



Department of Mechanical Engineering
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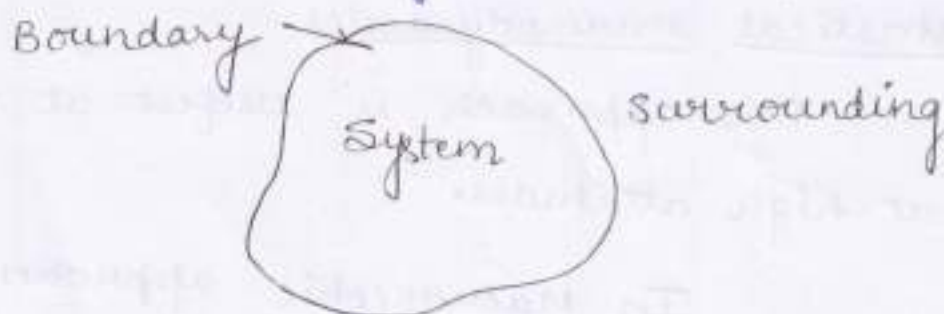
Hand Written Notes of Engineering Thermodynamics (PCME4201)

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Basic Concept

- Thermodynamics :- It is the science of energy transfer and its effects on properties of system.
- System :- It is a region in space upon which the study is focused or concentrated.
- Surroundings :- Anything external to the system is known as surroundings.
- Boundary :- The separation between system and surrounding is known as boundary.

Note :- A boundary can be rigid or flexible.



- Types of a System :-
- (1) closed system
 - (2) open system
 - (3) Isolated system

System	Energy Transfer	Mass transfer	Example
closed	✓	✗	Piston Cylinder without Valves
open	✓	✓	Turbine compressor Pump
Isolated	✗	✗	Hot cup of coffee in a well insulated Thermoflase

Microscopic & Macroscopic approach Thermodyna

In Microscopic approach, the behaviour of individual molecules is taken into consideration and this approach is also known as statistical thermodynamics.

This approach is useful at low density i.e. at high altitudes.

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

Property of a system:- Properties are characteristics of a system.

Ex:- Pressure, Temperature, volume etc.

Types of Properties:- (1) Intensive or Intensive
(2) Extensive or Extensive

(i) Intensive Properties:- Intensive properties are independent of mass.

Ex:- Pressure, Temperature, Density, viscosity, thermal conductivity.

(ii) Extensive Properties:- They are depending on mass.

Ex:- Volume, all forms of energy.

Notes:- (1) Ratio of two extensive properties is an intensive property.

(2) Specific quantities are intensive properties.

Ex:- Specific volume, specific internal energy (u), specific enthalpy, specific entropy.

State of the system:- It is a condition of a system.

It is specified by means of its properties.

" A change in a state is known as a process.

- Note :-
- (i) Properties are point function or state-
 - (ii) Properties are independent of past history i.e they are independent of path.
 - (iii) Properties are exact differentials.

Thermodynamic Equilibrium :- A system is said to be in a thermodynamic equilibrium if it is in thermal equilibrium (equality of temp. mechanical equilibrium (equality of forces) and chemical equilibrium (equality of chemical potentials).

Gibbs Phase Rule :- According to Gibbs phase rule

$$P + F = C + 2$$

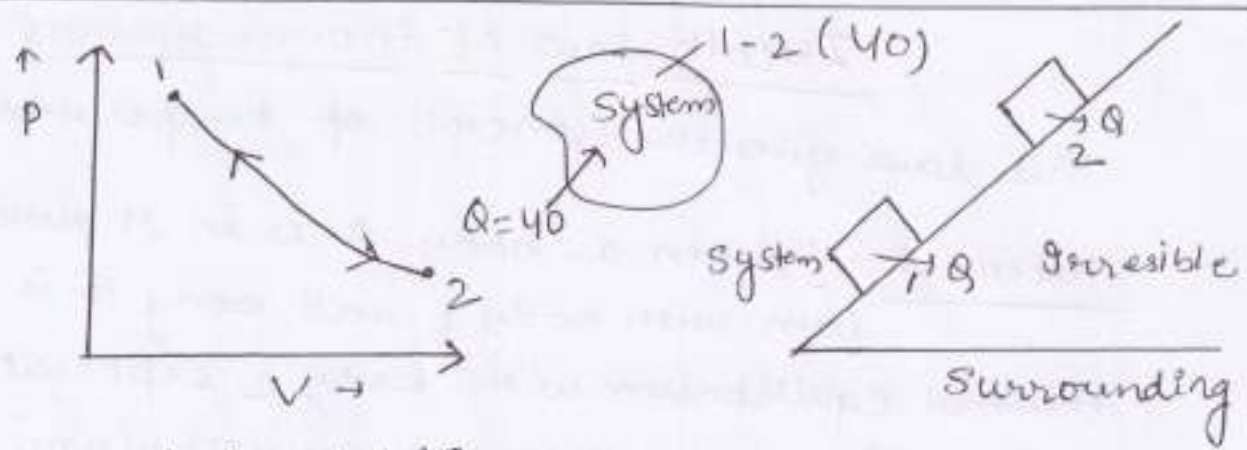
where P = No. of Phases

F = D.O.F (Min. no. of independent variables to the state)

C = No. of components

Reversible and Irreversible process :- A process is said to be reversible if when reversed in direction follow the same path that the exact forward path without leaving any effect on system and surrounding.

A reversible is the most efficient process. A process which is not a reversible process is known as irreversible process.



$$\begin{array}{rcl}
 1-2 & \rightarrow & +40 \\
 2-1 & \rightarrow & -40 \\
 \hline
 & & 0
 \end{array}$$

Thermodynamic cycle :- A system is said to be undergo a thermodynamic cycle, i.e if initial and final point are same.

Min. no. of process, required a cycle are - two.

For a cycle, the change in property is zero.

Pure substance :- A substance is said to be a pure substance if it is of constant chemical composition throughout the volume.

Ex:- ice + water, ice + water + water vapour etc.

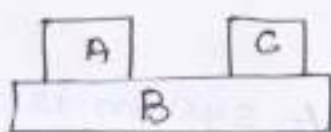
Quasi-Static process :- A process which is carried out in a very slow manner with small gradient is known as quasi-static process.

Note :- The aim of thermodynamic study is to convert disorganised form of energy (heat) into organised form of energy (work) in an efficient manner.

Zeroth law of thermodynamics (1931)

This law gives the 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."

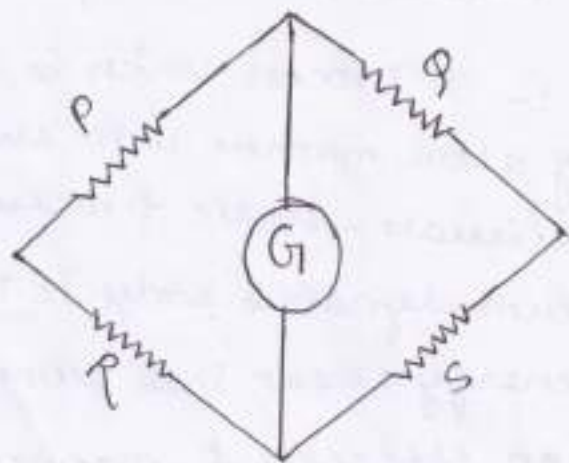


$$A \xrightarrow{TE} B \quad \text{Then} \quad A \xrightarrow{TE} C$$
$$B \xrightarrow{TE} C$$

The property which enables to find the temp. is known as thermometric property.

Types of thermometer:-

(1) Resistance thermometer (Thermistor): It is based on wheatstone bridge principle and in this thermometer resistance play the role of thermometric property.



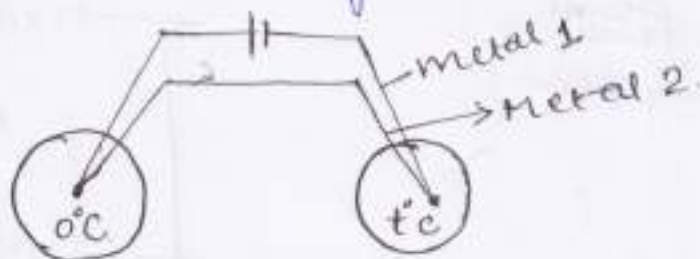
$$\frac{P}{Q} = \frac{R}{S}$$

$$R = R_0 [1 + \alpha t + \beta t^2]$$

$$S = S_0 [1 + \alpha t + \beta t^2]$$

(ii) Thermocouple :- This thermometer is based on Seebeck effect i.e. when two dissimilar metals are joined and if there form two different junction and if these junction are maintain at different temp., e.m.f. is generated and this e.m.f. \propto temp difference between two junction

In thermocouples e.m.f. plays the role thermometric property.



(iii) Constant volume gas thermometer :- A constant volume gas thermometer pressure play the role of thermometric property.

$$PV = nRT$$

$$V = \text{Constant}$$

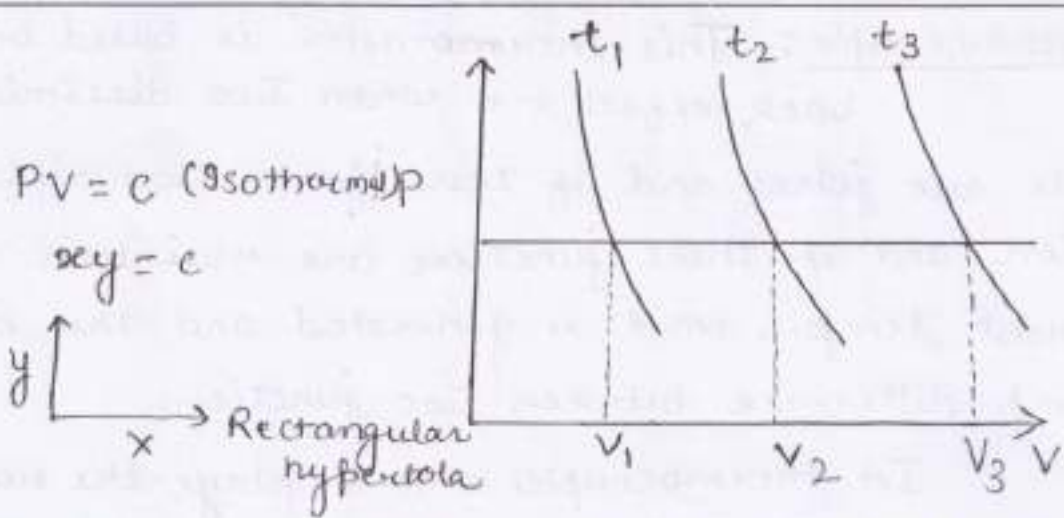
$$\boxed{P \propto t}$$

(iv) Constant Pressure gas thermometer :- In this thermometer volume play the role of thermometric property.

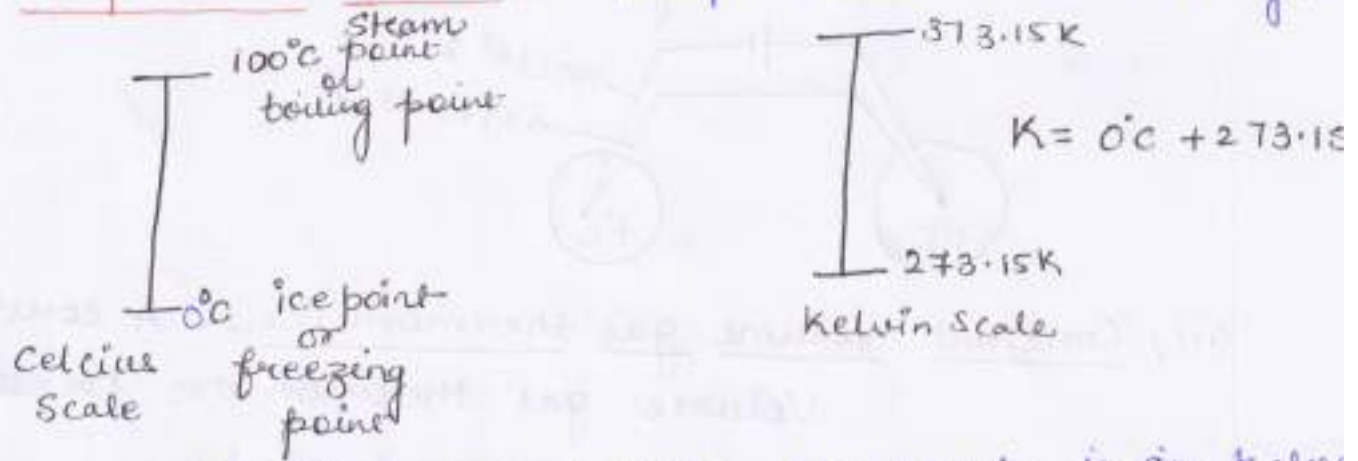
$$PV = nRT$$

$$P = \text{Constant}$$

$$\boxed{V \propto T}$$



Temperature Scale :- Temp. scales are arbitrary.



Note :- In ideal gas equation the temp. is in Kelvin Scale.

Methods used before 1954 :- It is based on two ref. temp. i.e. ice point (0°C) and steam point (100°C)

$$t = at + b$$

ice point (i) = $t_i = 0^\circ C$

Steam point (s) = $t_s = 100^\circ C$

$$t_s = a p_s + b$$

$$t_i = a p_i + b$$

$$100 = a p_s + b$$

$$-0 = -(a p_i + b)$$

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

$$a = \frac{100}{p_s - p_i}$$

$$0 = a p_i + b$$

$$0 = \frac{100}{p_s - p_i} \times p_i + b$$

$$b = \frac{-100 p_i}{p_s - p_i}$$

$$t = a p + b$$

$$t = \frac{100}{p_s - p_i} p + \left(\frac{-100 p_i}{p_s - p_i} \right)$$

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

by knowing the thermometric property p , the corresponding temp can be found.

Method used after 1954 :- It is based on single fixed temp. i.e. triple point of water

$$pV = nRT$$

$$V = \text{Constant}$$

$$p \propto T$$

$$p = KT$$

$$p_{tp} = K T_{tp}$$

$$K = \frac{p_{tp}}{T_{tp}}$$

$$\longrightarrow p = \frac{p_{tp}}{273.16} \times T$$

$$K = \frac{P_t P}{273.16}$$

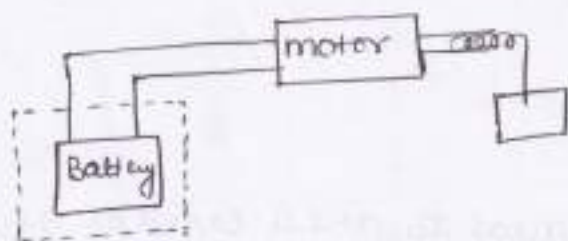
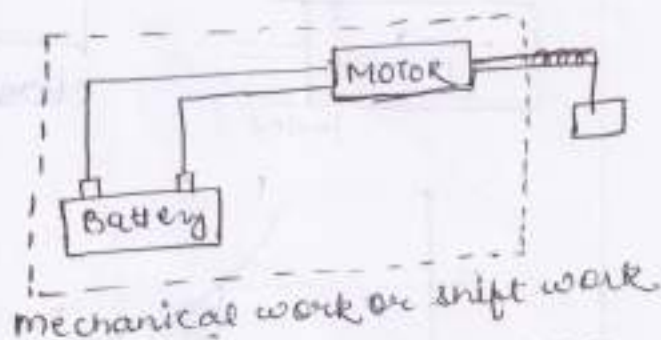
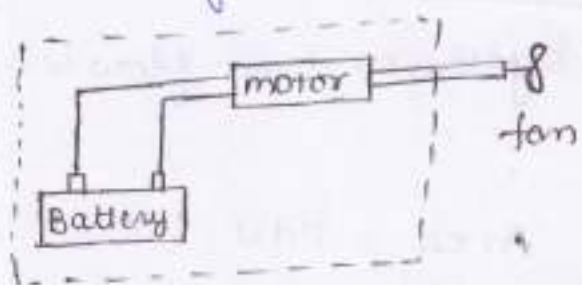
$$P = \frac{P_t P}{273.16} \times T$$

$$T = 273.16 \left(\frac{P}{P_t P} \right)$$

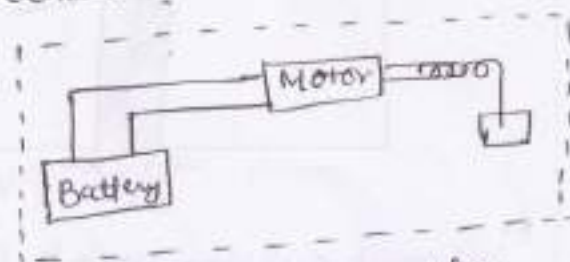
Note :- Ideal gas thermometer is independent of material of construction.

Energy Interaction (Work & Heat)

Work is said to be done by a system if the sole effect on things external to the system can be equated to rising of weight (weight may not be actually raised)

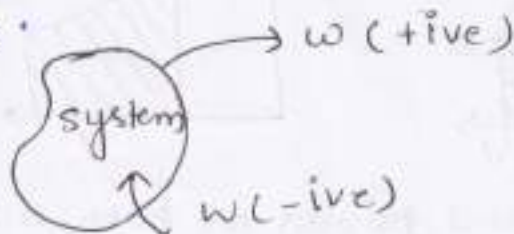


Electrical work transfer



No work transfer

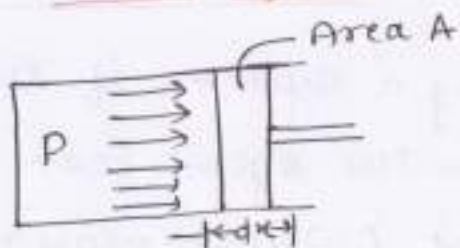
Convention :- Work done by the system is taken as +ive and work done on the system is taken as -ive.



Types of work :-

- ① closed system work or Non-flow work
- ② open system work or flow work

(i) closed system work or Non flow work :-



$$dw = F \cdot dx$$

$$P = \frac{F}{A}$$

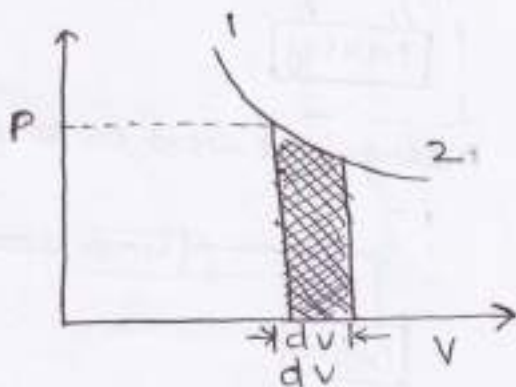
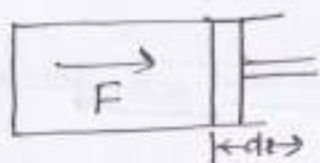
$$dw = PA dx$$

$$F = PA$$

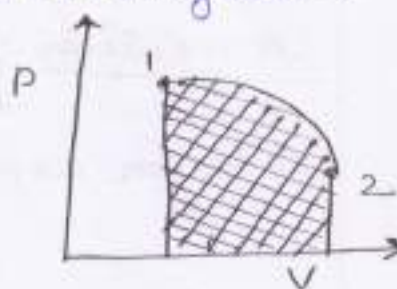
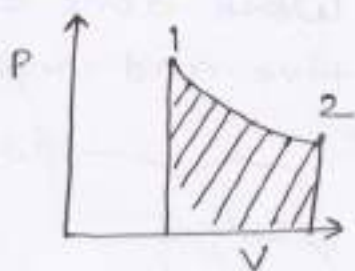
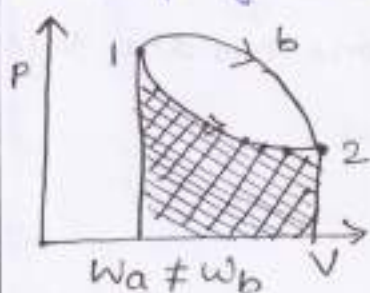
$$dw = P dv$$

$$W = \int P dv$$

closed system or Non flow work



"closed system work is equal to area under the curve when projected on volume axis on P-v diagram".



Though the end points or path a and b are same but the area is different and hence work transfer at a and b 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.

Note :- (1) Work transfer is an inexact differential (δw or δW).

(2) Work transfer is a boundary phenomenon.

Condition for applying the equation :-

$$W = \int P dv$$

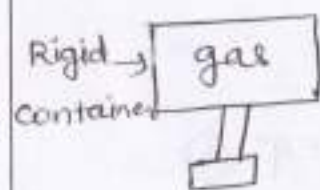
(1) A system must be a closed system.

(2) Work should cross the boundary.

(3) The process must be reversible process.

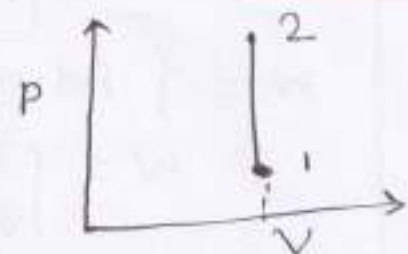
closed system or Non-flow work for various process :-

(i) constant volume process (Isochoric or isometric process)



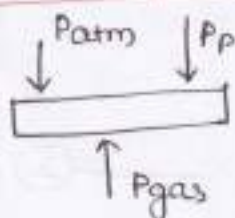
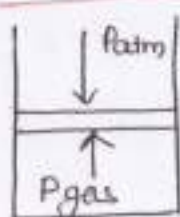
$$W = \int P dv$$
$$V = \text{constant}$$
$$dv = 0$$

$$W = 0$$

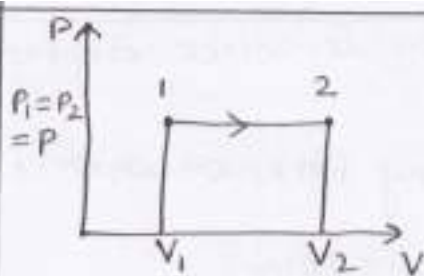


closed system constant volume work is equal to zero

(ii) constant pressure process (isobaric or isopiestic process)



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



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

$$W = P [V]_{V_1}^{V_2}$$

$$\boxed{W = P [V_2 - V_1]}$$

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

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

(iii) Isothermal Process (Const. temp.) :-

$$PV = mRT$$

(T = constant)

$$PV = C = mRT$$

$$P_1 V_1 = P_2 V_2 = C$$

$$PV = C$$

$$\boxed{P = \frac{C}{V}} \quad \text{--- (1)}$$

$$W = \int P \, dV$$

$$W = \int_{V_1}^{V_2} \frac{C}{V} \, dV \quad \text{--- from eqn (1)}$$

$$W = C \ln V \Big|_{V_1}^{V_2}$$

$$W = C [\ln V_2 - \ln V_1]$$

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

$$\boxed{W = mRT \ln \frac{V_2}{V_1}} \quad \text{--- (2)}$$

$$W = P_1 V_1 \ln \frac{V_2}{V_1}$$

$$P_1 V_1 = P_2 V_2$$

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

$$W = P_1 V_1 \ln \frac{P_1}{P_2}$$

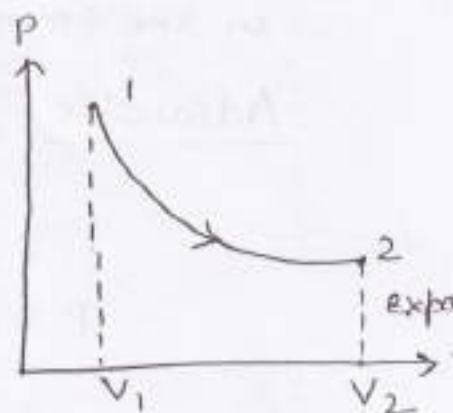
Observation :- $W = mRT \ln \frac{V_2}{V_1}$

$$V_2 > V_1$$

$$\frac{V_2}{V_1} > 1$$

$$\ln \frac{V_2}{V_1} = +ive$$

$$W = +ive$$



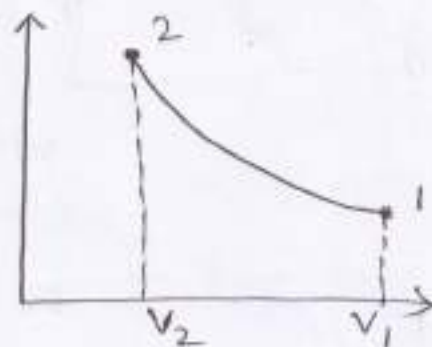
Work done by the system

$$V_2 < V_1$$

$$\frac{V_2}{V_1} < 1$$

$$\ln \frac{V_2}{V_1} = -ive$$

$$W = -ive$$



Work done on the system

(iv) Adiabatic Process :- In this process there is no heat transfer from the system.

$$PV^\gamma = C$$

$\gamma =$ Adiabatic Index

$$\gamma > 1$$

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

for an adiabatic process.

In adiabatic process, the energy interaction is only in the form of work transfer.

Adiabatic closed system work :-

$$W = \int P dv$$

$$PV^\gamma = C$$

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

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

$$P_1 = \frac{C}{V_1^\gamma} \Rightarrow P_1 = C V_1^{-\gamma}$$

$$P_2 = C V_2^{-\gamma}$$

$$W = \int_{V_1}^{V_2} C V^{-\gamma} dv$$

$$W = C \int_{V_1}^{V_2} V^{-\gamma} dv$$

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

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

$$W = \frac{1}{-\gamma+1} [C V_2^{-\gamma} \cdot V_2 - C V_1^{-\gamma} \cdot V_1]$$

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

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

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

(v) Polytropic Process :- In a polytropic process, the pressure and volume follows the law

$$P V^n = C$$

where n is known as polytropic index
 $n > 1$ and $n < \gamma$.

In polytropic process there is both heat transfer and work transfer.

Closed system Polytropic process :-

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

Closed system work

Process	Work
const vol.	0
const Pressure	$P(V_2 - V_1)$
Isothermal	$mRT \ln \frac{V_2}{V_1}$
Adiabatic	$\frac{P_1 V_1 - P_2 V_2}{\gamma - 1}$
Polytropic	$\frac{P_1 V_1 - P_2 V_2}{n - 1}$

$$PV^k = \text{constant}$$

$$PV^k = C$$

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

$$P^{1/k} \cdot V = \text{constant}$$

$$k = \infty = V = \text{constant}$$

$$PV = mRT$$

$$T = C$$

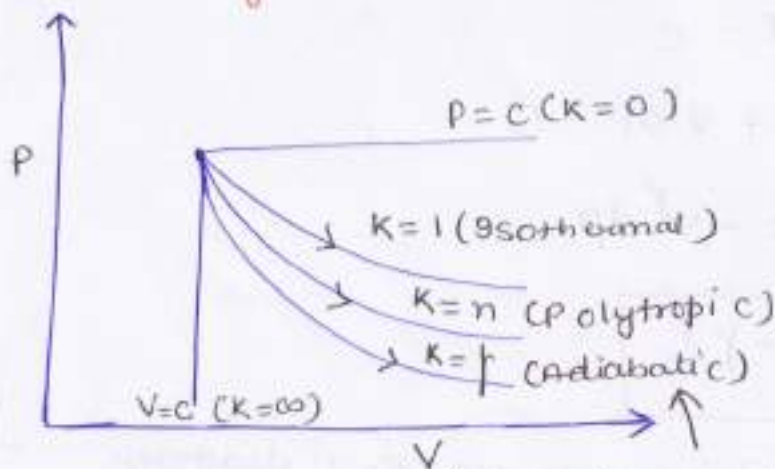
$$PV^1 = C$$

$$PV^\gamma = C$$

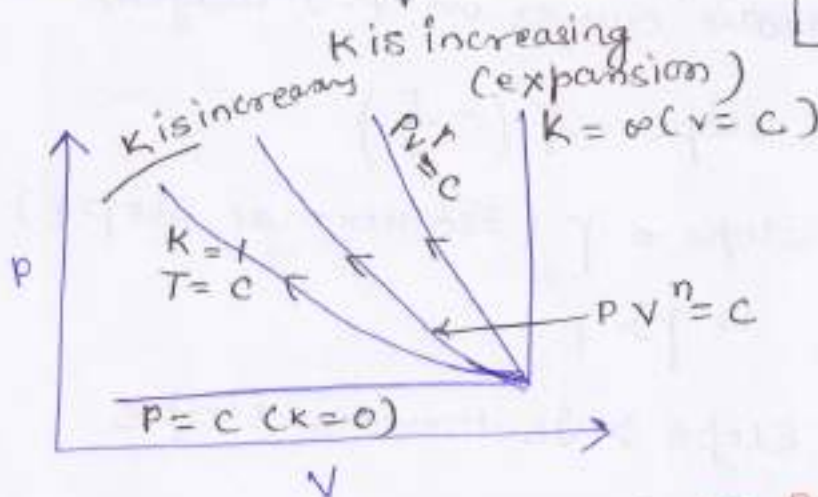
$$PV^n = C$$

Process	k
const vol.	∞
const. Pressure	0
Isothermal	1
Adiabatic	γ
Polytropic	n.

Ascending order of k :-



Process	k
$P = c$	0
$T = c$	1
Polytropic	n
Adiabatic	γ
$V = c$	∞



Slope of isothermal curves on P-V diagram:-

$$\frac{dy}{dx} = \frac{dp}{dv}$$

$$PV = nRT$$

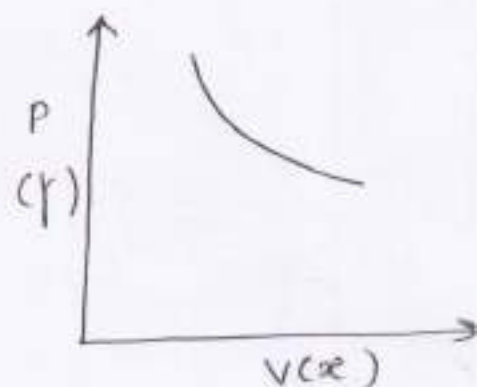
$$PV = c$$

$$PdV + VdP = 0$$

$$PdV = -VdP$$

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

Slope of isothermal curve on P-V diagram = $-P/V$



Slope of Adiabatic curves on P-v diagram :-

$$Pv^\gamma = c$$

$$P(\gamma v^{\gamma-1}) dv + v^\gamma dp = 0$$

$$\gamma \frac{P v^\gamma}{v} dv = -v^\gamma dp$$

$$\boxed{\frac{dp}{dv} = -\gamma \frac{P}{v}}$$

Slope of adiabatic curves on P-v diagram = $-\gamma \frac{P}{v}$

$$\text{Adiabatic slope} = \gamma \left(-\frac{P}{v}\right)$$

$$\text{Adiabatic slope} = \gamma (\text{Isothermal slope})$$

$$\text{as } \gamma > 1$$

A diabolic slope > Isothermal slope

Heat

Heat :- The energy transfer due to temp. difference is known as heat transfer.

$$Q \propto m$$

$$Q \propto \Delta t$$

$$Q \propto m \Delta t$$

$$Q = m c \Delta t$$

Here c = specific heat

Specific Heat :- It is amount of heat required to raise temp. of unit mass of substance to unit degree temp. difference

$$Q_p = m c_p \Delta t$$

$$Q_v = m c_v \Delta t$$

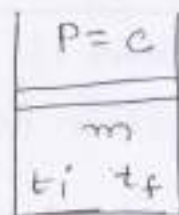
$$Q_p > Q_v$$

$$m c_p \Delta t > m c_v \Delta t$$

$$c_p > c_v$$

$$\gamma = \frac{c_p}{c_v}$$

for $\gamma = 1$ $\boxed{\frac{c_p}{c_v} = 1}$



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 energy only.

First law of thermodynamics

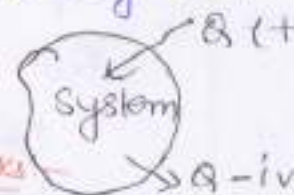
"Law of conservation of energy."

Statement :- For a closed system undergoing a cycle, summation of heat transfer is equal to summation of work transfer.

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

Valid for a closed system undergoing reversible or irreversible.

Convention of Heat transfer :- Heat supplied to the system is taken +ive and heat rejected from the system is taken as -ive.

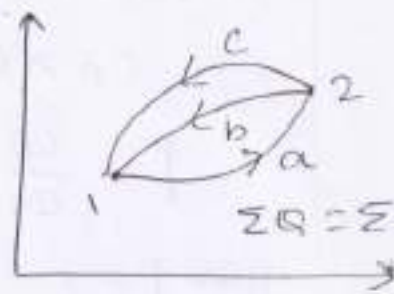


Consequence of first law of thermodynamics

(i) Heat transfer is a path function.

1-a-2-b-1 → cycle

1-a-2-c-1 → cycle



$$\cancel{(dQ)_{1a2}} + (dQ)_{2b1} = \cancel{(dW)_{1a2}} + (dW)_{2b1}$$

$$\cancel{(dQ)_{1a2}} + (dQ)_{2c1} = \cancel{(dW)_{1a2}} + (dW)_{2c1}$$

$$(dQ)_{2b1} - (dQ)_{2c1} = (dW)_{2b1} - (dW)_{2c1}$$

$$(dW)_{2b1} \neq (dW)_{2c1}$$

$$(dW)_{2b1} - (dW)_{2c1} \neq 0$$

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

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

Though for path b and c end points are same, heat transfer is different for different path and hence heat transfer is a path function and it is not a property and it is not an exact differential.

Some important point w.r.t heat transfer and work transfer.

- (1) Both are path functions.
- (2) Both are inexact differential.
- (3) Both are boundary phenomenon.
- (4) Both are not properties.
- (5) Both are transient form of energy.

(ii) Energy is a property :-

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

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

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

The quantity $\delta Q - \delta W$ is independent of path and its only dependence is on end points therefore $\delta Q - \delta W$ must be a property and this property is known as Energy.

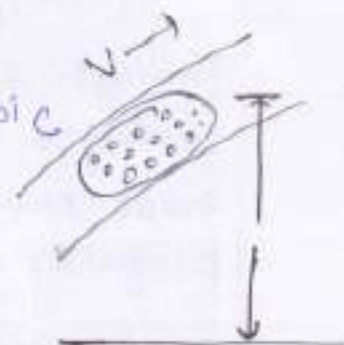
$$(\delta Q - \delta W)_{2b1} - (\delta Q - \delta W)_{2c1} = dE$$

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

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

This equation is valid for a closed system undergoing a reversible or irreversible process.

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



$$dQ = dE + \delta W$$

$$E = KE + PE + U$$

$$dE = d(KE + PE + U)$$

$$dE = d(KE) + d(PE) + dU$$

For a closed stationary system, K.E and P.E. changes are negligible and therefore

$$dE = dU$$

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

This is applicable for a closed stationary system undergoing reversible or irreversible process.

The equation $\boxed{\delta Q = dU + PdV}$ is applicable only to closed system undergoing reversible process.

Internal energy is a property and it is an extensive property.

(iii) Energy of an isolated system is always constant

$$\delta Q = dE + \delta W$$

$$0 = dE = 0$$

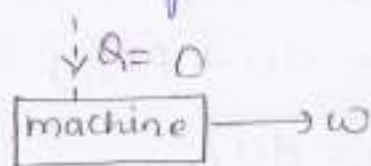
$$dE = 0$$

$$E_2 - E_1 = 0$$

$$E_2 = E_1 = \text{constant}$$

(iv) Perpetual machine motion machine of first kind
is impossible. (PMM-I) :-

There can be no machine which produces work continuously w/o absorbing some other form of energy. If such a machine is developed then it violates first law of thermodynamics.



Enthalpy :- In thermodynamics, the term $U+PV$ appears frequently and for convenience this term is taken as enthalpy.

It is an extensive property.

→
Extensive
property

$$H = U + PV$$

$$h = \frac{H}{m} = \frac{U + PV}{m}$$

$$h = \frac{U}{m} + \frac{PV}{m}$$

$$u = U/m$$

$$h = u + Pv$$

$$h = \frac{kJ}{kg}$$

h = sp. enthalpy is an intensive property.

Heat transfer in various process

(closed system or non flow process)

Imp

(i) Constant Volume Process :-

$$\delta Q = dU + \delta W$$

$$\delta Q = dU + PdV$$

$$V = c \quad dV = 0$$

$$\delta Q_V = dU + P(0)$$

$$\boxed{\delta Q_V = dU}$$

For a constant volume closed system process Heat transfer is equal to change in internal energy.

We know that $Q_V = m c_V dt$

$$\boxed{dU = m c_V dt}$$

This eqⁿ is applicable for any process because internal energy is property.

Imp

(ii) constant Pressure Process :-

$$\delta Q = dU + \delta W$$

$$\delta Q = dU + PdV$$

$$P = c$$

$$d\delta P = dU + d(PV)$$

$$\delta Q_P = d(U + PV)$$

$$\boxed{\delta Q_P = dH}$$

Heat transfer in a constant pressure closed system process is equal to change in enthalpy.

We know that heat transfer in constant pressure process is $m c_p dT$

$$\therefore \boxed{dH = m c_p dT}$$

This eqⁿ is applicable for any process because enthalpy is a property.

To show that $c_p - c_v = R$

$$H = U + PV$$

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

$$m c_p dT = m c_v dT + d(mRT)$$

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

$$c_p = c_v + R$$

$$\boxed{c_p - c_v = R}$$

$$\frac{c_p}{c_v} = \gamma \Rightarrow c_p = \gamma c_v$$

$$c_p - c_v = R$$

$$\gamma c_v - c_v = R$$

$$c_v (\gamma - 1) = R$$

$$\boxed{c_v = \frac{R}{\gamma - 1}}$$

$$\boxed{c_p = \frac{\gamma R}{\gamma - 1}}$$

For air:

$$c_p = 1.005 \text{ kJ/kg}\cdot\text{K}$$

$$c_v = 0.718 \text{ kJ/kg}\cdot\text{K}$$

$$R = 0.287 \text{ kJ/kg}\cdot\text{K}$$

$$\boxed{\gamma = \frac{c_p}{c_v} = 1.4}$$

(iii) Isothermal Process :- "Joule found from his experiments the internal energy of an ideal gas is a function of temp. alone.

$$U = f(T)$$

$$\delta Q = dU + \delta W$$

$$U = f(T) \rightarrow \text{for ideal gas}$$

$$T = C$$

$$U = \text{constant}$$

$$dU = 0$$

$$\delta Q = 0 + \delta W$$

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

For an ideal gas undergoing isothermal process heat transfer is equal to work transfer

(iv) Adiabatic Process :- $\boxed{\delta Q = 0}$

^{Imp}
(v) Polytropic Process :- $PV^n = C$
 $n > 1$ $n < \gamma$

$$\delta Q = dU + \delta W$$

$$\delta Q = m c_v dT + \frac{P_1 V_1 - P_2 V_2}{n-1}$$

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

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

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

$$\delta Q = (P_1 V_1 - P_2 V_2) \left[\frac{1}{n-1} - \frac{1}{\gamma-1} \right]$$

$$= (P_1 V_1 - P_2 V_2) \left[\frac{(\gamma-1) - (n-1)}{(\gamma-1)(n-1)} \right]$$

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

$$\boxed{\delta Q = \frac{\gamma-n}{\gamma-1} \times W_{\text{polytropic}}}$$

Polytropic specific heat :-

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

$$= \frac{\gamma-n}{\gamma-1} \times \frac{(mRT_1 - mRT_2)}{n-1}$$

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

$$Q_{\text{poly}} = \frac{\gamma-n}{n-1} m c_v (T_1 - T_2)$$

$$= m \frac{(\gamma-n)}{(n-1)} c_v (-dT)$$

$$dT = T_2 - T_1$$

$$dT = -(T_1 - T_2)$$

$$T_1 - T_2 = -dT$$

$$\boxed{Q_{\text{poly}} = m \left[\frac{\gamma-n}{n-1} c_v \right] dt}$$

c_{poly}

$$c_{\text{poly}} = \frac{\gamma-n}{n-1} c_v$$

For: $1 < n < \gamma$

Heat transfer in polytropic process is less than work done.

This extra work transfer comes for internal energy transfer. For such polytropic process though heat is supplied there is reduction in temp. and c_{poly} is neg.

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

$$\delta Q = du + PdV$$

$$\delta Q = m c_v dT + PdV$$

For adiabatic process $\delta Q = 0$

$$0 = m c_v dT + PdV$$

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

$$H = U + PV$$

$$dH = \underbrace{du + PdV}_{\delta Q} + VdP$$

$$dH = \delta Q + VdP$$

for adiabatic process $\delta Q = 0$

$$dH = VdP$$

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

$$\text{Eq. (2)} \div \text{Eq. (1)}$$

$$\frac{m c_p dT}{m c_v dT} = \frac{VdP}{-PdV}$$

$$\frac{c_p}{c_v} = \frac{+VdP}{-PdV}$$

$$\gamma = \frac{-v dp}{P dv}$$

$$\gamma \cdot \frac{dv}{v} = -\frac{dp}{P}$$

$$\gamma \frac{dv}{v} + \frac{dp}{P} = 0$$

$$\gamma \ln v + \ln p = \ln c$$

$$\ln v^\gamma + \ln p = \ln c$$

$$\ln p v^\gamma = \ln c$$

$$\boxed{p v^\gamma = c}$$

The above eqⁿ $p v^\gamma = c$ is valid for a reversible adiabatic process only, because while deriving the eqⁿ $P dv$ work is utilized and $P dv$ work is possible for reversible process only.

Free Expansion

The expansion against vacuum is known as free expansion.

Free expansion work is always equal to zero.

$$\delta Q = du + \delta w$$

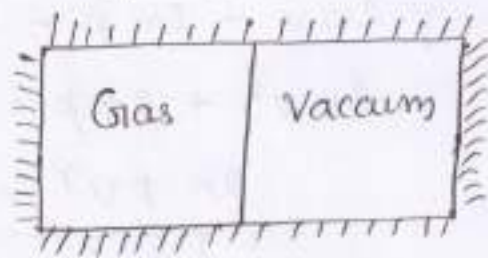
$$0 = du + 0$$

$$du = 0$$

$$du = 0$$

$$u_f - u_i = 0$$

$$u_f = u_i = \text{Constant}$$



We know that for an ideal gas internal energy is function of temp alone as the internal energy is constant.

$$\text{initial temp} = \text{final temp.}$$

Note:-

(i) when an ideal gas undergoes free expansion process.

$$(i) u_i = u_f \quad (ii) T_i = T_f \quad (iii) h_i = h_f$$

Open System Work

- Assumption :- (1) Neglect kinetic energy changes.
(2) Neglect potential energy changes.
(3) Reversible process.

$$\text{open system work} = -\int v dp$$

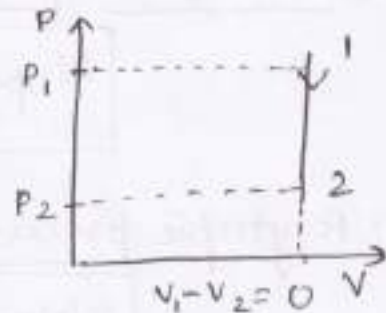
open system work equal to area under the curve when projected on pressure axis.

(i) Constant volume process :-

$$W = - \int_{P_1}^{P_2} P_2 v dp$$
$$= -v \int_{P_1}^{P_2} dp$$

$$W = -v(P_2 - P_1)$$

$$\boxed{W = (P_1 - P_2)v}$$

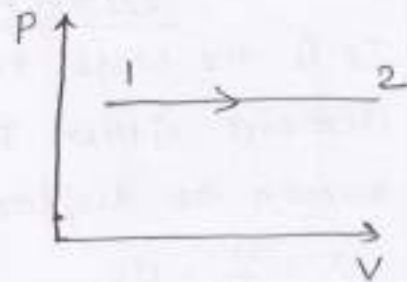


(ii) Constant pressure process :-

$$W = -\int v dp$$

$$P = c \quad W = 0$$

$$\boxed{dp = 0}$$



constant pressure open system work equal to zero.

(iii) Isothermal process :-

$$PV = mRT$$

$$T = c$$

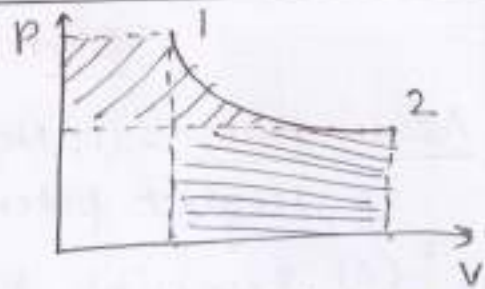
$$PV = c$$

$$Pdv + Vdp = 0$$

$$Pdv = -vdp$$

$$\int Pdv = -v \int dp$$

$$W_{\text{closed}} = W_{\text{open}}$$



For isothermal process of an ideal gas open system work equal closed system work because a rectangular hyperbol when projected pressure axis and volume axis gives same area!

(iv) Adiabatic process :-

$$W_{\text{open}} = \frac{\gamma (P_1 V_1 - P_2 V_2)}{\gamma - 1}$$

(v) Polytropic process :-

$$W_{\text{open}} = \frac{n (P_1 V_1 - P_2 V_2)}{n - 1}$$

DISPLACEMENT WORK

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

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

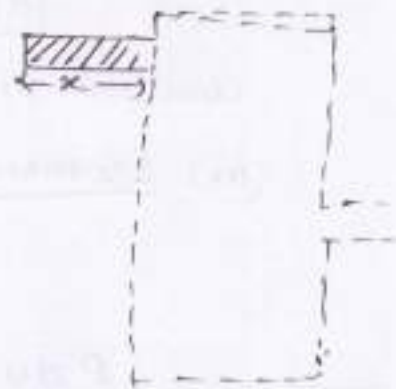
$$F = P \cdot dA$$

$$\delta W = F \times x$$

$$\delta W = PdA \times dx$$

$$\delta w = PdV$$

$$\delta w / \text{mass} = \frac{P \cdot dv}{dm}$$



$$\frac{\delta w}{\text{mass}} = pu$$

$$\text{Total work} = pu \times m$$

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

$$u \cdot m = V$$

$$\text{Total displacement work} = pV$$

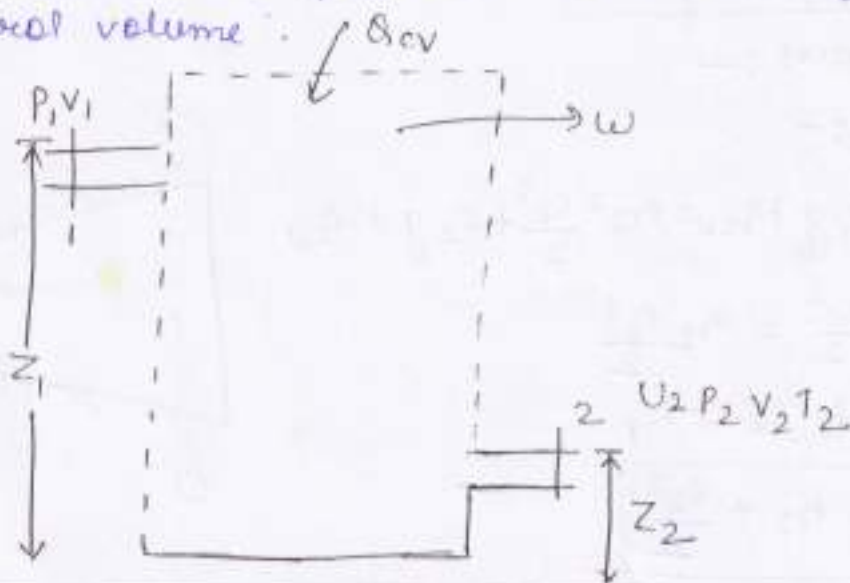
Note: - Entering displacement work is -ive and exit displacement work is +ive.

STEADY FLOW ENERGY EQUATION (S.F.E.E)

In steady flow process, the properties do not vary with time at any given section.

For steady flow process, the mass entering and leaving the control volume is same.

For steady flow process the total energy entering the control volume is equal to the total energy leaving the control volume.



Total energy entering the cv = Total energy leaving the cv

$$\frac{1}{2} m c_1^2 + m g z_1 + U_1 + Q_{cv} = \frac{1}{2} m c_2^2 + m g z_2 + U_2 + Q_w$$

W = Entry displacement work + work of exit disp. work

$$W = -P_1 V_1 + W_{cv} + P_2 V_2$$

$$\frac{1}{2} m c_1^2 + m g z_1 + U_1 + Q_{cv} = \frac{1}{2} m c_2^2 + m g z_2 + U_2 + P_1 V_1 + W_{cv} + P_2 V_2$$

$$\frac{1}{2} m c_1^2 + m g z_1 + U_1 + P_1 V_1 + Q_{cv} = \frac{1}{2} m c_2^2 + m g z_2 + U_2 + P_2 V_2 + W_{cv}$$

$$H_1 + \frac{1}{2} m c_1^2 + m g z_1 + Q_{cv} = H_2 + \frac{1}{2} m c_2^2 + m g z_2 + W_{cv}$$

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

while deriving this eqⁿ only one assumption is made i.e. the flow is steady. This eqⁿ is applicable for reversible or irreversible process.

This equation is also known as first law of thermodynamics for open system.

Special cases :-

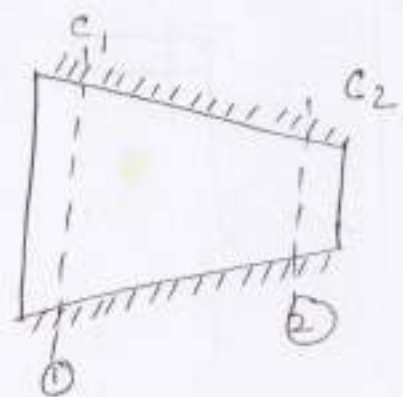
① Nozzle :-

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

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

if $c_2 \gg c_1$

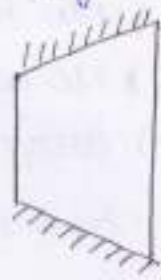
$$h_1 = h_2 + \frac{c_2^2}{2}$$



(ii) Turbine :- $h_1 + \frac{C_1^2}{2} + z_1 g = h_2 + \frac{C_2^2}{2} + z_2 g + w_{cv}$

$$h_1 = h_2 + w$$

$$W = h_1 - h_2$$



Conditions under which $W = h_1 - h_2$

- (1) The flow must be steady.
- (2) The turbine is perfectly insulated.
- (3) Kinetic energy changes negligible.
- (4) P.E. changes negligible.

(iii) Compressor :- In compressor work input is given to the system. Compressor work = $h_2 - h_1$

$$W = h_1 - h_2$$

$$W = -(h_2 - h_1)$$

$$-W = h_2 - h_1$$

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

Assumption under which $W = h_2 - h_1$

- (1) Same assumption as in the case of turbine.

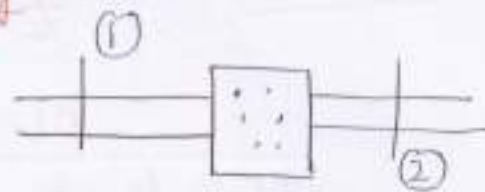
(iv) Throttling device or throttling valve :-

The examples for throttling are :-

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

Characteristics of throttling :-

- (1) No heat transfer.
- (2) No work transfer.
- (3) Reversible process.



$$h_1 + \frac{c_1^2}{2} + z_1/g + Q/\dot{V} = h_2 + \frac{c_2^2}{2} + z_2/g + W/\dot{V}$$

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

$$\boxed{h_1 \approx h_2}$$

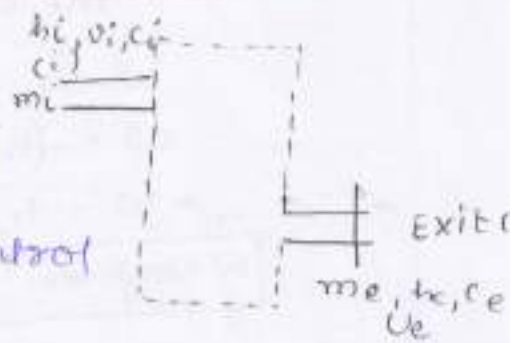
(iv) Throttling is an isenthalpic process.

Unsteady state (Transient state) Problems

(i) Conservation of mass :-

Let \dot{m}_i and \dot{m}_e be the mass entering and leaving the control vol,

Let m_i and m_f be the mass of control volume initially and finally.



(i) Conservation of mass :-

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

(ii) Conservation of energy :-

$$\dot{h}_i + \frac{c_i^2}{2} + z_i/g + q$$

$$\dot{h}_e + \frac{c_e^2}{2} + z_e/g + w$$

$$\dot{E}_i = \dot{m}_i h_i + \frac{1}{2} \dot{m}_i c_i^2 + \dot{m}_i g z_i + \dot{Q}$$

$$\dot{E}_e = \dot{m}_e h_e + \frac{1}{2} \dot{m}_e c_e^2 + \dot{m}_e g z_e + \dot{W}$$

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

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

If K.E. and P.E changes are negligible then $dE = du$

$$E = K.E + P.E + U$$

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

$$dE = dU$$

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

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

If the inlet enthalpy h_i and exit enthalpy h_e do not vary with time.

$$= \frac{d}{dt} (m_i h_i) + \dot{Q} - \frac{d}{dt} (m_e h_e) - \dot{W}$$

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

$$\boxed{\left(\frac{dU}{dt}\right)_{cv} = \dot{m}_i h_i + \dot{Q} - \dot{m}_e h_e - \dot{W}}$$

SECOND LAW OF THERMODYNAMICS

It is also known as directional law.

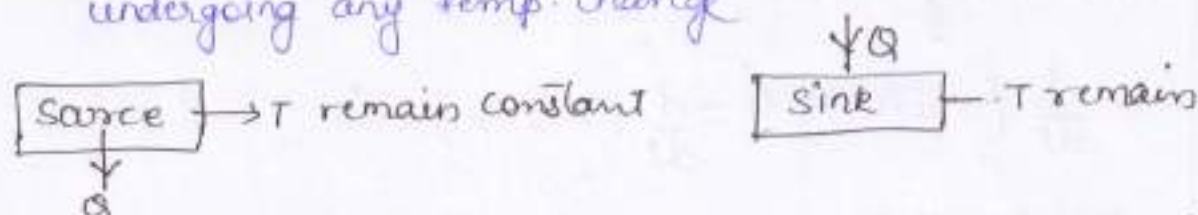
First law simply say that energy is conserved. It do not give any direction for a particular process. It is the second law of thermodynamics which gives direction for a particular process through the concept of entropy.

Hence second law is also know as directional law.

Thermal Energy Reservoirs:-

Source:- It has infinite amount of heat energy so that it can supply heat without undergoing any temp. change

Sink:- It is reservoir which can absorb heat without undergoing any temp. change



Note:- work is known as high grade energy and heat is known as low grade energy and complete conversion of low grade heat (energy) into high grade energy (work) in cycle is impossible

Statement of second law of thermodynamics

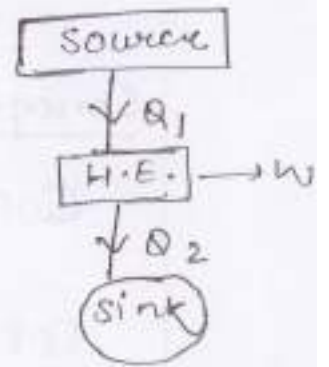
(i) Kelvin plank statement:- It is impossible to develop a device operating in a cycle and which produces work continuously by exchanging heat with a single reservoir.

Reservoir



PMM-2 is impossible

Concept of Heat engine :- A heat engine is a device which operates on a cycle and converts part of Heat into work and rejects remaining to the surroundings or sink.



Efficiency :- $\eta = \frac{\text{Output}}{\text{Input}} = \frac{W}{Q_1}$

$$Q_1 = W + Q_2$$

$$W = Q_1 - Q_2$$

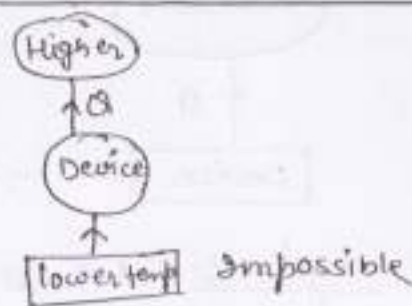
$$W = Q_S - Q_R$$

$$\eta = \frac{Q_S - Q_R}{Q_S}$$

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

This is applicable for reversible as well as irreversible cycle.

(2) Clausius Statement :- It is impossible to develop a device operating in a cycle and transfers heat from lower temp to higher temp. without any external aid (help).



Concept of Refrigerator and Heat Pump:-

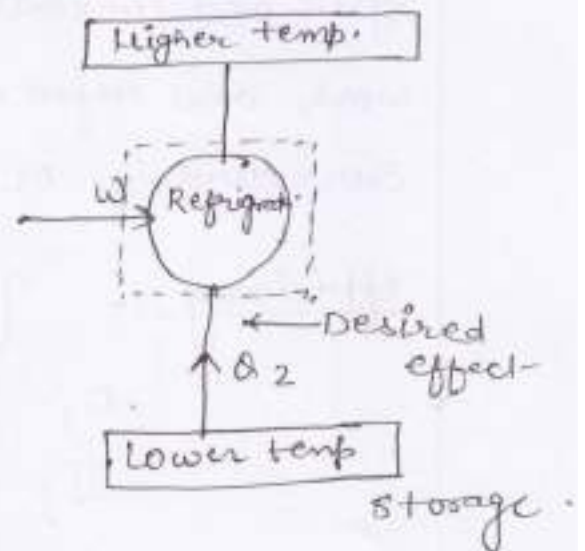
$$COP = \frac{\text{Desired effect}}{\text{Energy input}}$$

$$COP_R = \frac{Q_2}{W}$$

$$W + Q_2 = Q_1$$

$$W = Q_1 - Q_2$$

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



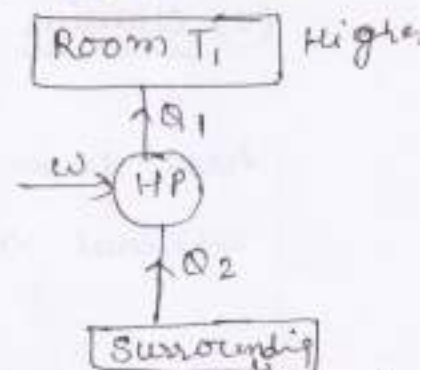
Note :- The eqⁿ is applicable for reversible as irreversible cycle.

Heat Pump :- Heat pump maintain higher temp compare to surrounding.

This eqⁿ is applicable for reversible as well as irreversible cycle.

$$COP_{HP} = \frac{Q_1}{W}$$

$$COP_{HP} = \frac{Q_1}{Q_1 - Q_2}$$



power

Relation between COP of HP and COP of Refrigerator:-

$$COP_{HP} = \frac{Q_1}{Q_1 - Q_2}$$

$$COP_{Ref} = \frac{Q_2}{Q_1 - Q_2}$$

$$COP_{HP} - COP_{Ref}$$

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

$$= \frac{1}{\cancel{Q_1 - Q_2}} [Q_1 - Q_2]$$

$$= 1$$

$$COP_{HP} = 1 + COP_{Ref.}$$

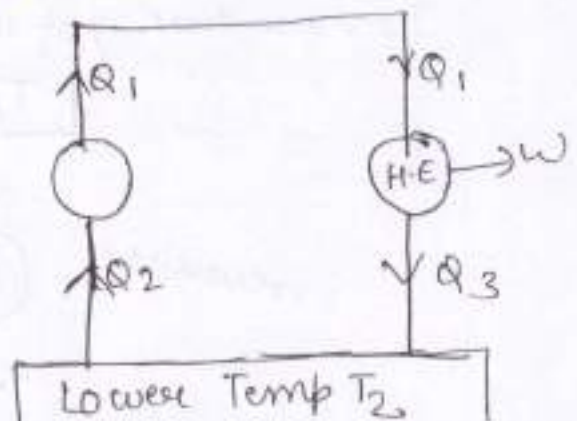
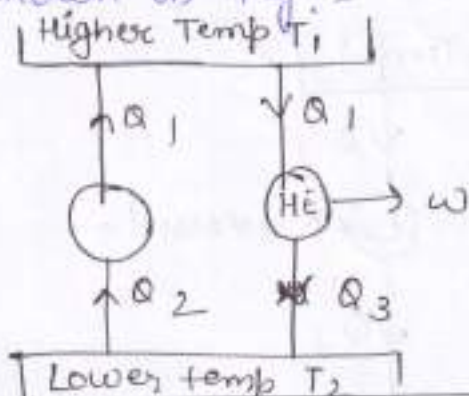
Note :- (i) HP and Refrigerator are reversed heat engine.

Kelvin-Planck and Clausius statement are parallel statements of second law of thermodynamics :-
i.e. violation of one statement amongst to the other statement.

Violation of Clausius statement :-

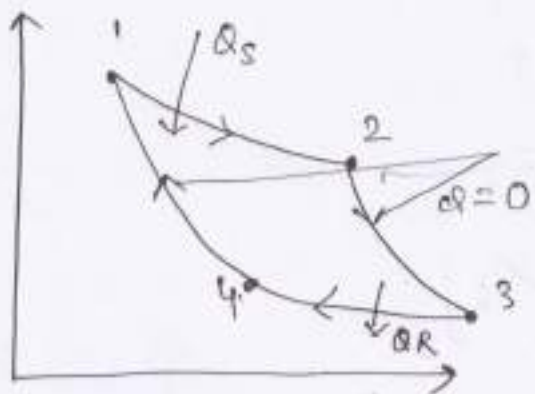
Let us violate Clausius statement as

Shown in fig:-



Carnot cycle :- It is a reversible cycle.

A cycle is said to be a reversible cycle when all processes are reversible process.



1-2 \rightarrow Isothermal expansion
(Heat addition)

2-3 \rightarrow Adiabatic expansion

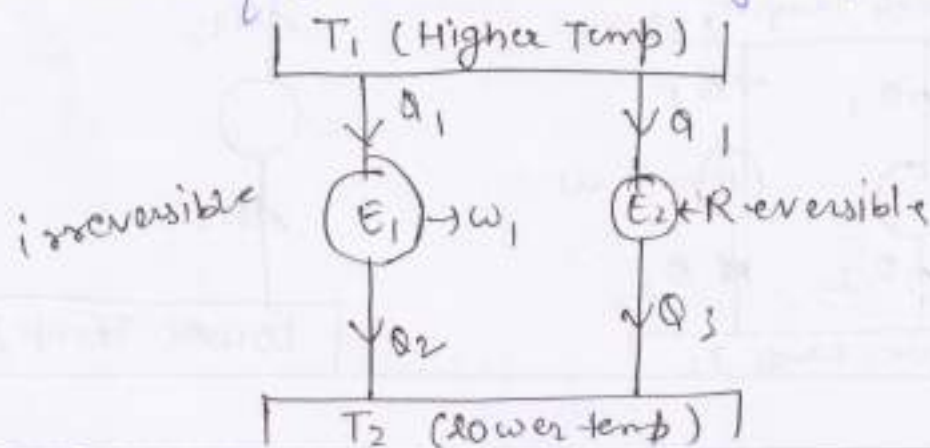
3-4 \rightarrow Isothermal compression
(Heat rejection)

4-1 \rightarrow Adiabatic compression

Carnot cycle consists of two reversible adiabatic processes and two reversible isothermal processes. To realize isotherm conditions the process must be carried very slowly and to realize adiabatic conditions, the process must be carried out in a very fast manner and hence there two combinations are not possible in a cycle. Therefore Carnot cycle is a theoretical cycle.

Carnot theorem :- For various engine working b/w two temp none has the efficiency greater than a reversible engine efficiency.

To show that η of an reversible engine $>$ irreversible Engine



Let us assume that $\eta_{irr} > \eta_{rev}$

$$\eta_1 > \eta_2$$

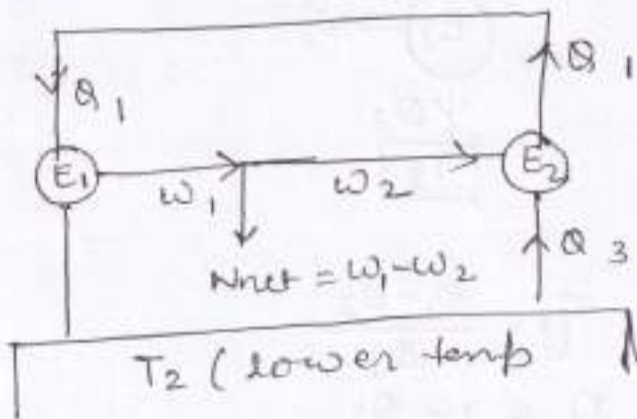
$$\eta_1 = \frac{W_1}{Q_1}$$

$$\eta_2 = \frac{W_2}{Q_1}$$

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

$$W_2 > W_1$$

If E_2 is reversible engine. Let us reverse the engine :-



This is a violation of Kelvin plank statement and hence our assumption is wrong i.e.

η_{irr} is not greater than η_{rev} .

Similarly by taking both η to be same amount - to the violation of Clausius statement and hence η of reversible cycle is greater than η of irreversible cycle operating b/w same temp. limit.

Important points w.r.t a reversible cycle :-

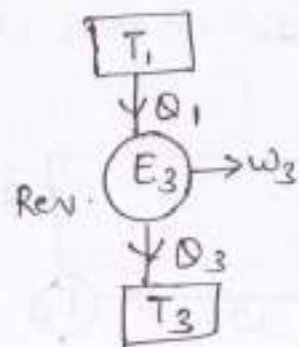
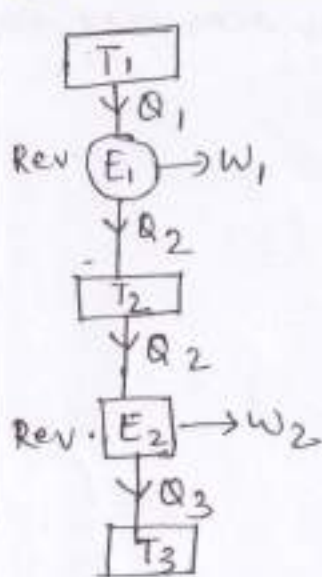
- 1) Efficiency of a reversible cycle is dependent on temp limits.

(2) All the reversible cycles operating b/w same temp limit have same effⁿ.

(3) Effⁿ of a reversible cycle is independent of working fluid.

Thermodynamic Temperature Scale

Let us assume three reversible cycle as shown in fig.



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

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

$$\eta_1 = f_1(T_1, T_2)$$

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

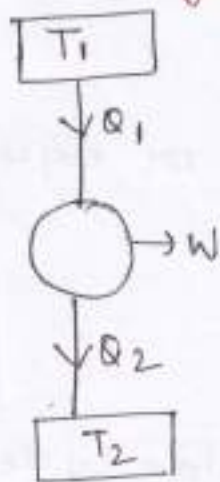
$$\frac{Q_2}{Q_1} = 1 - f_1(T_1, T_2)$$

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

$$\frac{Q_1}{Q_2} = \phi_1(T_1, T_2)$$

$$\frac{Q_2}{Q_3} = \phi_2(T_2, T_3)$$

Efficiency of a Reversible Heat



$$\eta = \frac{W}{Q_1}$$

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

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

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

$$\eta_{\text{rev}} = \frac{T_1 - T_2}{T_1}$$

$$\boxed{\eta_{\text{rev}} = \frac{T_h - T_c}{T_h} = \eta_{\text{max}}}$$

$$\frac{Q_1}{Q_3} = \phi_3(T_1, T_3)$$

$$\frac{Q_1}{Q_2} = \frac{\frac{Q_1}{Q_3}}{\frac{Q_2}{Q_3}} = \frac{\phi_3(T_1, T_3)}{\phi_2(T_2, T_3)}$$

$$\frac{Q_1}{Q_2} = \frac{\phi_3(T_1, T_3)}{\phi_2(T_2, T_3)}$$

$$\frac{Q_1}{Q_2} = \phi_1(T_1, T_2)$$

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

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

only for a Reversible cycle

COP of a Reversible Refrigerator

$$\text{COP}_R = \frac{Q_2}{Q_1 - Q_2}$$

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

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

$$Q_2 = K T_2 \quad Q_1 = K T_1$$

$$\text{COP}(\text{REV}) = \frac{K T_2}{K T_1 - K T_2}$$

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

$$\boxed{\text{COP}_{\text{max}}(R) = \frac{T_2}{T_1 - T_2}}$$

Note :- COP of a reversible heat pump = $\frac{T_1}{T_1 - T_2} = \frac{T_h}{T_h - T_c}$

Clausius Inequality :-

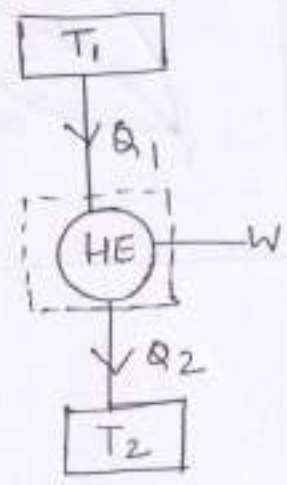
The cyclic integral of $\frac{\delta Q}{T}$ is less or equal to 0

$$\text{i.e.} = \oint \frac{\delta Q}{T} \leq 0$$

$$\oint \frac{\delta Q}{T} = 0 = \text{cycle is reversible.}$$

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

Case I:- Let us assume the cycle is a reversible cycle.



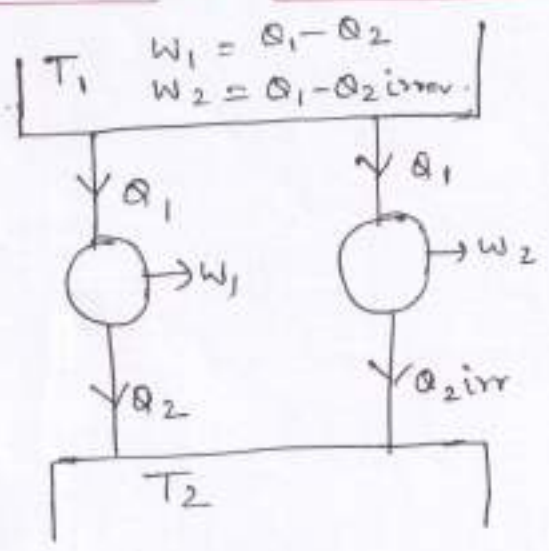
$$\oint \frac{\delta Q}{T} = +\frac{Q_1}{T_1} + \left(-\frac{Q_2}{T_2}\right)$$

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

$$\oint \frac{\delta Q}{T} = \frac{Q_1}{T_1} - \left(\frac{Q_1}{T_1}\right) = 0$$

$$\boxed{\oint_{rev} \frac{\delta Q}{T} = 0}$$

Case-2 :- Irreversible cycle



$$\oint_{irr} \frac{\delta Q}{T} = \frac{Q_1}{T_1} + \left(-\frac{Q_2}{T_2} irr\right)$$

$$\oint \frac{\delta Q}{T} = \frac{Q_1}{T_1} = \frac{Q_2 irr}{T_2}$$

$$\oint \frac{\delta Q}{T} = \frac{Q_2}{T_2} - \frac{Q_2 irr}{T_2} = \frac{Q_2 - Q_2 irr}{T_2}$$

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

$$Q_2 irr > Q_2$$

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

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

$$W_1 > W_2$$

for irreversible cycle.