

Chapter - 1 - Basic Introduction

- ① **Thermodynamics** ÷ Thermo - Heat & Dynamics is force
- ② **Macroscopic & Microscopic** ÷
 - ① Property of mass of substance as a whole
 - ② Property of atom or molecular behaviour → Nuclear physics
- ③ **Working substance** ÷ medium of conversion of energy from one form to the other - Air/Water
- ④ **Phase** ÷ Homogenous chemical & physical structure.
 - ① Solid
 - ② Liquid
 - ③ Gas
- ⑤ **Single phase matter** (a) **Two phase matter** (b) **Three phase matter**

(a) Water (b) Wet steam (c) Triple point
- ⑥ **Property** ÷ Observable & measurable ~~property~~ characteristics of a substance
- ⑦ **Intensive property** ÷ Independent on mass
 Temperature / Pressure / Density
- Extensive property** ÷ Dependent on mass
 Volume / Entropy / Enthalpy / Energy
 (All types of energy) → specific density.
- ⑧ **Specific Property** ÷ Extensive property defined in terms of Intensive property
- ⑨ **Point Function** ÷ Property depends on thermodynamic state & not on process
- Path Function** ÷ Property depends on path followed by the process.
- ⑩ **System** ÷ Qty of matter or Region in space where attention is concentrated for study
- ⑪ **Types of System** ÷

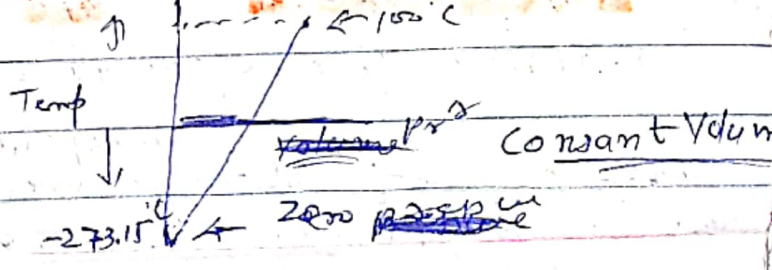
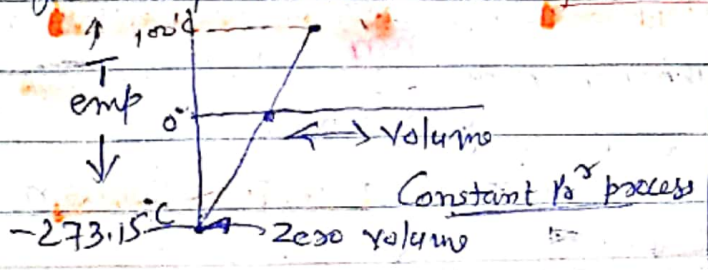
① Open System mass & Energy both cross boundary	② Closed System only energy crosses the boundary	③ Isolated System Neither energy nor mass crosses the boundary force between system & surrounding
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- ⑫ **Equilibrium** ÷
 - ① **Mechanical** ÷ No Pressure Unbalancing - No unbalanced force between system & surrounding
 - ② **Chemical** ÷ No inequality in Chemical Potential
 - ③ **Thermal** ÷ No inequality in Temperature
 - ④ **Thermodynamic Equilibrium** ÷ when any system satisfied all 3 types of equilibrium

(13) Temperature ÷ Hotness of body is called Temperature
Intensive Property

(14) Temperature scale ÷ "Anders Celsius" - 1851. Water - Freezing & boiling point divided in 100 equal divisions. & each division is called Celsius

Due to change in fluid the division was changing so a new scale was given that is "Absolute Celsius scale" or "Kelvin Thermodynamic scale"
 $0^\circ\text{C} = 273.15^\circ\text{K}$

(15) Temperature scale by (1) Constant Pressure (2) Constant Volume method
by experiments it was found that at -273°C the gases used for experiments had no volume & no pressure



(16) Zeroth law of Thermodynamics ÷ Two bodies which are equal in temperature to third body are equal in temperature with each other if surrounding remains unchanged.

(17) NTP ÷ 0°C & 1.01325 Bar STP ÷ 15°C & 1.01325 Bar

(18) Process & cycle ÷ Quasi-static process ÷
↳ (I) Reversible & Irreversible

(19) Forms of Energy ÷ (I) Potential (II) Kinetic (III) Internal Energy
(IV) Chemical (V) Electrical Energy

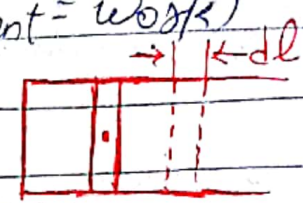
Total Energy ÷ $E = P.E + K.E + I.E + f(\text{Chemical \& Electrical \& magnetic})$

(20) Work ÷ It is made of energy transfer across the boundary between the system & the surroundings. $W_{1-2} = \int P dV$

$$W_{12} = \int_1^2 dw$$

Pure substance = $\int_1^2 Fx \, dL$ (Force * displacement = work)

whose chemical composition is homogeneous & constant is called pure substance = $\int_1^2 (Pressure * Area) * dL$



$= \int_1^2 P * dv = \int_{V_1}^{V_2} P \, dV$ Basic Intensive Property - They are evaluated w.r. to surroundings. e.g. - Temperature, volume, mass measured w.r. to some reference or datum. e.g. - Velocity & Elevation

$$W = \int_1^2 P \, dV$$

(21) Heat $\div Q$ \div Heat is Energy in Transition across boundary between the thermodynamic system & the surroundings without transfer of mass. Both work & heat are boundary phenomena

(22) Sign Convention of Work & Heat for any system

- (1) Work done by system on surrounding is (+ve)
- (2) Work done by surrounding on system is (-ve)
- (3) Heat transferred from surrounding to system (+ve)
- (4) Heat transferred from system to surrounding (-ve)

Objective of any system is to receive heat and convert it into work. Hence both are (+ve)

\rightarrow Heat system \div (+ve) \div Heat system \div (-ve)

(23) Specific Heat \div It is defined as the amount of heat required to pass the boundary of system to increase or reduce the temperature of the ^{unit mass of the} system by unit degree is called specific heat C

$$C = Q / m (T_2 - T_1) \quad [KJ/Kg \cdot ^\circ C]$$

$C = KJ / Kg \cdot K$ Unit of Specific Heat

There are two types of specific heat for gases

- (1) C_p \div Specific Heat at Constant Pressure
- (2) C_v \div Specific Heat at Constant Volume

24) Similarities & Differences between Work & Heat

Similarities: (1) Both are boundary phenomena & can be observed only on boundary of any system (2) Both are transient phenomena & exist whenever a system executes a process. (3) Both are path function

(Stable system) :- Here volume of system is constant & there is no movement of boundary

Differences: (1) In a stable system there can not be a work transfer how ever there are no restriction on Heat transfer (2) For transfer of Heat temperature difference is needed All other energy interactions can be termed as work transfer (3) The sole effect of surroundings in case of work transfer can be reduced to the raising of weight, but in case of Heat transfer other effects are also observed.

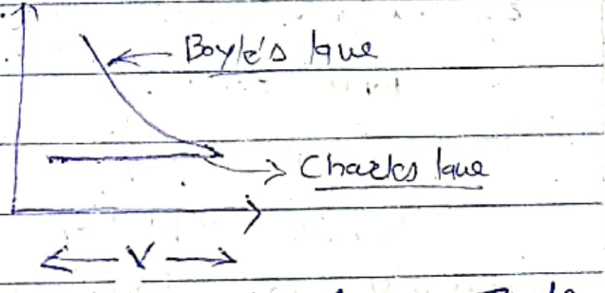
Pure Substance: A substance whose chemical & physical properties remain unchanged throughout the volume

CHAPTER - 2 - IDEAL LAWS

(1) Boyle's Law: If a gas is heated at constant temperature then its Volume & Pressure's multiplication is always constant.
 $PV = \text{Constant}$ (T is constant & gas is heated)

(2) Charles's Law: If gas is heated at constant pressure then its Volume is ~~inversely~~ directly proportion to its temperature $V \propto T$
 $\frac{V}{T} = \text{constant}$
 R = Characteristic Gas Constant

(3) Combination of Boyle's & Charles's Law: $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} = \frac{PV}{T} = \text{Constant (R)}$
 $PV = mRT$ so $R = \frac{PV}{mT}$



(4) $R = \frac{PV}{mT} = \frac{N \cdot \frac{m^2}{s^2}}{m^2 \cdot K} = \frac{N \cdot m}{Kg \cdot K} = \frac{Joule}{Kg \cdot K}$

Unit of R = $\frac{Joule}{Kg \cdot K}$

⑤ Avogadro's Hypothesis: Equal Volume of ^{different} gas at same temperature & pressure have same number of molecules. It has been found that mass in Kg of 22.4163 m^3 of any perfect gas at NTP is equal to its molecular mass. Note: 22.4163 m^3 of H_2 gas has mass of 2 Kg & for same volume O_2 has 32 Kg & N_2 gas has 28 Kg.

⑥ Universal / Molar Gas Constant: It means $\frac{V}{n}$ for all gases is same
 $m = nM$

Gas	Volume (m^3)	Molar mass	molecular mass	$m = \text{Total mass of gas}$
O_2	22.4163	32 Kg	32	$n = \text{no. of molecules}$
N_2	22.4163	28 Kg	28	$M = \text{Molecular mass}$
H_2	22.4163	2 Kg	2	

⑥ Molar Gas Constant or Universal Gas Constant R_u

Substituting the value of m in the characteristic gas equation of perfect gas we have $PV = mRT$ / $PV = nmRT$ ($\because m = nM$)

$$mR = \frac{PV}{nT} = R_u = \text{Universal Gas Constant}$$

As per Avogadro's law V/m is same for all gases at same value of P & T so thus PV/nT is constant.

$$R_u = 8.314 \text{ KJ / Kg} \cdot \text{mol} \cdot \text{K}$$

$$R_u = \frac{8314.89}{M} \text{ KJ / Kg} \cdot \text{mol} \cdot \text{K}$$

$$mR = R_u = 8314.89 \frac{\text{N} \cdot \text{m}}{\text{Kg} \cdot \text{mol} \cdot \text{K}} = \frac{\text{Joule}}{\text{Kg} \cdot \text{mol} \cdot \text{K}}$$

Here $R_u = \text{Universal Gas Constant}$

$$R = \frac{R_u}{M} = \text{Characteristic Gas Constant}$$

$$R_u = M \cdot R$$

$$R_u = m \cdot R$$

Unit of $R_u = \text{KJ / Kg} \cdot \text{mole} \cdot \text{K} = \text{Universal Gas Constant}$

Unit of $R = \text{KJ / Kg} \cdot \text{K} = \text{Characteristic Gas Constant}$

$$R = C_p - C_v = C_p - C_v \text{ (small c)} \quad (M = \text{molecular mass})$$

$$R_u = C_p - C_v = M (C_p - C_v) \quad (m = n \cdot M)$$

$m = \text{Total mass \& } n = \text{no. of moles of gas}$

⑦ Specific Heat - It is defined as the amount of heat required to pass through the boundary of the system to either raise or lower the temperature of system by unit degree.

$$Q = m C (T_2 - T_1) = m C dT$$

We have only one specific heat for solid & liquid but for gas we have different specific heat

① Specific Heat at Constant Volume C_v

② Specific Heat at Constant ~~Pressure~~ C_p

$$R = C_p - C_v$$

R is always (+ve) hence we can say that

C_p is always greater than C_v

$C_p > C_v$ always.

$Q = m C_p dT$ - Constant pressure process - Loss or Gain of Heat

$Q = m C_v dT$ - Constant Volume Process - Loss or Gain of Heat

⑧ Molar Specific Heat - Molar specific Heat is defined as quantity of heat required to pass the boundary of the system to raise temperature of one mole of mass through 1 unit degree.

(Molar Sp. Heat at constant pressure) $C_p = M C_p$

(Molar Sp. Heat at Constant Volume) $C_v = M C_v$

ALL EQUATIONS - Chapter 1 & 2

① $W = \int P dV = \int P dV$

② $PV = \text{constant}$ (Boyle's law) ($P \propto 1/V$)

③ $V \propto \frac{1}{T}$ (Charles's law) ($V \propto 1/T$)

④ $\frac{PV}{T} = \text{constant}$ (Combination of Boyle's & Charles's Law)

⑤ $PV = m R T$. Unit of $R = (\text{m/sec})^2 * (\text{1/K})$

⑥ $m R = PV/mT = R_u$ - Universal Gas Constant = $8314.89 \frac{\text{Nm}}{\text{kg.mol.K}}$

⑦ Heat Flow in Reversible Constant Pressure Process = $m C_p dT$

⑧ " " " " " " " " Volume Process = $m C_v dT$

⑨ $C_p/C_v = \gamma$ & $C_p - C_v = R$ | $R_u = C_p - C_v$ (Capital)

* CHAPTER 3 THERMODYNAMIC LAWS & ITS Application

① First Law of Thermodynamics For a system operating in a thermodynamic cycle the ~~work~~^{net} transfer is equal to net heat transfer if both are in same units.

$$\oint \delta W = \oint \delta Q \quad \text{or} \quad \oint \delta W - \oint \delta Q = 0$$

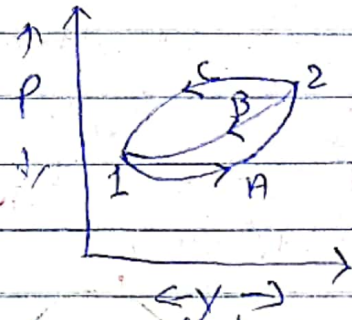
② Corollary - 1 - "Energy is a property" - It's a point function. There exist a property of a system called energy such that its value is equal to the difference between the heat supplied & the work done during any change of state.

$$\Delta E = [Q_2 - W_2] = E_2 - E_1$$

As shown in First law of Thermodynamics all heat given to the system gets transformed to work that is impossible so the difference between the heat supplied to the work done by system always exists. This difference can be attributed to gain in internal energy. (Note - We are neglecting all other losses here)

③ Proofs That energy is a property -

As shown in PV diagram point 1 & 2 are two different points & a system undergoes changes from 1 to 2 & back from 2 to 1. From 1 to 2 it goes via path A.



It returns from 2 to 1 via two different paths called B & C.

From first law of thermodynamics

$$\oint \delta Q = \oint \delta W$$

for cycle A-B

$$\int_{1A}^2 \delta Q + \int_{2B}^1 \delta Q = \int_{1A}^2 \delta W + \int_{2B}^1 \delta W$$

①

$$\int_{1A}^2 \delta Q + \int_{2C}^1 \delta Q = \int_{1A}^2 \delta W + \int_{2C}^1 \delta W$$

②

Subtracting equation of cycle 1A2B1 & 1A2C1 we get

$$\int_{1A}^2 \delta Q + \int_{2B}^1 \delta Q + \int_{1A}^2 \delta W - \left(\int_{1A}^2 \delta Q + \int_{2C}^1 \delta Q + \int_{1A}^2 \delta W \right) = 0$$

$$\int_{1A}^2 \delta Q + \int_{2B}^1 \delta Q - \int_{1A}^2 \delta Q - \int_{2C}^1 \delta Q = \int_{1A}^2 \delta W + \int_{2B}^1 \delta W - \int_{1A}^2 \delta W - \int_{2C}^1 \delta W$$

"COROLLARY - 1"

$$\int_{2B}^1 \delta Q - \int_{2C}^1 \delta Q = \int_{2B}^1 \delta W - \int_{2C}^1 \delta W$$

$$= \int_{2B}^1 \delta Q - \int_{2B}^1 \delta W = \int_{2C}^1 \delta Q - \int_{2C}^1 \delta W$$

$$= \int_{2B}^1 (\delta Q - \delta W) = \int_{2C}^1 (\delta Q - \delta W) = \text{Constant} = \Delta E$$

"There exist a property of the system which is equal to difference between workdone & Heat supplied"

We can say that for any process between 1 & 2 ($\delta Q - \delta W$) will be constant & will never change. Now as we know that this difference is dependent on the first & the last stage of the process & not on the method used to achieve. So it can be called as "Point function". $\delta Q - \delta W = \text{Constant}$ & its symbol is E.

Energy is a property | Energy is a point function.

- * Total Energy is summation of Internal Energy + Kinetic Energy + Potential Energy
- * Internal Energy is denoted as U

E	$=$	dU	$+$	$d(KE)$	$+$	$d(PE)$
Total Energy		Internal Energy		Kinetic Energy		Potential Energy
		(Microscopic Analysis Required)		(Macroscopic Analysis)		

NON FLOW = CLOSED SYSTEM

* Non-Flow Energy Equation (NFEE) - Its applied to a closed system. As there is no kinetic energy & Potential Energy are zero, hence it has only internal energy

$$\delta Q = \delta W + \delta U$$

$$U_2 - U_1 = {}_1Q_2 - {}_1W_2$$

→ The cyclic integral of E is always zero, while for Q & W it may not be zero

→ The differential dE is an exact differential in terms of ^{state} the variable (the independent property) that determine the ~~property~~

→ Internal energy is a quantity which is different in kind compared to work & heat. We can see ^{or} feel the work done ^{or} heat transmitted across the boundary in a system but change in internal energy can't be seen

→ ^{or} it can not be felt

→

* Corollary-2 :- Conservation of Energy :-

In an isolated system energy of system remain constant.

$${}_1Q_2 = 0$$

$${}_1W_2 = 0$$

$$\Delta U = 0$$

$$U_2 = U_1$$

* Corollary-3 :- Perpetual Motion Machine - I (Impossible) :-

The continuous output of work from a system working in a cycle with zero input of energy is impossible.

* Heating & Expansion in A non-flow process :- In a non-flow process the substance remains in closed system, only energy crosses the boundary in terms of heat & work. With resisted expansion work is obtained by displacement of boundary & its called displacement work. Its equal to $\int P dv$

* Total six different process are studied. *

- ① Constant Volume process (Isometric Process) Isochoric
- ② " Pressure process (Isobaric Process)
- ③ Constant Temperature process (Isothermal Process) ← 3rd same
- ④ Proof for Relations of C_p & C_v (i) $C_p - C_v = R$ (ii) $C_p/C_v = \gamma$ (iii) $C_v = R/\gamma - 1$
- ⑤ Hyperbolic Expansion process - $PV = \text{constant}$
- ⑥ Polytropic process $PV^n = \text{constant}$
- ⑦ Adiabatic process $PV^\gamma = \text{constant}$

All the above process are studied and for each of them following equations are derived.

- (i) Basic definition equation (ii) P-V-T relation
 (iii) Work done (iv) change in Internal energy (v) Heat added or rejected (vi) Enthalpy change (vii) Entropy change (viii) PV Diagram

Proof of $C_p - C_v = R$; $C_v = \frac{R}{\gamma - 1}$; $C_p = \frac{\gamma R}{\gamma - 1}$

$$dq = du + PdV$$

$$Q_2 = (U_2 - U_1) + P(V_2 - V_1)$$

We know $U = mC_v dT$ & $PV = mRT$

$$Q_2 = mC_v(T_2 - T_1) + mR(T_2 - T_1)$$

$$Q_2 = m(T_2 - T_1) [C_v + R]$$

$$Q_2 = m(T_2 - T_1) [C_p]$$

$$mC_p dT = m(T_2 - T_1) [C_v + R]$$

$$C_p = C_v + R$$

$$R = C_p - C_v$$

$$C_p - C_v = R \quad \text{--- ①}$$

$$C_p = \gamma$$

$$C_p \times (R) = \gamma R$$

$$C_p = \frac{\gamma R}{\gamma - 1}$$

We know $\gamma = C_p/C_v$

$$\gamma - 1 = \frac{C_p}{C_v} - 1$$

$$\gamma - 1 = \frac{C_p - C_v}{C_v}$$

$$\gamma - 1 = \frac{R}{C_v}$$

$$C_v = \frac{R}{\gamma - 1} \quad \text{--- ②}$$

$$C_p - C_v = R$$

$$C_p = C_v + R$$

$$C_p = \frac{R}{\gamma - 1} + R$$

$$C_p = \frac{R + \gamma R - R}{\gamma - 1} = \frac{\gamma R}{\gamma - 1} \quad \text{--- ③}$$

$$1 \text{ bar} = 100 \text{ kN/m}^2$$

Gibbs Phase Rule = $P + F = C + 2$

P = No of phase, F = Degree of freedom
 C = No of components

Polytropic process $w = \int P dv$ $PV^n = P_1 V_1^n = P_2 V_2^n$

$$W = \int_{V_1}^{V_2} P dy = \int_{V_1}^{V_2} \frac{P_1 V_1^n}{V^n} dy = \int_{V_1}^{V_2} P_1 V_1^n * V^{-n} dy$$

$$= P_1 V_1^n \int_{V_1}^{V_2} V^{-n} dy = P_1 V_1^n \left[\frac{V^{-n+1}}{-n+1} \right]_{V_1}^{V_2}$$

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

$$W = P_1 V_1^n \left[\frac{V_1^{-n+1} - V_2^{-n+1}}{-n+1} \right] = \frac{P_1 V_1 - P_2 V_2}{n-1} = W$$

Thermodynamic state : It is condition of systems at a given properties are fixed

Note : Properties are state function & are exact differential

Thermodynamic cycle : When the initial & final stage are same, we say that system has undergone a cycle

Energy is a point function & work done is a path function

(*) Iso Thermal - Constant Temp process

$PV = \text{constant}$ $PV = P_1 V_1$ so $(P = P_1 V_1 / V)$

$$W = \int_{V_1}^{V_2} P dy = \int_{V_1}^{V_2} \frac{P_1 V_1}{V} dy = P_1 V_1 \int_{V_1}^{V_2} \frac{1}{V} dy = P_1 V_1 [\ln V]_{V_1}^{V_2}$$

$$W = P_1 V_1 \ln (V_2 / V_1) = P_1 V_1 \ln (P_1 / P_2) = mRT_1 \ln (\gamma)$$

(*) Polytropic ↑

Polytropic process $W = \frac{P_1 V_1}{n-1} \left[1 - \frac{1}{\gamma^{n-1}} \right] \left[\gamma = V_1/V_2 \right]$

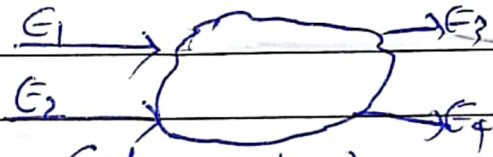
$\rightarrow Q = \frac{\gamma - n}{\gamma - 1} * \underline{P dy}$

$\rightarrow \Delta H = \text{Change in Enthalpy} = \frac{\gamma (P_2 V_2 - P_1 V_1)}{\gamma - 1}$

$1 \text{ mPa} = \text{~~1000~~ } 10^3$

Flow work :- The amount of work that is required to maintain continuous flow in control volume is called flow work

Thermal-Chap-3-SFEE-1



S.F.E.E. Steady flow Energy Equation (Open system)

Energy considered in open system. Total 5 types of Energy: Internal Energy, Flow work, K.E., P.E. & Heat

Inlet Energy = $\dot{m}_1 \left(\underbrace{U_1}_{I.E.} + \underbrace{P_1 V_1}_{F.W.} + \underbrace{\frac{C_1^2}{2}}_{K.E.} + \underbrace{g z_1}_{P.E.} \right) + \underbrace{Q}_{HEAT}$ -- (1) Energy + Heat supplied

Outlet Energy = $\dot{m}_2 \left(\underbrace{U_2}_{I.E.} + \underbrace{P_2 V_2}_{F.W.} + \underbrace{\frac{C_2^2}{2}}_{K.E.} + \underbrace{g z_2}_{P.E.} \right) + \underbrace{W}_{Work}$ -- (2) Energy + W.D

We know as flow is steady flow $\dot{m}_1 = \dot{m}_2 = \dot{m}$

Now equating 1 & 2 & taking \dot{m}_1 & \dot{m}_2 as \dot{m}

$$\dot{m} \left(U_1 + P_1 V_1 + \frac{C_1^2}{2} + g z_1 \right) + Q = \dot{m} \left(U_2 + P_2 V_2 + \frac{C_2^2}{2} + g z_2 \right) + W$$

$$\dot{Q} - \dot{W} = \dot{m} \left(U_2 - U_1 + (P_2 V_2 - P_1 V_1) + \frac{C_2^2 - C_1^2}{2} + g(z_2 - z_1) \right)$$

$h_1 = U_1 + P_1 V_1$ & $h_2 = U_2 + P_2 V_2$

$$\dot{Q} - \dot{W} = \dot{m} \left((h_2 - h_1) + \frac{C_2^2 - C_1^2}{2} + g(z_2 - z_1) \right) \text{ -- S.F.E.E.}$$

if $z_1 = z_2$

$$\dot{Q} - \dot{W} = \dot{m} \left[(h_2 - h_1) + \frac{C_2^2 - C_1^2}{2} \right] \text{ -- S.F.E.E.}$$

Unit analysis of SFEE

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

h = specific enthalpy
= enthalpy/unit mass

$\frac{kJ}{sec}$	$\frac{kJ}{sec}$	$\frac{kg}{sec}$	Joule	$\frac{m^2}{sec^2}$	$\frac{m}{sec^2} \times m$
Watt	Watt	kg	kg	$\frac{kg \cdot m^2}{sec \cdot sec}$	$\frac{kg \cdot m}{sec^2}$

$$\text{Watt} - \text{Watt} = \frac{kg}{sec} \times \frac{Joule}{kg} + \frac{kg \cdot m^2}{sec \cdot sec} \times \frac{1}{kg} + \frac{Joule}{sec} - \text{Watt}$$

$$= \frac{Joule}{sec} + \frac{kg \cdot m}{sec^2} = \text{Watt}$$

For unit mass

$$\dot{q} - \dot{w} = (h_2 - h_1) + \frac{(C_2^2 - C_1^2)}{2} + g(z_2 - z_1)$$

$$\dot{q} - \dot{w} = \Delta h + \Delta KE + \Delta PE$$

* Derivation of open system work

$$\dot{Q} - \dot{W} = \Delta h + \Delta KE + \Delta PE \quad \& \quad h = U + P \cdot V$$

$$\text{①} \quad dh = dU + Pdv + VdP \quad \text{②}$$

put value of dh in 1

$$d\dot{Q} - d\dot{W} = dU + Pdv + VdP + \Delta KE + \Delta PE$$

$$d\dot{Q} - d\dot{W} = d\dot{Q} + VdP + \Delta KE + \Delta PE$$

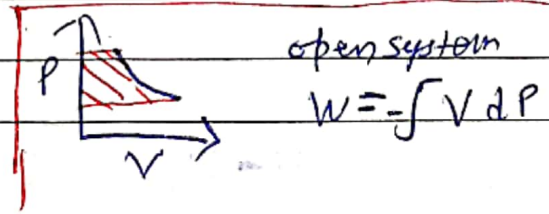
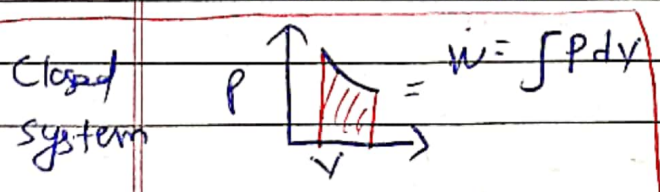
$$-d\dot{W} = VdP + \Delta KE + \Delta PE$$

let change in KE & PE are neglected

$$-d\dot{W} = VdP$$

$$\int -d\dot{W} = \int VdP$$

$$\boxed{W = -\int VdP} = \text{Work for open system}$$



$$-W = v \int_{P_1}^{P_2} dP = -v [P]_{P_1}^{P_2} = -v [P_2 - P_1] = [P_1 - P_2] v = \text{open system}$$

(a) $W = v [P_1 - P_2]$ open system constant volume process work $W = - \int v dP$

(b) Constant P $W = - \int v dP = 0$ ($dP = 0$)

Lecture-23

(c) Const temp process = $W = P_1 V_1 \ln(P_1/P_2) = nRT_1 \ln(V_2/V_1)$

(d) Polytropic process = $\frac{n(P_1 V_1 - P_2 V_2)}{(n-1)}$

$P v^n = C$ so $v = \frac{C}{P^{1/n}}$ $W_c = \int [-C/(P^{1/n})]$
 $= \frac{n(P_1 V_1 - P_2 V_2)}{(n-1)}$

(e) adiabatic = $\frac{\gamma(P_1 V_1 - P_2 V_2)}{\gamma-1}$ $(W_{adiabatic})_{open} = \gamma * (W_{adiabatic})_{close}$

Conclusion

$(W_{polytropic})_{open} = n * (W_{polytropic})_{close}$
 $= n \left[\frac{P_1 V_1 - P_2 V_2}{n-1} \right]$


Open system work for adiabatic process

SFEE-2

$$PV^r = \text{const}$$

$$P_1 V_1^r = C$$

$$\& P_2 V_2^r = C$$

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$$PV^r = C \quad \text{so} \quad V^r = \frac{C}{P} \quad \text{so} \quad V = \left[\frac{C}{P} \right]^{1/r} \quad / \quad V = C \cdot P^{-1/r}$$
$$V_1 = C P_1^{-1/r}$$
$$V_2 = C P_2^{-1/r}$$

$$W = \int V dP$$
$$= \int \frac{C}{P} \cdot P^{-1/r} \cdot dP$$

$$V_1 = -C \int_1^2 P^{-1/r} \cdot dP$$

$$= -C \left[\frac{-P^{-1/r+1}}{-1/r+1} \right]_1^2$$

$$= \frac{C}{\left(\frac{-1+r}{r} \right)} \left[P_2^{-1/r+1} - P_1^{-1/r+1} \right]$$

Note: Rebe note for sums on SFEE

Application of SFEE - 24

- ① Positive work device | Turbine
- ② Negative work device | Pump & Compressor
- ③ zero work device | Nozzle & Diffuser

Turbine ÷ It's a type of power producing device in which ^{Energy} ~~work~~ is transferred from working fluid to Rotor. (Energy Transfer)

Turbine is Insulated

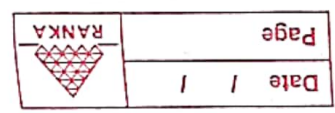
$W_T = h_2 - h_1$ ① wall of Turbine is insulated ② The change in K.E is neglected ③ The change in P.E is also neglected.

$\dot{Q} = \dot{W} = \dot{m} [h_2 - h_1]$ so $\dot{Q} = 0$
 $-\dot{W} = \dot{m} (h_2 - h_1)$ so $\dot{W} = \dot{m} (h_1 - h_2)$
 h_1 is always greater than h_2 $h_1 > h_2$

\dot{W} = Rate of doing work
 = Power

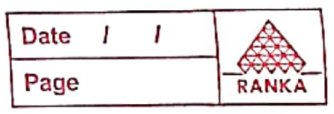
$P = W = \dot{m} (h_1 - h_2)$ = Power developed by turbine
 \dot{m} = mass flow rate & $(h_1 - h_2)$ = change in enthalpy

① Turbine ÷ $-W_2 = (h_2 - h_1) + \left(\frac{C_2^2}{2} - \frac{C_1^2}{2} \right)$



② In reciprocating machine
 $W_2 = (h_1 - h_2)$

$h_1 = U_1 + P_1 V_1$ I.E
 $h_2 = U_2 + P_2 V_2$ W.D



③ In nozzles ÷ $(h_1 - h_2) = \frac{1}{2} C_1^2 + h_1 = \frac{1}{2} C_2^2 + h_2$
 so $(h_1 - h_2) = \frac{1}{2} [C_2^2 - C_1^2]$

zero work device ÷ ① Nozzle ② Diffuser ③ Boiler ④ Condenser ⑤ Evaporator

① Nozzle ÷ Device which increases K.E at cost of P.E energy
 $\frac{1}{2} C_1^2 + h_1 = \frac{1}{2} C_2^2 + h_2 = h_0$ (Wall of Nozzle is insulated)

Assumptions

- ① Walls of Nozzle is insulated ② The work transfer is zero ③ The change in P.E is neglected ④ Inlet velocity is extremely less compared to outlet velocity

$C_2 = 44.72 \sqrt{(h_1 - h_2)}$ C_2 = Exit Velocity & C_2 very huge than C_1

② Diffuser ÷ ① It's a zero work device ② It ^{Increases} produces P.E on expense of K.E/velocity
 $C_1 = 44.72 \sqrt{h_2 - h_1}$

③ Boiler ÷ Heat is added at constant P.E.

Assumptions

- ① There is no work transfer ② The change in K.E is neglected

$\dot{Q} = (h_2 - h_1) \dot{m}$ heat addition in system

④ Condenser ÷ It is a type of Heat Exchanger in which heat is rejected by working fluid at constant p_3 .

$$\dot{Q} = -\dot{m} (h_1 - h_2)$$

This will be -ve

$$\dot{Q} - \dot{W} = \dot{m} (h_1 - h_2) + \left(\frac{C_2^2 - C_1^2}{2000} \right) + \frac{g(z_2 - z_1)}{1000}$$


⑤ Evaporator ÷ It is a type of H.E in which heat is absorbed from desired space by working fluid at constant p_3 . e.g. ÷ Vapour compression Refri system.

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

$$\dot{Q} = \dot{m} (h_2 - h_1)$$

(+ve)

⑥ Throttling device ÷ It is an Isoenthalpy process.
It is irreversible Adiabatic process

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$$h_2 - h_1 = 0 \text{ so } h_1 = h_2$$

CHAPTER-4. SECOND LAW OF THERMODYNAMICS

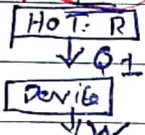
4.1

Limitation of First Law of Thermodynamics :- As defined in PMM-I, first law it fixes only exchange rate between heat and work done but does not place any restriction on its direction.

PMM-2

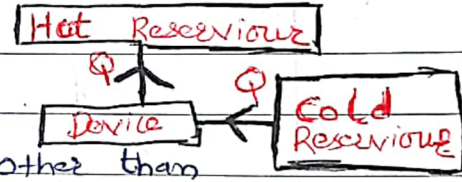
4.2

Second Law of Thermodynamics PMM-2 100% Efficient
Complete conversion of low grade energy to high grade energy is impossible. This defines path of Heat flow as well (WORK)



4.3

Kelvin-Planck & Clausius Statement :-



Kelvin-Planck

It is impossible to construct an engine operating in cycle which will produce ~~no~~ effect other than the exchange of heat from a single reservoir & produce work. Hence PMM-2 is impossible. (2 Nos of Reservoirs are always needed.)

Clausius

Heat cannot flow from lower temperature body to a higher temperature body without an aid of an external ^{working} agency.

So we can say that, a heat pump cannot work any input of work.

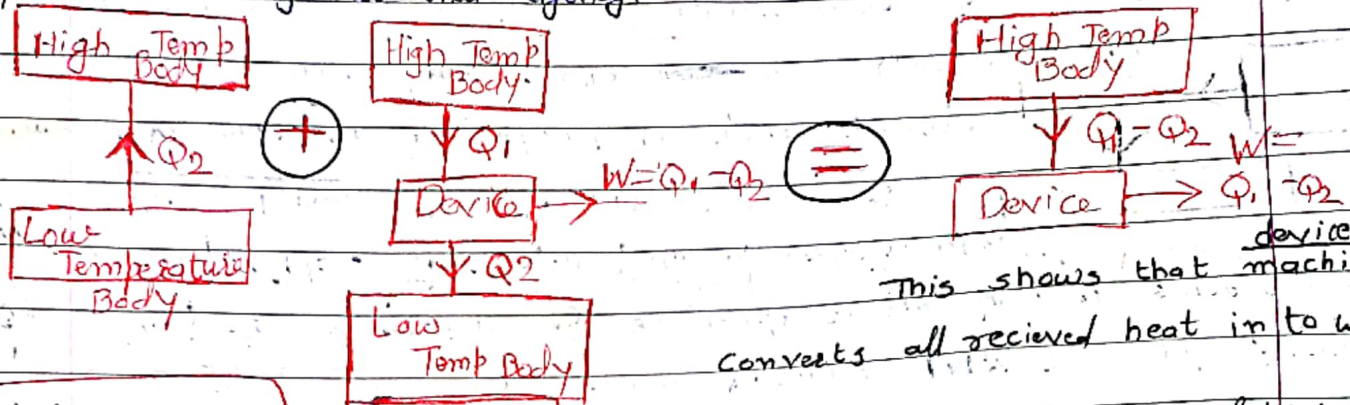
Note - Efficiency of Carnot Cycle is maximum & Efficiency of PMM-1 is 100%

4. Violation of Equivalence of The Kelvin Planck & Clausius statement of second law of Thermodynamics.

- (i) Violation of Clausius implies violation of Kelvin-Planck
- (ii) Violation of Kelvin-Planck implies violation of Clausius.

(i) Violation of Clausius implies violation of Kelvin-Planck.

Clausius statement says heat can not flow from low temp to high temp body without any external agency.

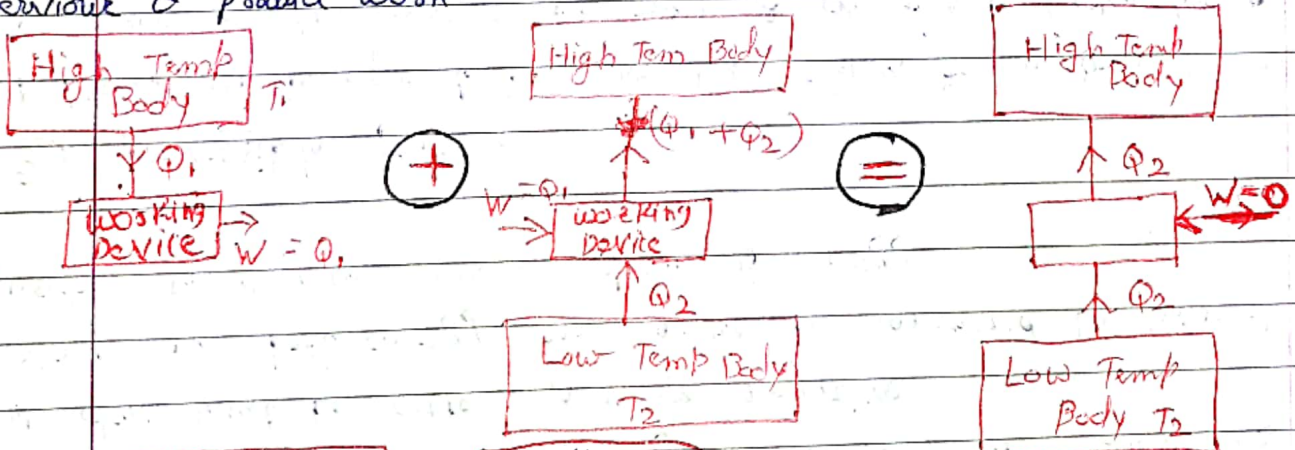


This shows that machine converts all received heat in to work = 100% conversion of heat to work.

The above phenomenon is not possible

(ii) Violation of Kelvin Planck implies violation of Clausius.

Kelvin Planck statement says that its impossible to construct an engine operating in a cycle will produce no effect other than exchange of heat from single reservoir & produce work.



Violating Kelvin-Planck statement + Possible Reversed Heat Engine = Heat Pump (Its taking heat from Low temperature to high Temp area) without any work done

The above phenomenon is not possible

Summary of Above Two Consequence i.e violation of one law & its effect

- ① If a system is taken through a cycle and produces work there must be two heat reservoirs at different temperature. From high temp reservoir system receives heat & rejects to a low temp reservoir
- ② If a system is taken through cycle with only one reservoir then work done must be either zero or negative
- ③ Since all heat energy can never be converted to work so work is considered to be more valuable form of energy.

4.5 Reversible process

A process can be said to be reversible only if it can be carried out in same manner in reverse direction & in forward direction the surroundings are in completely same condition.

Reversibility are

The condition which needs to be fulfilled for Thermodynamic

- ① The working substance at any instance must have same temperature as that of heat source, while the heat is being

absorbed, hence we can say that the cylinder head must be

a perfect conductor of heat. The temperature throughout the working fluid has to be same

- ② The working substance at any instant must the same temperature as that of the cold body, while heat is being rejected
- ③ There should be no frictional or mechanical losses
- ④ There should be no pressure difference between the expanding fluid & surrounding
- ⑤ There should be no mixing of fluids
- ⑥ There should be perfect Thermal equilibrium

By using second law of Thermodynamics we can say that a process can not be reversible it has ① Friction ② Unresisted Expansion ③ Heat Transfer with finite temperature difference

Note: Only Adiabatic & Isothermal these two processes are truly reversible, though only Hypothetically.

A process is said to be irreversible if a PMM-2 would result from its being reversible or cycle as per PMM-2 is followed to achieve the process.

We know that work done = heat supplied - heat rejected
 $= R T_1 \ln r - R T_2 \ln r$

$$\eta = \text{Efficiency of cycle} = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{Q_2 - Q_4}{Q_2} = 1 - \frac{Q_4}{Q_2}$$

~~$$\eta = \frac{R T_1 \ln r - R T_2 \ln r}{R T_1 \ln r}$$~~

$$\frac{T_1}{T_2} = \left(\frac{P_2}{P_1}\right)^{\frac{r-1}{r}} = \left(\frac{V_1}{V_2}\right)^{r-1}$$

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

$$= \frac{T_1 - T_2}{T_1}$$

$$= 1 - \frac{T_2}{T_1}$$

$$\eta = 1 - \frac{T_2}{T_1}$$

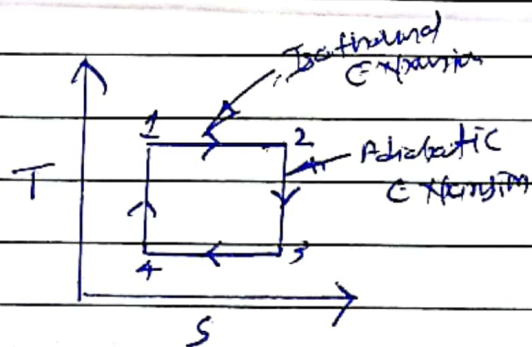
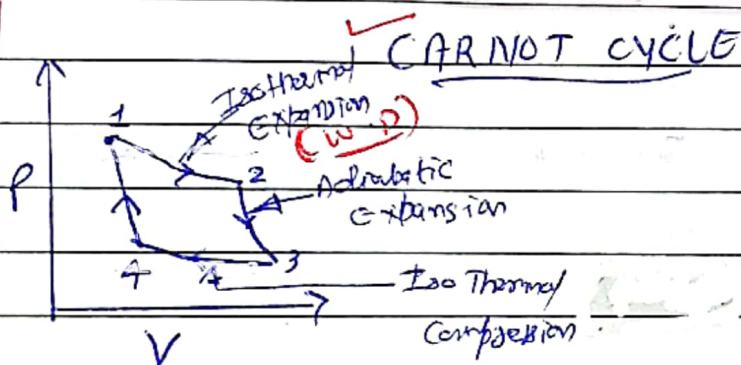
$$= 1 - \left(\frac{V_2}{V_1}\right)^{r-1}$$

$$= 1 - \left(\frac{V_2}{V_1}\right)^{r-1}$$

$$1 - \left(\frac{1}{r}\right)^{r-1}$$

here $r =$ adiabatic compression & expansion ratio
 ↓
 Volume

From above equation we can say that heat should be taken from highest temp source & rejected to lowest temp source for maximum efficiency.



1-2 Isothermal Expansion $Q = P_1 V_1 \ln(V_2/V_1) = W$

2-3 - Adiabatic Expansion $Q = 0$

3-4 Isothermal Compression $Q = P_3 V_3 \ln(V_4/V_3) = -W$

4-1 Adiabatic compression $Q = 0$

Net heat supplied

$$Q_{1-2} + Q_{3-4} = P_1 V_1 \ln(V_2/V_1) + P_3 V_3 \ln(V_4/V_3)$$

$$= P_1 V_1 \ln(V_2/V_1) - P_3 V_3 \ln(V_3/V_4)$$

$\left(\frac{V_2}{V_1}\right)$ is Isothermal Compression volume ratio

$\left(\frac{V_3}{V_4}\right)$ is also Isothermal Compression & Volume Ratio

both are same $\frac{V_2}{V_1} = \frac{V_3}{V_4}$

$$Q_{net} = mR T_1 \ln \left(\frac{V_2}{V_1} \right) - mR T_2 \ln \left(\frac{V_2}{V_1} \right)$$

Heat Input ~~is~~ is in cycle 1-2

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

$$\eta = \frac{Q_{net}}{Q_{in}} = \frac{mR T_1 \ln \left(\frac{V_2}{V_1} \right) - mR T_2 \ln \left(\frac{V_2}{V_1} \right)}{mR T_1 \ln \left(\frac{V_2}{V_1} \right)}$$

$$= \frac{T_1 - T_2}{T_1}$$

$$\eta = \frac{T_1 - T_2}{T_1}$$

$$\boxed{\eta = 1 - \frac{T_2}{T_1}}$$

Drawbacks of Carnot cycle

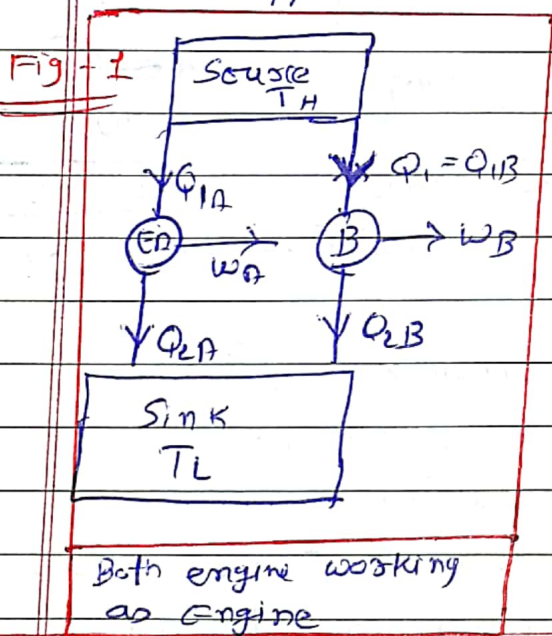
- ① To achieve Isothermal process are very slow & Adiabatic process is very fast such a cycle where one stage is ^{very} slow & other is very fast this combination is not possible to achieve, so Carnot cycle is not feasible.
- ② The reversible cycle engine (Carnot) is more efficient than irreversible
- ③ The efficiency of Reversible cycle is given by Carnot $\eta = 1 - T_2/T_1$
- ④ The efficiency of Reversible cycle depends on temperature of end points.
- ⑤ It is not depending on working medium.

*CARNOT THEOREM. ÷ Any heat engine other than Carnot engine can not have more efficiency than Carnot cycle H.E. But it can have same (η) as Carnot if processes are reversible.

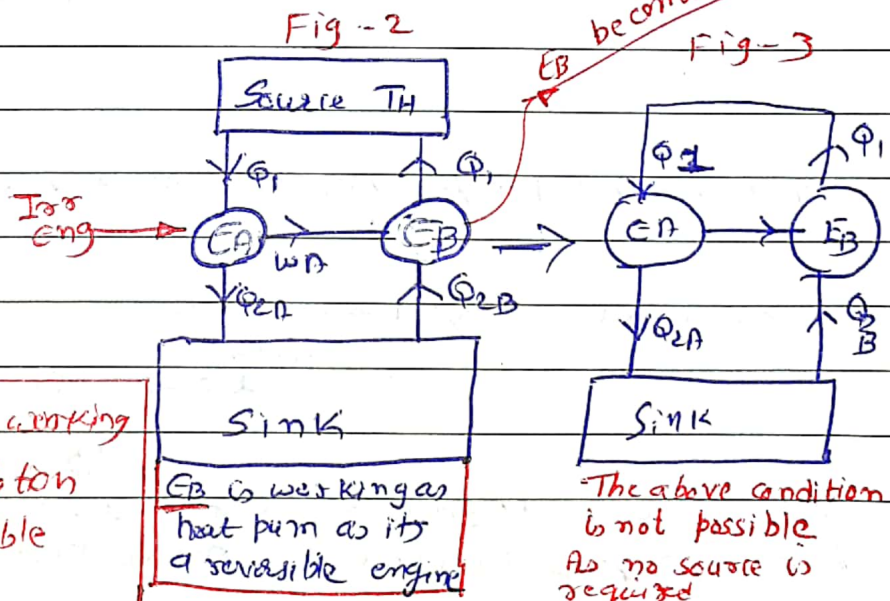
* Carnot cycle

Assuming Efficiency of Irreversible Engine is ^{efficient} more than Reversible & then proving it wrong.

→ Let E_A is an Irreversible engine & E_B is reversible engine working between same Heat source & sink
 → Heat supplied is also same for both engine



→ Let E_A is more efficient than E_B
 → Engine E_B Heat engine start worky like a heat pump



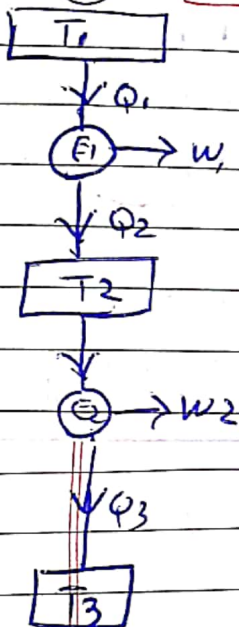
The condition in Fig-3 shows engine working with one Heat source which is violation of Kelvin-Planck's law, so not possible

→ This shows that assumptions made in stating that efficiency of an irreversible engine is more than a reversible engine is wrong.

→ Conclusion : ① Efficiency of reversible ^{engine} is more than irreversible engine

② It is impossible to construct a device which operates with help of single Reservoirs.

Thermodynamic Scale



The actual efficiency of Heat Engine

$$\eta_{act} = \frac{W_{net}}{H.S} = \frac{Q_{net}}{H.S} = \frac{H.S - H.R}{H.S} = 1 - \frac{H.R}{H.S}$$

$$\eta_{act} = 1 - \frac{Q_2}{Q_1}$$

Max possible efficiency of H.E

$$\eta_{act} = 1 - \frac{T_2}{T_1}$$

$$\eta_{act} = \eta_{max}$$

$$1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_1}$$

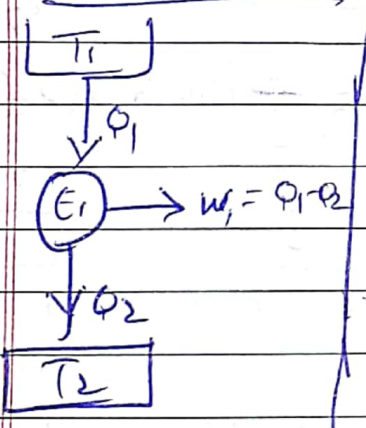
$$\frac{Q_2}{Q_1} = \frac{T_2}{T_1}$$

$Q \propto T$ For Reversible Carnot Cycle

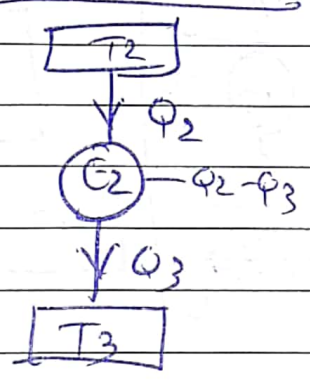
② Series combination of two reversible engine when work is same by both engine then relation between intermediate temp will be

$W_1 = W_2$

FBD for H.E. 1



FBD for H.E. 2



$W_1 = W_2$

$Q_1 - Q_2 = Q_2 - Q_3$

$Q_1 + Q_3 = 2Q_2$

$Q_2 = \frac{Q_1 + Q_3}{2}$

$T_2 = \frac{T_1 + T_3}{2}$

$Q_1 = Q_2 + W_1$
 $W_1 = Q_2 - Q_1$

$Q_2 = W_2 + Q_3$
 $W_2 = Q_3 - Q_2$

Same work done engine coupled in series.

Irreversibility

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

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

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

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

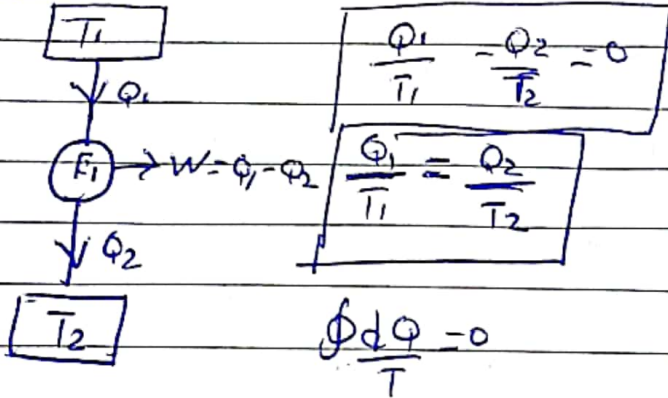
For Reversible

for Irreversible

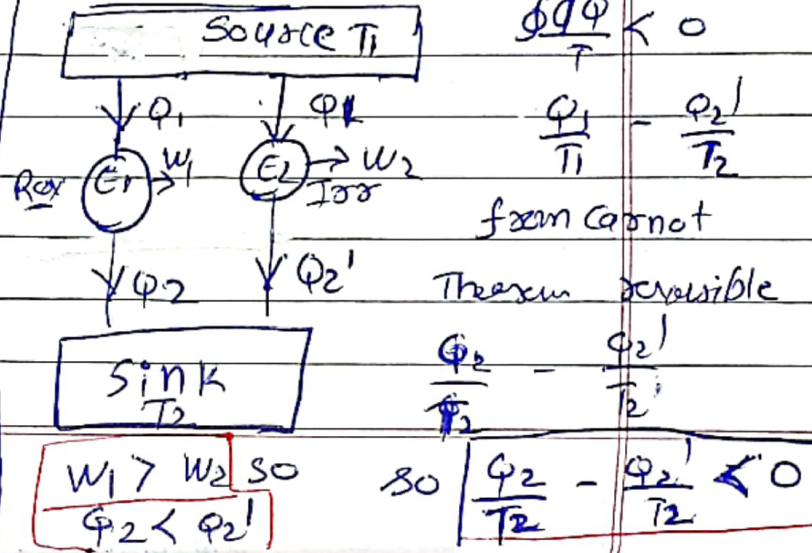
Not possible

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

Case - 1 Reversible H.E



Case - Irreversible



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$\oint \frac{dQ}{T} < 0$ for Irreversible

Numerical on 2nd Law of T.D

All Formulas

① $\eta = \frac{W_{net}}{\text{Heat supplied}}$ ② $\eta = \frac{Q_{net}}{H.S} = \frac{H.S - H.R}{H.S}$ ③ $\eta = 1 - \frac{H.R}{H.S}$

④ $\eta_{Carnot} = \eta_{rev} = 1 - \frac{T_{min}}{T_{max}}$ ⑤ $[COP]_{act} = \frac{Q_L}{Q_H - Q_L}$

⑥ $[COP]_{max} = \frac{T_L}{T_H - T_L}$ ⑦ $[C.O.P]_{actual} \text{ Heat Pump} = \frac{Q_H}{Q_H - Q_L}$

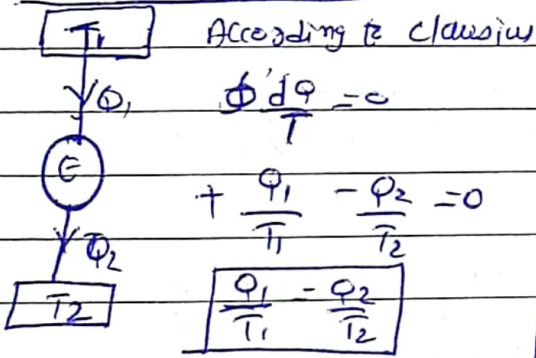
⑧ $[C.O.P]_{max} \text{ Heat Pump} = \frac{T_H}{T_H - T_L}$ ⑨ $\oint \frac{dQ}{T} = 0$ - For Reversible

⑩ $\oint \frac{dQ}{T} < 0$ Irreversible ⑪ $T_2 = \sqrt{T_1 \cdot T_3}$ $T_2 = \frac{T_1 + T_3}{2}$
 Same η in series Same work done coupled in series

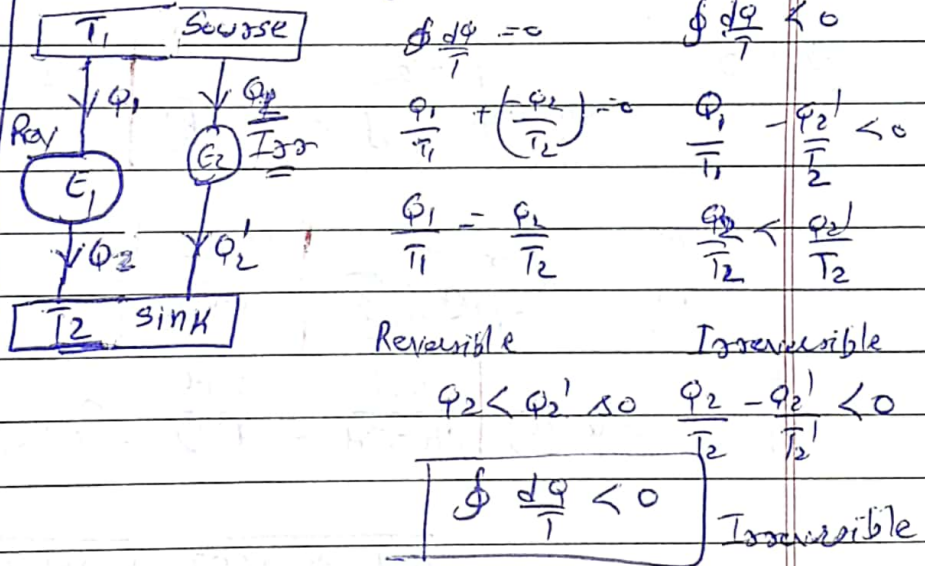
- * Clausius Inequality (a) $\oint \frac{dq}{T} < 0$ for Irreversible (b) $\oint \frac{dq}{T} = 0$ Reversible
 (c) $\oint \frac{dq}{T} > 0$ Not possible

We can say $\oint \frac{dq}{T} \leq 0$

Case-I for Reversible cycle:



Case-II for Irreversible cycle



Entropy

Refer Note for
sums

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→ Heat loss per unit temp

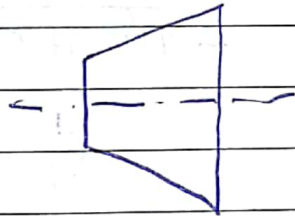
Defn → It's a thermodynamic quantity (as it depends on ends & not path taken) representing unavailability of thermal energy for conversion into Mechanical work.

$$ds = \frac{dQ}{T} = \frac{\text{Heat loss}}{\text{Temp}} = \text{Heat loss/unit temperature}$$

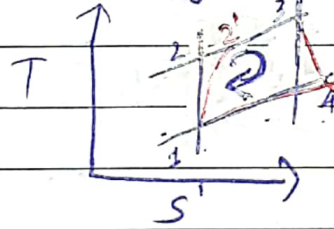
Defn → It is randomness or disorderness of any system.

→ As Entropy of system increases the efficiency of system decreases

→ Turbine



Closed Cycle Gas Turbine

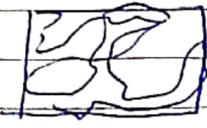


1-2-	Rev-Adiabatic Process
2-3	Const pr process
3-4	Rev-Adiabatic Process
4-1	Const pr process

1-2 = Reversible Adiabatic

1-2' = Actual Compression

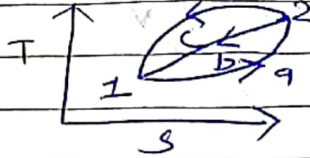
Entropy



Randomness increases does not follow any path

As randomness increases, energy loss increases & its efficiency decreases

Proof $ds = \frac{dq}{T}$



Entropy for Reversible cycle \div

1-2-b-1 - Reversible cycle

1-2-c-1 - Reversible cycle

From concept of Clausius Inequality

for reversible process $\oint \frac{dq}{T} = 0$



For 1-2-b-1 $\left(\frac{dq}{T}\right)_{12} + \left(\frac{dq}{T}\right)_{b1} = 0$ (1)

For 1-2-c-1 $\left(\frac{dq}{T}\right)_{12} + \left(\frac{dq}{T}\right)_{c1} = 0$ (2)

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subtract (2) - (1)

$$\left(\frac{dq}{T}\right)_{2c1} - \left(\frac{dq}{T}\right)_{2b1} = 0$$

$$\left(\frac{dq}{T}\right)_{2c1} = \left(\frac{dq}{T}\right)_{2b1}$$

→ Entropy is a property & a point function & not process intial

$\left(\frac{dq}{T}\right)_{Rev} = ds$ - (1) Change in entropy for reversible

→ Entropy is a property & its a point function so it depends on ends and entropy change will be same as long as end points are same

→

Entropy Change for Irreversible Cycle Lec-3^L

Let 1A2B1 = Reversible $\rightarrow \oint dQ/T = 0$

1A2C1 = Irreversible $\rightarrow \oint dQ/T < 0$

For 1A2C1 - For

$$\left(\frac{dQ}{T}\right)_{1a2} + \left(\frac{dQ}{T}\right)_{2c1} < 0 \quad \text{--- (1)}$$

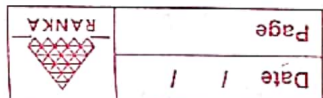
For 1A2B1
Rev

$$\left(\frac{dQ}{T}\right)_{1a2} + \left(\frac{dQ}{T}\right)_{2b1} = 0 \quad \text{--- (2)}$$

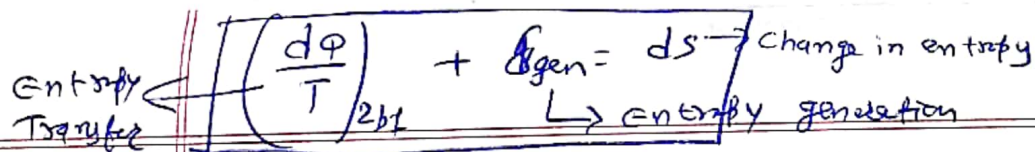
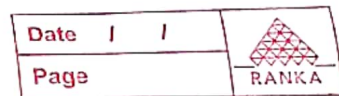
$$\left(\frac{dQ}{T}\right)_{1a2} = -\left(\frac{dQ}{T}\right)_{2b1}$$

$$-\left(\frac{dQ}{T}\right)_{2b1} + \left(\frac{dQ}{T}\right)_{2c1} < 0$$

$$\left(\frac{dQ}{T}\right)_{2c1} < \left(\frac{dQ}{T}\right)_{2b1}$$



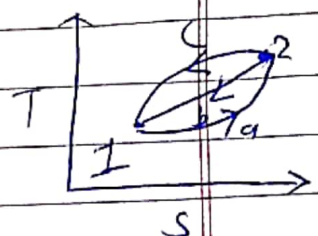
$$\left(\frac{dQ}{T}\right)_{2c1} + S_{gen} = \left(\frac{dQ}{T}\right)_{2b1}$$



Conclusion On Entropy

- ① Entropy is a point function & it depends only on end points as long as end points are same irrespective of process is reversible or irreversible
- ② In order to find out entropy change for an irreversible process it must be replaced with a reversible process
- ③ Entropy is a point function
- ④ " generation is a path function
- ⑤ A process is said to be internally & externally reversible

Internally Reversible	Externally Reversible
\rightarrow A process is said to be internally reversible if entropy generation in the system is zero	\rightarrow process is said to be externally reversible if entropy generation is zero.



Entropy change for closed system

Reversible process

① Case-1 ÷ Heat addition to closed system

$$ds = \frac{dq}{T} = \frac{\text{Heat add}^n}{\text{Temp}} = \frac{+ve}{+ve}$$

$ds = +ve$ - Change in entropy is +ve. Entropy increase
 $S_2 - S_1 = +ve$

② Case-2 Heat Rejection from closed system


$$ds = \frac{dq}{T} = \frac{\text{Heat reject}}{\text{Temp (Always +ve)}} = \frac{-ve}{+ve}$$

$ds = -ve$

$S_2 - S_1 = -ve$ ($S_2 < S_1$)

Entropy change is -ve

Entropy will ~~increase~~ decrease

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Case-3 Entropy change for ^{Reversible} Adiabatic ~~system~~ closed system process

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$$ds = \frac{dq}{T} = \frac{dq}{T} = 0 \quad \text{so} \quad \frac{dq}{T} = 0 = ds$$

<u>Heat addition</u>	<u>Heat Rejection</u>	<u>Adiabatic = Isentropic process</u>
$\frac{dq}{T} = ds$ is +ve	$\frac{dq}{T} = -ve$	$\frac{dq}{T} = ds = 0$

→ Entropy change for reversible process may be +ve, -ve, zero
It depends upon Heat Interaction negative

→ Entropy sign depends on dQ . If dQ +ve then dS +ve
 dQ -ve then dS -ve
 $dQ = 0$ then $dS = 0$

PART-2/5 CHAPTER - 4

CHAPTER 4
ASSUMPTIONS MADE DURING DERIVATION OF EXPRESSION OF EFFICIENCY OF CARNOT CYCLE

- ① The working fluid (nature ~~is~~ immaterial) say perfect gas
- ② Friction less piston sliding in a perfect sealed cylinder
- ③ Both Piston & Cylinder are perfect insulators
- ④ A perfectly conducting cylinder head
- ⑤ Heat source "the Hot body" is assumed at maximum temp (T_1) & sink is assumed at minimum Temperature (T_2)
- ⑥ All processes are truly reversible.

→ We know that Carnot has total four process, 2 Adiabatic & 2 Isothermal. Here we know that Isothermal process are very slow in nature & Adiabatic process are very fast.

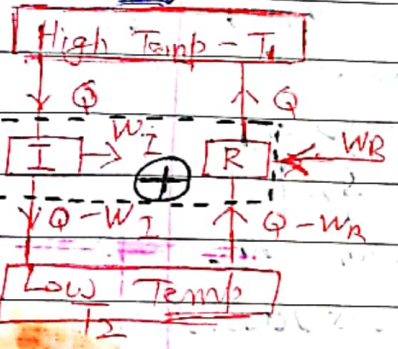
The variation of speed in some stroke of piston is not possible hence we can say Carnot cycle can not be implemented on a ~~real~~ heat engine

② Compared to the length of stroke the area of the indicator diagram is very small & hence the work done per cycle is very small so it may be able to overcome the friction of the reciprocating parts

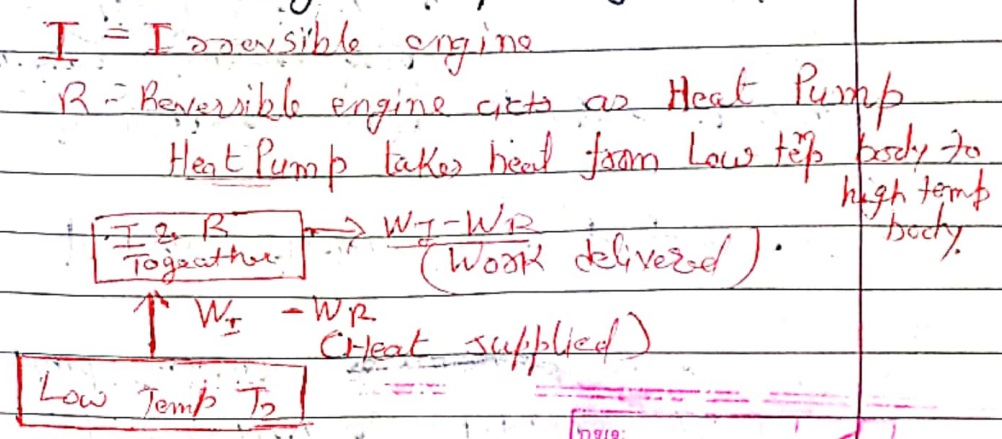
4.7 COROLLARIES OF SECOND LAW OF THERMODYNAMICS

* **Corollary-1** : It is impossible to construct an engine operating between two heat reservoirs which will have higher efficiency than a reversible engine operating between the same two source.

Proof :-



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Here we assume that Irreversible & Reversible both engines are coupled mechanically. "I" takes heat from High temp & gives to Low Temp body. "R" takes heat from low temp body & gives to high temp body.

When coupled together "I" & "R" will give result like third figure, "I & R Together". Which means ~~it~~ it takes $W_1 - W_R$ from low temp body & same amount of work is delivered.

This is impossible, hence we can say that the assumptions made in stating of the theory that it is possible to construct an irreversible engine having higher efficiency than reversible engine is impossible. The only possibility is that the efficiency of given Irreversible engine can be less than or equal to the Reversible engine.

$\eta_I =$ Efficiency of Irreversible engine
 $\eta_R =$ Efficiency of Reversible Engine

Cosollary-2 \div All reversible engine operating between same heat reservoirs have same efficiency. Cosollary supports this. Let's assume engine 1 is reversible, then its efficiency must be greater than that of R & vice-versa as both are reversible engine, mathematically.

$$\eta_I > \eta_R \quad \text{and} \quad \eta_R > \eta_I$$

This is possible only when $\eta_I = \eta_R$.

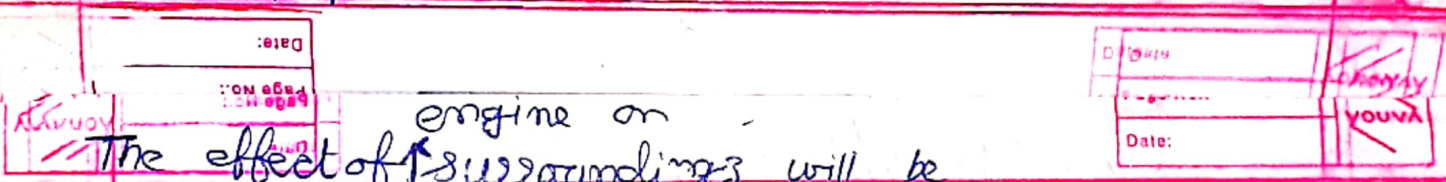
The efficiency of these device is the Carnot efficiency. $\eta = \frac{T_1 - T_2}{T_1}$

Thus $\eta_I \neq \eta_R$ & $\eta_R > \eta_I$

Cosollary-3 \div **CARNOT THEOREM FOR REVERSIBLE DEVICE**

The efficiency of any reversible engine operating between two heat reservoirs is independent of the nature of working fluid & depends solely on the temperature of Reservoir.

Proof \div Let the ^{two} Carnot engine be working between same thermal reservoir. One is an Engine & the other is a Heat pump.



Let's assume that the efficiency of Engine E be increased by other factors other than Temperature, let's say its the working substance. Its shown in Fig. 2

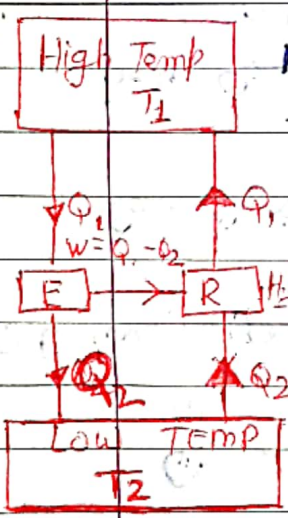


Fig-1

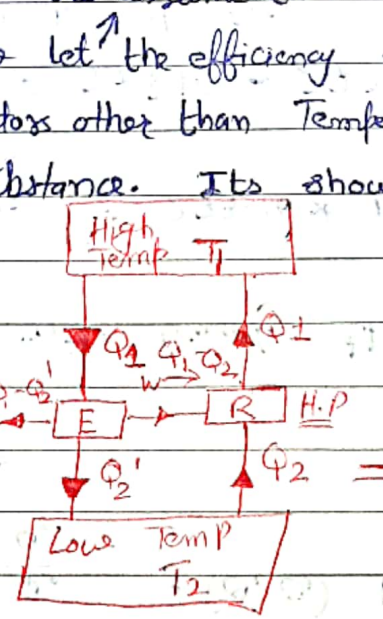
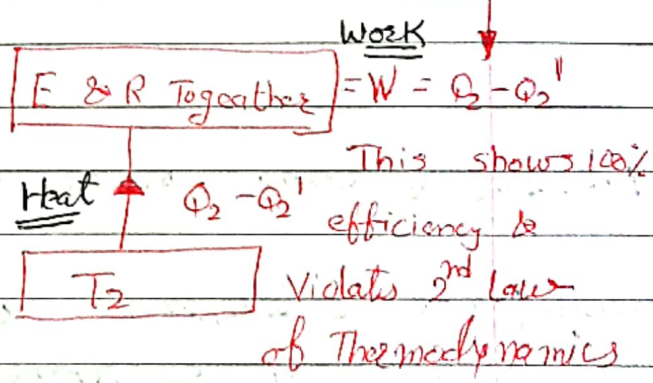


Fig. 2

Net work done will be $Q_1 - Q_2' - Q + Q_2 = Q_2 - Q_2' = \text{Net work done}$



4.8 COROLLARY-4. \div A scale of temperature can be defined which is independent of any thermometric substance & which provides absolute zero.

$$\eta = 1 - \frac{Q_2}{Q_1} = f(\theta_1, \theta_2) \text{ here } \theta_1 \text{ \& } \theta_2 \text{ are Source \& Sink Temp}$$

$$\frac{Q_2}{Q_1} = \frac{\theta_2}{\theta_1}$$

It was agreed internationally that $\theta_1 = 273.16 \text{ K}$ & $\frac{\theta_2}{\theta_1} = 1.36604$

$$\theta_2 = \theta_1 * \frac{Q_2}{Q_1} = 273.16 * 1.36604 = \underline{373.15 \text{ K}}$$

$$\text{here } \theta_2 - \theta_1 = 373.15 - 273.16 \approx 100$$

This means that Q_2/Q_1 at steam point of water at atmospheric pressure would be equal to 1.366049 and

$$\theta_2 = \theta_1 * \frac{Q_2}{Q_1} = 273.16 * 1.366049 = \underline{373.15 \text{ K}}$$

Thus $(\theta_2 - \theta_1) = 100$ (Approximately)

$$\text{Further } \eta_R = \eta_{\text{Carnot}} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_1}$$

4.9

TWO REVERSIBLE Adiabatic Cannot Intersect each other

Lets have negative approach to this, in terms as same way we do in other case. we have two adiabatic process

ab & ca & bc is a non-^{adiabatic} reversible

process. This makes a cycle abc & cba

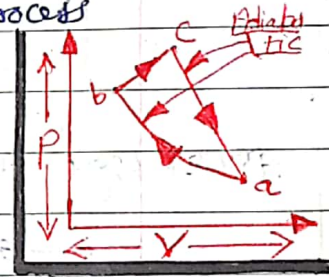
included by abc will be net work output of the

cycle. As ab & ca are Adiabatic so heat transfer can only occur in bc that is non-adiabatic process.

This violates Second law of Thermodynamics. Thus basic assumptions that intersection of two reversible adiabatic process is wrong.

→ Through one point there can pass only one adiabatic process & all adiabatics are parallel & they never intersect each other.

Two adiabatics cannot have common state that means there must be some property which remains constant along reversible Adiabatic process
This is Entropy.



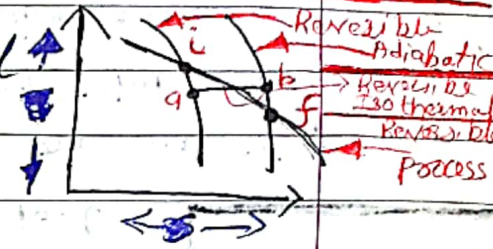
4.10 CLAUSIUS THEOREM & CLAUSIUS INEQUALITY.

* COROLLARY-5

→ Whenever a system undergoes a cycle $\oint \delta Q/T = 0$ if cycle is reversible & negative if cycle is irreversible. In general $\oint \delta Q/T \leq 0$

One Reversible process if can also be achieved by combination of two Adiabatic & One Isothermal process.

$a \rightarrow b$	Reversible Adiabatic	
$b \rightarrow f$	Reversible Adiabatic	
$a \rightarrow f$	Reversible Isothermal	Reversible Process



Heat transfer during Isothermal process ab is same as heat transfer during Reversible process af

This means Area Under Curve $a \rightarrow b \rightarrow f$ = Area Under $a \rightarrow f$
 (Total 3 Nos of Reversible Process) (Single Reversible Process.)

We know that $Q_{if} = (U_f - U_i) + W_{if}$

$$Q_{iabf} = (U_f - U_i) + W_{iabf}$$

Now we also know $Q_{iabf} = Q_{if}$

$$Q_{if} = Q_{ia} + Q_{ab} + Q_{bf}$$

$$Q_{if} = 0 + Q_{ab} + 0 \quad (Q_{ia} \text{ \& } Q_{bf} \text{ are Adiabatic Process})$$

$$Q_{if} = Q_{ab}$$

Heat transferred in process if will be equal to

Heat transferred in process ab

→ Let's consider a Carnot Cycle operating in temperature limits of T_1 & T_2 & absorbing heat Q_1 & rejecting heat Q_2

From Carnot Cycle we know $\frac{Q_1}{T_1} = \frac{Q_2}{T_2}$ so

$$\frac{Q_1}{T_1} - \frac{Q_2}{T_2} = 0 \quad \text{or if we take it algebraically}$$

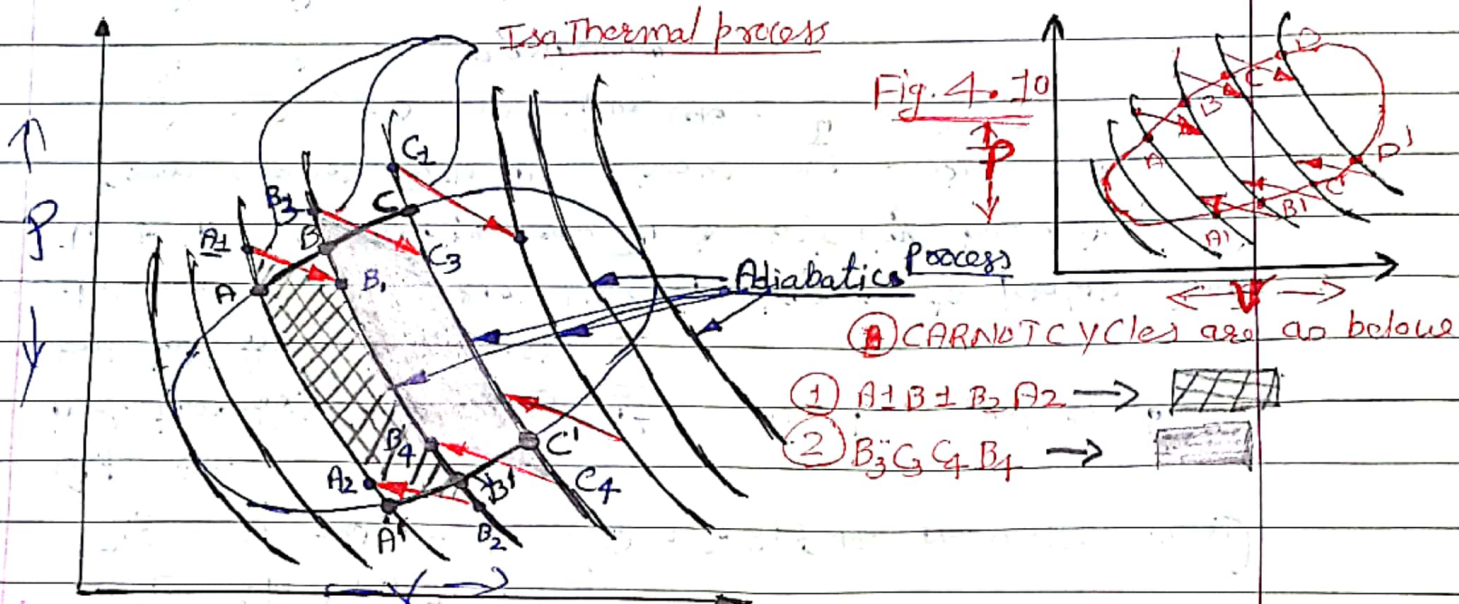
$$\frac{Q_1}{T_1} + \frac{Q_2}{T_2} = 0$$

summation of

So we can say that ratio of Heat Transfer to absolute Temperature $\oint (Q/T)$ for a reversible cycle equals to zero. We also know that there are two processes involved (1) Isothermal (2) Adiabatic

As there is no heat transfer during Adiabatic \Rightarrow the above equation may be written as $\oint \frac{\delta Q}{T} = 0$

This result if we apply on any reversible (e.g. = CARNOT CYCLE) heat may be added from infinite number of high temperature reservoirs & rejected to infinite number of low temp Reservoirs



A REVERSIBLE CYCLE SPLIT IN TERMS OF LARGE NUMBER OF CARNOT CYCLES

The complete cycle can be splitted into large number of CARNOT CYCLES & AB & B'A' can be replaced by BC & C'B' for next cycles & we get cycles like A₁B₁B₂A₂ & B₃C₃C₄B₄. The outer portion of these cycles follow the path of their original cycle whereas the inner portion cancel as they are traversed twice in opposite direction.

→ When two adiabatic process are drawn close to each other then the temperature at AB & A'B' can be approximated by that at their point of intersection, & the element cycle A₁B₁B₂A₂ δQ_1 heat is absorbed at temperature T₁ & δQ_2 heat is rejected at T₂, then

$$\frac{\delta Q_1}{T_1} + \frac{\delta Q_2}{T_2} = 0. \text{ This is for only one cycle but if}$$

$$\text{we now take for large of cycles. } \frac{\delta Q_1}{T_1} + \frac{\delta Q_2}{T_2} + \frac{\delta Q_3}{T_3} + \frac{\delta Q_4}{T_4} + \dots = 0$$

With this we can say CYCLIC Integration of δQ for a Reversible cycle is zero!!

$$\oint \left(\frac{\delta Q}{T} \right)_{rev} = 0 \text{ (For Reversible cycle)} \quad \text{--- (1)}$$

"CYCLIC INTEGRATION OF $\frac{\delta Q}{T}$ for a Reversible cycle is Zero. This is called CLAUSTIUS THEOREM. $\oint \left(\frac{\delta Q}{T} \right)_{Rev.} = 0$ " (I)

Now if we think of irreversibilities then an Irreversible engine absorbing heat from a reservoir at T_1 temperature & will reject more heat to low temp. reservoir T_2 than the reversible engine. (Logically we know that efficiency of irreversible engine will always be lower compared Reversible engine). Let heat rejected to sink in irreversible engine be Q_2' . [NOTE \div Q_2' will always be ^{Higher} ~~Lower~~ compared to Q_2] Then

$$\left[1 - \frac{Q_2'}{Q_1} \right] < \left[1 - \frac{T_2}{T_1} \right] \text{ or } \left[1 - \frac{Q_2'}{Q_1} \right] < \left[1 - \frac{Q_2}{Q_1} \right]$$

$$\oint \left(\frac{\delta Q}{T} \right)_{irr} = \left(\frac{Q_1}{T_1} + \frac{Q_2'}{T_2} \right) < 0$$

Q_2 = Heat Rejected Reversible
 Q_2' = Heat Rejected in Irreversible

Considering the engine cycle shown in figure 4-10 & assuming it to be irreversible Q_2' will always be higher than Q_2 .

[NOTE \div Q_2 & Q_2' are Heat Rejected to sink in ~~the same~~ reversible & Non-Reversible engine respectively. As efficiency of reversible engine is higher compared to Irreversible engine $Q_2' > Q_2$

Q_2' (Heat Rejected in Irreversible engine) $>$ Q_2 (Heat Rejected in Reversible engine)

by above relation we can say

$$\left[1 - \frac{Q_2'}{Q_1} \right] < \left[1 - \frac{Q_2}{Q_1} \right]$$

$$\left[1 - \frac{Q_2'}{Q_1} \right] < \left[1 - \frac{T_2}{T_1} \right]$$

This is efficiency of ~~Regular~~ Regular Cycle

Efficiency of CARNOT CYCLE

or We can say $\oint \left(\frac{\delta Q}{T}\right)_{\text{irrev}} = \left[\frac{Q_1}{T_2} + \frac{Q_2'}{T_1}\right] < 0$ [For Irreversible cycle]

from above equation we can say

$$\boxed{\oint \left(\frac{\delta Q}{T}\right)_{\text{irrev}} < 0} = \boxed{\sum \frac{\delta Q}{T} < 0} \text{ --- (2)}$$

From Equation 1 & 2 Combined we can say

$$\boxed{\oint \frac{\delta Q}{T} \leq 0} \quad \text{Note } \left(\oint \frac{\delta Q}{T}\right)_{\text{rev}} < 0 \text{ --- Equation - 1}$$

This is known as

CLAUSIUS INEQUALITY. $\left(\oint \frac{\delta Q}{T}\right)_{\text{rev}} = 0$ --- Equation - 2

This is derived from CARNOT CYCLE

& CARNOT CYCLE IS DERIVED FROM SECOND LAW OF THERMODYNAMICS

Hence this is regarded as COROLLARY TO SECOND LAW OF

THERMODYNAMICS

CHAPTER-4

PART-4/5 ENTROPY. = $S = \frac{\delta Q}{T} = \frac{KJ}{K}$

① Entropy is a point function

② Entropy is an extensive property
 (Dependent on mass)

We know that for a reversible cycle $\left(\frac{\delta Q}{T}\right)_{rev} = 0$

$$\oint \frac{\delta Q_R}{T} = 0 \quad \left| \quad \frac{dQ_R}{T} = dS \quad \right| \quad S_2 - S_1 = \int_1^2 \frac{dQ_R}{T}$$

COROLLARY-6

There exist a property of a closed system such that the change in its value is equal to $\int_1^2 \frac{\delta Q}{T}$ for any reversible cycle undergone by a system between state 1 & state 2. This property is called

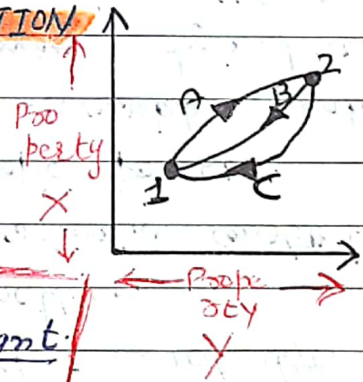
ENTROPY. PROOF OF ENTROPY IS A POINT FUNCTION

for cycle 1A2B1 $\int_{1A}^2 \frac{\delta Q}{T} + \int_{2B}^1 \frac{\delta Q}{T} = 0$ - (A)

for cycle 1A2C1 $\int_{1A}^2 \frac{\delta Q}{T} + \int_{2C}^1 \frac{\delta Q}{T} = 0$ - (B)

By equating A & B we get

$$\int_{2A}^1 \frac{\delta Q}{T} = \int_{2C}^1 \frac{\delta Q}{T} = \text{Constant}$$



We can say SQ/T is some property which does not depend on path followed thus it's a point function.

With this we can say that Entropy remains constant during reversible Adiabatic process, or Isoentropic process.

Note:- Since Entropy remains constant during reversible Adiabatic process it's also called Isoentropic Process, defined as a property which remains constant during reversible Adiabatic process, whereas other processes where entropy is not constant is called polytropic process.

→ Word Entropy was used by Clausius, its greek meaning word Trōpe → which means transformation.

Unit of Entropy $\Delta Q = \frac{KJ}{T}$

Unit of Specific Entropy = $\frac{\Delta Q}{T} / \text{mass} = \frac{KJ}{kg \cdot ^\circ K} = \frac{\text{Kilo Joule}}{kg \cdot ^\circ K}$

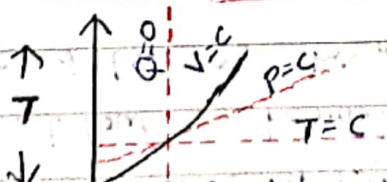
→ This equation shows that whenever there is a change in state of system from one state to the other state of system via any reversible or irreversible process there will be change in Entropy.

→ We can also say that the above equation $S = \frac{\Delta Q}{T}$ says nothing about absolute value of Entropy.

→ It is quite adequate to give values of entropy relative to some arbitrary selected reference state.

→ Reference of absolute Entropy 0.006112 bar Pressure & 0°C temperature

→ Existence of a property called Internal Energy was found when first Law of Thermodynamics was applied to a process. Same way Existence of property called Entropy was found when Second Law of Thermodynamics was applied to a process.



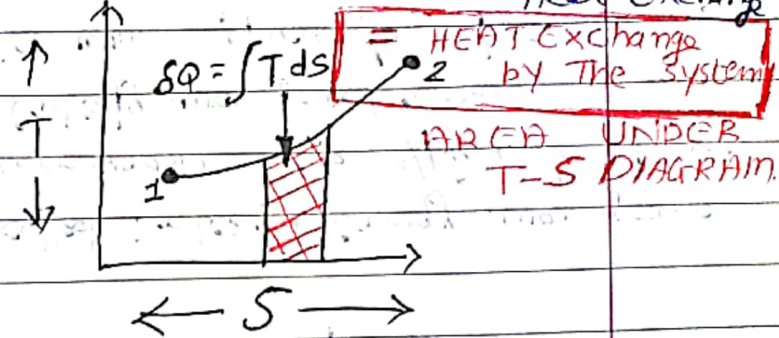
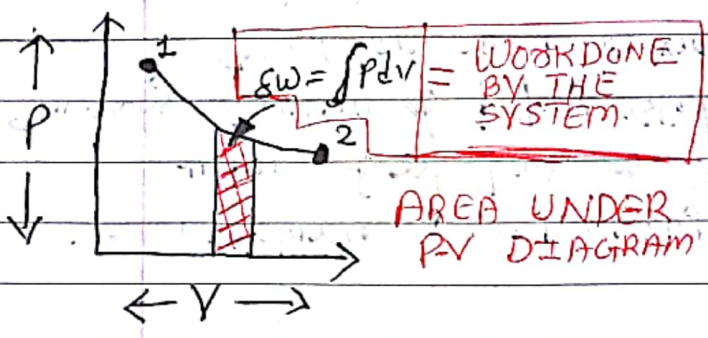
VARIOUS PROCESS ON TS DIAGRAM

Slope of line = $y/x = \frac{T}{S}$

4.12

TEMPERATURE-ENTROPY DIAGRAM. T-S DIAGRAM

From First Law of Thermodynamics we know PV curve gives Work done
 From Second Law of Thermodynamics we know TS curve gives Heat supplied
 Heat Exchange



4.13

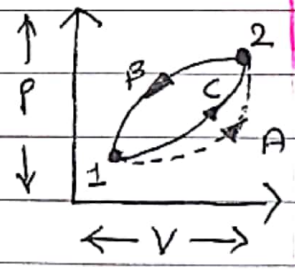
PRINCIPLE OF INCREASE IN ENTROPY.

COROLLARY-7: The Entropy of any ^{closed} system which is thermally isolated from the surroundings either increases (if process undergone by a system is irreversible) or remains constant (if the process is reversible).
 $dS = \frac{dQ}{T} > 0$ $dS = \frac{dQ}{T} \leq 0$

- For any Reversible Adiabatic Process $\frac{dQ}{T} = 0$
- For any Isothermal Process $dT = 0$
- Reversible Adiabatic process is also known as Isoentropic process

→ For any Irreversible ~~other~~ process $\frac{dQ}{T} > 0$

- 1B2 → Irreversible process
- 1C2 → Reversible process
- 2B1 → Reversible process



Now for ^{cycle} process 1A2B1 Irreversible cycle

S₁

$$\int_{1A}^2 \frac{dQ}{T} + \int_{2B}^1 \left(-\frac{dQ}{T} \right) < 0$$

cycle 1C2B1

For a reversible process ~~1A2B1~~

S₂

$$\int_{1C}^2 \frac{dQ}{T} + \int_{2B}^1 \left(-\frac{dQ}{T} \right) = 0$$

Now if we take S₂ - S₁

$$\int_{1C}^2 \frac{dQ}{T} + \int_{2B}^1 \left(-\frac{dQ}{T} \right) - \int_{1A}^2 \frac{dQ}{T} - \int_{2B}^1 \left(-\frac{dQ}{T} \right) < 0$$

$$\int_{1C}^2 \frac{dQ}{T} - \int_{1A}^2 \frac{dQ}{T} < 0 \quad \text{so we can say} \quad \int_{1C}^2 \frac{dQ}{T} < \int_{1A}^2 \frac{dQ}{T}$$

This means actual change in Entropy of system during an irreversible process is more than that obtained by dividing actual dQ by temperature, T , at which heat is supplied.

4.14 ENTROPY & IRREVERSIBILITY :-

From second law of Thermodynamics we know that Entropy can either increase or remain constant. It can never decrease.

Entropy increases in irreversible process &

Entropy remains constant in a reversible process

We know $\oint \frac{dQ}{T} \leq 0$ so $\oint \frac{dQ}{T} + I = 0$ $I = \text{measure of Irreversibility}$
 Unit: KJ/K

From equation 1 & 2 we can say $I \geq 0$. I can be zero or +ve
 I is measure of Irreversibility: & it can always be 0 or +ve
 Unit of $I = \text{KJ/K}$

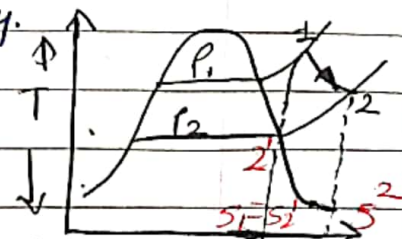
→ We can say gain in Entropy or Loss of work is a measure of Irreversibility.

→ Let's take two examples.

Steam turbine as shown in figure undergoes a reversible adiabatic process $S_2 - S_1 = S_2' - S_1'$

its called change in Entropy = Measure of Irreversibility

$I = \text{Measure of Irreversibility} \cdot \text{Unit} = \text{KJ/K}$



For perfect gas $S_2 - S_1 = S_2' - S_2'' = C_p \ln(T_2/T_1)$

We know by $PV^r = \text{constant}$ & $\frac{PV}{T} = \text{constant}$

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

4.15 PHYSICAL CONCEPT OF ENTROPY

Entropy of a substance is real physical quantity defining the state of body and can be easily evaluated for solid or perfect gas except for an additive constant representing the entropy at absolute zero. However it can not be felt like other physical quantity like temp, pressure etc, hence its difficult to form a tangible concept of Entropy.

4.16 First & Second Law of Thermodynamics Combined.

First law of Thermodynamics says $dQ = dU + \delta W$

$dQ = dU + PdV$ we can substitute enthalpy in place of Internal Energy

$$H = U + PV \quad \text{so} \quad dH = dU + PdV + VdP$$

We can say $dU = dH - PdV - VdP$

$$dQ = dU + PdV$$

$$dQ = dH - PdV - VdP + PdV$$

$$dQ = dH - VdP$$

Now from second law of Thermodynamics we know $dQ = Tds$

so we can say

$$dQ = Tds = dH - VdP = dU + PdV$$

4.17 CHANGE OF ENTROPY EQUATIONS FOR DIFFERENT PROCESSES

We know for perfect Gas

$$dQ = PdV + mC_v dT$$

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$$ds = \frac{dQ}{T} = \frac{PdV}{T} + \frac{mC_v dT}{T}$$

We know $PV = mRT$

$P = \frac{mRT}{V}$ - by replacing we get

taking it for 1 kg mass

$$ds = \frac{dQ}{T} = \frac{PdV}{T} + \frac{C_v dT}{T}$$

$$\frac{dQ}{T} = \frac{mRT}{V} \times \frac{dV}{T} + \frac{C_v dT}{T}$$

$$= R \frac{dV}{V} + C_v \frac{dT}{T}$$

$$\int_1^2 ds = \int_1^2 \frac{dQ}{T} = R \int_1^2 \frac{dV}{V} + C_v \int_1^2 \frac{dT}{T}$$

$$\int_1^2 ds = R \int_{V_1}^{V_2} \frac{dV}{V} + C_v \int_{T_1}^{T_2} \frac{dT}{T}$$

$$\int_1^2 ds = R \ln \left(\frac{V_2}{V_1} \right) + C_v \ln \left(\frac{T_2}{T_1} \right)$$

$$s_2 - s_1 = R \ln \left(\frac{V_2}{V_1} \right) + C_v \ln \left(\frac{T_2}{T_1} \right)$$

$$= R \ln \left(\frac{V_2}{V_1} \right) + C_v \ln \left(\frac{P_2 V_2}{P_1 V_1} \right)$$

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

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

We also know $C_p - C_v = R$

$$C_p = C_v + R$$

$$S_2 - S_1 = R \ln \left(\frac{V_2}{V_1} \right) - (R + C_p) \ln \left(\frac{P_2}{P_1} \right)$$

$$= R \ln \left(\frac{V_2}{V_1} \right) + C_v \ln \left(\frac{P_2}{P_1} \right) + C_p \ln \left(\frac{V_2}{V_1} \right)$$

$$= \ln \left(\frac{V_2}{V_1} \right) (C_p + R) + C_v \ln \frac{P_2}{P_1}$$

$$S_2 - S_1 = C_p \ln \left(\frac{V_2}{V_1} \right) + C_v \ln \left(\frac{P_2}{P_1} \right)$$

$$S_2 - S_1 = C_p \ln \left(\frac{T_2}{T_1} \right) - R \ln \left(\frac{P_2}{P_1} \right)$$

① For constant P process - $S_2 - S_1 = C_p \ln \frac{T_2}{T_1} = C_p \ln \frac{V_2}{V_1}$

② For constant Volume process $S_2 - S_1 = C_v \ln \left(\frac{P_2}{P_1} \right) = C_v \ln \left(\frac{T_2}{T_1} \right)$

③ For constant Temp process $S_2 - S_1 = R \ln \left(\frac{V_2}{V_1} \right) = R \ln \left(\frac{P_1}{P_2} \right)$

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④ For Adiabatic process $dQ = 0$ $dS = 0$ (?)

$$S_2 - S_1 = 0 = C_p \ln \left(\frac{V_2}{V_1} \right) + C_v \ln \left(\frac{P_2}{P_1} \right)$$