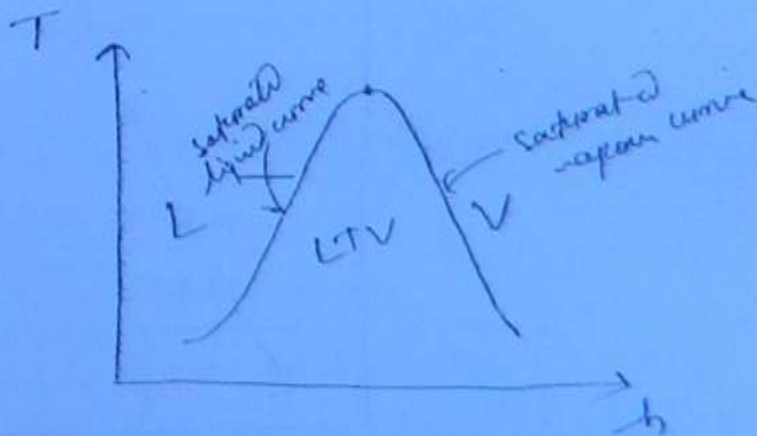
I. H_2O at $40^\circ C$ → H_2O at $100^\circ C$
 (1) (2)

II. H_2O at $100^\circ C$ → ~~H_2O~~ steam at $100^\circ C$
 (2) (3) critical point

III. steam at $100^\circ C$ → steam at $200^\circ C$
 (3) (4)



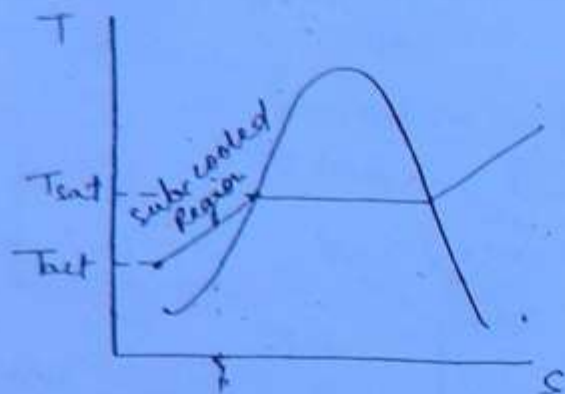
Critical point is the point at which saturated liquid and saturated vapour meet.



⇒* Sub-cooled or under cooled Region :-

It is a region in which the actual temperature is less than saturation temperature corresponding to that pressure.

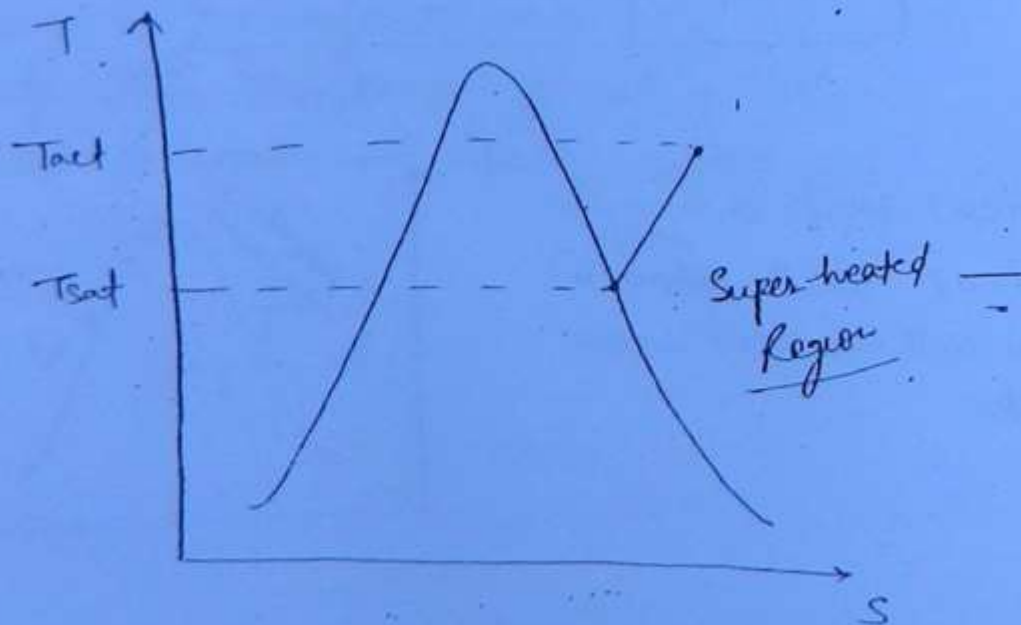
$$\text{Degree of subcooling} = T_{\text{saturation}} - T_{\text{actual}}$$



⇒* Super-heated Region :-

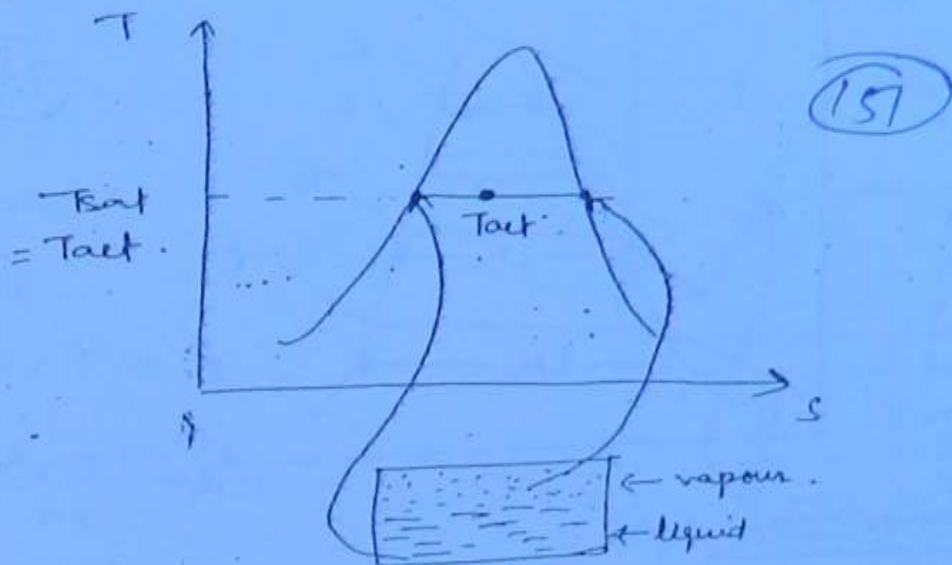
It is a region in which the actual temperature is greater than saturation temperature corresponding to that pressure.

$$\text{Degree of superheat} = T_{\text{act}} - T_{\text{sat}}$$



⇒ * Wet Region :-

It is a region in which both liquid and vapour exist in equilibrium. For wet region, the actual temperature is equal to saturation temperature i.e. ($T_{act} = T_{sat}$).

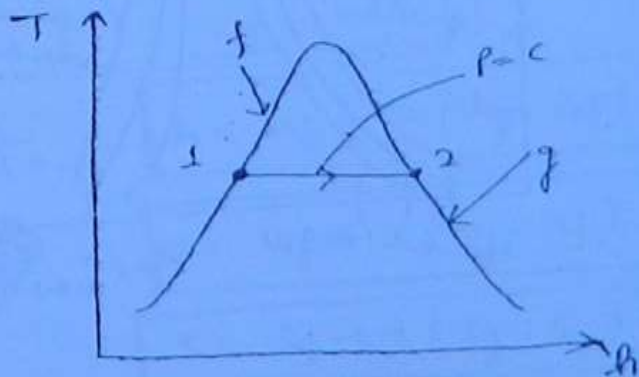


⇒ * SENSIBLE HEAT :-

The heat transfer associated with temperature change is known as sensible heat.

⇒ * LATENT HEAT :-

The heat transfer associated with phase change is known as latent heat. During phase change as the pressure remains constant, therefore latent heat is equal to change in enthalpy.



$$LH = Q_{12} = Q_p = dH$$

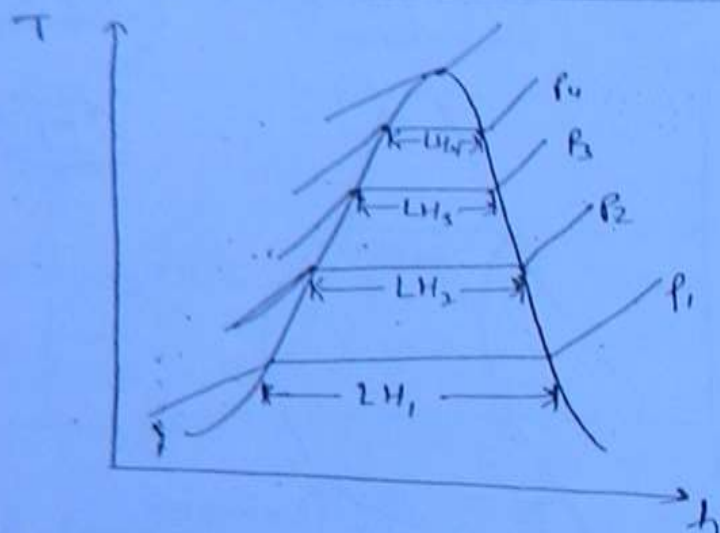
$$LH = dh$$

$$LH = h_2 - h_1$$

$$LH = h_g - h_f = h_{fg}$$

Note:-

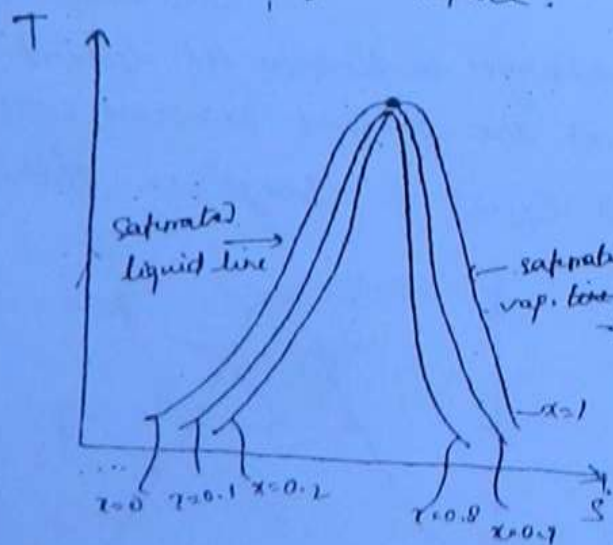
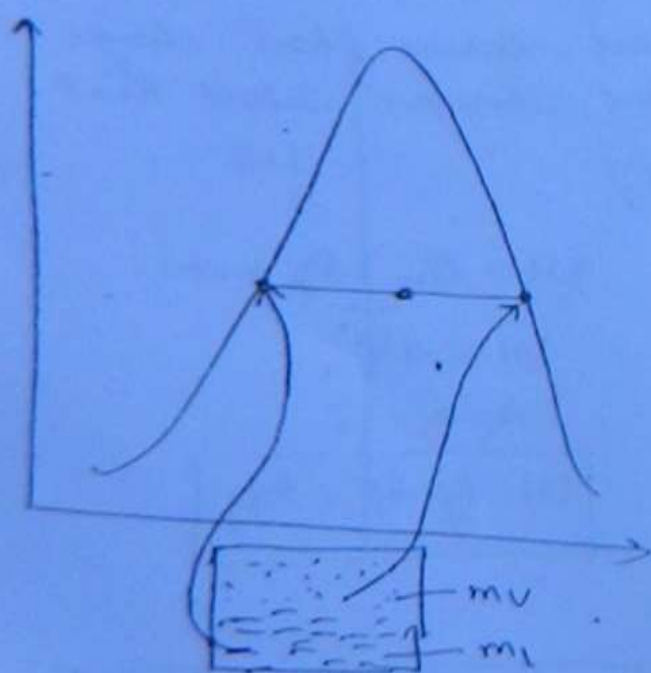
With increase in pressure, ^{the} latent heat of vaporization decreases and at critical point latent heat of vaporisation is equal to zero.



(152)

⇒ * DRYNESS FRACTION :->

It is defined as the ratio of mass of vapour to the total mass of the mixture. The dryness fraction along saturated liquid curve = 0 and the dryness fraction along saturated vapour curve is equal to 1. The dryness fraction is also known as quality of mixture.



$$x = \frac{m_v}{m_v + m_l}$$

⇒ * SPECIFIC VOLUME OF MIXTURE :-

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$$v = V/m$$

$$V = vm$$

$$m = m_v + m_l$$

$$V = v_v + v_l$$

$$mv = m_v v_v + m_l v_l$$

$$v = \frac{m_v v_v + m_l v_l}{m}$$

$$v = \frac{m_v}{m} v_v + \frac{m_l}{m} v_l$$

$$v = \frac{m_v}{m_v + m_l} v_v + \frac{m_l}{m_v + m_l} v_l$$

$$v = x v_v + (1-x) v_l$$

$$v = x v_v + v_l - x v_l$$

$$v = v_l + x (v_v - v_l)$$

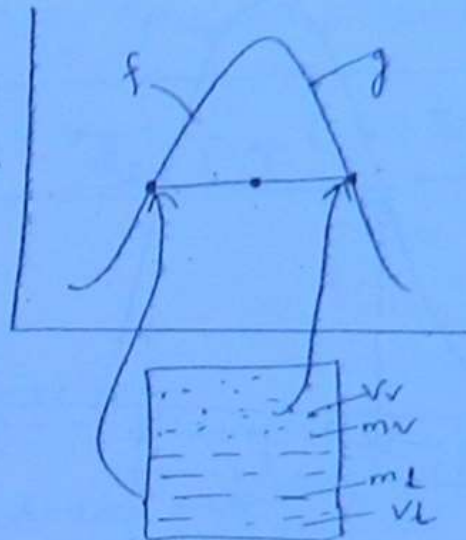
$$v = v_f + x (v_g - v_f)$$

Similarly

$$h = h_f + x (h_g - h_f)$$

$$u = u_f + x (u_g - u_f)$$

$$s = s_f + x (s_g - s_f)$$

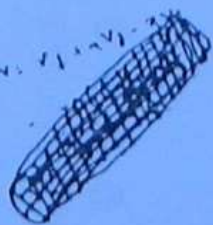


$$x = \frac{m_v}{m_v + m_l}$$

$$1-x = 1 - \frac{m_v}{m_v + m_l}$$

$$1-x = \frac{m_l}{m_v + m_l}$$

These equations must be used when the point is in wet region.

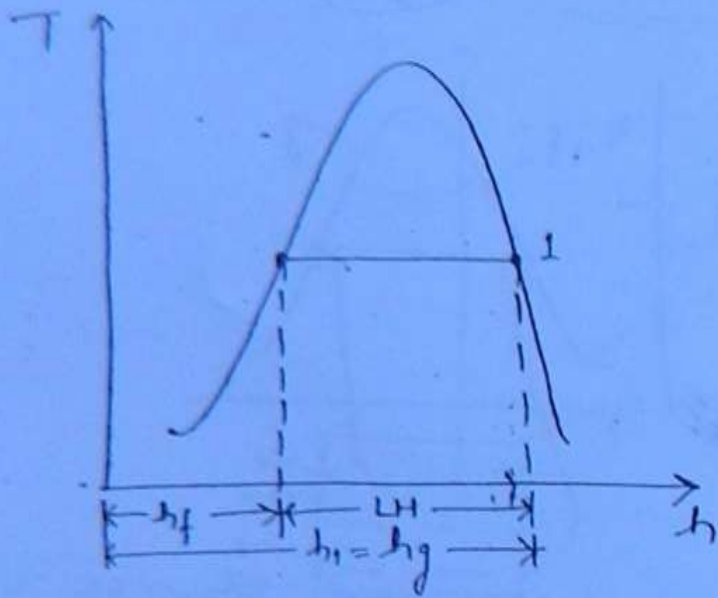


ENTHALPY AT VARIOUS POINTS I - (V.V.1)

CASE - I:

when the point is on saturated vapour curve.

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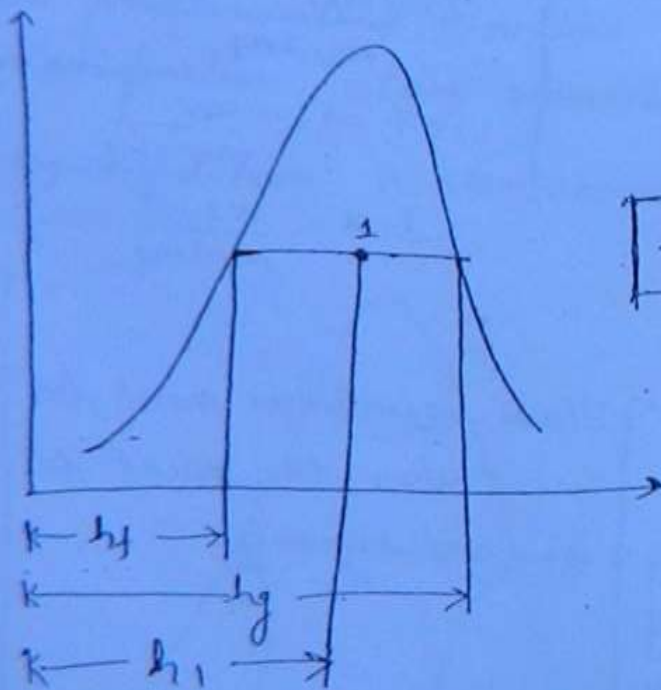
$$h_g = h_1 = h_f + LH$$

$$h_g = h_f + LH$$

$$\boxed{h_g - h_f = LH}$$

Case - II:

when the point is in wet region.



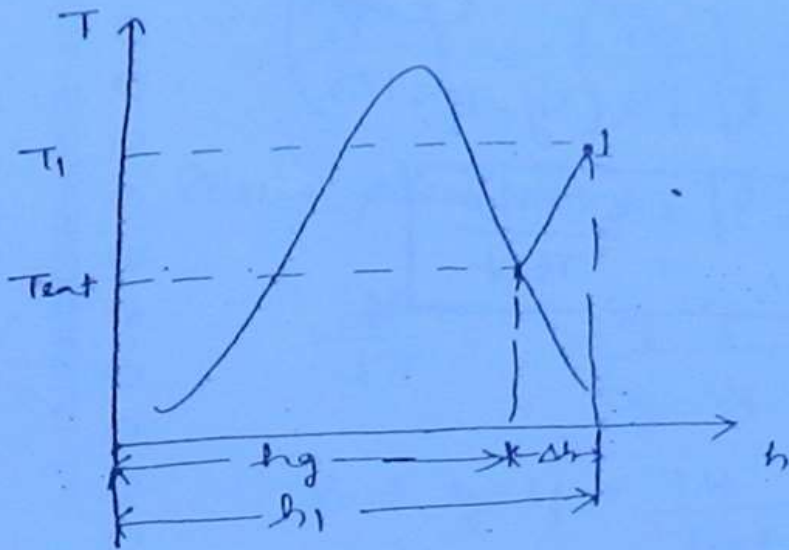
$$h_1 = h_f + x(h_g - h_f)$$

$$\boxed{h_1 = h_f + x(LH)}$$

$$\therefore (h_g - h_f) = h_{fg} = LH.$$

Case - III

when the point is in superheated region.



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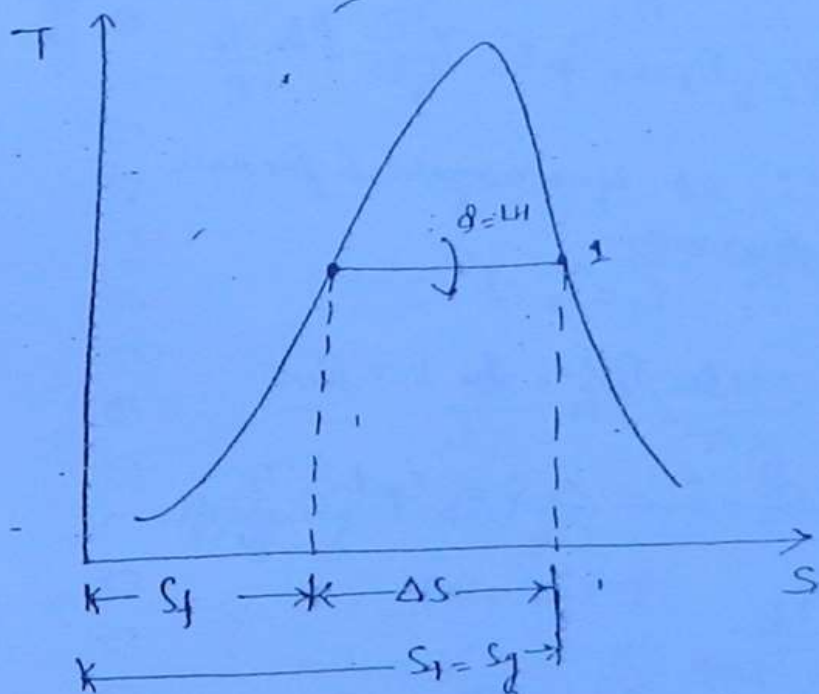
$$h_1 = h_g + \Delta h$$

$$\Delta h = C_{p, \text{vap.}} (T_1 - T_{\text{sat}})$$

$$h_1 = h_g + C_{p, \text{vap.}} (T_1 - T_{\text{sat}})$$

⇒ * ENTROPY AT VARIOUS POINTS :-

Case - I: when the point is on saturated vapour curve.



$$s_1 = s_f + \Delta s$$

$$ds = \frac{dq}{T}$$

$$\Delta s = \frac{LH}{T_{\text{sat}}}$$

$$s_1 = s_f + \frac{LH}{T_{\text{sat}}}$$

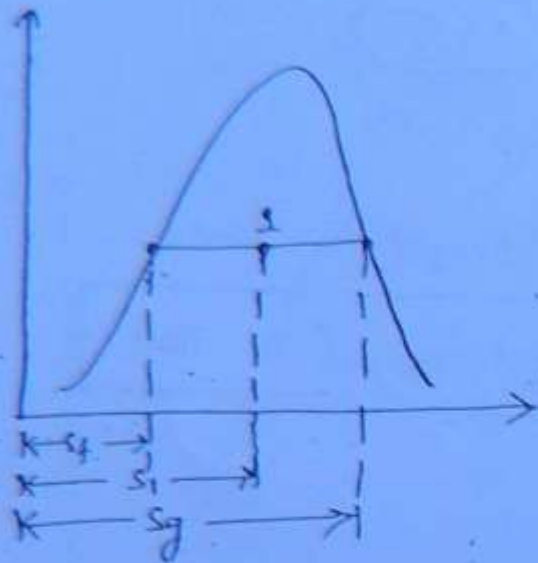
$$s_g = s_f + \frac{LH}{T_{\text{sat}}}$$

$$s_g - s_f = \frac{LH}{T_{\text{sat}}}$$

Case-II:

When the point is in wet region.

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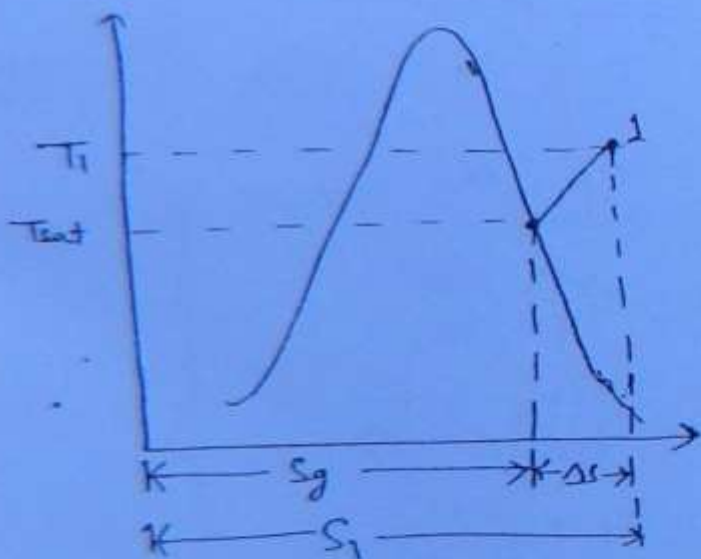


$$s_1 = s_f + x(s_g - s_f)$$

$$s_1 = s_f + x \frac{LH}{T_{sat}}$$

Case-III:

When the point is in super heated region.



$$s_1 = s_g + \Delta s$$

$$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1}$$

\because It is a constant pressure process.

$$\therefore p_1 = p_2$$

$$\therefore \ln \frac{p_2}{p_1} = \ln 1 = 0$$

$$\therefore s_2 - s_1 = \Delta s = c_p \ln \frac{T_2}{T_1}$$

Here, $\Delta s = c_{p, \text{vap}} \ln \frac{T_1}{T_{sat}}$

$$s_1 = s_g + c_{p, \text{vap}} \ln \frac{T_1}{T_{sat}}$$

CLAUDE
⇒ * CLAUSIUS CLAPEYRON EQUATION :->

$$\left(\frac{\partial p}{\partial T}\right)_V = \left(\frac{\partial s}{\partial V}\right)_T$$

(157)

During phase change p & T are independent of volume.

$$\therefore \frac{dp}{dT} = \frac{s_g - s_f}{v_g - v_f}$$

$$\text{But } s_g - s_f = \frac{LH}{T_{\text{sat}}}$$

$$\therefore \boxed{\frac{dp}{dT} = \frac{LH}{T_{\text{sat}}(v_g - v_f)}} \rightarrow \text{Clapeyron Equation}$$

05/08/2011

$$\frac{dp}{dT} = \frac{LH}{T_{\text{sat}}(v_g - v_f)}$$

$$\therefore v_g \gg v_f$$

$\therefore v_f$ can be neglected.

$$\text{Thus, } \frac{dp}{dT} = \frac{LH}{Tv_g} \quad \text{--- (1)}$$

Applying ideal gas equation,

$$pV = mRT$$

$$\Rightarrow \frac{v}{m} = \frac{RT}{p}$$

$$\text{or } v = \frac{RT}{p} \quad \text{--- (2)}$$

Putting the value of (2) in eq (1), we have.

$$\frac{dP}{dT} = \frac{LH}{T \times \frac{RT}{P}}$$

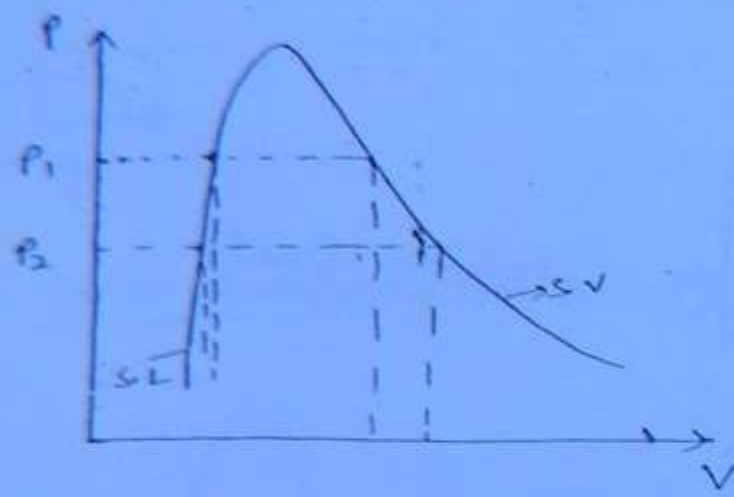
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$$\frac{dP}{dT} = \frac{P(LH)}{RT^2}$$

V.V.V

- This is known as Clausius - Clapeyron Equation.

P-V DIAGRAM! →



MOLLIER DIAGRAM! →

In subcooled region and superheated region, both temperature and pressure can be varied independently and hence, the degree of freedom in these regions is equal to two (2).

But in wet region, constant pressure and constant temperature lines are same and hence, the degree of freedom in wet region is equal to one (1).

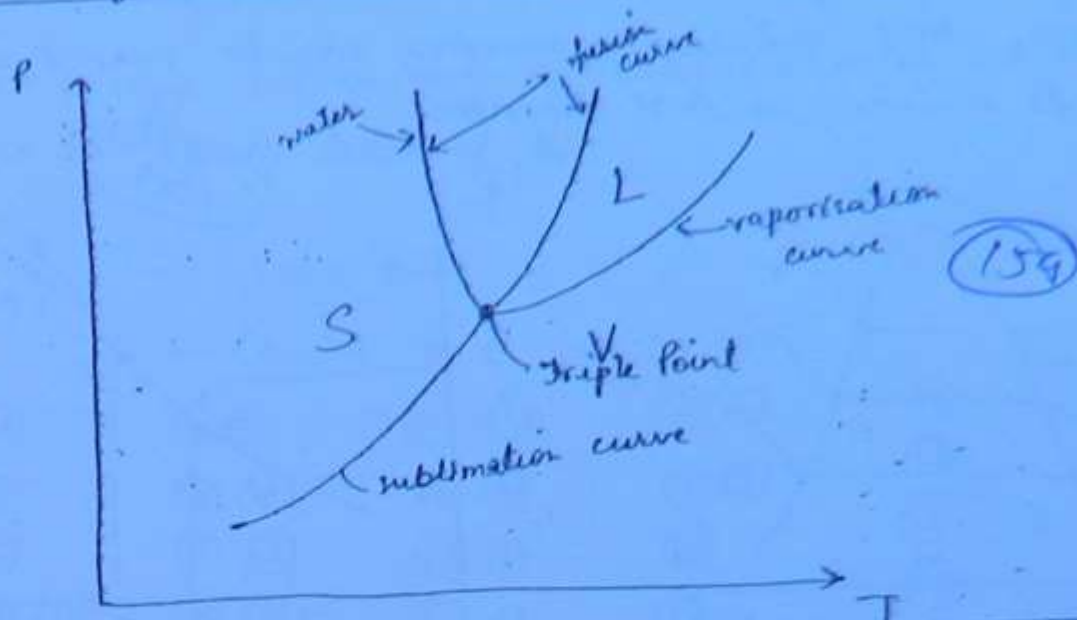
- L → Melting
- S → Freezing
- V → Vaporization
- L → Condensation
- V → Sublimation

General Substances
 S-L → Melts → Expands
 L-S → freeze → Contract

Water
 S-L → Melts → Contract
 L-S → freeze → Expands

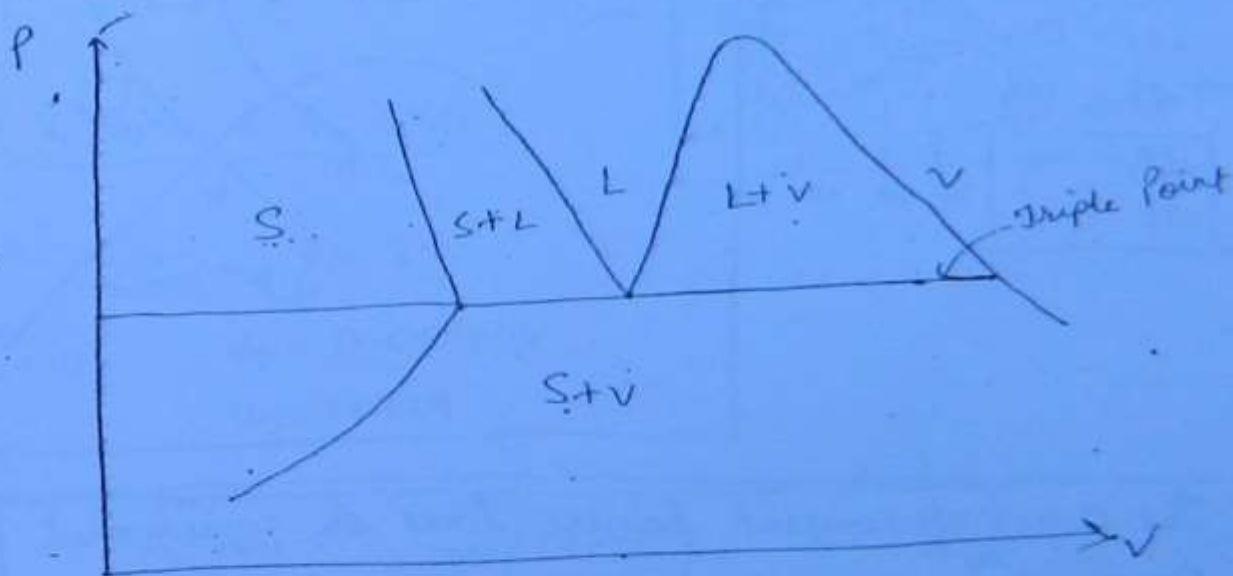
because of cleavage of hydrogen bonding and case like substance.

⇒* Solid - liquid and vapour curve with triple point



Note!

The slope of fusion curve on P-T diagram is positive for general substances and negative for water.



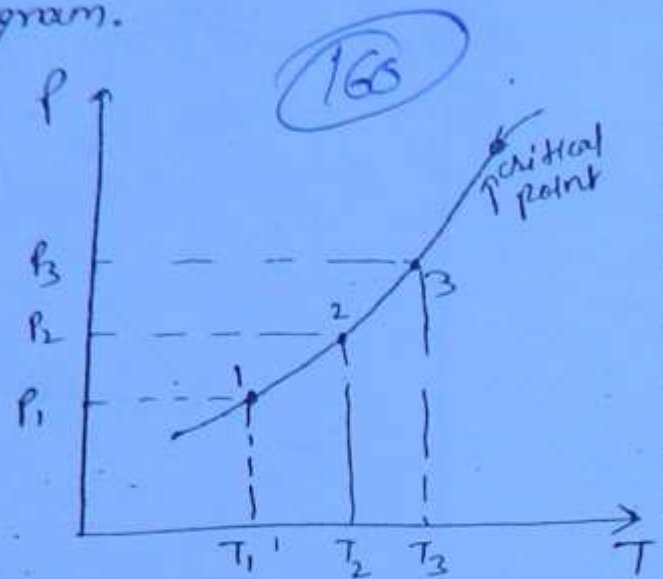
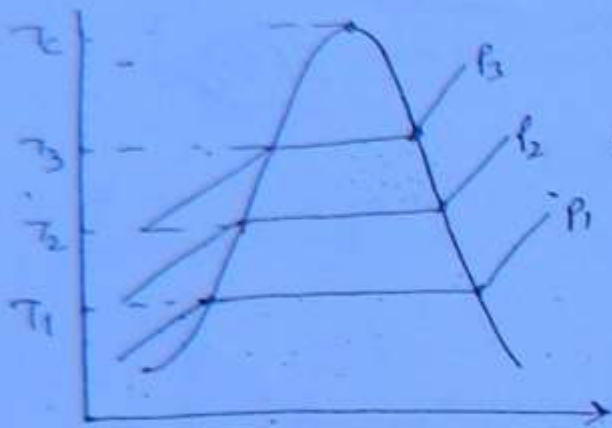
Triple Point data for water

$$P_{tp} = 0.006113 \text{ bar}$$

$$t_{tp} = 0.01^\circ\text{C}$$

According to Gibb's phase rule, the degree of freedom at triple point is 0 i.e. no intensive parameters can

be varied at triple point. Therefore, it is a point on P-T diagram, but extensive properties can be varied and hence it is a line on P-V diagram.



⇒ * MOLLIER DIAGRAM →

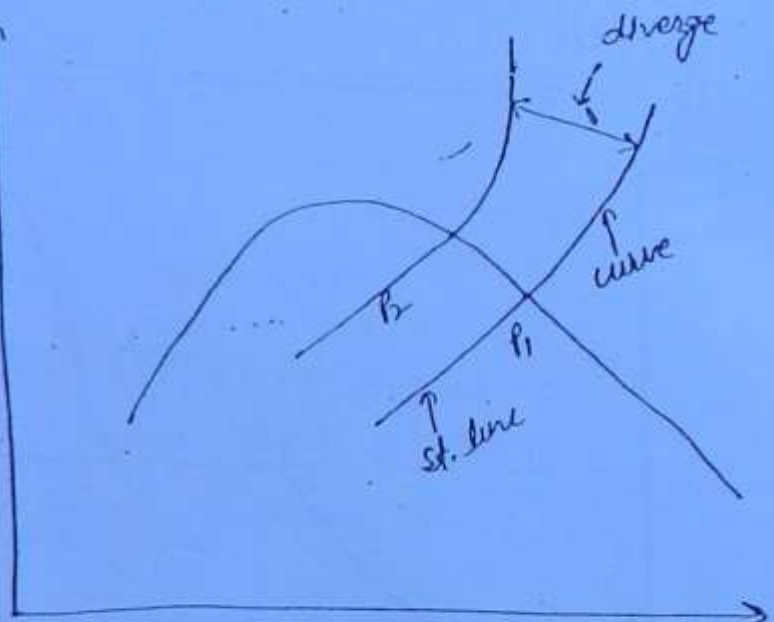
$$T ds = dh - v dp$$

$$p = \text{const}$$

$$dp = 0$$

$$T ds = dh$$

$$\therefore \boxed{\frac{dh}{ds} = T}$$



Note:

The slope of constant pressure lines in superheated region increases because the temperature increases and hence constant pressure lines diverge in superheated region.

⇒ * REFERENCE STATE IN STEAM TABLE: →

Internal energy and entropy of saturated water at triple point is arbitrarily taken as zero.

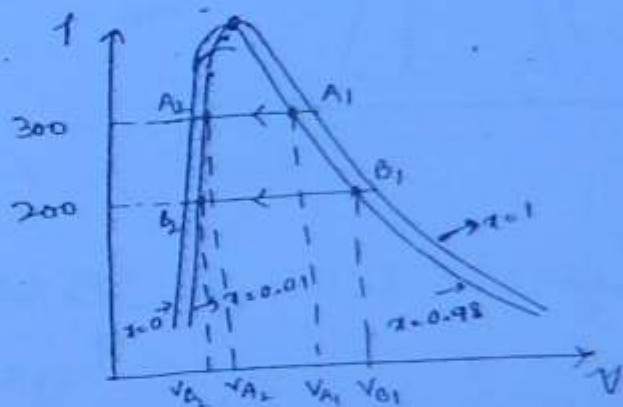
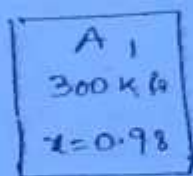
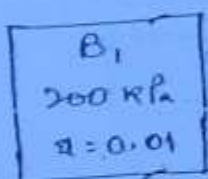
Work Book

(161)

Chapter - 6

- | | | | | | | | | | |
|---|------------------------------------------|---|-----|---|-----|---|-----|---|-----|
| ① | (d) | ⑥ | (c) | ⑪ | (a) | ⑱ | (b) | ⑳ | (a) |
| ② | (a) | ⑦ | (b) | ⑫ | (c) | ⑲ | (d) | ㉑ | (b) |
| ③ | (c) | ⑧ | (d) | ⑬ | (b) | ⑳ | (b) | ㉒ | (c) |
| ④ | (a), (b)
<small>small capital</small> | ⑨ | (b) | ⑭ | (b) | ㉓ | (b) | ㉔ | (b) |
| ⑤ | (c) | ⑩ | (c) | ⑮ | (c) | ㉔ | (c) | ㉕ | (c) |

①



④ $(V_{B1} > V_{A1} \text{ \& } V_{A2} > V_{B2})$

②



$V_V = 8V_L$

$x = \frac{mV}{mV + mL}$

$V_f = 0.001044$

$U_g = 1.6729$

$x = \frac{mV}{mV + mL} = \frac{mV}{mV(1 + \frac{mL}{mV})} = \frac{1}{1 + \frac{mL}{mV}}$

$V = V/m \text{ or } m = V/v$

$m_V = \frac{V_V}{v_V} \neq \frac{8V_L}{v_V}$

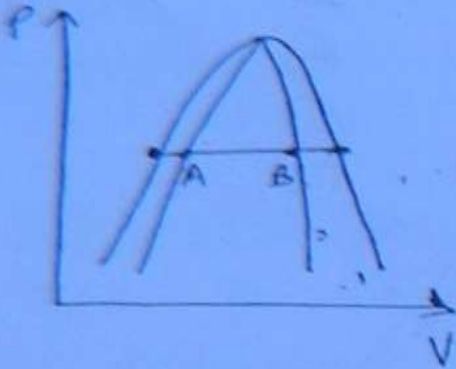
$m_L = \frac{V_L}{v_L}$

$$\alpha = \frac{1}{1 + \frac{V_L}{V_L} \times \frac{V_V}{8V_L}} \Rightarrow \alpha = \frac{1}{1 + \frac{V_L}{V_L} \times \frac{V_V}{8V_L}}$$

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$$= \frac{1}{1 + \frac{1}{8} \left(\frac{1.6729}{0.001044} \right)}$$

$$\therefore \alpha = 0.0049 \approx 0.005 \quad \text{④}$$



$$U_A = U_B$$

$$m_A U_A = m_B U_B$$

$$\frac{m_A}{m_B} = \frac{U_B}{U_A} = \frac{u_f + \alpha_B (u_g - u_f)}{u_f + \alpha_A (u_g - u_f)}$$

$$= \frac{u_f + u_g - u_f}{u_f}$$

$$= \frac{u_g}{u_f} = \frac{2583.6}{761.7} = \underline{\underline{3.4}} \quad \text{⑤}$$

$$\textcircled{7} \quad \rho = 36.12 \text{ kg/m}^3$$

$$T = -30^\circ\text{C} = 243 \text{ K.}$$

$$\rho_f = 1377 \text{ kg/m}^3, \quad \rho_g = 7.379 \text{ kg/m}^3.$$

$$v = v_f + x(v_g - v_f)$$

$$v = \frac{V}{m} = \frac{V/m}{v} = \frac{1}{\rho}$$

$$\underline{\underline{\text{or}}} \quad \rho = \frac{m}{V}$$

$$\frac{1}{\rho} = \frac{1}{\rho_f} + x \left(\frac{1}{\rho_g} - \frac{1}{\rho_f} \right)$$

$$\Rightarrow \frac{1}{36.12} = \frac{1}{1377} + x \left(\frac{1}{7.379} - \frac{1}{1377} \right)$$

$$\therefore \boxed{x = 0.2} \quad \textcircled{b}$$

$$\textcircled{8} \quad Q = h_2 - h_1$$

Given: $x = 0.4$, $v = 1 \text{ m}^3$, $P = 200 \text{ kPa}$, $h_2 = 125.7 \text{ kJ/kg}$.

$$h_1 = h_f + x(h_g - h_f)$$

$$= 504.7 + 0.4(2706.7 - 504.7)$$

$$\therefore h_1 = 1385.5 \text{ kJ/kg}$$

$$\therefore Q = h_2 - h_1 = (125.7 - 1385.5) = -1259.8 \text{ kJ/kg}$$

(-ve sign mean heat rejection)

Now,

$$v = \frac{V}{m} \quad \text{or} \quad m = \frac{V}{v}$$

$$v = v_f + x(v_g - v_f)$$

$$= 0.001061 + 0.4(0.3857 - 0.001061)$$

$$\therefore v = 0.355$$

$$\therefore m = \frac{V}{v} = \frac{1}{0.355} = 2.8 \text{ kg.}$$

$$\therefore Q = -1259.8 \times 2.8$$

$$= \underline{\underline{-3550 \text{ kJ}}} \quad \text{(d)}$$

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$$\textcircled{9} \quad T = 99.63^\circ\text{C}$$

$$s = s_f + x(s_g - s_f)$$

$$(s_g - s_f) = \frac{LH}{T_{\text{sat}}}$$

$$\Rightarrow (s_g - s_f) = \frac{(h_{fg} - h_f)}{T_{\text{sat}}} = \frac{2675.5 - 417.5}{372.63}$$

$$\therefore (s_g - s_f) = 6.0596$$

$$\therefore s_g = s_f + 6.0596 = 1.3026 + 6.0596$$

$$\therefore \boxed{s_g = 7.362 \text{ kJ/kg K}} \quad \text{(b)}$$

$$\textcircled{10} \quad V = 20 \text{ m}^3$$

$$x = 1, \quad p_1 = 1 \text{ MPa}, \quad p_2 = 0.1 \text{ MPa}$$

$$T = 300 \text{ K}$$

$$Q = u_2 - u_1$$

$$u_1 = u_f - x(u_g - u_f)$$

=

$$u_2 =$$

The system undergoes constant volume process and hence heat transfer is equal to change in internal energy.

(2)

Adiabatic ($dQ=0$)

Rev.

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

$$ds = 0$$

$$s = \text{const.}$$

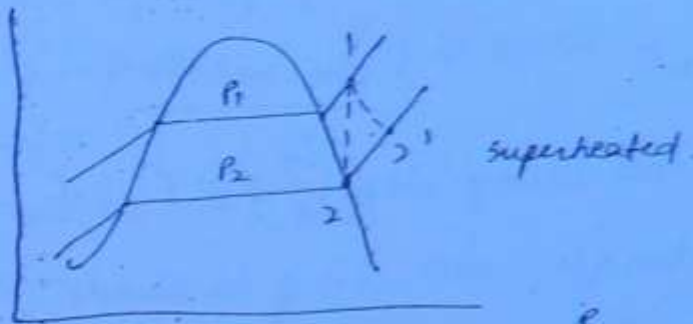
Irrev.

(165)

$$ds = \left(\frac{dQ}{T}\right)_{\text{irr.}} + (ds)_{\text{gen.}}$$

$$ds = (ds)_{\text{gen.}}; (ds) > 0$$

$$ds > 0$$



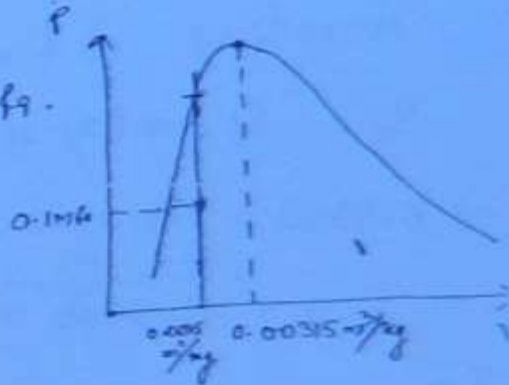
(18)

$$v_c = 0.003155 \text{ m}^3/\text{kg}$$

$$V = 0.025 \text{ m}^3, \quad P = 0.1 \text{ MPa} = 100 \text{ kPa}$$

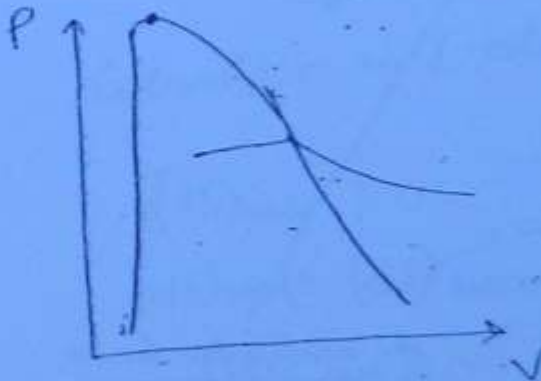
$$m = 10 \text{ kg}$$

$$v = \frac{V}{m} = 0.0025 \text{ m}^3/\text{kg}$$



As the m constant volume heating, the line is moving towards liquid line.
 Hence, liquid level will rise.

(19)



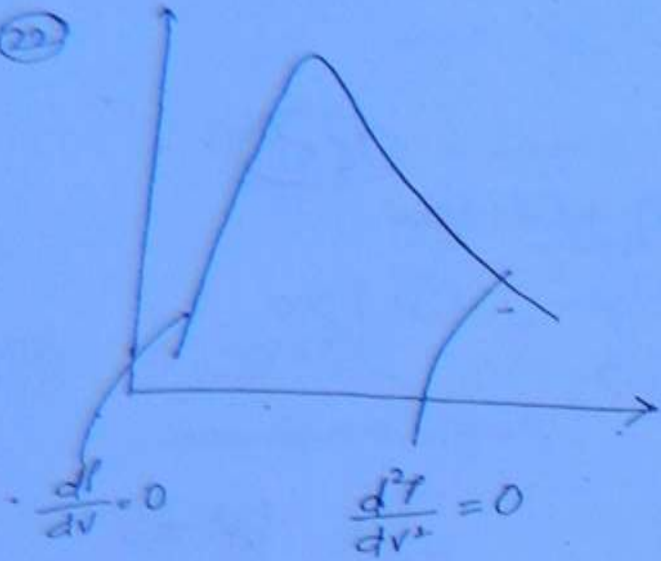
$$PV = nRT \rightarrow C$$

$$PV = C$$

(21)

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from Mathematics.

for max^m

$$\left(\frac{dy}{dx}\right) = 0 \text{ \& } \frac{d^2y}{dx^2} < 0.$$

for min^m

$$\left(\frac{dy}{dx}\right) = 0 \text{ \& } \frac{d^2y}{dx^2} > 0.$$

$$\frac{d^2y}{dx^2} < 0.$$

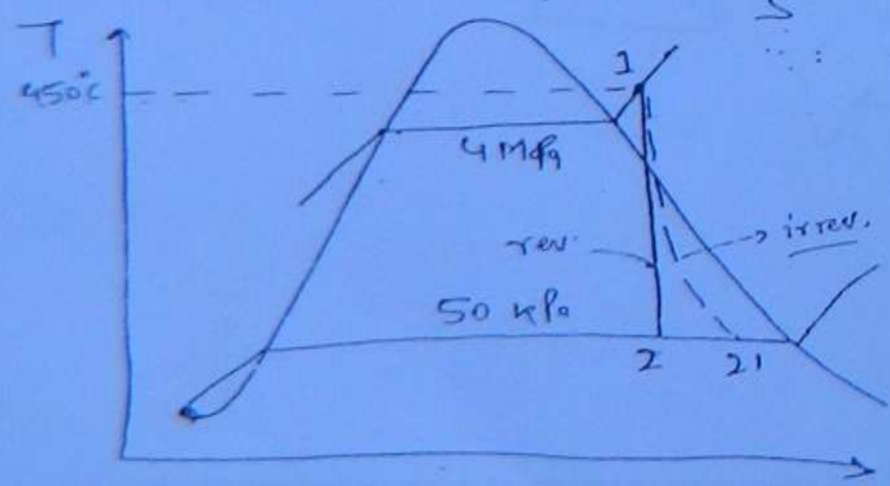
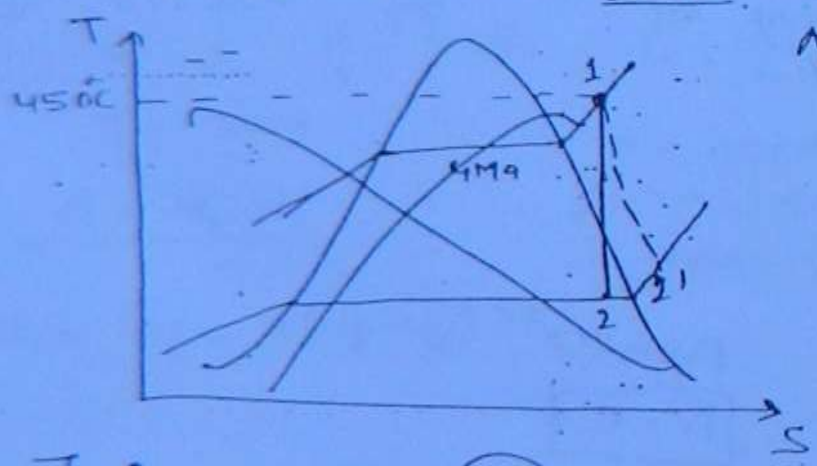
$$\frac{d^2y}{dx^2} > 0.$$

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$$S_2 = S_f + \alpha (S_g - S_f)$$

$$\Rightarrow 6.9362 = 1.091 + \alpha (7.5939 - 1.091)$$

$$\therefore \alpha = 0.8988 \approx \underline{\underline{0.9}}$$



for adiabatic process,

only two conditions are possible

S constant or

S increasing.

\alpha is minimum for 2.

(25)

1	2	3	4	5	6	7	8
t_i	$P(v_i)$	u_i	s_i	h_i	g_i	u_g	h_g
-20	190	88.76	0.3637	89.05	5.6155	1299.5	1418
40	1554.9	368.74	1.3574	371.43	4.7662	1341	1470.2

$$h_i = u_i + P v_i$$

$$h_{if} = u_{if} + P v_{if}$$

v_{if} is small, $\therefore P v_{if}$ is small.

$$h_{if} \approx u_{if}$$

But h_{if} will be slightly greater than u_{if} .

u_g & h_g should be greater than u_{if} and h_{if} .

\therefore Column (4) and (5) are not u_g & h_g . So they are s_f and g_f .

Also, g_f is greater than s_f

\therefore Column (6) is g_f and column (7) is s_f .

Again, $h_g = u_g + P v_g$

$$\therefore h_g > u_g$$

Column (8) is u_g & column (9) is h_g .

(26)

$$(ds)_{univ} > 0$$

$$(ds)_{syp} + (ds)_{sur} > 0$$

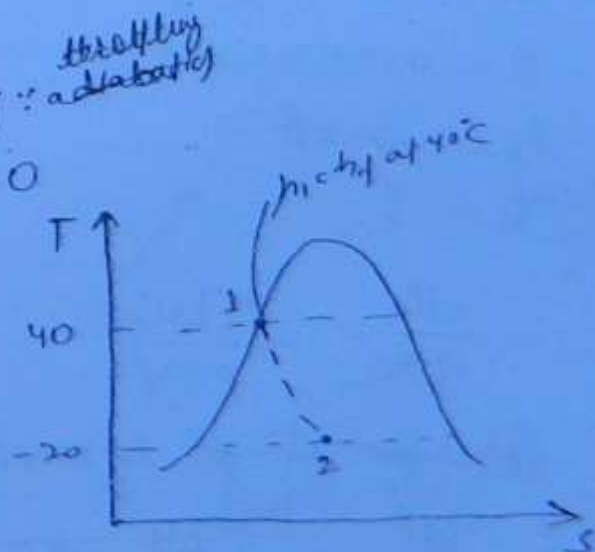
$$(ds)_{syp} > 0$$

$$h_1 = h_2 = 371.43$$

$$h_2 = h_1 + \alpha (h_g - h_f)$$

$$371.43 = 89.05 + \alpha (1418 - 89.05)$$

$$\therefore \alpha = 0.212$$



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- | | | | |
|----------|----------|----------|--------|
| 1 - a | 6 - d | 11 - c | 16 - a |
| 2 - a, b | 7 - b | 12 - c | 17 - b |
| 3 - b | 8 - a | 13 - d | 18 - a |
| 4 - c | 9 - a, b | 14 - d | 19 - a |
| 5 - c | 10 - c | 15 - ... | |

① $\left(\frac{df}{dT}\right) = 17.69 \text{ kPa/K}$

$v_f = 0.0008157 \text{ m}^3/\text{kg}$, $v_g = 0.0358 \text{ m}^3/\text{kg}$

from Clapeyron eqn

$$\frac{df}{dT} = \frac{LH}{T(v_g - v_f)}$$

$$LH = 17.69 \times 293 (0.0358 - 0.0008157)$$

$$= \underline{\underline{181.4}} \text{ (d)}$$

② $T_1 = 273 + 96 = 349 \text{ K}$

$P_1 = 101 \text{ kPa}$

$LH = 195 \text{ kJ/kg}$

$R = 0.055 \text{ kJ/kg K}$

$P_2 = 202 \text{ kPa}$

$T_2 = ?$

$$\frac{df}{dT} = \frac{P(LH)}{RT^2}$$

Assuming LH to be constant,

$$\frac{df}{f} = \frac{LH}{R} \cdot \frac{dT}{T^2}$$

Integrating above equation, we get.

$$\int_{P_1}^{P_2} \frac{dP}{P} = \int_{T_1}^{T_2} \frac{LH}{R} \cdot \frac{dT}{T^2}$$

(169)

$$\ln \frac{P_2}{P_1} = -\frac{LH}{R} \left[\frac{-1}{T} \right]_{T_1}^{T_2}$$

$$\ln \frac{P_2}{P_1} = \frac{-LH}{R} \left[\frac{1}{T_2} - \frac{1}{T_1} \right]$$

$$\Rightarrow \ln \frac{202}{101} = \frac{-195}{0.055} \left[\frac{1}{T_2} - \frac{1}{349} \right]$$

$$\therefore \boxed{T_2 = 374.5 \text{ K}} \quad \text{(A)}$$

(4) G-F

$$(H-TS) - (U-TS)$$

$$H-TS - U+TS$$

$$-H-U = PV$$

But, for ideal gas, $PV = nRT$

$$H-U = nRT$$

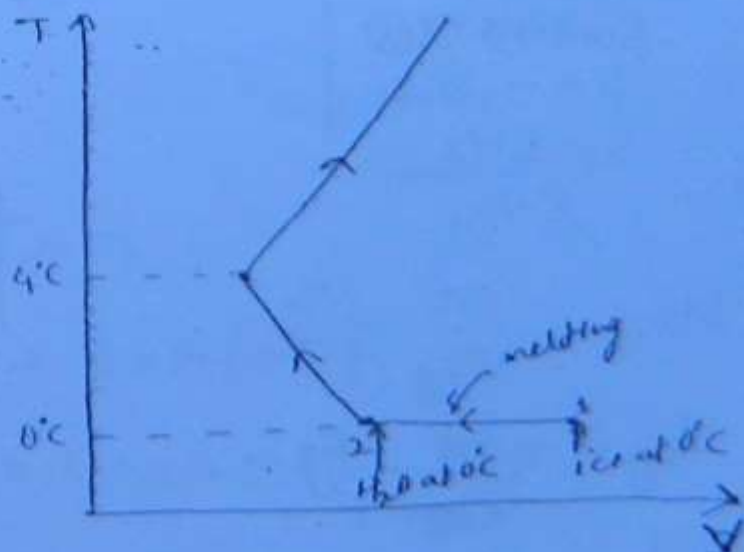
$\therefore H-U$ depends on T . (B)

$$\textcircled{5} \left(\frac{\partial S}{\partial P} \right)_T = \left(-\frac{\partial V}{\partial T} \right)_P$$

$\left(\frac{\partial V}{\partial T} \right)_P$ from 0°C to 4°C is +ve.

$$\text{but } \left(\frac{\partial S}{\partial P} \right)_T = \left(-\frac{\partial V}{\partial T} \right)_P$$

$\therefore \left(\frac{\partial S}{\partial P} \right)_T$ for 0°C to 4°C is positive.



(3) about 4°C \rightarrow of θ .

(170)

$$\text{and } \left(\frac{\partial S}{\partial T}\right)_r = \left(-\frac{\partial V}{\partial T}\right)_r$$

$\therefore \left(\frac{\partial S}{\partial T}\right)_r$ is 0 for temp^s above 4°C .

\therefore Answer is (A)

$\left(\frac{\partial S}{\partial T}\right)_r > 0$ at 3°C and < 0 at 5°C .

(4)

$$\frac{dL}{dT} = \frac{LH}{T(\Delta T_{fg})} = \frac{LH}{T \cdot \Delta T_{fg}} \quad \text{--- (1)}$$

$$\ln L = \ln A - \frac{B}{T}$$

differentiating

$$\frac{1}{L} \frac{dL}{dT} = 0 - 0 \left(-\frac{1}{T^2}\right)$$

$$\frac{1}{L} \frac{dL}{dT} = \frac{B}{T^2}$$

$$\frac{dL}{dT} = \frac{BL}{T^2} \quad \text{--- (2)}$$

from (1) & (2)

$$\frac{BL}{T^2} = \frac{LH}{T \cdot \Delta T_{fg}}$$
$$\Rightarrow LH = \frac{BL \cdot \Delta T_{fg}}{T}$$

$$\Rightarrow L_{fg} = \frac{BL \cdot \Delta T_{fg}}{T}$$

$$\Delta T_{fg} = \frac{P_{sat} \cdot \Delta T_{fg} \cdot B}{T_{sat}} \quad \text{--- (3)}$$

8



Temp. decrease & irreversible (1)

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from Maxwell's Eqⁿ

$$\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_V$$

for ideal gas $PV = nRT$

$$PV = nRT \quad (\text{Take } n=1)$$

$$P = \frac{n}{V} \cdot T$$

This is of the form $y = cx$
 $\frac{dy}{dx} = c$

$$\therefore \left(\frac{\partial P}{\partial T}\right)_V = \underline{\frac{P}{V}} \quad (2)$$

$$\frac{C_p}{C_v} = 1.67$$

$$\frac{C_p}{C_v} = \frac{C_p}{C_p - R} = 1.67$$

$$\left(\frac{C_p}{C_v}\right)_R = 1.67 \cdot C_p - R$$

$$C_p = 20.8 \text{ J/K}$$

10 — 11

$$(11) \quad (\Delta S) = -n_1 R \ln \frac{P_1}{P} - n_2 R \ln \frac{P_2}{P}$$

$$(\Delta S) = -n_1 R \ln x_1 - n_2 R \ln x_2$$

$$x_1 = \frac{n_1}{n_1 + n_2} = \frac{1}{1+4} = 0.2$$

$$x_2 = \frac{n_2}{n_1 + n_2} = 0.8$$

$$PV = nRT = nRT$$

$$nRT = nRT$$

$$nR = nR$$

$$n_1 R = n_1 R$$

$$n_2 R = n_2 R$$

$$(\Delta S) = -n_1 R \ln x_1 - n_2 R \ln x_2$$

$$= -R [1 \times \ln(0.2) + 4 \times \ln(0.8)]$$

$$= -8.314 \times [1 \times \ln(0.2) + 4 \times \ln(0.8)] = \underline{20.8}$$

- 10 — 11
- 11 — 12
- 12 — 13
- 13 — 14
- 14 — 15

13) $C_p - C_v = \frac{TV\beta^2}{K_T}$

$C_p - C_v = \frac{(243 + 25) \times 0.000114 \times (5 \times 10^{-5})^2}{8.6 \times 10^{-12}}$

$\therefore C_p - C_v = 9.8$

Again

$\frac{C_p}{C_v} = 1.024$

$\Rightarrow C_v = \frac{C_p}{1.024}$

$\therefore C_p - \frac{C_p}{1.024} = 9.87$

$\therefore C_p = \frac{9.87}{0.024} = \underline{\underline{421.3}}$

Chapter - 3
Work Book

- | | | | |
|-------|--------|--------|--------|
| 1 - d | 9 - b | 17 - d | 25 - a |
| 2 - a | 10 - c | 18 - d | 26 - c |
| 3 - a | 11 - d | 19 - d | 27 - b |
| 4 - d | 12 - c | 20 - a | 28 - a |
| 5 - c | 13 - b | 21 - a | 29 - b |
| 6 - a | 14 - d | 22 - a | 30 - c |
| 7 - a | 15 - a | 23 - a | 31 - a |
| 8 - c | 16 - d | 24 - c | 32 - |

2) $h_1 + \frac{C_1^2}{2} = h_2 + \frac{C_2^2}{2}$

$C_p = 1.005 \text{ kJ/kgK}$

$P_1 = 100 \text{ kPa}, T_1 = 500 \text{ K}, C_1 = 150 \text{ m/s}, T_2 = 510 \text{ K}$

$h_1 + \frac{C_1^2}{2} + z_1 g + v = h_2 + \frac{C_2^2}{2} + z_2 g + v$

$h_1 + \frac{C_1^2}{2} = h_2 + \frac{C_2^2}{2}$

$h_1 + \frac{C_1^2}{2000} = h_2 + \frac{C_2^2}{2000}$

$\Rightarrow C_p T_1 + \frac{C_1^2}{2000} = C_p T_2 + \frac{C_2^2}{2000}$

$= 1.005 \times 500 + \frac{(150)^2}{2000} = 1.005 \times 510 + \frac{C_2^2}{2000}$

$\Rightarrow C_2 = 48.98 \approx 49 \text{ m/s}$ (a) diffuser \therefore final velocity is less than initial

3) $m = 1 \text{ kg/s}, T_1 = 800 \text{ K}, P_1 = 200 \text{ kPa}, C_1 = 50 \text{ m/s}$

$T_2 = 650 \text{ K}, P_2 = 100 \text{ kPa}, v = -25 \text{ kW}$

$C_p = 1.005 \text{ kJ/kgK}$

$h_1 + \frac{C_1^2}{2} + z_1 g + v = h_2 + \frac{C_2^2}{2} + z_2 g + v$

$\Rightarrow C_p T_1 + \frac{C_1^2}{2000} + v = C_p T_2 + \frac{C_2^2}{2000}$

$\Rightarrow 1.005 \times 800 + \frac{(50)^2}{2000} - 25 = 1.005 \times 650 + \frac{C_2^2}{2000}$

$v = \frac{Q}{m} = \frac{25 \text{ kW}}{1 \text{ kg/s}} = -25 \text{ kJ/kg}$

$\Rightarrow C_2 = 503.98 \approx 504 \text{ m/s}$ (b)

① $\delta Q = dE + \delta W$
 $dE = \delta Q - \delta W$
 (properties are exact differentials)

⇒ * OPEN SYSTEM WORK * ⇐

Assumptions:

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- ① Steady flow
- ② Neglect K.E. and P.E. changes
- ③ Reversible

$$h_1 + \frac{C_1^2}{2} + z_1 g + q = h_2 + \frac{C_2^2}{2} + z_2 g + w$$

$$h_1 + q = h_2 + w$$

$$q = (h_2 - h_1) + w$$

$$q = dh + w \quad \text{--- ①}$$

Also

$$\frac{\delta Q}{T} = ds$$

$$\delta Q = T ds$$

$$dq = T ds$$

$$q = T ds \quad \text{--- ②}$$

from ① & ②

$$T ds = dh + w \quad \text{--- ③}$$

we also know $T ds = dh - v dp$ --- ④

from ③ & ④

$$\boxed{w = -v dp} \quad \text{open system work.}$$

⑥ $p_1 = 400 \text{ kPa}$, $T_1 = 900 \text{ K}$, $q = 0$.
 $p_2 = 100 \text{ kPa}$,

~~Flow is~~ flow is ideal means reversible.

$$h_1 + \frac{C_1^2}{2} + \cancel{z_1 g} + \cancel{q} = h_2 + \frac{C_2^2}{2} + \cancel{z_2 g} + \cancel{q}$$

$$\left(\frac{T_2}{T_1}\right) = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

(17.5)

$$\Rightarrow T_2 = 900 \times \left(\frac{100}{400}\right)^{\frac{0.4}{1.4}} = 605.6 \text{ K}$$

$$h_1 + \frac{C_1^2}{2000} = h_2 + \frac{C_2^2}{2000}$$

$$\Rightarrow C_p T_1 + \frac{C_1^2}{2000} = C_p T_2 + \frac{C_2^2}{2000}$$

$$\Rightarrow 1.005 \times 900 = 1.005 \times 605.6 + \frac{C_2^2}{2000}$$

$$\Rightarrow C_2 = \underline{769 \text{ m/s.}} \quad \text{①}$$

⑧ $m = 1 \text{ kg/s}$.

$p_1 = 0.1 \text{ MPa} = 100 \text{ kPa}$

$p_2 = 1000 \text{ kPa}$

$T_1 = 300 \text{ K}$.

$$T_2 = T_1 \times \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$= 300 \times \left(\frac{1000}{100}\right)^{\frac{0.4}{1.4}}$$

$$\therefore T_2 = \underline{579.2 \text{ K.}}$$

$$W = h_2 - h_1$$

$$= C_p (T_2 - T_1)$$

$$= 1.005 (579.2 - 300) = 280.6 \text{ kJ/kg}$$

$$\therefore \dot{W} = (280.6 \times 1) = \underline{280.6 \text{ kW.}} \quad \approx \underline{280 \text{ kW}}$$

⑩ $m = 1 \text{ kg}$

$$dQ = dU + dW$$

$$0 = dU + dW$$

$$0 = mc_v(T_2 - T_1) + dW$$

$$dW = -mc_v(T_2 - T_1)$$

$$dW = mc_v(T_1 - T_2)$$

$$= 1 \times c_v(T_1 - T_2) = c_v(T_1 - T_2) \quad \text{⑪}$$

⑪ - ⑩, ⑫ - ⑪

$$\delta Q = dU + dW$$

$$10 = 30 + 150$$

$$50 = 30 - 80$$

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⑫

1-2

$$V = C;$$

$$Q_{12} = 50$$

$$\therefore V = C$$

$$\therefore W_{12} = 0$$

2-3

$$T = C$$

$$W_{23} = 500 \text{ kJ}$$

for $T = C$

$$U = Q$$

$$\therefore Q_{23} = 500 \text{ kJ}$$

3-1

$$P = C$$

$$W_{31} = -200 \text{ kJ}$$

$$Q_{31} = ?$$

$$dU_{31} = ?$$

for a cycle

$$\sum Q = \sum W$$

$$\Rightarrow Q_{12} + Q_{23} + Q_{31} = W_{12} + W_{23} + W_{31}$$

$$\Rightarrow 50 + 500 + Q_{31} = 0 + 500 - 200$$

$$\Rightarrow \boxed{Q_{31} = -250 \text{ kJ}}$$

$$\delta Q = -\delta U + \delta W$$

$$\Rightarrow -250 = \delta U + 200$$

$$\Rightarrow \boxed{\delta U_{31} = -50 \text{ kJ}}$$

⑬

$$(14) E = (25 + 0.25t) \text{ kJ}$$

(17)

$$dQ = dE + dW$$

$$\frac{dQ}{dt} = \frac{dE}{dt} + \frac{dW}{dt}$$

$$\frac{dQ}{dt} = 0.25 + 0.75 = 1. \quad (d)$$

$$dQ = dE + dW$$

$$-50 = 30 - 80$$

$$E = 25 + 0.25t$$

$$\frac{dE}{dt} = 0.25$$

$$\frac{dW}{dt} = 0.75$$

(15)

$$\frac{1-2}{V=C_1}$$

$$Q_{12} = 170 \text{ kJ}$$

$$W_{12} = 0$$

$$U_{12} = 100 \text{ kJ}$$

$$dQ_{12} = dU_{12} + dW_{12}$$

$$\Rightarrow 170 = U_2 - U_1 + 0$$

$$\Rightarrow U_2 = 170 + 100 = 270 \text{ kJ}$$

$$\frac{2-3}{P=C}$$

$$Q_{23} = -180 \text{ kJ}$$

$$W_{23} = -40 \text{ kJ}$$

$$dQ_{23} = dU_{23} + dW_{23}$$

$$\Rightarrow -180 = (U_3 - U_2) + 40$$

$$\Rightarrow -140 = (U_3 - 270)$$

$$\Rightarrow U_3 = 130 \text{ kJ}$$

$$\frac{3-1}{}$$

$$Q_{31} = 0$$

$$\therefore U_1 = 100 \text{ kJ}$$

$$U_2 = 270 \text{ kJ}$$

$$U_3 = 130 \text{ kJ}$$

(a)

$$(16) P_1 = 10 \text{ bar}, P_2 = 1 \text{ bar}$$

$$\text{In throttling, } h_1 = h_2$$

$$\text{or, } U_1 + P_1 V_1 = U_2 + P_2 V_2$$

$$\Rightarrow (U_2 - U_1) = P_1 V_1 - P_2 V_2$$

$$= (1000 \times 0.5) - (100 \times 2)$$

$$= 300 \text{ kJ/kg.} \quad (d)$$

(17)

$$dQ = dU + dW$$

Question:

$$\frac{dU}{\rho_f} = ?$$

$$\frac{dU}{\rho_f} = \frac{dU}{dh} = \frac{m c_v dt}{m c_f dt} \quad (\because \text{ext. } \rho_f)$$

$$= \frac{c_v}{c_f} = \frac{1}{\gamma} = \left(\frac{5}{7} \right) \quad (d)$$

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A

$$T_1 = 300K$$

$$P = C$$

$$Q_A = Q_B$$

$$T_2 = 330K$$

~~$$Q_A = dh = mcpdT$$~~

$$(Q_A)_P = dh = mcpdT$$

Now, $mcpdT_A = mcvdT_B$

$$\Rightarrow dT_B = \frac{C_p}{C_v} \cdot dT_A$$
$$= 1.4 \times 30$$

$$\therefore \Delta T_B = 1.4 \times 30 = 42K$$

(d)

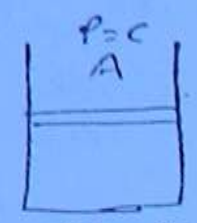
B

$$T_1 = 300K$$

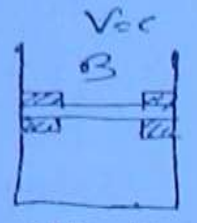
$$V = C$$

$$Q_B = Q_A$$

$$T_2 = ?$$



$$dT_A = 30$$



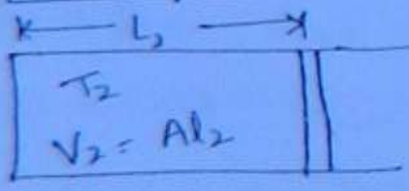
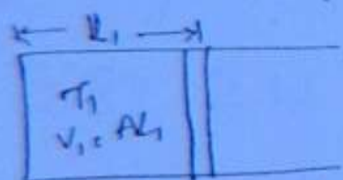
$$dT_B = ?$$

$$(Q_A = Q_B)$$

$$(Q_B)_V = mcvdT$$

(178)

19



for adiabatic process:

$$T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1}$$

$$\left(\frac{T_1}{T_2}\right) = \left(\frac{V_2}{V_1}\right)^{\gamma-1}$$

$$= \left(\frac{AL_2}{AL_1}\right)^{\frac{5}{3}-1}$$

$$= \left(\frac{L_2}{L_1}\right)^{\frac{2}{3}}$$

(d)

(20)

$$\delta Q = dU + \delta W$$

$$\Rightarrow \delta Q = dU \quad (\because \delta W = 0)$$

for ideal gas $U \rightarrow f(T)$.

$$\delta Q < 0 \text{ mean } dU < 0$$

\therefore Tempⁿ will decrease.

(21) $\Sigma Q = 5 \text{ kJ}$

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$$\underline{\Sigma Q = \Sigma W = 5 \text{ kJ}}$$

$$\therefore W_{AB} + W_{BC} + W_{CA} = 5$$

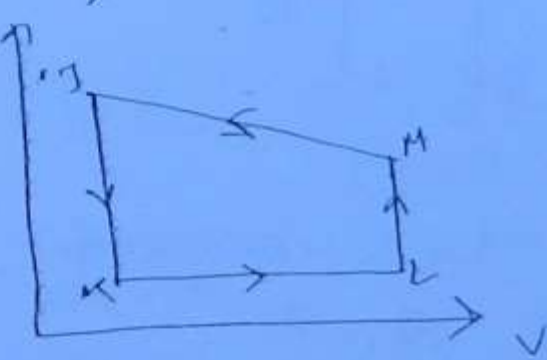
$$\Rightarrow W_{AB} + 0 + W_{CA} = 5$$

Now, $W_{AB} =$ Area under curve

$$= (10 \times 1) = 10 \text{ kJ}$$

$$\therefore W_{CA} = 5 - 10 = \underline{\underline{-5 \text{ kJ}}} \quad \textcircled{a}$$

(22)



$$J \rightarrow K \Rightarrow W = 0$$

$$\& Q < 0 \quad (\because \text{heat out})$$

$$P \propto \frac{1}{V} \Rightarrow P \propto T$$

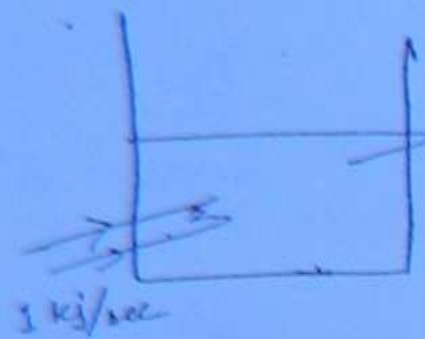
$$P \propto T$$

$$P \downarrow \rightarrow T \downarrow$$

$$\underline{\underline{L-M \Rightarrow W=0}}$$

②

23



$160 \text{ J/sec} = 0.16 \text{ kJ/sec}$

Net accumulation = $1 - 0.16$

$= 0.84 \text{ kJ/sec}$

160

for t seconds

$Q = 0.84 t \text{ kJ}$

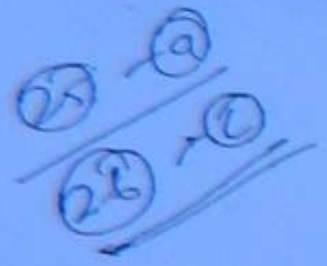
$Q = mc(\Delta T)$

$0.84 t = mc(\Delta T)$

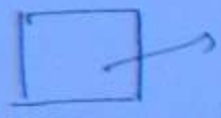
$\Rightarrow 0.84 t = 2 \times 4.2 (77 - 27)$

$t = 500 \text{ seconds}$

$t = \underline{8 \text{ min. } 40 \text{ sec.}}$ (a)



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1-2 discharging

$Q_{12} = -250 \text{ kcal.}$

$W_{12} = 0.$

$1 \text{ cal} = 4.18 \text{ J}$

$1 \text{ kcal} = 4.18 \text{ kJ}$

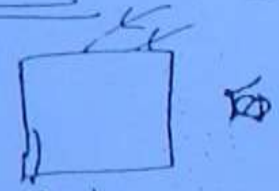
$\therefore Q_{12} = -250 \times 4.18 \text{ kJ}$
 $= -1045 \text{ kJ}$

$\Sigma Q = \Sigma W$

$Q_{12} + Q_{21} = W_{12} + W_{21}$

$-1045 + Q_{21} = 0 + (-1908)$

$\therefore \boxed{Q_{21} = -863 \text{ kJ}}$ (c)



2-1 charging

$W_{21} = -0.53 \text{ kWhr.}$

$Q_{21} = ?$

$= -0.53 \frac{\text{kJ}}{\text{sec}} \times 3600 \text{ sec}$

$W_{21} = -1908 \text{ kJ}$

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$$dQ = dU + \delta W$$

$$\frac{dQ}{dt} = \frac{dU}{dt} + \frac{\delta W}{dt}$$

$$\frac{dW}{dt} = -260 \text{ J/sec}$$

$$\frac{dQ}{dt} = -10 \text{ J/sec}$$

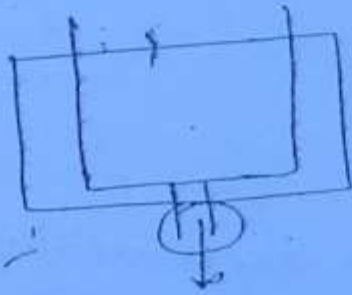
$$-10 = -260 + \frac{dU}{dt}$$

$$\therefore \frac{dU}{dt} = 250 \text{ J/sec}$$

$$\frac{250 \text{ J}}{\text{sec}} \times 3600 = 900 \times 10^3 \text{ J} = \underline{900 \text{ kJ}} \quad \text{B}$$

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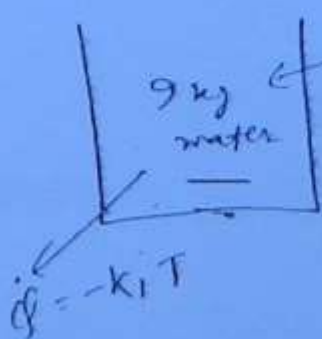


$$\left(\frac{dU}{dt}\right)_w = \dot{m}_i h_i + \dot{Q} - \dot{m}_e h_e - \dot{W}$$

$$\left(\frac{dU}{dt}\right)_w = -\dot{m}_e h_e$$

$$\frac{d}{dt}(m_u) = -\dot{m}_e h_e \quad \text{--- C}$$

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$$\frac{dU}{dt} = \dot{m}_i h_i + \dot{Q} - \dot{m}_e h_e - \dot{W}$$

(no mass entering, no mass leaving)

$$\frac{dU}{dt} = \dot{Q} - \dot{W} = -k_1 T - (-k_2 T)$$

$$\frac{dU}{dt} = (k_2 - k_1) T$$

$$\frac{dU}{dt} \cdot \frac{dT}{dT} = (k_2 - k_1)T$$

$$\frac{dU}{dt} \cdot \frac{dT}{dT} = (k_2 - k_1)T$$

from ideal gas eqⁿ, $dU = c dt$ or $\frac{dU}{dT} = c$

$$\therefore c \cdot \frac{dT}{dT} = (k_2 - k_1)T$$

$$\text{or } \frac{dT}{T} = \frac{(k_2 - k_1)}{c} dt$$

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Integrating:-

$$\ln T = \frac{(k_2 - k_1)}{c} t$$

$$T = e^{\left[\frac{(k_2 - k_1)}{c} \cdot t \right]}$$

if $k_2 > k_1$, T will increase exponentially

if $k_2 < k_1$, T will decrease exponentially.

Use steam table and find enthalpy at 1 MPa & 400°C and then calculate.

Ans is $\odot - 0.612$

31) $p_1 = 0.7 \text{ bar} = 70 \text{ kPa}$

$T_1 = 57^\circ\text{C} = 330 \text{ K}$

$C_1 = 200$

$A_1 = 0.4$

$p_2 = 1 \text{ bar}$

$A_2 = 0.6$

$\dot{m} = f_1 A_1 C_1 = f_2 A_2 C_2$

$\dot{m} = f_1 A_1 C_1$

\therefore Ideal gas, ... $pV = mRT$

$\frac{m}{V} = \frac{p}{RT}$

$f = \frac{p}{RT}$

$\therefore f_1 = \frac{p_1}{R_1 T_1} = \frac{70}{0.287 \times 330} = 0.739$

$\therefore \dot{m} = 0.739 \times 0.4 \times 200$

$\dot{m} = 59.1 \text{ kg/sec}$ (CM) (a)

32) From steady flow equation :-

$h_1 + \frac{C_1^2}{2000} + z_1 g + q = h_2 + \frac{C_2^2}{2000} + z_2 g + w$

$\therefore h_1 + \frac{C_1^2}{2000} = h_2 + \frac{C_2^2}{2000}$

or $C_p T_1 + \frac{C_1^2}{2000} = C_p T_2 + \frac{C_2^2}{2000}$ — (1)

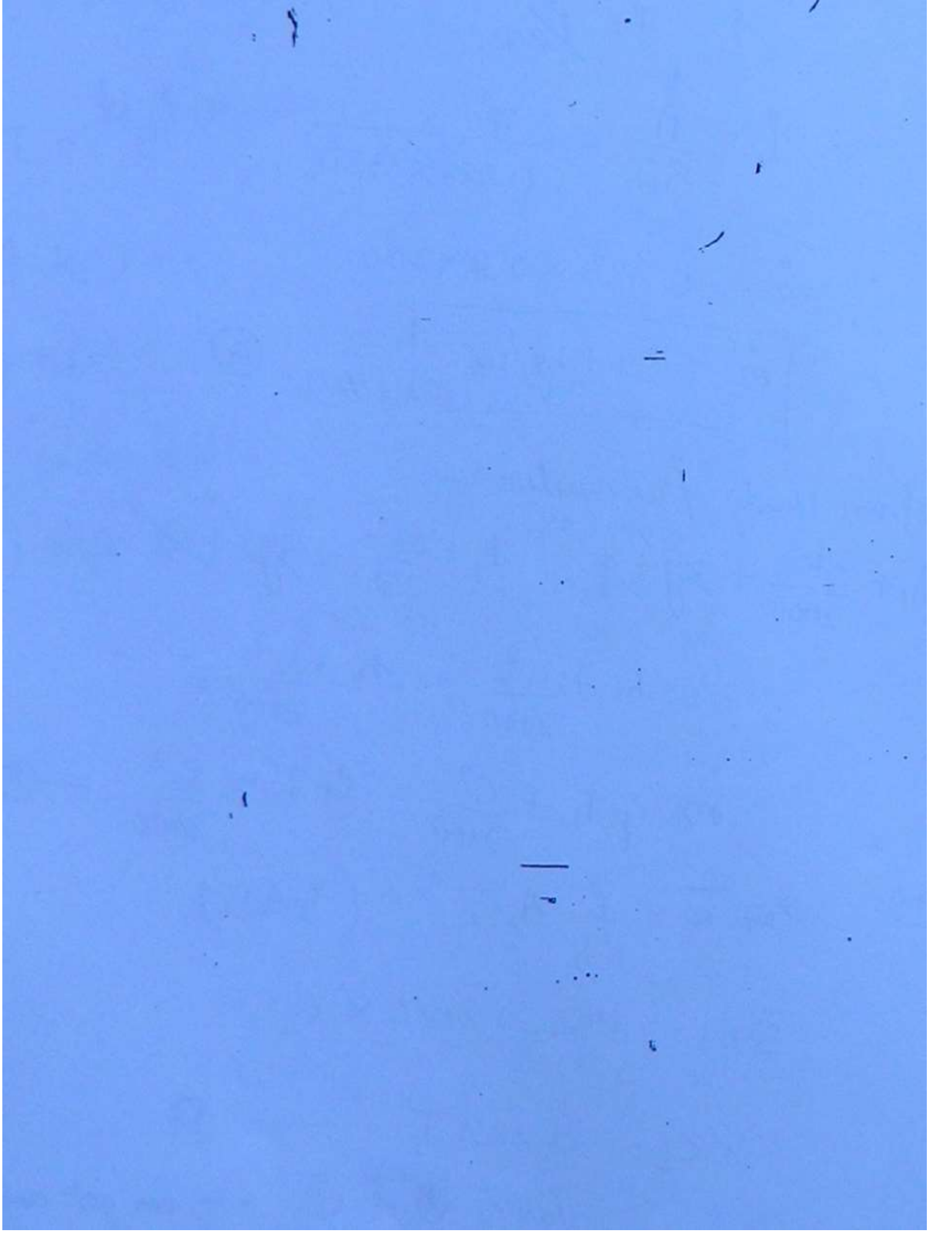
Now $\dot{m} = \frac{p}{RT_2} A_2 C_2$ ($f_2 A_2 C_2$)

$59.1 = \frac{100}{0.287 T_2} \times 0.6 \times C_2$

$\rightarrow C_2 = 0.283 T_2$ — (2)

Putting (2) in (1), we can get answer

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I.C. ENGINE :-

B. G. S. S. S. S.

An I.C. Engine comprises of a piston cylinder arrangement where the combustion takes place internally for attaining the useful work output. The different important cycles that are involved for attaining useful work output are :-

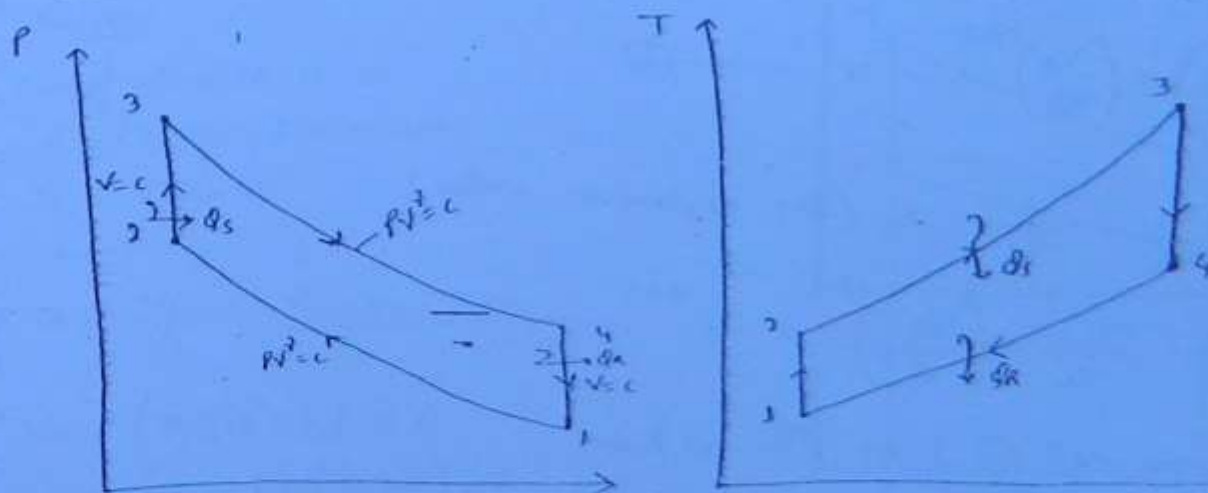
- 1) The Otto cycle or the constant volume cycle. (185)
- 2) The Diesel cycle or the constant pressure cycle.
- 3) The Dual combustion cycle

The common processes that are involved for the above cycles are :-

- a) Isentropic expansion,
- b) Heat rejection at constant volume,
- c) Isentropic compression.

The different cycles are different from one another because of heat addition taking place differently.

THE OTTO CYCLE OR THE CONSTANT VOLUME CYCLE :-



$$\left. \begin{aligned} P_1 V_1^\gamma &= P_2 V_2^\gamma \\ \frac{P_1 V_1}{T_1} &= \frac{P_2 V_2}{T_2} \end{aligned} \right\} \left(\frac{P_1}{P_2} \right)^{\frac{\gamma}{\gamma-1}} = \frac{T_2}{T_1}$$

$$ds = mc_v \ln \frac{T_2}{T_1} \quad (\text{Change in entropy when volume is constant})$$

If T_2 is greater, ds will be greater than 0.

→ Derivation of efficiency of Otto cycle:-

$$\eta = \frac{WD}{HS} = \frac{HS - HR}{HS} = 1 - \frac{HR}{HS}$$

$$\eta = \frac{WD}{HA} = \frac{HA - HR}{HA} = 1 - \frac{HR}{HA}$$

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HA =

We know that the efficiency of the cycle

$$\eta_v = \frac{WD}{HA} = \frac{HA - HR}{HA} = 1 - \frac{HR}{HA}$$

$$HA = mc_v (T_3 - T_2)$$

$$HR = mc_v (T_4 - T_1)$$

$$\eta_v = 1 - \frac{mc_v (T_4 - T_1)}{mc_v (T_3 - T_2)} \quad \text{--- (a)}$$

Let $\frac{v_1}{v_2} = r$, (the compression ratio)

We know that for an adiabatic process;

$$\left(\frac{T_2}{T_1}\right) = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = r^{\gamma-1} \quad \text{--- (b)}$$

But, $\frac{v_4}{v_3} = \frac{v_1}{v_2} = r$, (the expansion ratio)

$$\& \frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{\gamma-1} = r^{\gamma-1} \quad \text{--- (c)}$$

from eq. (b) & eq. (c), we have

$$\frac{T_2}{T_1} = \frac{T_3}{T_4}$$

$$\therefore \frac{T_4}{T_3} = \frac{T_1}{T_2}$$

from componendo and dividendo, we have :-

$$\frac{a}{b} = \frac{c}{d} = \frac{a-c}{b-d}$$

$$\therefore \frac{T_4}{T_3} = \frac{T_1}{T_2} = \frac{T_4 - T_1}{T_3 - T_2} \quad (\text{from algebra}) \quad \text{--- (d)}$$

Thus, we have :-

$$\eta_v = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_1}{T_2} \quad (\text{from eq. (d)})$$

$$\text{or, } \boxed{\eta_v = 1 - \left(\frac{1}{r}\right)^{\gamma-1}} \quad \text{--- (e)} \quad (\text{from equation (d)})$$

Problem

ESE-2009

Q. The bore and stroke of the cylinder of a 6-cylinder engine working on an Otto cycle are 17 cm and 30 cm respectively. Total clearance volume is 9225 cm^3 . Find the compression ratio.

Soln: Given:

No. of cylinders, $n = 6$

$d = 17 \text{ cm}$, $L = 30 \text{ cm}$

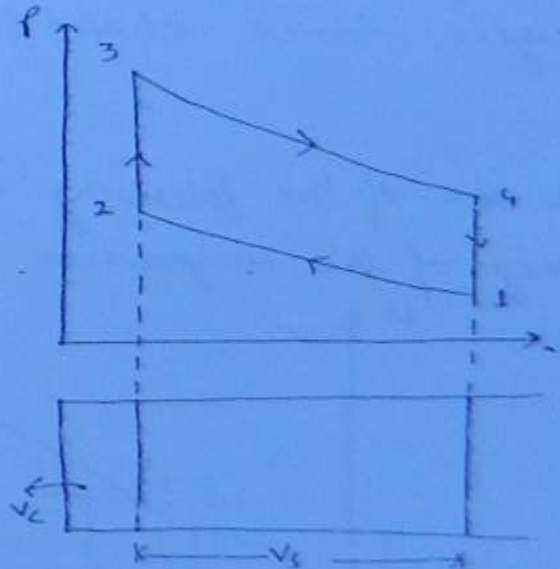
$V_c = 9225 \text{ cm}^3$

$r = ?$

$$r = \frac{V_1}{V_2} = \frac{V_s + V_c}{V_c}$$

$$\begin{aligned} V_s &= \left(\frac{\pi}{4} d^2 \times L\right) \times 6 \\ &= \left(\frac{\pi}{4} \times (17)^2 \times 30\right) \times 6 \end{aligned}$$

$$\therefore V_s = 40856.4 \text{ cm}^3$$



$$\gamma = \frac{V_s + V_c}{V_c}$$

$$= \frac{40856.4 + 9225}{9225}$$

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Shashi
Shashi

$$\therefore \gamma = 5.43 \quad (\text{Ans})$$

E-2008

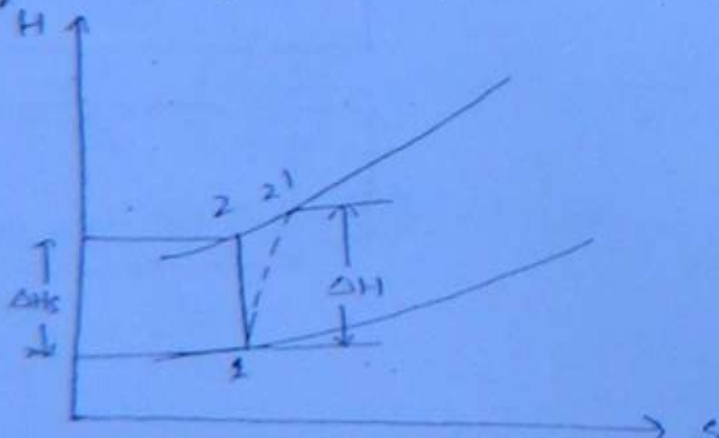
Q. Which gas power cycle consists of four processes? During which work done alone is transferred during two processes and heat added alone during two processes?

- (A) Atkinson cycle
- (B) Carnot cycle
- (C) Diesel cycle
- ✓ (D) Otto cycle. (Ans)

During compression and expansion process, there is no heat transfer for an Otto cycle, there is existence of work done. The heat addition and heat rejection process is at constant volume. The work done during constant volume process is zero (0). As there is only one type of transfer during each process of an Otto cycle, hence, choice (d) is correct.

-2005

Which one of the following expressions, the isentropic efficiency of the compression process is indicated in the figure.



$$\textcircled{a} \eta = \frac{\Delta H_s}{\Delta H}$$

$$\textcircled{b} \eta = \frac{\Delta H}{\Delta H_s}$$

$$\textcircled{c} \eta = \frac{\Delta H - \Delta H_s}{\Delta H}$$

$$\textcircled{d} \eta = \frac{\Delta H - \Delta H_s}{\Delta H_s}$$

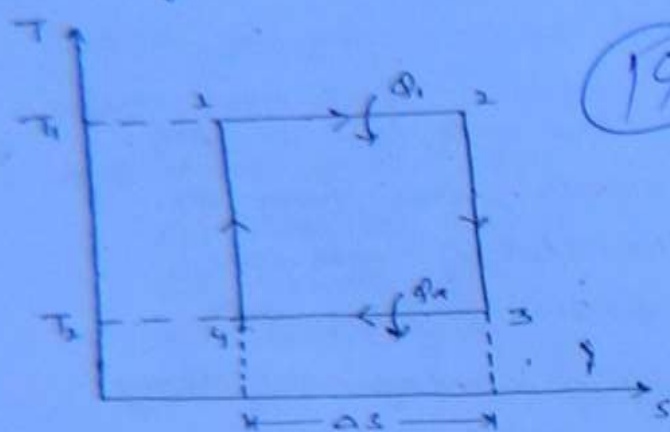
189

When the compression is without friction, the work done is ΔH_s (see figure). When friction is taken in account, then from the figure, the work done will be ΔH . The ratio of work done without friction to the work done ^{when} ~~with~~ friction is taken into account is defined as compression efficiency or isentropic efficiency. This efficiency for the given figure is $\eta = \frac{\Delta H_s}{\Delta H}$ (choice \textcircled{a} is correct).

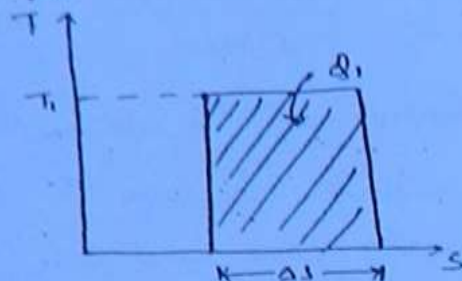
3.2 - AVAILABLE ENERGY, AVAILABILITY & IRREVERSIBILITY :-

* Available Energy (AE) :-

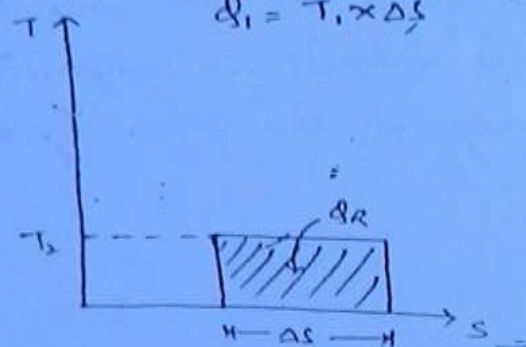
→ The maximum possible amount of work that can be obtained in a cycle is known as available energy.



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$$Q_1 = T_1 \times \Delta s$$



$$Q_R = T_2 (\Delta s)$$

$$\eta = W/Q_1$$

$$\eta_{max} = \frac{W_{max}}{Q_1}$$

also, $\eta_{max} = 1 - \frac{T_2}{T_1}$

$$\Rightarrow \frac{W_{max}}{Q_1} = 1 - \frac{T_2}{T_1}$$

$$\Rightarrow \boxed{W_{max} = Q_1 \left(1 - \frac{T_2}{T_1}\right)}$$

For a given source T_1 and for a given input Q_1 this work is further maximum when T_2 is minimum. The lowest possible tempⁿ of heat rejection is that of surroundings ($T_2 = T_0$).

Therefore,

$$\boxed{AE = W_{max} = Q_1 \left(1 - \frac{T_0}{T_1}\right)}$$

Now, by process graph:

$$Q_1 = T_1 \Delta S$$

$$\Rightarrow \frac{Q_1}{T_1} = \Delta S$$

(19)

Heat rejection:

$$Q_2 = T_0 \Delta S$$

min. heat rejection

↓
UAE

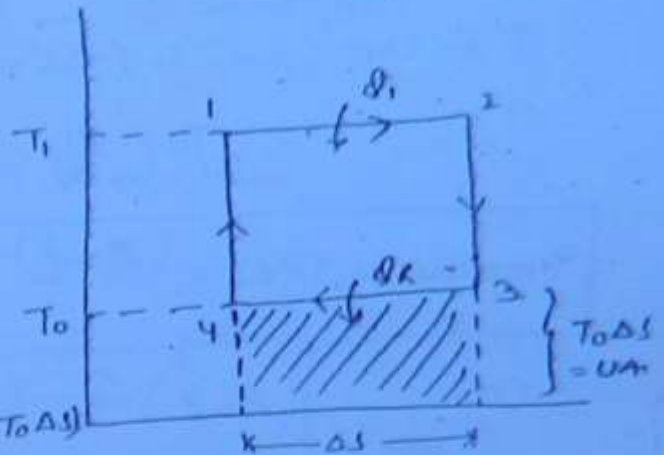
Now, $AE = Q_1 \left(1 - \frac{T_0}{T_1}\right)$

$$= Q_1 - \frac{Q_1}{T_1} T_0$$

$$= Q_1 - T_0 \Delta S$$

$$\Rightarrow Q_1 = AE + T_0 \Delta S$$

$$\boxed{Q_1 = AE + UAE}$$

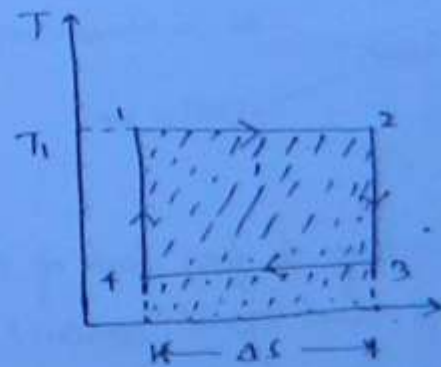
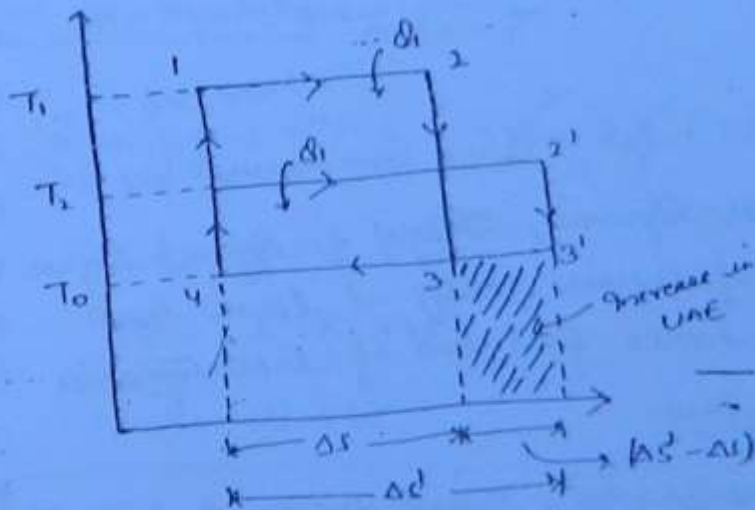


The minimum possible heat rejection ($T_0 \Delta S$)

is known as unavailable energy (UAE) i.e. area below atmospheric

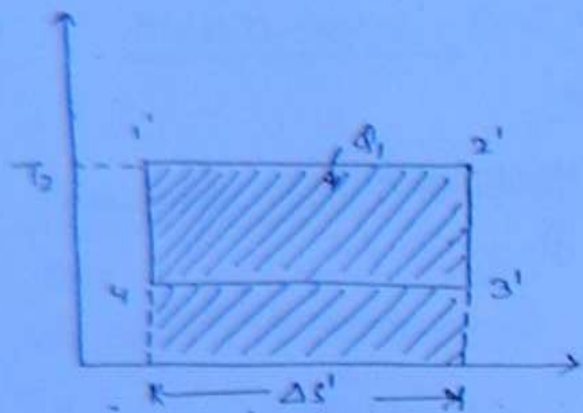
temp T_0 always represents unavailable energy.

* Loss of Available Energy (increase in unavailable energy) when heat is transferred through a finite temp:-



$$Q_1 = T_1 \Delta S$$

$$\Rightarrow \Delta S = \frac{Q_1}{T_1}$$



$$Q_1 = T_2 \times \Delta s'$$

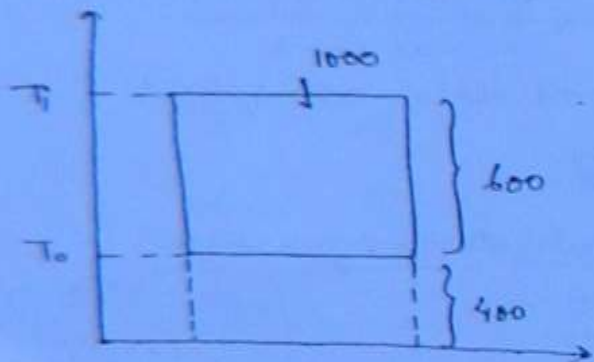
$$\Rightarrow \Delta s' = \frac{Q_1}{T_2}$$

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Now, \uparrow in UAE = $T_0 (\Delta s' - \Delta s)$

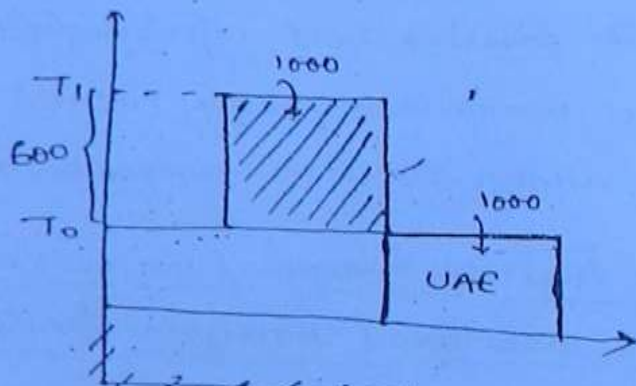
$$= T_0 \left(\frac{Q_1}{T_2} - \frac{Q_1}{T_1} \right)$$

Increase in UAE = $Q_1 T_0 \left(\frac{T_1 - T_2}{T_1 T_2} \right)$



$Q_1 = 1000$

- AE = $W_{max} = 600$
- UAE = 400



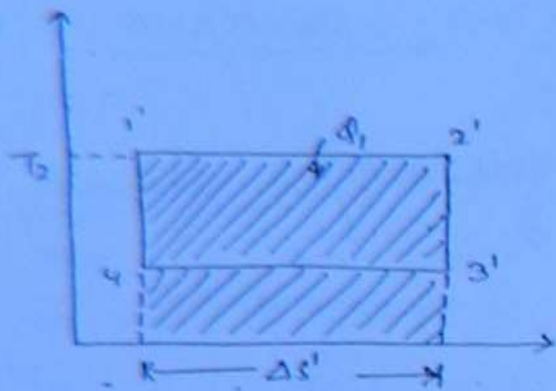
$T_1 \rightarrow 1000$

- $\rightarrow 600$ AE = W
- $\rightarrow 400$ UAE

$T_0 \rightarrow 1000 \rightarrow$ UAE but $W=0$.

* According to first law of thermodynamics, thermal energy at higher temp and equal amount of thermal energy at lower temp have same meaning and hence first law of thermodynamics is known as quantitative law.

* According to 2nd law of thermodynamics, thermal energy at higher temperature has greater significance when compared to the same amount of thermal energy at lower temp? because thermal energy at higher temp? is capable of producing more power and



$$Q_1 = T_2 \times \Delta s'$$

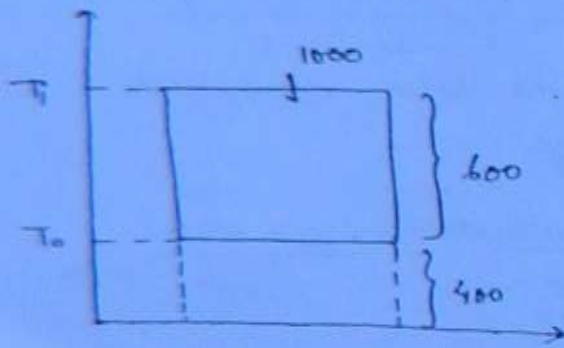
$$\Rightarrow \Delta s' = \frac{Q_1}{T_2}$$

192

Now, \uparrow in UAE = $T_0 (\Delta s' - \Delta s)$

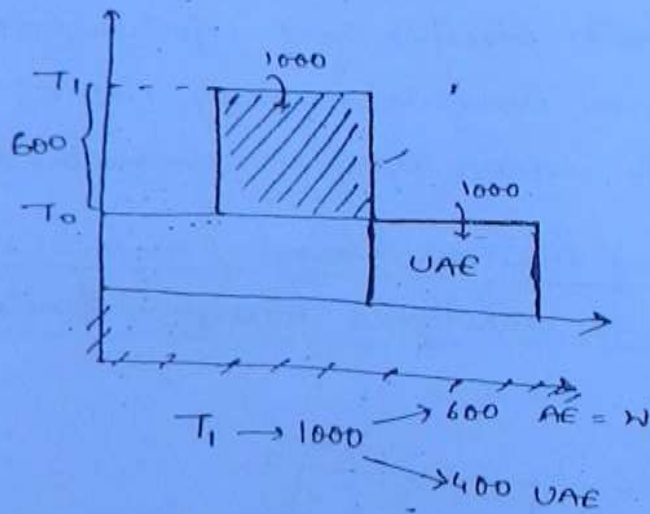
$$= T_0 \left(\frac{Q_1}{T_2} - \frac{Q_1}{T_1} \right)$$

$$\text{Increase in UAE} = Q_1 T_0 \left(\frac{T_1 - T_2}{T_1 T_2} \right)$$



$Q_1 = 1000$

- AE = $W_{max} = 600$
- UAE = 400



$T_1 \rightarrow 1000 \rightarrow 600$ AE = W

$T_0 \rightarrow 1000 \rightarrow 400$ UAE

$T_0 \rightarrow 1000 \rightarrow$ UAE but $W=0$.

* According to first law of thermodynamics, thermal energy at higher temp and equal amount of thermal energy at lower temp have same meaning and hence first law of thermodynamics is known as quantitative law.

* According to 2nd law of thermodynamics, thermal energy at higher temperature has greater significance when compared to the same amount of thermal energy at lower temp^s because thermal energy at higher temp^s is capable of producing more power and

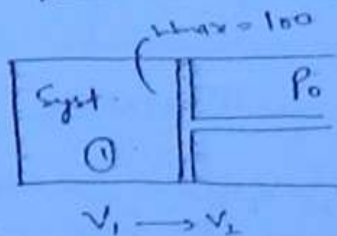
$$\Rightarrow dW_{\text{sys}} = T_0 (\Delta S)_{\text{sys}} - dU_{\text{sys}} \quad \text{--- (from 1)}$$

$$\Rightarrow W_{\text{max}} = T_0 (S_2 - S_1) - (U_2 - U_1)$$

$$= T_0 (S_2 - S_1) - U_2 + U_1$$

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$$\Rightarrow \boxed{W_{\text{max}} = (U_1 - U_2) - T_0 (S_1 - S_2)} \quad \text{--- for closed system only.}$$



$$W_{\text{max useful}} = W_{\text{max}} - W_{\text{atm}}$$

$$W_{\text{atm}} = P_0 (V_2 - V_1)$$

$$\text{So, } \boxed{W_{\text{max useful}} = (U_1 - U_2) - T_0 (S_1 - S_2) - P_0 (V_2 - V_1)}$$

$$= (U_1 - T_0 S_1 + P_0 V_1) - [U_2 - T_0 S_2 + P_0 V_2]$$

$$W_{\text{max useful}} = \Phi_1 - \Phi_2 \quad \text{where, } \Phi_i = U_i - T_0 S_i + P_0 V_i$$

$$\Rightarrow \boxed{\Phi = U - T_0 S + P_0 V} \quad \text{--- availability function for closed system.}$$

Max^m work for open system:

$$h_1 + \frac{C_p^2}{2} + z_1 g + \Phi = h_2 + \frac{C_p^2}{2} + z_2 g + W$$

$$\Rightarrow h_1 + \Phi = h_2 + W$$

$$\Phi = h_2 - h_1 + W$$

$$\Phi = dh + W$$

$$\text{So, } \boxed{W_{\text{max}} = h_1 - h_2 - T_0 (S_1 - S_2)} \quad \text{--- change of availability}$$

$$= (h_1 - T_0 S_1) - (h_2 - T_0 S_2)$$

$$\boxed{W_{\text{max}} = \Phi_1 - \Phi_2} \quad \text{--- change of availability.}$$

$$\Rightarrow dW_{\text{sys}} = T_0 (\Delta S)_{\text{sys}} - dU_{\text{sys}} \quad \text{--- (from 1)}$$

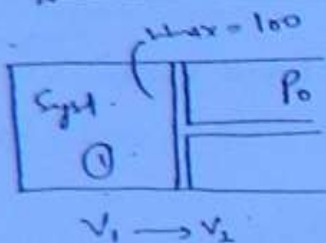
$$\Rightarrow W_{\text{max}} = T_0 (S_2 - S_1) - (U_2 - U_1)$$

$$= T_0 (S_2 - S_1) - U_2 + U_1$$

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$$\Rightarrow \boxed{W_{\text{max}} = (U_1 - U_2) - T_0 (S_1 - S_2)} \quad \text{--- for closed systems only.}$$

Now,



$$W_{\text{max useful}} = W_{\text{max}} - W_{\text{atm}}$$

$$W_{\text{atm}} = P_0 (V_2 - V_1)$$

So,

$$\boxed{W_{\text{max useful}} = (U_1 - U_2) - T_0 (S_1 - S_2) - P_0 (V_2 - V_1)}$$

$$= (U_1 - T_0 S_1 + P_0 V_1) - [U_2 - T_0 S_2 + P_0 V_2]$$

$$W_{\text{max useful}} = \phi_1 - \phi_2 \quad \text{where, } \phi_1 = U_1 - T_0 S_1 + P_0 V_1$$

$$\Rightarrow \boxed{\phi = U - T_0 S + P_0 V} \quad \text{--- availability function for closed system.}$$

Max^m work for open system:-

$$h_1 + \cancel{\frac{C_1^2}{2}} + \cancel{z_1 g} + \phi = h_2 + \cancel{\frac{C_2^2}{2}} + \cancel{z_2 g} + W$$

$$\Rightarrow h_1 + \phi = h_2 + W$$

$$\phi = h_2 - h_1 + W$$

$$\phi = dh + W$$

$$\text{So, } \boxed{W_{\text{max}} = h_1 - h_2 - T_0 (S_1 - S_2)} \quad \text{--- net change of availability}$$

$$= (h_1 - T_0 S_1) - (h_2 - T_0 S_2)$$

$$\boxed{W_{\text{max}} = \phi_1 - \phi_2} \quad \text{--- change of availability.}$$

$$Q_1 = h_1 - T_0 S_1$$

generalisation

$$\boxed{Q = h_2 - T_0 S}$$

↓
availability function for open system.

* IRREVERSIBILITY :- (I) :-

$$I = W_{\max} - W_{\text{actual}}$$

$$I = T_0 [(\Delta S)_{\text{sys}} + (\Delta S)_{\text{surroundings}}]$$

$$\boxed{I = T_0 (\Delta S)_{\text{univ.}}} \rightarrow \text{valid for open and closed system.}$$

* Gouy Stodola Theorem :-

A/c to it, rate of increase of irreversibility is proportional to rate of increase of entropy of the universe.

$$\boxed{\dot{I} \propto (\dot{\Delta S})_{\text{univ.}}}$$

* Gibb's function (G) :-

$$\boxed{G = H - TS} \rightarrow \text{gives sq open system work.}$$

* Helmholtz Function (F) :-

$$\boxed{F = U - TS} \rightarrow \text{gives closed system work.}$$

** Equations to be remembered :-

$$1) \quad AE = Q_1 \left(1 - \frac{T_0}{T_1}\right)$$

$$2) \quad \text{Increase in UAE due to heat transfer} = \frac{Q_1 T_0}{T_1 T_2} \left(\frac{T_1 - T_2}{T_1 T_2}\right)$$

$$3) \quad W_{\max} = U_1 - U_2 - T_0 (S_1 - S_2) \quad \text{for closed system.}$$

$$4) \quad W_{\max} = h_1 - h_2 - T_0 (S_1 - S_2) \quad \text{for open system.}$$

$$5) \quad W_{\max \text{ useful}} = U_1 - U_2 - T_0 (S_1 - S_2) - P_0 (V_2 - V_1) \quad \text{Closed system}$$

$$6) \quad I = W_{\max} - W_{\text{act}} = T_0 (\Delta S)_{\text{univ.}}$$

Q: find the loss of available energy associated with in the transfer of 1000 kJ of heat from a const. temp system at 600 K to another at 400 K and ambient temp^s is 300 K.

Sol:

$$\begin{aligned}\uparrow \text{ in UAE} &= Q_1 T_0 \left(\frac{T_1 - T_2}{T_1 T_2} \right) \quad 196 \\ &= 1000 \times 300 \left(\frac{600 - 400}{600 \times 400} \right) \\ &= 250 \text{ kJ}\end{aligned}$$

→ loss of available energy = increase in UAE.

Q: for a steady flow process from state 1 to state 2 enthalpy changes from $h_1 = 400 \text{ kJ/kg}$ to $h_2 = 100 \text{ kJ/kg}$ and entropy changes from $S_1 = 1.1 \text{ kJ/kg K}$ to $S_2 = 0.7 \text{ kJ/kg K}$ and $T_0 = 300 \text{ K}$. Find the change in availability.

Sol:

$$\begin{aligned}W_{\text{max}} &= Q_1 - Q_2 \\ &= (h_1 - h_2) - T_0 (S_1 - S_2) \\ &= (400 - 100) - 300 (1.1 - 0.7) \\ &= 180 \text{ kJ/kg.} \quad \underline{\text{(Ans)}}$$