AE 223 -

Thermodynamics -

- pressure, work, vol of a gas → energy
- energy conversion (KE, PE, Int E...)
- Energy stored → Mech work → Drive mechanics (steam engine)
- energy conversion devices → working fluid.
- LTD: Quantify properties & energy.

E.g. - engines (fuel - mech work)
- power generation (PE → elec)
- Appliances (Elec — heat/freeze)
- Supersonic/Hypersonic flow (KE ⇄ Heat)
- nature (clouds, Human body ...)

Internal Combustion Engine -

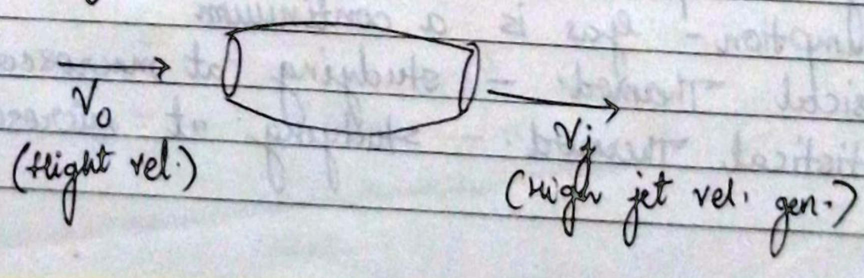
Compression i) circular motion of crank shaft is used to drive the piston (compress (air) → increase P, T)

Combustion ii) Inject fuel at high P, T → Ignite (combustion) Results to Highly Energetic Gas

Expansion iii) Push piston out → Generate work which drives machine → Low P, T (Expansion)

- common engines in automobiles, small aircrafts, boats, lawn mover

Turbo - jet engine -



only if pressure is const / mass of air/sec.

↳ Thrust $= \dot{m}(V_j - V_0)$ — (Δ in momentum)

(Air path in Turbo-jet engine)

Intake → Compressor → Combustor → Turbine → Nozel

(Generates power)

Fuel

Actual Thrust $= \dot{m}(V_j - V_0) + (1+\varepsilon)(p_j - p_0) A_j$

Gas Turbine -

- Flow through device: Compressor, combustor, Turbine (expansion)

↳ Represent three basic steps in 3 diff. components

(FLTD used) Chem. energy (fuel) → KE of jet (Thrust)

↓

Thermal energy of jet

(Hot exhaust (waste))

(SLTD used) Minimize waste ⟷ ~~Maximise thrust~~

System & Properties :-

Gas in the cylinder — system → Energy.

piston / cylinder — surrounding

(Heat/work) Energy exchanges — Boundary [no mass transfer]

- Closed system has fixed mass.
- change shape, move
- Assumption - Gas is a continuum
- Classical Thermod. — studying at macroscopic level
- Statistical Thermod. - studying at microscopic level.

Ideal Gas Law :-

$$PV = nRT \quad — \quad R = 8314\ J/K \cdot kmol$$
$$P = \rho RT \quad — \quad R = 287.1\ J/kg \cdot K$$

Assump - Air is a perfect gas (calorically)

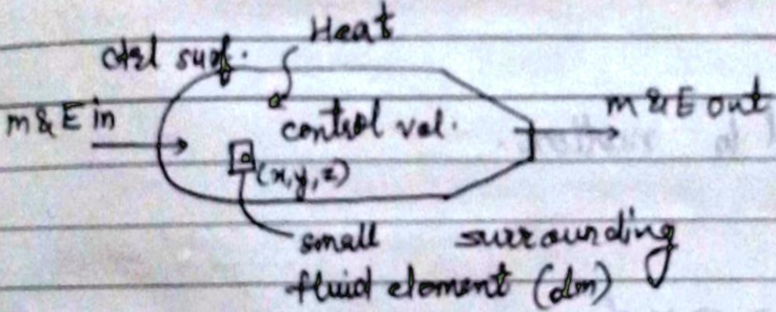
$$C_v = \frac{R}{\gamma - 1}, \quad C_p = \frac{\gamma R}{\gamma - 1},$$

$$C_p - C_v = R \quad \& \quad \gamma = \frac{C_p}{C_v} = \frac{n}{n+2} \quad \frac{n+2}{n} \quad \frac{f+2}{f}$$

For air :- $\gamma = 1.4$ — normal P, T
$\gamma = 1.3$ — high T

$$\left.\begin{aligned} U &= mC_vT \\ H &= U + d(PV) = mC_pT \end{aligned}\right\} C_v, C_p - \text{const.}$$

Control volume :-



ctrl. surf :- E exchange + m exchange
ctrl. vol :- open system (can be part/whole engine)

Thermod. properties → $P(x,y,z,t)$, $T(x,y,z,t)$, etc.

$$U_{cv} = \int_{cv} C_v T(x,y,z,t)\, dm$$

Specific properties → per unit mass

$$u = C_vT = U/m$$
$$h = C_pT = H/m$$
$$v = V/m = 1/\rho$$

Thermodynamic eqbm → System ⟶ IC engine → $f(t) \nRightarrow f(x,y,z)$
ctrl. vol ⟶ Gas Turbine engine → $f(x,y,z) \nRightarrow f(t)$

During steady state operation,

$$\underset{\text{(mass flow rt.)}}{\dot{m}} = \rho A v \quad \text{— (const. in time)}$$

Work interactions :-

$$\text{sys / CV} \xleftrightarrow{\text{E exchange}} \text{surr.}$$

- Path func^n :-

$$W_{1-2} = \int_1^2 P\,dV \quad \text{— (depends on path)}$$

area under the curve

- Point func^n :- P V T . . . independent of path.
(define state of system)

- shaft work :-

$$W_{shaft} = \tau\theta$$

$$P_{shaft} = \dot{W}_{shaft} = \tau\omega \text{ — (rpm or rad/s)}$$

- Flow work :-
W by fluid in motion.

$$dW = P_1\,dV_1$$

$$v = dV_1/dm_1$$

$$\therefore dW = P_1 v_1\,dm_1$$

$$W_{flow} = \frac{dW_{flow}}{dm_1} = P_1 v_1$$

$$\dot{W}_{flow} = \frac{dW_{flow}}{dt} = P_1 v_1 \frac{dm_1}{dt} = P_1 v_1 \dot{m}_1$$

- sign convention :-
W by sys. on surr. → +ve

Heat interactions :-

E exchange due to temp. diff

Heat – Energy in transit

3 modes – conduction, convection & Radiation.

– Heat add^n by combustion.

- Conduction -
  - Heat transfer due to molecular collision
  - Requires a medium (Stationary)

- Fourier's law of cond^n :-

Heat flux $= \frac{Q}{tA}$

$$\dot{q} = -K \frac{dT}{dx}$$

conductivity of medium

- Convection :-
  - Heat transfer due to bulk motion of medium.
  - Medium is moving.
  - Local cond^n + driven by flow
  - Faster than cond^n.

- Newton's law of cooling :-

$$\dot{q}_{conv} = h_{conv} (T_{Hot} - T_{cool})$$

conv. heat transfer coeff.
(depends on medium & flow geometry)

$$h_{conv.} = Nu \cdot \frac{K}{D}$$

D – size/diameter of coolant

Nu – nusselt no.

- Radiation -
    - Heat transfer due to EM waves
    - No medium req.
- Stefan- Boltzmann law:-

$$\dot{q}_{rad} = \varepsilon \sigma T^4$$

$\sigma \to 5.76 \times 10^{-8}\ W/m^2K^4$ (S.B. const)

$\varepsilon \to$ emissivity

- Heat add^n by combu^n :-

Fuel + air $\longrightarrow$ comb^n products + Q

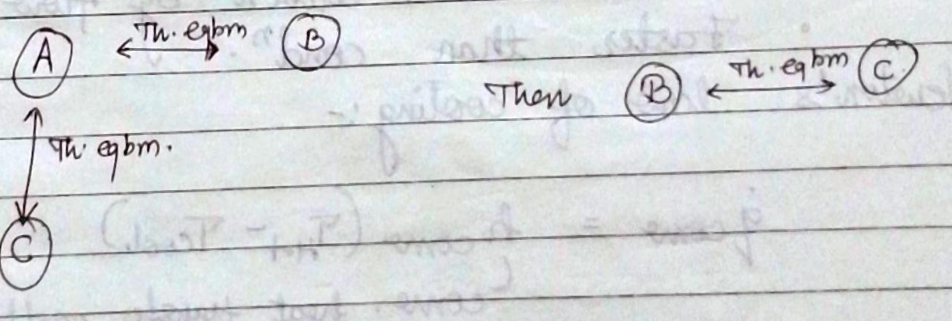
$\cancel{Q_{reac}}$ $\Rightarrow$ $m_{fuel}\, Q_{reac} \rightarrow$ [J/kg]

$$Q = m_{fuel}\, Q_{reac} \quad (sys.)$$

$$\dot{Q} = \dot{m}_{fuel}\, Q_{reac} \quad (CV)$$

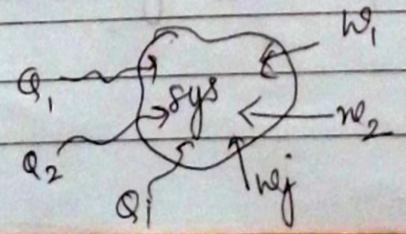
- Neglect fuel mass (change in it)

Zeroth Law of Thermd:-



Zeroth law conserves energy.

First Law :-



$$\sum_i Q_i - \sum_j W_j = \Delta E_{sys} - (\Delta KE + \Delta PE + \Delta U)$$

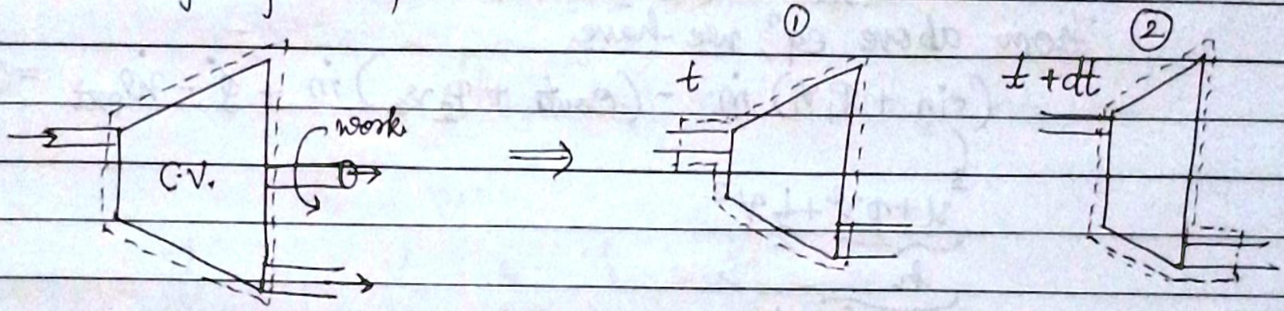
For the system at rest,

$$Q - W = \Delta U$$

Cyclic process :- $\Delta E = 0$ — (pt. func.)

$$\oint dQ = \oint dW$$

First law for flow process :-



$$Q - W = \Delta E = \Delta \cancel{P}E + \Delta KE + \Delta U$$

$$\Delta E = E(t+dt) - E(t)$$

$$= E_{C.V.} + \Delta E_{C.V} + E_{exit} - E_{C.V.} - E_{entry}$$

$$Q - W + E_{entry} - E_{exit} = \Delta E_{C.V.}$$

$$\frac{dQ}{dt} - \frac{dW}{dt} + \frac{dE_{in}}{dt} - \frac{dE_{out}}{dt} = \frac{dE_{CV}}{dt}$$

$$\dot{Q} - \dot{W} + \dot{E}_{in} - \dot{E}_{out} = \frac{dE_{CV}}{dt}$$

$$\dot{E}_{in} = e_{in} \dot{m}_{in}, \quad \dot{E}_{out} = e_{out} \dot{m}_{out}$$

$$\dot{Q} - \dot{W} + e_{in} \dot{m}_{in} - e_{out} \dot{m}_{out} = \frac{dE_{CV}}{dt}$$

For steady state, $\frac{dE_{CV}}{dt} = 0$ & $\dot{m}_{in} = \dot{m}_{out} = \dot{m}$.

$$\therefore \quad \dot{Q} - \dot{W} + (e_{in} - e_{out})\,\dot{m} = 0$$

Total Enthalpy :-

In the case of CV,

W = Flow work + Ext. work — (shaft work)

$$dW = dW_{ext} + \underbrace{P_2 v_2}_{\text{Lower case}} dm - P_1 \underbrace{v_1}_{\text{Lower case}} dm$$

$$\dot{W} = \dot{W}_{ext} + (P_2 v_2 - P_1 v_1)\,\dot{m}$$

From above eq^n, we have

$$(e_{in} + P_1 v_1)\,\dot{m} - (e_{out} + P_2 v_2)\,\dot{m} + \dot{Q} - \dot{W}_{ext} = 0$$

$$\underbrace{\underbrace{u + pv}_{h} + \frac{1}{2}V^2}_{h_{Total}}$$

$$\therefore \quad h_t = h + \frac{1}{2}V^2$$

$$\therefore \quad \dot{m}\,(h_{t_{out}} - h_{t_{in}}) = \dot{Q} - \dot{W}_{ext}$$

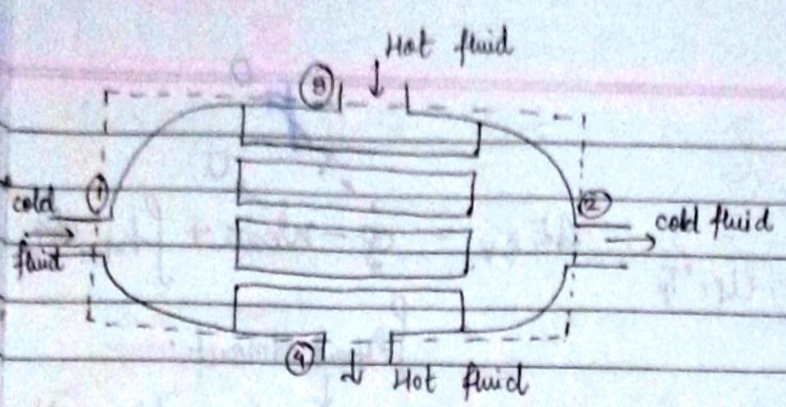
When there's no heat transfer,

$$h_{t_1} = h_{t_2}$$

$$\therefore \quad h_1 - h_2 = \frac{1}{2}(V_2^2 - V_1^2)$$

Heat exchanger :-

Used for both heating or cooling a fluid.



$$\sum_{exit} h_{t,e}\dot{m}_e - \sum_{inlet} h_{t,i}\dot{m}_i = \dot{Q} - \dot{W}_{ext}$$

no heat exchange

no external work

& $\dot{m}_1 = \dot{m}_2 = \dot{m}_c$

$\dot{m}_3 = \dot{m}_4 = \dot{m}_h$

$$\therefore h_{t_4}\dot{m}_4 + h_{t_2}\dot{m}_2 - h_{t_3}\dot{m}_3 - h_{t_1}\dot{m}_1 = 0$$

$$\therefore (h_{t_3} - h_{t_4})\dot{m}_h = (h_{t_2} - h_{t_1})\dot{m}_c$$

$$\dot{m} = \rho A V.$$

If $V_1 \simeq V_2$ & $V_3 \simeq V_4$

then $(h_3 - h_4)\dot{m}_h = (h_2 - h_1)\dot{m}_c$

If the KE & PE are very small compared to the U & H,

then $\dot{m}_h c_{p,h}(T_3 - T_4) = \dot{m}_c c_{p,c}(T_2 - T_1)$

First law for unsteady processes:-

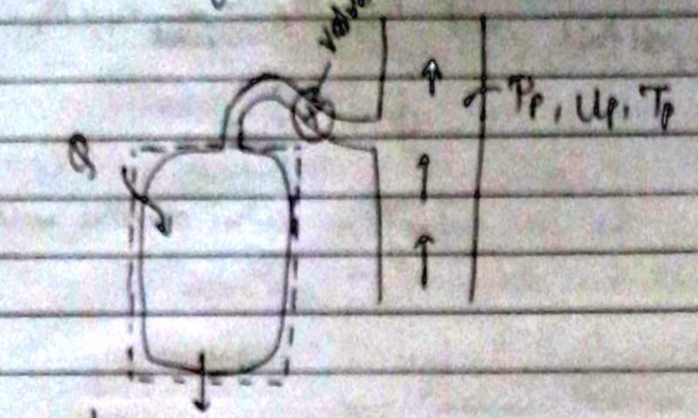
$$\frac{dE_{cv}}{dt} = \dot{Q} - \dot{W}_{ext} + h_{t,in}\dot{m}_{in} - h_{t,out}\dot{m}_{out}$$

Also, mass is changing with time,

$$\therefore \frac{dm_{cv}}{dt} = \dot{m}_{in} - \dot{m}_{out}$$

$$\therefore \Delta E_{cv} = Q - W_{ext} + \int h_{t,in}\, dm_{in} - \int h_{t,out}\, dm_{out}$$

Bottle filling example :-



$$\Delta E_{CV} = \overset{0}{\dot{Q}} - \overset{0}{\dot{W}_{ext}} + \int h_{p,in}\, dm_p - \int h_{out}\, dm_{out}.$$

we are only tracking all incoming fluid.

t_1: m_1, P_1 ... $E_{CV} = E_1 = m_1 u_1$

t_2: m_2, P_2 ... $E_2 = m_2 u_2$

$\therefore \Delta E_{CV} = m_2 u_2 - m_1 u_1$

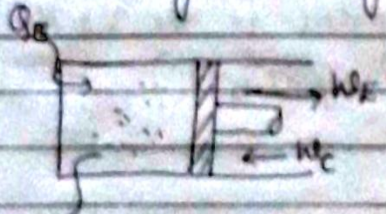
$\therefore \int h_{in}\, dm_{in} = (m_2 - m_1)\left(u_p + P_p v_p + \frac{V_p^2}{2}\right)$

Second law :-

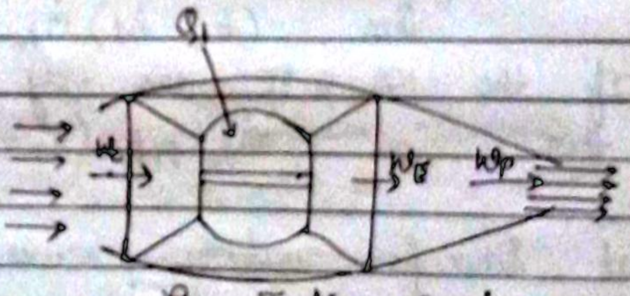
$W \Rightarrow Q$

$Q \geq W$.

Heat Engine → Cycle

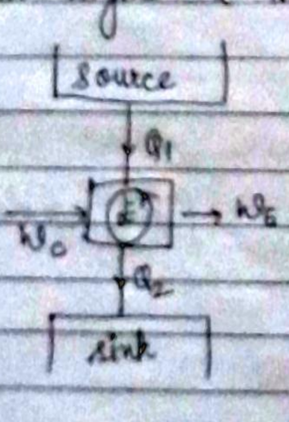


Piston-cylinder



Gas-Turbine Engine

Heat Engine & Heat Pump :-



$Q_1 - Q_2 = \Delta U + W_E - W_C + W_P$

For cyclic process, $\Delta U = 0$.

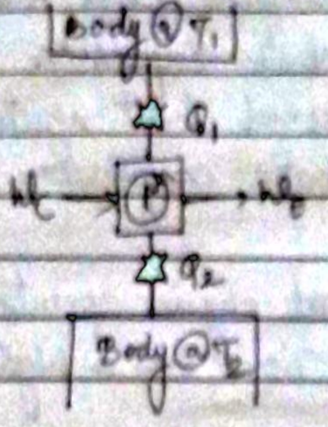
$Q_1 - Q_2 = W_{net} > 0$

[All Q's & W's are only MAGNITUDES]

Efficiency: $\eta = \frac{W_{net}}{Q_1} = 1 - \frac{Q_2}{Q_1}$

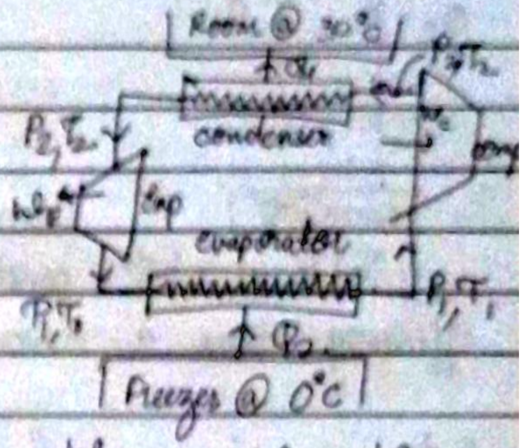
For heat pump, $Q_2 \to T_2$ & $Q_1 \to T_1$ & $T_1 > T_2$

Take up   Deliver



$W_C > W_E$

Refrigerator,



$$-Q_1 + Q_2 = \Delta U + W_E - W_C \quad , W_C > W_E$$

$$W_{net} = W_C - W_E > 0$$

$$\therefore Q_1 - Q_2 = W_{net} \quad - (\Delta U = 0)$$

Co-eff. of Performance (COP):- $\frac{Q_1}{W_{net}} = \frac{Q_1}{Q_1 - Q_2}$,

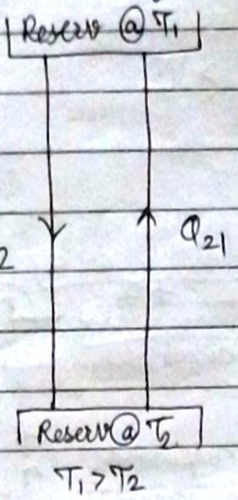
COP > 1

Kelvin-Planck : It's impossible for a heat engine to produce net work in a cycle, if it exchanges heat with bodies at a single fixed temp.

Clausius: Impossible to construct a cyclic device which'll produce no effect other than transferring heat from a cooler to hotter body.

Irreversibilities → Losses (friction, viscous, etc.)
→ finite ΔT, ΔP ...

Heat transfer across finite ΔT:-



Carnot cycle :-

Step 1: Reversible Isothermal Heat Add^n.

Step 2: Reversible Adiabatic Expansion

Step 3: Reversible isothermal heat rejection

Step 4:- Reversible adiabatic compression.

Carnot Theorem :- Of all heat engines operating bet^n const. temp. source & sink, None has a higher efficiency than a reversible engine.

Entropy :- $\oint \frac{dQ}{T} = 0$ — cycle

$\int \frac{dQ_{rev}}{T} = \Delta S$ — for a process (reversible)

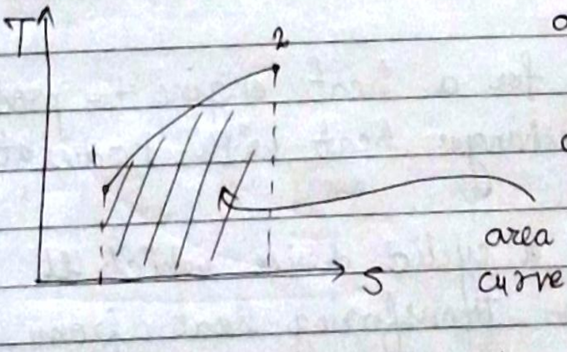
Two elementary process :- Rev. isothermal → T - const.

Rev. adiabatic → S - const.

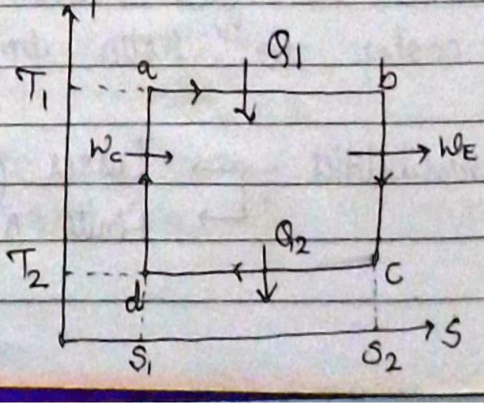
$$dS = \frac{dQ_{rev}}{T}$$

$$dQ_{rev} = dS\,T$$

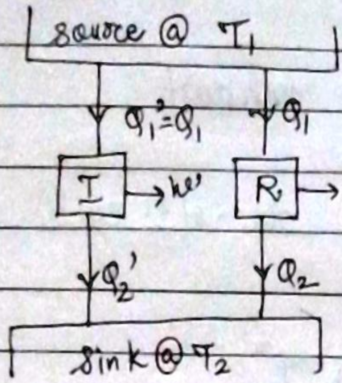
$$\therefore Q_{rev} = \int T\,dS$$



For Carnot cycle, T-S Diagram is



Entropy for irreversible process:-



For rev. process → $\frac{|Q_1|}{T_1} - \frac{|Q_2|}{T_2} = 0$

$$\sum_{\text{rev cyc.}} \frac{Q_i}{T_i} = 0$$

For irrev. process →

$$\frac{Q_1}{T_1} + \frac{Q_2'}{T_2} < 0 \quad - (\because Q_2' > Q_2,\ W_{net}' < W_{net},\ \eta_{irrev.} < \eta_{rev.})$$

$$\therefore \sum_{\text{irrev. cyc.}} \frac{Q_i}{T_i} < 0$$

$$dS = \frac{dQ_{rev.}}{T}$$

$$dS > \frac{dQ_{irrev.}}{T} = \frac{dQ}{T} + dS_{irrev.}$$

Gibb's equation -

$$dQ - dW = dU$$

$$dQ_{rev.} = T\,dS$$

$$dW = p\,dV \quad - (\text{displacement work})$$

$$T\,dS = dQ = dU + dW = dU + P\,dV$$

$$dH = dU + p\,dV + V\,dp$$

$$\therefore T\,dS = dH - V\,dp$$

$$dH = T\,dS + V\,dp$$

For ideal gas,

$$P = \rho R T$$

$$dh = c_p\,dT$$

$$\therefore ds = c_p \frac{dT}{T} - \frac{dp}{\rho T} = c_p \frac{dT}{T} - R\frac{dp}{P}$$

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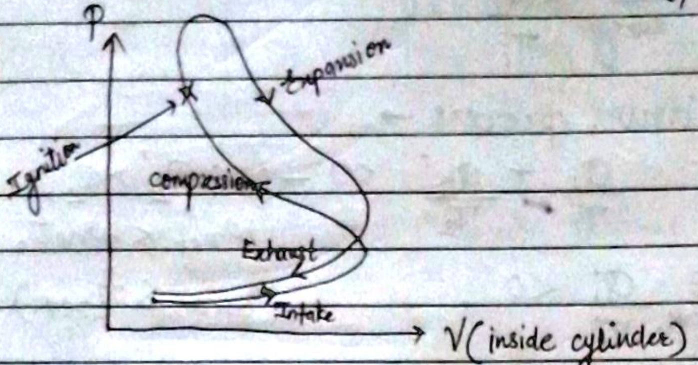
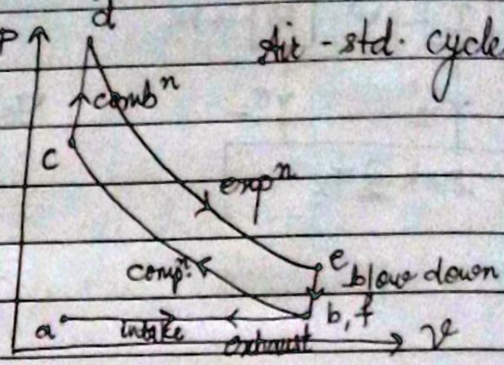
$$\therefore \; s_2 - s_1 = C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

Four-stroke Engine :-

Intake → compression → expansion (power stroke) → exhaust



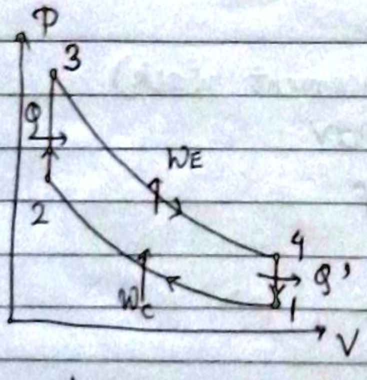
Real cycle

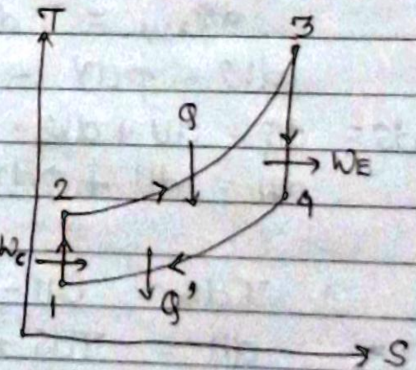


Ideal cycle
[otto cycle]

Assumption for ideal -

i) Air → perfect gas
ii) Combustion → Heat addⁿ @ const. vol. w/o change in property of working fluid
iii) Blow down step
iv) No intake - No exhaust





1 → 2 : Reversible Adiabatic compression
2 → 3 : Constant vol. Heat Addⁿ
3 → 4 : Reversible Adiabatic expansion
4 → 1 : Constant Vol. Heat Rejection

$$Q = mC_v(T_3 - T_2), \quad Q' = mC_v(T_4 - T_1)$$

$$\eta = 1 - \frac{Q'}{Q} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

Compression ratio, $r_k = \frac{v_1}{v_2} = \frac{V_1}{V_2}$

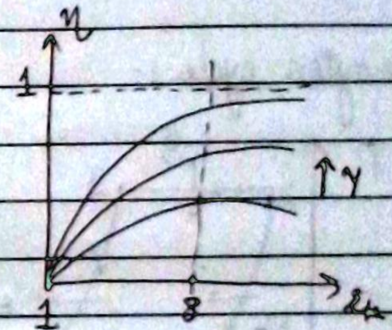
$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1}, \quad \frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{\gamma-1}$$

$$V_1 = V_4,\ V_3 = V_2 \Rightarrow \frac{T_2}{T_1} = \left(\frac{v_4}{v_3}\right)^{\gamma-1}$$

$$\therefore \frac{T_4}{T_3} = \frac{T_1}{T_2} \Rightarrow \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

$$\therefore \frac{T_4 - T_1}{T_3 - T_2} = \frac{T_1}{T_2}$$

$$\therefore \eta = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{r_k^{\gamma-1}}$$

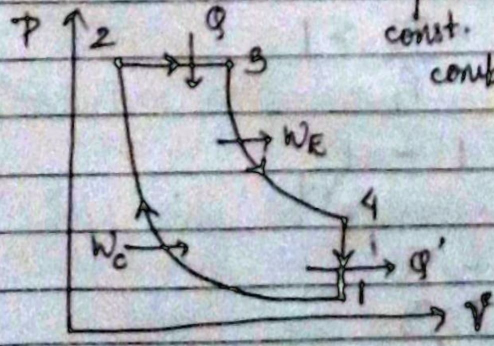


Diesel cycle:-

Compress only air $\longrightarrow$ Inject fuel $\longrightarrow$ Spontaneous comb^n

Compression Ignition (CI) & spark ignition (SI)

const. pressure comb^n



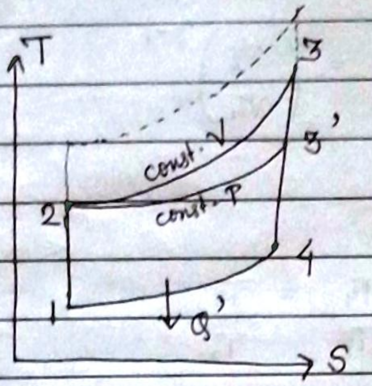
$$Q = mC_p(T_3 - T_2)$$

$$Q' = mC_v(T_4 - T_1)$$

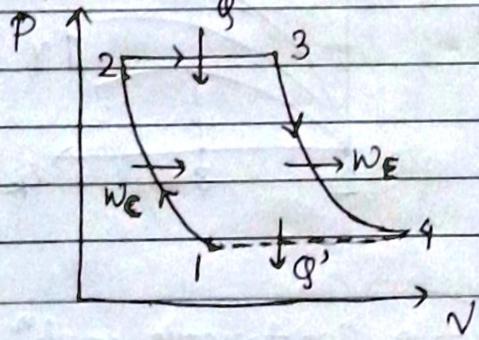
$$\eta = 1 - \frac{1}{\gamma}\left(\frac{T_4 - T_1}{T_3 - T_2}\right)$$

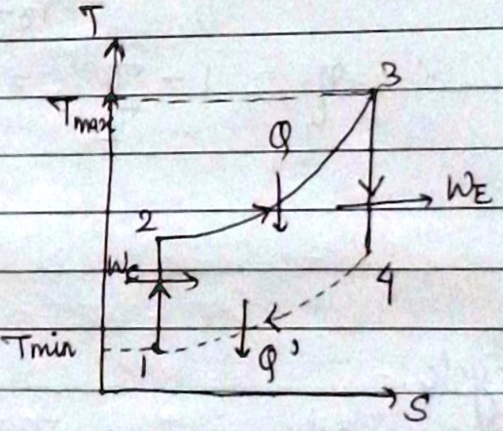
$r_k = \frac{v_1}{v_2}$, $r_e = \frac{v_4}{v_3}$, $r_c = \frac{v_3}{v_2}$ — (cut-off)

$$\eta = 1 - \frac{1}{r_k^{\gamma-1}}\left[\frac{1}{\gamma}\left(\frac{r_c^{\gamma-1} - 1}{r_c - 1}\right)\right]$$



Brayton cycle :-



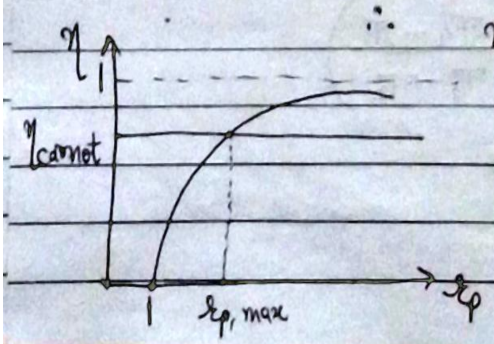


$Q = mC_p(T_3 - T_2)$

$Q' = mC_p(T_4 - T_1)$

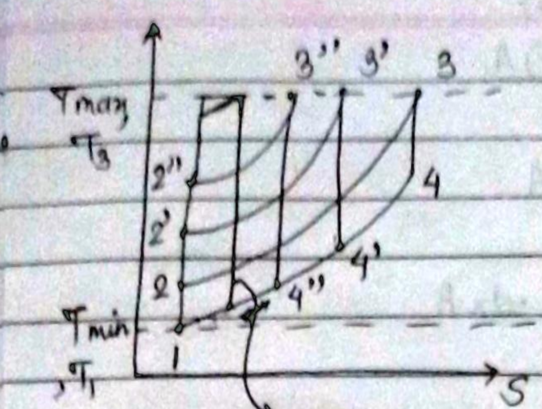
$\eta = 1 - \frac{Q'}{Q} = 1 - \left(\frac{T_4 - T_1}{T_3 - T_2}\right)$

Compressor pressure ratio : $r_p = \frac{P_2}{P_1} > 1$



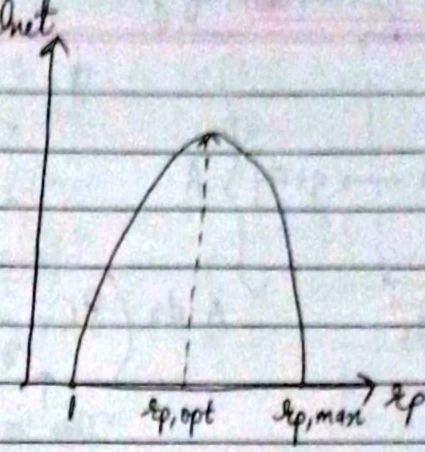
$\therefore \eta = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{r_p^{\gamma-1}}$

$\eta_{carnot} = 1 - \frac{T_1}{T_3}$



$\eta \to \eta_{carnot}$

$W_{net} \to 0$ - (as efficiency ↑)



$W_{net} = Q - Q'$

$= mC_p[(T_3-T_2)-(T_4-T_1)]$

$\frac{dW_{net}}{dr_p} = 0 \Rightarrow r_p^{\gamma-1/\gamma} = \sqrt{\frac{T_{max}}{T_{min}}}$

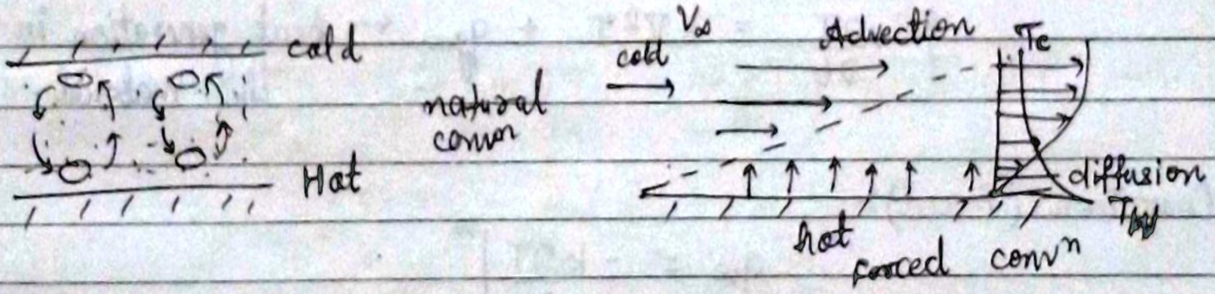
$$\eta_{opt} = 1 - \sqrt{\frac{T_{min}}{T_{max}}}$$

Heat Transfer -

Cond^n - Molecular motion in the medium

Conv^n - Bulk motion of the medium

Rad^n - E.M. waves (no medium req^d)



q =

Conduction eq^n:-

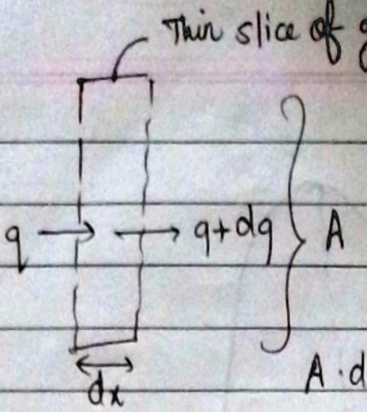
$Q - W = \Delta U$, $\dot{Q} = \frac{dU}{dt}$

For only heat transfers, $\dot{W} = 0$

/vol. $\to U = \rho C_v T$

$\frac{dU}{dt} = \rho C_v \frac{\partial T}{\partial t}$

If $q = -k\frac{\partial T}{\partial x}$ is the Heat flux (per unit time) then



$$\dot{g} = qA - (q+dq)A$$
$$= -dq \cdot A$$
$$= -\frac{\partial q}{\partial x}\, dx\, A$$

$$A \cdot dx \left(\rho C_v \frac{\partial T}{\partial t}\right) = -\frac{\partial q}{\partial x} \cdot dx\, A$$

This is per unit vol.

$$\therefore \rho C_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right)$$

$$\therefore \rho C_v \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}$$

In 3D :- Heat flux $\longrightarrow$ vector

$$\bar{q} = q_x \hat{i} + q_y \hat{j} + q_z \hat{k}$$
$$= -k\frac{\partial T}{\partial x}\hat{i} - k\frac{\partial T}{\partial y}\hat{j} - k\frac{\partial T}{\partial z}\hat{k}$$
$$= -k \bar{\nabla} T$$

$$\rho C_v \frac{\partial T}{\partial t} = k \nabla^2 T + q_{gen.}$$ $\leftarrow$ heat generation in the material.

Convection (Forced):-

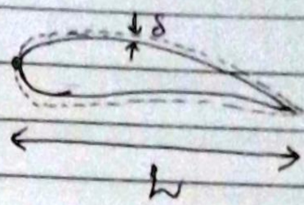
$$q_w = -k \frac{\partial T}{\partial y}\bigg|_0^w$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \overbrace{-\frac{1}{\rho}\frac{\partial p}{\partial x}}^{0} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)$$

$$\frac{\partial}{\partial x} << \frac{\partial}{\partial y}, \quad v << u, \quad u\frac{\partial u}{\partial x} \sim v\frac{\partial u}{\partial y}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2}$$



$$u\frac{\partial u}{\partial x} \sim V_\infty \cdot \frac{V_\infty}{L}$$

*

$$v\frac{\partial u}{\partial y} \sim V_\infty \frac{\delta}{L} \cdot \frac{V_\infty}{\delta} \sim \frac{V_\infty}{L^2}$$

$$u^* = \frac{u}{V_\infty}, \quad v^* = \frac{v}{\frac{V_\infty \delta}{L}}, \quad x^* = \frac{x}{L}, \quad y^* = \frac{y}{\delta}$$

$$\left(u^*\frac{\partial u^*}{\partial x^*} + v^*\frac{\partial u^*}{\partial y^*}\right) = \frac{1}{Re_L}\left(\frac{\partial^2 u^*}{\partial y^{*2}}\right), \quad Re_L = \frac{\rho_\infty V_\infty L}{\mu_\infty}$$

$$\tau_w = \mu\frac{\partial u}{\partial y}\Big|_w, \quad C_f = \frac{\tau_w}{\frac{1}{2}\rho_\infty V_\infty^2}$$ → skin-friction coeff

$$C_D = \frac{D}{\frac{1}{2}\rho_\infty V_\infty^2 S}$$

$$= \frac{2}{Re_L}\frac{\partial u^*}{\partial y^*}$$

convective HT :- $\rho C_p\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = k\frac{\partial^2 T}{\partial y^2}$

$$C_L, C_D = fn(Re_L)$$

$$T^* = \frac{T - T_w}{T_w - T_\infty} = \frac{T - T_w}{T_w - T_\infty}$$

$$\frac{V_\infty \rho_\infty C_p}{L}\left(u^*\frac{\partial T^*}{\partial x^*} + \cdots\right) = \frac{k}{L^2}\frac{\partial^2 T^*}{\partial y^{*2}}$$

$\alpha = \frac{k}{\rho C_p}$ = Thermal diffusivity. , $\frac{\nu}{V_\infty L} = \frac{1}{Re_L}$,

$\frac{\mu C_p}{k} = \left(\frac{\alpha}{\nu}\right)^{-1} = P_r$ = Prandtl No. $= 0.72$ for air

$$u^* \frac{\partial T^*}{\partial x^*} + \ldots\ldots = \frac{1}{P_r Re_L} \frac{\partial^2 T^*}{\partial y^2}$$

$$q_w = -k \frac{\partial T}{\partial y}\Big|_{y=0} = \frac{-k}{L} (T_\infty - T_w) \frac{\partial T^*}{\partial y^*}\Big|_{y^*=0}$$

$$= h (T_w - T_\infty)$$

$\uparrow$ convection coeff.

Nusselt no. $\rightarrow$ $Nu = \frac{hL}{k} = \frac{\partial T^*}{\partial y^*}\Big|_{y^*=0}$

$$Nu = fn(Re_L, P_r)$$

Laminar Boundary Layer on flat plate :-

Blasius profiles - $\quad Re_x = \frac{\rho_\infty V_\infty x}{\mu}$, $C_f = \frac{0.664}{\sqrt{Re_x}}$

$$Nu = \frac{hx}{k} = 0.332 \sqrt{Re_x}\, P_r^{1/3}$$

$$\text{Avg. } \overline{Nu}_L = \frac{\bar{h} L}{k}, \quad \bar{h} = \frac{1}{L} \int_0^L h(x)\, dx$$

$$\overline{Nu}_L = 0.664 \sqrt{Re_L}\, P_r^{1/3}$$

For turbulent flow, $\quad Nu = 0.0296\, Re_x^{4/5}\, P_r^{1/3}$

Turbulent pipe flow, $\quad Nu = \frac{(f/8)(Re - 1000) P_r}{1 + 12.7 (f/8)^{1/2} (P_r^{2/3} - 1)}$

$$f = [0.79 \ln Re - 1.64]^{-2}$$