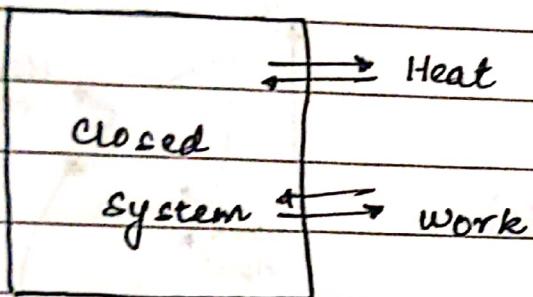


Thermodynamics

Thermodynamics deals with the relationship between heat and work, and the properties of the system.

- Energy and its transformation
- Feasibility of a process
- Equilibrium process



- Systems possess energy, but not heat or work.
- Both are associated with a process
- Both are path fn.

→ (E)
Total energy of a closed system can be changed only via heat and work interaction across system boundary

Heat and work are energy in transfer
↳ Both are boundary phenomena.

$$E = KE + PE + U + \text{Others}$$

↓ ↗
Macroscopic Microscopic/
KE of system Molecular KE

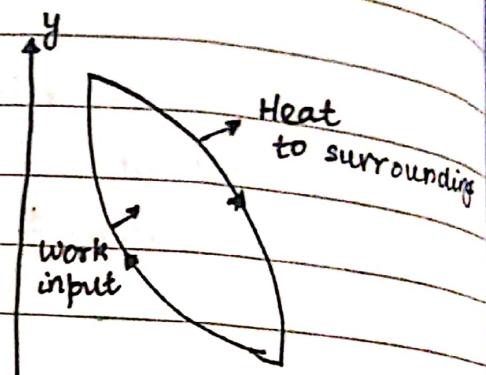
Heat is a form of energy that is transferred between two systems (or a system and surroundings) by virtue of temp. diff. Thus, an energy interaction is heat only if it takes place because of a temp. diff.

→ Thermodynamic work done in free expansion is zero.

Joule's Experiment

\Rightarrow coz it's
a path fr
 $8w \approx 8Q$

$$\rightarrow \delta w = \mathcal{J}(\delta Q)$$



The change of energy of a system is proportional to mechanical work done on the system in adiabatic process

$$\oint \delta w = \oint \delta Q$$

$$f_{\bar{w}} - \bar{Q} = 0$$

$$\Delta E = 0$$

$$\delta W - \delta Q = dE$$

$$\text{Thermodynamic Work} = \text{Generalized force (Intensive variable)} \times \text{displacement (Extensive variable)}$$

- 8) Determine power required for a 2000 kg car to climb 100 m long uphill with a slope of 30° in 10 s
- At constant velocity
 - From rest to final velocity

a) $E \rightarrow \text{macroscopic K.E} + \text{P.E}$

$$P = \frac{mgh \sin\theta}{\Delta t}$$

$$= 2000 \times 10 \times 100 \times \frac{1}{2} \times \frac{1}{10}$$

$$= 98.1 \text{ kW}$$

b) $P = \frac{mgh \sin\theta + \frac{1}{2} \frac{(v_2^2 - v_1^2)}{\Delta t} m}{\Delta t}$

$$v_1 = 0$$

$$v_2^2 = gh$$

$$\Rightarrow P = 188 \text{ kW}$$

Thermodynamic Properties

The distinguishing characteristics of a system, basically quantities needed to specify a macroscopic description / state of system completely

- Either directly or indirectly measurable
- Change is independent, hence can be written as exact differential.

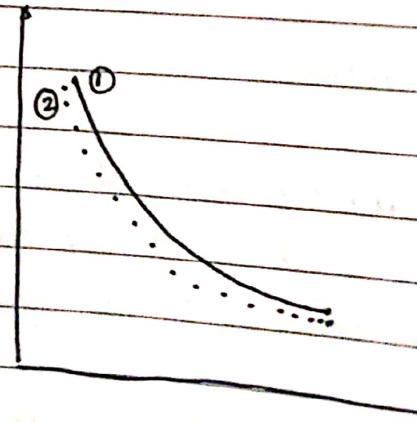
Internally Reversible Process (Quasi static)

A quasi static process is a process, where system goes through infinite no. of eq. process, that we can say it's a cont. process.

- We have info about only the initial and final paths.
- We don't have info about how the intensive variable varied, going from $1 \rightarrow 2$.
- More the extent of internal rev. of a process, larger the work done can be extracted from the system

A reversible process is:

- Reversible both internally and externally. When reversed, retraces its forward path, and goes to its initial state



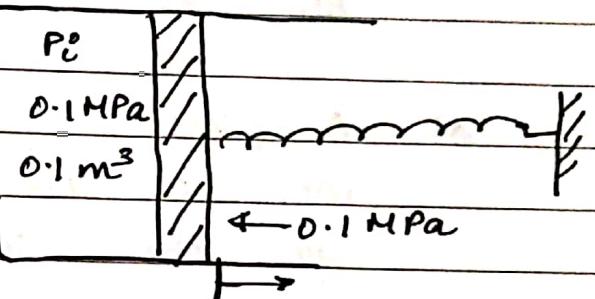
① → Quasistatic process (cont.)

② → Non-quasi static process

Q) A piston cylinder assembly is shown, initially it consists of 0.1 m^3 air at 0.1 MPa . The atmospheric pressure of 0.1 MPa acts on the other side of piston. At this stage the spring just touches the piston and doesn't exert any force. Now the gas is heated till the vol. is 0.3 m^3 and at this stage P is 0.6 MPa . When the spring is compressed, it exerts a force proportional to the decrease in length. calculate work done by the gas.

$$P_i A = P A + kx$$

$$x = \frac{A(P_i - P)}{k}$$



$$W = \int P_i \, dv$$

$$A \, dx = dv$$

$$dv = A \, d\left(\frac{A(P_i - P)}{k}\right)$$

$$dv = \frac{A^2}{k} \, dP_i$$

$$W = \frac{A^2}{k} \int P_i \, dP_i$$

$$P_i A = P A + \frac{kx}{A}$$

$$k(P_i - P) = kdx$$

$$\Delta x = \frac{V - V_0}{A} \Rightarrow P_i A = P A + \frac{k \Delta V}{A}$$

$$W = \int \left(P + \frac{R}{A^2} \left(\frac{V - V_0}{A^2} \right) \right) dV$$

$$= Pa(V_f - V_0) + \frac{R}{A^2} \frac{(V_f - V_0)^2}{2}$$

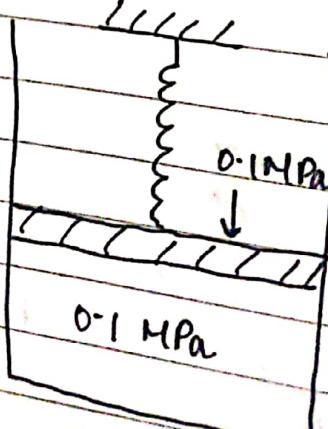
Force balance at initial and final position

After, doing the above

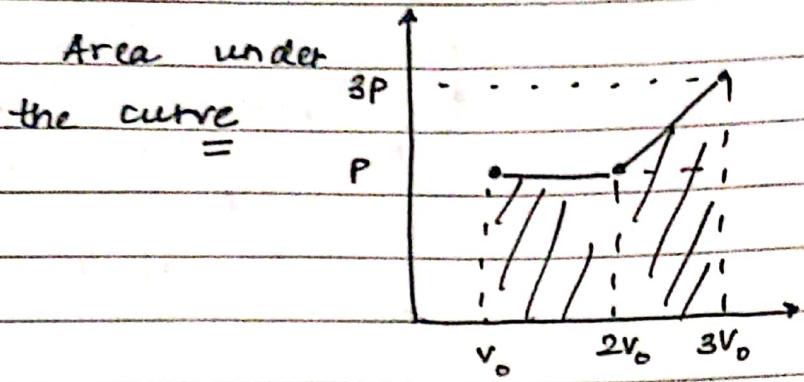
$$w_{\text{gas}} = (V_f - V_0) \left(\frac{P_1 + P_2}{2} \right)$$

Ans : 70 kJ

- 8) A piston-cylinder assembly contains one mole of gas at 0.1 MPa and 300K. The gas obeys the relation $PV = nRT$. The piston is massless and frictionless and atmospheric pressure of 0.1 MPa acts on the other side of the piston. The gas is heated allowing piston to move. Once the gas volume is doubled, the piston touches the spring which is fixed at a distance above the cylinder. When $V \rightarrow 3V$, $P = 0.3 \text{ MPa}$. Calculate work done by gas and change in P.E of spring.



A) Work done = Area under
the curve

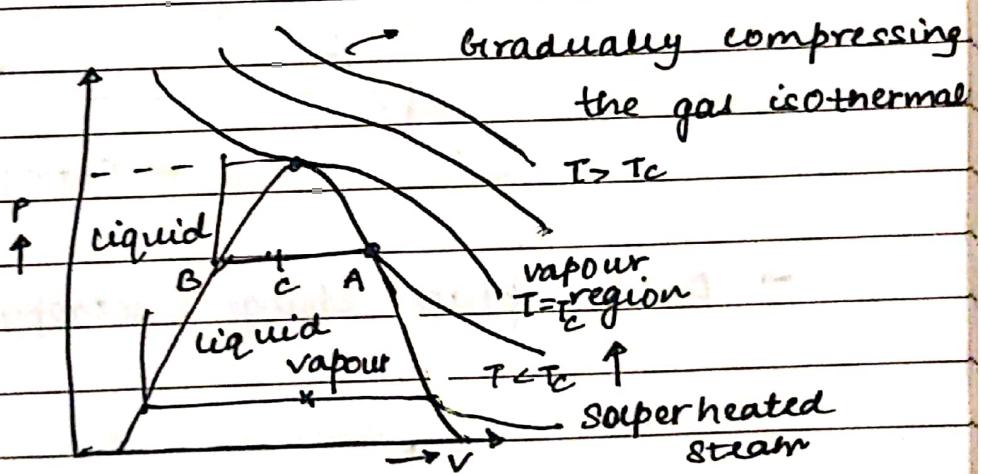


Pure substance

→ Single chemical species having fixed comp., generally described by two variables

Phase

→ A specified mass of a substance having uniform composition and physical state throughout.



$$V_i = V_g x + V_f (1-x)$$

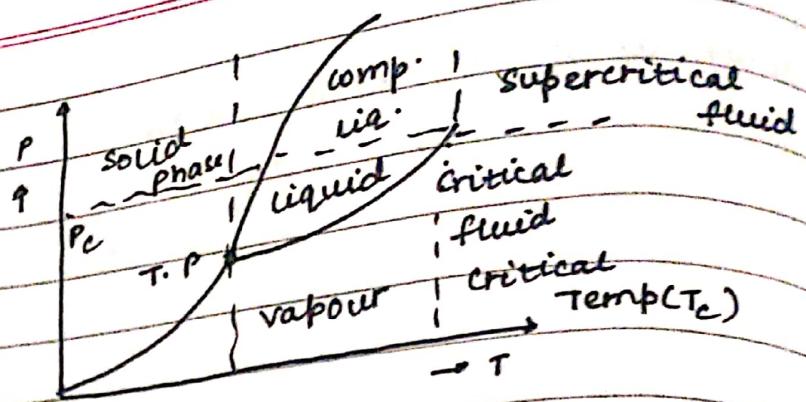
$A \rightarrow$ sat. vapour

$C \rightarrow$ sat. vapour
+ sat. liq.

$x \rightarrow$ quality of steam

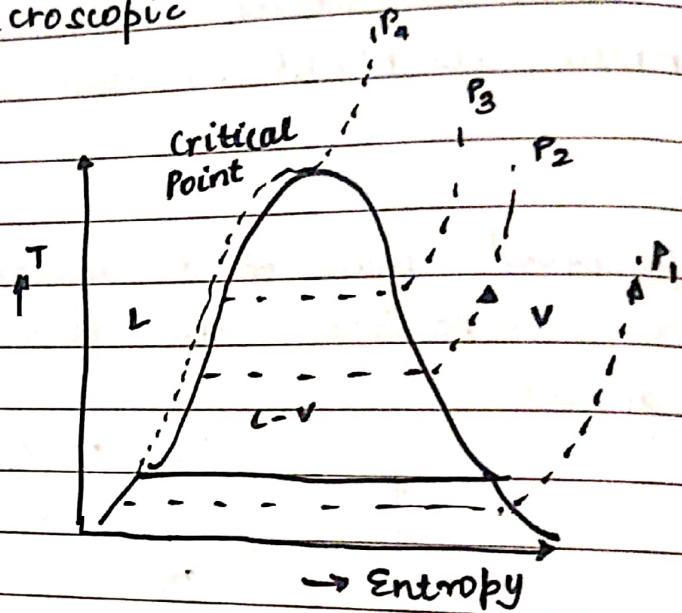
$B \rightarrow$ sat liq.

$$x = \frac{m_g}{m_g + m_f}$$

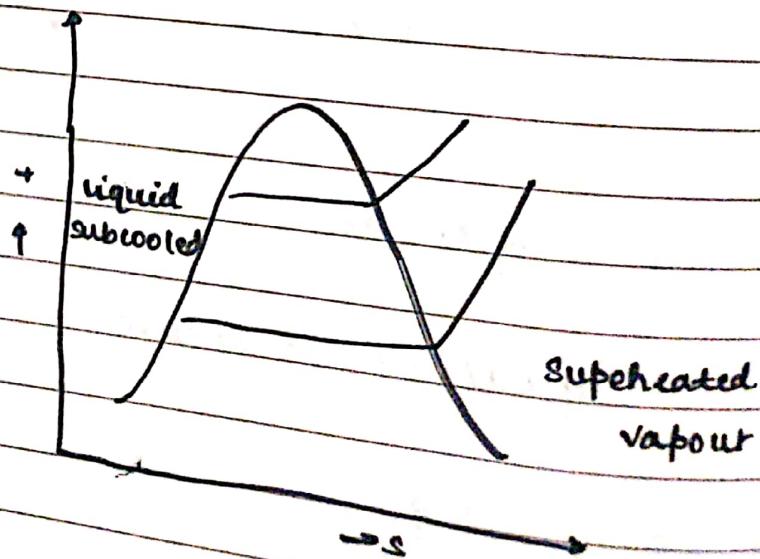


$$dS = \frac{\delta Q}{T} \rightarrow \text{supply heat (rev.)}$$

↳ Macroscopic



→ During phase change, entropy changes

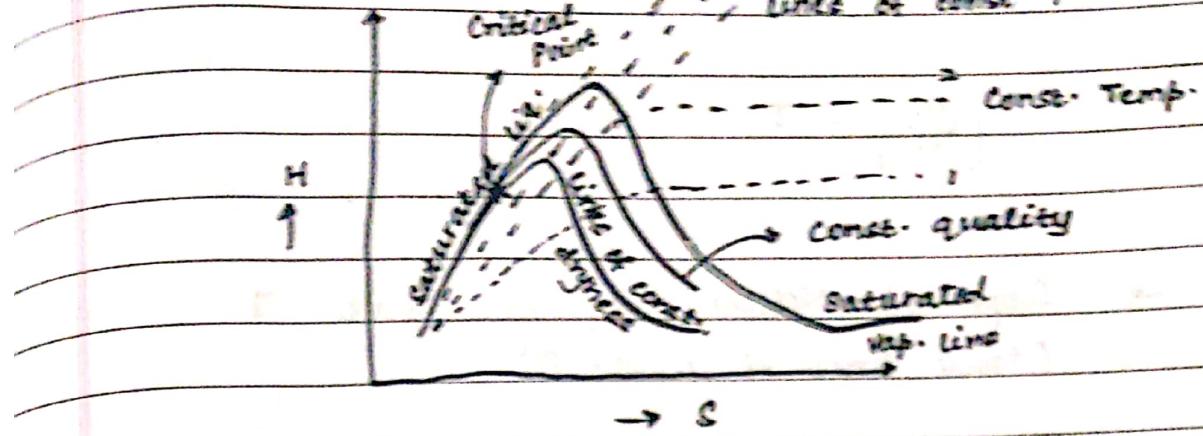


Hollier Diagram

$$P_3 > P_2 > P_1$$

$$T_3 > T_2 > T_1$$

lines of const. P



$$\text{Quality} = \frac{m_g}{m_g + m_f}$$

Assume that there is no other form of energy

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

Consider a compressible substance (only quasi-static work, compression / expansion)

$$\delta Q = dU + PdV$$

If process is at constant pressure

$$(\delta Q)_P = d(U + PV)$$

$$dh = (\delta Q)_P$$

↑

Indirectly measurable
thermodynamic quantity

$$\frac{(dq)_p}{T} = ds$$

$$(dq)_p = dh$$

$$\left(\frac{dh}{ds}\right)_p = T$$

→ Slope of Mollier Diagram, gives T
(Only lines of const. P)

→ H-S curves are monotonically increase, coz
 T is always > 0

$$\left(\frac{dh}{dp}\right)_s = v$$

a) 1kg of superheated steam at 3bar, 400°C ,
contained in a cylinder piston system
is allowed to expand reversibly and
adiabatically till the pressure inside the
cylinder becomes equal to P_{atm} . ($P_{atm} = 1\text{ bar}$)

b) Find state of system at stage 2

b) At stage 2 the piston is brought in contact
with spring. All the walls are thermally
insulated and a resistor connected to a
battery has been used to heat the system
upto a pressure of 2bar and temp. 40°C
(2 bar saturated vapour $\alpha = 1$). Find out
the work done by the battery in bringing
the system from $2 \rightarrow 3$

$$s_1 = s_2 = 8.0338$$

Stage - 1 : 3 bar, 400°C

Stage - 2 : 1 bar

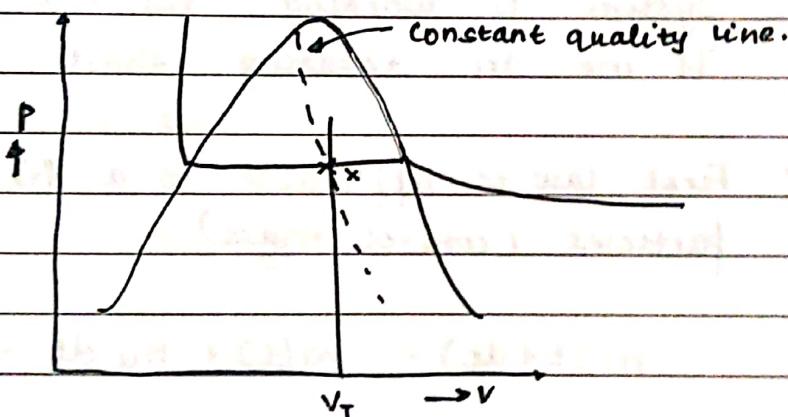
$$s_g = 7.3598$$

$$s_f = 1.3027$$

$$s_2 = s_{200} + \left(\frac{s_{250} - s_{200}}{250 - 200} \right) (T_2 - 200)$$

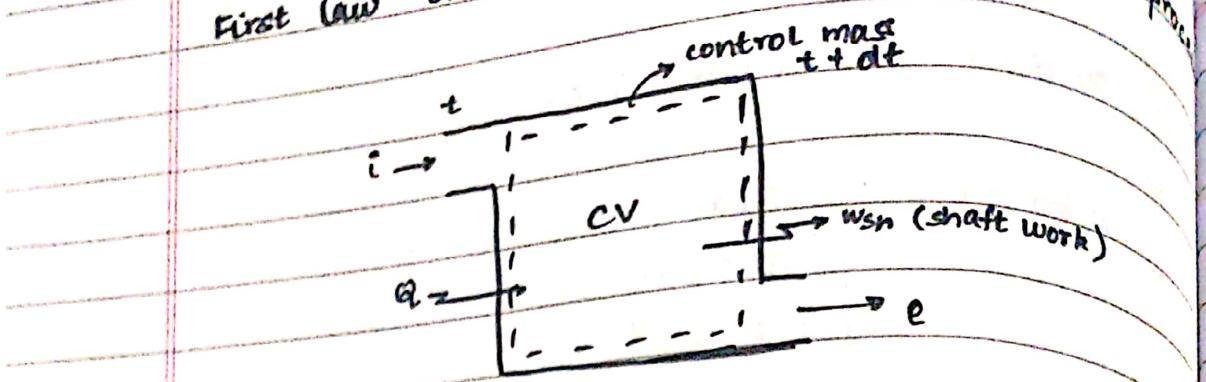
$$s_2 = s_g x + (1-x)s_f$$

$$\therefore x = 0.928$$



As T_1 , v_g makes more contribution to v_T

First law of Thermodynamics (for flowing process)



$$\frac{dE}{dt} = \left(m_i \left(h_i + \frac{V_i^2}{2} + g z_i \right) + Q \right) - \left(m_e \left(h_e + \frac{V_e^2}{2} + g z_e \right) + w_{sh} \right)$$

shaft work is always used by system.

System is working, $w_{sh} > 0$

If we are rotating shaft, $w_{sh} < 0$

- First law is applicable to a fixed set of particles (control mass)

$$m(t+dt) = m(t) + m_i dt - m_e dt$$

$$\Delta E_{sys} = E_{sys}(t+dt) - E_{sys}(t)$$

$$\dot{Q} dt - (w_{shaft} + w_{pv}) dt = E_{sys}(t+dt) - E_{sys}(t)$$

Work done near boundary except inlet and outlet is zero

- No slip cond. at boundary.

$$E_{sys}(t) = E_{cv}(t) + \int_{cv} m_i e_i dt$$

$$e_i = u_i + \frac{v_i^2}{2} + g z_i \quad e_e = u_e + \frac{v_e^2}{2} + g z_e$$

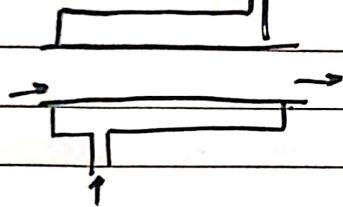
$$v_2 \gg v_1$$

Nozzle

$$h_i + \frac{v_i^2}{2} = h_2 + \frac{v_2^2}{2}$$

$$\frac{dE}{dt} = \left(m_i \left(h_i + \frac{v_i^2}{2} + g z_i \right) + \dot{Q} \right)$$

$$- \left(m_e \left(h_e + \frac{v_e^2}{2} + g z_e \right) + \dot{W}_s \right)$$



$$\sum m_i h_i = \sum m_i h_i$$

Consider ideal gas, $v_2 \gg v_1$

$$h_i = h_e + \frac{v_e^2}{2}$$

$$\therefore v_e = \sqrt{2(h_i - h_e)}$$

$$P V^r = \text{const.}$$

$$v_e = \sqrt{2 C_p T_i \left(1 - \left(\frac{P_e}{P_i} \right)^{\frac{r-1}{r}} \right)}$$

Compressor (Work shaft is -ve)

Turbine (Work is being done by system)

Work shaft is +ve.

$$h_e = h_i - W_{\text{shaft}}$$

Bernoulli's Eqn:

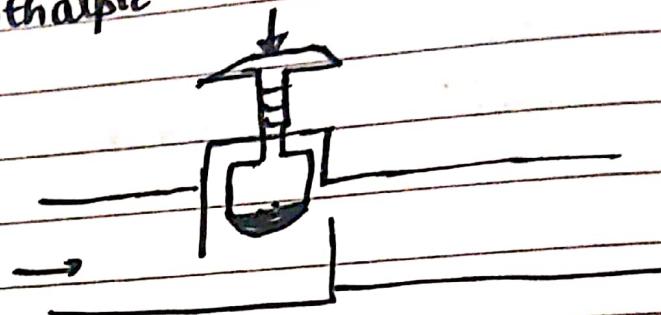
$$\left(P_i V_i + \frac{V_i^2}{2} + g Z_i \right) = \left(P_e V_e + \frac{V_e^2}{2} + g Z_e \right) + (U_e - U_i)$$

↑
losses

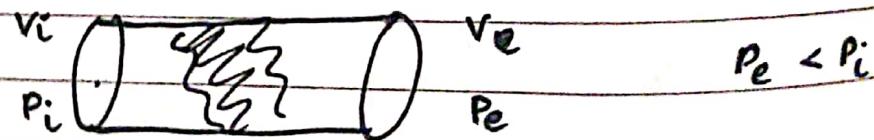
Throttling Process (Isenthalpic process)

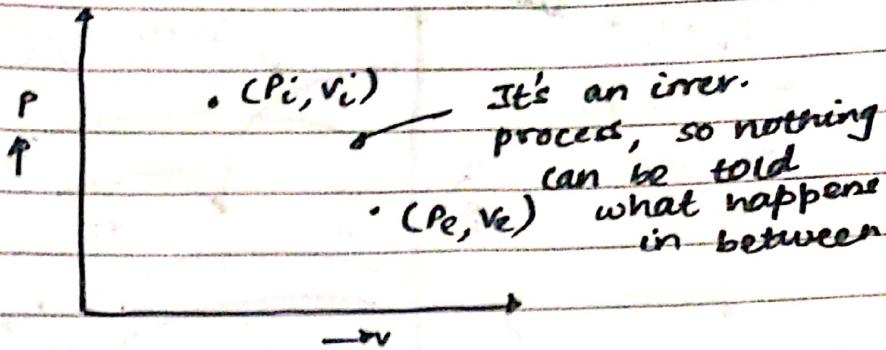
- Irreversible
- Isenthalpic

→ No work transfer
→ No heat transfer



Fluid enters through a flow constriction (orifice), suddenly the flow confronts a narrowed zone, and when it passes through the zone, it goes back to a low P region. This process is called throttling.





Throughout the process h need not be const., but $h_i = h_e$.

$$T_e < T_i \quad (?)$$

$$\left(\frac{\partial h}{\partial T}\right)_P = C_p$$

ideal gas

$$dh = C_p dT$$

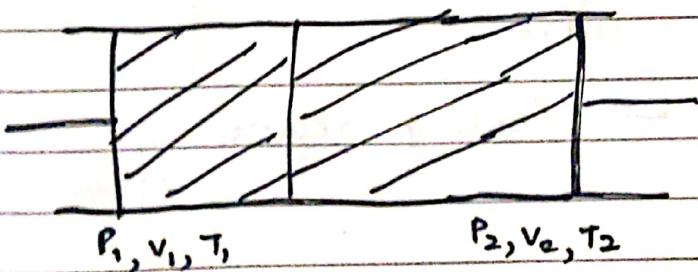
$$h(T)$$

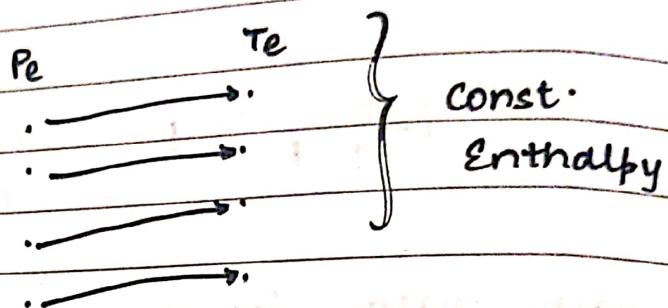
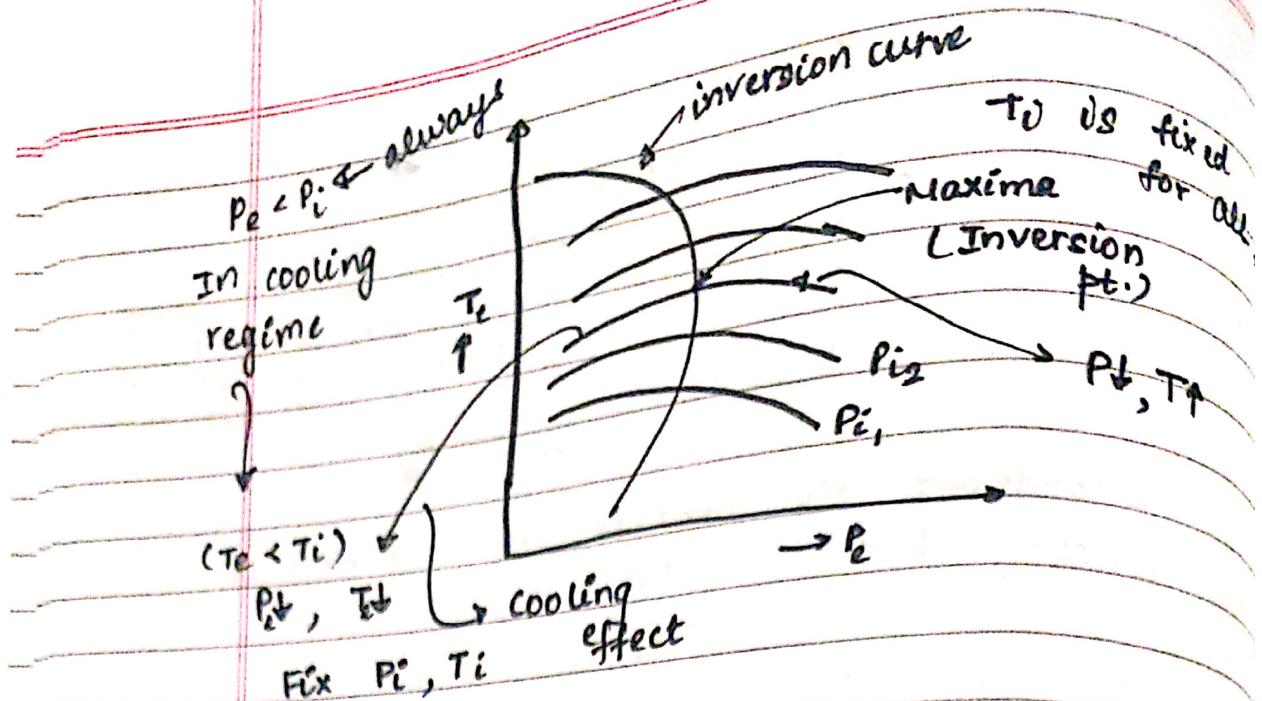
Enthalpy change for any real gas is given by:

$$h_2 - h_1 = \int_{T_1}^{T_2} C_p dT + \int_{P_1}^{P_2} v(1-\beta T) dP$$

$\hookrightarrow h(T, P) \rightarrow \text{real gas}$

Joule Thomson Effect





For given P_i , if we decrease pressure (P_e) $T_e \uparrow$ till inversion pt- and then $T_e \uparrow$

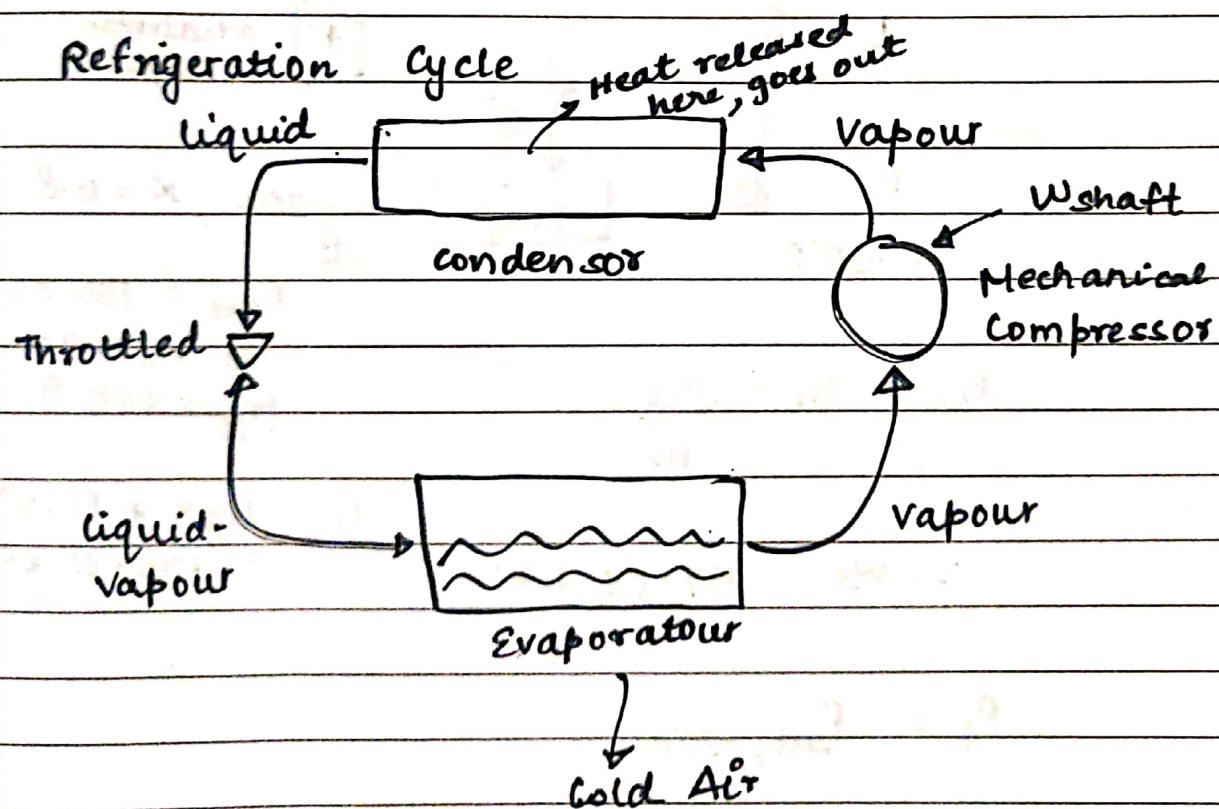
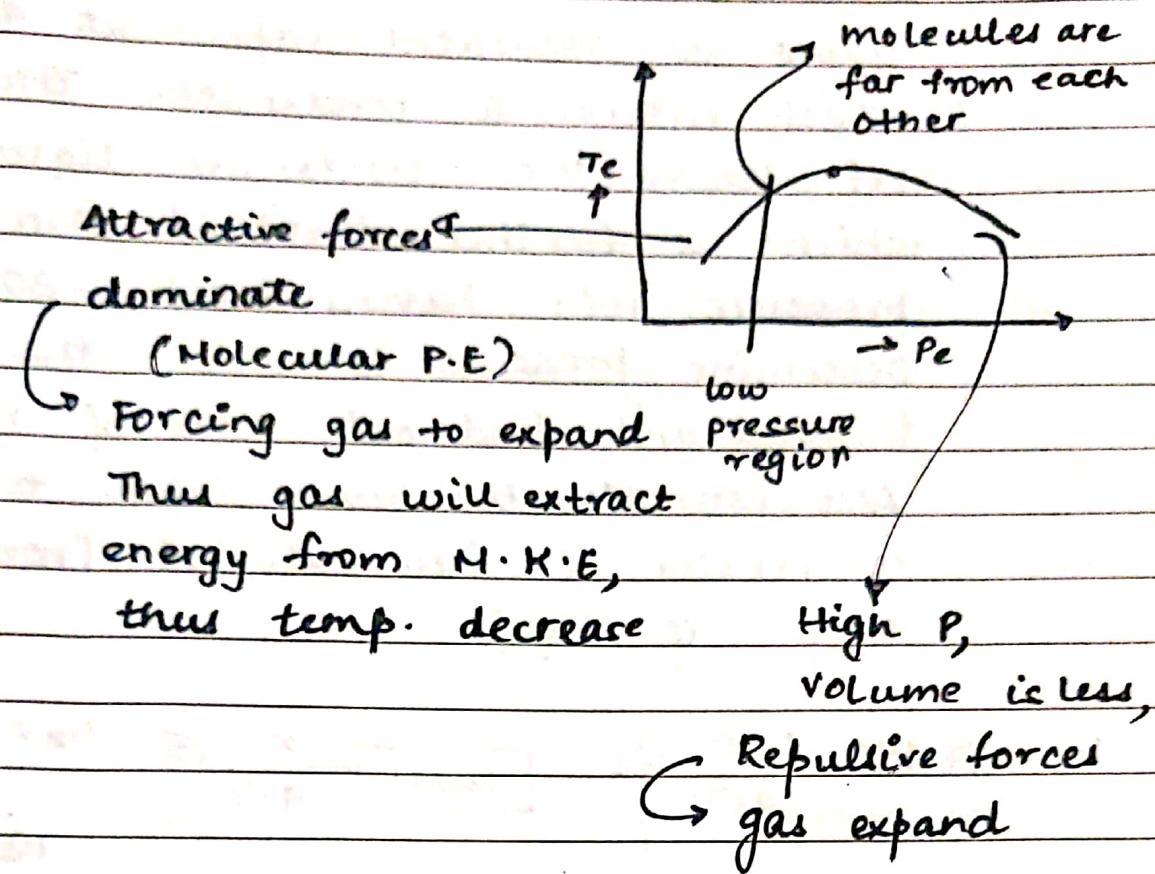
$$M_{JT} = \left(\frac{\partial T}{\partial P} \right)_H$$

slope of
curve

$M_{JT} > 0 \rightarrow$ Cooling region

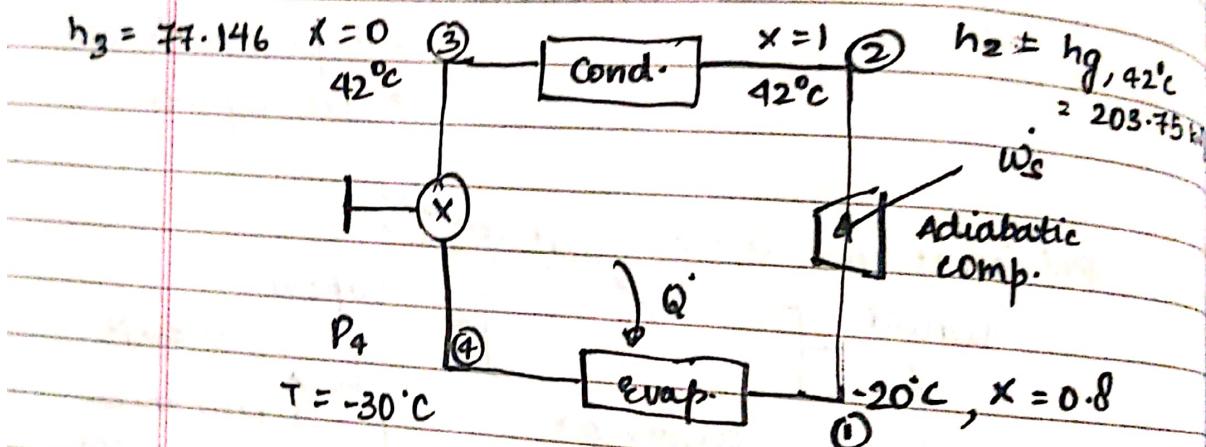
Molecular interpretation of JT effect

Molecular K.E + Molecular P.E



In a vapour compression ref., saturated Freon - 12 at -20°C and quality 0.8 enters an adiabatic compressor and leaves as saturated vapour at 42°C , which enters a condenser. The ref. leaves the condenser liquid at 42°C which is further throttled to a low pressure ref. having temp. -30°C . Determine pressure to which the ref. is throttled and find out state of ref.

Also estimate the power input to the compressor if flow rate of frozen comp. is 1 kg/s



$$h_2 = h_1 - \frac{w_s}{m}$$

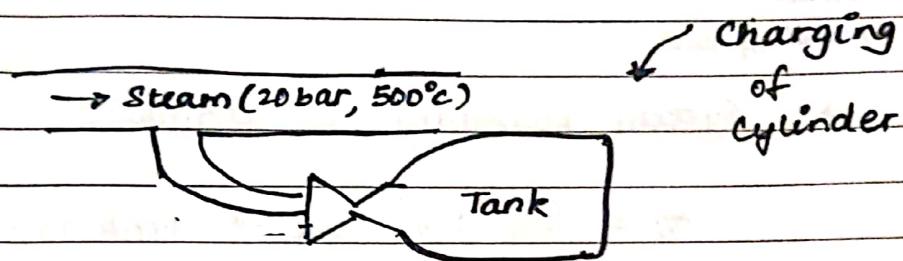
$$\begin{aligned} P_{sat} &= 150.83 \text{ kPa} \\ h_f &= 17.95 \\ h_g &= 178.9 \end{aligned}$$

$$\therefore -w_s = 57.04 \text{ kW}$$

$$\begin{aligned} h_1 &= h_g x + (1-x) h_f \\ &= 196.71 \text{ kJ/kg} \end{aligned}$$

$$P_4 = P_{sat, -30^{\circ}\text{C}}$$

Steam at pressure 20 bar and temp., 500°C is flowing in a pipe. An evacuated tank is connected to this pipe through a valve. The valve is opened and the tank is allowed to fill with steam; until the $P_{\text{tank}} = 20 \text{ bar}$, then valve is closed. Assuming adiabatic process and negligible change in K.E and P.E. Determine the temp. of steam in the tank at the end of filling.



$$P_f = 20 \text{ bar}$$

Steam \rightarrow Superheated

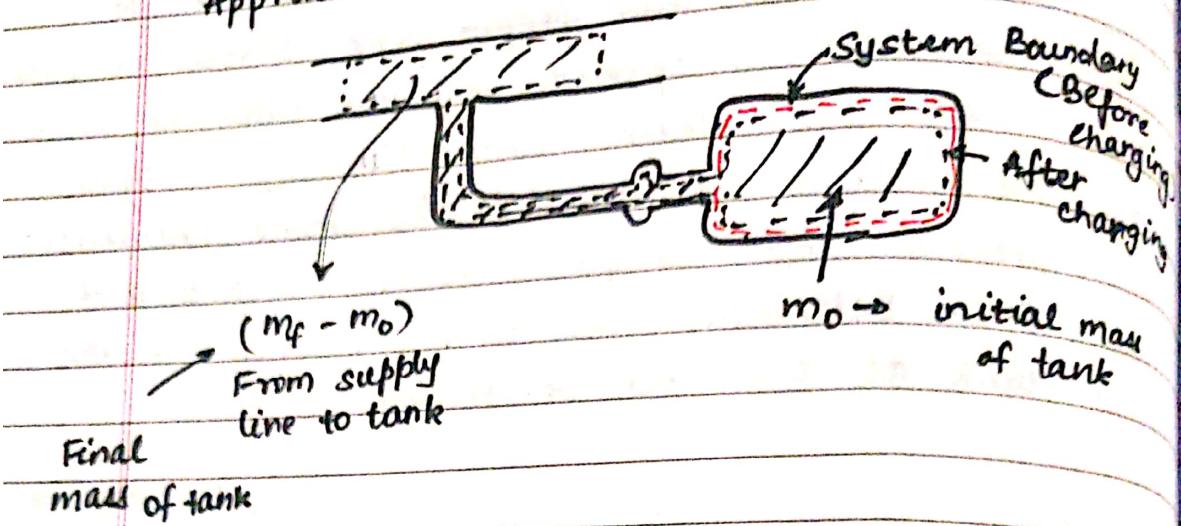
$$m_0 = 0 \Rightarrow u_f = h_{\text{supply}} = 3467.2 \text{ kJ/kg}$$

$$P = 20 \text{ bar}$$

$$\begin{array}{c} u_1 \\ \xrightarrow{T_1} \\ u_2 \end{array} \quad \begin{array}{c} T_2 \\ \xrightarrow{T_f} \\ T_1 \end{array}$$

$$T_f = \left(\frac{u_2 - u_1}{T_2 - T_1} \right) (u_f - u_1) + T$$

Transient flow Analysis (Control Mass Approach)



→ System boundary is shrinking

$$\dot{V}_i = (m_f - m_0) v_{\text{supply}} + \text{Tank Vol.}$$

$$\dot{V} = \text{Tank Vol.}$$

$$W_{\text{by syst}} = \leftarrow (P_{\text{supply}} (m_f - m_0) \cancel{v_{\text{supply}}})$$

$$\Delta E = \delta Q^0 - \delta W$$

$$E_f - E_0 = - W_{\text{by sys}}$$

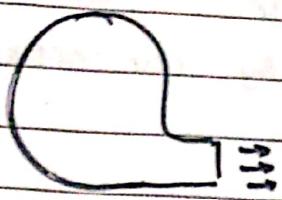
$$E_0 = u_0 m_0 + (m_f - m_0) u_{\text{supply}}$$

$$E_f = m_f u_f$$

$$m_f u_f - m_0 u_0 = (m_f - m_0) [u_s + P_s v_s]$$

$$m_f v_f - m_0 u_0 = (m_f - m_0) [h_{\text{supply}}]$$

Discharging of Tank



$$\frac{dE}{dt} = -m_e h_e$$

$$\frac{dm}{dt} = -m_e$$

$$E_f - E_0 = \int_0^t m_e h_e dt$$

$$m_f u_f - m_0 u_0 = - \int_0^t m_e h_e dt$$

For ideal gas, $h = c_p T$

$$m_f c_p T_f - m_0 c_p T_0 = - \int_0^t c_p T m_e dt$$



$$\frac{T_f}{T_0} = \left(\frac{m_f}{m_0} \right)^{r-1}$$

Second law of Thermodynamics

→ Quality of energy: potential to do work.

$$E = E_{useful} + E_{useless}$$

can be determined by

extracting work from system
quasi-statically

- A gas at higher pressure has more capacity to do work as compared to low temp.
- Work can be completely converted heat

Generation of Entropy $(ds) \propto dE - dE_{AV}$

For an isolated system, the quality of energy never remains conserved, it always degrades

$$dE_A \approx 0$$

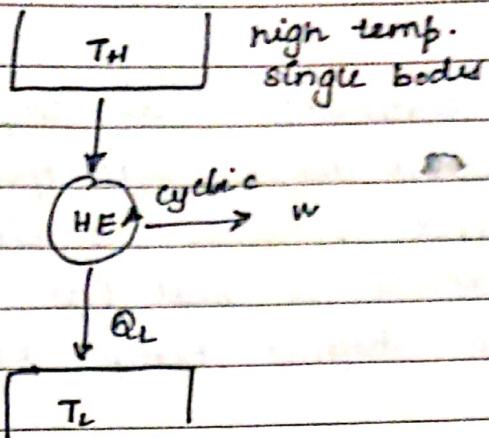
$$ds \propto dE - dE_{AV}$$

$$ds = C(dE - dE_{AV})$$

For isolated system : $dE = 0$ (first law)

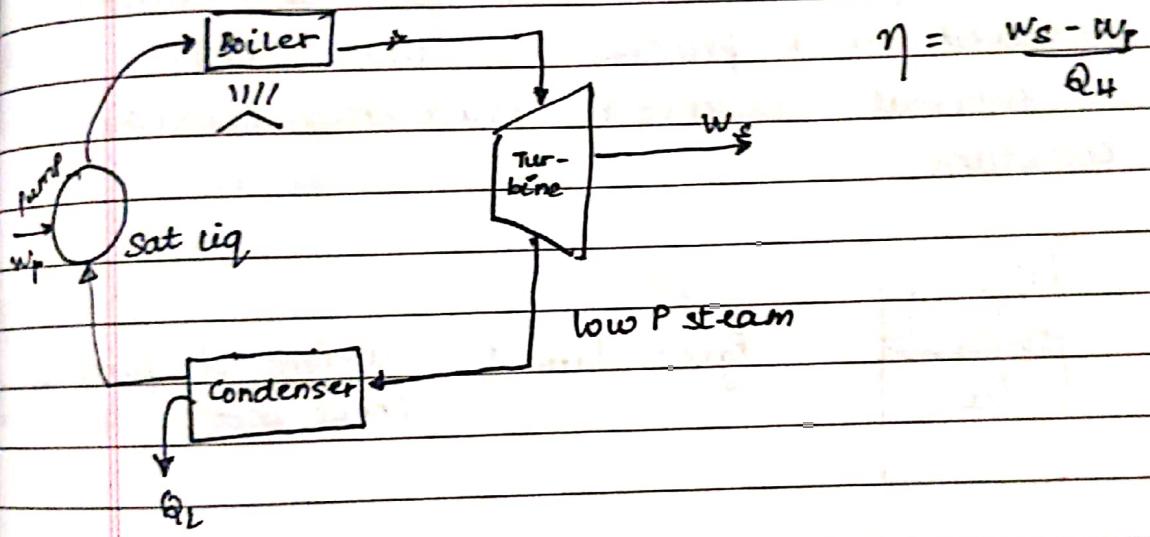
$$\Delta S_{uni} \geq 0$$

Heat Engine



Thermal Power Plant

Compressed steam



$$\eta = \frac{w_s - w_p}{Q_H}$$

$$\eta_{H.E} = \frac{w_c}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

Karvin Planck's statement

It's impossible for any device that operates in a cycle to receive heat from single reservoir and produce a net amt. of work

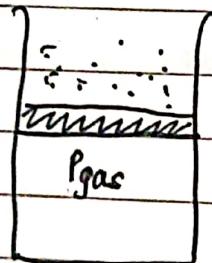
→ Impossible to construct a cyclically operating device such that it produces no other effect than the absorption of heat energy from a single thermal reservoir & perform an eq.

amount of useful work.

Claussius Statement - It's impossible to construct a device that operates in a cycle and produces no effect than the transfer of heat from a lower-temp body to higher temp. body

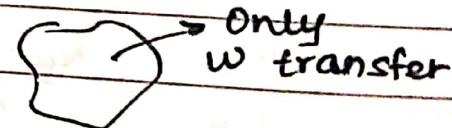
Thermal reservoir :

A body of very large heat capacity as compared to amount of heat transfer involved in a process so that temp. of thermal reservoir practically remains constant



$$P_{\text{gas}} = P_{\text{atm}} + \frac{\text{Weight of particle}}{\text{cross section of piston}}$$

Work Reservoir



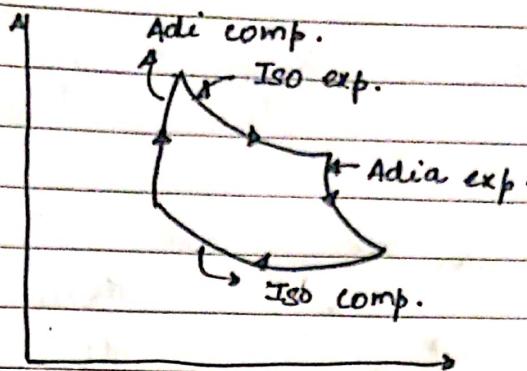
Lost / unavailable energy
 $\hookrightarrow S$

to

Carnot Cycle

$$-\frac{Q_L}{T_L} + \frac{Q_H}{T_H} = 0$$

Rev. HE



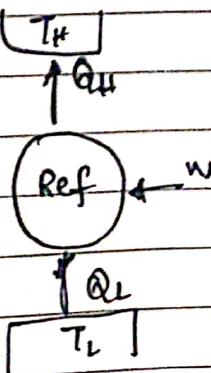
→ All heat engines b/w two heat reservoirs are less efficient than carnot cycle

→ Carnot cycle must operate b/w pair of heat reservoirs.

$$\eta = 1 - \frac{Q_L}{Q_H}$$

$$= 1 - \frac{T_L}{T_H}$$

Refrigerator



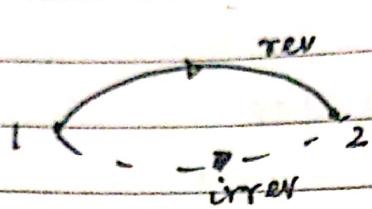
$$COP = \frac{Q_L}{W}$$

Internal irreversibility

$$dS_{sys} \xrightarrow{?} \frac{dQ_{sys}}{T_{sys}}$$

$$dS_{sys} = \frac{\delta Q_{sys}}{T} + \dot{S}_G$$

\uparrow Entropy creation



$$\begin{aligned} dQ_{rev} &= dE + dW_{rev} & (1) \\ dQ_{irrev} &= dE + dW_{irrev} & (4) \end{aligned}$$

$$dS_{sys} = \frac{\delta Q_{rev}}{T_{sys}} - (2)$$

$$dS_{sys} = \frac{\delta Q_{irrev}}{T} + d\dot{S}_G - (3)$$

$$\delta Q_r - \delta Q_{irr} = d(W_{rev} - W_{irr})$$

$$TdS - (dS - d\dot{S}_G)_T = d(W_{rev} - W_{irrev})$$

$$Td\dot{S}_G = d(W_{rev} - W_{irrev}) \quad \xrightarrow{\text{irreversibility}}$$

$$dI = T d\dot{S}_G$$

Flow process (open system)

$$dS = \frac{dQ}{T} + d\dot{S}_A + \dot{S}_{in} dm_{in} - \dot{S}_{out} dm_{out}$$

$$d\dot{S}_A = dS + \dot{S}_{out} dm_{out} - \dot{S}_{in} dm_{in} - \frac{dQ}{T} \geq 0$$

$$d\dot{S}_A = \frac{dS}{dt} + \dot{S}_{out} \frac{dm_{out}}{dt} - \dot{S}_{in} \frac{dm_{in}}{dt} - \frac{\dot{Q}}{T} \geq 0$$

$$\Rightarrow \Delta \dot{S}_A = \sum_{out} \dot{m} s - \sum_{in} \dot{m} s - \sum \frac{\dot{Q}_k}{T_k} \geq 0$$

If process is rev. and adiabatic

$$\sum_{out} \dot{m} s_{out} = \sum_{in} \dot{m} s_{in}$$

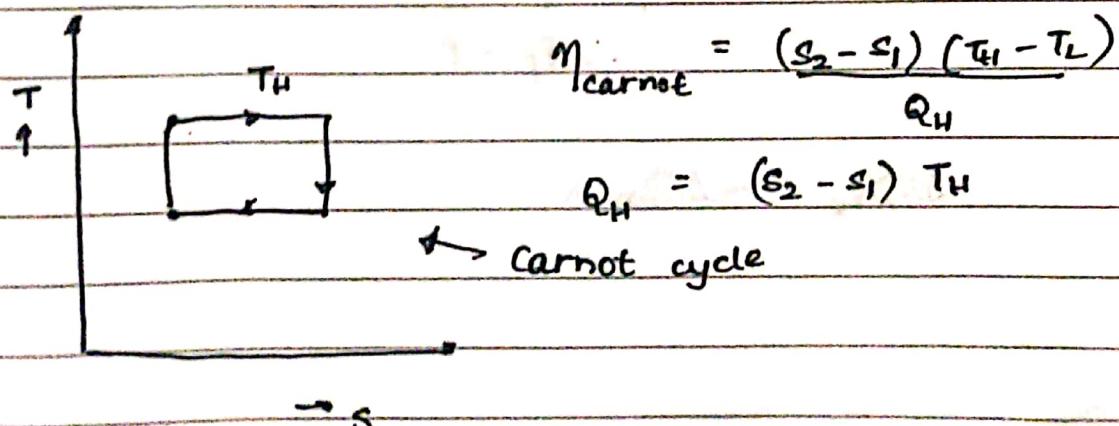
$$\dot{T} = T \dot{S}_A$$

$$\Delta S_{univ} = \Delta S_{hot} + \Delta S_{cold}$$

$$= -\frac{Q}{T_H} + \frac{Q}{T_L}$$

$$= Q \left(\frac{1}{T_L} - \frac{1}{T_H} \right)$$

$$\therefore \Delta S_{univ} > 0, T_H > T_L$$



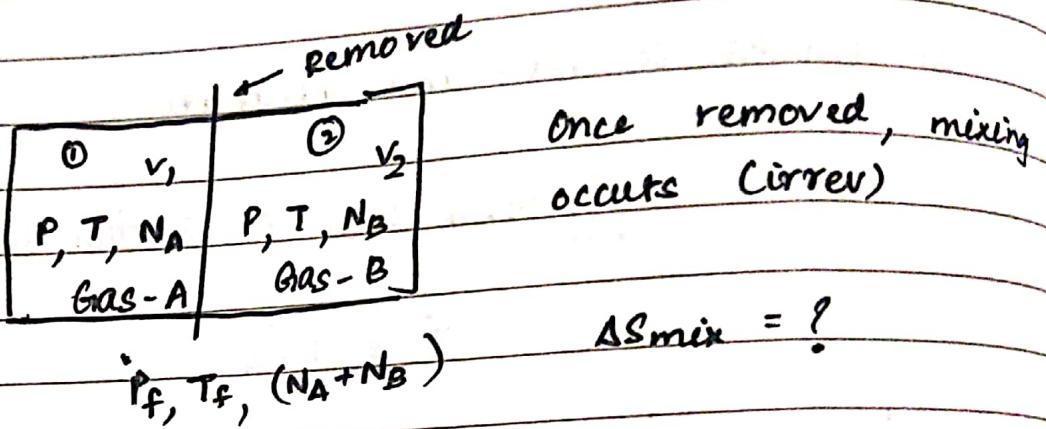
$$\Delta S_{\text{univ}} = 0$$

$$\Delta S_{H_2} + \Delta S_{H_2} + \Delta S_{H-E} = 0$$

$$-\frac{Q_H}{T_H} + \frac{Q_L}{T_C} = 0$$

$$\frac{Q_H}{T_H} = \frac{Q_L}{T_C}$$

$$\eta = \frac{W}{Q_H} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H}$$



$$P(v_1 + v_2) = (N_A + N_B) RT$$

$$P_f(v_1 + v_2) = (N_A + N_B) R T_f$$

$$\frac{P}{P_f} = \frac{T}{T_f}$$

$$n_C v (T_f - T) + n_C v (T_f - T) = 0$$

$$\Rightarrow T_f = T$$

$$\therefore P_f = P$$

$$\Delta S_{\text{max}} = -\Delta S_{\text{univ}} =$$

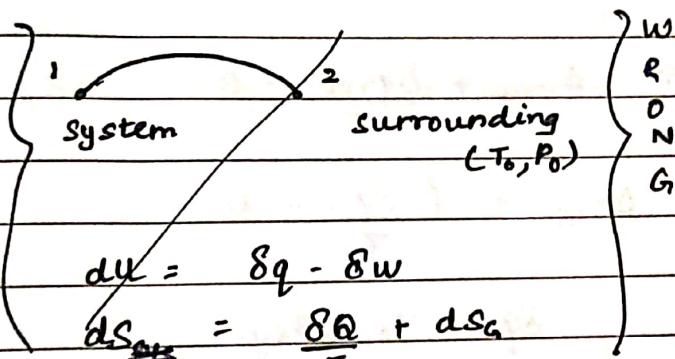
$$\Delta S = \int \frac{dh}{T} - \int v \frac{dp}{T}$$

$$= \int c_p \frac{dT}{T} - \int v \frac{dp}{T}$$

$$\Delta S_{\text{mix}} = - (N_A R \ln Y_A + N_B R \ln Y_B)$$

$$\Delta S_{\text{mix}} > 0 \quad \uparrow \text{irrev}$$

$$dS = \frac{dq_{\text{rev}}}{T}$$

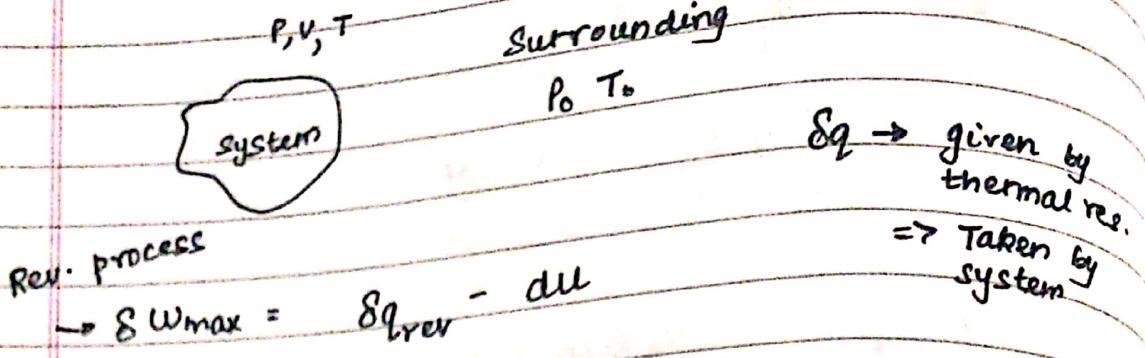


$$dS \stackrel{?}{=} \frac{dq}{T}$$

$$dS = \frac{dq_{\text{sys}}}{T} + dS_0$$

$$\Delta S_0 \geq 0$$

$$\Delta S_0 + \Delta S_{\text{sur}} \geq 0$$



From second law, $\Delta q_{rev} = T dS$

$$\Delta S_{univ} = \Delta S_{sys} + \Delta S_{surr}$$

Process is rev,

$$\Rightarrow \Delta S_{sys} + \frac{\Delta q_{rev}}{T} = 0$$

$$\Delta S_{sys} + \frac{(-\Delta q)}{T} = 0$$

$$\Delta q = T_0 \Delta S_{sys}$$

$$\Delta W_{max} = T_0 \Delta S_{sys} - dU$$

$$\therefore W_{max} = T_0 (S_0 - S) - (U_0 - U)$$

$$W_{max,useful} = W_{max} - \text{Boundary work} \\ (\text{Against surr} \\ \text{PV work})$$

$$= T_0 (S_0 - S) - (U_0 - U) - P_0 (V_0 - V)$$

↓ EXERGY

$$X E_x = (U + P_0 V - T_0 S) - (U_0 + P_0 V_0 - T_0 S_0)$$

$$\text{Availability } (\phi) = (U + P_0 V - T_0 S) - (U_0 + P_0 V_0 + T_0 S_0)$$

$$\Delta S_{\text{U}} \geq 0$$

$$\Delta S_0 + \Delta S_{\text{U}} \geq 0$$

$$\Delta S_{\text{C}} + \frac{-\dot{Q}_0}{T_0} \geq 0$$

$$T_0 dS_{\text{sys}} \geq \dot{Q}_0$$

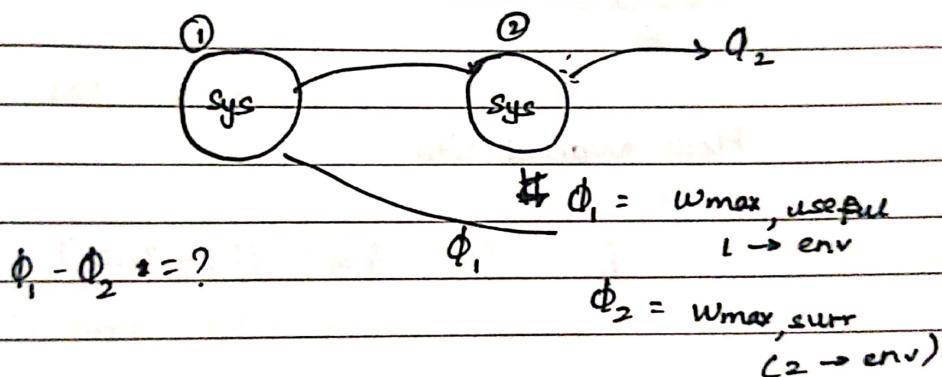
$$\dot{W}_{\text{U}} = \dot{Q}_0 - dU$$

$$W_{\text{by sys}} = \dot{Q} - (v_f - v_i) = T \Delta S_{\text{sys}} - (v_f - v_i)$$

$$W_{\text{useful,max}} = W_{\text{max}} - P_0(v_f - v)$$

$$= T_0(s_f - s) - (v_f - v) - P_0(v_f - v)$$

(*) Exergy = $(v_f + P_0 v_f - T_0 s_f) - (v_i + P_0 v_i - T_0 s_i)$



$$\Phi_1 - \Phi_2 = (v_f + P_0 v_f - T_0 s_f) - (v_i + P_0 v_i - T_0 s_i)$$

Flow exergy (availability)

$$(h_e + \frac{V_e^2}{2} + g z_e) - (h_i + \frac{V_i^2}{2} + g z_i) = \frac{\dot{Q} - \dot{W}_s}{m}$$

↑ First law

$\Delta K \cdot E \approx 0$

$\Delta P \cdot E \approx 0$

$$h_e - h_i = \frac{\dot{Q} - \dot{W}_s}{m}$$

$$\therefore \dot{W}_s = \dot{Q} - m(h_e - h_i)$$

$$\dot{w}_{s,\max} = ?$$

$$\dot{w}_{s,\max} = \dot{Q} - m(h_0 - h_1)$$

$$\Delta s \geq \Delta s_{sys} + \Delta s_{sur} \geq 0$$

$$\geq \Delta s_{sys} + \frac{(-\dot{Q})}{T_0} \geq 0$$

$$\Delta s \geq m(s_0 - s_1) - \frac{\dot{Q}}{T_0} \geq 0$$

$$T_0 m (s_0 - s_1) \geq \dot{Q}$$

$$\dot{w}_{s,\max} = T_0 m (s_0 - s_1) - m(h_0 - h_1)$$

$$\frac{\dot{w}_{\max,s}}{m} = (h_1 - T_0 s_1) - (h_0 - T_0 s_0)$$

Flow availability

$$\dot{w}_1 = (h_1 - T_0 s_1) - (h_0 - T_0 s_0)$$

$$\frac{\dot{w}_1 - \dot{w}_2}{\text{max useful work / max}} = (h_1 - T_0 s_1) - (h_2 - T_0 s_2)$$

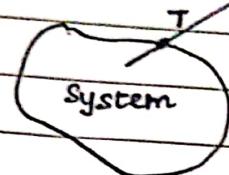
Always $\dot{w}_{rev} < \dot{w}_{irrev}$.

$$dU = \delta q - \delta W$$

$$\Delta S_U = \Delta S_S + \Delta S_{Sur} \geq 0$$

$$ds = \frac{\delta q}{T_0} + dS_a$$

$$dU - T_0 ds = -\delta q + T_0 dS_a$$



surrounding (reservoir)
(T_0, P_0)

heat reservoir

$$dS_{sys} = \left(\frac{\delta Q}{T} + dS_a \right)$$

Quasi-static $\rightarrow \int P dv$

can't say internally rev.

Only when $S_a = 0$

Thermal Reservoir

Rev. $\Delta S_{univ} = S_a = 0$

Irrrev $\Delta S_{univ} = S_a > 0$