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UNIT-I- Boiler & Its performance

Steam Generator / Boiler :→

A Boiler is a closed vessal in which water is heated, vaporised, and converted in to steam at a press. higher than the atmospheric pressure. The heat energy required for steam generation is produced by burning fuel in the furnace. generally coal is used as a fuel.

A Boiler is made up of ~~cone~~ steel in which chemical energy of fuel is converted in to heat energy and, these heat energy is utilised for heating the water and thus evaporated. & produce steam.

Applications / why it is needed :→

→ The heat content of steam is large and thus it is suitable for process heating (curing, drying etc) in many industries like sugar mills, Textiles industries, & chemical Industries.

→ Its also used for power generation in Thermal power plant.

→ Due to large heat content steam is used for cooking item liked steamed rice, idlies etc.

→ Steam can also be used for heating buildings. & producing hot water in winter.

→ Steam is also used for creation of vaccum, ejection of gases & sterlisation.

→ Steam is also used for Refrigeration System. (steam jet Refrigeration System).

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Classification:→

1) Depending upon the Relative position of water & flue gases:→
   a) Fire Tube Boiler
   b) Water Tube Boiler

2) Depending upon the position of furnace
   a) Internally fired
   b) Externally fired

3) Depending upon the position of Axis of Boiler
   a) Horizontal Boiler
   b) Vertical Boiler

4) Depending upon the fuel used.
   a) Solid   b) Liquid   c) Gaseous

5) Depending on the Service
   a) Stationary   b) Portable

6) Accd to Steam press. Generated
   a) Low press.   b) High press.

7) Accd to the method of water circulation.
   a) Natural Circulation
   b) Forced Circulation

8) Accd to the fuel feeding method.
   a) Hand fired. b) Stocker fired.

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Boiler Mountings:→

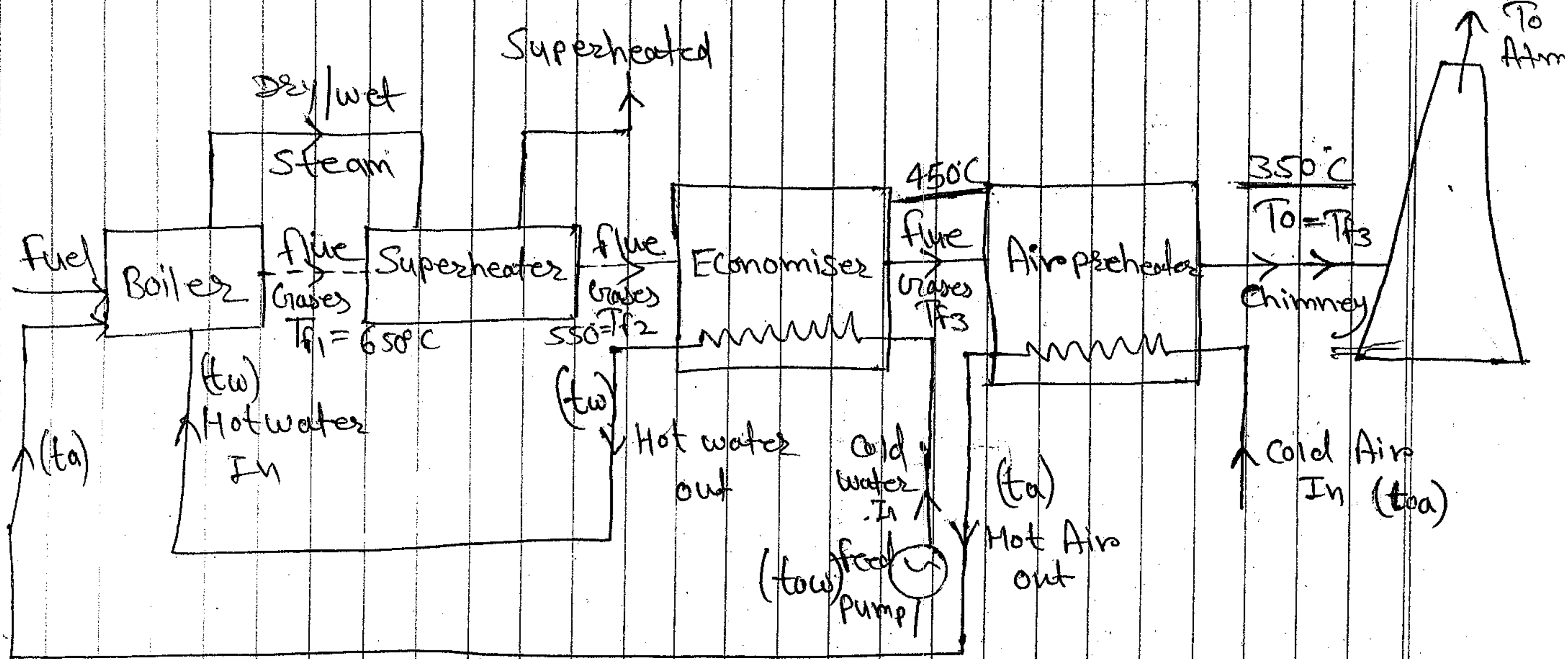
The necessary devices used for Safety purpose of boiler and its Control, without mountings, boiler Can not work.

→ pressure gauges
→ Temperature gauges
→ water level Indicator
→ Saftey Valves
→ feed check Valve
→ Blow off Cock
→ fusible plug
→ Man hole & mud hole

Boiler Accessories:→

Those components of Boiler which is not mandatory, but we have to improve the performance of Boiler, then we can use of Boiler accessories.

→ Superheater
→ Economiser
→ Air preheater
→ feed pump.



Position of Boiler Accessories in Boiler Plant

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Boiler Draught →

The Draught is one of the essential system of thermal power plant; which supplies required quantity of air for combustion and removes the burnt products from the system.

Draught means, the force needed to draw. The term draught refers to the small pressure difference that causes the flow of gases takes place inside the boiler.

It performs two function.

1) To maintain & provide sufficient quantity of air for the proper combustion of fuel.

2) To Discharge the flue gases from the chimney to the surroundings.

→ Draught can be obtained by use of chimney fan, steam or air jet or combination of these.

→ When the Draught is produced by use of chimney only it is called Natural Draught.

→ When the Draught is produced by any other means except chimney it is known as Artificial Draught.

→ Small pressure diff^n causing flow of air & gases through the Boiler.

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Classification of Draught :→

- Draught
  - Natural Draught (produced by Chimney)
  - Artificial Draught
    - Mechanical Draught (produced by fan)
      - Induced
      - Forced
      - Balanced
    - Steam jet D (Prod. by jet of Steam)
      - Induced
      - Forced

Advantages & Limitations of Chimney / Natural Draug

Advantages :→

1) It does not Require any External power for producing the Draught.
2) The Capital investment is less.
3) Maintainance cost is Nil, there is No mechanic parts.
4) Chimney keeps flue gases at a high place in the atmosphere which prevent the Contamination of Atmosphere
5) It has long life.

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Limitation :→

1) The maximum press. avilable for producing natural Draught by chimney hardly 10 to 20 mm of water, under the normal atmosphere and flue gas temperatures.

2) The avilable draught decreases with increase in ~~air~~ outside air temp. and for producing Sufficient draught.

3) As there is no mixing of air and fuel in the Combustion chamber due to low velocity of air there fore Combustion is Very poor. This increase the specific fuel consumption.

4) The chimney has no flexibillity to creat more draught under peak load Condition, because the draught avilable is Constant for a particular height of chimney and the draught Can be increased by allowing the flue gases to leave the Combustion chamber at higher temp. This reduce the overall Efficiency of the plant.

Nearly 20% heat released by the fuel is lost to the flue gases. The chimney draught is only used for Very Small Boiler.

Nowadays the chimney is never used for Creating draught in thermal power plant as it for high generating Capacity.

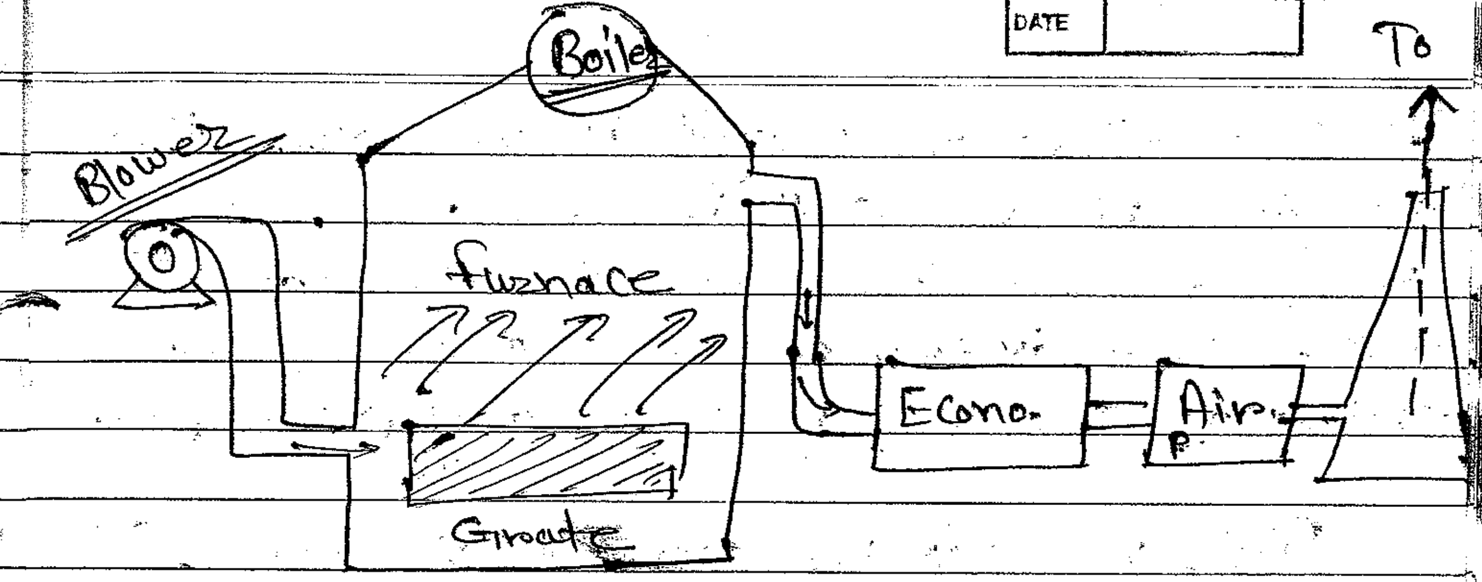
→ The chimney is used in all power plant only to discharge the flue gases high in the atmosphere to maintain the cleanliness of the Surrounding atmospheric air.

Artificial Draught :→

Because of Insufficient head and lack of flexibility the use of Natural Draught is limited to Small capacity Boilers only. The Draught required in actual power plant is sufficiently high (300 mm of wat and to meet high draught requirements, some other system must be used Known as Artificial Draught.

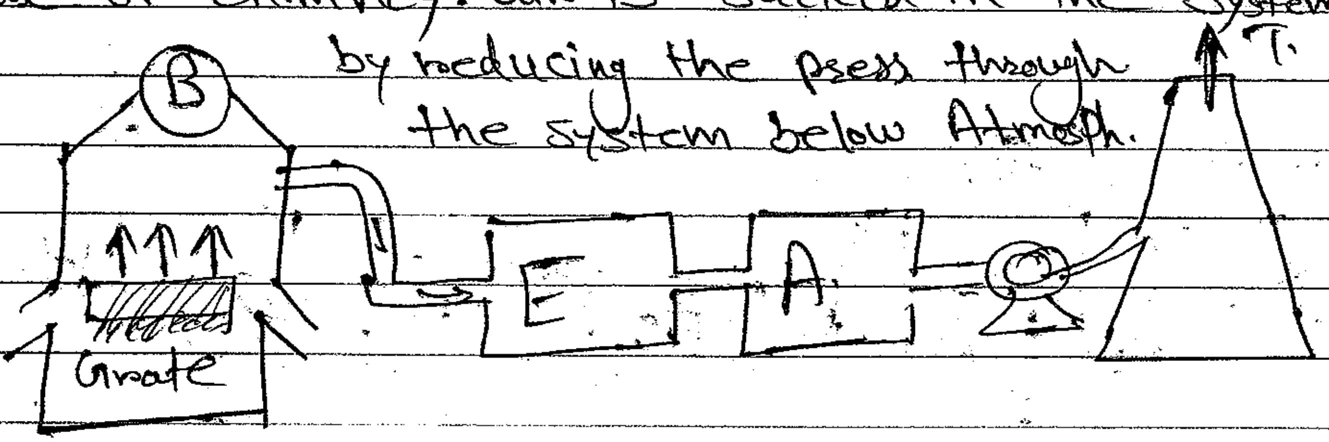
Forced Draught :→

In a forced draught system, a blower is installed near the base of ~~chimney~~ Boiler. This draught system is known as positive Draught system or forced Draught system because the pressure of air throughout the system is above atmospheric pressure and air is forced to flow through the system.



forced Draught Arrangement

Induced Draught :→ Blower is Located near the Base of chimney. air is sucked in the System by reducing the press through the system below Atmosph.



Induced Draught Arrangement.

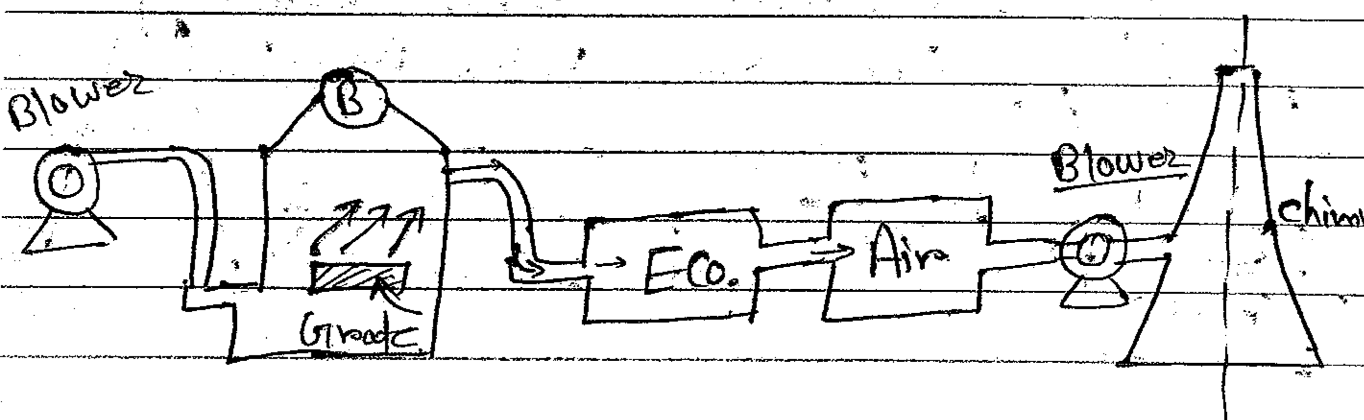
Balanced Draught :→

→ In the forced draught is furnace can't be opened either for firing or inspection because high press. air inside the furnace will try to blow out suddenly and there is every chance of

→ In the Induced draught is used alone, then also the furnace can't be open either for firing or inspection because the cold air will try to rush in to the furnace as the press. inside the furnace is below atmospheric press.

This reduces the effective Draught & dilutes the combustion.

To overcome both the difficulties mentioned above either using forced draught or induced draught alone, a balanced Draught is always preffered.



Arrangement of Balanced Draught.

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Advantages of Mechanical Draught over Natural

1) The artificial Mechanical Draught is better in Control & more Economical than Natural Draught.
2) The rate of Combustion is high as the avilable Draught is more. The better distrib. & mixing of air with fuel is possible, therefore the air Required per kg of fuel is less.
3) The air flow can be regulated acc^d to the requirement by changing the draught press.

4) The height of chimney used is mechanical draught can be reduced sufficiently as the function of the chimney is only to Exhaust the gases high in the atmosphere to prevent the Contamination.

5) The efficiency of artificial Draught is nearly 7%, whereas the efficiency of chimney draught is hardly 1%.

6) The fuel Consumption per kW due to artificial draught is 15% less than the Natural Draught.

7) It prevent the formation of smoke as Complete Combustion is possible even with less Excess Air.

Dis advantage is only high capital cost Required

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Steam jet Draught :→

The Draught produced by steam jet is called steam jet draught and it is of two types.

→ In forced draught, the jet of steam after have been throttled to 1.5 to 2.5 bar gauge are applied below the ash pit, which is located under the fire grate of furnace

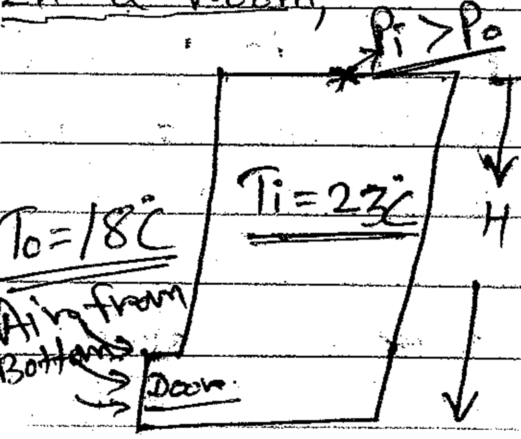
→ In Induced draught there is a blast of low press. Exhaust steam in the smoke box, at the base of chimney. The partial vacuum thus created forces the flue gases out through the chimney.

Press. diff^n Concept :→

In a room;

i = inside room
o = outside room

P = press.
ρ = Density.



$$[P = \rho \times g \times h]$$

$$\boxed{P \propto \rho} \quad \text{—}(1)$$

$PV = mRT$

$P = \frac{m}{V} RT$

$P = \rho RT$

$\rho = \frac{P}{RT}$ $\quad$ P = constant

$$\boxed{\rho \propto \frac{1}{T}} \quad \text{—}(2)$$

$\left\{ \begin{array}{l} \rho_o > \rho_i \\ P_o > P_i \end{array} \right\}$
upward

Reduction in press is outside is

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Performance of Boiler:

The performance of boiler is calculated for comparing the boilers for its evaporating capacity. energy consumption & Heat balance sheet.

Evaporating capacity of Boilers
→ quantity of steam generated by a boiler at full load is called Evaporative capacity.

$$E_P = \frac{\text{mass of steam Generated}}{\text{Time period in hrs.}} = kg/hr$$

$$E_P = \frac{\text{mass of steam Generated per hr}}{\text{Heating Area of grate in } m^2} = \frac{kg}{hr\ m^2}$$

$$E_P = \frac{\text{mass of steam Generated per hr}}{\text{Volume of heating Surfaces}} = \frac{kg}{hr.\ m^3}$$

Equivalent Evaporation:→

It is the amount of steam generated from feed water at 100°C at 1.01325 bar atm. press. In short it is defined as the amount of ~~heat~~ steam generated "from and at 100°C".

Let;

m_s = mass of water actually evaporated.
m_f = mass of fuel consumed during the (m_s) mass of water actually evaporated.

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m_e = Amount of water Evaporated actually kg/hr or kg/kg of fuel; by consuming of Coal (m_f)

$$\boxed{m_e = \frac{m_s}{m_f}}$$

when the m_f is given then we used m_e; If, m_s & m_f given

$$\boxed{E = \frac{(h_{Total} - h_{f1})}{2257} \times m_e}$$

$$\boxed{m_e = \frac{m_s}{m_f}}$$

kg/kg of fuel

h_{total} = Total Enthalpy of steam (KJ/kg)

$$\left[\begin{array}{l} h_{sup} = h_g + C_{ps}(T_{sup} - T_{sat}) \\ h_{dry} = h_g = h_f + x h_{fg} \quad (x=1) \\ h_{wet} = h_f + x h_{fg} \end{array}\right]$$

h_{total} = may be h_{sup} / h_{dry} / h_{wet}

$$\boxed{h_{f1} = C_p \times t_1}$$

h_{f1} = Enthalpy of feed water at temp (t_1) °C

t_1 = Temp. of feed water to the Boiler °C

2257 = Latent heat of Vapourisation at 1bar

C.V = Calorific value of fuel

factor of Evaporation:→

$$\left\{ F = \frac{(h_{total} - h_{f1})}{2257} \right\}$$

It may be defind as the Ratio of heat absorbed by 1kg of water under the working Condition to heat absorbed by 1kg of water from & at 100°C.

Boiler Efficiency:→

It is defined as the Ratio of heat Energy utilized by feed water in converting in to Steam in the Boiler, to the heat Energy produced by combustion of fuel during the Same time.

$$\left[\eta_{boiler(th)} = \frac{\text{Energy Absorbed By feed water}}{\text{Energy produced By fuel}}\right]$$

$$\eta_{Boiler(ther)} = \frac{m_e(h_{total} - h_{f1})}{C.V}$$

$$\boxed{\eta_{Boiler} = \frac{m_s \times (h_{total} - h_{f1})}{m_f \times C.V}}$$

C.V = Calorific value of fuel (KJ/Kg)

h_{f1} = enthalpy of feed water at temp (t_1)

$h_{f1} = C_p \times t_1$

C_p = specific heat of water (4.18 KJ/kgK)

or

We can directly read from Steam Table (1) at temp. (t_1).

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Tutorial Qustions;

① Calculate the Equivalent Evaporation of a boiler per kg of Coal fired; if the boiler produces 50,000 kg of wet steam per hour with a dryness fraction 0.95 and operating 10 bar. The Coal burnt 5500 kg per hour. Also calculate the thermal efficiency of Boiler when the Calorific value of fuel is 34,000 KJ/kg. & feed water temp is 40°C. [E = 10.1 kg/kg of fuel, $\eta = 67\%$]

② Calculate the Equivalent evaporation from & at 100°C for a Boiler, which recives water at 60°C and produces steam at 1.5 MPa and 300°C. The steam generation rate is 16000 kg/hr. Coal is burnt at the rate of 1800 kg/hr. The Calorific value of coal is 34,750 KJ/kg. Also Calculate thermal efficiency of Boiler.

• If the thermal efficiency of Boiler is increased by 5% due to use of Economiser find the saving in coal consumption per hour.

Ans [E = 10.1 kg/kg of fuel, $\eta_{boiler} = 71.31\%$, $S_{fuel} = 118$ kg/hr

③ A boiler generates steam at the rate of 6000 kg/hr. at a press. of 800 kPa with a dryness fraction of 0.98. The feed water supplies at 40°C. If the efficiency of boiler is 75%. Calculate the rate of Coal Consumption which has Calorific Value of 31000 KJ/kg. what is Equival. Evap.

If the superheat is used, and its Temp. of steam reaches 250°C then, what is Equivalent Evaporation & thermal efficiency of Boiler. Take $C_{ps} = 2.27$ KJ/kg K

Boiler Trial & Heat Balance Sheet :→

In a Boiler, the heat is produced by burning of fuel in the presence of atmospheric air. A part of this heat is used to generate the steam & the remaining portion is lost.

Energy supplied ⇒ By combustion of fuel

→ Heat utilised in steam generation.
→ Heat carried away by the flue gases.
→ Heat lost in moisture present in fuel.
→ Heat lost due to unburnt fuel & Incomplet combustion of fuel.
→ Radiation & convection losses to the surround.

The Boiler Trial is made due to,

1) To Determine thermal efficiency of the plant.
2) To check the steam generating capacity of the Boiler.
3) To prepare the heat Balance sheet, so that suitable measure are taken to improve the working of our plant.

⇒ for making performance study of boiler it is run on test condition for 3 to 4 hrs to obtain steady state condition.

→ feed water temp., press. & Rate of steam
→ water level, rate of fuel feeding.
→ Steam press, steam quality,

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The heat released by Combustion of fuel in the furnace or grate is always more than the heat utilised in formation of steam and the diff^n represent the heat lost.

(1) Heat supplied by fuel / Heat Release by fuel → (3)

$$\left[(Q) = m_f \times C.V\right]$$

m_f = mass of fuel Consumed (kg/hr)
C.V = Calorific value of fuel (KJ/kg)

(2) Heat utilised for generation of steam (Q_1)

(a) Boiler $\left\{Q_1 = m_s \times (h - h_f)\right\}$ (4)

m_s = mass of steam genr (kg/hr)
h = Enthalpy of wet steam / Dry & Saturated steam
h_f = Enthalpy of water at temp. (t) which is inlet to B

(b) Superheater $\left[Q_2 = m_s \times (h_{sup} - h)\right]$ (5)

h_{sup} = Enthalpy of superheated steam
h = Enthalpy of wet / Dry steam.

(c) Economiser :→ $\left[Q_3 = m_s \times (h_{f_1} - h_{f_0})\right]$
$\left[Q_3 = m_s \times C_{pw} \times (t_w - t_{wo})\right]$

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the

h_{f1} = Enthalpy of water at temp. (t_w)
h_{f0} = Enthalpy of water at temp. (t_{ow})
t_w = temp of water at outlet of Economiser
t_{ow} = temp of water at inlet of Economiser

③ Heat Carried away by dry flue gases :→ (Q_4)

$$\left\{ Q_4 = m_g \times C_{pg} \times (T_g - T_a) \right\} = m_g \times m_f \times C_{pg} (T_g - T_a)$$

m_g = mass of dry flue gases kg/kg of F
C_{pg} = Mean specific heat of flue gases (kJ/kg K)
T_g = Temp of flue gases (K)
T_a = Temp of air in Boiler room.

④ Heat lost due to unburnt fuel (Q_5) :→

$$\left[Q_5 = m_u \times C.V \right] = \cancel{m_u \times m_f \times C.V}$$

m_u = mass of unburnt fuel / kg of Coal
C.V = Calorific Value of Unburnt fuel

⑤ Heat lost due to Radiation & Convection (Q_6) :→ / Heat unaccounted

$$\left[Q_6 = Q - (Q_1 + Q_2 + Q_3 + \text{---}) \right]$$

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Tutorial Questions :→

Q. following results were obtained in Boiler Trial

$m_w = 700\,kg/hr$ at $t_1 = 27°C$

$m_f = 100\,kg/hr$, $C.V = 25{,}000\,kJ/kg$

$m_{unb.} = 7.5\,kg/hr$ $CV_{unbu} = 2000\,kJ/kg$

$m_g = 17.3\,kg/kg$ of fuel, $T_g = 327°C$

$P_{sat} = 8\,bar$ $x = 0.97$ $T_{air} = 16°C$

$C_{pg} = 1.025\,kJ/kg\,K$

Draw the Energy Balance sheet per minute basis, also calculate Equivalent Evaporation & Boiler efficiency.

Q. The following ~~Data~~ obtained in a boiler Trial

→ mass & Temp of feed water = 680 kg/hr & 20°C

→ Steam pres & its Temp. = 15 bar & 300°C

→ Coal used & its CV = 98 kg/hr & 26,500 kJ/kg

→ flue gases formed & its temp at chimney

$= 18\,\frac{kg}{kg\ of\ fuel}$ & 300°C , $T_a = 30°C$

→ unburnt coal found & it's C.V

$= 4\,\frac{kg}{hr}$ $C.V = 2200\,kJ/kg$

→ mean specific heat ~~of flue gases~~ & ~~feed water~~ specific heat.

$= 1\,\frac{kJ}{kg\,K}$ & $C_{pw} = 4.187\,kJ/kg\,K$

find:

→ Heat unaccounted & its % (percentage)

→ Equivalent Evaporation

→ Boiler Efficiency.

Q.(3) The following Data Recorded from a Certain boiler

Steam press = 1.2 MPa

Quality of steam leaving the Boiler = 0.97

Temp. of steam leaving superheater = 250°C

Quantity of Coal fired = 750 kg/hr

feed water supplied = 115 kg/min.

C.V of Coal = 32 MJ/kg.

feed water temp. entering/leaving the Economizer = 25°C / 80°C

find → 1) Thermal Efficiency of Boiler

2) Heat Absorbed by feed water in various components as a % of total heat Absorbed.

Q.(4) Draw heat Balance sheet - per minute Basis

Boiler generating Steam = 500 kg/hr

Steam press = 10.5 bar $x = 0.97$

fuel used & its C.V = 75 kg/hr, 31,500 kJ/kg

moisture present in fuel = 6% by mass

mass of dry flue gases = 10 kg/kg of fuel

Temp of flue gases = 315°C

Specific heat of flue gases = 1.1 kJ/kg K

Temp. of Boiler room = 38°C

Temp of feed water = 50°C

⇒ If Moisture % is given then,

$$= \left(1 - \frac{6}{100}\right) \times m_f = (1 - 0.06) \times m_f = 0.94 \times 75$$

$$(m_f)_{Actual} = 70.5 \text{ kg/hr}$$

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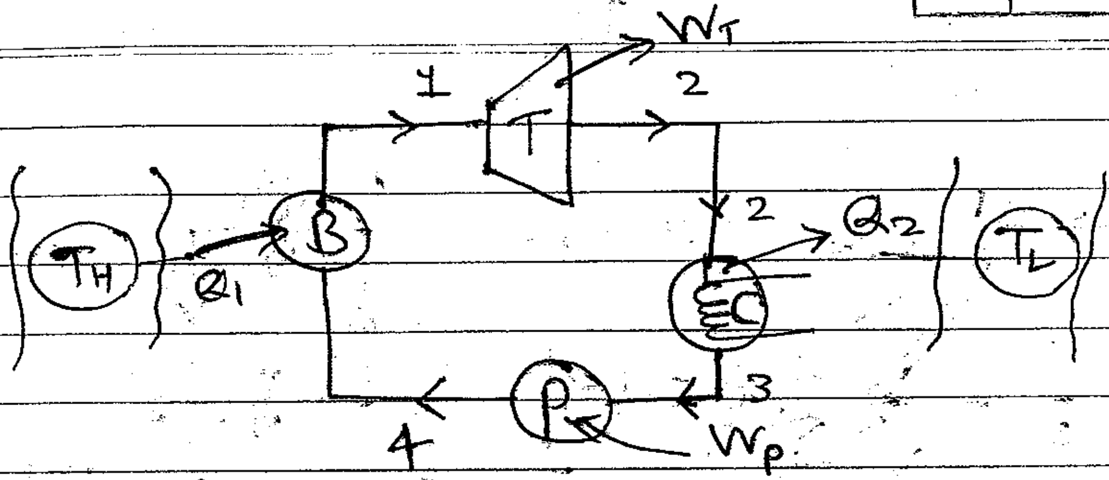
Vapour power Cycle

In the vapour power cycle the working fluid which is water, undergoes a change of phase. allows more energy to be stored in the working substance that can be stored by only sensible heating.

The working substance expands as a vapour but it is compressed as a liquid with much smaller specific volume, thus a very little of ~~examp~~ expansion work is used for compression process. The most common working substance is water and thus the cycle is called steam power cycle and plant is called steam power plant.

Steam power plant consist of following main components:

→ Boiler with its mountings & Accessories.(B)
→ Turbine (T)
→ Condenser (C)
→ feed water pump.(P)
→ Electric generator
→ Cooling Tower
→ Chimney
→ Draught system.
→ feed water Treatment plant.



When we think of power cycle of maximum efficiency; the Carnot cycle immediatly conjure up in our mind. It is a cycle, which has maximum efficiency, operating b/n given temperatures limit & its efficiency is independent of properties of working fluid.

__Carnot vapour power cycle:→__

1-2 = Reversible Adiabatic expansion.
2-3 = Heat Rejection at constant press. (Reversible Controlled Condensation
3-4 = Reversible Adiabatic Compression.
4-1 = Heat supplied at constant press. (Reversible)

$$\left\{ \eta_{car} = \frac{\text{Network-Done}}{\text{Heat Supplied}} = \frac{W_{net}}{Q_1} = \frac{W_T - W_P}{Q_1} \right]$$

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

$$\left\{ \eta_{car} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1} \right\} \text{— (A)}$$

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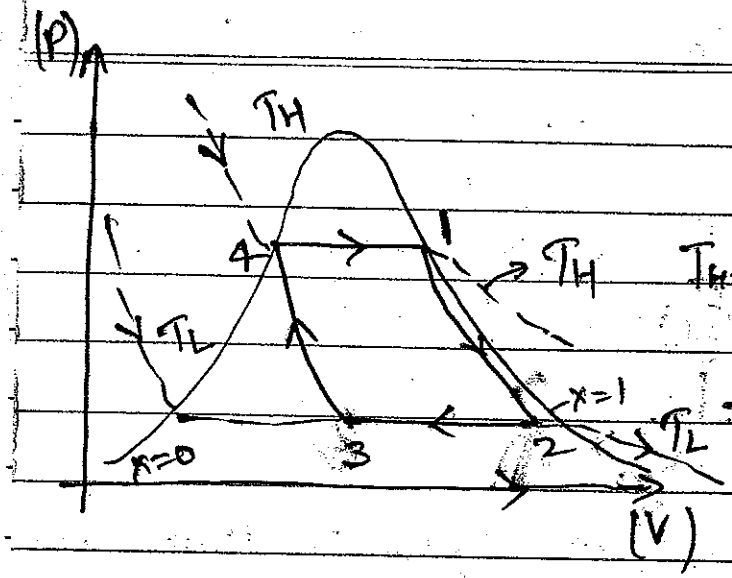

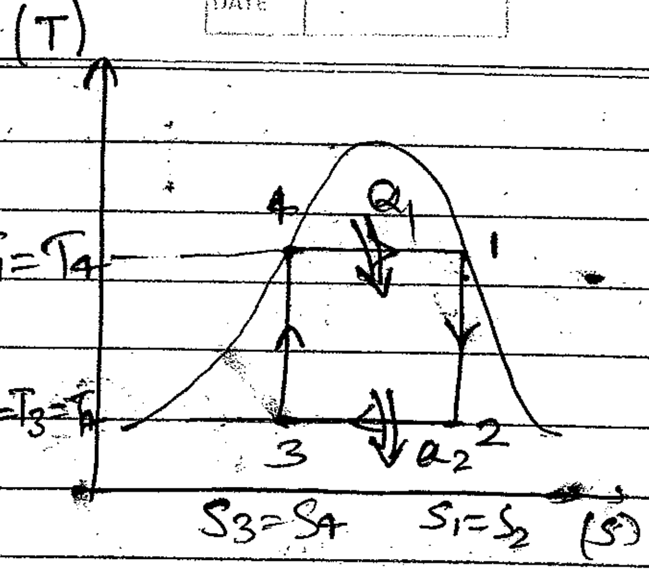

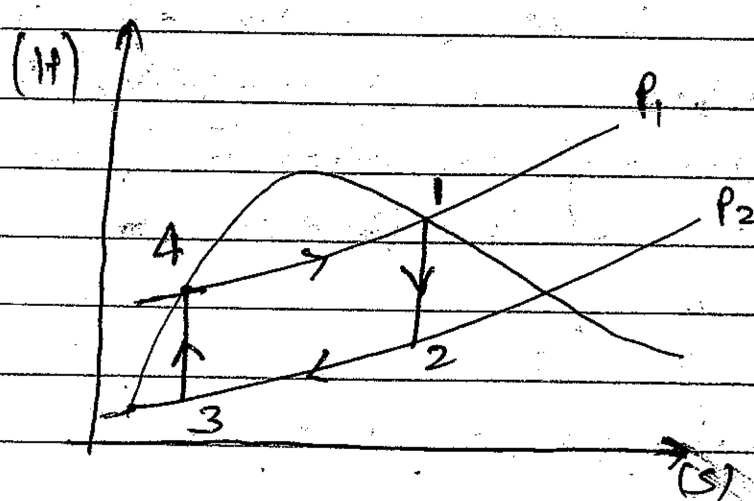

Isothermal heat addition at Boiler (Q_1)

$$Q_1 = T_H \times ds$$
$$= T_H \times (S_1 - S_4) \quad \text{— (a)}$$

Isothermal heat Rejection at Condenser (Q_2)

$$Q_2 = T_L \times ds$$
$$= T_L \times (S_2 - S_3) \quad \text{— (b)}$$

put the value of (a) & (b) in (A)

$$\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_L\,(S_2 - \cancel{S_3})}{T_H\,(S_1 - \cancel{S_4})}$$

$S_1 = S_2$
$S_3 = S_4$

$$\boxed{\eta_{ca} = 1 - \frac{T_L}{\;} = 1 - \frac{T_2}{\;}}$$

Temper:
T_1 = Source

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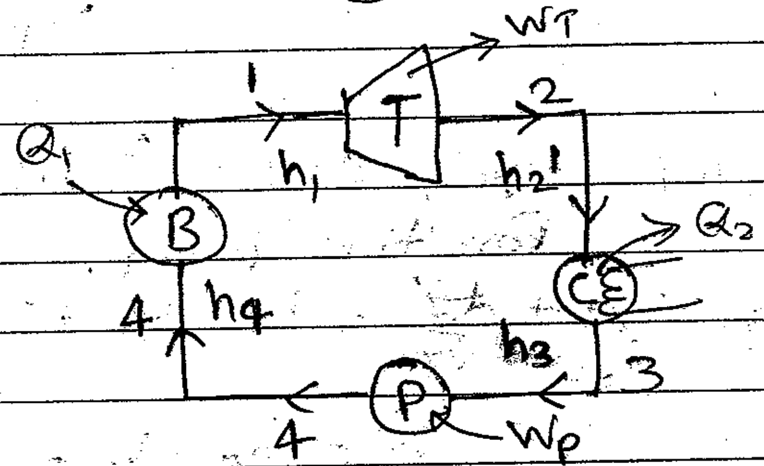
Analysis of Carnot cycle :→



Apply S.F.E.E. to all main parts of Steam power plant :→

1) Turbine :→ 1 inlet 2 - outlet

$$\left[h_1 + \cancel{\frac{V_1^2}{2}} + \cancel{z_1 g} + \underbrace{\cancel{\frac{dQ}{dm}}}_{=0} = h_2 + \cancel{\frac{V_2^2}{2}} + \cancel{z_2 g} + \frac{dw}{dm} \right] \quad (A)$$

$\Delta K.E = 0$

$\Delta P.E = 0$

$h_1 + 0 = h_2 + W$

Reversible Adiabatic = Expansion $Q = 0$

$$\boxed{W = h_1 - h_2}$$

In other ways input = output

$h_1 = h_2 + W$ $\boxed{W = h_1 - h_2}$

2) Condenser :→

Apply equ. (A) S.F.E.E for Condenser

$h_2 + Q_2 = h_3$ $\boxed{\cancel{Q_2 = h_3 - h_2}}$

$h_2 - Q_2 = h_3$ $Q_2 = -ve$

(or) $h_2 = h_3 + Q_2$

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(3) pump:→ $\{h_3 + W_p = h_4\}$ $\underline{W_p = -ive}$

$\{W_p = h_4 - h_3\}$

$$\boxed{\begin{aligned} W_p &= -\int v\,dp \\ W_p &= V_f(P_h - P_L) \end{aligned}}$$

Apply S.F.E.E (3) inlet & (4) outlet for the pump

$$h_3 + \cancel{\frac{V_3^2}{2}} + \cancel{Z_3 g} + \cancel{\frac{dQ}{dm}} = h_4 + \cancel{\frac{V_4^2}{2}} + \cancel{Z_4 g} + \frac{dW}{dm}$$

$$h_3 = h_4 - W$$

$$\boxed{h_4 = h_3 + W_p}$$

(4) Boiler → $\{Q_1 + h_4 = h_1\}$

$$\boxed{Q_1 = h_1 - h_4}$$

Apply S.F.E.E, (4) inlet & (1) outlet;

$$h_4 + \cancel{\frac{V_4^2}{2}} + \cancel{Z_4 g} + \frac{dQ}{dm} = h_1 + \cancel{\frac{V_1^2}{2}} + \cancel{Z_1 g} + \cancel{\frac{dW}{dm}}$$

$$h_4 + Q_1 = h_1 \qquad \boxed{Q_1 = h_1 - h_4}$$

performance parameters :→

1) Efficiency of Carnot :→

$$\boxed{\eta_{Carnot} = 1 - \frac{T_2}{T_1} = 1 - \frac{T_L}{T_H}} \quad \boxed{\eta_{Car} = \frac{W_{net}}{Q_1}}$$

2) Work Ratio :→ The Ratio of Network output of the cycle to the work developed by Turbine

$$\left[W_R = \frac{W_{net}}{\ } = \frac{W_T - W_P}{\ } = 1 - \frac{W_P}{\ } \right]$$

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3) Back work Ratio :→ $\boxed{B.W_r = \frac{W_P}{W_T}}$

3) Steam Rate :→(SSC)

Specific Steam Consumption; It is the amount of steam Requiered in per hour to get per KW power output

$$S.S.C = \frac{\text{mass of steam in kg/hr}}{\text{Power output in KW}}$$

$$= \frac{\dot{m}_s\ (kg/hr)}{\dot{m}_s\ (kg/sec) \times W_{net}\ (KJ/kg)}$$

$$S.S.C = \frac{3600}{W_{net}}$$

Power Developed by Turbine :→

$$\boxed{P = \dot{m}_s \times (W_{net})} \text{ —— KW.}$$

$\dot{m}_s$ = mass of steam/sec

W_{net} = Net work Done (KJ/kg)

Comparison of (a) Carnot vapour & (b) Rankine Vapour cy

1) Cycle → (a) It is a Reversible cycle.
(b) It is an Irreversible cycle.

2) Cycle Efficiency :→
(a) It has theoretical Maximum efficiency
(b) It has less thermal efficiency than that of Carnot vapour power cycle.

3) Heat addition :→
(a) At Constant temperature
(b) At Constant pressure

4) pump Work :→
(a) It Requires large pump work to handle the two phase mixture
(b) It Require Negligible pump work to handle the liquid water only.

5) Superheated steam :→
(a) use of superheated steam is practically difficult. (b) use of superheat steam perform better

6) Condensation :→
(a) Condensation is terminated before being saturated liquid
(b) Condensation Completly takes place until saturated

7) Steam Quality after Expansion :→
(a) poor
(b) better due to use of superheat

8) Standard of cycle :→
(a) It is a just theoretical cycle & can not be used in practice.

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Numerical :->

Q A Carnot engine contain 0.1 kg of water, During heat addition process, Saturated liquid is converted in to Saturated Vapour. Heat addition occurs at 12 MPa & Heat rejection occurse at 30 KPa. Determine.

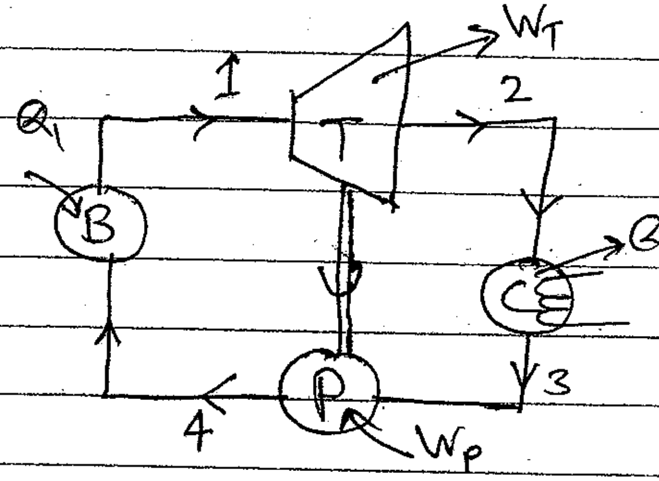
(a) Quality of steam at the end of isentropic expansion & at the end of isothermal heat Reje.
(b) Heat added per cycle.
(c) Net work Developed in cycle
(d) The efficiency of cycle
(e) work Ratio (f) SS.C (g) ~~Back~~

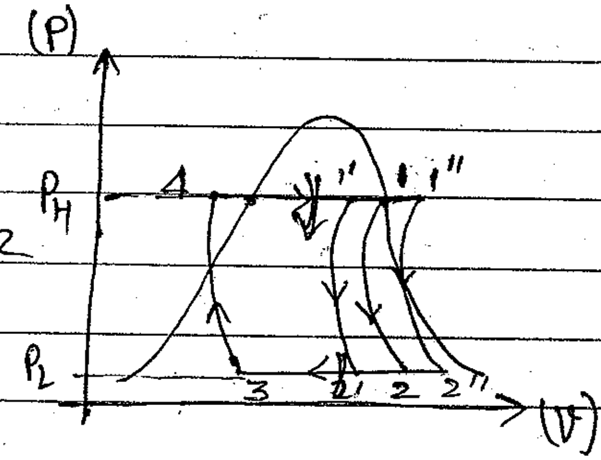
Q. The Boiler produces dry & Saturated Steam. at 30 bar. The steam expands in the turbine to a Condenser press. of 20 KPa. Compare the cyclic workdone & thermal efficiency of Carnot & Rankine cycle for these conditions.

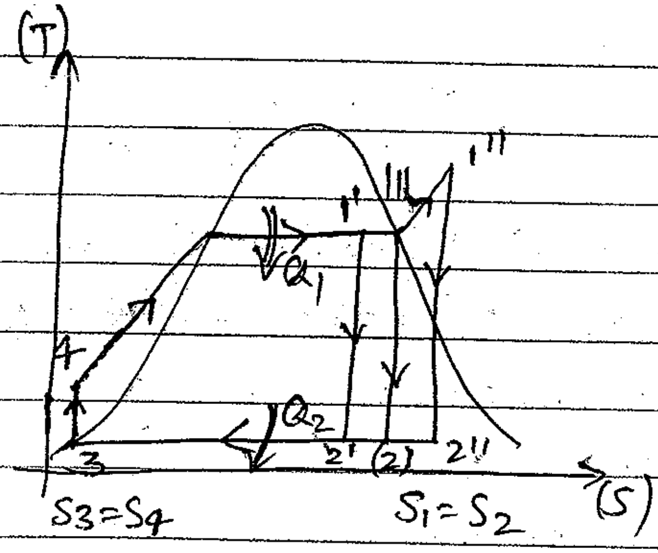
Q. A steam power plant operates on ideal Rankine cycle. The steam enters the turbine at 3 MPa, 350°C and is condensed in the Condenser at a press. of 75 KPa. Determine thermal efficiency, Back work Ratio & work Ratio of this cycle.

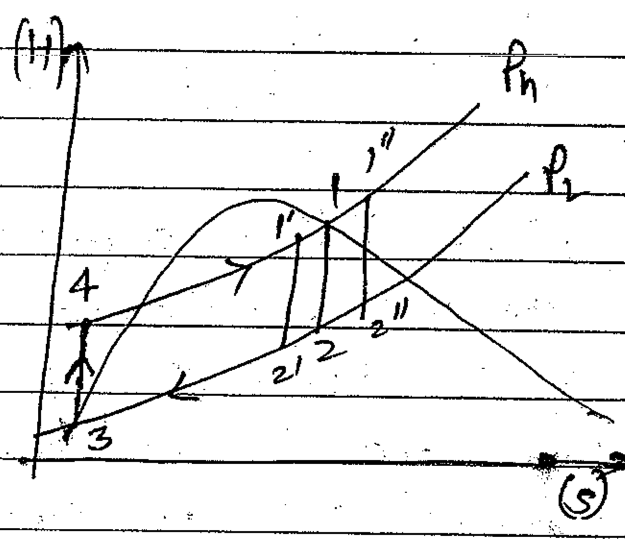
Q. In Rankine cycle, the steam at inlet to turbine is Saturated at a press. of 35 bar and the exhaust press. is 0.2 bar & Assume flow rate of steam 9.5 kg/sec find -> 1) The pump work 2) Turbine work 3) Rankine effic.

Rankine Cycle :→









1-2 = Isentropic Expansion (T)
2-3 = Heat Rejection at Constant press. (C)
3-4 = Isentropic Compression (P)
4-1 = Heat Addication at Constant press. (B)

[1-2-3-4-1 = Rankine cycle Dry & Saturated ste
1'-2'-3-4-1' = Rankine cycle for wet steam.
1''-2''-3-4-1'' = Rankine cycle for superheated stea]

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Analysis of Rankine cycle:→

→ Boiler →

$\boxed{Q_1 = h_1 - h_4}$

$\rightarrow h_4 + Q_1 = h_1$

$\boxed{Q_1 = h_1 - h_4}$

→ Turbine →

$h_1 + W_T = h_2$ $\boxed{W_T = h_1 - h_2}$

→ Condenser:→

$h_2 = Q_2 + h_3$ $\boxed{Q_2 = h_2 - h_3}$

→ pump:→

$W_P = -\int v\,dP = v \int dP$

$\Rightarrow \boxed{W_P = V_f\,(P_H - P_L)} \Rightarrow V_f = m^3/kg\ \frac{N}{m^2}$

V_f = specific volume of liquid @ P_L (condenser press.)

→ or In other words By T-ds eqn

$\left[T\,ds = dh - v\,dP\right]$ $\left[ds = 0,\ \text{Isentropic}\right]$

$dh = v\,dP$

$(h_4 - h_3) = v\,dP$ $dh =$

$(h_4 - h_3) = W_P$

$\boxed{h_4 = h_3 + W_P}$

Enthalpies :→

h_1 = from steam Table; depends on the Condition of steam h_{wet}, h_g, h_{sup}.

$h_2 = h_{wet} = (h_{f2} + x_2 h_{fg2})$ @ P_L (condenser p.) (Stea.

$h_3 = h_f = h_f$ @ condenser press.

Stea $h_4 = h_3 + W_P$

$\boxed{W_P = V_f\,(P_H - P_L) \times 100}$

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$$\boxed{\eta_{Rankine} = \frac{W_{net}}{Q_1}} \qquad \boxed{W_{net} = W_T - W_P}$$

$$\boxed{W_{net} = Q_1 - Q_2}$$

$$\eta_{Ra} = \frac{Q_1 - Q_2}{Q_1}$$

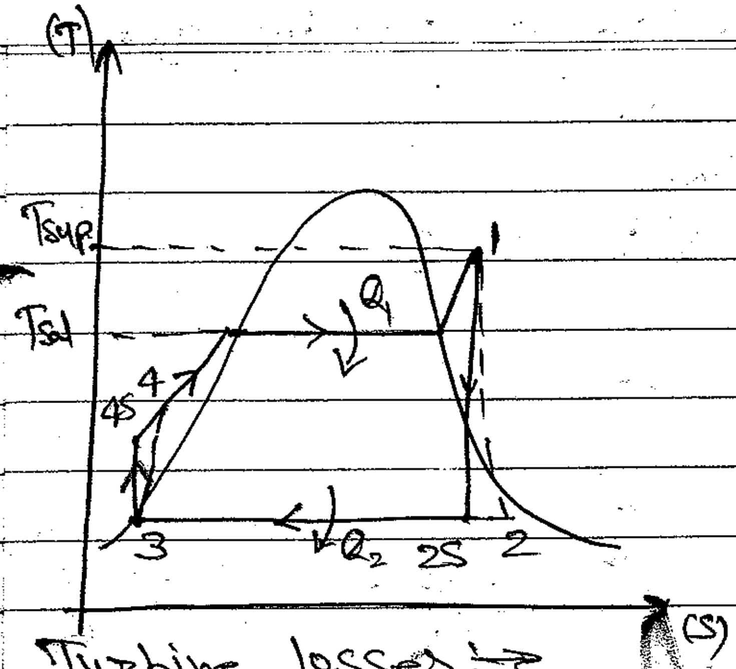
$$= 1 - \frac{Q_2}{Q_1} = 1 - \frac{(h_2 - h_3)}{(h_1 - h_4)}$$

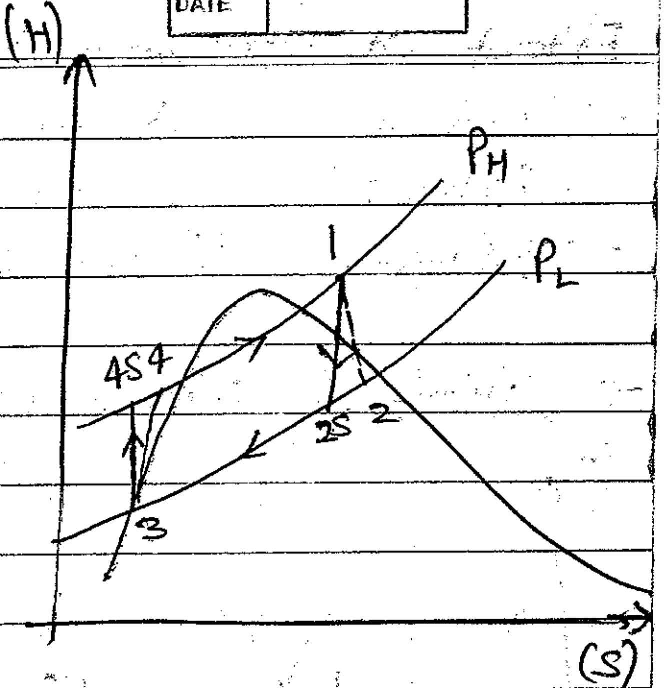
$$\boxed{\eta_{Ran} = 1 - \left(\frac{h_2 - h_3}{h_1 - h_4}\right)}$$

Irreversibilities & losses in vapour cycle:- In actual practice all four processes of the cycle involve irreversibilities and losses and therefore, the efficiency of the actual power cycle is less than that of ideal Rankine cycle.

→ Piping losses.
→ Turbine losses
→ pump losses
→ Condenser losses.

Piping losses:→ when the working fluid passes the tubes of boiler & Condenser the pressure drop due to frictional effect & transfer to surrounding. Both press drop & heat transfer decreases the availability of steam entering the turbine. However the effects are negligible.





Turbine losses :→

In turbine the actual work developed in the turbine is less than the work corresponding to isentropic process (1-2S). thus the isentropic efficiency,

$$\boxed{\eta_t = \frac{\text{Actual work}}{\text{Isentropic work}} = \frac{\text{Actual enthalpy drop}}{\text{Isentropic enthalpy drop}} = \frac{h_1 - h_2}{h_1 - h_{2s}}}$$

$= \frac{25}{30}$

Pump losses :→

The pump losses are very similar to turbine losses. The actual compression process (3-4) in the pump is an irreversible process. The entropy increases during actual process. Therefore Actual work input in the pump is more than the work corresponding to isentropic process (3-4S).

$$\eta_p = \frac{\text{Isentropic work input}}{\text{Actual work input}} = \frac{\text{Isentropic enthalpy drop}}{\text{Actual enthalpy drop}}$$

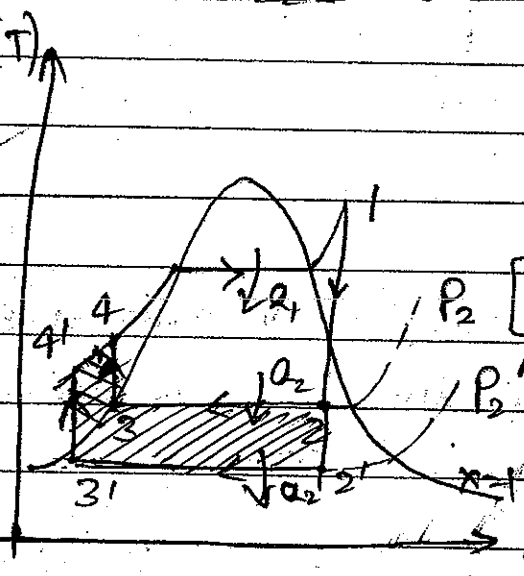
$$\eta_p = \frac{h_{4s} - h_3}{\quad}$$

25

Effect of operating variables on Rankine cycle :-

→ Effect of exhaust press.
→ Effect of superheating.
→ Effect of Increase in Boiler pressure.

→ Effect of exhaust pressure :→



$$\eta_{Ra} = \frac{W_{net}}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

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

$Q_2 \downarrow,\ \eta_{Ra} \uparrow$

(a) When the back press. is reduced, the moisture content of the steam leaving the turbine. It is unfavorable factor. It should not exceed 10%.

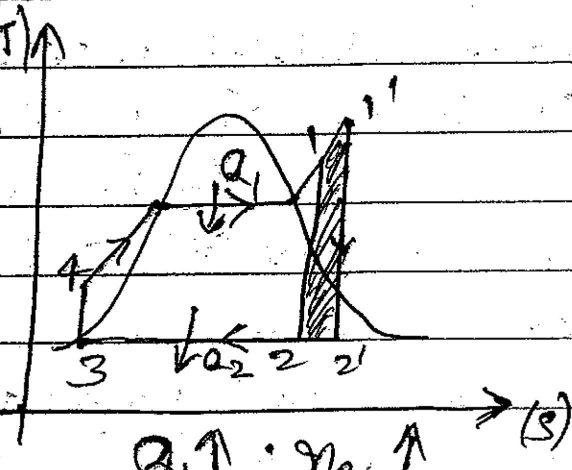
(2) The Area under the curve in (T−S) diag. Q_2' is decreases, the efficiency of Rankine cycle is increases.

(3) To maintain high vaccum, the air extraction pump will run continously and its work input will increase thus reducing the useful work.

(4) When the saturation press. is lowered than the saturation temp. is also decreased means, that; the cooling water is required at lowered temp.

Sr. No.	Operating variable	Work Done	Efficiency
1.	Decrease in Exhaust pressure	Increases	Increases
2.	Increase in Boiler Pressure	No effect	Increases
3.	Superheating Steam	Increases	Increase

Effect of Superheating :→



① Superheating increase the mean temp. of heat addition So the heat input is increases thus the efficiency increases.

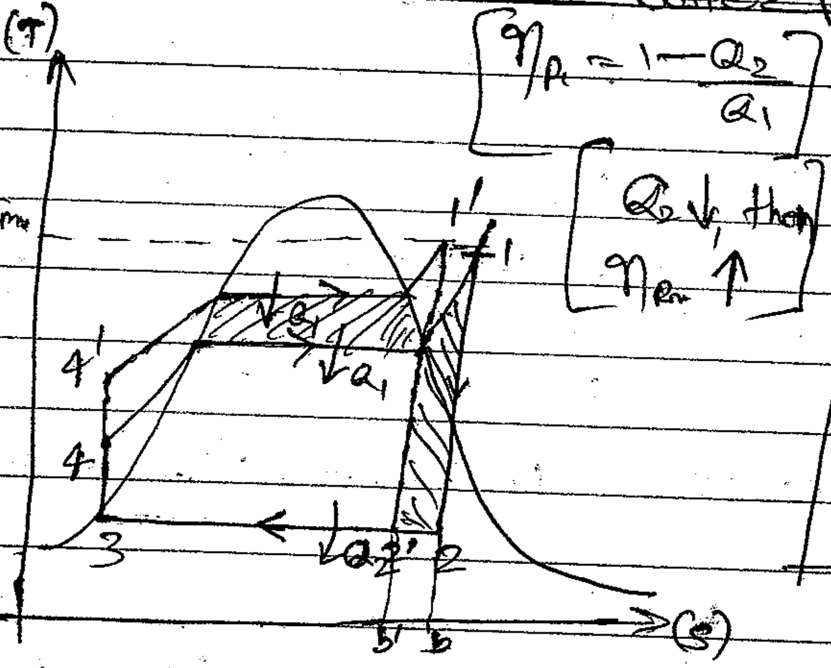
$Q_1 \uparrow$, $\therefore \eta_R \uparrow$

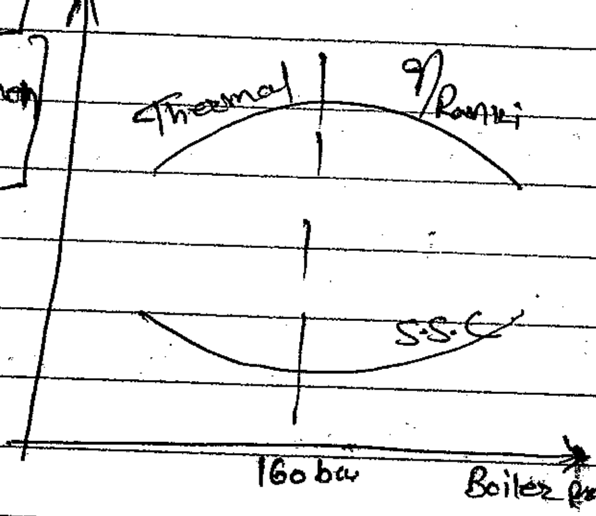
② When the Superheating of steam is increases the workdone is also increases, but it is observed that (SSC) is decreased.

③ Due to the Superheating the moisture in the steam is also improved.

But the metallurgical Consideration restrict the Superheating of steam at very high temp.

Effect of increase in Boiler press:->





(1) By increasing the Boiler press, the mean temp of heat addition increases and thus raises thermal efficiency of cycle.

By keeping the maximum temp. (Tmax) & Condenser press. (P_2) Constant if Boiler press increases the heat rejection decreases by an area (b'-2'-2-b-b'), the net work done will be the same, thus the Ranking cycle due to (Q_2) decreases.

(2) As shown in Above fig. the moisture Content in the steam is increases. it is undesirable effect

(3) Specific Steam Consumption also decreases first and than increases after reaching an minimum level at 160 bar.

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Q. Two Steam turbine (A) & (B) operate with the Same initial press. namely 15 bar and the degree of superheat 102°C. in turbine A, Exhaust press is 0.1 bar, whereas in turbine B the Exhaust press. is 0.03 bar. Calculate the Net work done, Thermal efficiency, & S.S.C. for both the turbine, and also write the Conclusion of turbines.

Q. In a Steam power plant operating on ideal Rankine cycle, the Steam enters the turbine at 3 MPa & 400°C & it Exhausted at a 10 kPa.
Determine :→
(a) Thermal Efficiency.
(b) Thermal Efficiency, if the steam is Superheated to 500°C at 3 MPa, before it enters the turbine.
(c) Thermal efficiency, if steam enters the turbine at 10 MPa & 400°C.

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Rankine Cycle with Reheat :→

If the Steam Expands Completly in a Single Stage Turbine, then the Steam Coming out of these turbine is very wet, the wet steam carries Suspended moisture particle, which are heavier than vapour particle, thus deposited in the blades and causing Erosion.

In order to increase the life of turbine blades it is necessary to keep the steam dry during Expansion. hence it is done by allowing the steam Expand to an intermediate press. in a high press. Turbine and then taking it out & Sending back to the boiler, where it is Reheated at Constant press. until it reaches the inlet ~~it~~ temp. of first Stage as shown fig. This process is called reheating during which heat is added to the steam. The reheated Steam further Expand in next stage of turbine. Due to Reheating the work output of the turbine increases, thus the improving thermal Efficiency.

The quality of Steam at the state (2) is either just dry or Slightly wet or some times it may be superheated, and then taken in back to the boiler and is Reheated to its original Superheat temp. [$T_3 = T_1$] at Constant press. (P_2). then this Steam is at state (3) enters the Next Stage turbine & further Expands to back press. at State (4).

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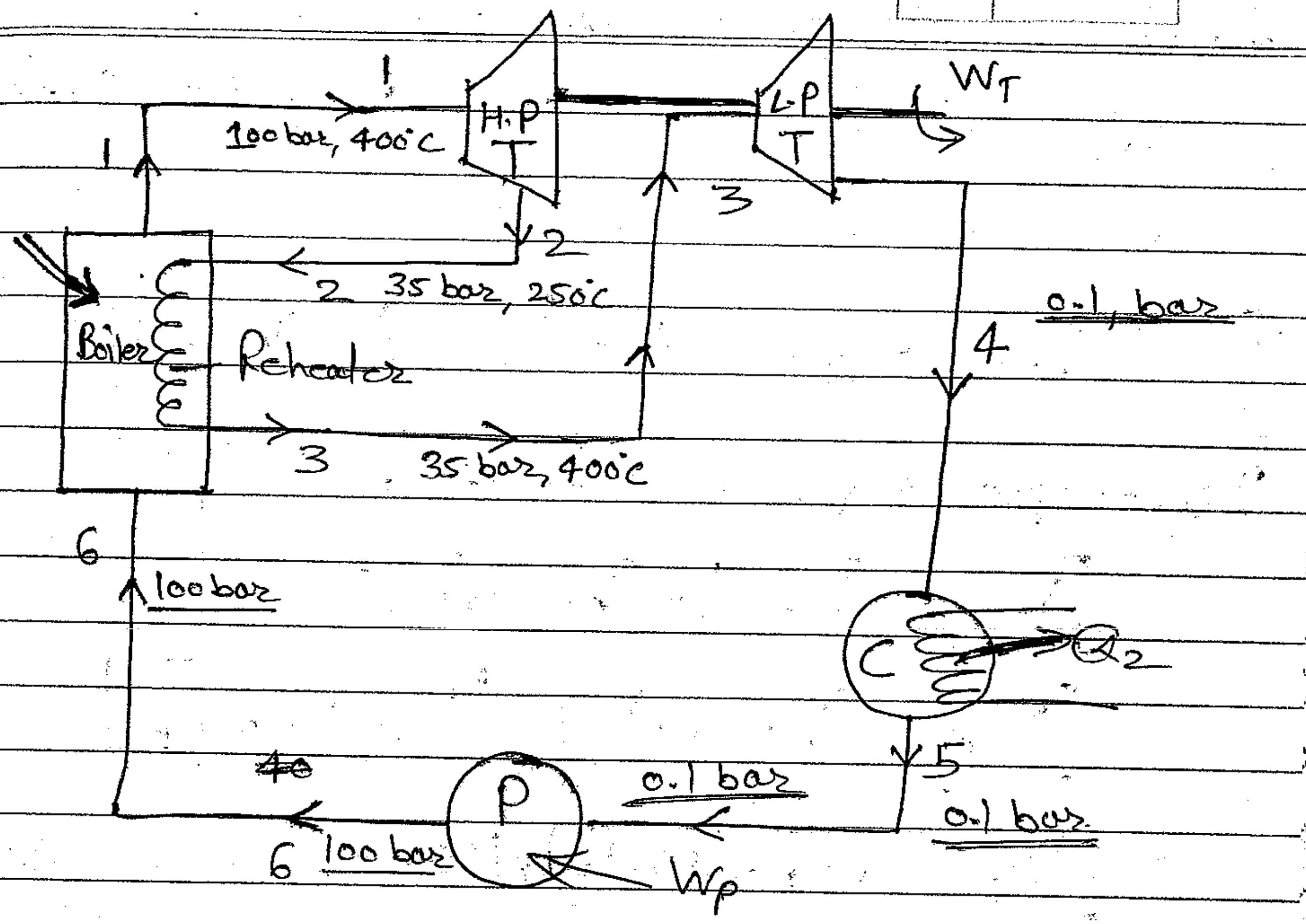

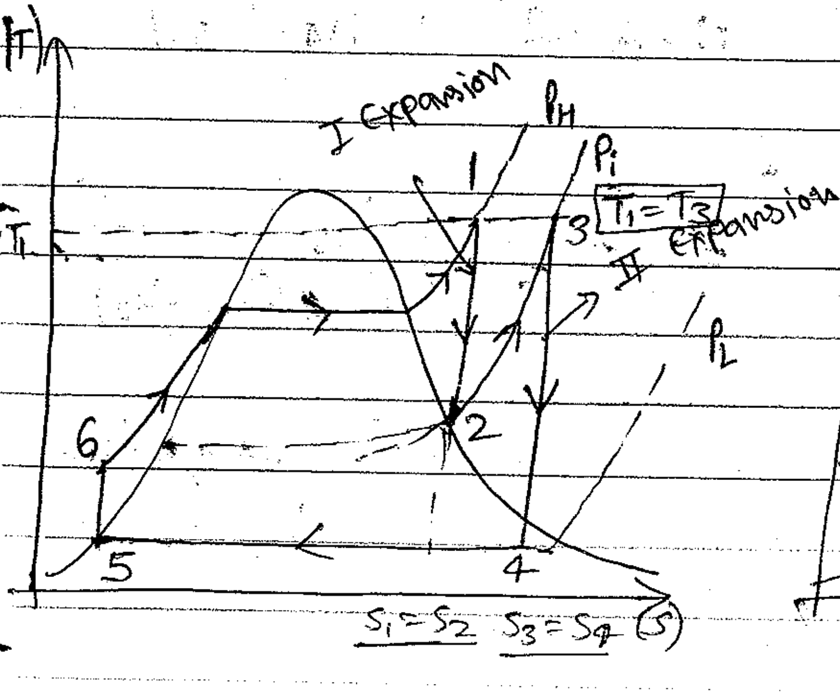

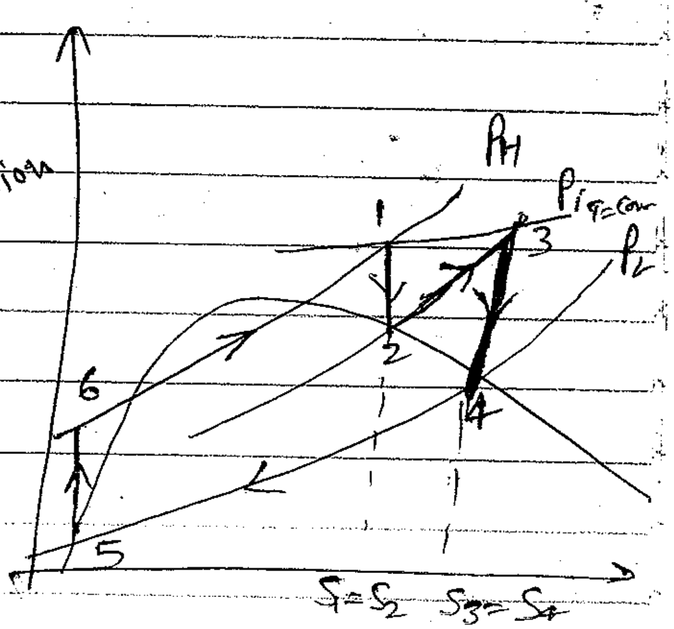

State 4 is just wet condition Appox. = 0.95

Analysis of Reheat Rankine Cycle :→

Amount of heat added in Boiler & Reh.

$Q_B = h_1 - h_6$

$Q_{Reh} = h_3 - h_2$

$$\left[\text{Total heat supplied } (Q) = (h_1 - h_6) + (h_3 - h_2)\right]$$

Isentroopic Expansion both turbine

$$\boxed{W_T = (h_1 - h_2) + (h_3 - h_4)}$$

$$\boxed{W_P = (h_6 - h_5)} \qquad \boxed{h_6 = h_5 + W_P}$$

$$\boxed{W_P = V_{f @ P_L} \times (P_H - P_L) \times 100}$$

$$\left[\text{Amount of heat Rejected } (Q_2) = h_4 - h_5\right]$$

$$\left[\eta_{Ra} = 1 - \frac{Q_2}{Q_1}\right] = \left[1 - \frac{(h_4 - h_5)}{(h_1 - h_6) + (h_3 - h_2)}\right]$$

It is evident from the (T-S) Diag. that is very less gain in thermal efficiency by reheating of steam, only the quality of exhausted steam is improved.

However the mean temp. of heat addition can be increased by including the number of expansion & Reheating processes. Thus the thermal

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Reheat factor :→

In actual practice, when the steam expands through the turbine, a considerable friction is always involved when the steam glides over the blades. This friction resists the flow of steam. The isentropic enthalpy drop is not fully converted in to kinetic energy but some of its part is utilized to overcome the frictional resistance. Thus the kinetic energy produced is less than that correspon to theoretical enthalpy drop, further this friction is converted in to heat, consequently the steam becomes dry & saturated even superheated. This frictional heating causes an increase in entroopy & hence actual enthalpy drop is always less than that of isentropic enthalpy drop.

Let us consider the expansion of steam in three stage turbine as shown in fig. on the (h-S) Diag. The superheated steam initially at a press. (P_1) expands through three stages to exhaust press. (P_4).

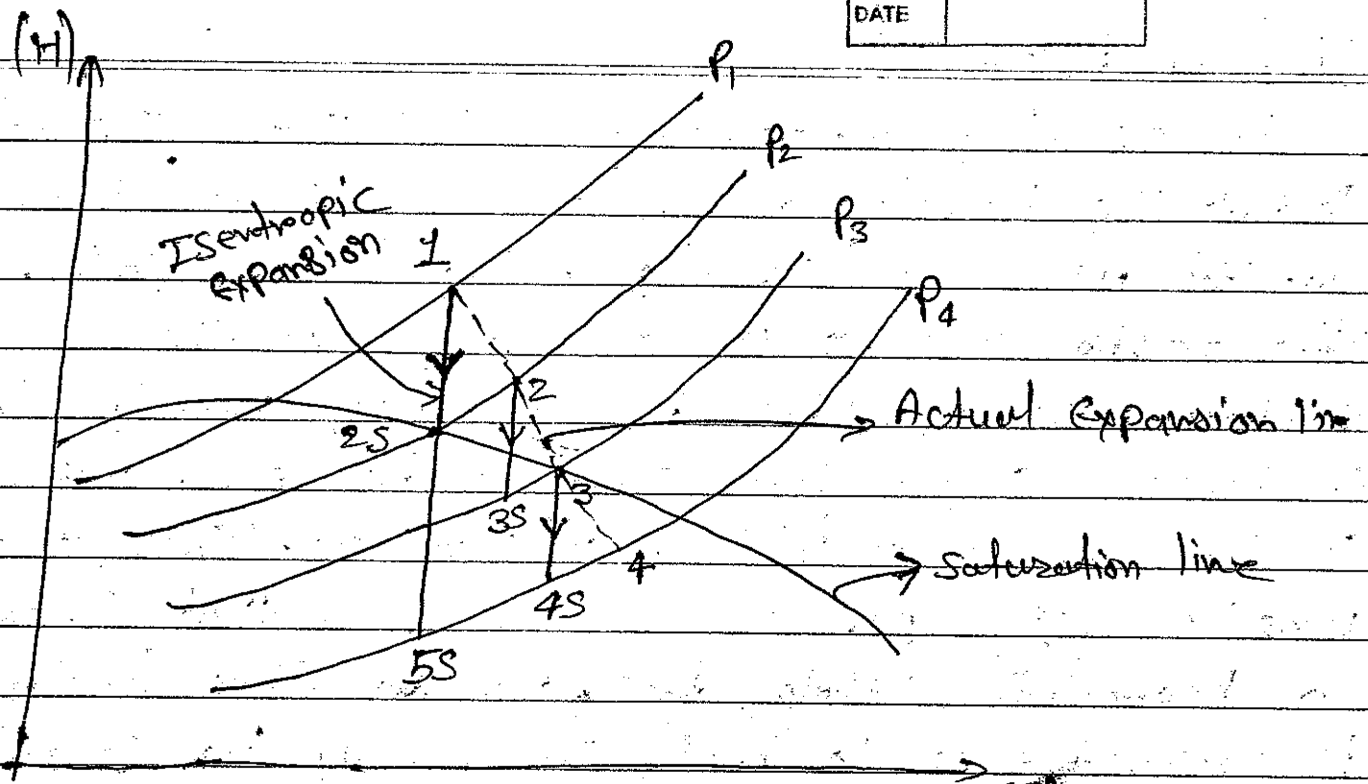
I Stage → Isentropic expansion P_1 to P_2.

II Stage → Isentropic expansion P_2 to P_3

III stage → Isentropic expansion P_3 to P_4.

Due to friction & Irreversibilities the actual state after expansion is (2) instead of (2S).

(h_1-h_2) = Actual enthalpy drop | (h_1-h_{2S}) = Isentropic
(h_2-h_3) = Actual enthalpy drop | (h_2-h_{3S}) = Isentrop



We Know that, Isentropic efficiency of I stage Turbine

$$\eta_{stage(I)} = \frac{\text{Actual Enthalpy drop}}{\text{Isentropic Enthalpy drop}} = \frac{h_1 - h_2}{h_1 - h_{2s}}$$

$$(h_1 - h_2) = \eta_{stage\ I} (h_1 - h_{2s})$$

$$\boxed{h_2 = h_1 - \eta_{stage(I)} (h_1 - h_{2s})}$$

Similarly

we can find out the enthalpy at (3) & (4)

$$\boxed{h_3 = h_2 - \eta_{stg(II)} (h_2 - h_{3s})}$$

$$\boxed{h_4 = h_3 - \eta_{stg(III)} (h_3 - h_{4s})}$$

The Sum of all Isentropic enthalpy drop is reffered as a cumulative isentropic enthalpy drop and is designed as

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If there was no irreversibility present during expansion of steam, then steam would expand isentropically through all stages from press. (P_1) to press. (P_4) as shown by the line (1-5s). The enthalpy drop during expansion is ($h_1 - h_{5s}$).

Now,

Reheat factor is defined as the Ratio of cumulative isentropic enthalpy drop (Individually in every stages in turbine, sum off) to the overally Isentropic enthalpy drop from initial press. to final press.

$$R.F = \frac{h_{cum}}{h_{overall}} =$$

$$R.F = \frac{(h_1 - h_{2s}) + (h_2 - h_{3s}) + (h_3 - h_{4s})}{(h_1 - h_{5s})}$$

(4)

[Value of Reheat factor is (Range → 1.03 to 1.05)]

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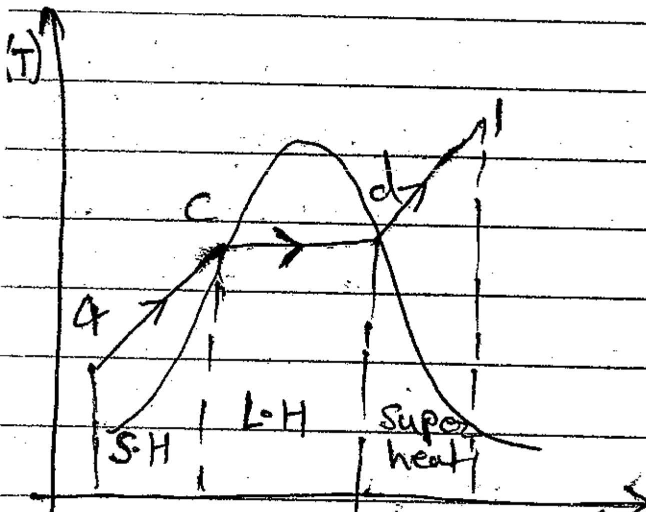
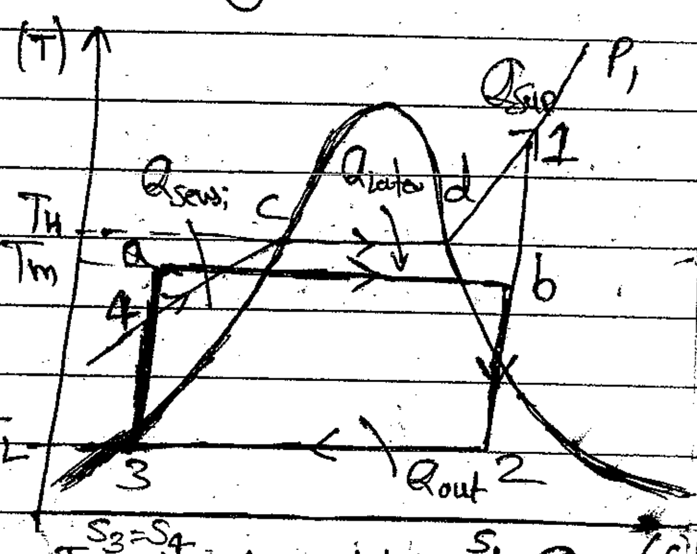
Mean Temp of Heat Addition:→

In simple Rankine cycle, the heat addition pattern as shown in fig. below; initially the heat added as sensible heat to compressed liquid coming out of the pump is at much lower average temp. the latent heat of vapourisation is constant temp. & then the superheat at higher average temperature.



Heat addition pattern ①



Mean Temp&Heat addition ②

If the mean temp. (T_m) of heat addition as shown above fig. is assumed in such a way that the area under curve (4-c-d-1) is equal to the area under the curve (a-b) on (T-S) diag(2) then;

$$q_{in} = h_1 - h_4$$

$$q_{in} = T_m (S_1 - S_4)$$ Assumed area equal then

$$q_{in} = h_1 - h_4 = T_m (S_1 - S_4)$$

$$T_m = \frac{h_1 - h_4}{\dots}$$ = Amount of heat supplied in Boiler

ition

heat Rejected per kg of steam;

$$q_{out} = T_L \times (S_2 - S_3)$$

$$q_{out} = h_2 - h_3 = T_L (S_1 - S_4)$$

The Rankine cycle efficiency;

$$\eta_{Ran} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_L \cancel{(S_1 - S_4)}}{T_m \cancel{(S_1 - S_4)}}$$

$$\boxed{\eta_{Ran} = 1 - \frac{T_L}{T_m}}$$

where; T_L = Temp. of Heat Rejection

the lower value of Temp. (T_L) for given (T_m) will increase thermal efficiency of the Rankine cycle. But the temp of heat rejection can not be lower than the temp. of surroundings.

Therefore;

$$\boxed{\eta_{Rank} = f(T_m) \text{ only}}$$

Thus;

The Higher the mean temp of heat addition, the higher will be thermal efficiency of Rankine cycle.

Boiler

Numerical :→ (Reheating)

1. An steam power plant operates on a theoretical reheat cycle. The steam from boiler at 150 bar & 550°C Expands through the high press. Turbine. It is reheated at Constant press. of 40 bar to 550°C and Expands through the low press. turbine to a Condenser press. of 0.1 bar. Draw (T-S) & (H-S) diag. & find →
   a) Quality of Steam at turbine Exhaust
   b) Thermal Efficiency of the cycle
   c) Steam rate / Specific Steam Consumption.

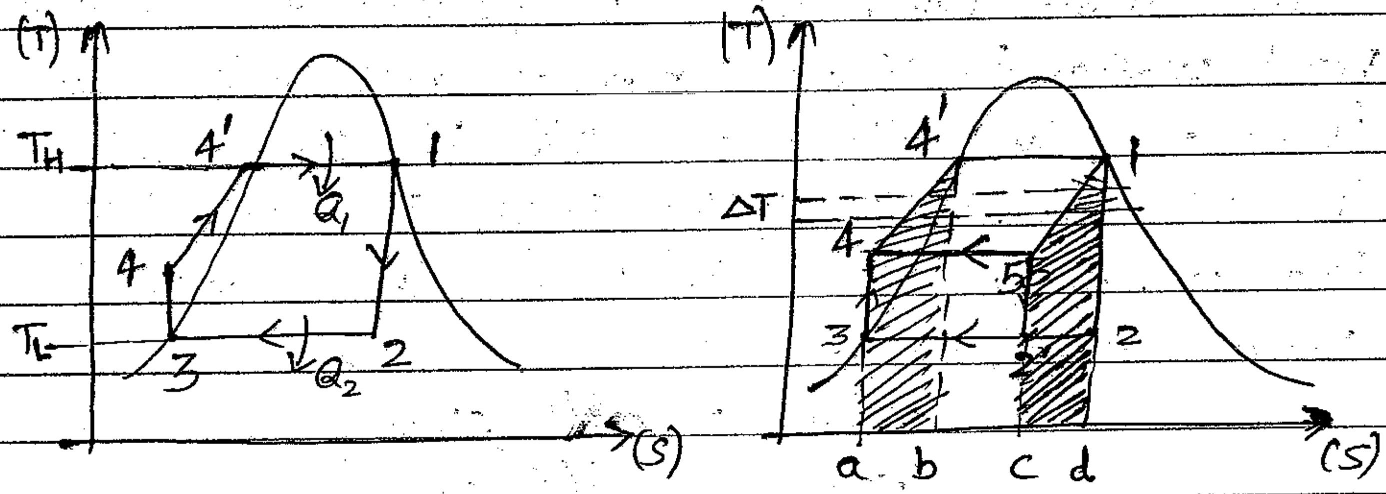
2. A steam power plant operate on Reheat Rankine Cycle. The Steam enters the high press turbine at 150 bar and 600°C & after Expansion in two stages is Exhausted at 10 KPa. If the moisture content of the Exhausted Steam should not Exceed 10.4 %. find.
   a) The press. at which the steam should be Reheated
   b) Thermal Efficiency. (Assume Steam Reheated Same Temp)

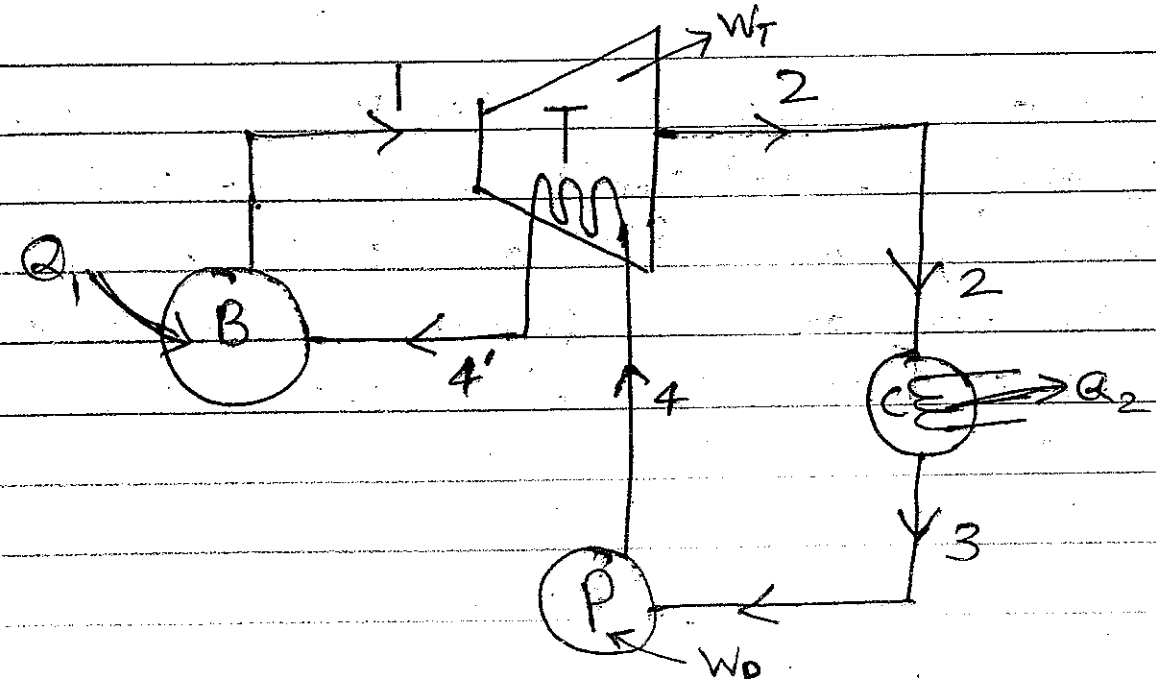
3. A Steam power plant operates on an ideal Reheat Rankine cycle. b/n the press. limit of 9 MPa & 10 KPa. The Mass flow rate of steam through the cycle is 25 kg/sec. Steam enters both the stages of the turbine at 500°C. If the moisture Content of the Steam exiting the low. press. turbine should not excess 10%.

Determine →
   a) The Reheat pressure
   b) Total rate of heat Input in the boiler.
   c) Total rate of heat Rejection in Condenser

Principle of Regeneration :→

The mean temp. of heat addition in the Rankine cycle can be improved by increasing the heat supplied at high temp. such as increasing Superheat, increasing boiler press., & using Reheat. The mean temp. of heat addition can also be increased by decreasing the amount of heat Supplied at lower temp.





In Saturated Rankine cycle shown fig. if the feed water enters the boiler at the state 4' and all heat supplied at Constant temp. (T_H), then the cycle is called an ideal regenerative cycle.

In ideal Regenerative cycle, the Condensate leaving the pump enters the turbine at the state (4) & flows in Counterflow direction to the steam flow. Thus it is passible to heat the feed water to steam temp. at inlet to the turbine if at all points the temp diff^n b/n steam & feed water is negligibly Small then the heat transfer takes place in reversible manner. for such process.

$$\left\{ \begin{array}{l} (\Delta T)_{water} = -(\Delta T)_{steam} \\ (\Delta S)_{water} = -(\Delta S)_{steam} \end{array} \right\}$$

During an ideal regeneration the steam cools first to the state (5) and then Expands to the state 2'. The slop of line (1-5) and (4-4'), in fig (2) will be identical at every point. The area (a-4-4'-b and (c-5-1-d-c) are equal & Congruous. There fore, all the heat in the boiler is supplied at Constant temp. (T_H) and all the heat is rejected at Constant (T_L) both being reversible

$$q_{in} = h_1 - h_{4'} = T_H (S_1 - S_{4'})$$

$$q_{out} = h_{2'} - h_3 = T_L (S_{2'} - S_3) \qquad (S_1 - S_{4'}) = (S_{2'} - S_3)$$

$\boxed{\eta_R = 1 - \frac{q_{out}}{}}$ $\boxed{1 - \frac{T_L}{}}$

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The efficiency of an ideal Regenerative cycle is thus equal to efficiency of Carnot cycle. Since the steam is first used to heat the feed water from (1-5) & then allows to expand from state 5 to 2', & therefore, the net work output of an ideal regenerative cycle is less & steam rate will be more although it is more efficient as compared with simple Rankine cycle.

However such a proposition is not practical for some reason.

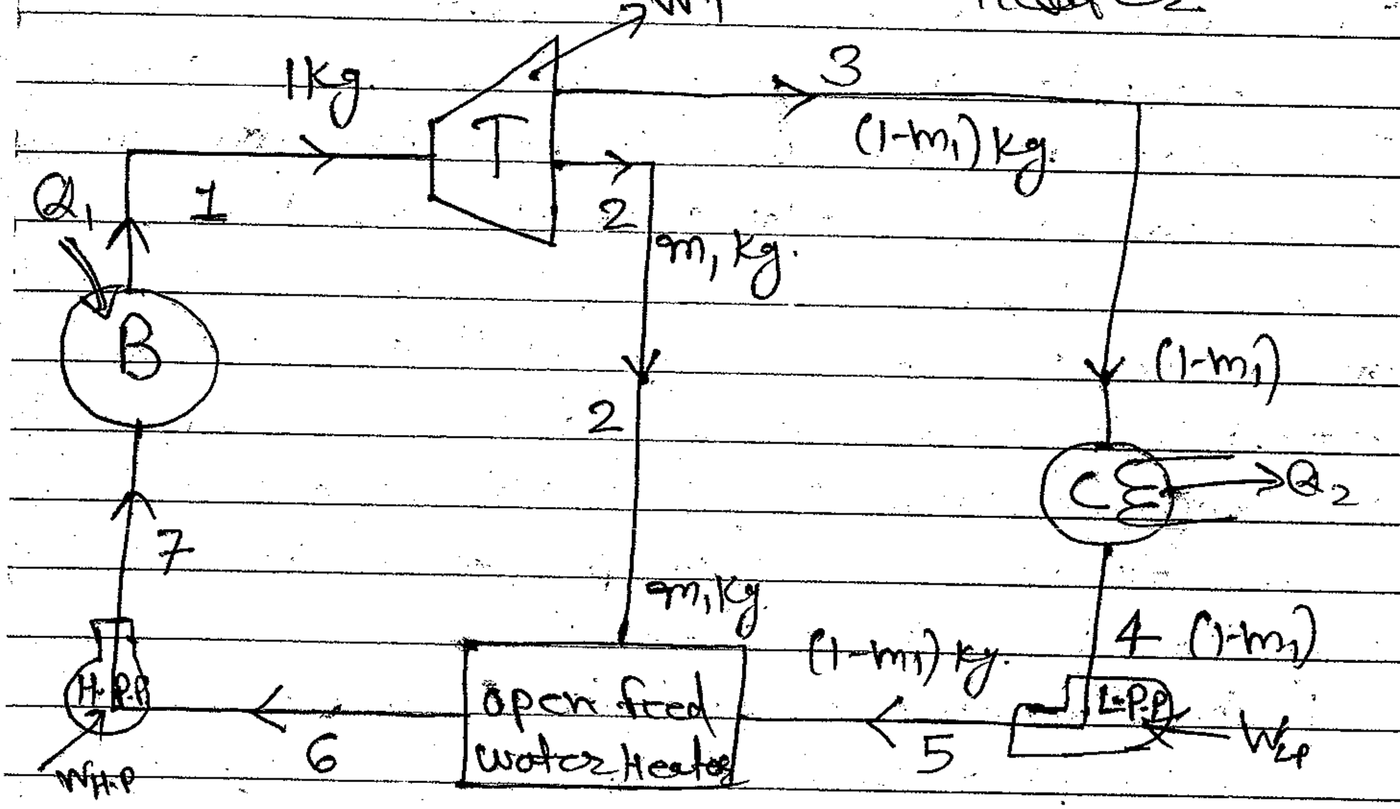
1. The Transfer of heat in reversible manner takes place very slowly.
2. Heat exchange in the turbine is not mechanic feasible.
3. The moisture content of steam in the turbin will be very high.

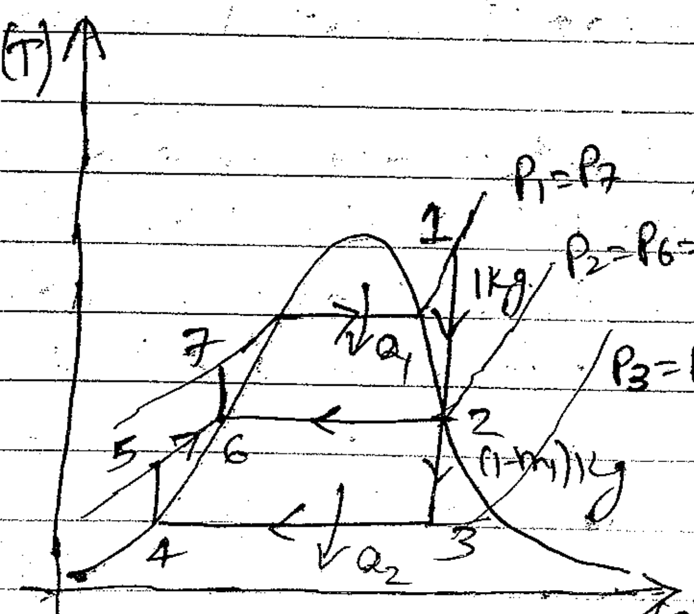
In actual practice advantage of Regenerative heating principle is used by extracting a) a part of the steam from turbine at a certain stage of the expansion & it is used for heating of feed water in seprate feed water heaters. This arrangement does not reduce the dryness fraction of remaining steam passing through Turbine.

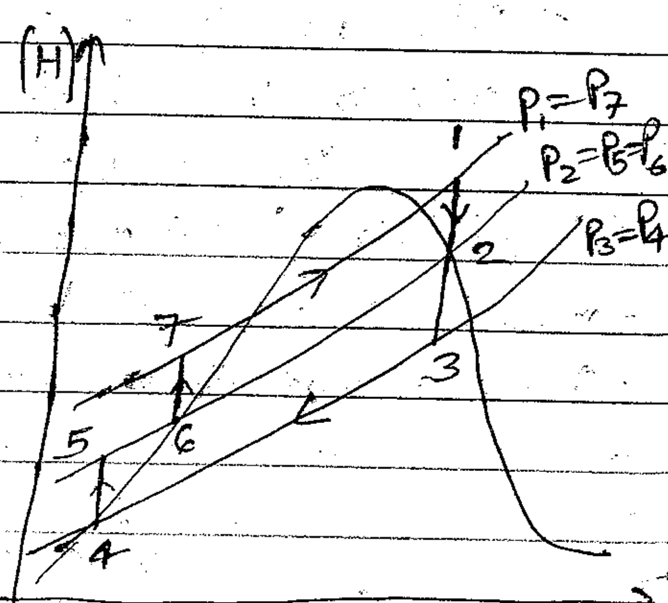
If there are no of feed water heat increased for heating water, then the resulting cycle would approach to be Carnot cycle

Regeneration with Open feed water Heater :→

(a) Single feed water Heater







Let, 1kg of steam flow through turbine

m_1 = Mass of steam Extracted from turbine (kg)

$(1-m_1)$ = Mass of steam is condensed.

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In these cycle, with open feed water heater is used. in which a part of steam (superheated) which enters the turbine at state (1). is extracte from the turbine at the intermidiate state (2) of the turbine expansion process. The extracted steam is supplied to a heat exchanger known as feed water heater. The remaining amount of steam in the turbine expand completly to a condenser press. state (3). The condensate a saturated liquid at state (4) is pumped isentroopically by Low press pump (LPP), to the press. of extracted steam. The compressed liquid at state (5) enters the feed water heater & its mixes with steam extracted from turbine due to direct mixing process the feed water is called open feed water heater (Direct mixing) type feed water heater.

$P_7 = P_5 = P_6$

$P_3 = P_4$

The portion of steam extracted is so adjuste to make the mixture leaving the feed water heater to be saturated at the state (6). Now this saturated water is pumped by High press. to boiler press. state (7) with regeneration. the average temp. at which heat is added has been increased; therefore the efficiency of Rankine cycle can be improved.

(5)

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Analysis;

$$\left\{\begin{array}{l}\text{Heat supplied in Boiler } (Q_1) = h_1 - h_2 \\ \text{Heat Rejected in Condenser } (Q_2) = (1-m_1)(h_3 - h_4)\end{array}\right.$$

Energy Balance in feed water heater
Calculate (m_1)

$$E_{in} = E_{out}$$

$$m_1 h_2 + (1-m_1) h_5 = h_6$$

$$m_1 h_2 + h_5 - m_1 h_5 = h_6$$

$$m_1 (h_2 - h_5) = h_6 - h_5 \qquad \boxed{m_1 = \frac{h_6 - h_5}{h_2 - h_5}}$$

Turbine Work $\boxed{W_T = (h_1 - h_2)\times 1 + (1-m_1) h_2 - h_3}$

Pump work;

$$\left\{\begin{array}{l} W_{L.P} = (1-m_1)(h_5 - h_4) \\ W_{H.P} = (h_7 - h_6)\end{array}\right. \qquad \boxed{\begin{array}{l} W_{L.P} = V_{f@P_4} \times (P_5 - P_4) \times 100 \\ W_{H.P} = V_{f@P_6} \times (P_7 - P_6 \times 100\end{array}}$$

$$W_{\text{Total pump work}} = (1-m_1)(h_5 - h_4) + (h_7 - h_6)$$

$$\eta_{R_0} = \frac{W_{net}}{Q_1} = \frac{W_T - W_P}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

In Regenerative type Cycle;
The feed water enters the boiler at temp (T_7) and its mean temp. of heat addition.

heat
b/w
T
be

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$$T_m = \frac{h_1 - h_7}{S_1 - S_7}$$

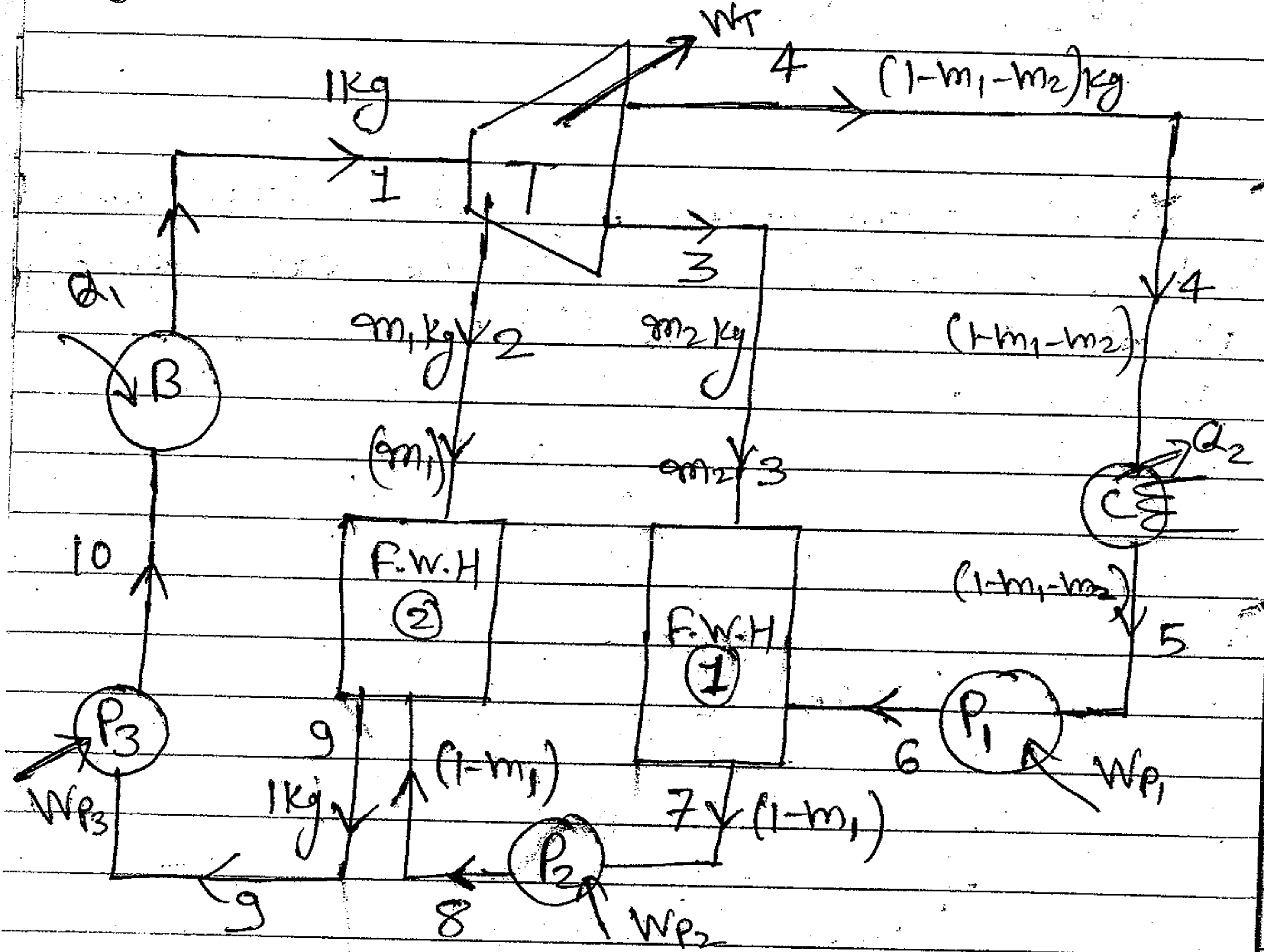
If, the mean temp of heat addition, without heat generation for simple Rankine cycle operating b/n the Same press (P_1) & (P_3) would be; & Temp of water which is enters to the boiler is

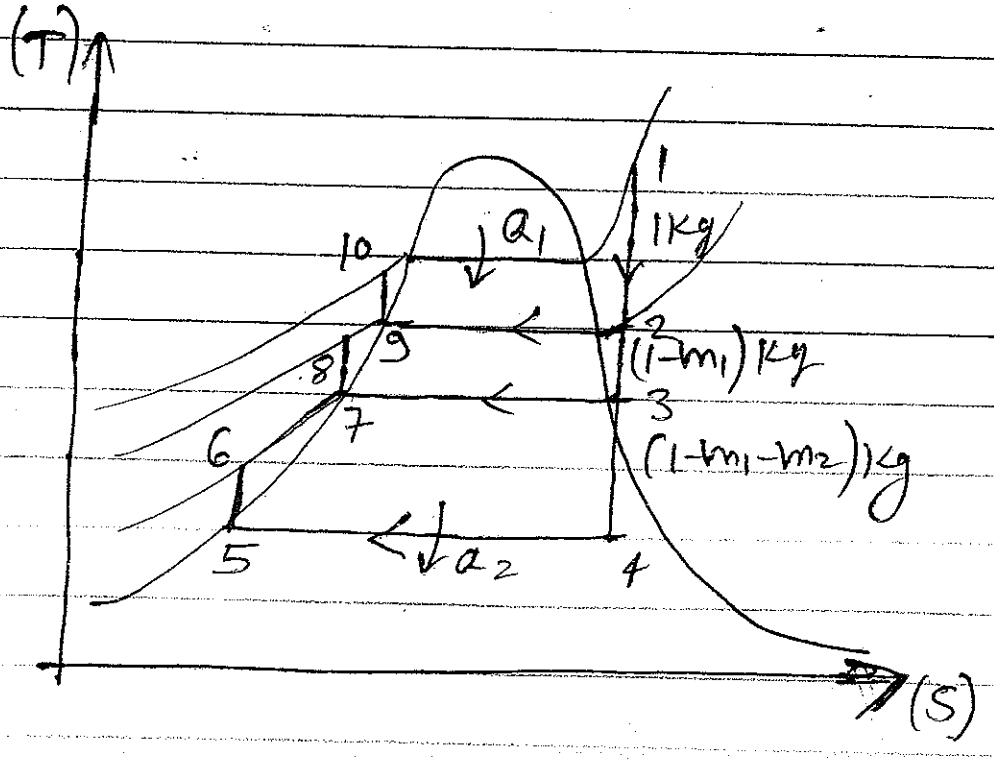
$$Q_1 = h_1 - h_7 = T_m (S_1 - S_5)$$

$$\boxed{T_{m(Reg)} = \frac{Q_1}{S_1 - S_5} = \frac{h_1 - h_7}{S_1 - S_5}}$$

$$\boxed{T_{m(Reg)} > T_{m(R)}}$$

Regeneration with Double feed water heater :→





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→ Analysis of Regeneration cycle;

$$W_T = (h_1 - h_2) + (1-m_1)(h_2 - h_3) + (1-m_1-m_2)(h_3 - h_4)$$

$$W_{P_1} = (1-m_1-m_2) \times (h_6 - h_5)$$
$$W_{P_2} = (1-m_1)(h_8 - h_7)$$
$$W_{P_3} = 1 \times (h_{10} - h_9)$$

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

Q_2

$$\boxed{W_{Total}(P) = (1-m_1-m_2)(h_6 - h_5) + (1-m_1)(h_8 - h_7) + (h_{10} - h_9)}$$

Heat added in Boiler $(Q_1) = (h_1 - h_{10})$

Heat Rejected in Condenser $(Q_2) = (1-m_1-m_2) \times (h_4 - h_5)$

Energy Analysis in [F.W.H-1]

$$E_{in} = E_{out}$$

$$m_2 h_3 + (1-m_1-m_2) h_6 = (1-m_1) h_7$$

$$m_2 h_3 + h_6 - m_1 h_6 - m_2 h_6 = h_7 - m_1 h_7$$

$$m_2 h_3 + h_6 - \left(\frac{h_9 - h_8}{h_2 - h_8}\right) h_6 - m_2 h_6 = h_7 - \left(\frac{h_9 - h_8}{h_2 - h_8}\right) h_7$$

Solve them, get

[F.W.H. - 2]

$$E_{in} = E_{out}$$

$$m_1 h_2 + (1-m_1) h_8 = h_9$$

$$m_1 h_2 + h_8 - m_1 h_8 = h_9$$

$$m_1 (h_2 - h_8) = h_9 - h_8$$

$$m_1 = \frac{h_9 - h_8}{}$$

$m_2 =$

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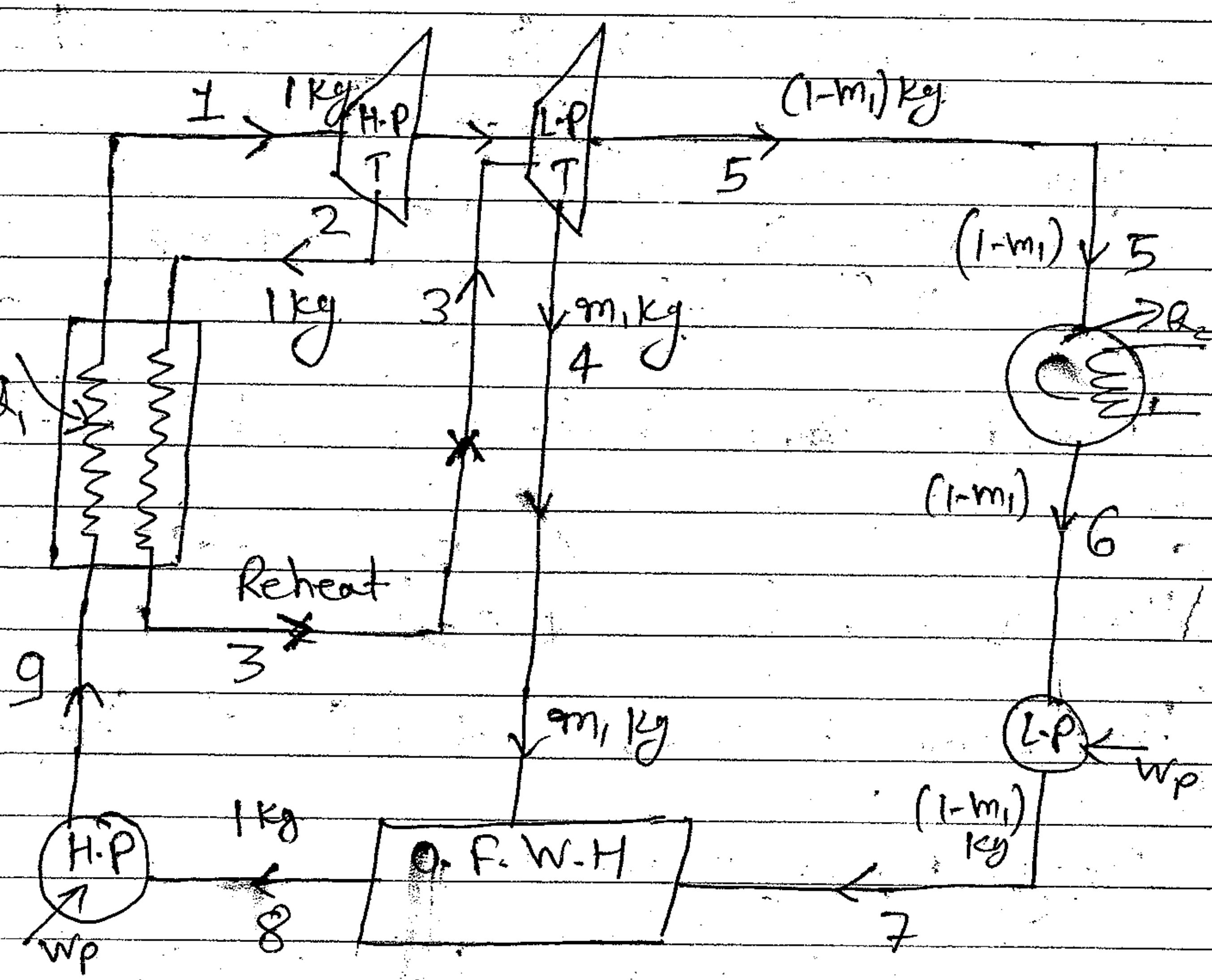
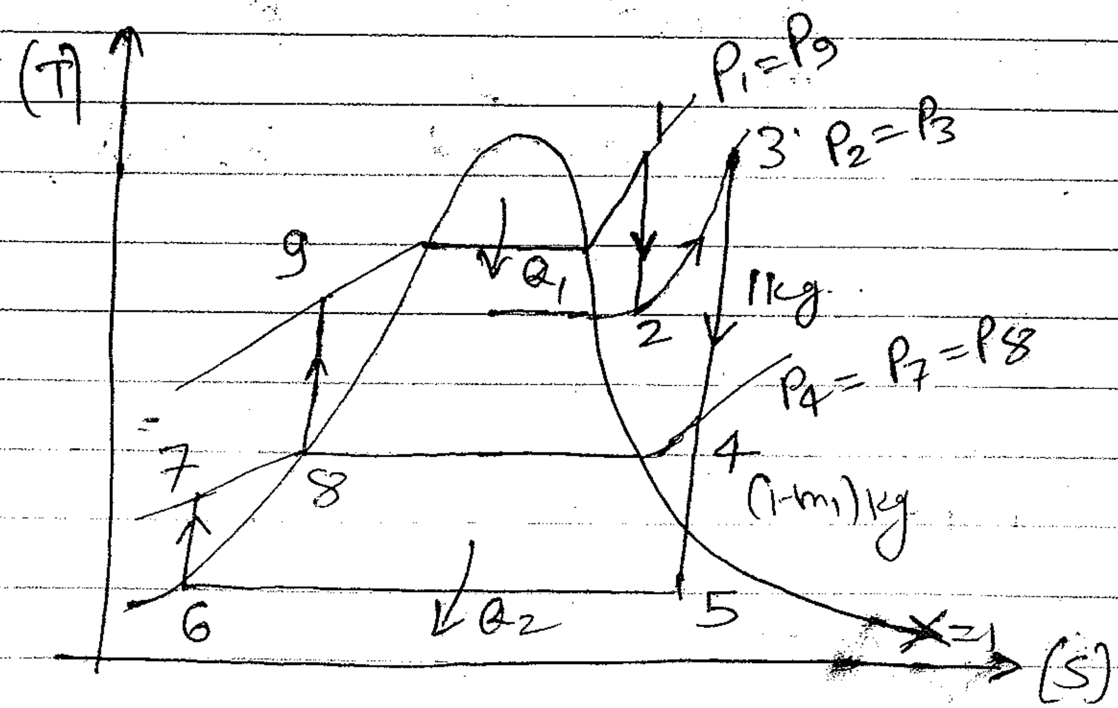
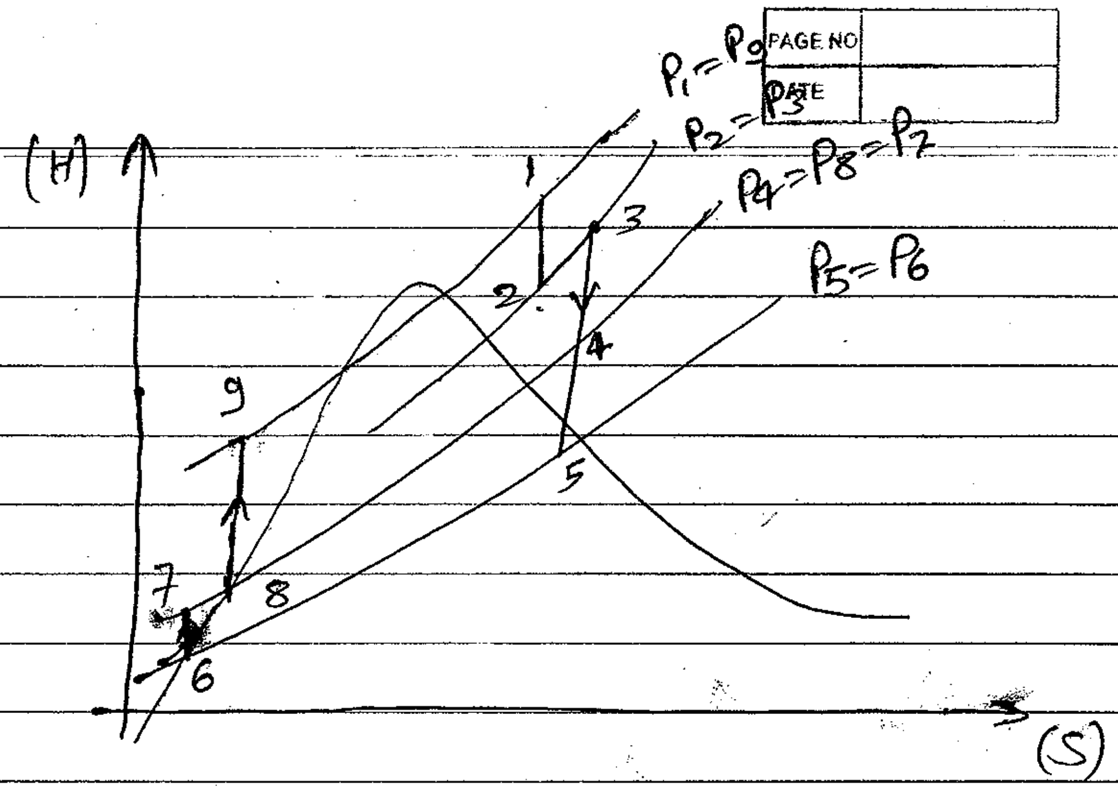
Reheat & Regenerative Rankine cycle :→







Q_2

Apply. S.F.E.E in Open feed water $E_{in} = E_{out}$

$$m_1 h_4 + (1-m_1) h_7 = h_8$$

$$m_1 h_4 + h_7 - m_1 h_7 = h_8$$

$$h_8 - h_7 = m_1 (h_4 - h_7)$$

$$\boxed{m_1 = \frac{h_8 - h_7}{h_4 - h_7}}$$

$$Q_1 = (h_1 - h_9) + (h_3 - h_2)$$

$$Q_2 = (1-m_1)(h_5 - h_6)$$

$$\boxed{\eta_{R} = \frac{W_{net}}{Q_1} = \frac{W_T - W_P}{Q_1}}$$

$$W_T = (h_1 - h_2) + (h_3 - h_4) + (1-m_1)(h_4 - h_5)$$

$$W_{L.P} = (1-m_1)(h_6 - h_7) \qquad W_{H.P} = (h_9 - h_8)$$

$$\boxed{W_{L.P} = (1-m_1) \times V_{f@P_6} \times (P_7 - P_6) \times 100}$$

$$\boxed{W_{H.P} = V_{f@P_7} \times (P_9 - P_8) \times 100}$$

$$\boxed{\begin{aligned} h_7 &= h_6 + W_{L.P} \\ h_9 &= h_8 + W_{H.P} \end{aligned}}$$

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UNIT-III "Gas Dynamics"

"Compressible fluid flow"

fluid is the substance which deforms continously due to the some shear. In fluid the intermolecular forces are week as compare to solids. ie Liquid & Gases

Liquid :→ A something which having finite/fixed volume. it takes the shape of container. Rate of change of density with respect to press. is Negligible $\frac{\delta \rho}{\delta P} \simeq 0$, $\frac{\delta \delta}{\delta P} = 0$

$\rho \neq f(P)$; Assumed Density is constant.

Gases :→ Volume is not finite. Rate of change of density with respect to press. is not Negligible $\frac{\delta \rho}{\delta P} \neq 0$

$\rho = f(P), (T)$ with leads Equation of State.

A compressible flow is defined as that flow in which the density of the fluid does not remains constant during the flow. This means the density changes from point to point in compressible flow.

But; In-compressible flow, the density of fluid is assumed to be constant.

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Applications

1) flow of gases through orifices & Nozzles.
2) flow of gases in machines such as Compressor
3) flow of gases in projectiles & airplanes flying at high altitude with which high velocity the density of fluid changes during this flow

The change in density of fluid is a accompained by changes in pressure & temp. & hence the thermodynamic behaviour of fluid will have to be taken in to account.

$$\rho = f(P, T)$$

Equation of state;

$$[PV = RT]$$

$$\frac{1}{V} = \rho \qquad \frac{1}{\rho} = V$$

$$\frac{P}{\rho} = RT$$

$$\boxed{P = \rho RT} \qquad \left\{\frac{P}{\rho} = RT\right\}$$

P = pressure in (N/m²)

ρ = Density of fluid (kg/m³)

R = Characterstic gas Constant (KJ/kg·K)

T = Absolute Temp. (K)

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Expansion & Compression of perfect gas:→

When the Expansion or compression of a perfect gas takes place, the press, temp, & density are changed. The change in press, temp, & density of gas is brought about two process.

1) Isothermal process.
2) Adiabatic process.

1) Isothermal process:→ $\left[PV = C\right]$ $\left[T = 0\right]$ V = Specific Volume
P = press.

$$\boxed{\frac{P}{\rho} = \text{Constant}} \qquad V = \frac{1}{\rho}$$

In which gas is compressed or Expand while the temp. is kept constant.

2) Adiabatic process:→ $\left[Q = 0\right]$ $PV^K = C$

$$\boxed{K = \frac{C_p}{C_v}} \qquad \boxed{\frac{C_p}{C_v} = 1.4}$$

K = Ratio of specific heat at Constant press to the Specific heat at Constant volume,

then

$$PV^K = \text{Const} \qquad \frac{1}{V} = \rho$$

$$\boxed{\frac{P}{\rho^K} = \text{Constant}}$$

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Basic Equation used in Compressible flow.

1) Continuity Equation
2) Bernoulli's Equation
3) Momentums Equation
4) Equation of State.

Continuity Equation:→

This is based on the law of conservation of mass, which state that the matter can not be created nor destroyed, or in other word, the matter or mass is constant. for one dimensional Steady flow, the mass per second $= \rho \times A \times V$

ρ = Density of fluid (kg/m³)
A = Cross-section Area (m²)
V = Velocity (m/sec)

$$\boxed{\rho AV = \text{Const}}$$

diffn above equation

$$d(\rho AV) = 0$$
$$\rho\, d(AV) + AV\,d\rho = 0$$
$$\rho[A \cdot dV + V \cdot dA] + AV\,d\rho = 0$$
$$\rho A\,dV + \rho V\,dA + AV\,d\rho = 0$$

divided by ρAV

$$\frac{\rho A\,dV}{\rho AV} + \frac{\rho V\,dA}{\rho AV} + \frac{AV\,d\rho}{\rho AV} = 0$$

Continuity Equation $\boxed{\frac{dV}{V} + \frac{dA}{A} + \frac{d\rho}{\rho} = 0}$

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2) Bernoulies Equation :→

We Know that, Euler's Equation;

$$\left\{ \frac{dP}{\rho} + VdV + gdz = 0 \right\} \text{——— (1)}$$

Intrigating above Equation

$$\int \frac{dP}{\rho} + \int VdV + \int gdz = \text{Const}$$

$$\boxed{\int \frac{dP}{\rho} + \frac{V^2}{2} + gz = \text{Const}} \text{——— (2)}$$

In case of incompressible flow, the density (ρ) is constant & hence intrigation $\left(\frac{dP}{\rho}\right)$ is equal to the $\left(\frac{P}{\rho}\right)$.

But in case of Compressible flow the density (ρ) is not Constant. hence (ρ) can not be taken outside the intrigation sign. This change of (ρ) & (P) takes place acc to the Isothermal & Adiabatic process during Compressible flow.

The value of $|\rho|$ from these Equation in terms of (P) is obtained and is Substituted in $\int \frac{dP}{\rho}$ and then intrigation done.

Then the Bernoulies Equation is diffn for diffn process.

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(a) Isothermal process:→ $\left[\frac{P}{\rho} = \text{Const}\right]$ $\frac{P}{\rho} = C_1$

$$\rho = \frac{P}{C_1}$$

$$\int \frac{dP}{\rho} = \int \frac{dP}{P/C_1} = \int \frac{C_1\, dP}{P} = C_1 \int \frac{dP}{P}$$

$$= C_1 \log_e P$$

$$= \frac{P}{\rho} \log_e (P)$$

Substitue the value in equ (29)

$$\int \frac{dP}{\rho} + \frac{V^2}{2} + gz = \text{Const.}$$

$$\frac{P}{\rho} \log_e (P) + \frac{V^2}{2} + gz = \text{Const.}$$

Divided by g

$$\boxed{\frac{P}{\rho g} \log_e P + \frac{V^2}{2g} + z = \text{Const}}$$

for Inlet - outlet section; (1-1) & (2-2)

$$\boxed{\frac{P_1}{\rho_1 g} \log_e P_1 + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\rho_2 g} \log_e P_2 + \frac{V_2^2}{2g} + z_2}$$

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→ (b) Adiabatic process: → $PV^{\gamma} = Con$ $K = \gamma$

$$PV^{K} = Const.$$

$$\left[\frac{P}{\rho^{K}} = C_1\right] \qquad \frac{1}{V} = \rho$$

$$\rho^{K} = P/C_1 \Rightarrow \rho = (P/C_1)^{1/K}$$

$$\Rightarrow \int \frac{dP}{\rho} = \int \frac{dP}{\left(\frac{P}{C_1}\right)^{1/K}} = \int \frac{C_1^{1/K}}{P^{1/K}}\, dP = C_1^{1/K} \int \frac{1}{P^{1/K}}\, dP$$

$$\Rightarrow C_1^{1/K} \int \left(P^{-1/K}\right) dP \Rightarrow C_1^{1/K} \times \frac{\left(P^{-\frac{1}{K}+1}\right)}{\left(-\frac{1}{K}+1\right)}$$

$$\Rightarrow \frac{C_1^{1/K} \times P^{\left(\frac{K-1}{K}\right)}}{\left(\frac{K-1}{K}\right)} \Rightarrow \frac{K}{K-1} \times C_1^{1/K} \times P^{\left(\frac{K-1}{K}\right)}$$

$$\Rightarrow \left(\frac{K}{K-1}\right) \times \left(\frac{P}{\rho^{K}}\right)^{1/K} \cdot P^{\frac{K-1}{K}}$$

$$\Rightarrow \frac{K}{K-1} \times \frac{P^{1/K}}{\rho} \times P^{\frac{K-1}{K}} \Rightarrow \left(\frac{K}{K-1}\right) \times \frac{P^{\frac{1}{K}+\frac{K-1}{K}}}{\rho}$$

$$\Rightarrow \left(\frac{K}{K-1}\right) \times \frac{P}{\rho}$$

put in equ (2)

$$\Rightarrow \left(\frac{K}{K-1}\right) \times \frac{P}{\rho} + \frac{V^2}{2} + gZ = Const$$

divided by g

$$\boxed{\left(\frac{K}{K-1}\right) \times \frac{P}{\rho g} + \frac{V^2}{2g} + Z = Constant}$$

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Velocity of Sound/pressure wave in fluid →

The disturbance in a solid, liquid or gas is transmitted from one point to the other. The velocity with which the disturbance is transmitted depends upon the distance between the molecules of the medium.

In case of solid, molecules are closely packed and hence the disturbance is transmitted instantaneously. In case of liquids and gases (fluids) the molecules are relatively apart. The disturbance will transmitted from one molecule to next molecules. Thus the velocity of disturbance in case of fluids will be less than the velocity of the disturbance in solids.

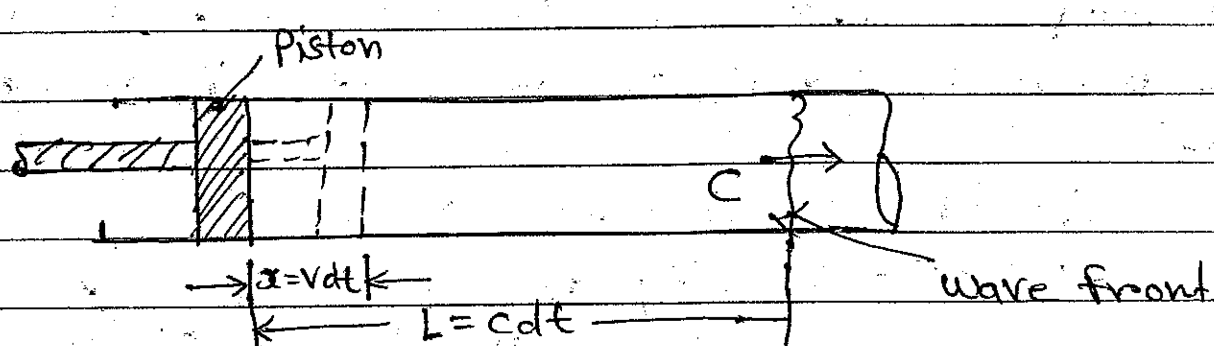
The distance between the molecules is related with the density, which in turn depends upon press. in case of fluids. hence the velocity of disturbance/press wave in a fluid depends upon the change in press. and density of the fluids.

Expression

$$\boxed{c = \sqrt{\frac{dp}{d\rho}}}$$

The disturbance creates the press. wave in a fluid, these press. wave travel with a velocity of sound waves in all direction, but for the sake of simplicity, one dimensional case will be considered.

Fig shows the model for one dimensional propagation of the press. wave. It is a right-long pipe of uniform cross-sectional area, fitted with piston. Let the pipe is filled with a compressible fluid which is at rest initially. The piston moves towards right & disturbance is created in the fluid. This disturbance is in the form of press. wave, which travels in the fluid with a velocity of sound wave.



Let; A = Cross-sectional area of pipe (m^2)
V = Velocity of piston (m/sec)
P = Press. of the fluid in pipe before the movement of piston.
ρ = Density of fluid before the movem. of
dt = A small interval of time, with which piston is moved
C = Velocity of press. wave or sound wave travelling in the fluid.

Distance travelled by the pistion in time (dt)
= Velocity × time

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Net force on the fluid = Rate of change of m V

$(P+dP)\times A - P\times A$ = Mass per second

$\cancel{PA} + dP.A - \cancel{PA}$ = $\frac{\text{Total mass}}{\text{time}}$ × Change in velocity

$$dP\times A = \frac{\rho\times A\times L}{dt}\times(V-0)$$

$$dP\times A = \frac{\rho\times A\times L\, V}{dt} \qquad L = C.dt$$

$$dP\times A = \frac{\rho\times A\times C.\cancel{dt}.V}{\cancel{dt}}$$

$$dP\times \cancel{A} = \rho\times \cancel{A}\times C V$$

$$dP = C\times \rho V \qquad \boxed{C = \frac{dP}{d\rho V}} \text{ — (5)}$$

multiply equation (4) & (5)

$$C^2 = \frac{dP}{d\cancel{\rho V}}\times\frac{\cancel{\rho V}}{d\rho}$$

$$C^2 = \frac{dP}{d\rho} - \boxed{C = \sqrt{\frac{dP}{d\rho}}} \text{ — (A)}$$

Hence the above equation gives the velocity of sound wave, which is the square root of the ratio of change of pressure to the change of density of fluid due to disturbance.

<u>Velocity of Sound for Isothermal process:→</u>

$$\frac{P}{\rho} = \text{Const.}$$

city

$$P\rho^{-1} = \text{Constant}$$

diff^n the above equation (P & ρ) both are Vario

$$-P\rho^{-1-1}\cdot d\rho + \rho^{-1}dP = 0$$

$$-P\rho^{-2}d\rho + \rho^{-1}dP = 0$$

divied by ρ^{-1}

$$-\frac{P\rho^{-2}}{\rho^{-1}}d\rho + \frac{\cancel{\rho^{-1}}}{\cancel{\rho^{-1}}}dP = 0$$

$$-P\rho^{-1}d\rho + dP = 0$$

$$dP = P\cdot\rho^{-1}d\rho$$

)

$$\frac{dP}{d\rho} = \frac{P}{\rho}$$

$$\frac{dP}{d\rho} = \frac{P}{\rho}$$

[from equation of State $P/\rho = RT$]

(A) $$\frac{dP}{d\rho} = RT$$

we also know th

$$\frac{dP}{d\rho} = c^2$$

city

$$c^2 = RT$$

of

$$\boxed{C = \sqrt{RT}}$$

nge

where, R = characteristic gas constant

Velocity of Sound for Adiabatic process :→

$$\frac{P}{\rho^{K}} = \text{constant}$$

$$P\rho^{-K} = \text{Const.}$$

Diff^{n} the above Equation we get;

$$-P \times K \times \rho^{-K-1}\, d\rho + \rho^{-K}\, dP = 0$$

divided by ρ^{-K} both side

$$-P \times \frac{\cancel{\rho^{-K}} \times \rho^{-1} \times K\, d\rho}{\cancel{\rho^{-K}}} + \frac{\cancel{\rho^{-K}}\, dP}{\cancel{\rho^{-K}}} = 0$$

$$-\frac{P}{\rho} K \cdot d\rho + dP = 0$$

$$dP = \frac{P}{\rho} \times K\, d\rho$$

$$\frac{dP}{d\rho} = \frac{P}{\rho} \times K \qquad \left[\frac{P}{\rho} = RT\right]$$

$$\frac{dP}{d\rho} = RT \times K$$

$$\frac{dP}{d\rho} = K \times RT \qquad \left[\frac{dP}{d\rho} = c^{2}\right]$$

$$\boxed{C = \sqrt{KRT}}$$

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→ Imp. 1) for the propagation of the minor disturbance through air, the process is assumed to be adiabat the velocity of the disturbances (press. waves) through air is very high & hence no time fo any appreciable heat transfer.

2) Isothermal process is considered for the calculation of the velocity of sound waves or (press. waves) only when it is given in the numerical problem that process is isothermal. If no process is mentioned, it is assumed to be adiabatic.

Stagnation properties:→

when analyzing control volumes, we find it very convenient to combine the internal energy & flow energy of fluid in to a single term. Enthalpy.

$$h = U + P \times V$$

$$h = U + P/\rho$$

→ whenever the K.E & P.E of the fluid are negligible as in these case the enthalp represent total energy of the fluid.

→ for high speed flow such as jet engines, the potential energy of the fluid is still negligible but the kinetic energy is not. In such cases, it is convienient to combine the enthalpy & kinetic energy of the fluid in or total Enthalpy (h_0) defined per unit mass as

$$\boxed{h_0 = h + \frac{V^2}{2}}$$

When the potential energy of the fluid is negligible, the stagnation enthalpy represent the total energy of a flowing fluid stream per unit mass. Thus it simplifies the thermodynamic analysis of high speed flows

h = static enthalpy
h_0 = stagnation enthalpy.

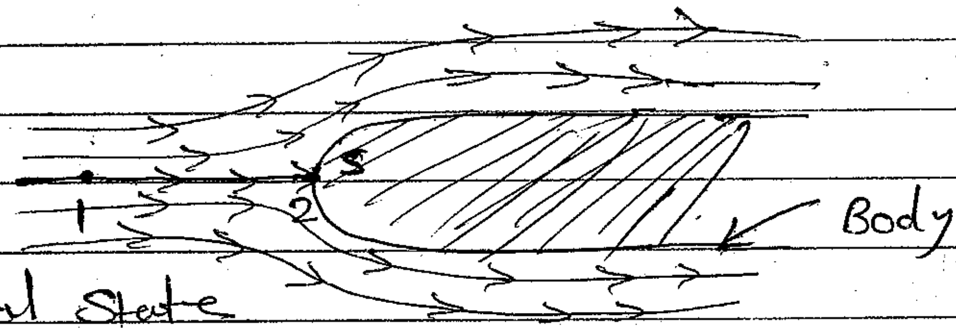
When the kinetic energy is negligible than the two enthalpies are identical.

→ The isentropic stagnation state, is also defined as the state of fluid in motion would reach, if it brought to rest isentropically in a steady flow, adiabatic zero work output device.

When a fluid is flowing past in immersed body and at a point on the body if the resultant velocity becomes zero, the value of press, temp & density at that point ~~[illegible]~~ called stagnation properties and these point is called stagnation point

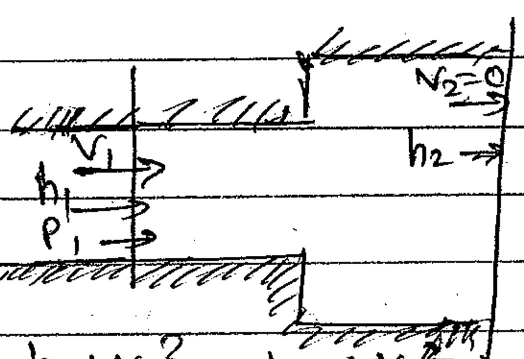
Consider a compressible fluid flowing past an immersed body under frictionless adiabatic condition as shown fig.

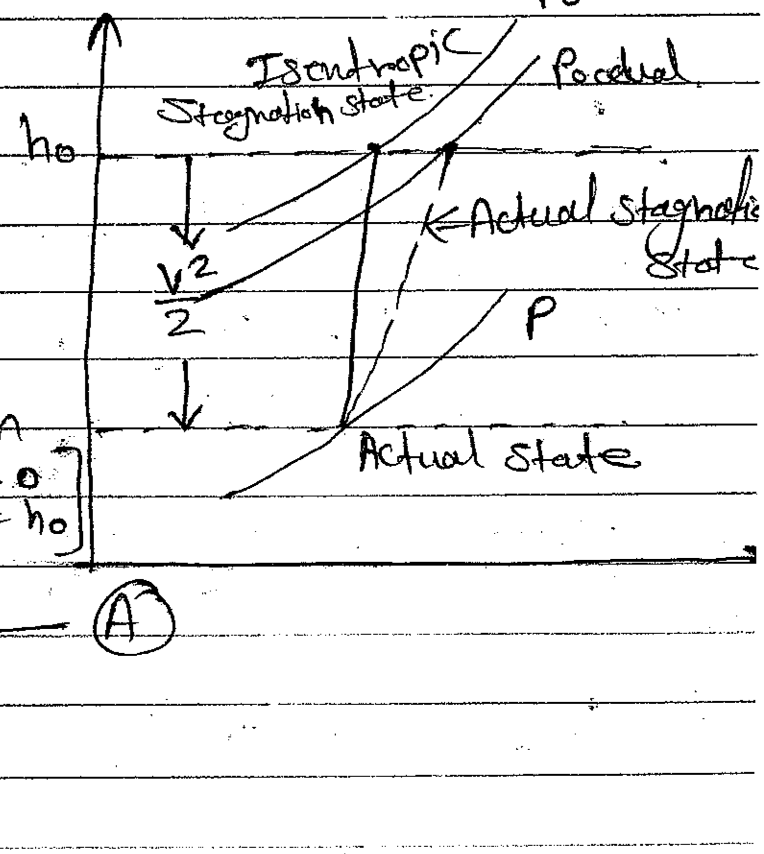
Consider two point (1) & (2) on stream line



1 = Initial State

2 = Stagnation point.





$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2} \qquad \begin{bmatrix} V_2 = 0 \\ h_2 = h_0 \end{bmatrix}$$

$$\boxed{h_0 = h + \frac{V^2}{2}} \quad \text{—— (A)}$$

$$h_0 - h = \frac{V^2}{2}$$

$$h = C_p \times T \quad \text{i.e.} \quad h_0 = C_p T_0$$

$$C_p T_0 - C_p T = \frac{V^2}{2}$$

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$$T_0 - T = \frac{V^2}{2C_p}$$

$$T_0 = \frac{V^2}{2C_p} + T$$

$$T_0 = T\left(1 + \frac{V^2}{2C_pT}\right)$$

$$\frac{T_0}{T} = 1 + \frac{V^2}{2C_pT}$$

$$C_p - C_v = R$$
$$C_p\left(1 - \frac{C_v}{C_p}\right) = R$$
$$C_p\left(1 - \frac{1}{K}\right) = R$$
$$C_p\left(\frac{K-1}{K}\right) = R$$
$$C_p = R \times \left(\frac{K}{K-1}\right)$$

$$\frac{T_0}{T} = 1 + \frac{V^2}{2 \times R \times \left(\frac{K}{K-1}\right) \times T}$$

$$\frac{T_0}{T} = 1 + \frac{(K-1) \times V^2}{2RKT}$$

$$C = \sqrt{KRT}$$
$$C^2 = KRT$$

$$\frac{T_0}{T} = 1 + \frac{K-1}{2}\,\frac{V^2}{C^2}$$

$$\left[M = \frac{V}{C}\right]$$

$$\boxed{\frac{T_0}{T} = 1 + \left(\frac{K-1}{2}\right)M^2} \quad \text{--- (1)}$$

mach No.

T = Local Temp.

We Also know that;
$$\frac{T_0}{T} = \left(\frac{P_0}{P}\right)^{\frac{K-1}{K}}$$

$$\frac{P_0}{P} = \left(\frac{T_0}{T}\right)^{\frac{K}{K-1}}$$

$$\boxed{\frac{P_0}{P} = \left[1+\left(\frac{k-1}{2}\right)m^2\right]^{\frac{k}{k-1}}} \quad (2)$$

Stagnation press.

Similarly for, Stagnat Density

$$PV^k = \text{Con} \qquad \frac{P}{\rho^k} = C$$

$$P = \rho^k$$

$$\frac{P_0}{P} = \left(\frac{\rho_0}{\rho}\right)^k \Rightarrow \frac{\rho_0}{\rho} = \left(\frac{P_0}{P}\right)^{\frac{1}{k}}$$

put in Above Equation (2)

$$\frac{\rho_0}{\rho} = \left[\left[1+\left(\frac{k-1}{2}\right)m^2\right]^{\frac{k}{k-1}}\right]^{\frac{1}{k}}$$

$$\boxed{\frac{\rho_0}{\rho} = \left[1+\left(\frac{k-1}{2}\right)m^2\right]^{\frac{1}{k-1}}}$$ Stagnation Density

$$\boxed{\frac{P_0}{P} = \left[1+\left(\frac{k-1}{2}\right)m^2\right]^{\frac{k}{k-1}}}$$ Stagnation pressure

$$\boxed{\frac{T_0}{T} = \left[1+\left(\frac{k-1}{2}\right)m^2\right]}$$ Stagnation Temp.

Mach Number :→

It is dimensionless number which is frequently used in study of jet engine, Aircraft and flow through a duct, Nozzles & diffuser etc.

It is the Ratio of local fluid Velocity to the Sonic Velocity / Acoustic velocity in the medium. [Mach No. at a point in flow field.

$$M = \frac{\text{fluid velocity}}{\text{Speed of Sound}} = \frac{V}{C}$$

The definition of mach. No. can also be interpreted as the Square root of the Ratio of the Inertia force due to the flow to the elastic force of fluid.

$$M = \sqrt{\frac{\text{Inertia force of flow}}{\text{Elastic force of fluid}}}$$

flow Regimes :→

1) $M<1$, Subsonic flow

If the fluid flow with a mach. No. less than unity that is $(V<C)$ then the flow is called Subsonic flow. Such flow is characterised by Smooth Stream lines & continously varying properties. $[M = 0.3 \text{ to } 1.]$

2) $M=1$; Sonic flow

In case $V=C$; fluid velocity & the speed of sound is equal.

3) ~~8M < 1.2~~ Transonic $[0.8 < M < 1.2]$

Compressor, Aircraft, fans, & steam turbines

4) Supersonic; $[M>1, \text{ or } 1.2]$

When the fluid velocity is more than the velocity of sound $(V>C)$ is called Supersonic flow.

5) Hypersonic flow; $M>5$; missilies, space Shuttle

If the fluid flow with a very high mach. No. ie $M>5$, then the flow is called (mach. No>5) hypersonic flow. Dynamical changes the properties of flow.

Q. Derive the Expression for Area-velocity Relationship for Compressible fluid in the form

or

prove That;

$$\boxed{\frac{dA}{A} = \frac{dv}{V}(m^2-1)}$$

Sol^n →

As we know that for a compressible fluid flow;

$$[\rho \times A \times V = C] \quad \text{—— (1)}$$

where;

ρ = Density of fluid (kg/m^3)
A = Cross-section area (m^2)
V = velocity of fluid (m/sec)

$$\rho A.V = C \quad \text{diff}^n \text{ eq}^n$$

$$\rho\, d(AV) + AV d\rho = 0$$

$$\rho[Adv + vdA] + AVd\rho = 0$$

$$\rho Adv + \rho vdA + AVd\rho = 0$$

divided by ρAV both s.

$$\frac{\cancel{\rho A}dv}{\cancel{\rho A}V} + \frac{\cancel{\rho V}dA}{\cancel{\rho}A\cancel{V}} + \frac{\cancel{AV}d\rho}{\cancel{A}\rho\cancel{V}}$$

$$\left[\frac{dv}{V} + \frac{dA}{A} + \frac{d\rho}{\rho}\right] \quad \text{—— (2)}$$

As we know that; it is equation of continuity with diff^n form.

ocity

form We Also Know that; Eulers Equation for Compressible fluid;

$$\left[\frac{dP}{\rho} + VdV + gdz = 0\right]$$

ble

Neglect potential ter(z).

$$\frac{dP}{\rho} + VdV = 0$$

dividing & multiply by ter $(d\rho)$

$$\frac{d\rho}{d\rho} \cdot \frac{dP}{\rho} + VdV = 0$$

$$\frac{dP}{d\rho} \cdot \frac{d\rho}{\rho} + VdV = 0$$

$$\left[\frac{dP}{d\rho} = C^2\right]$$

So

$$C^2 \cdot \frac{d\rho}{\rho} + VdV = 0$$

$$C^2 \frac{d\rho}{\rho} = -VdV$$

Hinuth

$$\left[\frac{d\rho}{\rho} = -\frac{V}{C^2} dV\right]$$

$$\boxed{\frac{dv}{V} + \frac{dA}{A} + \frac{d\rho}{\rho} = 0}$$

$$\frac{dv}{V} + \frac{dA}{A} - \frac{V}{c^2}\,dV = 0$$

$$\frac{dA}{A} = \frac{V}{c^2}\,dV - \frac{1}{V}\,dV$$

$$\frac{dA}{A} = dV\left[\frac{V}{c^2} - \frac{1}{V}\right]$$

$$\frac{dA}{A} = \frac{dV}{V}\left[\frac{V^2}{c^2} - 1\right]$$

$$\left[\frac{V}{c} = M\right]$$

$$\frac{dA}{A} = \frac{dV}{V}\left[M^2 - 1\right]$$

$$\boxed{\frac{dA}{A} = \frac{dv}{V}\left(M^2 - 1\right)}$$

Relationship b/n change of Area, with change of Velocity for different mach No.

Significance of Equation $\left\{\frac{dA}{A} = \frac{dv}{V}(M^2 - 1)\right\}$.

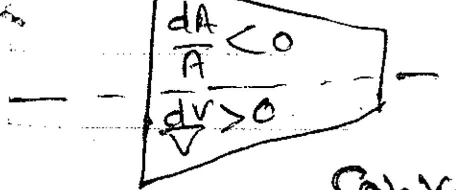
Ratio $\left(\frac{dA}{A}\right)$ can be Negative or positive depending upon the mach Number of the flow

① for Subsonic velocity $(M<1)$; (dA) & (dV) are opposite sign; an increase in Area of Cross-section, causes reduction in velocity & Vice-versa. This statement is also true for incompressible fluid flow.

② for supersonic velocity $(M>1)$ (dA) & (dV) are Same Sign, an increase of cross-section Area; then cause also increase in velocity & vice-versa

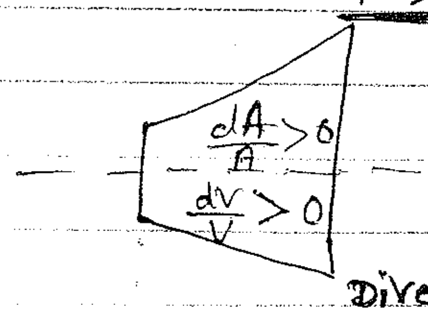
③ when $(M=1)$; dA must be zero and since the second derivative is positive (A) must be minimum, Thus the flow velocity equal to the Sonic velocity any where, it must be do so; where the cross-section is of minimum Area.

Subsonic	Supersonic
$\underline{M<1}$	$\underline{M>1}$



Converging

Area decreases



Diverging

Area Increases

Numericals

Q(1) Calculate the mach. No. of a point on a jet propelled air craft, which is flying at 1100 km/hr at sea level where air temp. is 20°C, Take $K = 1.4$ & $R = 287\ J/kg\,K$

Ans = $M = 0.89$

(2) An Aeroplane is flying at an height of 15 km, where the temp is -50°C The speed of the plane is Corresponding to $M = 2.0$. Assuming $K = 1.4$ & $R = 287\ J/kg\,K$ find the speed of plane

Ans :- $V = 2155.17\ km/hr$

(3) find the mach. No. when an aeroplane is flying at 1100 km/hr through still air having a pressure of $7\ N/cm^2$ and temp. -5°C, wind velocity may be taken as zero. Take $R = 287.14\ J/kg\,K$ Calculate the press., temp., & density of air at stagnation point on the nose of the plane.

Ans $M = 0.931$, $P_0 = 12.24\ N/cm^2$ $T_s = 314.4\ K$

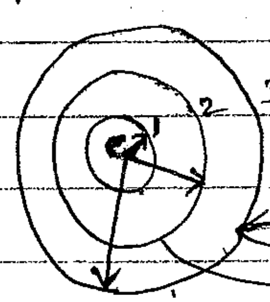
Propagation of pressure wave (DISTURBANCE) in a Compressible fluid flow:→

Whenever a disturbance is produced in a compressible fluid, the disturbance is propagated in all direction with velocity of Sound (Equal to C). The nature of propagation of the disturbance depends on the mach No.

Let us consider a Small projectile moving from left to right in a straight line in a stationary fluid. Due to the movement of the projectile the disturbances will be created in the fluid. The disturbance will be moving in all direction with a velocity (c).

→ press. field due to Stationary Source;

How press wave is created due to disturbance.



[Two Dimensional]

$C, \Delta t = 0$ After $3\Delta t$;

$1 \to \Delta t$ time $\to C\Delta t$ press. field.

$2 \to 2\Delta t$ time $\to 2C\Delta t$

$3 \to 3\Delta t$ time $\to 3C\Delta t$

... field due to moving a source;

Q Let;

V = Velocity of the projectile
C = Velocity of the press. wave/ Disturbance created in the fluid.

2 Nature of propagation of the disturbance of different Mach Number :→ Then to ...

(a) M < 1 ; Subsonic flow give...

$M = \frac{V}{C}$; $V < C$ whe... rea... the...

$V = 1$ unit.

find the Nature of propagation $C = 2$ unit Seco... 3C...

$\boxed{\frac{V}{C} = M = \frac{1}{2} = 0.5}$ $\quad 0.5 = \frac{V}{C} \Rightarrow \frac{V}{C} = \frac{1}{2}$ Simi...

$\boxed{2V = C}$

Let the projectile is at (A) is moving toward right. Let in 4 second the projectile reaches the position (B). At a point 4 is mark.
→ The projectile after 1 sec, 2 sec, 3 sec, 4 sec, along the line are shown in the point 3, 2, 1.

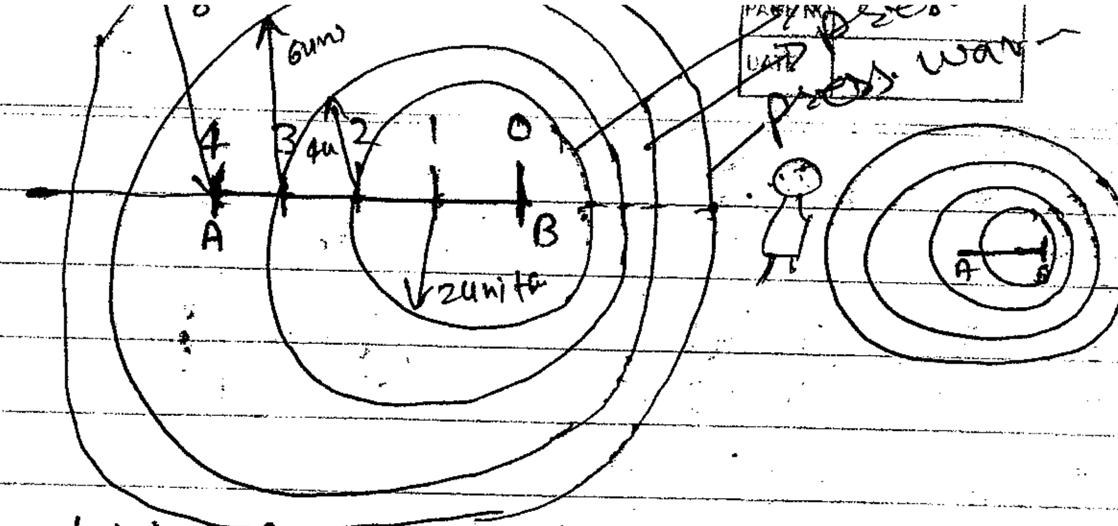
A... the... proj... Sphe...

→ Projectile moves A to B in 4 sec

$AB = 4V = 4 \times 1 = 4$ unit

→ The disturbance created at (A) in 4 sec. will move a distance $= 4C = 4 \times 2$ un $= 8$ unit.

at ... first...



Hence taking A as a center and radius equal to 8 unit, a circle is drawn. This circle gives the position of disturbance after 4 seconds.

When the projectile at point 3, it will be reach in 3 seconds. $3B = 3 \times V = 3$ units, but the disturbance created at point 3 in three second will move a distance having a radius $3C = 3 \times 2 = 6$ unit

Similarly at point 2 $\rightarrow 2C = 2 \times 2 = 4$ units
at point 1 $\rightarrow 1C = 1 \times 2 = 2$ unit

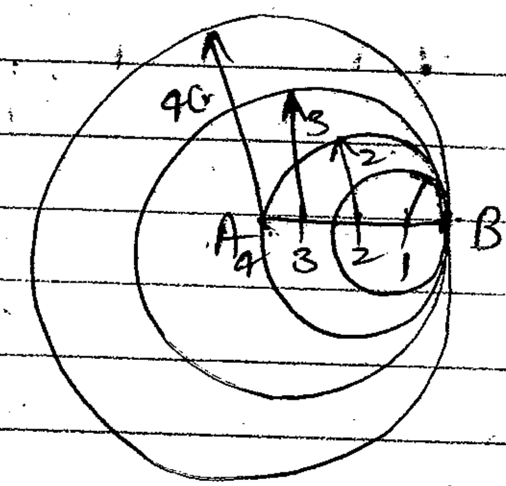
As in this case; $V < C$; means that the press wave is always ahead of the projectile and point B is inside the sphere of radius 8 units.

It means that when a observer at standing near point B, it listen or sees firstly the press wave before the projectile.

Q. (b) when $M=1$;

$$\boxed{M = \frac{V}{C} = \frac{1\ \text{units}}{1\ \text{units}}}$$

Sonic flow;



→ Disturbance / pressure wave allways travels with the projectiles.

Let the projectiles moves in 4 sec. from point (A) to (B)

→ The Disturbance Created (A) in 4 Sec at a distance having a radius $4C = 4 \times 1 = 4$ un. in all direction

→ The projectiles from point 3 will move to position (B) in three Seconds. The disturbance created at point 3, will move a distance having a radius $3C = 3 \times 1 = 3$ units.

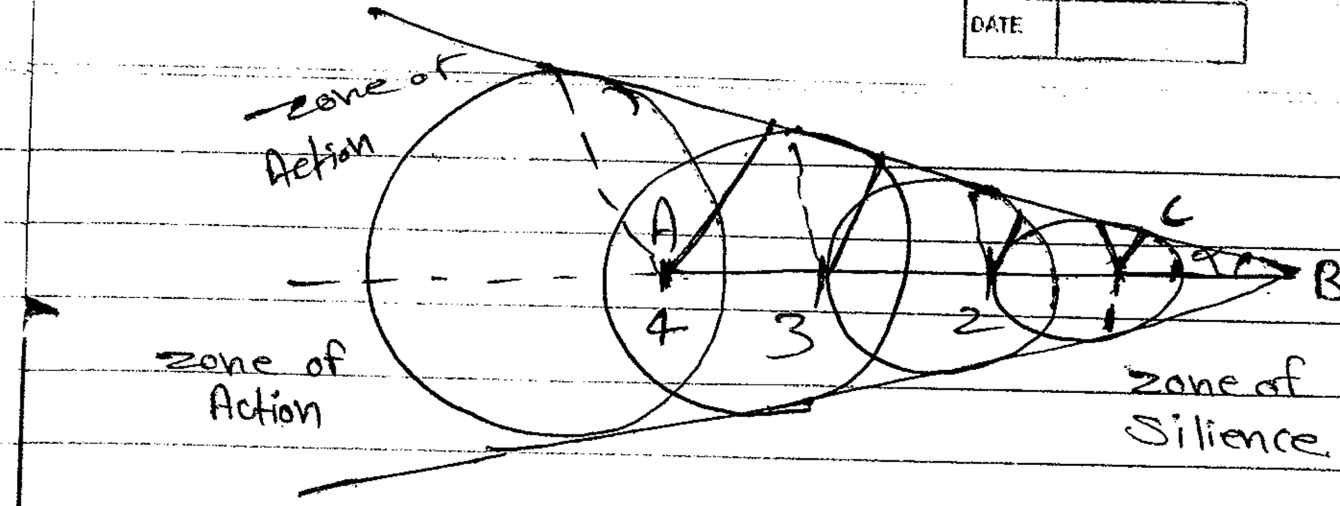
Means That; If a observer Standing behind the point (B), it observe that pressure wave/field and projectile both are reach similtaneously.

(c) when $M>1$; Supersonic flow,

let $V = 1$ unitc $C = 0.5$ Units

$$M = \frac{V}{C} = \frac{1\ \text{Units}}{0.5\ \text{Units}} \quad M = 2$$

$(M)\ 2 > 1$



let the proiectiles moves from (A) to (B) in 4 seconds. The distance travelled by proiectile in 4 sec. from A to B. $= 4V = 4$ units. hence take $AB = 4$ units

The disturbance created at (A) will move in all direction and in (4) seconds. the radius of disturbance will be equal to $4C$ $4 \times 0.5 = 2$ units, hence taking (A) as a centre draw a circle with radius equal to 2 units. After one second from (A) the proiectile will be at point (3) at distance $A3 = 3V = 3 \times 1 = 3$ units. The disturb. create $= 3C = 3 \times 0.5 = 1.5$ units. draw a circle as a centre (3).

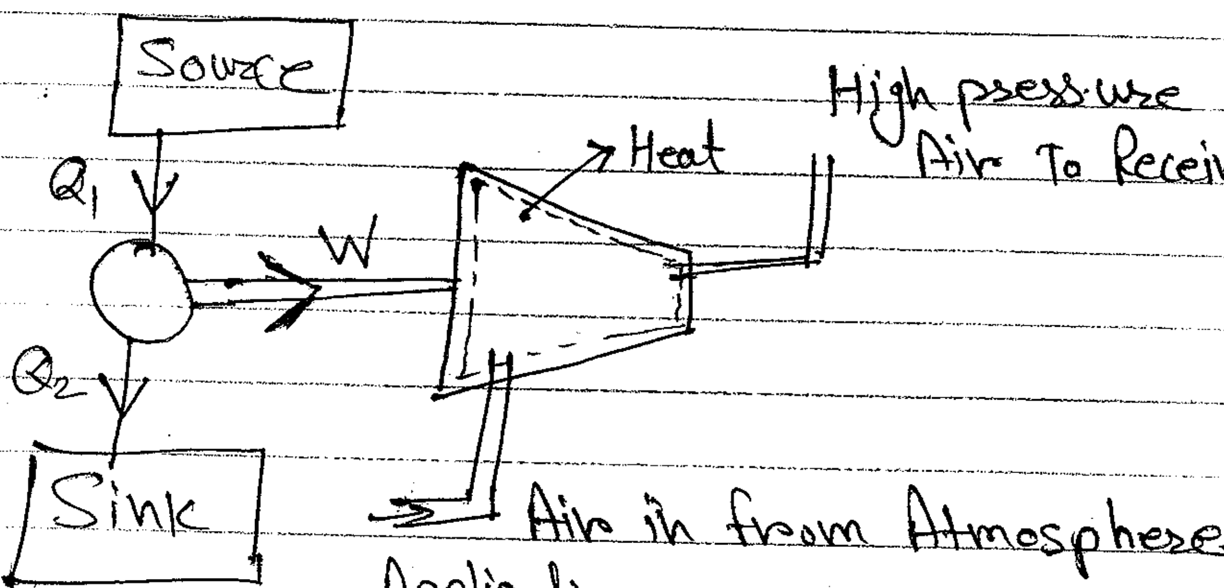
Mach Angle :→ $\sin\alpha = \frac{1C}{1V} = \frac{C}{V} \Rightarrow \alpha = \sin^{-1}\left(\frac{1}{V/C}\right) = \frac{1}{M}$

Zone of Action :→ when $M > 1$, the effect of disturbance is felt only in the region inside the mach cone.

Zone of Silence :→ when $M > 1$, there is no effect of disturbance in the region outside the

UNIT-IV (Air Compressors)

An air Compressor is a machine which takes in atmospheric air, Compresses it with the help of some mechanical energy and delivers it at higher pressure. It is also called Air pump. An air Compressor increase the press. of air by decreasing its specific Volume using mechanical means. The compressed air carries an immense potential of energy. The controlled expansion of compressed air provide motive force in air motors, Pneumatic hammers, air drills, Sand blasting machines & paint spray etc.



Application

→ Air Refrigeration & cooling of Large Building
→ Driving Pneumatic tool in shop like drills, Screw
→ Cleaning purposes, Blast furnace,
→ Spray painting & spray fuel in Diesel engine
→ Operating air brakes in buses trucks etc

Classification;

- Compressor
  - Positive Displacement
    - Reciprocating Compressor
    - Rotary Compressor
      - Roots Blower
      - Van type.
  - Dynamic Compressor
    - Centrifugal Compressor
    - Axial Compr

Positive Displacement type; →

In these type of Compressor air is physically trapped b/n two relatively moving components and forced to occupy lower volume there by increasing its pressure. The term positive displacement means that the volume of air is physically being displaced output of these Since the Constant volume is displaced by moving part every time.

Non positive/ Dynamic Compressor →

In these type a Rotating Component impart its Kinetic Energy to the air which is eventually Converted in to pressure energy. In these there is no physical displa

→ A Reciprocating is used to produce high press gas, it uses the displacement of piston in the cylinder for compression. It handles a low mass of gas & high press. Ratio.

→ A Rotary Compressor are used for low & medium press. They usually consist of bladed wheel or impeller that spins inside a circular housing. They handle Large mass of gas

Terminology used :→

→ Single Acting → one side of piston Acting
→ Double Acting. → Both side of piston Acts.
→ Single Stage / Double Stage / multistage
→ pressure Ratio — (P_f/P_i)
→ Free Air — At Atmospheric press, Temp Air
→ Compressor Displacement Volume
→ Capacity of compressor — (m^3/min / m^3/sec)

Compressed Air System :→

→ Intake Air filters
→ Inter Stage Cooler
→ After Cooler
→ Moisture Drain Traps
→ Air Receiver Tank
→ Air Dryers →

The Remaining traces of moisture after an intercooler are removed by using air

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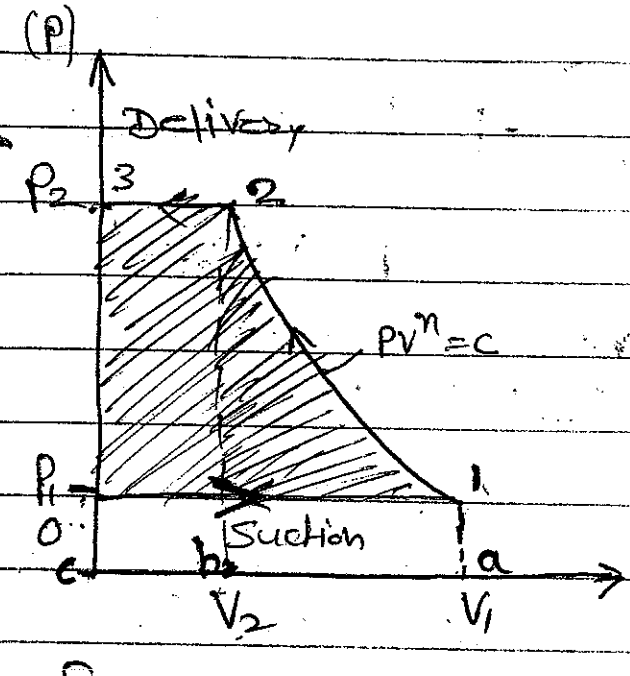
Indicated work for Single acting Compressor without Clearance :→



(1-2-3-0-1) = Area under the curve Represent the work done

$$\boxed{W_{Poly} = -\int_1^2 P\,dV \qquad W_{Poly} = -\left[\frac{P_2V_2 - P_1V_1}{1-n}\right]}$$

for process = 0-1 = suction at Constant pre

= 1-2 = Compress (polytropic)

= 2-3 = Delivery at Const. pres

$$(1-2-3-0-1) = (2-3-c-b-2) + (1-2-b-a-1) - (1-0-c-a)$$

$$W_{ind.} = \frac{P_2V_2 - P_1V_1}{n-1} + P_2V_2 - P_1V_1$$

$$W_{ind.} = (P_2V_2 - P_1V_1)\left[\frac{1}{n-1} + 1\right]$$

$$= (P_2V_2 - P_1V_1)\left[\frac{\cancel{1} + n - \cancel{1}}{n-1}\right]$$

$$= \frac{n}{n-1} \times (P_2V_2 - P_1V_1)$$

$$\boxed{W_{ind.} = \frac{n}{n-1} \times m_a R (T_2 - T_1)} \quad kJ/cycle$$

$$= \frac{n}{n-1} \times m_a R\, T_1 \left(\frac{T_2}{T_1} - 1\right)$$

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

$$\boxed{W_{in} = \frac{n}{n-1} \times m_a \times R \times T_1 \times \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]} \text{ KJ/Cycle}$$

$$P_1 V_1 = m_a R T_1$$

$$\boxed{W_{in} = \frac{n}{n-1} \times P_1 V_1 \times \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]} \text{ KJ/cycle}$$

If $\dot{m}_a$ = kg/sec then it indicated that Indicated power.

Similarly $\dot{V}_1 = m^3/sec$, then its also indicate, indicated power without clearance.

$$W_{in} = I.P = \frac{n}{n-1} \times \dot{m}_a \times R \times T_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] \text{ KW}$$

$$W_{in} = I.P = \frac{n}{n-1} \times P_1 \dot{V}_1 \times \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] \text{ KW}$$

→ M

acte

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$I_m = \frac{1}{2}$

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→ Mean effective press:→

It is a hypothetical average press., which is acted on the face of the piston during the entire Compression Stroke, will Require the same power input as Required during the actual cycle.

$$P_m = \frac{\text{Work Input}}{\text{Swept volume}} \quad \left\{ P_m = \frac{W_{in}}{V_s} \right\} \Rightarrow \left\{ W_{in} = P_m \times V_s \right\}$$

Powers & Mechanical Efficiency :→

Indicated power :→ (I.P)

The work done on air per unit time is called indicated power. Input to the Compressor. The power Required by an air Compressor running r.p.m;

$$I.P = \text{Work Input}/\text{cycle} \times \frac{\text{No. of cycle}}{\text{Time}}$$

$$\boxed{I.P = \frac{W_{in} \times N \times K}{60}} \quad \underline{\underline{KW}}$$

$$\boxed{I.P = \frac{P_{mi} \times L \times A \times N \times K}{60}} \quad \underline{\underline{KW}}$$

K = 2 = Double Act
K = 1 Single Acting

P_{mi} = Indicated mean effective press. (KN/m^2)
A = Cross-section Area of cylinder ($A = \pi/4 d^2$)
N = Number of Rotation per minute (R.P.M)

Brake power = (B.P) = (S.P)

The actual power (Shaft power) more than the indicated power, because Some work is Requiered to overcome the Irreversibilites & mechanical frictional effects. Shaft power is power supplied by electric motor to

$$\boxed{B.P = \text{Indicated power} + \text{Friction power}}$$

$$\boxed{B.P = I.P + F.P}$$

Mechanical efficiency → $\boxed{(\eta_{mec}) = \frac{I.P}{B.P}}$

The Brake power is desired from driving motor / Engine. The input of a driving motor Can be Expressed as.

$$\text{Motor power} = \frac{\text{Shaft power / Brake power}}{\text{mechanical efficiency}}$$

$$\boxed{\text{Motor power} = \frac{B.P}{\eta_{mech}}}$$

Minimization of Compressor Work :→

The work done on the gas for Compression can be minimized when the compression process is executed in an internally Reversible manner by minimizing the irreversibilities. The other way of reducing the compression work is to keep the Specific volume of a gas as small as possible during Compression process.

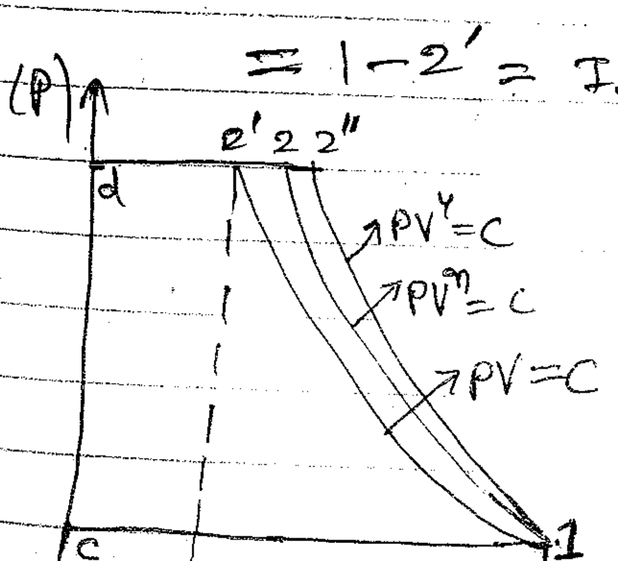
It is achieved by keeping the gas temp. as low as possible during compression. Since the Specific volume of a gas is proportional to the temp. therefore the Cooling Arrangement is provided on the Compressor to cool the gas during the Compression.

For better understanding of the effect of cooling during compression process, we consider three types of compression process executed b/n same press. levels (P_1 & P_2)

$P_1 - P_2 = 1-2'' =$ Isentropic compression (No Cooling)

$= 1-2 =$ ~~Inr~~ polytropic Compression (partial Cooling)

$= 1-2' =$ Isothermal ~~Cooling~~ compression. (perfect Cooling)



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$$\boxed{W_{poly} = \frac{n}{n-1} \times P_1 \times V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]}$$

$$\boxed{W_{isen} = \frac{\gamma}{\gamma-1} \times P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]}$$

$$\left\{ W_{isoth.} = -\int_1^2 P\,dV + \cancel{P_2 V_2} - \cancel{P_1 V_1} \right\} \leftarrow (1) \qquad P_1 V_1 = P_2 V_2$$

$$W_{is} = -\int_{V_1}^{V_2} P\,dV = \frac{c}{V}\int dV = c\int \frac{1}{V}\,dV \qquad \underline{PV = c} \qquad P = \frac{c}{V}$$

$$W_{iso} = P_1 V_1 \ln\left(\frac{V_1}{V_2}\right) \qquad \frac{V_1}{V_2} = \frac{P_2}{P_1}$$

$$\boxed{W_{iso} = P_1 V_1 \ln\left(P_2/P_1\right)}$$

It is interesting to obseverve from this diag. that among the three process Considered. the area with isentropic Compression is maximum. Thus it Requires max^m work input and with isothermal compression, the area of indicator diag. is minimum.

Thus for the Isothermal Compression will require Minimum work Input.

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Adiabatic Efficiency :→

The adiabatic efficiency of an air compressor is defined as the ratio of isentropic work input to actual work input.

$$\left\{ \eta_{adiabatic} = \frac{\text{Isentropic Work Input}}{\text{Actual work Input}} \right\}$$

Compressor Efficiency :→

It compares the indicated work input to isothermal work input. It is the Ratio of Isothermal work input to indicated work input.

$$\left\{ \eta_{comp} = \frac{\text{Isothermal work Input}}{\text{Indicated Work Input}} \right\}$$

Isothermal Efficiency :→

It compares the actual work done on the gas with isothermal compression work, and is defined as the ratio of Isothermal work input to actual work input during compression.

$$\left[\eta_{isoth} = \frac{\text{Isothermal work Input}}{\text{Actual work Input}} \right]$$

Compressor efficiency & Isothermal efficiency both terms are same.

Clearance Volume in a Compressor :→

As we know that there is some space is left in the cylinder when the piston reaches its topmost position ie T.D.C it is provided.

→ To avoided the piston striking the cylinder Head.

→ To accommodate the valve's actuation Inside the cylinder, because suction & delivery valves are located in the clearance Volume.

A Compressor should have the smallest possible clearance volume, because the Compressed air left in the clearance volume, first re-expand in the cylinder during suction thus reducing suction capacity.

The Ratio of clearance volume to swept volume is called clearance Ratio & may vary from 2 to 10 %.

Effects of clearance volume :→

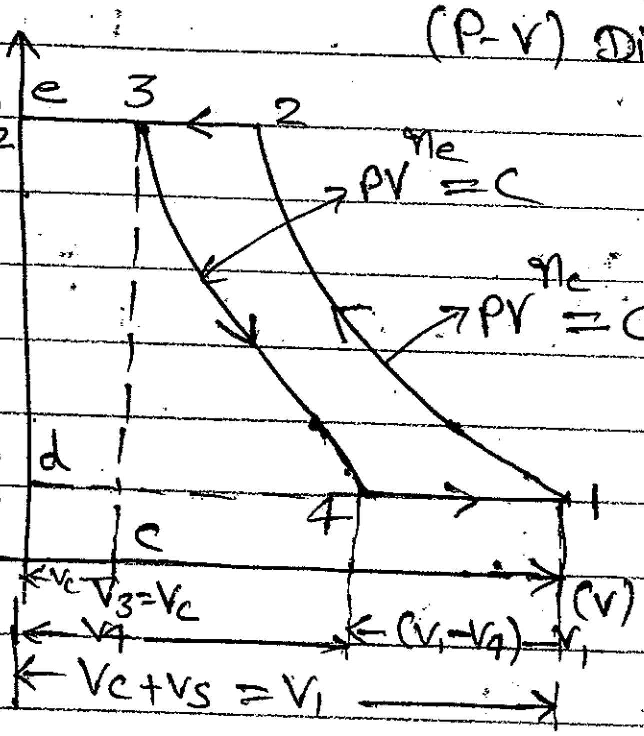
→ The volume of air taken in per stroke is less than the swept volume, thus the volumetric efficiency decreases.

→ More power Input is Required to drive the Compressor for same press. Ratio, due to increase in volume to be handled.

→ The maximum Compression pressure is Controlled by the Clearance Volume.

Indicated Compression work with clearance :→

(P-V) Diag. with clearance.
Single stage, Single



→ After delivery of compressed air, the air remaining in the clearance volume at pressure (P_2) expands, when the piston proceeds for the next suction stroke. As soon as the press. (P_1) reaches at state (4), the induction of fresh charge starts & continues to the end of stroke at state (1)

Indicated work done for Area = 1-2-3-4-1

Area(1-2-3-4-1) = Area[(1-2-e-d-1) - (3-e-d-4

Area (1-2-ed)

$$W_{com} = \frac{n}{n-1} \times P_1 \times V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n_c - 1}{n_c}} - 1 \right] \quad \text{—— (1)}$$

Area (3-e-d-4)

$$W_{exp.} = \frac{n}{n-1} \times P_4 \times V_4 \left[\left(\frac{P_3}{P_4}\right)^{\frac{n_e - 1}{n_e}} - 1 \right] \quad (2)$$

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$$= \frac{n_e}{n_e - 1} \times P_1 \times V_4 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] \quad — (23) \quad [P_1 = P_4, P_2 = P_3]$$

Net work of Compression;

$$W_{in} = \frac{n_c}{n_c - 1} \times P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n_c - 1}{n_c}} - 1 \right] - \frac{n_e}{n_e - 1} \times P_1 V_4 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n_e - 1}{n_e}} - 1 \right] \quad P_1 = P_4$$

If $n_c = n_e = n$

$$\boxed{W_{in} = \frac{n}{n-1} \times P_1 \times (V_1 - V_4) \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]} \quad — (A)$$

$(V_1 - V_4)$ = Effective swept volume.

→ **Volumetric Efficiency :→**

Actual Volume sucked in to the cylinder during suction stroke is always less than the swept volume. due to

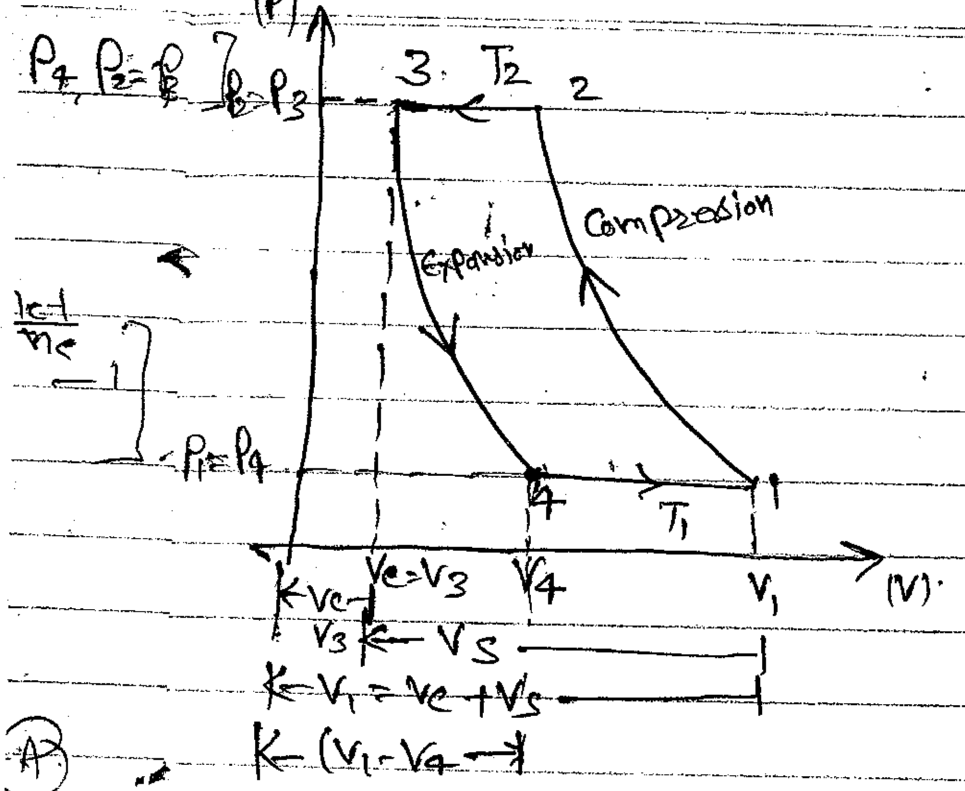
→ Resistance offered by inlet valve to incoming Air

→ Temp. of Incoming Air

→ Back press. of Residual gases left in the clearance Volume.

It is the Ratio of Actual volume of air sucked in to the compressor, measured at atmospheric press. & temp. to the piston displacement Volume.

It is Also defined as the Ratio of actual mass of air sucked per stroke to the mass of air corresponding



(A)

$$\eta_{volu} = \frac{\text{Effective Swept Volume}}{\text{Piston Displacement volume}}$$

les

$$\eta_v = \frac{V_1 - V_4}{V_s} = \cancel{\frac{V_1 - V_4}{V_c + V_s}} \qquad \left[V_1 = V_s + V_c \right]$$

ing Air

$$\eta_v = \frac{V_1 - V_4}{V_s} = \frac{V_1 - V_4}{V_1 - V_3} = \frac{V_s + V_c - V_4}{V_s + \cancel{V_c} - \cancel{V_3}} \qquad V_3 = V$$

ance

$$\boxed{V_1 = V_s + V_c}$$

$$\eta_v = \frac{V_s + V_c - V_4}{V_s} = \frac{\cancel{V_s}}{\cancel{V_s}} + \frac{V_c}{V_s} - \frac{V_4}{V_s}$$

sucked

ress.

$$\eta_v = 1 + \frac{V_c}{V_s} - \frac{V_4}{V_s} \times \frac{V_c}{V_c} = 1 + \frac{V_c}{V_s} - \frac{V_c}{V_s} \times \frac{V_4}{V_c}$$

process

respectively

$$\eta_v = 1 + C - C \times \left(\frac{V_4}{\ldots}\right) \quad \text{—— (1)}$$

for Expansion of gas in a clearance Volume

$$\frac{V_4}{V_3} = \left(\frac{P_3}{P_4}\right)^{\frac{1}{n_e}}$$

$$PV^{n_e} = C$$

$$P_3 V_3^{n_e} = P_4 V_4^{n_e}$$

$$\boxed{n_e = n_c = n}$$

$$\frac{V_4}{V_3} = \left(\frac{P_3}{P_4}\right)^{\frac{1}{n}}$$

$$\boxed{\begin{matrix} P_3 = P_2 \\ P_4 = P_1 \end{matrix}}$$

$$\frac{V_4}{V_3} = \left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}$$

put in (1)

$$\boxed{\eta_v = 1 + C - C\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}}$$

The volumetric efficiency decreases with press. Ratio (P_2/P_1) in the Compressor.

factors Affecting them :→

1. To large Clearance Volume.
2. obstruction at Inlet Valve.
3. High Speed of Compressor.
4. Heated Cylinder wall.
5. Leakage Past in piston.

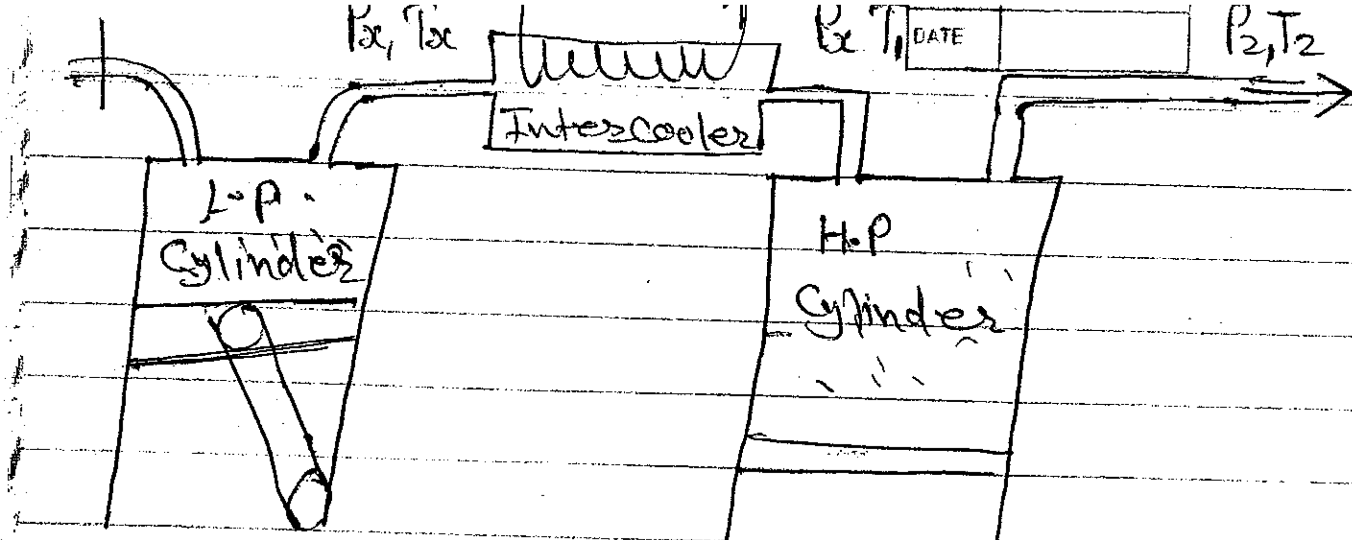
Multistage Compression :→

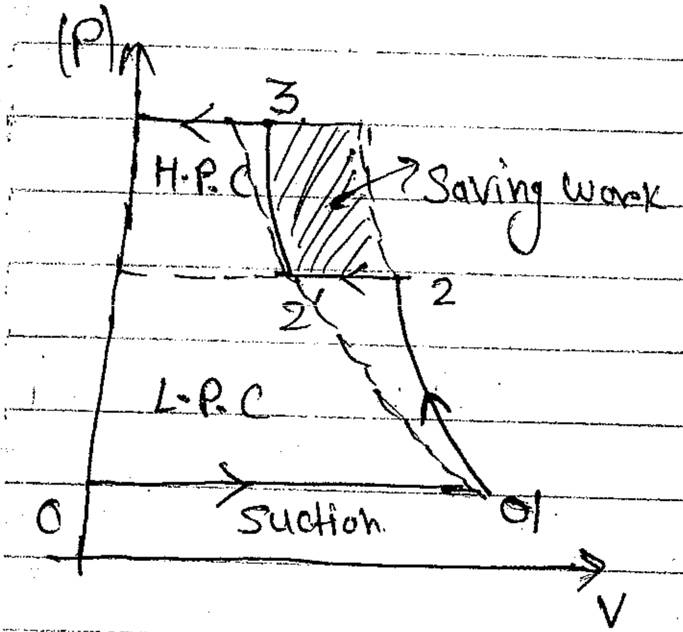
we As we know that the compression Requir minimum work input with isothermal compression, but the delivery temp. (T_2) increase with press. Ratio, and the volumetric efficiency decreases with press. ratio increases.

As the above problem can be reduced to minimum level by increasing the no. of cylinder use for compression the air. for the same pressure Ratio. The compression of air in two or more cylinder in series is called Multistage compression. Air cooling b/n the stages provides the means to acheiving an appreaciable reduction in the compression work and maintaing the air temp. within safe working limits.

→ When compressing air to high press., it is advantages to do it in stages The condition for minimum work requires the compression to be isothermal. Since the temp. after the compression is given by $T_2 = T_1 (P_2/P_1)^{n-1/n}$ the delivery, T_2 is increases with press. Ratio. Also the volumetric efficiency $[1+C-C(P_2/P_1)^{1/n}]$ decreases as the press. Ratio increases as mentioned earlier.

The volumetric efficiency can be improved by carrying out the compression in two stages.





<u>without clearance</u>

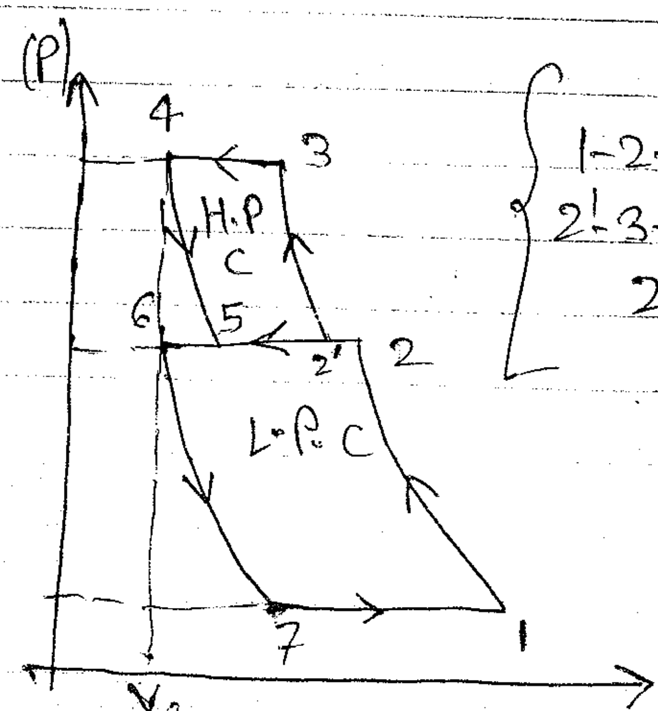
2-2' = Inter cooling

1-2 = Compression in Low press. cylinder

2'-3 = Compression in High press. cylinder

3-4 = Delivery of Air.

<u>With clearance</u>



1-2-6-7 = Low press. cylinder
2'-3-4-5 = High press. cylinder
2-2' = Inter cooling.

The intermediate press. (P_2) has a optimum value for minimum work of compression.

$$W_{L.P} = \frac{n}{n-1} \times P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] = \frac{n}{n-1} \times \dot{m}a \times R.T_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

$$W_{H.P} = \frac{n}{n-1} \times P_2 \times V_2' \left[\left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}} - 1 \right] = \frac{n}{n-1} \times \dot{m}a R \times T_2 \left[\left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}} - 1 \right]$$

$$W_{Total} = W_{L.P} + W_{H.P}$$

$$W_{total} = \frac{n}{n-1} \times \dot{m}a \times R \times T_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] + \frac{n}{n-1} \times \dot{m}a.R \times T_2 \left[\left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}} - 1 \right]$$

Since the intercooling is perfect $P_1V_1 = P_2V_2$;

$ma R.T_1 = P_1 V_1$ $[PV = C]$

$ma R \times T_2 = P_2 V_2$. then;

$$W_{total} = \frac{n}{n-1} ma \times R \times T_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} + \left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}} - 2 \right] \quad \text{--- (A)}$$

If the suction press. (P_1) & the discharged press. (P_3) are fixed, then we can determine the optimum intermediate press. required for the minimum work of compression. It can be evaluated diffn above equation with respect to (P_2) and equal to zero.

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$$\frac{dW}{d(P_2)} = \frac{d}{d(P_2)}\left[\frac{n}{n-1} \times m_a \times R \times T_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 2\right]\right]$$

Let $\frac{n-1}{n} = x$

then $$0 = \frac{d}{d(P_2)}\left[\frac{1}{x} \times m_a R T_1 \left[\left(\frac{P_2}{P_1}\right)^{x} + \left(\frac{P_3}{P_2}\right)^{x} - 2\right]\right]$$

$$0 = \frac{1}{x} \times m_a \times R \times T_1 \left[P_2^{x} \cdot P_1^{-x} + P_3^{x} \cdot P_2^{-x} - 0\right]$$

$$0 = x \cdot P_2^{x-1} \cdot P_1^{-x} - x \cdot P_2^{-x-1} \cdot P_3^{x}$$

$$\cancel{x} \cdot P_2^{x-1} \cdot P_1^{-x} = \cancel{x} \cdot P_2^{-x-1} \cdot P_3^{x}$$

$$P_2^{x-1} \cdot P_2^{x+1} = P_3^{x} P_1^{x}$$

$$P_2^{2x} = P_3^{x} P_1^{x}$$

$$P_2^2 = P_1 \cdot P_3 \qquad \boxed{P_2 = \sqrt{P_1 \cdot P_3}}$$

$$P_2 \cdot P_2 = P_1 \cdot P_3$$

$$\left\{\frac{P_2}{P_1} = \frac{P_3}{P_2}\right\} \text{———} (2)$$

So that the press. Ratio is Same for both the Stages. then from equation No (A)

$$W_{tel} = \frac{n}{n-1} \times P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 2\right]$$

$$W = \frac{n}{n-1} \times P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 2 \right]$$

$$W = \frac{n}{n-1} \times P_1 V_1 \left[2 \times \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 2 \right]$$

$$\boxed{W = 2 \times \frac{n}{n-1} \times P_1 \cdot V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1 \right]}$$

2 = for Two stage (2 cylinder)
3 = Three stage (3 cylinder)

By Equation no. (2) we can get

$$\frac{P_2}{P_1} = \frac{P_3}{P_2} = \frac{P_4}{P_3} = \frac{P_5}{P_4} = \text{------} Z = \frac{P_{x+1}}{P_x}$$

$$\boxed{(I.P)_{min} = 2 \times \frac{n}{n-1} \times P_1 \dot{V}_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1 \right]}$$

In terms of overall pres Ratio

$$\frac{P_2}{P_1} = \frac{\sqrt{P_1 \cdot P_3}}{P_1} = \frac{\sqrt{\cancel{P_1}} \sqrt{P_3}}{\sqrt{\cancel{P_1}} \sqrt{P_1}} = \sqrt{\frac{P_3}{P_1}} = \left(\frac{P_3}{P_1}\right)^{1/2}$$

th.

putin above e

$$\boxed{I.P = 2 \times \frac{n}{n-1} \times P_1 \dot{V}_1 \left[\left(\frac{P_3}{P_1}\right)^{\frac{1}{2} \times \frac{n-1}{n}} - 1 \right]}$$

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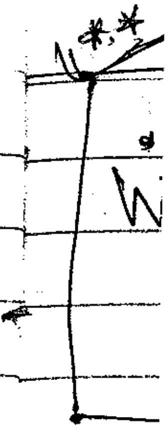
$$\frac{P_2}{P_1} = \frac{P_3}{P_2} = \frac{P_4}{P_3} = \frac{P_5}{P_4} = \ldots \frac{P_{NS+1}}{P_{NS}}$$



$$\frac{P_3}{P_2} = \frac{P_4}{P_3} \qquad\qquad \frac{P_3}{P_2} = \frac{P_2}{P_1}$$

$$P_3^2 = P_2 . P_4 \qquad\qquad P_2^2 = P_1 . P_3$$

$$P_4 = \frac{P_3^2}{P_2} \quad \text{— (a)} \qquad\qquad P_3 = \frac{P_2^2}{P_1} \quad \text{— (b)}$$

$$P_4 = \frac{P_3^2}{P_2} = \frac{\left(P_2^2/P_1\right)^2}{P_2} \quad \boxed{\text{by equ (b)}}$$

$$P_4 = \frac{P_2^4}{P_1^2 . P_2} = \frac{P_2^3}{P_1^2} \quad \boxed{\text{Divided by } (P_1) \text{ both side}} \Longrightarrow \frac{P_4}{P_1} = \frac{P_2^3}{P_1^3}$$

P_4 = Delivery press when No of stage (3) $\boxed{N.S = 3}$

in general.

$$\boxed{\frac{P_{NS+1}}{P_1} = \left(\frac{P_2}{P_1}\right)^{N.S}} \quad (*)$$

when, N.S = 2

$$\frac{P_3}{P_1} = \left(\frac{P_2}{P_1}\right)^2 \Rightarrow \left(\frac{P_2}{P_1}\right)^{1/2} = \frac{P_3}{P_1}$$

$$\boxed{\dot{W} = N_s \times \frac{n}{n-1} \times \dot{m} R \times T_1 \left[\left(\frac{P_{N_s+1}}{P_1} \right)^{\frac{1}{N_s} \times \frac{n-1}{n}} - 1 \right]}$$

(b)

stage(3)

free Air Delivery (FAD)

The volume of compressed air corresponding to atmospheric condition is known as free Air Delivery (FAD).

Actual quantity of compressed air converted back to the inlet condition of compressor. FAD is the volume of compressed air measured in m^3/min. reduced to atmospheric press. & temp.

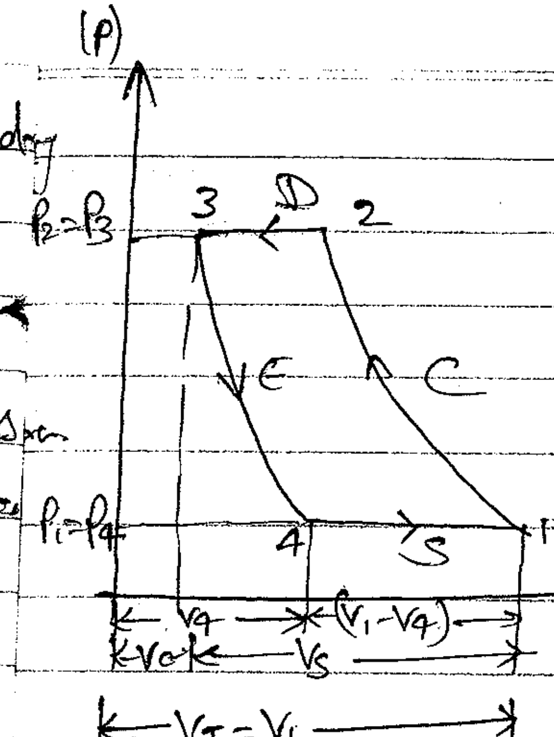
The free air delivered volume, is less than the compressor displacement volume due to

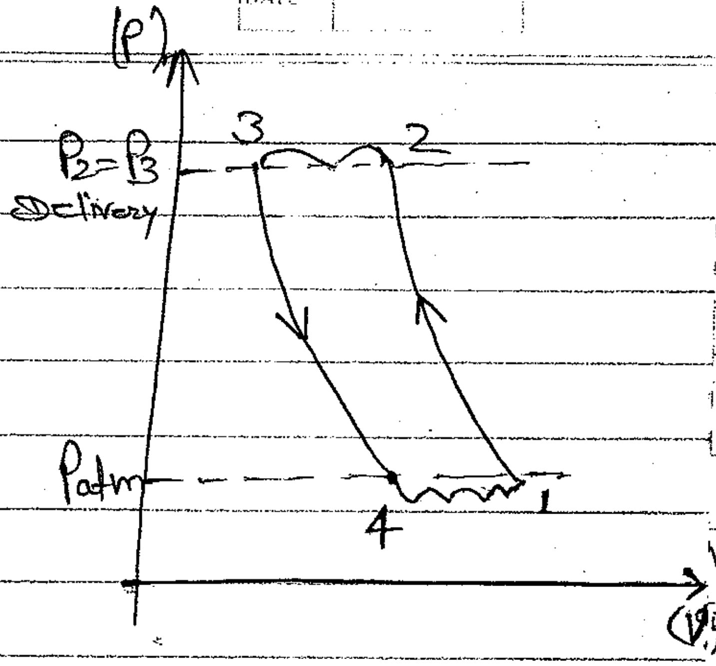
1. obstruction at inlet valve, it offers the resistance to air flow through the narrow passage of valve.

2. Re-expansion of High press. air in clearance volume, it reduce the effective suction stroke.

3. presence of Hot cylinder walls of compressor. Air gets heated as it enters the cylinder thus, it expand & reduce the mass of air sucked in to the cylinder.

→ In the Actual indicator Diag., we know that the air sucked at press. and temp which are lower than the atmospheric Air.





let; a/f = Ambient Condition

1 = Actual Condition

Using Property Relation for Ideal gas $\left(\frac{PV}{T}\right)$

$$\left\{ \frac{P_f \times V_f}{T_f} = \frac{P_1}{T_1} \times (V_1 - V_4) \right\}$$

Then the free air delivered, Actual Volume of free air Deliv

$$\boxed{V_f = \frac{P_1}{P_f} \times \frac{T_f}{T_1} \times (V_1 - V_4)}$$

or

$$\boxed{V_f = \frac{P_1}{P_a} \times \frac{T_a}{T_1} \times (V_1 - V_4)}$$

Volumetric efficiency with respect to (F.A.D)

$$\left\{ \eta_{volu} = \frac{V_f}{V_s} \right\} = \frac{V_f}{V_1 - V_c} = \frac{P_1 T_f}{P_f T_1} \times \left(\frac{V_1 - V_4}{V_1 - V_c} \right)$$

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Q. A Single stage, single acting. Reciprocating Compressor has a bore of 20 cm & stroke of 30 c.m. The compressor runs at 600 r.p.m. The clearance volume is 4% of the swept volume and index of expansion & compress. is 1.3. The suction condition are 0.97 bar, 27°C and delivery press is 5.6 bar. The atmospheric condition are 1.01 bar & 17°C

find → (a) Free Air Delivered in m^3/min.

(b) The volumetric efficiency Refered to FAD condition.

(c) The Indicated Power.

Sol^n → Given)

$d = 20cm = 0.2 mtr$

$l = 30cm = 0.3 mtr$

$V_s = \frac{\pi}{4} \times d^2 \times l$

$N = 600$ r.p.m

$V_s = 9.42 \times 10^{-3} m^3$

$V_c = 4\% V_s = 0.04 V_s$

$= 0.04 \times \frac{\pi}{4} \times d^2 \times l$

$V_c = 3.76 \times 10^{-4} m^3$

$n_e = n_c = 1.3$

$P_1 = 0.97$ bar, $P_2 = 5.6$ bar,

$T_1 = 27°C + 273 = 300K$

$P_f = 1.01$ bar

$T_f = 17°C + 273 = 290K$

find → FAD.

$\eta_{volum.}$ at ambient condition.

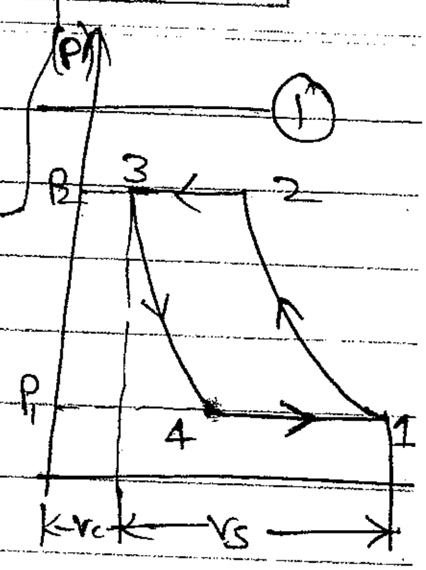
FHD,

cooling.
stroke
600 r.p.m.
. Swept
compress.
7 bar.
. The
7°C
/min.
ferred.

2 ×d.

$10^{-3} m^3$

$$\boxed{V_f = \frac{P_1}{P_f} \times \frac{T_f}{T_1} \times (V_1 - V_4)} \quad (1)$$



Using Relation,

$$P_3 V_3^n = P_4 V_4^n$$

$$\frac{V_4}{V_3} = \left(\frac{P_3}{P_4}\right)^{1/n} = \left(\frac{P_2}{P_1}\right)^{1/n}$$

$$V_4 = V_3 \times \left(\frac{P_2}{P_1}\right)^{1/n} \Rightarrow V_3 \times \left(\frac{5.6}{0.97}\right)^{1/1.3}$$

$$\boxed{V_4 = 0.00145 \, m^3}$$

$V_1 = V_s + V_c = 9.76 \times 10^{-3} \, m^3$ put in (1)

$$V_f = \frac{0.97}{1.01} \times \frac{290}{300} \times (0.00976 - 0.00145)$$

$$V_f = 0.00774 \, m^3/cycle$$

free Air Delivered per min $V_f = 0.00779 \times N$

$$V_f = 0.00779 \times 600$$

$$\boxed{V_f = 4.65 \frac{m^3}{min}}$$ Ans

$\Rightarrow$ $\boxed{\eta_{vol} = \frac{V_f}{V_s}} = \frac{0.00774}{0.00942}$ Ans $\eta_v = 82.16\%$

$\Rightarrow$ Indicated power $\rightarrow$

$$W_{in} = \frac{n}{n-1} \times P_1 \times (V_1 - V_4) \times \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] = 1.75 \, kJ/cyc$$

$W_{in} = 1.75 \times 600$ ...

Q. A Single-stage, Single acting reciprocating air Compressor delivers 0.6 kg/min of air at 6 bar. The temp. & press. at Suction Stroke are 30°C and 1 bar respectively. The bore & Stroke are 100mm & 150 mm respectively. The clearance Volume is 3% of swept volume. The index of Compression & Expansion is 1.3 find

(a) Volumetric efficiency of Compressor.

(b) Power Required, if mechanical efficiency is 85%.

(c) Speed of the Compressor.

<u>Given;</u> $P_1 = 1$ bar $\quad P_2 = 6$ bar

$\dot{m}_a = 0.6$ kg/min $\qquad C = \frac{V_c}{V_s} = 0.03$

$T_1 = 30°C + 273 = 303K$

$L = 150$ mm $= 0.150$ mtr $\qquad \eta_{mech} = 85\%$

$d = 100$ mm $= 0.10$ mtr $\qquad n = 1.3$

<u>find;</u> → (1) $\eta_v = ?$

(2) $I.P = ?$, $B.P = ?$ $\qquad \eta_{mech} = I.P/B.P$

(3) $N = ?$

(1) $$\boxed{\eta_v = 1 + C - C \times \left(\frac{P_2}{P_1}\right)^{1/n}}$$

$$\boxed{\eta_v = 91.0\%}$$

(2) $$\boxed{I.P = \frac{n}{n-1} \times \dot{m}_a \times R \times T_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]}$$

$$\boxed{\begin{array}{l} I.P = 1.99\,KW \\ B.P = 2.27\,KW \end{array}}$$

$P_1 (\dot{V}_1 - \dot{V}_4) = \dot{m}_a R T_1$

$(\dot{V}_1 - \dot{V}_4) = \frac{\dot{m}_a R T_1}{P_1} \Rightarrow \eta_v = \frac{\dot{V}_1 - \dot{V}_4}{\dot{V}_s} \Rightarrow \dot{V}_s = \frac{\pi}{4} \times d^2 \times L \times N$

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mg air ② A Two stage, Single acting Reciprocating Compressor
. at 6 bar takes an air at 1 bar & 300 K, air is discharged
re 30°C at 10 bar. The intermediate press. is ideal for
e are Minimum work & perfect intercooling. The law
earance Compression is $PV^{1.3}$ = const. The rate of discharge
ie index is 0.1 kg/sec. Calculate.

e. (a) power Requ. to Drive the Compressor.

ency is (b) Saving in Compression work, as compare to Single stage.

(c) Isothermal Efficiency.

(d) Heat transfered in Intercooler.

Sol^n → Given → $P_1 = 1$ bar $P_3 = 10$ bar

1.03 find ↓ $T_1 = 300K$ $P_2 = ?$ $n = 1.3$

$I.P_m = ?$ $\dot{m}_a = 0.1$ kg/sec. $C_p = 1.01$ KJ/kg K

35% $I.P_{sin} = ?$ $R = 0.287$ KJ/kg

$\eta_{iso} = ?$

$Q_{in} = ?$

$$\left\{ Q = \dot{m}_a \cdot C_p \times (T_2 - T_1) \right\}$$

9.13 KW

P/BP → Power Requ. to Drive the Compressor →

$$\text{(a)} \left\{ I.P_{multi} = 2 \times \frac{n}{n-1} \times \dot{m}_a \times R \times T_1 \left[\left(\frac{P_3}{P_1} \right)^{\frac{1}{2} \times \frac{n-1}{n}} - 1 \right] \right\}$$

%

22.7 KW

$$\text{(b)} \left\{ I.P_{sin} = \frac{n}{n-1} \times \dot{m}_a \cdot R \cdot T_1 \times \left[\left(\frac{P_3}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] \right\}$$

9 KW

.27 KW

26.16 KW

(c) Saving work 26.16 - 22.7 = 3.46 KW

$I \times d^2 \times l N$

$$\text{(d)} \left(\eta_{iso} = \frac{I.P_{iso}}{I.P_{multi}} \right) \left\{ I.P_{iso} = P_1 V_1 \ln \left(\frac{P_3}{P_1} \right) \right\} = 19.85 \text{ KW}$$

= 2 R.P.M.

Q. In a three Stage Compressor air is Compressed from 98KPa to 20 bar. Calculate for (1 m³/sec)

(a) Work under Ideal Condition for $n = 1.3$

(b) Isothermal work

(c) Saving in work due to Multistaging

(d) Isothermal Efficiency.

Given;

$P_1 = 98\,KPa = 0.98\,bar$; $N.S = 3$

$P_4 = 20\,bar$

$$\boxed{\frac{P_{N.S+1}}{P_1} = \left(\frac{P_2}{P_1}\right)^{N.S}}$$

$$\left(I.P\right)_{iso} = P_1 \dot{V}_1 \ln\left(\frac{P_4}{P_1}\right)$$

$$\underline{295.56\,KW}$$

$$\frac{P_4}{P_1} = \left(\frac{P_2}{P_1}\right)^3$$

$$\left(\frac{20}{0.98}\right)^{1/3} = \frac{P_2}{P_1}$$

$$\boxed{P_2/P_1 = 2.732}$$

$$\left(I.P\right)_{III} = 3 \times \frac{n}{n-1} \times P_1 \dot{V}_1 \times \left[\left(\frac{P_4}{P_1}\right)^{\frac{1}{3} \times \frac{n-1}{n}} - 1\right]$$

$$\underline{332.62\,KW}$$

$$\left(I.P\right)_{I} = \frac{n}{n-1} \times P_1 \dot{V}_1 \left[\left(\frac{P_4}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$\underline{427.08\,KW}$$

Saving work $= 427.08 - 332.62 = \underline{94.42\,KW}$

$$\% = \frac{94.42}{427.08} \times 100 = \underline{22.2\%}$$

$$\eta_{iso} = \frac{(I.P)_{iso}}{(I.P)_{III}} = \frac{295.56}{332.62} = \underline{88.85\%}$$

UNIT-V (a) Condensers

In thermal power plants, condenser are used to condense the exhaust steam, from a steam turbine to obtain maximum efficiency and also to convert in to pure water, So that it may be ~~used~~ Reused in steam generator as feed water.

A Condenser is a device in which Vapour condense to liquid phase at Saturation temp. at constant press. during condensation, the working substance changes its phase from vapour to liquid and rejects latent heat. A condenser maintain a very low press. due to sudden decrease in specific volume of the working substance.

In a steam condenser the cooling steam is accomplished by circulating water as cooling agent in the condenser. The exhaust press. in the condenser is maintain nearly 7 to 10 KPa, which is corresponding to temp (40°C).

function of steam condenser :→

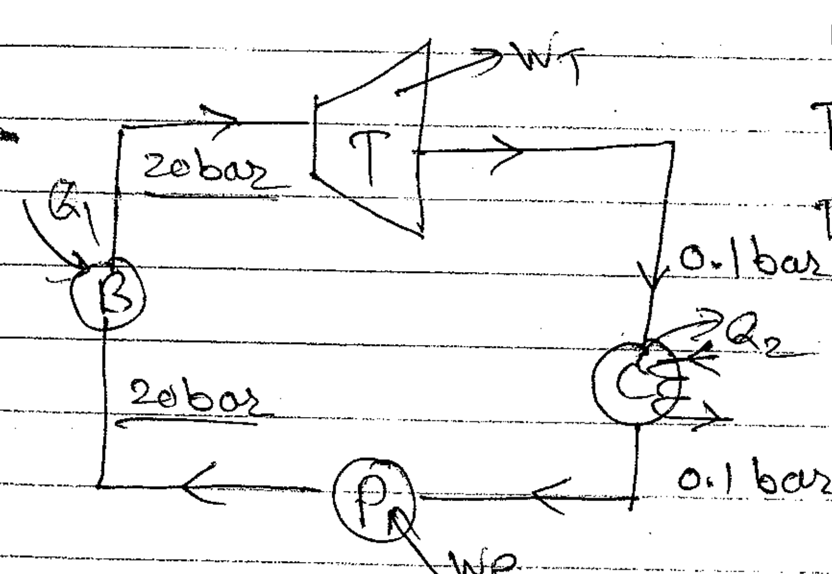
(1) The condenser lower the back press. of the turbine exhaust. Thus steam expands throug a higher press. Ratio across the turbine.

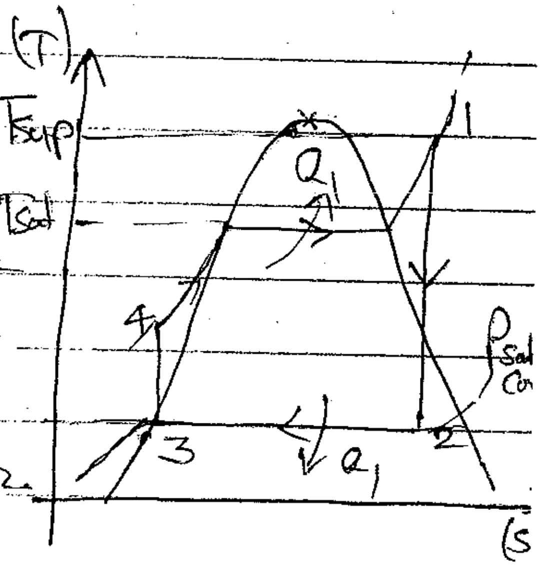
thus (1) work done per cycle Increased.
(2) Improved thermal efficiency of cycle.
(3) Reduced steam consumption.

(2) The condenser Enables the Recovery & Recirculation of pure feed water in to plant.

(a) The cost of water softening plant is Reduc
(b) It also saves the cost of fresh water to be supplied to the boiler.

(3) The Condenser Also Enable the removal of air noncondensable gases from steam thus the heat transfer rate is improved & tube Corrosion is Reduced.





Elements of Condensing plant:→

1) Condenser
2) Condensation Extraction pump.
3) Air Extraction pump.
4) Circulating pump.
5) Cooling Tower

Types of Jet Condenser →

Broadly classified in two

→ Jet Condenser / Mixing Type Condenser
→ Surface Condenser / Non mixing Type Conde.

Jet Condenser :→ / mixing Type
1) Low level Counter flow Jet Condenser.
2) Low level Parallel flow Jet Condenser.
3) High level jet Condenser / Barametric Condenser.
4) Ejector Condenser.

Surface Condenser / Non mixing Type
1) Shell & Tube Type Surface Condenser
Acc^{g} to Direction of Steam flow
a) Down flow
b) Central flow
c) Inverted flow.
2) Evaporative type Condenser

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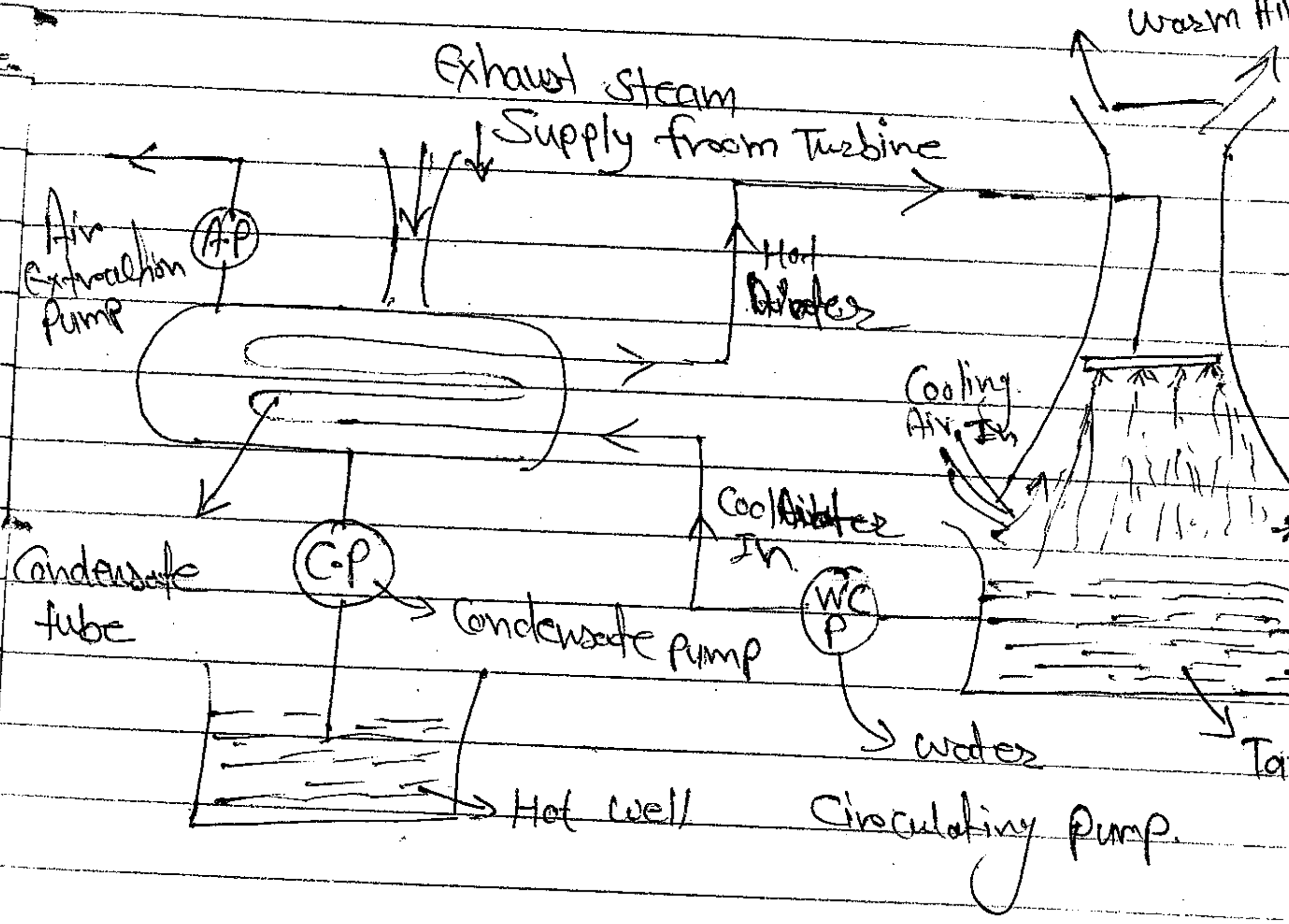
Schematic diag. of Elements of Condensing plan



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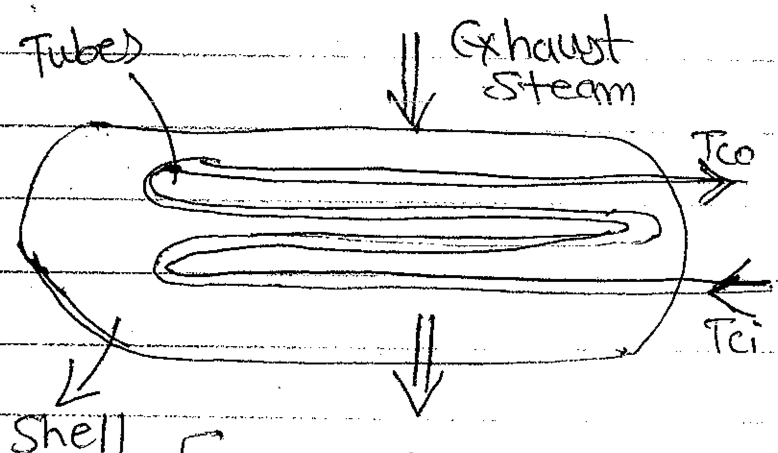
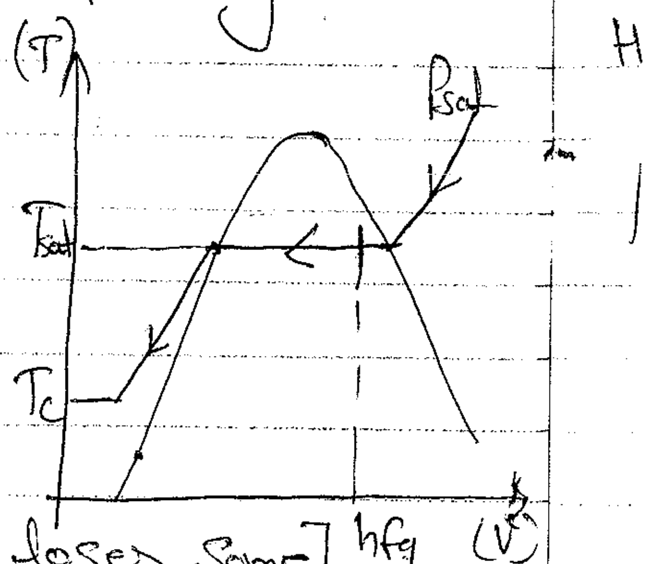
Estimation of cooling water Requiered:→

The steam Condenser is used to Condensed Several thousand kg of steam/hr. in a power plant. The steam release its latent heat of Condensation and some time a portion of sensible heat also. There fore a huge amount of cooling water is Requierd for steam Condensation approx. 30 to 50 kg of cooling water Requiered per kg of steam to be Condensed.





[Usually the Condensate loses some of sensible heat;]

Let;

T_c = Temp. of Condensate leaving the Condenser

$T_{sat} - T_c$ = Underccoling / subcooling of the Condensate

Thus; $[T_c < T_{sat}]$

The Rate of heat lost by the exhaust steam is equal to the rate of heat gain by Cooling Water.

Heat lost by Exhaust steam ($\dot{Q}_{steam}$)

$\dot{Q}_{steam}$ = Sum of (latent heat + Sensible heat)

$= \dot{m}_s (h_{fg} + C_p (T_{sat} - T_c))$

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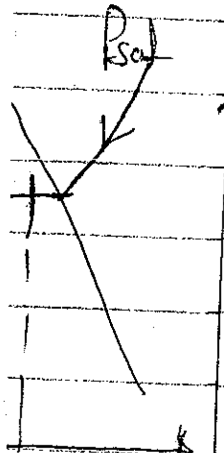

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$$= \dot{m}_{steam} \times (x h_{fg} + C_{pw} \times T_{sat} - C_{pw} T_c)$$

$C_{pw} \cdot T_{sat} = h_f$

$C_{pw} T_c = h_{fc}$

$$\dot{Q}_{stea} = \dot{m}_{steam} \left[(h_f + x h_{fg} - h_{fc}) \right] \quad \text{——— (A)}$$

$(h_f + x h_{fg})$ @ Condenser pressure.

h_{fc} @ Sensible heat at Condensat

Heat gain by Cooling water ⇒

$$\dot{Q}_{water} = \dot{m}_{water} \times C_{pw} \times (T_{co} - T_{ci}) \quad \text{——— (B)}$$

T_{co} = Water temp. at condenser outl

T_{ci} = Water temp at Condenser Inl

$A = B$

$$\dot{Q}_{steam} = \dot{Q}_{water}$$

$$\dot{m}_{steam} (h_f + x h_{fg} - h_{fc}) = \dot{m}_{water} \cdot C_{pw} \times (T_{co} - T_{ci})$$

$$\boxed{\dot{m}_{water} = \frac{\dot{m}_{steam} (h_f + x h_{fg} - h_{fc})}{C_{pw} \times (T_{co} - T_{ci})}}$$

h_f → h_{fg} @ P_c (Condenser press)

h_{fc} - Sensible heat of condensate

Analysis of Condenser Operation :→

When the steam is condensed in a closed vessel the vapour phase of working substance (water) changes to liquid phase & thus is specific volume reduced to more than one Thousand time. Due to change in specific volume, the absolute press in the Condenser falls below atmospheric press. and high vaccum is created.

This low press. in condenser permits more expansion of steam in the turbine & more work developed. The minimum press. that can be attained depends on the temp. of condensate & air present in the condenser.

The term vaccum means the press. is less than the atms. press the vacum in condenser is generally measured in mm of hg. The vaccum is Negative gauge press. and is equal to the diffⁿ of barametric press. & absolute press. in condenser as shown fig.

Absolute press. = Atmospheric press. − Vaccum gauge press.

Absolute press. = Barometer Reading − Vaccum gauge Reading

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Condenser efficiency :→

The Condenser is a heat exchanger its efficiency can be defined as the ratio actual temp rise to the Maximum possible temp. rise of cooling water.

$$\eta_{conden} = \frac{\text{Actual temp rise of cooling water}}{\text{Max}^m \text{ possible temp. rise of cooling}}$$

$$\eta_{conde} = \frac{(\Delta T)_{Actual}}{(\Delta T)_{max^m}} = \frac{T_{co} - T_{ci}}{T_{sat} - T_{ci}}$$

$T_{sat.}$ = Saturation temp. Corresponding to absolute press. in the Condenser.

Vaccum efficiency :→

In the steam Condenser a mix of steam & Air present, there fore the absolut in the Condenser is the Sum of partial press of air & Steam.

$$\{P_{abs.} = P_{air} + P_{steam}\}$$

The presence of Air in the Condens is disturb the Vaccum & thus the actual Vaccum is less than than that Could be attaind in the Condenser, if only Steam is present.

If there is no air is present in the Condenser, than absolute press in the Conde...

vacuum would be attained.

$$\eta_{vaccum} = \frac{\text{Actual vaccum in the Condenser}}{\text{Max}^m \text{ possible Vaccum Gauge}}$$

$$\eta_{vaccum} = \frac{P_g}{P_{g(max^m)}} =$$

P_g = Barometric press − Absolute press in Condenser

$$P_g = P_b - P_{abs} = P_{atm} - P$$

$$\cancel{P_g = P_{atm} - P}$$

$P_{g\,max^m}$ = Barometric press − Satur press of steam at Condensate Temp.

$$P_{g\,max^m} = P_{atm} - P_{sat}$$

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Q. Calculate the vaccum efficiency & Condenser efficiency following data Record in ~~test~~ on Condenser :→

Condenser Vaccum = 700 mm of Hg.
Barometer Reading = 754 mm of Hg.
Hot well temp. = 30°C
Inlet temp of cooling water = 12°C
outlet temp of cooling water = 26°C

Given; $T_{ci} = 12$
$T_{co} = 26$ Hot well temp. = 30°C

$$\eta_{cond} = \frac{\text{Actual temp. rise of cooling water}}{\text{Max}^m \text{ possible temp. rise of cooling water}}$$

$$\eta_{con} = \frac{T_{co} - T_{ci}}{T_{sat} - T_{ci}} = \frac{26-12}{39-12} = 51.85\%$$

$$\boxed{\eta_{cond} = 51.85\%}$$ Ans

Absolute press = Barometeric − Vaccum gauge
$= 754 - 700$
$P_{abs.} = 54$ mm of Hg.
$P_{abs} = \frac{54}{760}$ bar

{1 mm of Hg $= \frac{1}{760}$ bar}

{$P_{abs} = 0.0710$ bar}

from steam table at 0.0710 bar $T_{sat} = 39°C$

$P_{abs} = P_{steam} + P_{air}$
{$P_{abs} = P_{steam}$} – If there is no Pw in ①

At hot well temp. 30°C {Condensate temp}
from steam table at 30°C, $P = 0.0401$ bar

$$P = 0.4001 \times 760 \text{ mm of Hg.}$$

$$\boxed{P_h = 30.4 \text{ mm of Hg.}}$$

max^m possible vaccum = Barometer − P_h

$$= 754 - 30.4$$

$$= 732.6 \text{ mm of Hg.}$$

$$\left\{ \eta_{vaccum} = \frac{\text{Actual vaccum in Condenser}}{\text{max}^m \text{ possible vaccum in Condenser}} \right\}$$

$$\eta_{vac} = \frac{700 \text{ mm of Hg.}}{732.6 \text{ mm of Hg.}}$$

$$\boxed{\eta_{vaccum} = 96.73\%} \text{ Ans}$$

X———X