THEORY OF MACHINES

CHAPTER – 1 ⟶ SIMPLE MECHANISMS

Theory of m/c is a branch of science which deals with the study of relative motion between the various parts of a m/c, & the forces which are acting upon them.

It is broadly divided into two parts.

Kinematics	Dynamics
It deals with the study of relative motion between the various parts of the machine, but the various forces involved in the motion, are not considered.	It deals with the study of various forces involved in the various parts of the m/c. The forces may be static or dynamic.

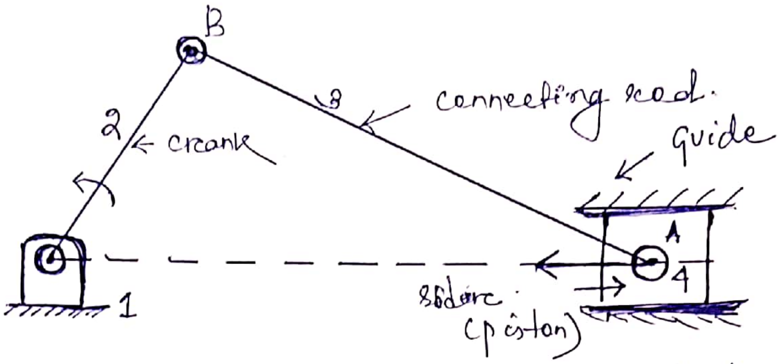
Mechanism & Machine

① Mechanism ⟶ If a no. of rigid bodies are assembled in such a way that the motion of one causes ~~constraint~~ constrained and predictable motion to the another, is known as a m/c. mechanism.

A mechanism also transmits & modify motion.

② Machine ⟶ A machine is a mechanism or combination of mechanisms which not only imparts definite motions to the parts but also transmits & modify the available mechanical energy into some kind of useful energy. This useful energy may be in the shape of some kind of desired work.

for example :— Slider crank mechanism



The above fig. shows a mechanism which is known as slider-crank mechanism. It is a combination of rigid bodies namely crank, connecting rod & slider. They are also so shaped & connected that they move upon each other with definite relative motion.

The slider-crank mechanism will become a m/c become a m/c when it is used in automobile engine by adding valve mechanism etc. In that case it will convert the available energy (force on the piston) into the desired energy (torque on the crank shaft). This torque will move the vehicle.

Link

A link is defined as a member or a combination of members, connecting other members & having motion relative to them. A slider-crank mechanism consist of following four links.

i) frame
ii) crank
iii) connecting rod
iv) slider

The slider (4) reciprocates in guide, which is connected to frame. Hence guide also becomes link 1.

Types of link → Rigid link
Flexible link
Fluid link

Kinematic Pair

Two links or element of a machine, when in contact with each other they said to form a paire.

Types of kinematic pair

1. According to nature of contact.

- Lower pair
- Higher pair

Lower pair – A pair of link having surface or area contact between them known as lower paire. The contact surface of two links are similar.

eg. shaft rotating in bearing
Nut turning in a screw.

Higher pair – When a pair has a point or line contact between the links, is known as higher paire. The contact surface bet^n two surface are dissimilar.

eg. cam follower paire

*

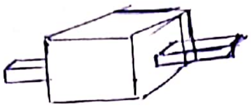
2. Acc. to nature of Mechanical constraint

closed pair – When the elements of a paire of link are held together mechanically, it is known as closed paire. The two elements are geometrically identical & are one element envelope the other one. eg.

unclosed paire – When two links of a paire are in contact either due to gravity are called unclosed paire.

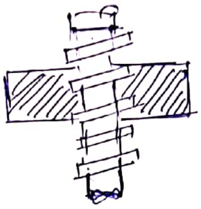
3. Acc. to nature of relative motion

Sliding pair -



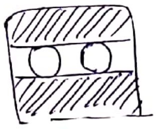
eg. piston & cylinder

Turning pair -



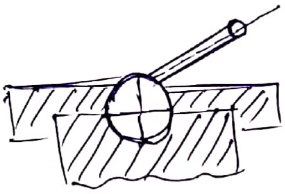
lathe spindle supported in head stoke

Rolling pair -



Roller bearing

Spherical pair -



ball & socket Joint attachment of care mirror.

Degree of freedom

It can be defined as the no. of independent motion both translational & rotational a body can have.

→ Translation motion along x, y & z axis.

→ Rotational motion along x, y, z axis.

$$n = 3(l-1) - 2j - h$$

l → no. of links

j – no. of binary joint

h → no. of higher pair.

It is called as kutzbach criterion, for a mechanism.

Kinematic chain

When a kinematic pair are coupled in such a way that the last link is joined to the first link to transmit definite motion, it is called as a kinematic chain.

* The relation betn no. of link (L) & pair (p) is given by

$$L = 2p - 4 \quad \text{—— (1)}$$

* The relation betn no. of link (L) & Joints (J) is given by

$$j = \frac{3}{2}L - 2 \quad \text{—— (2)}$$

In the equation (1) & (2) if

LHS > RHS → then the chain is locked

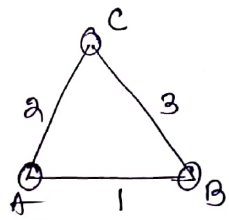
LHS < RHS → then the chain is unconstrained

LHS = RHS → " " is constrained

<u>example - 1</u>

A 3 link ~~Jot~~ chain with 3 Joints.

prove the chain is locked



$j = 3$

$L = 3$

$P = 3$

(1) $L = 2P - 4$

$\Rightarrow 3 = 6 - 4 = 2$

$\Rightarrow 3 > 2$ LHS > RHS

(2) $j = \frac{3}{2}L - 2$

$\Rightarrow 3 = \frac{3}{2} \times 3 - 2$

$\Rightarrow 3 > 2.5$ LHS > RHS

Hence proved.

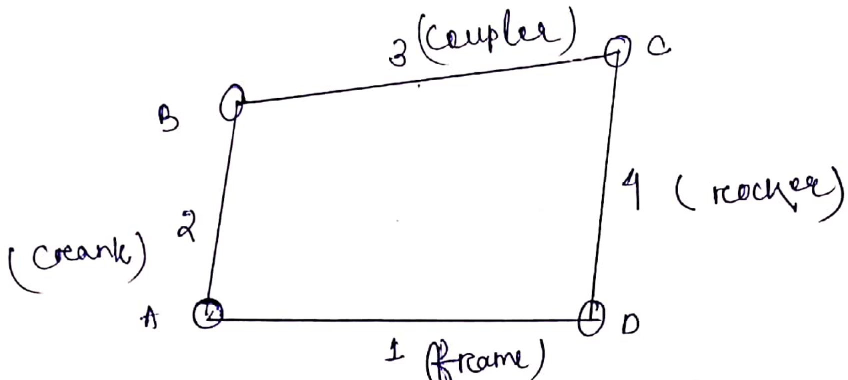
Inversion Mechanism

Mechanism is a kinematic chain whose one link is fixed. As there are many link in a chain, by fixing one at a time, we can obtain a no. of Mechanism. & This method is known as inversion.

1) Four bar chain Mechanism & its Inversion.

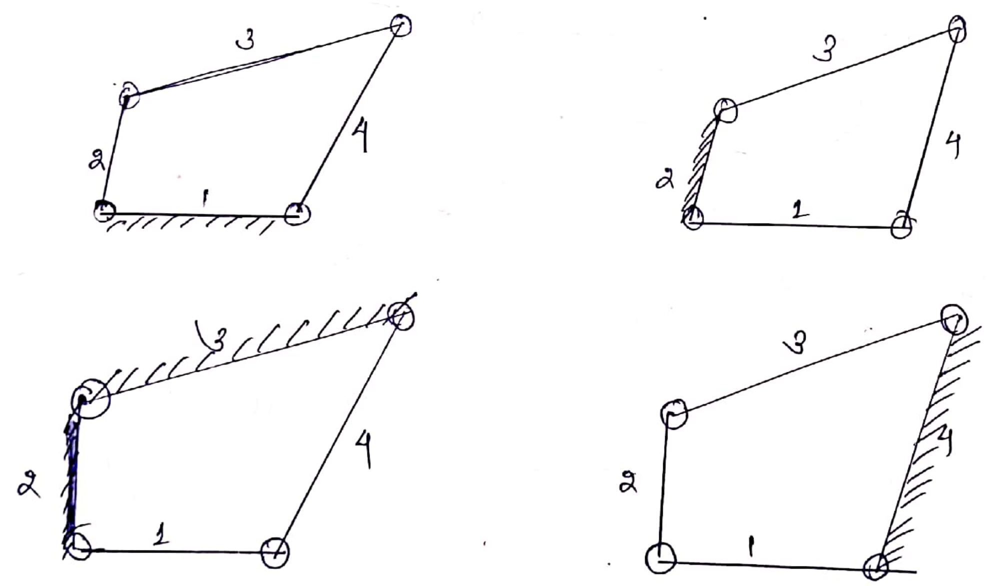
This is the simplest kinematic chain. It consist of four rigid links which are connected in the form of a quadrilateral by 4 pin Joints.

It consists of four turning pairs. Link 1 & link 2. forms first turning pair, link 2 & link 3 form second turning pair. link 3 & 4 3rd & 4 & 1 4th turning pair respectively.



A link that makes complete revolution is known as crank. The fixed link is known as frame of the mechanism. The link opposite to the fixed link is known as connecting rod. The forth link is known as lever, or rocker (if oscillates) or an another crank (if it rotates).

If different links of the four bar mechanism are fixed, four diff. mechanism will be obtained.



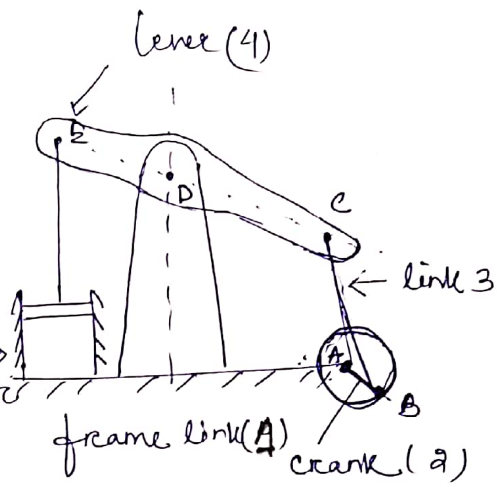
<u>Conditions for four bar Mechanism</u> / (Grashof condition)

- The length of one link should not be greater than the sum of the ~~other~~ other three links.
- One of the shortest link should make a complete revolution relative to other 3 link.
- The sum of the longest & shortest link should not be greater than the sum of the other 2 links.

Examples of inversions

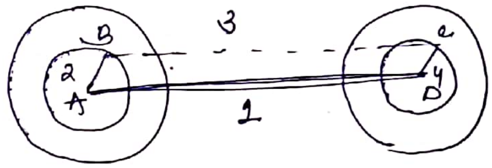
1. Beam engine (crank lever mechanism)

It is also known as crank lever mechanism. which consist of 4 links. As shown in the figure, when the crank rotates about pt A the lever oscillates about fixed centre D. The end 'E' of the lever EDC is connected to a piston rod which reciprocates due to revolution of crank. Means the rotary motion is converted into reciprocating motion.



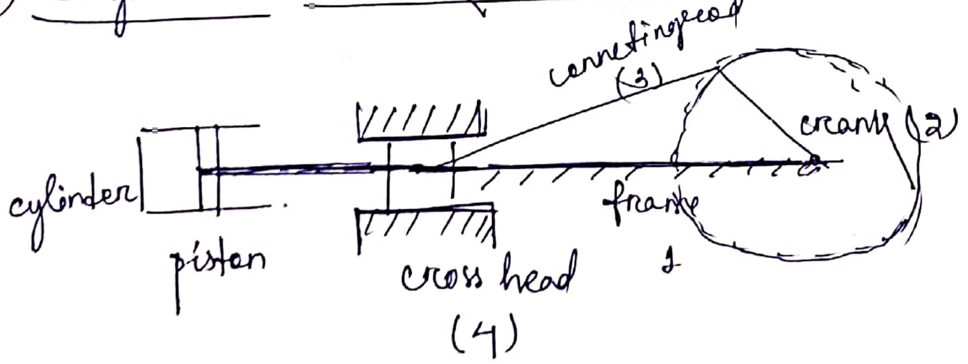
2. coupling rod of locomotive (double crank mechanism)

Here the links AB & CD are act as cranks & connected to the respective wheels. The link BC act as coupling rod. & AD act as frame or fixed.



- used to transmit rotary motion from one wheel to another wheel.

3) Single slider crank chain



- It consist of 4 links having one sliding pair & 3 turning pair.
- It converts rotary motion into reciprocating motion & vice versa.

1-2, 2-3, 3-4 → turning pair

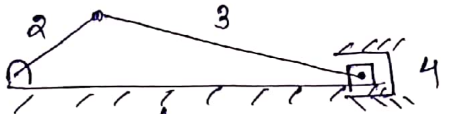
4-1 → sliding pair

Inversion of single slider crank chain

1> **1st inversion**

It is obtained when 1 link is fixed & link 2 is the crank & link 4 becomes slider.

Application – reciprocating engine

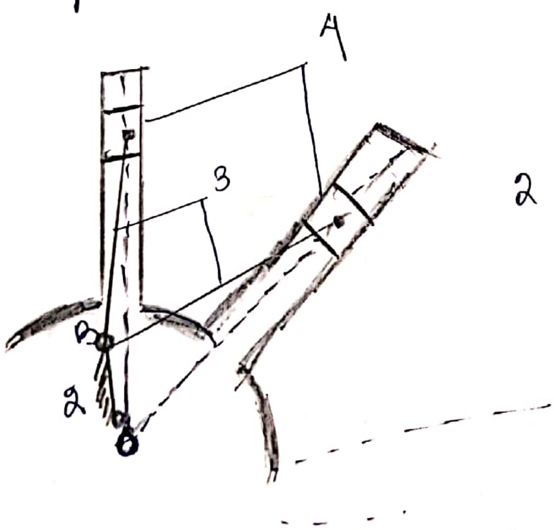


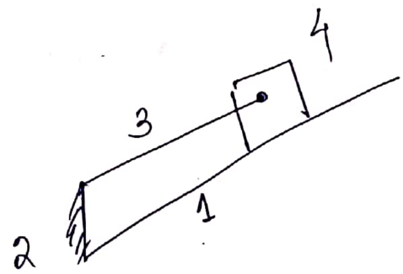
Here link 1 is fixed & 2 is the crank & link 4 is the slider.

2> **2nd inversion**

It is obtained when link 2 is fixed. When link 2 is fixed instead of link 1, the link 3 along with slider 4 will become the crank. It causes link 1 to rotates about pt. O, with the slider reciprocating.

Application – Rotary engine.

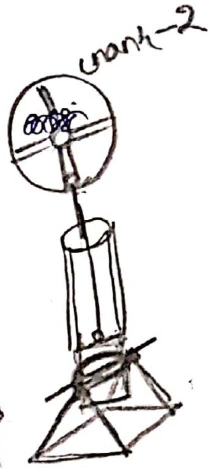




The fig shows the rotary engine mechanism. In this mechanism link 2 is fixed. Link 4 is made as the ~~cylinder~~ piston arrangement. & link 1 made as the cylinder, which reciprocates about link 4. Here instead of one cylinder, seven or nine cylinders are symmetrically placed in regular intervals in the same plane. All the cylinders rotates about the common fixed center O. The fixed link 2 is common to all cylinders. The only difference between the 1st & 2nd inversion is that, in 1st inversion, the body is fixed & crank is rotating whereas in 2nd inversion, the crank is fixed & body rotates.

3) 3rd inversion

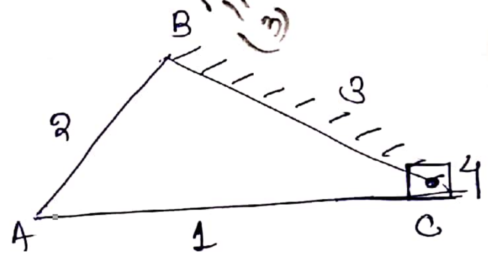
When link 3 is fixed and link 2 act as crank & link 4 oscillates.



Application – oscillating cylinder
crank & slotted lever mechanism

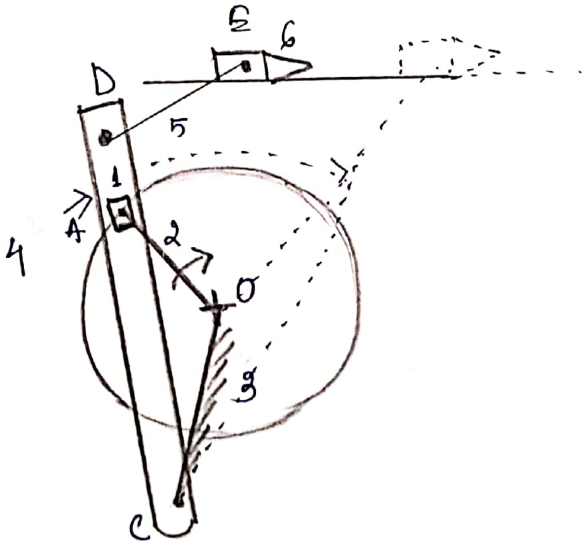
i) oscillating cylinder

The piston reciprocates inside the cylinder pivoted to the fixed link 3. When the piston reciprocates the crank rotates. about B.



ii) crank & slotted lever Mechanism

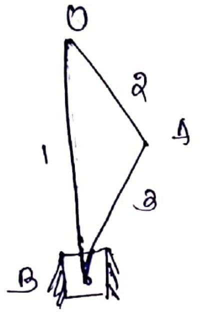
In the fig, link 1 is the slider which slides upon link 4. Link 3 is fixed and link 2 is the crank which rotes counter clockwise about a fixed center O. The link 4 is extended to pt. D which is another link, link, 5. At the end to link 5 link 6 is attached, which is the cutting tool.

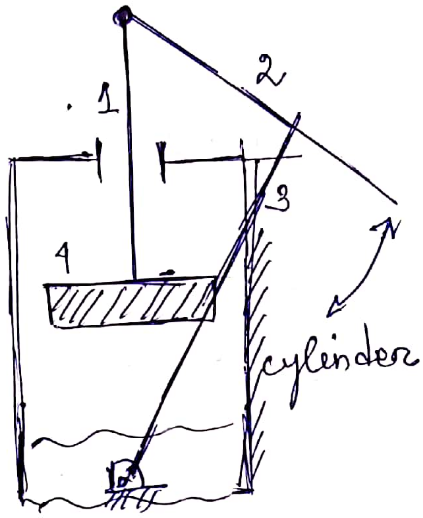


4) 4th inversion

When the 4th link is fixed, the 4th. inversion is obtained. Link 3 can oscillates about the fixed point B on the link 4. It causes link 2 to oscillates about B & the end O. to reciprocates along the axis of the fixed link. 4.

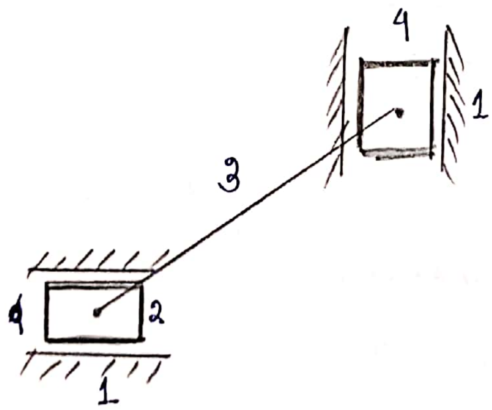
Application - Hand pump.





3) Double slider crank chain

A four bar chain having 2 turning pair & 2 sliding pair such that two pairs of same kind are adjacent is called double slider crank chain.



link 1-2, 4-1 } sliding pair

link 2-3, 3-4 } turning pair

i) 1st inversion

It is obtained when link 1 is fixed & 2-3, 3-4 are turning pair and 1-2 & 4-1 are sliding pair.

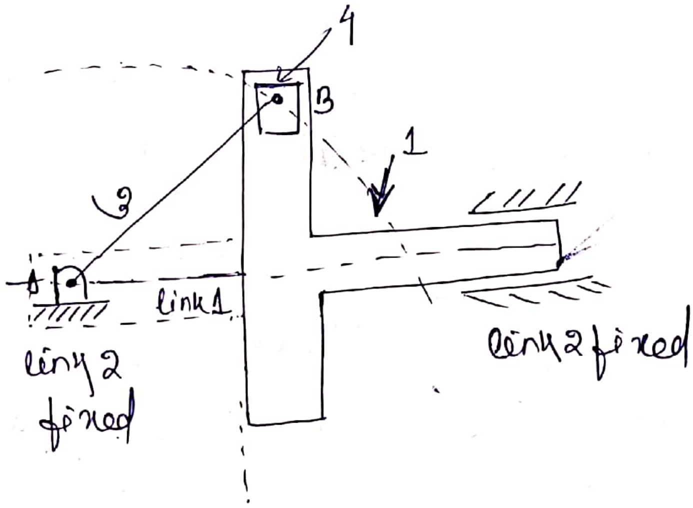
Application – Elliptical trammel

It is an instrument used to draw ellips.

ii) 2nd inversion

It is obtained when any slide block in the 1st inversion is fixed. ~~then~~

Application : Scotch yoke mechanism.



Here link 2 is fixed and 'B' end link of 3 rotates about pt A. and link 1 reciprocates in the horizontal direction. The link 1 reciprocates about fixed link 2.

iii) 3rd inversion

When link 3 is fixed it is called as the 3rd inversion.

Application – oldham's coupling.

It is used for connecting 2 parallel shaft whose axes are at a small distance apart. The shafts are coupled such that if one shaft rotates, the other shaft also rotates with the same speed.

1) completely constrained motion

→ when the motion between the two elements of a pair is in a definite direction irrespective of the direction of the force applied.

→ It may be linear or rotary.

eg. piston & cylinder of the steam engine.
Here the motion of the piston is limited to definite direction.

2) incompletely constrained motion

When motion between two elements of a pair is possible in more than one direction & depends on the direction of force applied.

Eg. shaft in circular hole.
(It can slide as well as rotates)

3) Successfully constrained motion

When the motion between two elements of a pair is possible in more than one direction but is made to have motion only in one direction by using some external means.

Eg. Shaft in a foot step bearing, the vertical motion is restricted in upward direction by applying load, apart from rotary motion.

FRICTION

When a solid body slides over a stationary solid body, a force is exerted at the surface of contact by the stationary body on the moving body. This force is called as friction.

Types

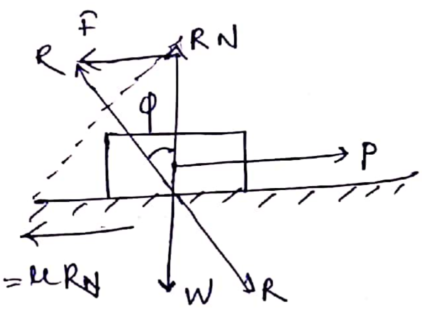
→ static friction → It is the friction, experiend by a body, when at rest.

→ Dynamic friction → experienced by a body, when it is in motion.

coefficient of friction (μ)

$$\mu = \frac{\text{limiting friction}}{\text{Normal reaction}} = \frac{F}{R_N}$$

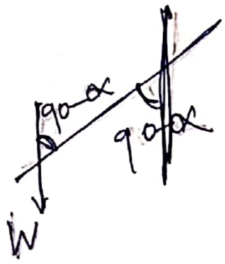
$$\Rightarrow \boxed{F = \mu R_N} \quad \text{—— ①}$$

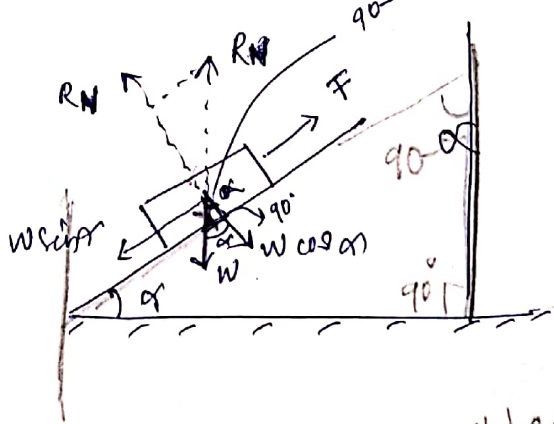


angle of friction (ϕ)

$$\tan\phi = \frac{F}{R_N} = \frac{\mu R_N}{R_N}$$

$$\boxed{\tan\phi = \mu} \quad \text{—— ②}$$





Angle of repose (α)

$$W \sin\alpha = F$$
$$= \mu R_N$$
$$= \mu W \cos\alpha$$

$$\Rightarrow \mu = \tan\alpha$$

$$\Rightarrow \boxed{\tan\phi = \tan\alpha} \quad \text{—— ③}$$

$$\boxed{\alpha = \phi}$$

|| to each other

alternate interior angle.
concurrent angle.

Screw Friction

Screws, bolts, studs, nuts etc are widely used in various m/c and structures for temporary fastening. These fastening have screw threads, which is made of cutting a continuous helical groove on a cylindrical surface. If the cuts are outside it is called as external threads & if the cuts are internal it is called as internal threads. Screw threads are 2 types. square thread.

& V. thread.

Terms related to threads

Helix – It is the curve traced by a particle, while ~~describing a circular path~~ moving along a screw thread.

pitch – It is the distance from a point of a screw to a corresponding point on the next thread measured parallel to the axis of the screw.

lead – It is the distance which a screw thread advances axially in one turn. (P)

Helix angle – Slope of thread with the horizontal.

$$\tan\alpha = \frac{\text{Lead}}{\text{circumference of screw}} = \frac{P}{\pi d} \quad \text{— (4)}$$

Screw Jack

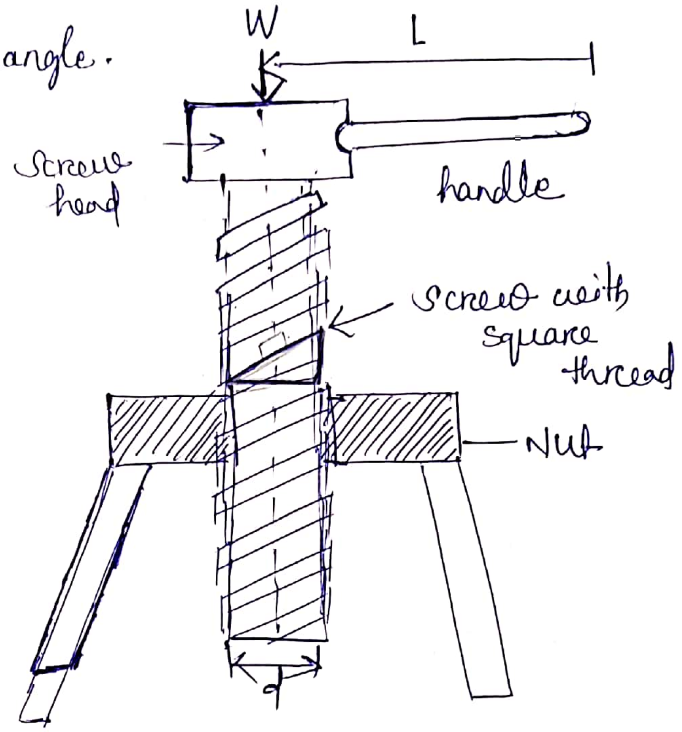
It is a device used for lifting of heavy loads, with very small effort. It ~~consi~~ consist of a nut, screw & a handle fitted to the head of the screw. The nut also forms the body of the Jack.

W = Weight placed on the screw head.

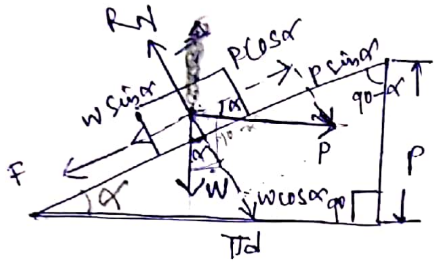
P = Effort applied at the end of handle.

L = Length of the handle.

p = pitch of the screw
d = mean dia of the screw
α = angle of the screw o.e helix angle.
φ = angle of friction
μ = co.efficient of friction.



Torque required to lift the load



Since the load is being lifted, therefore force of friction will act downward.

from the above fig

$$P\cos\alpha = W\sin\alpha + F$$

$$\Rightarrow P\cos\alpha = W\sin\alpha + \mu R_N \quad \text{—— (5)} \qquad (\because F = \mu R_N)$$

(Resolution along horizontal)

$$R_N = P\sin\alpha + W\cos\alpha \quad \text{—— (6)}$$

putting R_N in eqⁿ (5)

$$P\cos\alpha = W\sin\alpha + \mu(P\sin\alpha + W\cos\alpha)$$

$$\Rightarrow P\cos\alpha = W\sin\alpha + \mu P\sin\alpha + \mu W\cos\alpha$$

$$\Rightarrow P\cos\alpha - \mu P\sin\alpha = W\sin\alpha + \mu W\cos\alpha$$

$$\Rightarrow P(\cos\alpha - \mu\sin\alpha) = W(\sin\alpha + \mu\cos\alpha)$$

$$\Rightarrow P = W\left[\frac{\sin\alpha + \mu\cos\alpha}{\cos\alpha - \mu\sin\alpha}\right]$$

putting $\mu = \tan\phi$

$$\Rightarrow P = W\left[\frac{\sin\alpha + \tan\phi\cos\alpha}{\cos\alpha - \tan\phi\sin\alpha}\right]$$

$$= W\left[\frac{\sin\alpha + \frac{\sin\phi}{\cos\phi}\cdot\cos\alpha}{\cos\alpha - \frac{\sin\phi}{\cos\phi}\sin\alpha}\right]$$

$$\Rightarrow P = W \times \frac{\sin\alpha \cdot \cos\phi + \sin\phi \cdot \cos\alpha}{\cos\alpha \cdot \cos\phi - \sin\alpha \sin\phi}$$

$$\Rightarrow P = W \frac{\sin(\alpha+\phi)}{\cos(\alpha+\phi)}$$

$$\Rightarrow \boxed{P = W\tan(\alpha+\phi)} \quad \text{— (7)}$$

Torque required to over come friction between screw & nut

$$T = P \times \frac{d}{2}$$

$$\boxed{T = W\tan(\alpha+\phi)\frac{d}{2}} \quad \text{— (8)}$$

without friction

$$\boxed{P = W\tan\alpha}$$

* speed of screw (N) = $\frac{\text{speed of nut}}{\text{pitch of screw}}$

Torque required to lower the load by a screw jack.

$$\boxed{T = W\tan(\phi-\alpha)\frac{d}{2}} \quad \text{— (9)}$$

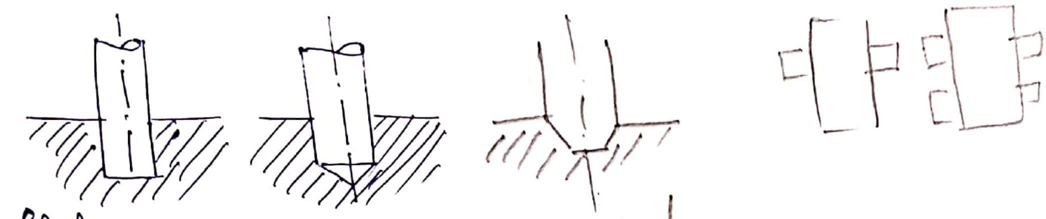
Bearing

A bearing is a m/c element that constraints relative motion to only the desired motion and reduces friction between moving parts. For example rotary bearings hold rotating components such as shafts & axles with in mechanical system.

Types – ball bearing
- Roller bearing
- plain bearing
- needle bearing

The rotating shaft are subjected to axial thrust. These shafts can be kept in correct axial position if bearing surface are provided. The bearing surface which is placed at the end of a shaft are known as pivots.

- A pivot may be of flat or conical surface.

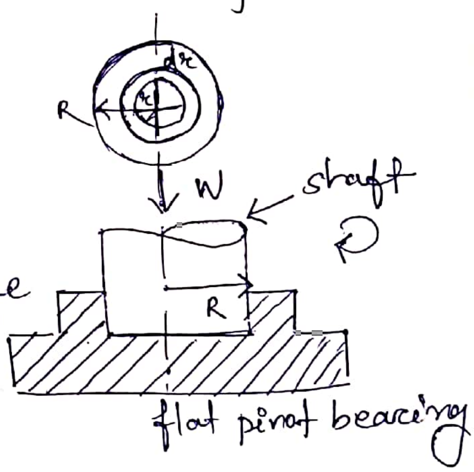


For describing friction in bearing, two assumption has to be taken:

UPT ① The pressure is uniformly distributed throughout the bearing surface.

UWT ② The wear is uniform throughout the bearing surface.

Flat pivot bearing / Foot step bearing



It is also known as footstep bearing.

W → load transmitted over bearing surface due to shaft

R → Radius of bearing surface.

p → Pressure (intensity of) per unit area.

μ → co-efficient of friction.

T → Total frictional torque.

Consider a small ring having radius r & thickness dr.

Area of $dA = 2\pi r \cdot dr$. Area of bearing surface for ring

bearing surface $= 2\pi \times 2d \cdot dr$

$= 4\pi d \cdot dr$

i) uniform pressure

Total pressure $p = \frac{W}{\pi R^2}$

$A = 2\pi r \cdot dr$

load transmitted at the ring $\delta W = p \times A$

$= p \times 2\pi r \cdot dr$

Frictional resistance to sliding acting at the ring

$F_r = \mu \cdot \delta W = \mu p \, 2\pi r \cdot dr$

$F_r = 2\pi \mu p r \cdot dr$

Frictional torque $T_r = F_r \times r$

$T_r = 2\pi \mu p r^2 dr$

Total torque. $T = \int_0^R T_r = \int_0^R 2\pi \mu p r^2 dr$

$\Rightarrow T = 2\pi \mu p \int_0^R r^2 dr$

$= 2\pi \mu p \left. \frac{r^3}{3} \right|_0^R = 2\pi \mu p \frac{R^3}{3}$

$\Rightarrow T = \frac{2}{3} \pi \mu \times \frac{W}{\pi R^3} \times \frac{R^3}{3} \quad \left(\because p = \frac{W}{\pi R^2} \right)$

$\Rightarrow \boxed{T = \frac{2}{3} \times \mu \times W \times R}$ —— (10)

power lost in friction $P = T \times \omega$

$\Rightarrow \boxed{P = \frac{2\pi N T}{60}}$

ii) uniform wear

The rate of wear depends upon the intensity of pressure & the velocity of the rubbing surface (v). This rubbing velocity increases with the distance from the axis of bearing (i.e radius)

$P \cdot r = C$ (C → constant)

$\Rightarrow P = \frac{C}{r}$

$\delta W = p \times 2\pi r \times dr$

$= \frac{C}{r} \times 2\pi r \times dr$

$= 2\pi C \cdot dr.$

Total load transmitted to the bearing $W = \int_0^R dW$

$= 2\pi C \, r \Big|_0^R$

$W = 2\pi C R$

Total torque

$T_r = 2\pi \mu p r^2 dr \quad (F_r \times r)$

$= 2\pi \mu \frac{C}{r} r^2 dr$

$= 2\pi \mu \, C \cdot r \cdot dr$

Total $T = \int_0^R T_r = \int_0^R 2\pi \mu C \, r \cdot dr = 2\pi \mu C \int_0^R r \cdot dr = 2\pi \mu C \left. \frac{r^2}{2} \right|_0^R$

$\Rightarrow T = 2\pi \mu C \frac{R^2}{2}$

$\Rightarrow T = 2\pi$

$\Rightarrow \boxed{T = \pi \mu C R^2}$ —— (11)

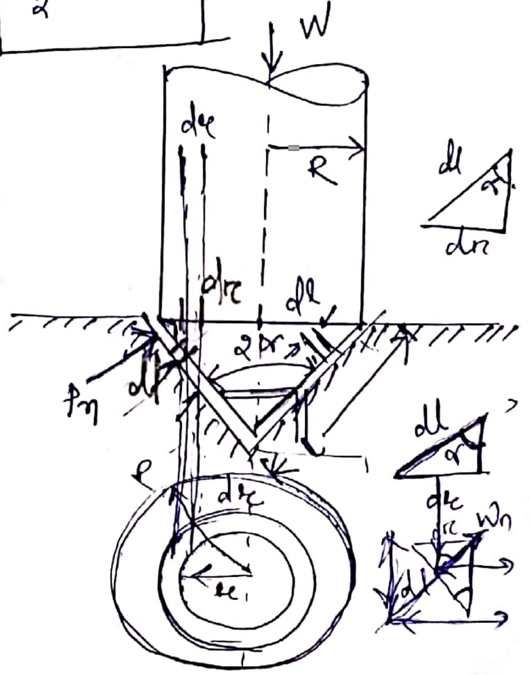
$\Rightarrow T = \pi \times \frac{W}{2\pi R} R^2 \times \mu = \boxed{\frac{1}{2} \mu W R}$

CONICAL PIVOT BEARING

P_n → intensity of pressure normal to cone.

α → semi angle of cone.

R → radius of shaft.



Consider a small ring of having radius r & thickness dr. & length dl in the length of cone.

$dl = dr\ cosec\ \alpha$ (∵ load acting on the circular ring, normal to the conical surface)

$A = 2\pi r \cdot dl$ (Area of the small element)

$= 2\pi r \cdot dr \cdot cosec\ \alpha$

i) uniform pressure

$\delta W_n = p_n \times A$ (normal load)

$\Rightarrow \delta W_n = p_n \times 2\pi r \cdot dr \cdot cosec\ \alpha$

Vertical load will be

$\delta W_v = \delta W_n \cdot \sin\alpha$

$= p_n \times 2\pi r \cdot dr \cdot cosec\ \alpha \cdot \sin\alpha$

$\delta W_v = p_n \times 2\pi r \cdot dr$. (∵ $cosec = \frac{1}{\sin}$)

total vertical load.

$$W = \int_0^R p_n \times 2\pi r \cdot dr$$

$$= p_n 2\pi \int_0^R \frac{r^2}{2}$$

$$= 2\pi p_n \times \frac{R^2}{2}$$

$$W = \pi p_n R^2$$

$$\Rightarrow \boxed{p_n = W/\pi R^2}$$

Frictional force acting tangentially

$F_r = \mu \times \delta W_n$

$= \mu \times p_n \times 2\pi r \cdot dr \cdot cosec\ \alpha$

$= 2\pi\mu p_n \cdot cosec\ \alpha \cdot r \cdot dr$.

Torque $T_r = F_r \times r$

$= 2\pi\mu p_n\ cosec\ \alpha\ r^2 dr$.

integrating T_r

$$T = \int_0^R 2\pi\mu p_n\ cosec\ \alpha \cdot r^2 dr$$

$$T = 2\pi\mu p_n\ cosec\ \alpha \frac{R^3}{3}$$

$$T = \frac{2}{3} \times \pi R^3 \mu p_n\ cosec\ \alpha$$

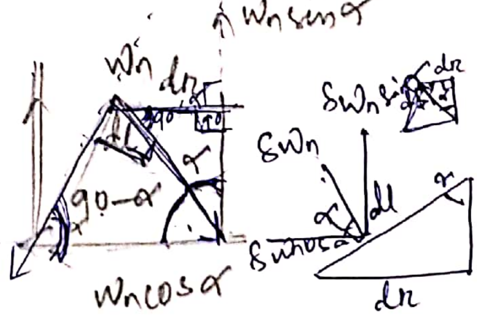
putting $p_n = \frac{W}{\pi R^2}$

$$\Rightarrow T = \frac{2}{3} \times \pi R^3 \times \mu \times \frac{W}{\pi R^2}\ cosec\ \alpha$$

$$T = \frac{2}{3} \times \mu W R\ cosec\ \alpha$$

$$\boxed{T = \frac{2}{3} \times \mu W l} \quad (12)$$

($R\ cosec\ \alpha = l$)



Uniform Wear

As we derived previously

$p_r \times r = C$

$\delta W = p_r \times 2\pi r . dr.$ $(A = 2\pi r . dr)$

$W = \int_0^R 2\pi C . dr$

$W = 2\pi C . R$

$\Rightarrow C = W/2\pi R$

Frictional torque acting on the ring.

$T_r = 2\pi \mu p_r . \operatorname{cosec} \alpha . r^2 . dr$

$= 2\pi\mu \times \frac{C}{r} \times \operatorname{cosec} \alpha \; r^2 dr$

$T_r = 2\pi\mu C \operatorname{cosec} \alpha \; r . dr$

$\therefore T = \int_0^R T_r = \int_0^R 2\pi\mu C . \operatorname{cosec}\alpha \; r . dr$

$= 2\pi\mu C . \operatorname{cosec}\alpha \left. \frac{r^2}{2} \right|_0^R$

$= 2\pi\mu C . \operatorname{cosec}\alpha \frac{R^2}{2}$

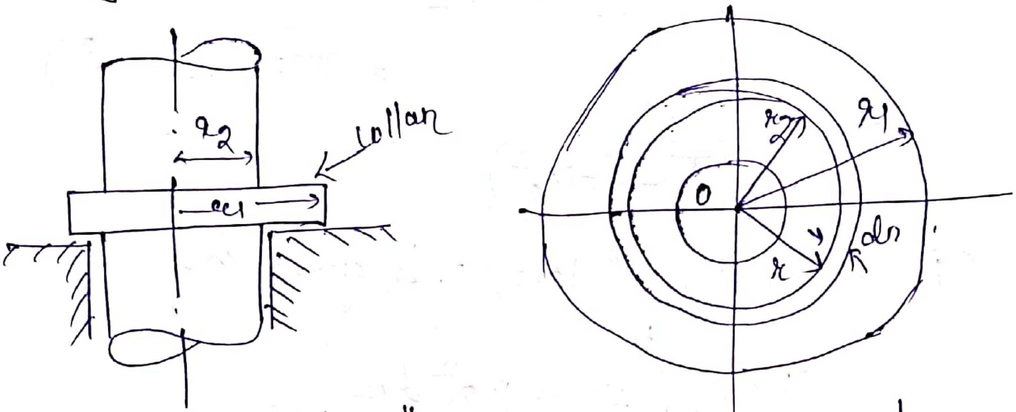
$T = \pi\mu C . \operatorname{cosec}\alpha . R^2$ (putting $C = W/2\pi R$)

$\Rightarrow T = \frac{1}{2}\mu . W . R \operatorname{cosec}\alpha$

$\Rightarrow \boxed{T = \frac{1}{2}\mu W \times l}$ —— (13)

Flat collar bearing

These are also called as thrust bearing. The bearing surface provided at any position along the shaft to carry axial thrust known as collar.



$r_1 \rightarrow$ ext. radii of collar
$r_2 \rightarrow$ internal " "
$p \rightarrow$ intensity of press.

$W \rightarrow$ Axial load
$\mu \rightarrow$ co-effi
$T \rightarrow$ Total frictional load.

Consider a circular ring of thickness dr at a radius r.

Area of ring $= 2\pi r \cdot dr$

Load on the ring $= p \times 2\pi r\, dr$

Frictional force on ring $= \mu \times$ load
$= \mu\, p\, 2\pi r\, dr$

Torque on ring $dT = \mu \times p\, 2\pi r\, dr \times r$
$= 2\pi \mu p r^2 dr$

Total Frictional torque $= T = \int_{r_2}^{r_1} dT$

$$= \int_{r_2}^{r_1} 2\pi \mu p\, r^2 dr$$

i) uniform pressure

$p = C$

Total load transmitted on the bearing

$$= \int_{r_2}^{r_1} \text{load on the ring}$$

$$W = \int_{r_2} p \times 2\pi r \, dr$$

$$= p \times 2\pi \int_{r_2}^{r_1} r \cdot dr$$

$$= 2\pi p \left[\frac{r^2}{2}\right]_{r_2}^{r_1} = 2\pi p\left[\frac{r_1^2 - r_2^2}{2}\right]$$

$$= \pi p (r_1^2 - r_2^2)$$

$$\Rightarrow p = \frac{W}{\pi(r_1^2 - r_2^2)}$$

Total frictional torque is given by

$$T = \int_{r_2}^{r_1} 2\pi \mu p r^2 \, dr$$

$$= 2\pi \mu p \int_{r_2}^{r_1} r^2 \, dr$$

$$= 2\pi \mu p \left.\frac{r^3}{3}\right]_{r_2}^{r_1}$$

$$= 2\pi \mu p \left[\frac{r_1^3 - r_2^3}{3}\right]$$

$$= 2\pi \mu \times \frac{W}{\pi(r_1^2 - r_2^2)} \times \left[\frac{r_1^3 - r_2^3}{3}\right]$$

$$= \frac{2}{3} \mu W \left[\frac{r_1^3 - r_2^3}{r_1^2 - r_2^2}\right]$$

Uniform wear

$$p \times r = \text{const}$$

$$p = \frac{C}{r}$$

Total load transmitted to the bearing.

$$= \int_{r_2}^{r_1} \text{load on ring}$$

$$= \int_{r_2}^{r_1} p \times 2\pi r \times dr$$

$$W = \int_{r_2}^{r_1} p \times 2\pi r \times dr$$

$$= \int_{r_2}^{r_1} \frac{c}{r} \times 2\pi r \times dr = \int_{r_2}^{r_1} \frac{c}{r} \times 2\pi r \times dr$$

$$= 2\pi c \int_{r_2}^{r_1} dr = 2\pi c \left[r \right]_{r_2}^{r_1} = 2\pi c (r_1 - r_2)$$

$$C = \frac{W}{2\pi (r_1 - r_2)}$$

Total Frictional torque is given by equ^n

$$T = \int_{r_2}^{r_1} 2\pi \mu p r^2 dr$$

$$= 2\pi\mu \int_{r_2}^{r_1} p r^2 dr = 2\pi\mu \int_{r_2}^{r_1} \frac{c}{r} \times r^2 \times dr$$

$$= 2\pi\mu \int_{r_2}^{r_1} cr . dr = 2\pi\mu c \int_{r_2}^{r_1} r . dr$$

$$= 2\pi\mu c \left| \frac{r^2}{2} \right|_{r_2}^{r_1} = 2\pi\mu c \left[\frac{r_2^2 - r_1^2}{2} \right]$$

$$= 2\pi\mu \times \frac{W}{2\pi (r_1 - r_2)} \times \left[\frac{r_2^2 - r_1^2}{2} \right]$$

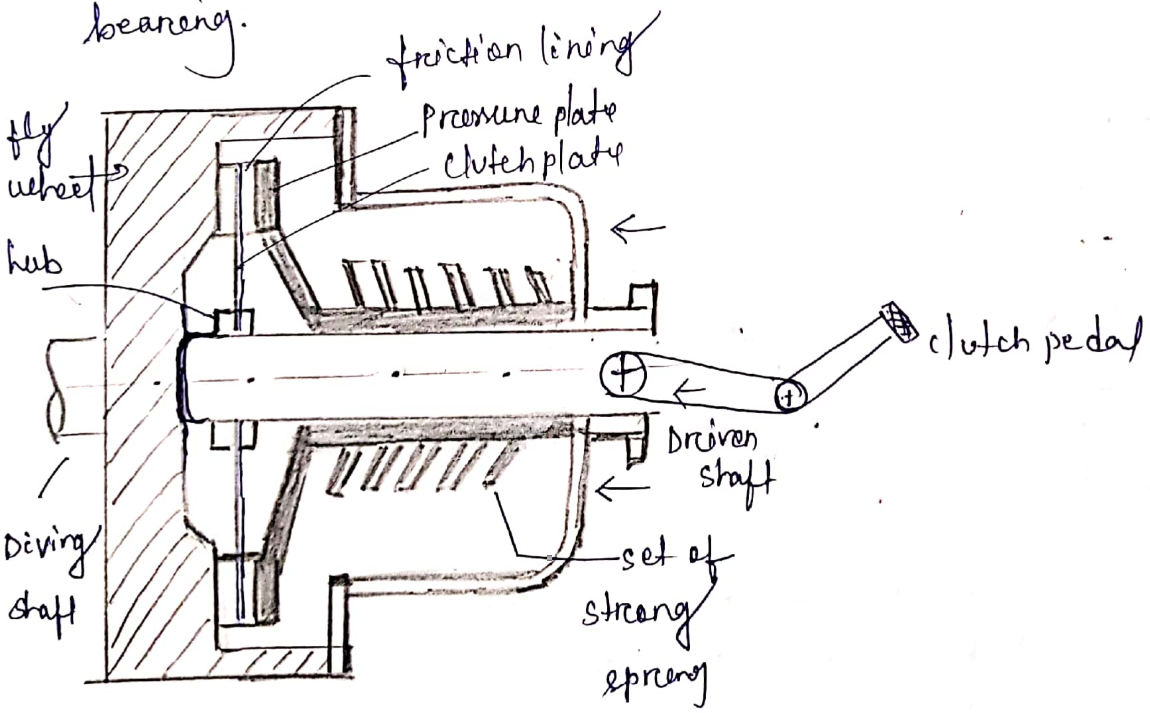
$$= \frac{\mu W}{2} (r_1 + r_2)$$

Friction clutch

The device used to transmit the rotary/ motion of one shaft to another or driver shaft to driven shaft is known as friction clutch or "clutch." The engine shaft and the gear box shaft is connected with the help of friction clutch.

1. Single plate clutch

A single plate clutch consist of a single clutch plate with friction lining on Both side. This plate is attached to a hub which is free to move axially along the splines of the driven shaft. There is a pressure plate inside the clutch body. This pressure plate pushes the clutch plate towards the flywheel by a set of strong springs. The total clutch body is bolted to the flywheel. The pressure plate & the flywheel rotate with the driving shaft. The movement of the clutch pedal is transferred to the pressure plate through thrust bearing.



Engaged position

When the foot is taken away from the pedal, the set of strong spring (-) will move forward to the pressure plate & a contact is made bet the clutch plate and the flywheel with both side friction lining. Due to the friction lining a tight grip is created between the pressure plate & flywheel, thus the power from the driving shaft is transmitted to the driven shaft. And when the pedal is pressed the both shaft got detached from each other & power trans^n stops.

Torque transmitted

let r_1 = ext. radius of friction lining

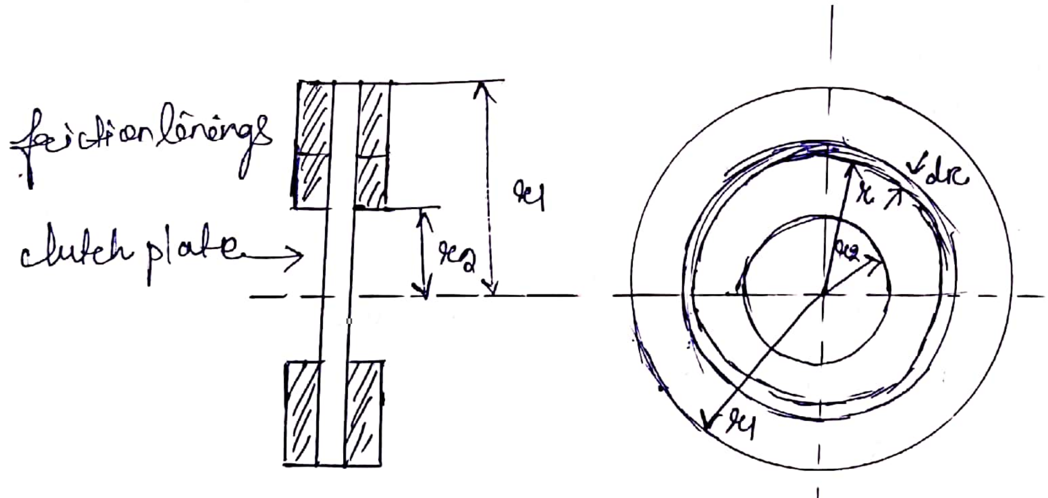
r_2 = int. " "

p = intensity of pressure

W = total axial load.

μ = co. effi. of friction

T = Torque transmitted.



* For a new clutch the intensity of pressure is approximately ~~high over~~ ~~at~~ uniform over the entire surface where in an old clutch the uniform wear theory is more approximate.

Area of the ring $dA = 2\pi r \cdot dr$

Axial load in the ring $dW = p \times 2\pi r \cdot dr$

Frictional force " $dF = \mu \times$ load in the ring

$= \mu \times p \times 2\pi r \cdot dr$.

Frictional torque dT = frictional force × Radius

$$= dF \times r$$

$$= \mu p \times 2\pi r \cdot dr \times r$$

$$= \mu p \, 2\pi r^2 \, dr$$

i) For uniform pressure.

$$p = \text{constant}$$

$$= \frac{\text{Load}}{\text{Area}} = \frac{W}{\pi(r_1^2 - r_2^2)} \quad (\text{average pressure})$$

$$T = \int_{r_2}^{r_1} dT = \int_{r_2}^{r_1} \mu p \, 2\pi r^2 dr$$

$$= 2\pi \mu p \left[\frac{r^3}{3}\right]_{r_2}^{r_1} = 2\pi \mu p \left[\frac{r_1^3 - r_2^3}{3}\right]$$

$$= 2\pi \mu \times \frac{W}{\pi(r_1^2 - r_2^2)} \times \left[\frac{r_1^3 - r_2^3}{3}\right]$$

$$\boxed{T = \frac{2}{3} \mu W \left[\frac{r_1^3 - r_2^3}{r_1^2 - r_2^2}\right]} \quad \text{—— (16)}$$

The above torque for a single friction plate.

So the total torque on the total clutch plate will be

$$\boxed{T_c = 2T}$$

ii) For uniform wear

$$p \times r = \text{const.}$$

$$p \times r = C \qquad (\because W = 2\pi C (r_1 - r_2))$$

$$\Rightarrow p = C/r$$

We know $dW = 2\pi r \, dr \times p$

total axial load $W = \int_{r_2}^{r_1} dW = \int_{r_2}^{r_1} 2\pi r \cdot dr \times \frac{C}{r} = 2\pi C [r_1 - r_2]$

$$\Rightarrow \boxed{C = \frac{W}{2\pi [r_1 - r_2]}}$$

Total frictional torque.

$$T = \int_{r_2}^{r_1} dT = \int_{r_2}^{r_1} \mu \times p \times 2\pi r^2 \, dr$$

$$= \int_{r_2}^{r_1} \mu \times \frac{c}{r} \times 2\pi r^2 \, dr = \int_{r_2}^{r_1} \mu c \times 2\pi r \cdot dr$$

$$= 2\pi \mu c \int_{r_2}^{r_1} r \cdot dr = 2\pi \mu c \left. \frac{r^2}{2} \right|_{r_2}^{r_1} = 2\pi c \mu \left[\frac{r_1^2 - r_2^2}{2} \right]$$

$$= \mu \times \frac{W}{2\pi (r_1 - r_2)} \times \frac{r_1^2 - r_2^2}{2} \times \pi \qquad \left\{ \text{putting value of } c = \frac{W}{2\pi (r_1 - r_2)} \right.$$

$$= \frac{\mu \times W}{2} (r_1 + r_2)$$

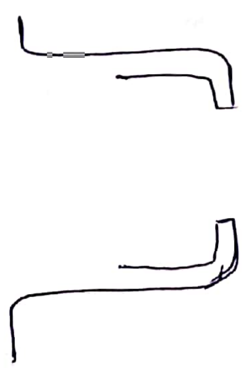
$$\boxed{T = \frac{\mu \times W (r_1 + r_2)}{2}} \quad \text{—— (17)}$$

Total torque on clutch plate $\boxed{T_c = 2T}$

Multiplate clutch

The working & construction is same as the single plate clutch except, the friction lining & disc plate. As the name suggest it contains a no. of friction & disc plate.

diagram.



Torque is same.

$$T = n \times \mu \times W \times \frac{2}{3} \left[\frac{r_1^3 - r_2^3}{r_1^2 - r_2^2} \right]$$

$$T = \frac{n \times \mu \times W \times (r_1 + r_2)}{2}.$$

$n = n_1 + n_2 - 1$

$n_1 \rightarrow$ no. of friction plate

$n_2 \rightarrow$ " " disc.

BRAKES

A brake is a mechanical device by means of which artificial frictional resistance is provided or applied to a moving machine, in order to retard or stop the motion of the machine. The energy absorbed by brake is dissipated in the form of heat. The heat is dissipated to the surrounding air.

The capacity of a brake depends upon the following factors.

- The unit pressure betn the breaking surface.
- The co-efficient of friction betn the breaking surfaces.
- The projected area of the friction surface
- The ability of ~~break~~ brake to relese heat.

Material for brakes

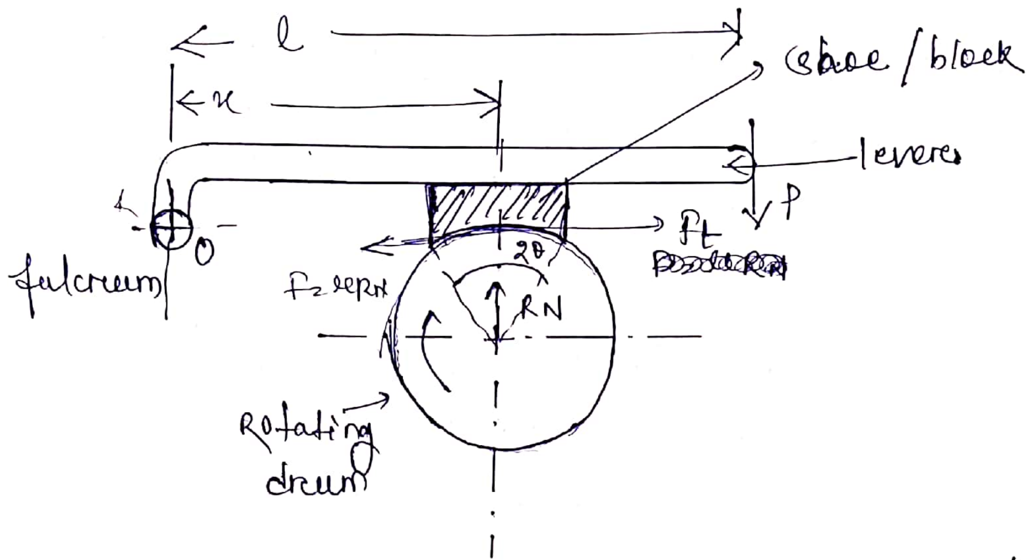
The material used for brake lining should have following characteristic.

- It should have high co-efficient of friction.
- It should have low weare rate.
- It should have high heat resistant.
- It should have enough mechanical strength.
- It should not be effected by moisture & oil.

Some important type of Mechanical brakes are.

1) simple shoe / block brake
2) Double block brake
3) Band brake
4) Internal expanding brake etc.

1) Single block or shoe brake



- This above fig. is the arrangement of simple shoe/block brake. The face of a brake has a special frictional material which has high value of co-efficient of friction.

- A single block or shoe brake consist of a block which is pressed against a rotating drum. This block is rigidly fixed to the lever. The force is applied at one end of the lever and other end of the lever is pivoted to a fixed fulcrum O. As the force is applied to the lever, the block is pressed against the rotating drum. The friction betn the block & the drum causes a tangential force to act on the drum, which tends to prevent the rotation.

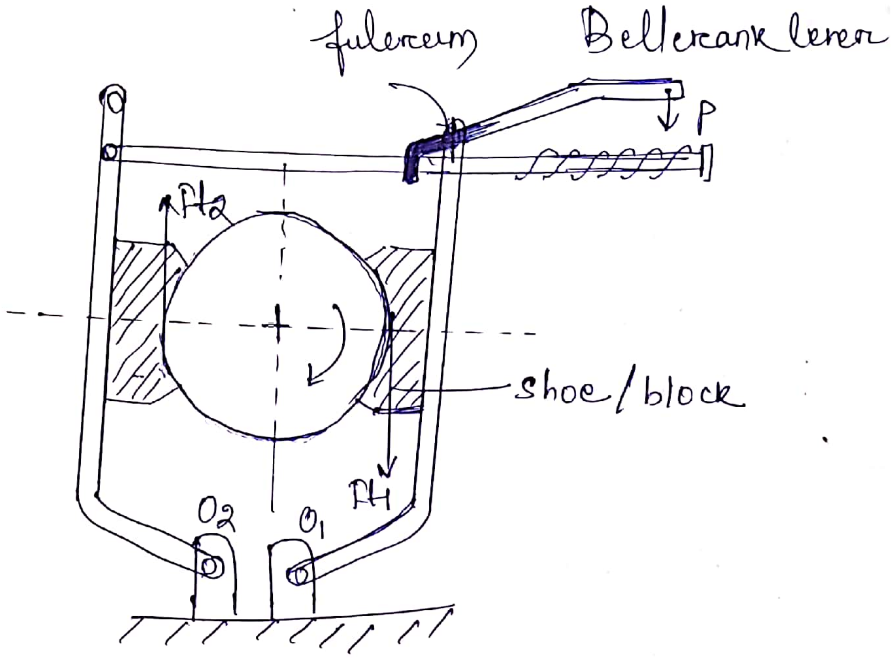
- The block is made up softer material than that of drum, so the block can be replaced on wearing. for eg. bicycle.

2) Double shoe / block brake

- It consist of two block or two shoe applied at opposite ends of a diameter of the wheel. The brake is set by a spring which pulls the upper ends of the brake arm together.

- when a force p is applied to the bell crank lever, the spring is compressed and the brake is released.

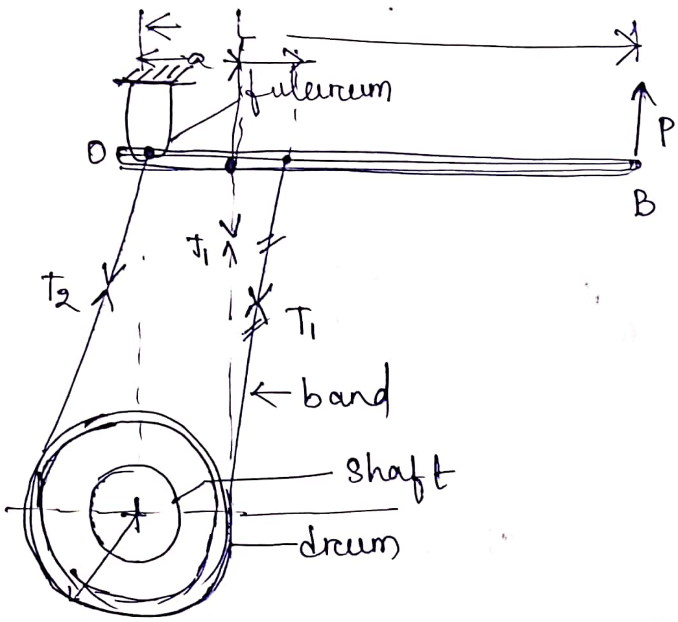
This type of breakes often used on electric cranes.



Simple band brake

A band brake is consist of one or more reapes, belt or flexible steel band lined with friction material, which encircle the circumference of rotating drum. The fig. shows a simple band breake in which one end is attached with the fulcrum (fixed pin) of the lever while other end is attached to the lever at distance 'a' from the fulcrum. In order to apply the brake, the band is tightened round the drum & the friction between the band and the drum provides the breaking torque.

The force p is applied at the free end of the lever which turns about the fulcrum O. This tightens the band on the drum and hence break is applied. The breaking force is provided by the friction between the band & the drum.



$T_1 \rightarrow$ Tension in the tight side

$T_2 \rightarrow$ " " slack "

$t \rightarrow$ thickness of the band.

$r \rightarrow$ radius of drum

$r_e = r + t/2$.

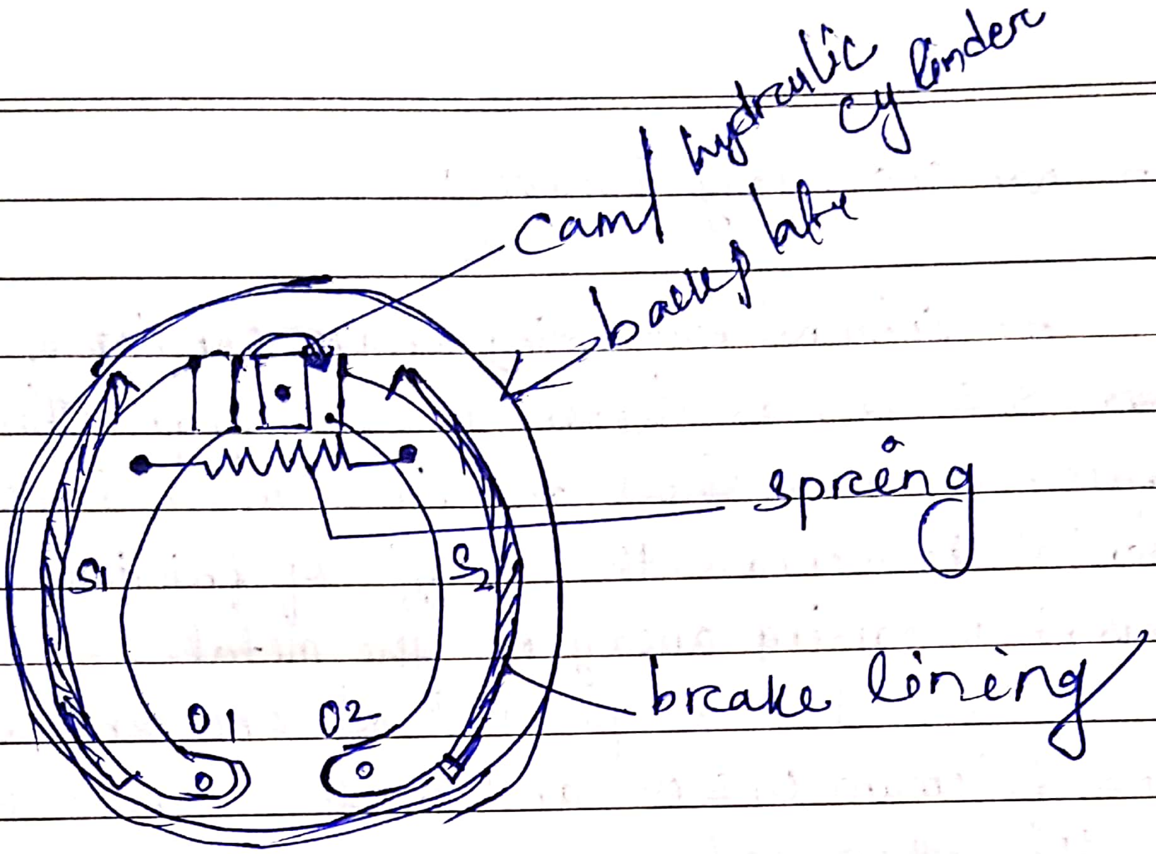
$t \rightarrow$ thickness of band.

Breaking/ torque on the drum.

$T_B = (T_1 - T_2) r$ (neglecting thickness)

$T_B = (T_1 - T_2) r_e$

$= (T_1 - T_2)(r + t/2)$ considering thickness.


cam/ hydraulic cylinder
back plate
spring
S1
S2
O1
O2
brake lining

Internal expanding Brake:

An internal expanding brake consist of 2 shoe ~~brake~~ S_1 & S_2, as shown in the fig. The outer surface of the shoes are lined with some friction material to increase the co-effi of friction and to prevent wearing away of the metal.

— Each shoe is pivoted at one end about a fixed fulcrum O_1 & O_2 and made to contact a cam at the other end.

— When the cam rotates, the shoes are pushed outwards against the rim of the drum. The friction between the shoes and the drum produces the braking torque & hence reduces the speed of the drum. The shoes are normally held in off position by a spring, as shown in the figure. The drum encloses the entire mechanism to keep out dust & moisture.. These are used in motor cars & light weight trucks.

Dynamometere

A dynamometer is a breake but in addition, it has a device to measure the frictional resistance. By measuring the frictional resistance, we may obtain the torque transmitted & hence the power of the engine.

It is broadly divided as 2 categories.

① Absorption dynamometer.

② Transmission dynamometer.

In absorption dynamometer the entire energy or power produced by the engine is absorbed by the friction resistances of the breake & transformed into heat.

In transmission dynamometer, the energy is not wasted in friction but it is used for doing work. Here the energy or power produced by the engine is transmitted through the dynamometer to some other m/c where the power developed is suitably measured.

Absorption dynamometer

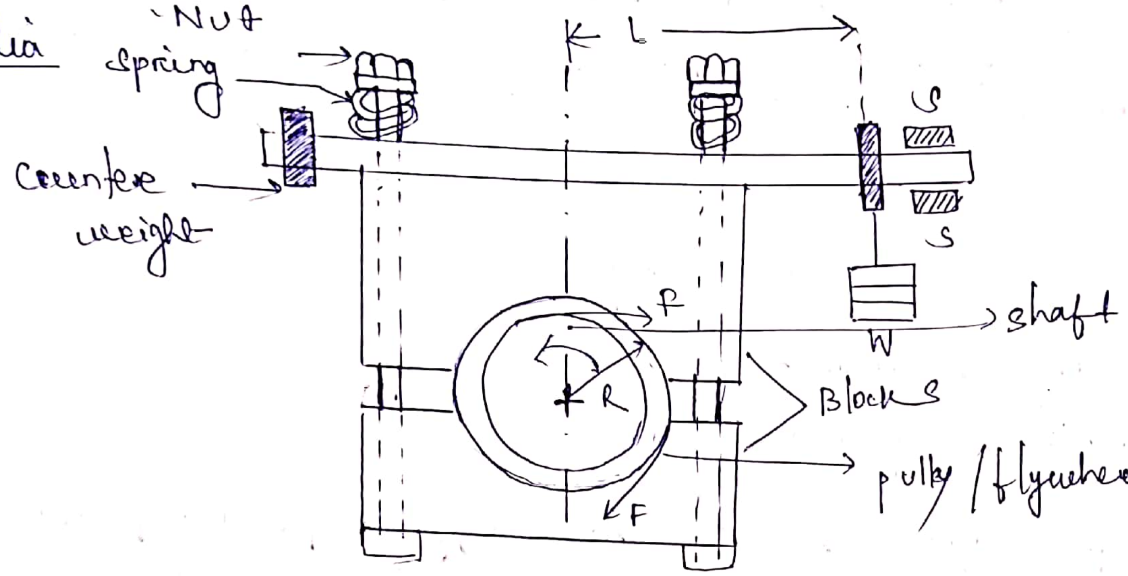
- pony breake dynamometer.
- Rope breake dynameter.

pony breake dynamometere

A simplest form of an absorption type dynamometer is a pony breake dynamometer. It consist of two wooden block placed arround a pully fixed to the shaft of an engine whose power is required to be measured. The blocks are clamped by means of two bolts & nuts, as shown in the fig. A helical spring is provided between the nut and upper block to adjust the pressure on the pully to control its speed. The upper block has a long lever attached to it & carries a weight 'W' at its outer end. A counter weight is placed at the

Other end of the lever which balances the brake when unloaded
Two stops S, S are provided to limit the motion of the lever.

dia



When the brake is to be put in operation, the long end of the lever is loaded with suitable weights W & the nuts are tightened untill the engine shaft runs at a const. speed & the lever is in horizontal position. Under these conditions, the moment due to the weight W must balance the moment of the frictional resistance between the blocks & the pulley.

W = weight of the outer end of the lever.

L = horizontal distance of the weight W, from the centre of the pulley.

F = frictional resistance between the blocks & the pully in newton.

R = radius of the pulley.

N = speed of the shaft.

$T = W \times L$

Work done in one revolution = Torque X Angle turned in radian

$= T \times 2\pi$ N-m

Work done/min = $T \times 2\pi \times N$ N-m

$B.P = \frac{T \times 2\pi N}{60}$ Watts

Rope brake Dynamometer

It is another type of absorption type dynamometer, which is commonly used for measuring the break power of the engine. It is consist of one, two or more ropes wound around the flywheel or rim of a pully fixed rigidly to the shaft of the engine. The upper end of the ropes is attached to a spring balance while the lower end of the rope is kept in position by applying a dead wt. as shown in the fig. To avoid slipping of rope over the flywheel, wooden blocks are placed at regular internals around the whole circumference of flywheel.

In operational condition of the brake, the engine is made to run at a const. speed. The frictional torque, due to the rope must be equal to the torque being transmitted by the engine.

W = Dead load

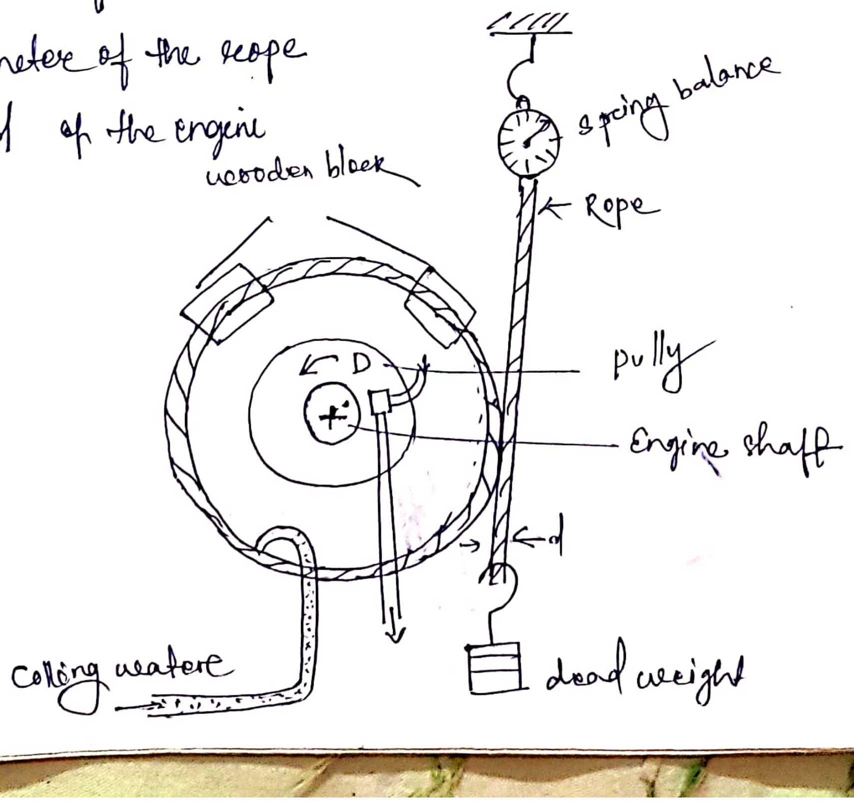
S = spring balance

D = Diameter of the wheel

d = diameter of the rope

N = Speed of the engine

diagram



Net load on the brake = W − S N

We know the distance moved in one revolution

$$= \pi (D + d) \text{ m}$$

Work done / revolution = $(W - S)\pi(D+d)$ N-m

& work done / min = $(W-S)\pi(D+d)N$ N-m

Break power = $\frac{\text{Work done / min}}{60}$

$$B.P = \frac{(W-S)\pi(D+d)N}{60} \text{ watts.}$$

If dia of rope (d) is neglected, then,

$$B.P = \frac{(W-S)\pi(D)N}{60} \text{ watts.}$$

Bearing

A bearing is a m/c element that constraints relative motion to only the desired motion, & reduces friction between moving part. It is a device that support load.

Types of bearing

- Acc. to dirn of applied load
  - Radial bearing
    - ball bearing
    - Rollar bearing
  - Thrust bearing
    - collar bearing
    - pivot bearing
- Acc to nature of contact
  - Sliding contact
    - collar &
    - pivot
  - Rolling contact
    - Ball bearing
    - Rollar bearing

Rolling contact bearing

When the action between Journal and bearing is of rolling instead of sliding than it is called rolling contact bearing. It is also called as antifriction bearing as the value of μ is very low.

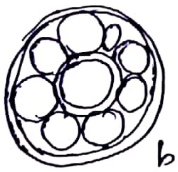
Advantages

- less friction
- Low cost of maintainance
- easy operation
- comparatively clean.

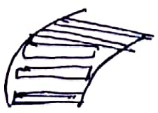
Limitations

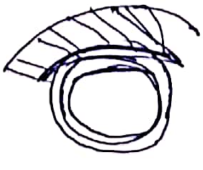
- more intial cost
- Degin is complicated
- less resistant to shock.

eg. ball bearing & Roller bearing



ball.





Rollor bearing

- very high load capacity
- good speed capability

Application

- gear box
- Rolling mills
- Electric motors

Types

- cylindrical
- spherical
- Taper

Ball bearing

- high speed
- With stand high axial load
- loger life
- Maintainance is less

Application

- Gearbox
- pump / compressore

Types

- Deep groove ball bearing
- self aligning ball bearing
- Angular contact ball "

Material for both bearing is same, bronze, babbit, cast iron etc.

Roller needle bearing

It is a special type of bearing which is used in automobile componets like rocker arm, compressor, transmission.

- compared to ball bearing it have greater surface area in contact & can support greater load.

Mechanical advantage of screw jack

Ratio betn load required to raise or lower the load to the effort required.

$$M.A = \frac{W}{P}$$

It is always > 1.

Self locking & over hauling screw →

$$P_{\text{to lower the load}} = W\tan(\phi-\alpha)$$

if $\phi < \alpha$

$P = -ve$

$T = -ve$

(over hauling)

if $\phi > \alpha$

$P = +ve$

$T = +ve$

(self locking)

* If $\phi > \alpha$ then torque req. to lower the body will be +ve. This condn is called self locking of screw.

* if $\phi < \alpha$, the torque required to lower the load will be -ve i.e load will move downward without application of torque, this condn is over hauling.

$\eta_{\text{self locking}} < 50\%$ $\eta_{\text{overhauling}} > 50\%$

$$\boxed{\eta = \frac{\tan\alpha}{\tan(\alpha+\phi)}}$$

<CHAPTER=3>

Power transmission

- It can be defined as the transmission of power from one point to another.

- There are various means of power transmission means, for eg. belt drive
  Chain drive
  Gear drive etc.

Belt drive

The belt drive is used to transmit power from one shaft to another by means of pullys which rotate at the same speed or diff speed.

Types of drives

Light drives — the belt speed is up to 10m/s eg. agriculture m/c.
Medium drives — 10 - 22 m/s eg. m/c tools
Heavy drives — more then 22m/s eg compressor.

Types of belts

Flat belts — used in factories & both the pollies are 8 m apart.
V belts — used in workshops & " " very near to eachother
Circular belts — more the 8 m.

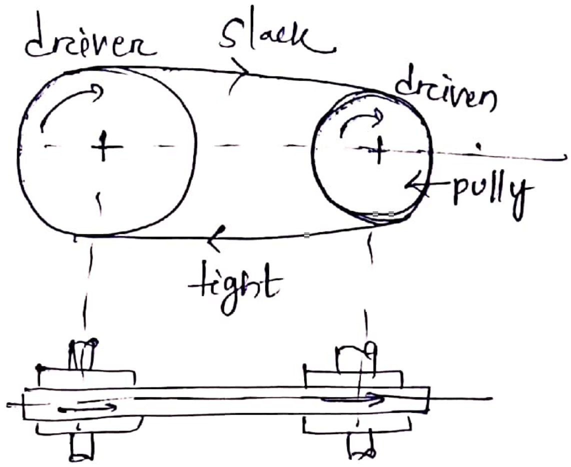
Materials for belts

- leather
- cotton
- Rubber etc.

Types Belt drive

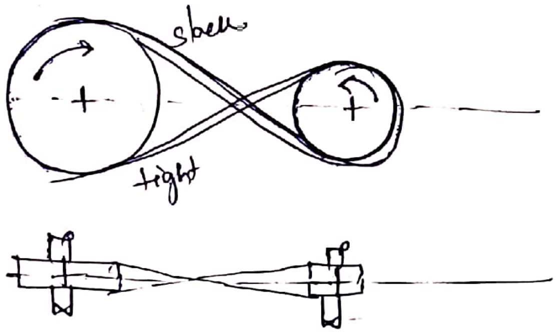
1) open belt drive

It is used when shafts are || & rotating in same direⁿ. Tension in lower side is more than tension in upper side as the driver pulls the belt from one side & deliver it to driven side



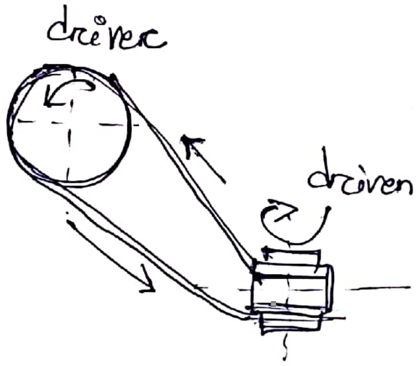
2) crossed belt drive

It is used when shafts are || but moving in opposite direction. At the point where the belt crosses, it rub agnist each other so excessive wear & teare occurs. To avoid this the shafts should placed at a minᵐ distance 20b. b→ width of belt.



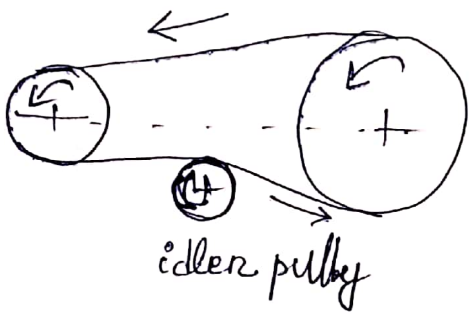
3) Quater turn belt drive

It is also called as right angle beltdrive. used when shafts are right angle & rotating in one direction.



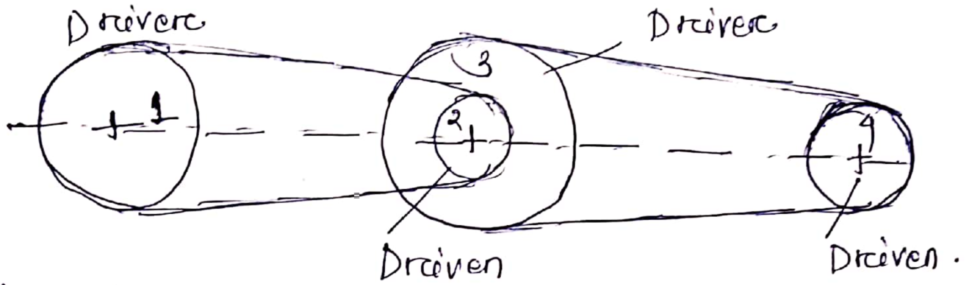
4) Belt drive with idler pulleys

Used when shafts are || & when open belt drive cannot be used due to small angle of contact on the smaller pulleys. Belt drive with many idlear pulley are used when motion has to be transformed from one shaft to several shafts.



Compound belt drive

It is used when power is transmitted from one shaft to another through a no. of pullys.



Velocity ratio of belt drive

It is the ratio betn velocities of the driver to driven.

Let d_1, d_2 → dia of driver & driven respectively

N_1, N_2 → speed in rpm of " "

Length of belt passing over driver in 1 min $= \pi d_1 N_1$

" " " driven " " $= \pi d_2 N_2$

As the length is same so. $\pi d_1 N_1 = \pi d_2 N_2$

$$\Rightarrow \boxed{\frac{N_2}{N_1} = \frac{d_1}{d_2}}$$ - velocity ratio.

If thickness of belt is considered $\frac{N_2}{N_1} = \frac{d_1+t}{d_2+t}$

Velocity ratio of compound belt drive

Let pully 1 driving polly 2.

" 2 & 3 are mounted on same shaft so, 1 also drives 3 & ultimately drives 4.

Let d_1, d_2, d_3, d_4 → dia of pully 1, 2, 3 & 4

N_1, N_2, N_3, N_4 → speed " " 1, 2, 3 & 4

velocity ratio of pully 1 & 2 $= \frac{N_2}{N_1} = \frac{d_1}{d_2}$ ——— (1)

3 & 4 $= \frac{N_4}{N_3} = \frac{d_3}{d_4}$ ——— (2)

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multiplying (i) & (ii) $\frac{N_2}{N_1} \times \frac{N_4}{N_3} = \frac{d_1}{d_2} \times \frac{d_3}{d_4}$

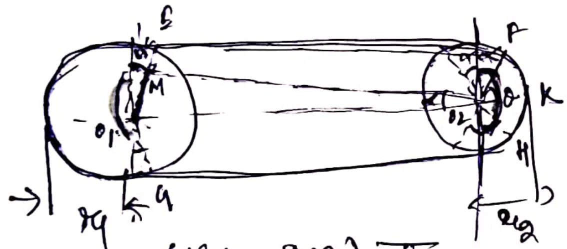
$$\Rightarrow \boxed{\frac{N_4}{N_1} = \frac{d_1 d_3}{d_2 d_4}} \quad (\because \text{ as } N_2 = N_3)$$

$$\frac{\text{speed of driven}}{\text{speed of driver}} = \frac{\text{Product of dia of drivers}}{\text{'' '' driven}}$$

Angle of contact

$$\sin\alpha = \frac{O_1M}{O_1O_2} = \frac{O_1E - ME}{O_1O_2} = \frac{r_1 - r_2}{x}$$

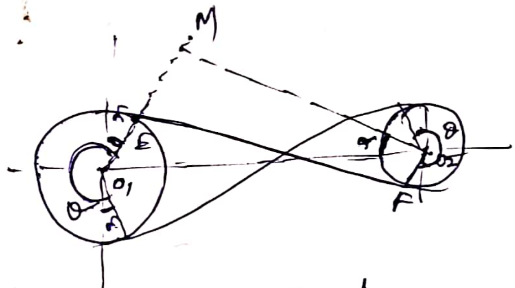
open belt drive



$\theta = (180 - 2\alpha)\frac{\pi}{180}$

always taken in the small pully.

crossed belt drive.



$\theta = (180 + 2\alpha)\pi/180$

Same on both the pully.

$$\sin\alpha = \frac{O_1M}{O_1O_2} = \frac{O_1E + EM}{O_1O_2} = \frac{r_1 + r_2}{x}$$

power transmission by belt

As driving pully pulls the belt from one side and delivers it to the other side, so tension on the tight side is more than tension in slack side.

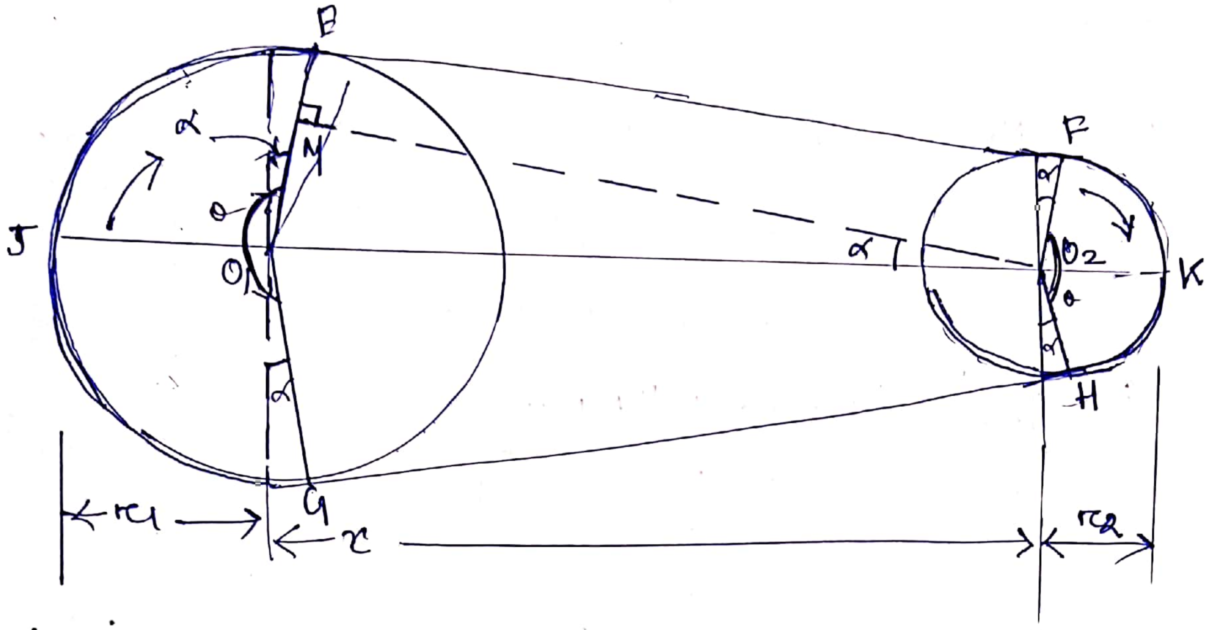
let T_1, T_2 → Tensions in tight & slack side

r_1, r_2 → radii of driver & follower pully

V → velo. of belt in m/s

Length of an open belt drive:

Angle of contact
$\theta = (180 - 2\alpha)\frac{\pi}{180}$



Let r_1 & r_2 → Raddi of the larger & smaller pulleys

x → Distance between the centres of two pulleys (i.e O_1 & O_2)

L → Total length of the belt.

Let the belt leaves the larger pulley at E & G & the smaller pulley at F & H. Through O_2 draw O_2M ∥ to EF. Now O_2M is ⊥ to O_1E.

Let $MO_2O_1 = \alpha$

We know that the length of the belt

$L = \text{Arc } GJE + EF + \text{Arc } FKH + HG$

$= 2(\text{Arc } JE + EF + \text{Arc } FK)$ — (1)

From the geometry of the fig, we find that

$\sin\alpha = \frac{O_1M}{O_1O_2} = \frac{O_1E - EM}{O_1O_2} = \frac{r_1 - r_2}{x}$

∵ $\sin\alpha$ → very very small we can write α.

$\alpha = \frac{r_1 - r_2}{x}$ — (2)

$$\text{Arc } JE = r_1\left(\frac{\pi}{2} + \alpha\right) \quad \text{——} (3)$$

$$\text{Arc } FK = r_2\left(\frac{\pi}{2} - \alpha\right) \quad \text{——} (4)$$

$$EF = MO_2 = \sqrt{(O_1O_2)^2 - (O_1M)^2}$$

$$= \sqrt{x^2 - (r_1 - r_2)^2} = x\sqrt{1 - \left(\frac{r_1 - r_2}{x}\right)^2}$$

~~$= x\sqrt{1 -}$ [illegible]~~

By applying binominal theorem.

$$EF = x\left[1 - \frac{1}{2}\left(\frac{r_1 - r_2}{x}\right)^2 + \cdots\right] = x - \frac{(r_1 - r_2)^2}{2x} \quad \text{——} (5)$$

putting the values of eqn 3 & 4 & 5 in eqn (1).

$$L = 2\left[r_1\left(\frac{\pi}{2} + \alpha\right) + x - \frac{(r_1 - r_2)^2}{2x} + r_2\left(\frac{\pi}{2} - \alpha\right)\right]$$

$$= 2\left[r_1 \times \frac{\pi}{2} + r_1\alpha + x - \frac{(r_1 - r_2)^2}{2x} + r_2 \times \frac{\pi}{2} - r_2\alpha\right]$$

$$= 2\left[\frac{\pi}{2}(r_1 + r_2) + \alpha(r_1 - r_2) + x - \frac{(r_1 - r_2)^2}{2x}\right]$$

$$= \pi(r_1 + r_2) + 2\alpha(r_1 - r_2) + 2x - \frac{(r_1 - r_2)^2}{x}$$

Now putting the value of $\alpha = \frac{r_1 - r_2}{x}$

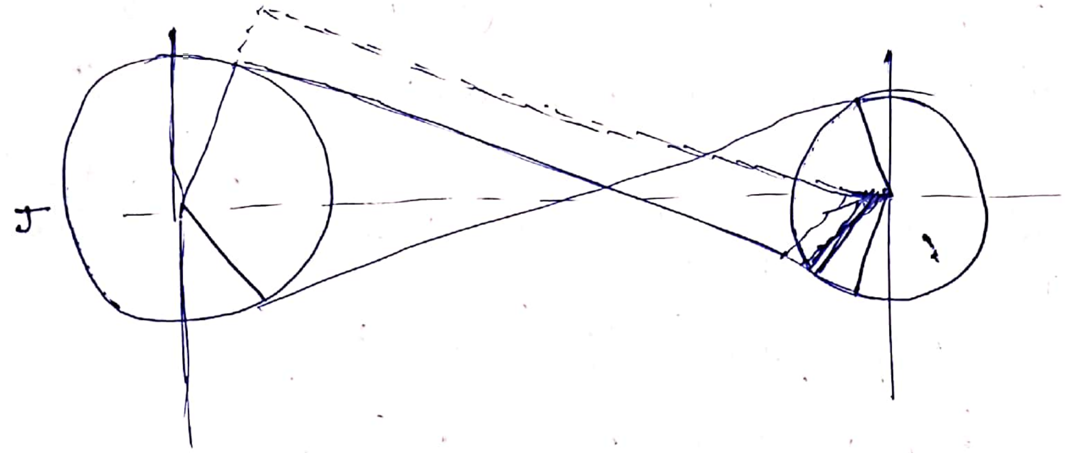
$$= \pi(r_1 + r_2) + 2\left(\frac{r_1 - r_2}{x}\right)(r_1 - r_2) + 2x - \frac{(r_1 - r_2)^2}{x}$$

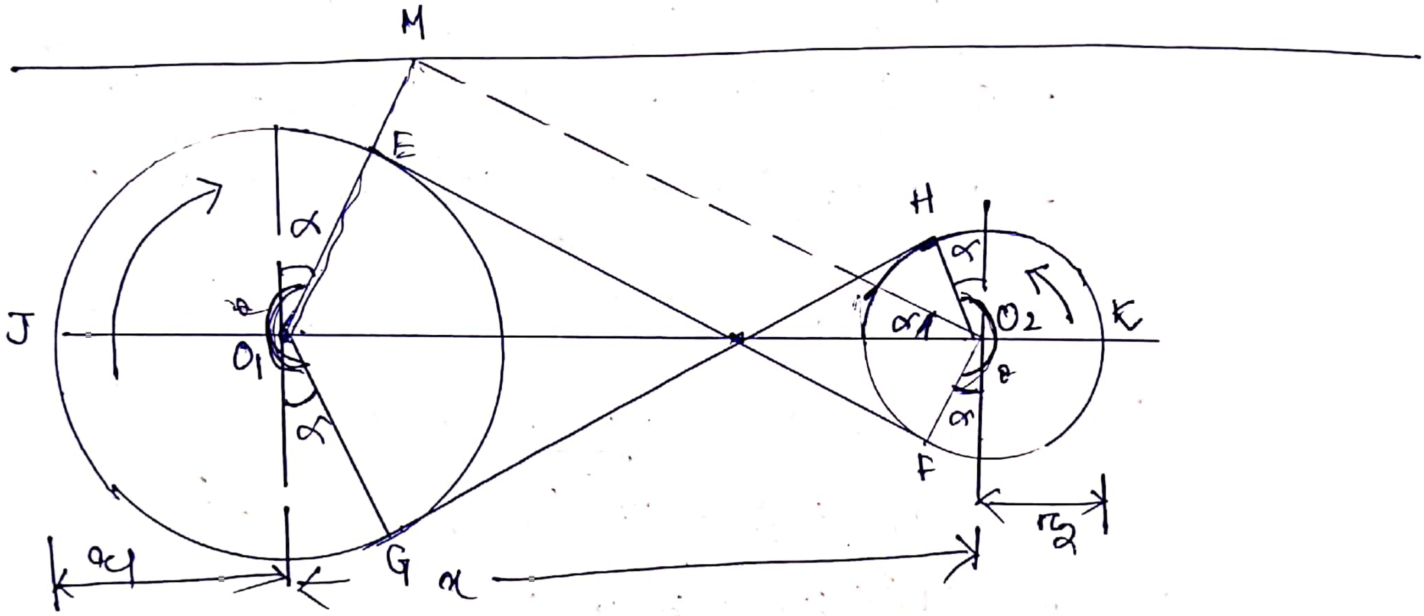
$$= \pi(r_1 + r_2) + \frac{2(r_1 - r_2)^2}{x} + 2x - \frac{(r_1 - r_2)^2}{x}$$

$$\boxed{= \pi(r_1 + r_2) + 2x + \frac{(r_1 - r_2)^2}{x}}$$

In diameter. $= \boxed{\frac{\pi}{2}(d_1 + d_2) + 2x + \frac{(d_1 - d_2)^2}{4x}}$

Length of an cross belt drive





r_1 & r_2 → radii of larger & smaller pulley

x → distance betn centers O_1 & O_2

L → total length of pulley

$\theta = (180 + 2\alpha)\pi/180$

Let belt leaves larger pulley at E & G at smaller pulley at F & H

draw O_2M ∥ to EF Now O_2M is ⊥ O_1E

Let $MO_2O_1 = \alpha$

Now $L = \text{Arc } GJE + EF + \text{Arc } FKH + HG$

$= 2(\text{Arc } JE + EF + \text{Arc } FK)$ —— (1)

$\sin\alpha = \frac{O_1M}{O_1O_2} = \frac{O_1E + EM}{O_1O_2} = \frac{r_1 + r_2}{x}$

Since sin α ≈ very small ≈ $\alpha = \frac{r_1 + r_2}{x}$

Arc JE $= r_1\left(\frac{\pi}{2}+\alpha\right)$ — ②, Arc FK $= r_2\left(\frac{\pi}{2}+\alpha\right)$ — ③

$EF = MO_2 = \sqrt{(O_1O_2)^2 - (O_1M)^2} = \sqrt{x^2 - (r_1+r_2)^2} = x\sqrt{1-\left(\frac{r_1+r_2}{x}\right)^2}$

Expanding this equⁿ in binomial form $EF = x\left[1 - \frac{1}{2}\left(\frac{r_1+r_2}{x}\right)^2 + \dots\right]$

$= x - \frac{(r_1+r_2)^2}{2x}$ — ④

Now putting value of equⁿ 2, 3 & 4 in equ ①

$$L = 2\left[r_1\left(\frac{\pi}{2}+\alpha\right) + x - \frac{(r_1+r_2)^2}{2x} + r_2\left(\frac{\pi}{2}+\alpha\right)\right]$$

$$= 2\left[r_1\frac{\pi}{2} + r_1\alpha + x - \frac{(r_1+r_2)^2}{2x} + r_2\left(\frac{\pi}{2}+\alpha\right)\right]$$

$$= 2\left[\frac{\pi}{2}(r_1+r_2) + \alpha(r_1+r_2) + x - \frac{(r_1+r_2)^2}{2x}\right]$$

$$= \pi(r_1+r_2) + \alpha(r_1+r_2)2 + 2x - \frac{(r_1+r_2)^2}{x}$$

Now putting $\alpha = \frac{r_1+r_2}{x}$ the equⁿ will become.

$$L = \pi(r_1+r_2) + \frac{r_1+r_2}{x}\times 2(r_1+r_2) + 2x - \frac{(r_1+r_2)^2}{x}$$

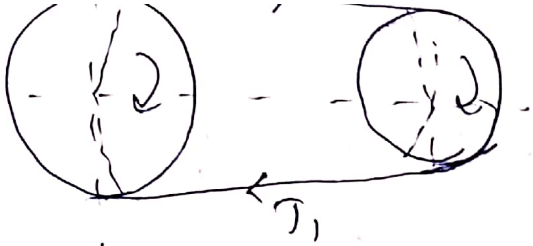
$$= \pi(r_1+r_2) + \frac{2(r_1+r_2)^2}{x} + 2x - \frac{(r_1+r_2)^2}{x}$$

$$\boxed{L = \pi(r_1+r_2) + 2x + \frac{(r_1+r_2)^2}{x}}$$

In terms of pulley diameter $\boxed{\frac{\pi}{2}(d_1+d_2) + 2x + \frac{(d_1+d_2)^2}{4x}}$

work done / sec $= (T_1 - T_2)v$

power transmitted $= (T_1 - T_2)v$ N-m/s



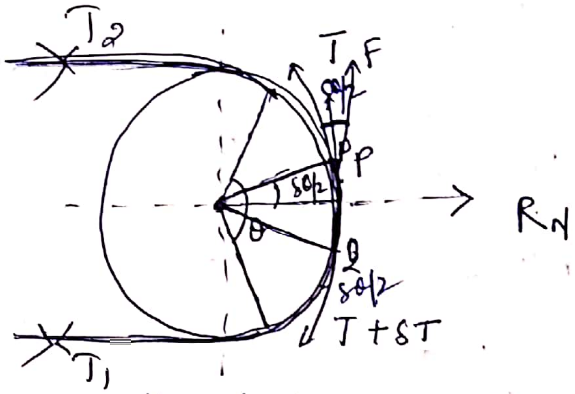
Torque produced on driver pully $= (T_1 - T_2) r_1$ ✓

" " driven " $= (T_1 - T_2) r_2$. ✓

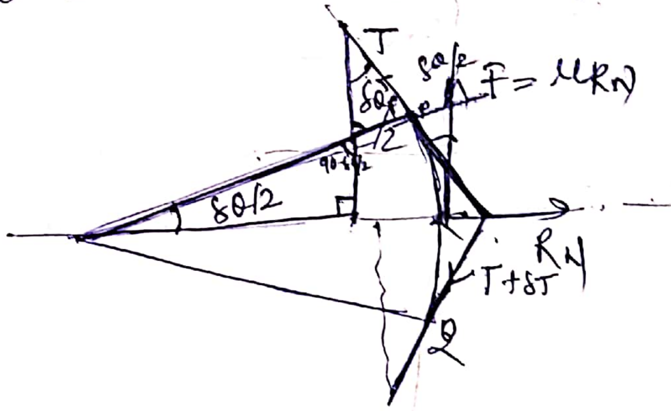
Ratio of belt tension for flat belt drive :-

Let $T_1, T_2 \rightarrow$ Tension in the belt on tight side & slack side.

$\theta \rightarrow$ Angle of contact.



Consider a small element PQ on the belt which makes a angle $\delta\theta$. with the center of the pully.



Forces acting on PQ.

- belt tension (T) at P
- " " $(T + \delta T)$ at Q
- Normal reaction R_N
- Frictional force F.

Resolving the forces in horizental direction.

$$R_N = T\sin\left(\frac{\delta\theta}{2}\right) + (T + \delta T)\sin\frac{\delta\theta}{2}$$

$$= T\left(\frac{\delta\theta}{2}\right) + (T + \delta T)\frac{\delta\theta}{2}$$

$\left(\because \sin\frac{\delta\theta}{2} \simeq \text{small} \simeq \frac{\delta\theta}{2} \right)$

$= T\frac{\delta\theta}{2} + T\frac{\delta\theta}{2} + \cancel{\delta T \frac{\delta\theta}{2}}^{0}$ (very small)

$$\boxed{R_N = T\delta\theta} \quad \text{---} \ (1)$$

Resolving vertically.

$F + T\cos\left(\frac{\delta\theta}{2}\right) - (T+\delta T)\cos\delta\theta/2 = 0$ } As $\delta\theta \approx$ small, $\cos\frac{\delta\theta}{2} = 1$

$\Rightarrow \mu R_N + T - (T+\delta T) = 0$

$$\Rightarrow \boxed{\mu R_N = \delta T} \quad \text{---} \ (2)$$

$\Rightarrow \mu T\delta\theta = \delta T_{\theta}$

$\Rightarrow \int_{T_2}^{T_1} \delta T/T = \mu\int_0^{\theta} \delta\theta$ (integrating over total angle of contact)

$\Rightarrow \ln T|_{T_1}^{T_2} = \mu\theta$

$\Rightarrow \ln(T_1/T_2) = \mu\theta =$

$$\Rightarrow \boxed{T_1/T_2 = e^{\mu\theta}} \quad \text{---} \ (3) \qquad \text{or} \qquad \boxed{2.3\log\left(\frac{T_1}{T_2}\right) = \mu\cdot\theta}$$

Slip of Belt :-

- The difference in motion between the belt and pully in driving or driven side is called slip. which occurs due to insufficient frictional grip.
- It reduces the velocity ratio.
- Generally expressed as %.

velo. of driver pully/sec. = velo. of pulley − slip

$$= \frac{\pi d_1 N_1}{60} - \left[\left(\frac{\pi d_1 N_1}{60}\right)\cdot\frac{S_1}{100}\right]$$

$$v = \frac{\pi d_1 N_1}{60}\left[1 - \frac{S_1}{100}\right]$$

velo. of driven pully/sec $= \frac{\pi d_2 N_2}{60} = \left[v - v\left(\frac{S_2}{100}\right)\right]$

$$\Rightarrow \frac{\pi d_2 N_2}{60} = v\left(1-\frac{S_2}{100}\right)$$

$$\Rightarrow \frac{\pi d_2 N_2}{60} = \frac{\pi d_1 N_1}{60}\left(1-\frac{S_1}{100}\right)\left(1-\frac{S_2}{100}\right)$$

$$\Rightarrow \frac{N_2}{N_1} = \frac{d_1}{d_2}\left[1-\left(\frac{S_1+S_2}{100}\right)\right]$$

$$\Rightarrow \boxed{\frac{N_2}{N_1} = \frac{d_1}{d_2}\left[1-\frac{S}{100}\right]}$$

$S \Rightarrow$ total slip.

Creep in belt drive :-

During working one side of the belt act as tight side & the othere side act as slack side. So the elongation are stress produced at different part of belt material are different. This different elongation effects the velocity/ratio of belt drive. This phenomenon is called creep.

$$\frac{N_2}{N_1} = \frac{d_1}{d_2}\left(\frac{E+\sqrt{\sigma_2}}{E+\sqrt{\sigma_1}}\right)$$

$E \to$ young's modulus of belt materials

$\sigma_1 \to$ stress in tight side

$\sigma_2 \to$ stress in slacy side:

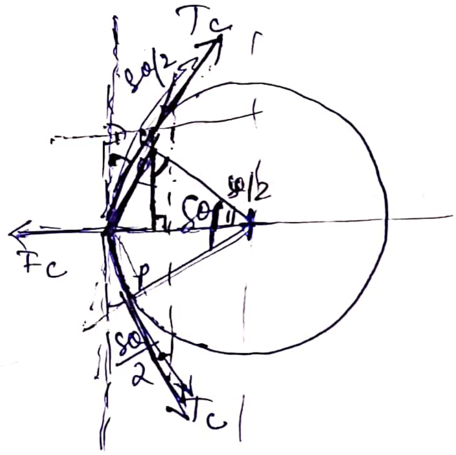
Crowning of pully

- → slight convexity of pully rim is called crowning.
- → It is made to keep the belt in centre on a pulley while in motion.
- → It prevents axial slipping of belt during operation.
- → The amount of crowning is usually $\frac{1}{96}$ of the pulley face width.

Centrifugal tensions (T_c)

Tension caused by centrifugal force is called centrifugal tens. Its effect is to increase tension on both side. When the belt is rotating on the pulley it possess centrifugal force. Due to this force, the belt tends to move away from the pulley.

Consider a small element of the belt making an angle $\delta\theta$ at the centre of the pulley.



Let $m \rightarrow$ mass of belt/unit length

$v \rightarrow$ velo. of belt

$r \rightarrow$ radius of pulley.

Centrifugal force produced in belt in small element.

Length of $PQ = r d\theta$

mass " " $PQ = m r d\theta$

$$F_c = m r d\theta \frac{v^2}{r} = m d\theta v^2$$

For equation resolving the forces.

$$T_c \sin\left(\frac{\delta\theta}{2}\right) + T_c \sin\left(\frac{\delta\theta}{2}\right) = F_c$$

$$\Rightarrow T_c\left(\frac{\delta\theta}{2}\right) + T_c \frac{\delta\theta}{2} = F_c$$

($\sin \frac{\delta\theta}{2}$ is very small $= \frac{\delta\theta}{2}$)

$$\Rightarrow F_c = T_c \delta\theta$$

$$\Rightarrow m d\theta v^2 = T_c \delta\theta$$

$$\Rightarrow \boxed{T_c = m v^2}$$

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Note:-

considering centrifugal tension,

tension in tight side = $T_{t1} = T_1 + T_c$

" " slack " = $T_{t2} = T_2 + T_c$

* Centrifugal tension has no. effect on power transmission.

Max^m tension in the belt

σ = max^m stress in belt material in N/mm^2

b = width of belt in mm

t = thickness.

Max^m tension in belt = max^m σ × A

$= \sigma b t$

If T_c is considered $T = T_1 + T_c$ ✓

If T_c is not " $T = T_1$ ✓

Condition for maximum power transmission

$P = (T_1 - T_2) v$

$= T_1 \left(1 - \frac{T_2}{T_1}\right) v$

$= T_1 \left(1 - \frac{1}{e^{\mu\theta}}\right) v$

$\Rightarrow P = T_1 K v$ $\left(\because K = 1 - \frac{1}{e^{\mu\theta}}\right)$

Max^m tension $= T = T_1 + T_c$

$\Rightarrow T_1 = T - T_c$

or $P = (T - T_c) K v$

$\Rightarrow P = (T - mv^2) K v$

power becomes max^m when

$\frac{dp}{dv} = 0$

$\Rightarrow \frac{d}{dv}\left[(T - mv^2) Kv\right] = 0$

$\Rightarrow TK - mK3v^2 = 0$

$\Rightarrow$ ~~TK = mK 3v²~~

$\Rightarrow TK = mK\,3v^2$

$\Rightarrow T = 3mv^2$

$\Rightarrow 3T_c = T$

$\Rightarrow$ $\boxed{T_c = T/3}$

initial tension in belt drive (T_0)

When belt is wound round the pulleys, its ends are joined & it continuously move over the pulley by frictional grip. So even when the pulley is stationary, the belt is subjected to some tension called initial tension.

$$T_0 = \frac{T_1 + T_2}{2} \quad (T_c \rightarrow \text{neglect}), \quad T_0 = \frac{T_1 + T_2 + 2T_c}{2}.$$

$T_c \rightarrow$ considering.

Length of a belt

$$L = \pi(r_1 + r_2) + \frac{(r_1 - r_2)^2}{x} + 2x \quad (\text{for open belt drive})$$

$$L = \pi(r_1 + r_2) + \frac{(r_1 + r_2)^2}{x} + 2x \quad (\text{for crossed belt drive})$$

Q

A shaft rotating at 200 rpm drives another shaft at 300 rpm and transmits 6 kW, through a belt. The belt is 100 mm wide and 10 mm thick. The distance between the two shafts is 4 m. The smaller pully is .5 m dia. calculate the stress in the belt if it is.

i) an open belt drive

ii) cross belt drive. take $\mu = 0.3$

data

Sol^n

$N_1 = 200$ rpm $b = 100$ mm $d_2 = 0.5$

$N_2 = 300$ rpm $t = 10$ m $\mu = 0.3$

$P = 6$ kW $x = 4$ m

$\log\left(\frac{T_1}{T_2}\right) = \mu\theta$

$\Rightarrow \log \frac{T_1}{T_2} = \frac{.3 \times 3.04}{2.3} = .3965$

$\Rightarrow \frac{T_1}{T_2} = 2.5$ — (2) (antilog of .3965)

$T_1 = 2.5 T_2.$

$T_1 + T_2 = 4677$

$2.5 T_2 + T_2 = 4677$

$\Rightarrow 3.5 T_2 = 4677$

$\Rightarrow T_2 = \frac{4677}{3.5} = 1336\ N$

$T_1 = 2.5 \times T_2$

$= 3341\ N.$

$P = (T_1 - T_2) V$

$= (3341 - 1336) \times 21$

$P = 42100$ watt

$P = 42.1\ KW$ Ans

Q) Two parallel shaft whose center lines are 4.8m apart, are connected by open belt drive. The diameter of the larger pulley is 1.5 m & smaller is 1m. The initial tension in the belt is 3kN. The mass of the belt is 1.5 kg/m length. The co-efficient of friction between belt & pulley is 0.3. Taking centrifugal tension in to account. i) cal. power transmitted when smaller pulley rotates at 400rpm.

soln

data given

$x = 4.8$ m

$d_1 = 1.5$m

$d_2 = 1$m

$N_1 = ?$

$N_2 = 400$rpm

$T_0 = 3$kN $= 3000$N

$\mu = 0.3$

$m = 1.5$ kg/m.

$P = (T_1 - T_2)\,v$

velo. of belt. $v = \frac{\pi d_2 N_2}{60} = \frac{\pi \times 1 \times 400}{60} = 21$ m/s

$T_c = mv^2 = 1.5 \times (21)^2 = 661.5$ N

$T_0 = \frac{T_1 + T_2 + 2T_c}{2}$

$\Rightarrow 3000 = \frac{T_1 + T_2 + 2 \times 661.5}{2}$

$\Rightarrow T_1 + T_2 = 3000 * 2 - 2 * 661.5$

$\Rightarrow T_1 + T_2 = 4677$ N ——— (1)

For open belt drive $\alpha = \sin^{-1} \frac{r_1 - r_2}{x}$

$= \sin^{-1} 0.0521$

$\alpha = 3$

$\theta = (180 - 2\alpha) \times \frac{\pi}{180} = (180 - 6)\,\pi/180 = 3.04$ rad.

$\frac{N_1}{N_2} = \frac{d_2}{d_1}$

$\Rightarrow \frac{200}{300} = \frac{.5}{d_1}$

$\Rightarrow d_1 = .75m$ ✓

$\theta = 180 - 2\alpha$

$\sin\alpha = \frac{r_1 - r_2}{x}$ (for open belt drive)

$= 1.79$

$\theta = 180 - (2 \times 1.79) = 176.42^\circ$

$= 176.42 \times \frac{\pi}{180}$

$V = \frac{\pi d_1 N_1}{60} = \frac{\pi d_2 N_2}{60} = 7.854\ m/s$

$P = (T_1 - T_2)V$

$\frac{T_1}{T_2} = e^{\mu\theta}$

$\Rightarrow T_1 = 2.52 T_2$

$\rightarrow P = (T_1 - T_2)V = (2.52 T_2 - T_2)V$

$T_2 = 502.6\ N$

$\Rightarrow T_1 = 2.52 \times 502.6\ N$

$= 1266.55\ N$

$T_1 = \sigma b t$

$\Rightarrow 1266.55 = \sigma \times .1 \times .01$

$\Rightarrow \sigma = \frac{1266.55}{0.001} = 1266550.\ N/m^2$

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Q. Find the power transmitted by a belt running over a pulley of 600 mm diameter at 200 rpm. The co-efficient of belt and the pulley is 0.25. angle of lap 160° and maxi^m tension in the belt is 2500 N.

Sol^n

$d = 600\ mm = 0.6m$ $\mu = .25$

$N = 200\ rpm$ $\theta = 160° = 160 \times \pi/180$.

$T_1 = 2500\ N$

we know the velo. of the belt $v = \frac{\pi d N}{60} = \frac{\pi \times .6 \times 200}{60} = 6.284\ m/s$

T_2 = tension in the slack side of the belt.

$$2.3 \log\left(\frac{T_1}{T_2}\right) = \mu \cdot \theta = .25 \times 2.793$$
$$= 0.6982$$

$$\log\left(\frac{T_1}{T_2}\right) = \frac{0.6982}{2.3} = 0.3036$$

$$\frac{T_1}{T_2} = 2.01$$

$$\Rightarrow T_2 = \frac{T_1}{2.01} = \frac{2500}{2.01} = 1244\ N$$

we know that power transmitted by the belt

$$P = (T_1 - T_2)v = (2500 - 1244)\ 6.284$$
$$= 7890 W$$

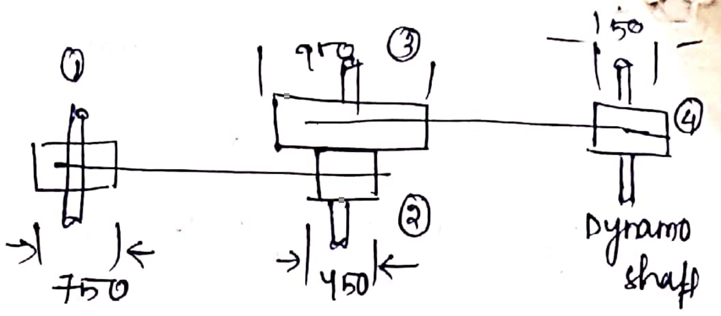
or 7.89 KW Ans

2) An engine running at 150 rpm, drives a line shaft by means of a belt. The engine pulley is 750 mm dia & pulley on line shaft is 450 mm. A 900 mm dia pulley on the line shaft drives a 150 mm dia pulley keyed to a dynamo shaft. find the speed of the dynamo shaft, when there is i) no slip ii) with slip is 2 %. at each drive.

Soln

i) with no slip

$$\frac{N_4}{N_1} = \frac{d_1 \times d_3}{d_2 \times d_4}$$



$$\Rightarrow \frac{N_4}{150} = \frac{750 \times 900}{450 \times 150}$$

$$\Rightarrow N_4 = 1500 \text{ rpm}$$

ii) with slip

$$\frac{N_4}{N_1} = \frac{d_1 d_3}{d_2 d_4}\left(1 - \frac{s_1}{100}\right)\left(1 - \frac{s_2}{100}\right)$$

$$\Rightarrow N_4 = 150 \times \frac{750 \times 900}{450 \times 150}\left(1 - \frac{2}{100}\right)\left(1 - \frac{2}{100}\right)$$

$$\Rightarrow N_4 = 1440 \text{ rpm}.$$

Q2. The power is transmitted from a pulley 1m dia running at 200 rpm to a pulley 2.25m by belt. Find the speed lost by the driven pulley as a result of creep. If stress on tight side 1.4 Mpa & slack side is 0.5Mpa. E = 100 Mpa

Soln

$d_1 = 1 m$ $\quad \sigma_1 = 1.4 Mpa = 1.4 \times 10^6 N/m^2$

$d_2 = 2.25 m$ $\quad \sigma_2 = 0.5 Mpa = .5 \times 10^6 N/M^2$

$N_1 = 200$ $\quad E = 100 Mpa = 100 \times 10^6 N/m^2$

$$\frac{N_2}{N_1} = \frac{d_1}{d_2} \Rightarrow N_2 = 200 \times \frac{1}{2.25} = 88.9 \text{ rpm}$$ with out

$$\frac{N_2}{N_1} = \frac{d_1}{d_2} \times \frac{E \times \sqrt{\sigma_2}}{E \times \sqrt{\sigma_1}} = 88.7 \text{ rpm}.$$

Speed lost $= 88.9 - 88.7 = .2$ rpm

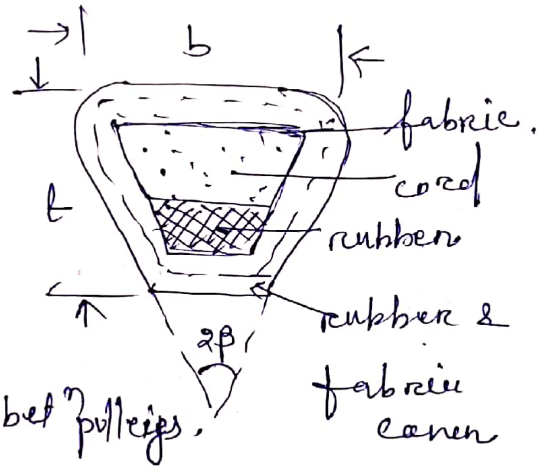
V belt drive

→ It is used in factories and workshops where large amount of power has to be transmitted and the two pulleys are very near to each others.

→ V belts are made of fabric and cords modulated in rubber and covered with fabric & rubber.

→ They are trapezoidal in shape. & the angle included is 30°-40°.
→ Hence the rim of the pulley is grooved where it runs.

→ To increase the power o/p several V, belts should be operated side by side.



Advantages

- More compact struct. due to small distance betn pulleys.
- Slip is negligible.
- provide longer life i.e 3 to 5 yrs.
- Can be easily installed & removed.
- operation is quite.
- power transmission is more
- It can be operated horizontal, vertical or inclined.

Dis advantage

- It can be used, where the center distance is large.
- construction of pulleys for V belt is very complecated.

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Ratio of belt tension in v-belts

$$\frac{T_1}{T_2} = e^{\mu \operatorname{cosec} \beta \times \theta}$$

Rope Drive

- It is used where large power has to be transmitted between two pulleys.
- Frictional grip of rope drive is more than v-belt.
- A no. of separate drives can be taken from one driving pulley.
- Generally 2 types of ropes are used.
  - i) fibre rope (when pulleys are 60 m apart)
  - ii) wire rope (" " 150m ")

Materials :- hemp, manila, cotton — dia ranges bet 38 to 50mm

- These are strong & more durable.
- These are used in elevators, mines hoists, cranes suspension bridge etc.

- Here $\frac{T_1}{T_2} = e^{\mu \cos ec \beta \theta}$

Advantages
- give smooth, steady & ser
- high mechanical efficiency
- less affected by out door conditions.

Dis

-

Chain drive

- made up of rigid links hinged together to provide necessary flexibility for wrapping around the wheels.
- wheels have protecting teeth & fit into the corresponding recesses in the links of the chain.
- So wheel & chain are constrained together to move without slipping & ensures perfect velocity ratio.
- It is used for motion transmission when two shafts are apart by short distance.

Advantages

- No slip.
- occupy less space
- give high transmission
- Can transmit motion to several shafts by one chain only.

Disadvantage

- production cost is high
- need accurate mounting
-

Gears

A gear is a rotating element having cut teeth & mesh with another toothed path to transmitt torque. when 2 or more gear work in sequence they are called gear train or a transmission.

When 2 gear meshed, one is bigger then another then a mechanical advantage is produced.

$$\text{mechanical advantage} = \frac{\text{load}}{\text{effort}}$$

smaller one is pinion & longer one driver.

Material for geare.

Numerous nonferrous alloys, cast iron, powder metallurgy & plastic are used. However steels are most commonly used becoz. of there high strength & low cost.

Classification of gears

1) spur
2) helical
3) double helical / herringbone
4) internal
5) Rack & pinion
6) Straight bevel gear.
7) Spiral bevel gear.
8) hypoid bevel gear
9) worm gear
10) spiral gear.

Type	Features	Application
Spur	∥ shafting high speed & load highest effi	to all type of gear trains & a wide range of velocity ratio.
Helical	∥ sharfting veryhigh speed & load effi. less then spur.	Appliceable to high speed load.
crossed helical.	Skewed shafting, pt. contact. low speed, low load high sliding	for low velo. ratio light loads. any angle skew shaft
internal spur.	∥ shafts high speed high load	Internal drives requiring high speeds & high load. offer low sliding, long life.
Bevel.	intersecting shafts high speed high load	good for high capacity high velo. ratio & right angle meshes.
worm	Right angle skew shaft high velo. ratio high speed & loads. low efficiency	high velo. ratio. Angular meshes high loads.

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Advantages of gear drive.

- It transmits exact velo. ratio.
- It maybe used to transmit large power
- It has high efficiency.
- It has reliable service.
- It has compact layout.

dis advantage

- The manufacture of gear require special tool & equipments.
- Error in cutting teeth may cause vibration.

Classification.

1) Acc. to position of axis of shaft

- parallel — spur
- intersecting — bevel
- Non intersecting — skew bevel.

2) Acc. to peripheral velo.

- low — velo. < 3 m/s
- Medium — 3 to 15 m/s.
- high — > 15 m/s.

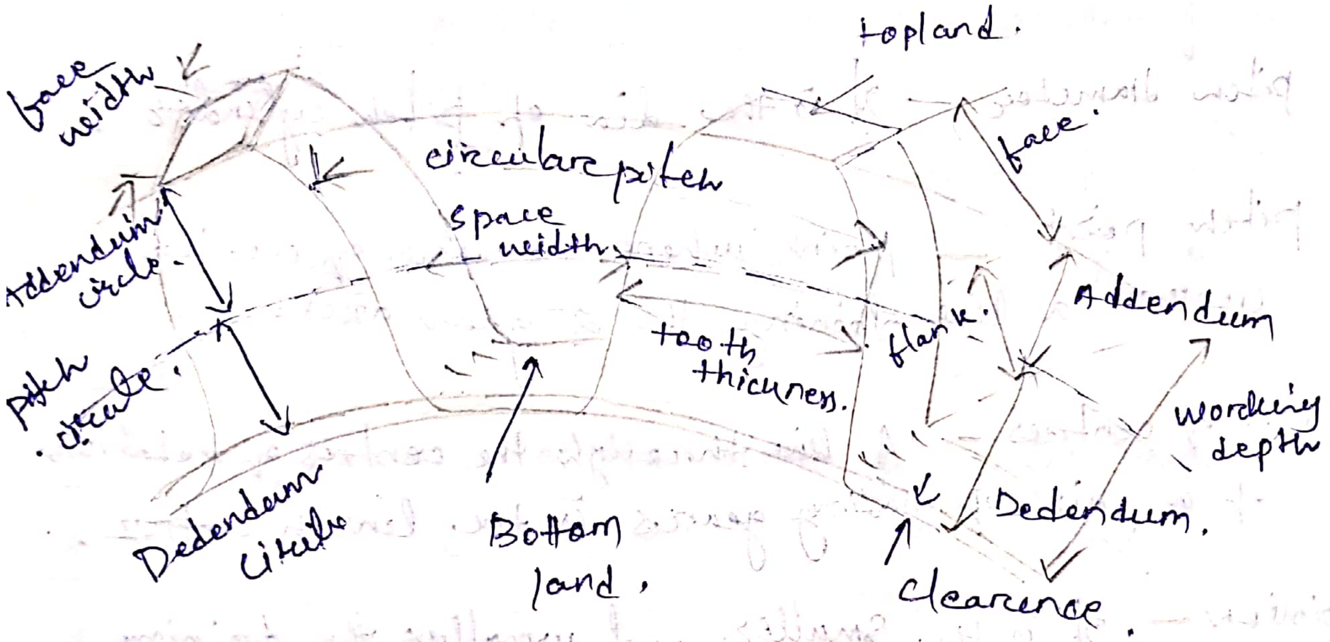
3) Acc. to type of gearing.

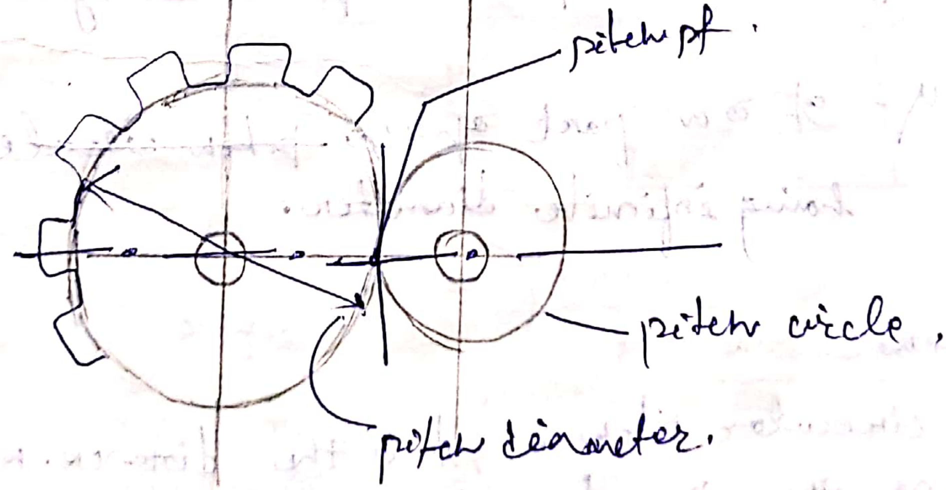
- External — Rack & pinion
- internal

Acc to. position of teeth

- Straight — Spur.
- inclined — helical
- curved — spiral,

Gear terminology.





pitch cylinder –

It is a pair of gears in mesh are the imaginary friction cylinder which by pure rolling together, transmit the same motion as pair of gear.

pitch circle – A predetermined diametral position on the gear where the circular tooth thickness pressure angle, helix angle are defined.

pitch diameter – It is the dia of pitch cylinder –

pitch point – point where the line of action crosses a line joining the 2 gear axes.

line of centres – A line through the centres of rotation of a pair of mating gears is the line of centres.

pinion – It is the smaller and usually the driving gear of a paired of mated gear.

Rack – It is a part of the ~~pitch circle~~ gear wheel having infinite diameter.

pitch –

circular pitch – It is the distance measured along the circumference of the pitch circle from a point on one tooth to the corresponding point on the adjacent tooth.

$$P = \frac{\pi d}{T}$$

P → circular pitch
d → pitch diameter.
T → no. of teeth.

Dimetrical pitch – It is the no. of teeth per unit length of the pitch circle dia in inches.

$$p = \frac{\pi}{d}$$

Gear ratio (G)

It is the ratio of no. of teeth on the gear to that on the pinion.

$$G = \frac{T}{t}$$

T → no. of teeth on gear.
t → no. of " " pinion.

Velocity ratio. (VR)

The VR is defined as the ratio of angular velo. of follower to the angular velo. of driving gear.

Subscript 1 – driven
2 – follower.

$$VR = \frac{\omega_2}{\omega_1} = \frac{N_2}{N_1} = \frac{d_1}{d_2} = \frac{T_1}{T_2}$$

$V = \omega r$
$= \frac{2\pi N}{60} \times r$
$= \frac{2\pi N \times \frac{d}{2}}{60}$

$\omega = 2\pi N$

$2\pi d_1 N_1 = 2\pi d_2 N_2$

$$\frac{d_1}{d_2} = \frac{N_2}{N_1}$$

$$P = \frac{\pi d_1}{T_1} = \frac{\pi d_2}{T_2}$$

$$\frac{d_1}{d_2} = \frac{T_1}{T_2}$$

module

$$M = \frac{\text{Pitch dia}}{\text{no. of teeth}}$$

$\omega = \frac{2\pi N}{60}$.

Addendum circle - It is the circle passing through the tips of teeth.

Addendum - It is the radial height of a tooth above the pitch circle. Its standard value is 1 module.

dedendum circle - passing through roots of the teeth.

dedendum - It is the radial depth of a root below the pitch circle.

Its standard value is 1.157m.

Clearance - Radial difference betn addendum & dedendum of a tooth.

$C = 0.157m$

addendum circle dia = d + 2m

dedendum " " = d − 2×1.157m

module - $m = \frac{D}{T}$

D → pitch circle dia 1.157m − m

T → no. of teeth. = .157m.

Full depth of teeth.

It is the total radial depth of the tooth space.

full depth = Addendum + Dedendum

working depth of teeth

It is maxm depth to which a tooth penetrates into the tooth space of mating gear.

WD = sum of Addendums of 2 gears.

Gear Drive

A gear is a rotating m/c part having teeth in it's periphery. When gears are used for power transmission it is called as gear drive. In case of belt drive and rope drive sometimes slipping occurs which reduces the velo. ratio. But in case of gear drive no. such slipping occurs, so exact velocity ratio can be obtained. It is also called as positive drive.

Advantages

- It transmits exact velo. ratio
- It has high efficiency
- It has reliable service
- It has compact layout.

Dis

- The manufacting of gears require special tools.
-

Classification

According to position of axis

- parallel
  - spur gear
  - helical gear
- Intersecting
  - bevel gear
- Nonintersecting
  - spiral gear
  - skew bevel gear etc.

According to velocity of gears

- low: velo < 3 m/s
- medium: 3 – 15
- high: velo > 15 m/s

Gear Train

When two or more gears are mesh with each other to transmitt power from one shaft to another, such combination is called as gear train.

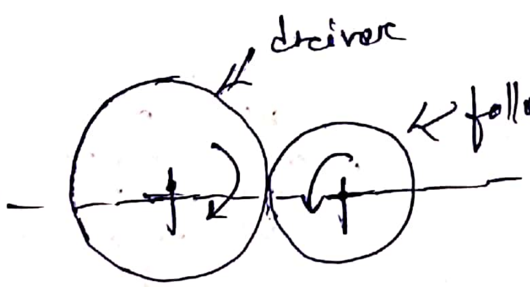
Types of gear train

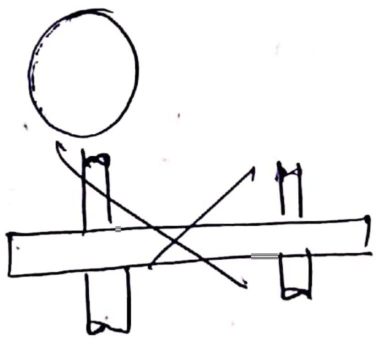
Depending up on the arrangement.

- Simple gear train
- Compound "
- Reverted "
- Epicyclic "

1) Simple gear train.

When there is only one gear on each shaft, is known as simple gear train. The gear which drives is called as driver & the driven gear is called as follower. The motion of both the gear are opposite to each other.





N_1 → speed of driver

N_2 → " " follower

T_1 → No. of teeth in driver

T_2 → " " in follower.

$V.R = \frac{\omega_1}{\omega_2} = \frac{2\pi N_1}{2\pi N_2} = \frac{N_1}{N_2}$

$v = \omega \times r$

- The speed ratio / velocity ratio is given by

$= \frac{2\pi N}{60} \times r$

$= \frac{2\pi N}{60} \times \frac{d}{2} = \frac{\pi d N}{60}$

$$\boxed{\frac{N_1}{N_2} = \frac{T_2}{T_1}}$$

$\frac{\pi d_1 N_1}{60} = \frac{\pi d_2 N_2}{60} \Rightarrow \frac{d_1}{d_2} = \frac{N_2}{N_1}$

- The train value is the reciprocal of speed ratio,

$$\frac{1}{\text{Speed ratio}} \quad \text{or} \quad \boxed{\frac{N_2}{N_1} = \frac{T_1}{T_2}}$$

$p = \frac{\pi d}{T}$, $\frac{\pi d_1}{T_1} = \frac{\pi d_2}{T_2}$

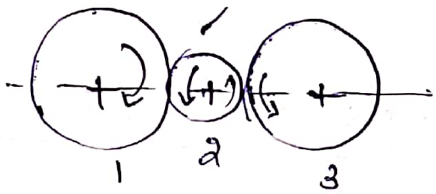
$\Rightarrow \frac{d_1}{d_2} = \frac{T_1}{T_2}$

$\Rightarrow \frac{N_2}{N_1} = \frac{T_1}{T_2}$

When there are 3 gears.

Speed ratio. $\boxed{\frac{N_1}{N_3} = \frac{T_3}{T_1}}$

idle gear

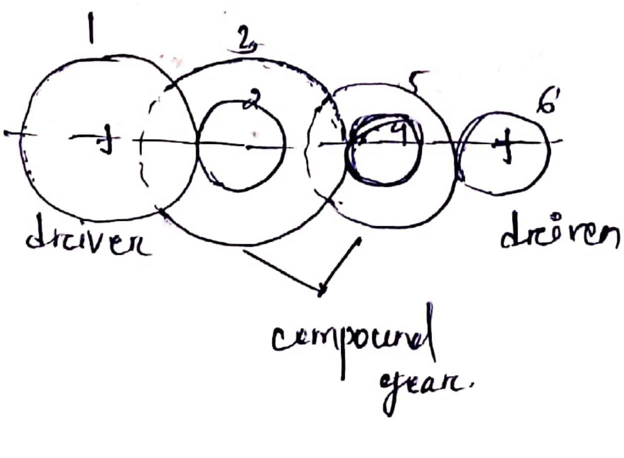


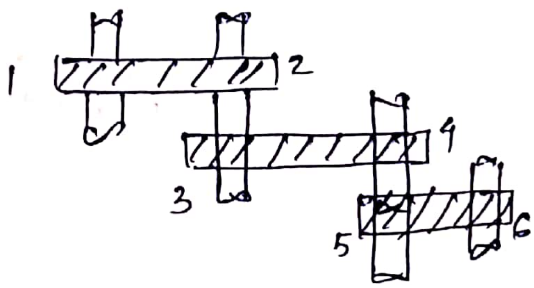
$$\boxed{V.R = \frac{\omega_2}{\omega_1} = \frac{N_1}{N_2} = \frac{d_2}{d_1} = \frac{T_2}{T_1}}$$

provided where centre distance is larger in the meshing gear. It is also called as intermediate gears

2) compound gear train

- When there are more than one gear on a shaft, it is called compound gear train.





$N_1, N_2, N_3, N_4, N_5, N_6 \rightarrow$ rpm of gear 1, 2, 3, 4, 5 & 6
$T_1, T_2, T_3, T_4, T_5, T_6 \rightarrow$ Teeth " " "

Since gear 1 is meshed with gear 2.

$$\frac{N_1}{N_2} = \frac{T_2}{T_1}$$

Similarly 3 & 4 $\frac{N_3}{N_4} = \frac{T_4}{T_3}$

" 5 & 6 $\frac{N_5}{N_6} = \frac{T_6}{T_5}$

combining the 3 equation, the speed ratio of compound gear train will be.

$$\frac{N_1}{N_2} \times \frac{N_3}{N_4} \times \frac{N_5}{N_6} = \frac{T_2}{T_1} \times \frac{T_4}{T_3} \times \frac{T_6}{T_5}$$

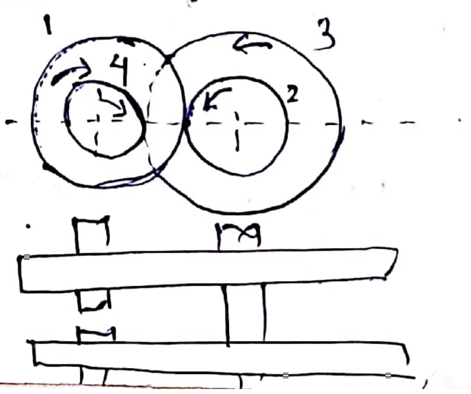
Since $N_2 = N_3$ & $N_4 = N_4$

$$\boxed{\frac{N_1}{N_6} = \frac{T_2 \times T_4 \times T_6}{T_1 \times T_3 \times T_5}}$$

③ Reverted gear train

When the axis of 1st gear is co-axial with the last gear, it is known as reverted gear train.

$T_1 \rightarrow$ no. of teeth on gear 1
$T_2 \rightarrow$ pitch circle of gear 1
$N_1 \rightarrow$ speed of "



$T_2, T_3, T_4 \longrightarrow$ Teeth on 1, 2, 3

$r_1, r_2, r_3 \rightarrow$ pitch circle radius of 1, 2, & 3

$N_1, N_2, N_3 \rightarrow$ rpm of 1 & 2 & 3

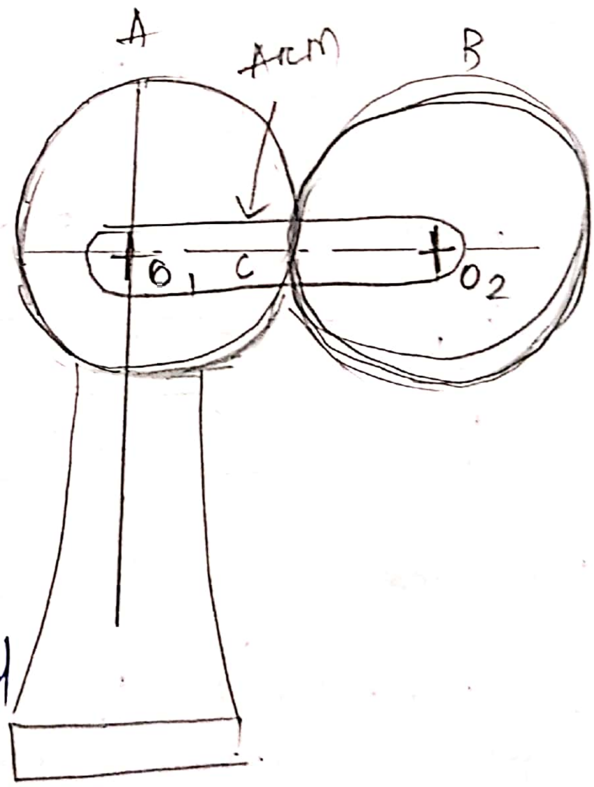
Speed ratio = $\boxed{\frac{N_1}{N_4} = \frac{T_2 \times T_4}{T_1 \times T_3}}$

where $r_1 + r_2 = r_3 + r_4$

& $T_1 + T_2 = T_3 + T_4$

4) Epicyclic gear train

A simple epicyclic gear train is shown in the fig. Where gear A and the arm c has a common axis at O_1 about which they can rotate. The B gear is mixed with gear A and rotate about O_2. When the gear is fixed and the arm c is rotating, then it will carry the gear B also. and both the arm & gear B rotate ~~about~~ around the gear A. Such motion is called as epicyclic gear trains.



The speed ratio will be. $\boxed{\frac{N_B}{N_C} = 1 + \frac{T_A}{T_B}}$

<CHAPTER - 04> Governors

- The function of a governor is to maintain the speed of an engine with in specified limits whenever there is variation of load.
- If the load on the shaft increases, the engine speed decreases, thus the supply of fuel is increased by opening the throttle valve. & vise versa.
- The throttle valve is operated by the governor through a mechanism for the purpose.

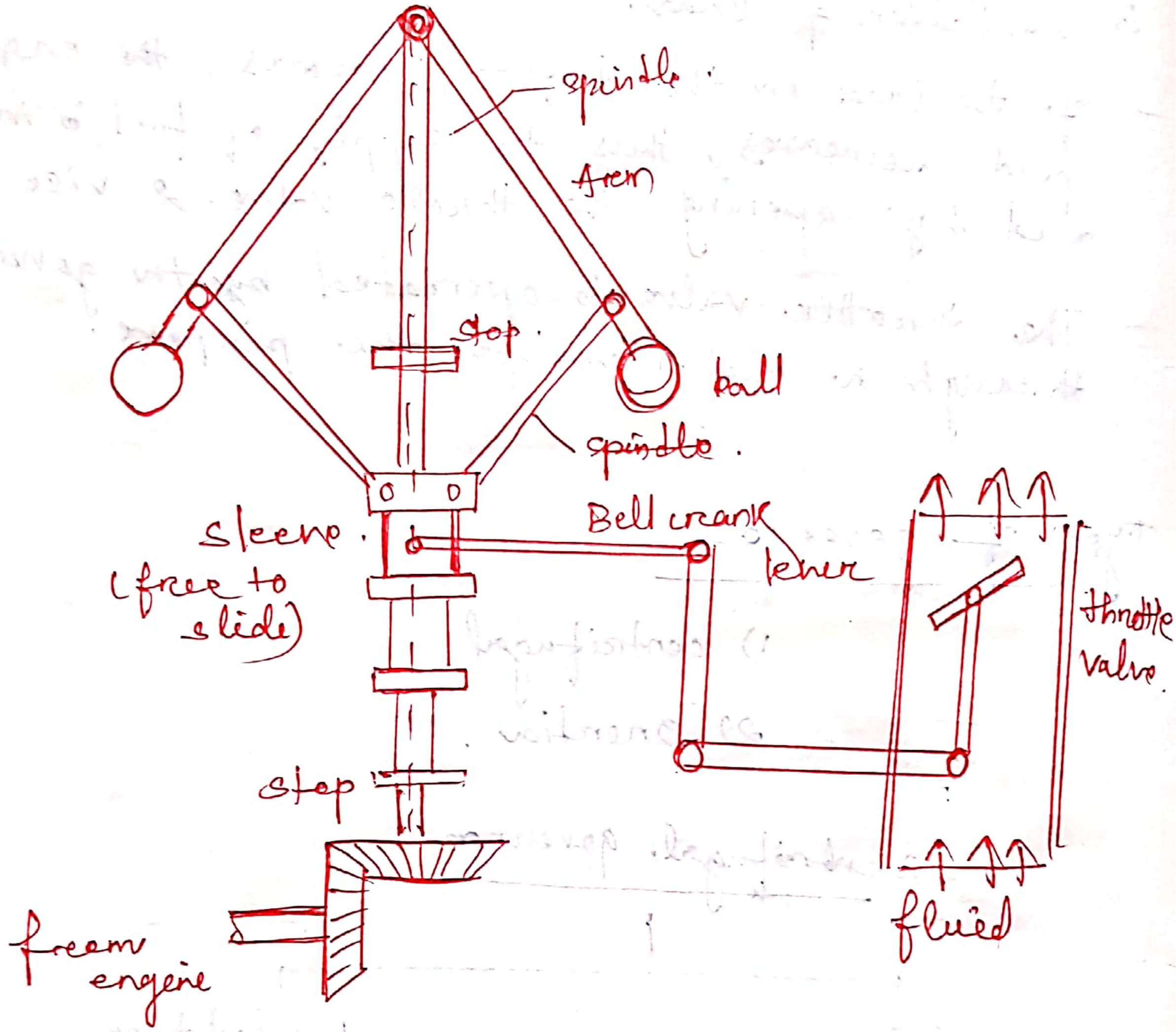
Types of governors.

1) centrifugal
2) Inertia.

centrifugal governor

- Pendulum type (watt governor)
- Loaded type
  - gravity loaded / dead weight
    - porter
    - proell
  - spring controlled
    - Hartnell
    - Hartung
    - wilson Hartnell
    - pickering

Centrifugal Governer



This is the more common type. It's action depends on the change of speed. It has a pair of mass, known as governer balls, which rotate with a spindle.

- This spindle is driven by an engine through bevel gear.

- The action of the governer depends upon the centrifugal effects produced by the masses of 2 balls.

with increases in speed, the balls tend to rotate at a greater radius from the axis. 93

- This causes the sleeve to slide up on the spindle & this movement of the sleeve is communicated to the throttle valve through the bell crank lever.
- This closes the throttle valve to the req. extend.
- when speed decreases the vise versa will happen

Inertia Governors

- In this type the position of the balls are affected by the forces set up by an angular accln or deceleration of the given spindle in addition to centrifugal forces on the balls. using suitable linkages & springs, the change in posin of the balls is made to open or close the valve.

Thus where as the balls are operated by the actual change of engine speed in case of centrifugal governers, it is the rate of speed in case of inertia governer.

There fore, the response of inertia governer is faster than that of centrifugal type.

Terms used in governer

1) Height of governere(h) → It is the vertical distance from the centre of the ball to a point where the axis of the arm intersects on the spindle axis.

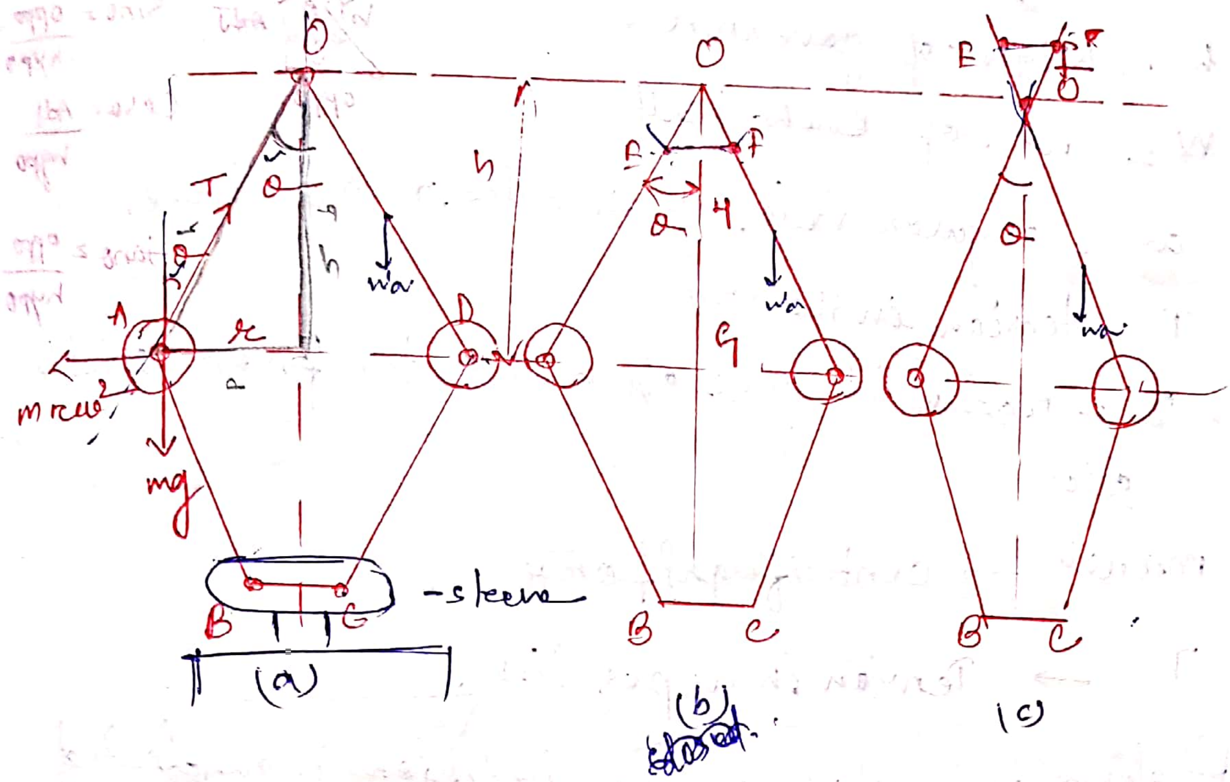
2) Equillibrium speed → It is the speed at which the governer balls, arm etc are in complete equillm & the sleeve does not tend to move upward & down word.

3) Mean equillm speed → It is the speed at the mean position of the balls or the sleeve.

4) Sleeve lift → It is the vertical distance which the sleeve travels due to change in equillm.

Watt governere.

- The simplest form of a centrifugal governer is a watt governere
- In this, a pair of balls is attached to the spindle with the help of links.
- The fig shows 3 forms of a watt govern



In fig (a) the upper links are pinned at O.
in " (b) the " " , connected by a horizontal link & the governor is known as open-arm type.

in fig (c) the upper links are cross the spindle & are connected by a horizontal link & the governor is said to be crossed arm.

→ In the above 3 cases the lower link is fixed to the sleeve free to move on vertical spindle.

a) Neglecting the weight of arms.

PTO

$0.02-(-0.02) = 0.04$

Let m = mass of each ball

h = height of governor.

W = wt. of each ball

ω = angular velo. of the balls, arm & sleeve.

T = tension in the arm

r = radial distance of ball centre from spindle axis

9

sin θ =

cos θ =

tan θ =

$mr\omega^2$ → centrifugal force

T → Tension in upper link.

If sleeve is massless & also friction is neglected the lower links will be tension free.

The equilibrium of the mass provides.

$T\cos\theta = mg$

$T\sin\theta = mr\omega^2$

$\tan\theta = \frac{r\omega^2}{g} \Rightarrow \frac{r}{h} = \frac{r\omega^2}{g}.$

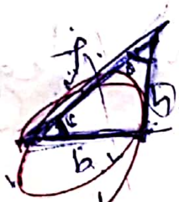
$\Rightarrow h = \frac{g}{\omega^2}$

$\Rightarrow h = \frac{g}{(2\pi N/60)^2} = \left(\frac{60}{2\pi}\right)^2 \times \frac{9.81}{N^2}$

$= \frac{895}{N^2}$ m

$h = \frac{895000}{N^2}$ mm

$= \frac{895}{N^2}$ m

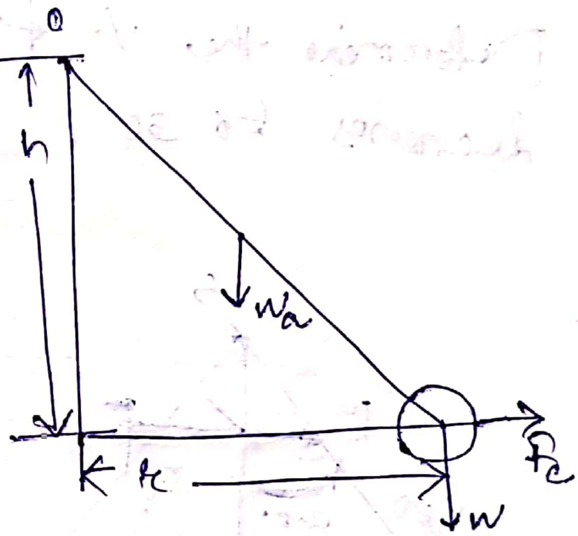


sin θ = b/p

cos θ = b/p

Q- A simple watt governor rotates at 75 rpm. Cal. its vertical height & the change if the speed increases to 80 rpm. Also cal. the height at 75 rpm if the wt. of ball is 20N & arm 5N.

Sol^n



$N_1 = 75$ rpm

$N_2 = 80$ rpm

without considering wt of arm.

$$h_1 = \frac{895}{N_1^2} m$$

$$= 0.159 m.$$

$$h_2 = \frac{895}{N_2^2}$$

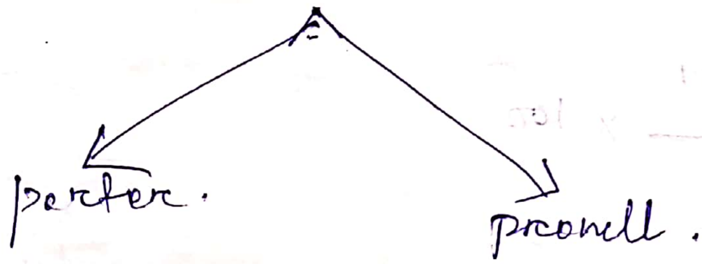
$$= .139 m = .14 m.$$

change in height $= h_1 - h_2$

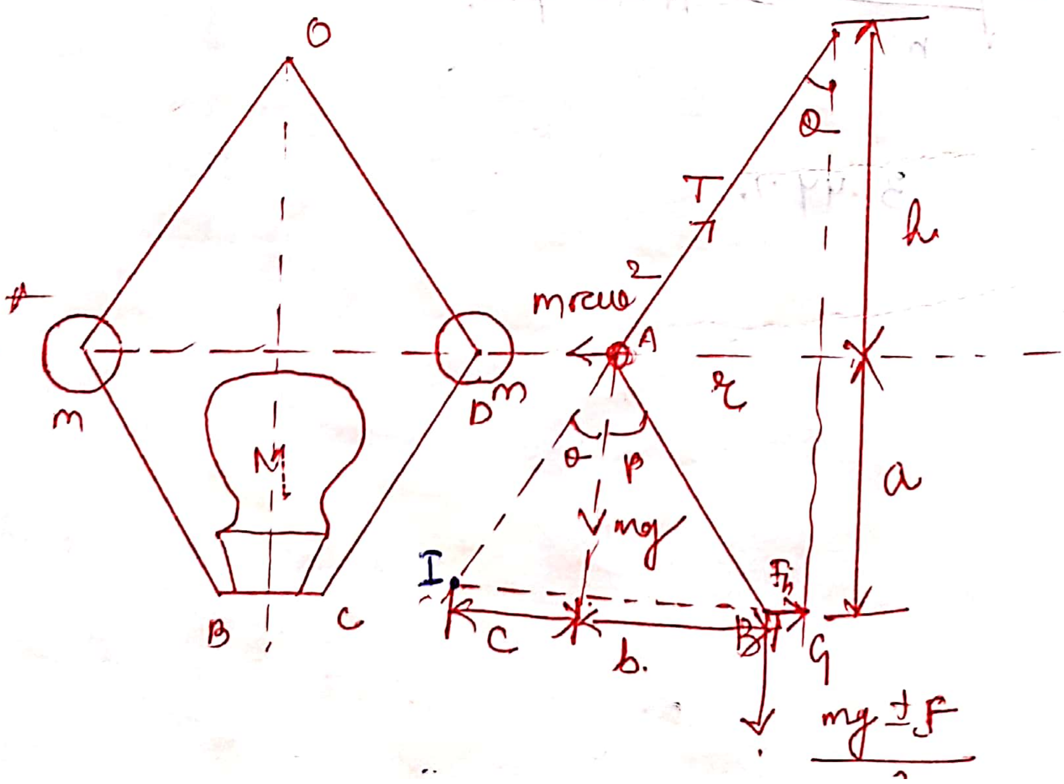
$= 0.0209 m. = .019 m.$

gravity loaded governore

- In the gravity loaded governore, a central load is attached to the sleeve, which slides on the spindle.
- There is a force of friction between the loaded sleeve & spindle.
- The frictional force acts downward when the sleeve moves up & acts upwards when the sleeve moves down. Thus the height of governor increases & decreases from normal value.



Porter governore.



M = mass of the sleeve

m = mass of each ball

f = force of friction at the sleeve.

→ As when the sleeve moves up, frictional force acts downward & the downward force acting on the sleeve is (Mg + f)

→ when sleeve moves down, f. f acts upward. The force on sleeve is (Mg − f).

− Net force acting on the sleeve is (Mg ± f)

h → height of governor

r → distance of each ball from axis of rotation.

considering the equilm of left hand half of the governor & taking moment about I.

$$m r \omega^2 \cdot a = mg \times c + \left(\frac{Mg \pm f}{2}\right)(c + b)$$

$$\Rightarrow m r \omega^2 = mg \frac{c}{a} + \frac{Mg \pm f}{2}\left(\frac{c}{a} + \frac{b}{a}\right)$$

$$= mg \cdot \tan\alpha + \frac{Mg \pm f}{2}(\tan\alpha + \tan\beta)$$

$$= \tan\alpha \left[mg + \frac{Mg \pm f}{2}(1+K)\right]$$

Let $\frac{\tan\beta}{\tan\alpha} = K$

$$= \frac{r}{h}\left[mg + \frac{Mg \pm f}{2}(1+K)\right]$$

$$\Rightarrow \omega^2 = \frac{1}{mh}\left[\frac{2mg + (Mg \pm f)(1+K)}{2}\right].$$

$$\left(\frac{2\pi N}{60}\right)^2 = \frac{g}{h}\left[\frac{(2mg + (Mg \pm f)(1+K))}{2mg}\right]$$

$$\Rightarrow N^2 = \frac{895}{h}\left(\frac{2mg + (Mg \pm f)(1+K)}{2mg}\right)$$

$g = 9.81\ m/s^2$

This eqn would provide a value for N for the same height.

if $K = 1$ $\quad N^2 = \frac{895}{h}\left[\frac{mg + (Mg \pm f)}{mg}\right]$

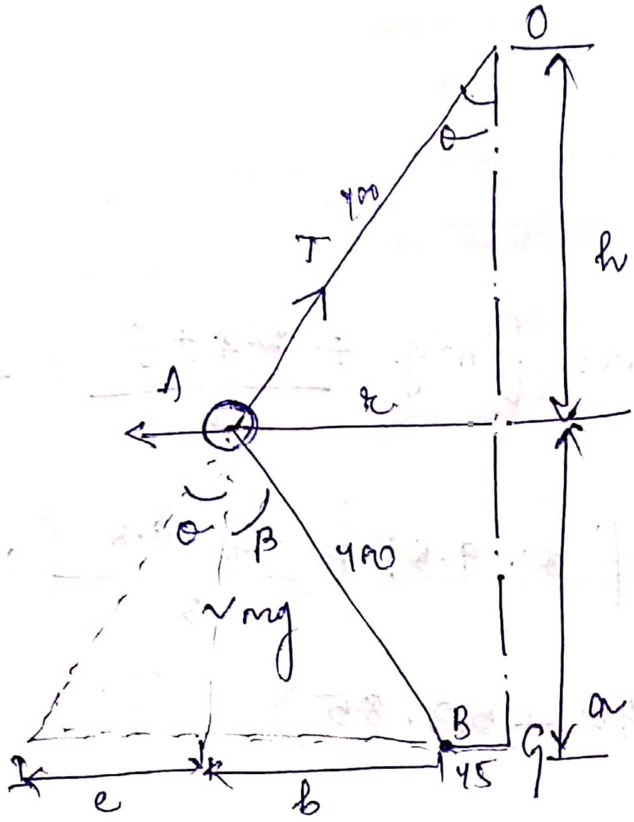
if $f = 0$. $\quad N^2 = \frac{895}{h}\left[\frac{2m + M(1+K)}{2m}\right]$

if $K = 1$ & $f = 0$. $\quad N^2 = \frac{895}{h}\left[\frac{M+m}{m}\right]$

Q2 In a porter governor, each of the four arm is 400 mm long. The upper arm are pivoted on the axis of the sleeve whereas the lower arm are attached to the sleeve, at a distance of 45mm from the axis of rotation. Each ball has a mass of 8 kg & load on the sleeve is 60 kg

– what will be the equilm speed for 2 extreme raddi of 250 mm & 300 mm. of rotation of the governer balls.

Soln



when i) $r = 250$.

$$\tan\theta = \frac{r}{h} = \frac{r}{\sqrt{(OA)^2 - r^2}}$$

$$= \frac{250}{\sqrt{(400)^2 - (250)^2}} = 0.8$$

$$K = \frac{\tan\beta}{\tan\theta} = \frac{b/a}{\tan\theta}$$

$b = 250 - 45$

$= 205\text{mm}$

$$a = \sqrt{(AB)^2 - (b)^2}$$

$$= \sqrt{(400)^2 - (205)^2}$$

$= 343.4\text{mm}$

$$\mu = \frac{205/343.4}{0.8}$$

$$= 0.764$$

$$m r \omega^2 = mg \tan\alpha \left[mg + \frac{Mg \pm f}{2} (1+k) \right]$$

$$\Rightarrow 8 \times .25 \times \omega^2 = 0.8 \left[8 \times 9.81 + \frac{60 \times 9.8}{2} (1+.746) \right]$$

$$\Rightarrow 2\omega^2 = 0.8 (78.48 + 513.85)$$

$$\omega^2 = 237$$

$$\omega = \frac{2\pi N}{60} = 15.39$$ $f = 0$

$$N = 147 \text{ rpm.}$$

ii) fein when $r = 300$ mm

& range of speed. ans

12.1 rpm

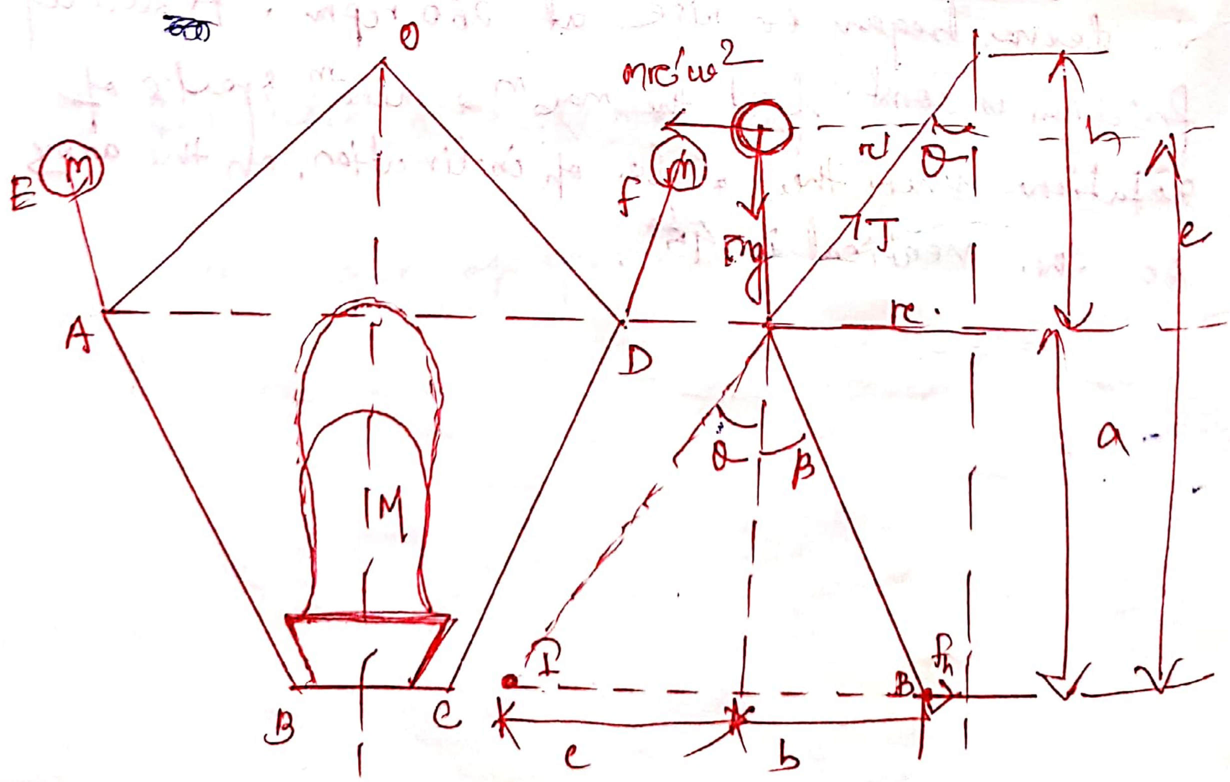
Proell governor.

A porter governor is known as a proell governor if the two balls are fixed on the upward extensions of the lower links which are in form of bent links BAE & CDF.

Considering the equill^m of link,

The forces acting upon BAE

- The wt. of ball mg.
- Centrifugal force $mr'\omega^2$
- tension in the link AO.
- horizontal reaction of the sleeve.
- the wt. of the sleeve & friction. $\frac{1}{2}(Mg \pm f)$



$$mr\omega^2 = \frac{a}{e} \times \frac{r}{h}\left[\frac{2mg + (Mg \pm f)(1+k)}{2}\right]$$

$$\omega^2 = \frac{a}{e} \times \frac{1}{mr \cdot h} \times r\left[\frac{2mg \mp (Mg \pm f)(1+k)}{2}\right]$$

$$= \frac{a}{e} \times \frac{g}{r} \times \frac{r}{h}\left[2mg + (Mg \pm f)(1+k)\right]$$

$$= \frac{a}{e} \times \frac{g}{h}\left[\frac{2mg + (Mg \pm f)(1+k)}{2mg}\right]$$

(divide g & multiply g)

$$\omega^2 = \frac{a}{e} \times \frac{g}{h}\left[\frac{2mg + (Mg \pm f)(1+k)}{2mg}\right] \qquad g = 9.81$$

$$\Rightarrow N^2 = \frac{895}{h} \times \frac{a}{e}\left[\frac{2mg + (Mg \pm f)(1+k)}{2mg}\right]$$

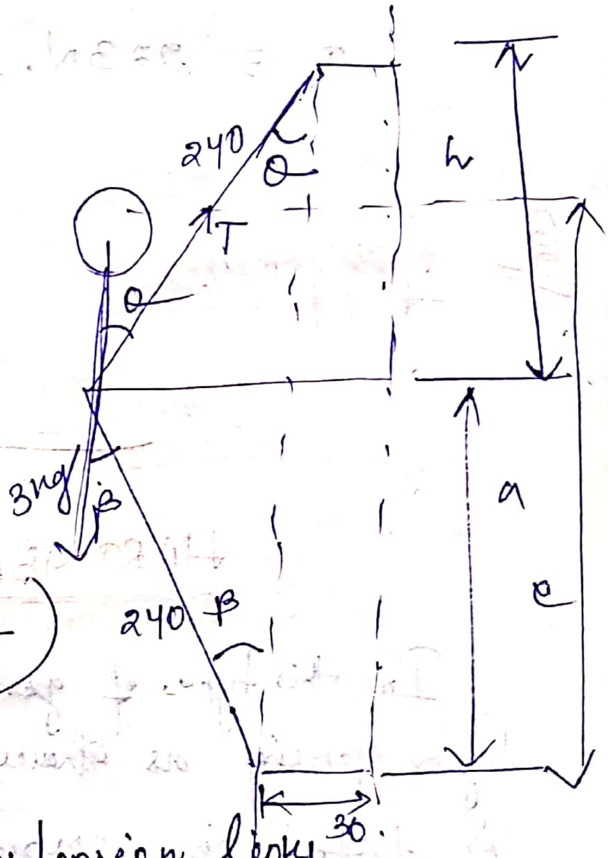
if $k = 1$ $\qquad N^2 = \frac{895}{h} \times \frac{a}{e}\left[\frac{mg + (Mg \pm f)}{mg}\right]$

if $f = 0$ $\qquad N^2 = \frac{895}{h} \times \frac{a}{e}\left(\frac{2m + M(1+k)}{2m}\right)$

if $k = 1, f = 0$ $\qquad N^2 = \frac{895}{h} \frac{a}{e}\left(\frac{m+M}{m}\right)$

Q. Each arm of a Porter governor is 240 mm long & each rotating ball has mass 3 kg. The central load acting the sleeve is 30 kg. The pivots of all the arms are 30 mm from the axis of rotation. The vertical height of the governor is 190 mm. The vertical height ... the lower arms are vertical & the extension links of the lower arms are vertical & the governer speed is 180 rpm, when the sleeve is in mid position. Determine the length of the extension links & the tension in the upper arms.

Soln



$m = 3 kg$

$h = 190 mm$

$N^2 = \frac{895}{h} \cdot \frac{a}{e} \left(\frac{m+M}{m} \right)$

$180^2 = \frac{895}{.19} \cdot \frac{.19}{e} \left(\frac{3+30}{3} \right)$

$e = 0.304 mm$

Therefore, length of the extension links

$= e - a = 304 - 190.$

$= 104 mm.$

Let T be the tension in upper arm.

considering the vertical components of the forces on the lower links,

$$T\cos\alpha = mg + \frac{Mg}{2}.$$

$$\cos\alpha = \frac{0.19}{.24} = .792$$

$$T \times 0.792 = 3\times 9.81 + \frac{30\times 9.81}{2}.$$

$$T = 223N.$$

Q Assignments

HARTNELL GOVERNER

In this type of governer, the balls are controlled by a spring as shown in fig. Initially, the spring is fitted in compression, so that a force is applied to the sleeve. Two bell crank lever each carrying a mass at end & a roller at the other, are pivoted to a pair of arm which rotate with the spindle. The rollers fit into a groove in the sleeve.

W_1 = wt. of ball.

W = wt of sleeve.

r_1, r_2 = Maxm & minm radii of rotation of the ball.

ω_1, ω_2 = " " angular speed of rotation.

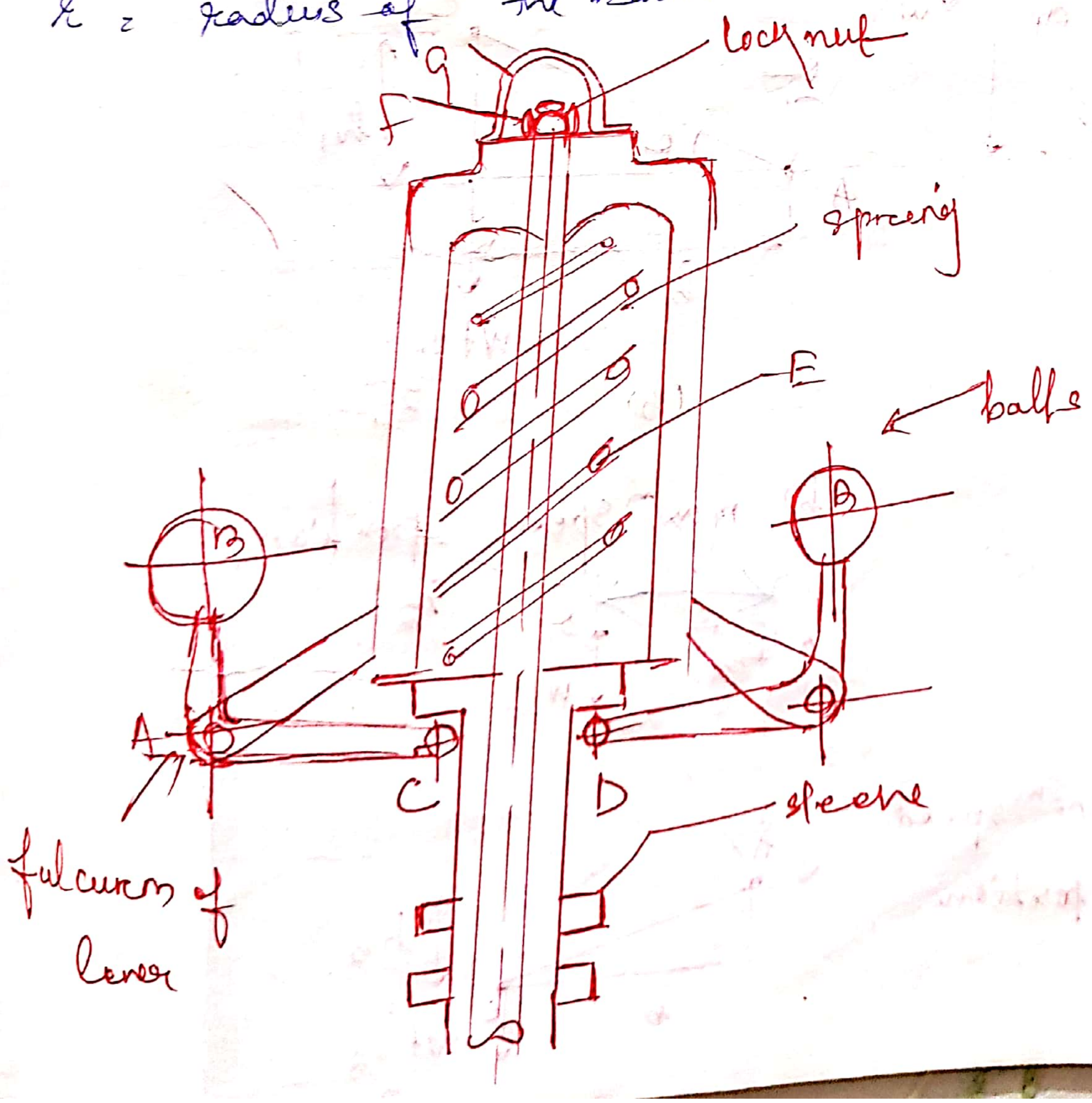
S_1, S_2 = Maxim & minim spring force.

F_{c1}, F_{c2} = centrifugal forces at speed ω_1 & ω_2 respectively

λ = stiffness of the spring

a, b = Vertical & horizontal length of arm of bell crank lever.

r = radius of the ball.



Isochronism

- When a governor shows a equilibrium speed for all positions of the sleeve or the balls is known as isochronous governor.

- However this is not practical due to friction in the sleeve.

for eg. porter governor (neglecting friction)

$$h_1 = \frac{g}{\omega_1^2}\left(1+\frac{M}{m}\right) \qquad h_2 = \frac{g}{\omega_2^2}\left(1+\frac{M}{m}\right)$$

for isochronism $\omega_1 = \omega_2$ thus $h_1 = h_2$

Stability

- Stability and the sensitivity are two opposite characteristics.
- A governor is said to be stable if it brings the speed of engine to the req. value & there is not much hunting.

Effort of governor

- The mean force acting on the sleeve to raise or lower it for a given change of speed is called effort of governor.
- At const. speed, the governor is in equilib^m & the resultant force acting on sleeve is zero.
- If the force acting at the sleeve changes gradually from zero to a value E for an increased speed of governor, the mean force or the effort is

$$\frac{0+E}{2} = E/2.$$

<CHAPTER - 05> BALANCING OF ROTATING MASSES

→ Balancing is defined as the process of designing or modifying a m/c in which unbalance force is minimum. If in high speed engines the rotating & reciprocating masses are not balanced properly then dynamic forces will induce, which increases the stress in m/c member.

1) – Balancing of single rotating mass
2) – Balancing of several rotating masses in same plane.
3) – Balancing of " " " " diff. plane.

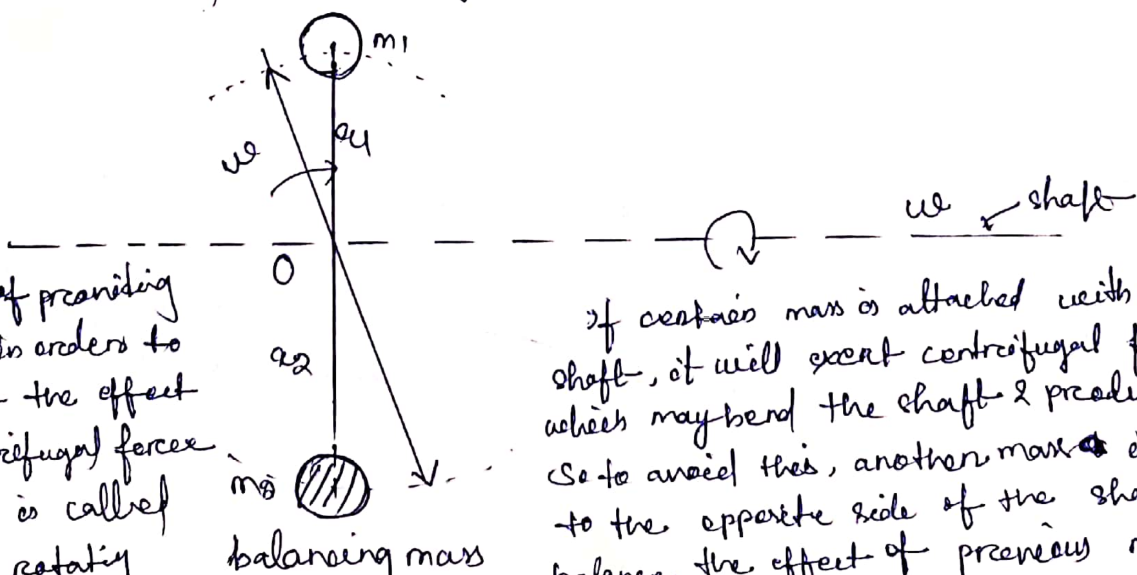
1) Balancing of single rotating mass.

A single rotating mass can be balanced in 2 diff. way.

i) The balance mass may be rotating in the same plane.
ii) The balance mass is not rotating in same plane.

i) The balance mass may be rotating in same plane :–

The fig shows a disturbing mass m_1 attached to a shaft which is rotating with a angular velo. ω rad/s.



The process of providing the 2nd mass in order to counteract the effect of centrifugal force of 1st mass is called balancing of rotating masses.

If certain mass is attached with a rotating shaft, it will exert centrifugal force, which may bend the shaft & produce vibration. So to avoid this, another mass is attached to the opposite side of the shaft to balance the effect of previous mass.

The axis of shaft is ⊥ to plane of paper & passing through O.

r_1 → is the distance c.g. of mass m_1 from pt. O.

m_2 → balancing mass.

r_2 → the distance of c.g of mass m_2 from axis of rotation.

The centrifugal force acting radially outward on mass m_1

$$F_c = m_1 \omega^2 r_1 \quad \text{--- (1)}$$

This centrifugal force induce a bending moment on the shaft & to conteract this moment a balance mass m_2 is attached to the shaft in same plane.

centrifugal force due to m_2.

$$F_c = m_2 \omega^2 r_2 \quad \text{--- (2)}$$

equating both eqn. $m_1 r_1 \omega^2 = m_2 r_2 \omega^2$

$$\Rightarrow \boxed{m_1 r_1 = m_2 r_2} \quad \text{--- (3)}$$

This eqn shows that the product of mass & radius is const.

ii) The balancing mass is not rotating in the same plane.

If balance mass is not in the same plane of rotation as disturbing mass, then we can't get accurate result by using a single balancing mass.

the fig shows the mass (m_1) & mass (m_2) are in a diff. plane. The centrifugal force induced by these 2 masses have same magnitude but the directions of these 2 force are opposite. Hence they will form a couple. Hence to balance this couple a second balancing mass will be used so to balance the system.

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$m_2 r_2 \cdot d = m \cdot r \cdot d_1$

$\Rightarrow m_2 r_2 = \frac{m \times r \times d_1}{d}$ ——— (2)

moment about p.

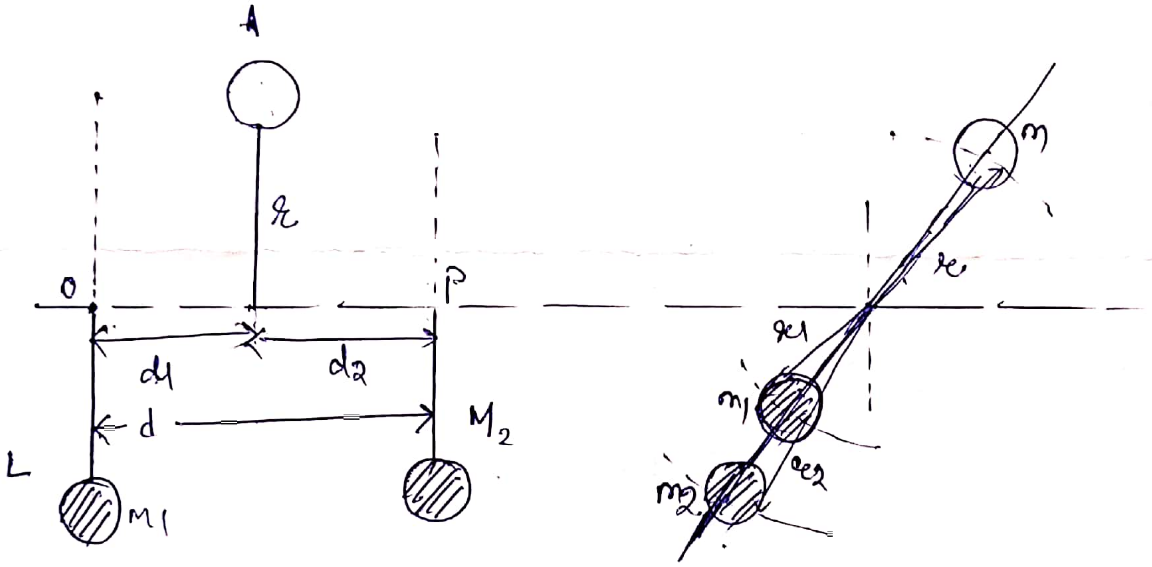
$F_{c1} \times d = F_c \times d_2$

$\Rightarrow (m_1 r_1 \omega^2) d = (m r \omega^2) d_2$

$\Rightarrow m_1 r_1 d = m r d_2$

$\Rightarrow m_1 r_1 = \frac{m r d_2}{d}$ ——— (3)

b) The masses are either side of the disturbing mass in different plane



$F_c = m r \omega^2$

$F_{c1} = m_1 r_1 \omega^2$

$F_{c2} = m_2 r_2 \omega^2$

$F_{c1} + F_{c2} = F_c$

$\Rightarrow m_1 \times r_1 \times \omega^2 + m_2 \omega^2 r_2 = m r \omega^2$

$\Rightarrow m_1 r_1 + m_2 r_2 = m r$ ——— (1)

Taking moments of the forces about pt. O.

$F_c \times d_1 = F_{c2} \times d.$

$\Rightarrow m r \omega^2 \times d_1 = m_2 r_2 \omega^2 \times d.$

$\Rightarrow m_2 r_2 = \frac{m \times r \times d_1}{d}$ ——— (2)

$\Rightarrow \boxed{M_2 r_2 \times d = m r \times d_1}$

taking moment about p

$\boxed{m_1 r_1 d = m r d_2}$

$m_2 r_2 \cdot d = m \cdot r \cdot d_1$

$\Rightarrow m_2 r_2 = \frac{m \times r \times d_1}{d}$ —— (2)

moment about P.

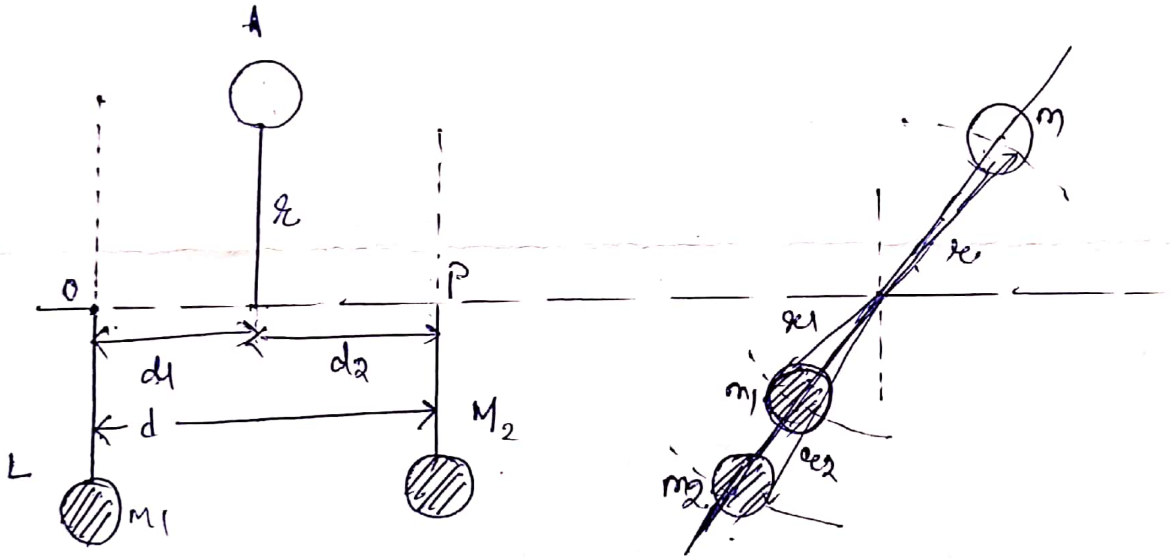
$F_{c1} \times d = F_c \times d_2$

$\Rightarrow (m_1 r_1 \omega^2)d = (m r \omega^2) d_2$

$\Rightarrow m_1 r_1 d = m r d_2$

$\Rightarrow m_1 r_1 = \frac{m r d_2}{d}$ —— (3)

6) The masses are either side of the disturbing mass in different plane



$F_c = m r \omega^2$

$F_{c1} = m_1 r_1 \omega^2$

$F_{c2} = m_2 r_2 \omega^2$

$F_{c1} + F_{c2} = F_c$

$\Rightarrow m_1 \times r_1 \times \omega^2 + m_2 \omega^2 r_2 = m r \omega^2$

$\Rightarrow m_1 r_1 + m_2 r_2 = m r$ —— (1)

Taking moments of the forces about pt. O.

$F_c \times d_1 = F_{c2} \times d.$

$\Rightarrow m r \omega^2 \times d_1 = m_2 r_2 \omega^2 \times d.$

$\Rightarrow m_2 r_2 = \frac{m \times r \times d_1}{d}$ —— (2)

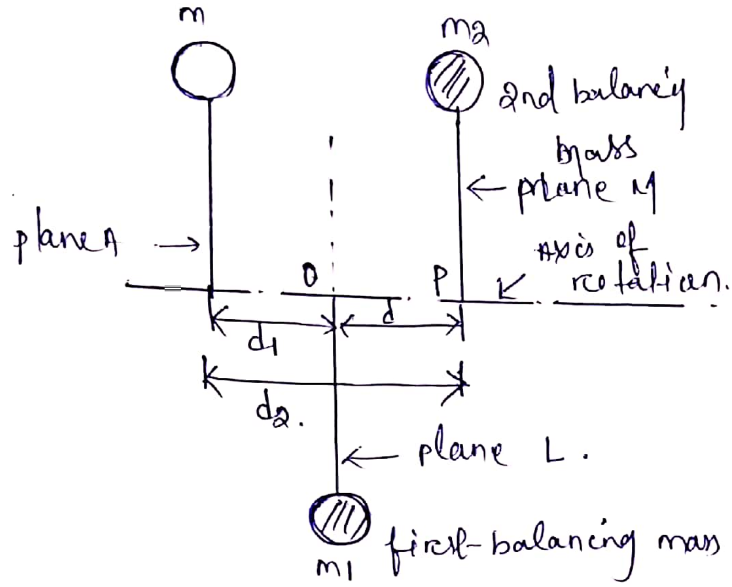
$\Rightarrow \boxed{m_2 r_2 \times d = m r \times d_1}$

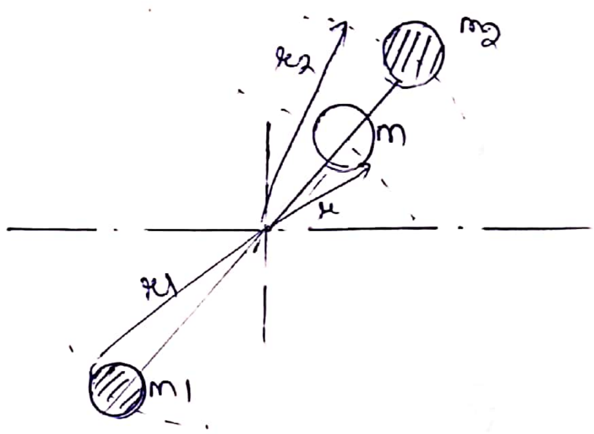
taking moment about P

$\boxed{m_1 r_1 d = m r d_2}$

& this is possible if the line of action of 3 centrifugal forces are parrallel & the sum of their moments about any pt is 0.

a) <u>The masses at same side of the plane.</u>





$F_c = m r \omega^2$

$F_{c1} = m_1 r_1 \omega^2$

$F_{c2} = m_2 r_2 \omega^2$

$F_c + F_{c2} = F_{c1}$

$\Rightarrow m r \omega^2 + m_2 r_2 \omega^2 = m_1 r_1 \omega^2$

$\Rightarrow m r + m_2 r_2 = m_1 r_1$ ——— (1)

Acc. to another condition the sum of moment about any pt. should be 0.

Let. pt. O is the pt. of intersection of plane L with axis of rotation, & P is the pt " " " " M " " "

moment about O, we get.

$F_{c2} \times d = F_c \times d_1$

$\Rightarrow (m_2 r_2 \omega^2) \times d = (m r \omega^2) d_1 \Rightarrow$ $\boxed{m_2 r_2 d = m r d_1}$

Similarly taking moment about P.

$$F_c \times d_2 = F_{c1} \times d$$

$$\Rightarrow (m r \omega^2) d_2 = (m_1 r_1 \omega^2) \times d.$$

$$\Rightarrow \boxed{m_1 r_1 = \frac{m r d_2}{d}} \quad \text{--- (3)}$$

Problem

Q. A disturbing mass 600 kg is attached to a shaft. The shaft is rotating at a uniform angular velo. ω rad/s. & the distance of the C.G of the disturbing mass from the axis of rotation is 270 mm. The disturbing mass is to be balanced by 2 masses in 2 diff planes. The distance of the CG of the balancing masses from the axis of rotation is 450 mm each. The distance betn the two planes of the balancing mass is 1.5 m. & distance betn the plane of disturbing mass & one of the planes of the balancing masses is 300 m.

Determine — i) the distance betn the plane of disturbing mass & the plane of other balancing masses.

ii) Magnitude of balancing masses when.

a) The plane of balancing are on the same side of the plane of disturbing masses.

b) The planes of the balancing masses are on either side of the plane of disturbing mass.

Soln

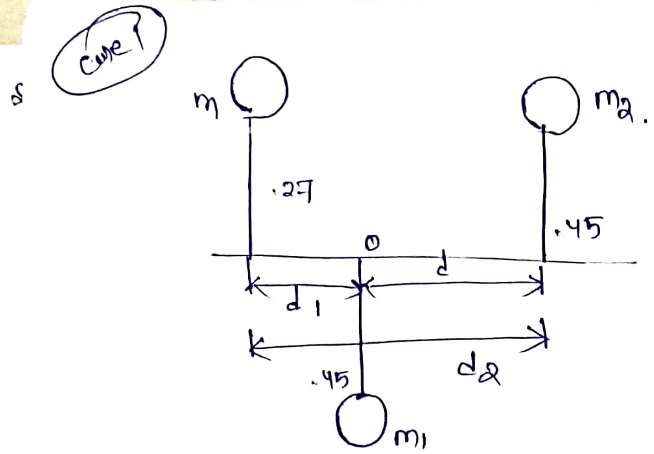
m = 600 kg.

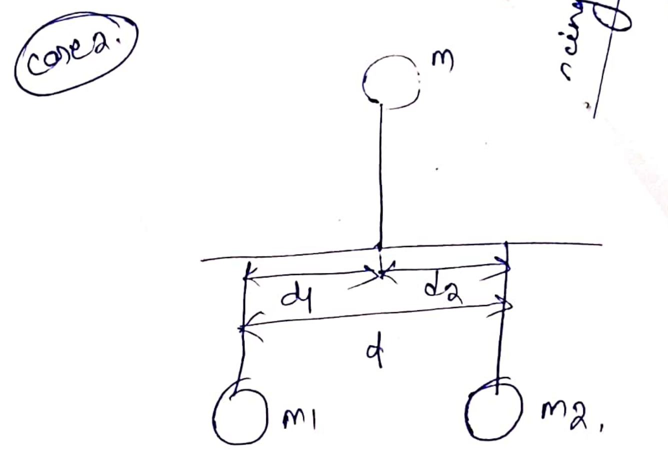
distance of C.G of the mass m from axis of rotation r = 270 mm = .27 m

" " balancing mass from axis of rotation $r_1 = r_2$ = 450 = .45 m

distance betn the plane of disturbing mass & the plane of 1st balancing mass = 0.3 m

distance betn 2 planes of balancing mass. d = 1.5 m.





Case 1

$m \times r + m_2 r_2 = m_1 r_1$

$\Rightarrow 600 \times .27 + m_2 (.45) = m_1 \times .45$

Again resultant moment

$m_2 r_2 \times d = m \times r\, d_1$

$m_2 r_2 = \dfrac{m r d_1}{d}$

$\Rightarrow m_2 \times .45 = \dfrac{600 \times .27 \times .03}{1.5}$

$\Rightarrow m_2 = 72\ kg.$

Now $m_1 = \dfrac{600 \times .27 + 72 \times .45}{.45}$

$= 432\ kg$

To find d_2.

$m_1 r_1 d = m_2 r \times d_2$,

$d_2 = \dfrac{m_1 r_1 d}{m r}$

$= \dfrac{432 \times .45 \times 1.5}{600 \times .27} = 1.8m$ Ans

Case 2

$m_1 r_1 + m_2 r_2 = m \times r$

$\Rightarrow m_1 .45 + m_2 .45 = 600 \times .27$

The resultant moment to be zero at pt O.

$m r d_1 = m_2 r_2 d_2$

$\Rightarrow m_2 = 72\ kg.$

$m_1 = 288\ kg.$

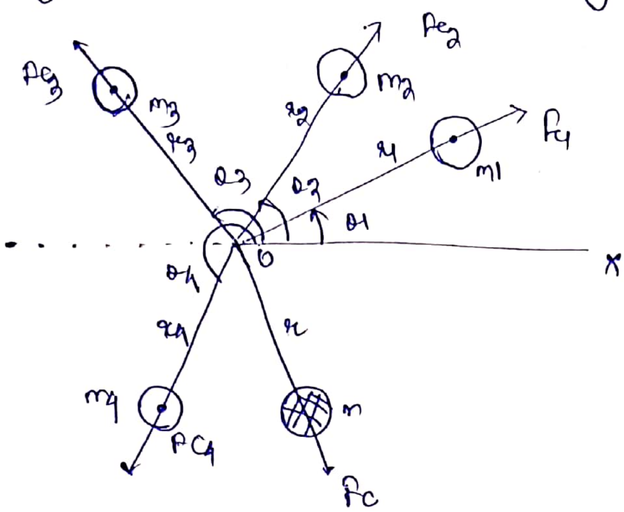
Value of d_2.

$m \times r \times d_2 = m_1 r_1 d.$

$\Rightarrow d_2 = 1.2m.$

Ans

[Bala]ncing of Several masses Rotating in the same plane



The above fig shows a no. of masses m_1, m_2, m_3 & m_4 which are rigidly attached to a shaft which is revolving at ω rad/s. The radius of rotation of masses r_1, r_2, r_3 & r_4 & the angle subtended by them with the horizontal axis $\theta_1, \theta_2, \theta_3$ & θ_4.

The centrifugal forces impressed by them F_{c1}, F_{c2}, F_{c3} & F_{c4} & these forces are proportional to corresponding product of mass & radius $F_{c1} \propto m_1 r_1$, $F_{c2} \propto m_2 r_2$, $F_{c3} \propto m_3 r_3$, $F_{c4} \propto m_4 r_4$

1. Analytical method.

Resolving each centrifugal forces horizontally & vertically.

$$\Sigma H = F_{c1}\cos\theta_1 + F_{c2}\cos\theta_2 + F_{c3}\cos\theta_3 + F_{c4}\cos\theta_4$$

$$\Sigma H = m_1 r_1 \omega \cos\theta_1 + m_2 r_2 \omega \cos\theta_2 + m_3 r_3 \omega \cos\theta_3 + m_4 r_4 \cos\theta_4$$

$$\Sigma H = m_1 r_1 \cos\theta_1 + m_2 r_2 \cos\theta_2 + m_3 r_3 \cos\theta_3 + m_4 r_4 \cos\theta_4$$

Similarly. ΣV

$$\Rightarrow \Sigma V = m_1 r_1 \sin\theta_1 + m_2 r_2 \sin\theta_2 - - + m_4 r_4 \sin\theta_4 = 0.$$

Resultant centrifugal force $F_c = \sqrt{(\Sigma H)^2 + (\Sigma V)^2}$

Position of the balancing mass $\rightarrow \tan\theta = \frac{\Sigma V}{\Sigma H}$.

Since the Resultant force & centrifugal force by same magi but oppo. in direction. Hence dirn of bal. mass $(180+\theta)$

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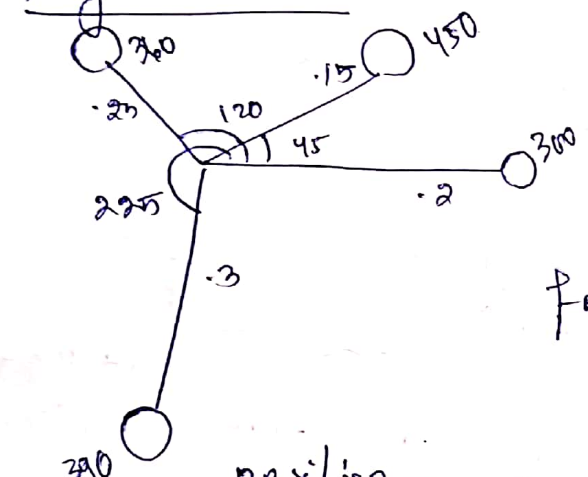
Q A shaft is rotating at a uniform angular speed. Four masses $m_1, \ldots m_4$ — 300, 450, 360 & 390 kg are attached to the shaft. All the masses are rotating in a same plane. The radius of rotations are 200, 150, 250, 300 mm respectively. Angle are 0°, 45, 120, 225. Find. $\omega = 1$ rad/s.

i) find the resultant force. ~~The radius of rotation of balancing mass 0.2 m~~

ii) position of the balancing mass if its radius is 0.2 m

Analytical meth



$m_1 r_1 \cos\theta$
$= 60 + 47.72 + -45 + -87.73 = -25.01$

$\Sigma H = 32.45$ kgm

$\Sigma V = 12.65$

$Force = \sqrt{(\Sigma H)^2 + (\Sigma V)^2}$

$= 34.82$ kg m.

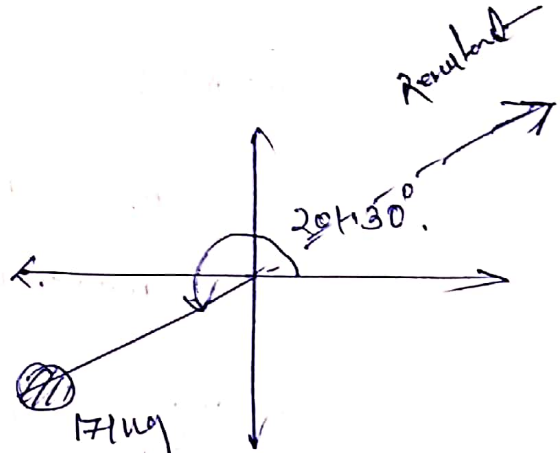
position $= \theta = \tan^{-1}\frac{\Sigma V}{\Sigma H}$.

iii) magnitude of balancing mass

Resultant force $F = mr$

$\Rightarrow F = m \times 0.2$

$\Rightarrow m = 174.1$ kg.



$\theta = 21.30°$

ii) Direction of balancing mass. $= 180 + \theta$

$= 180 + 21.30$

$= 201.30$.

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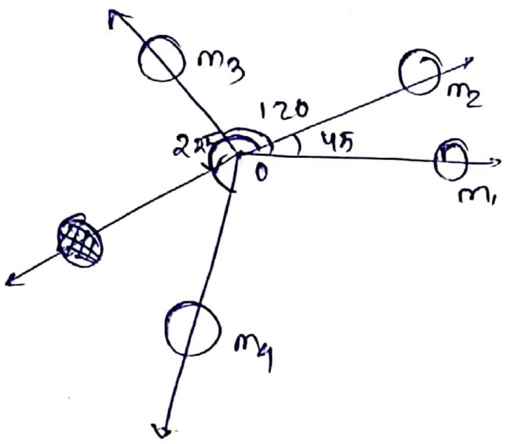
graphical Methode.

1) draw the space diag



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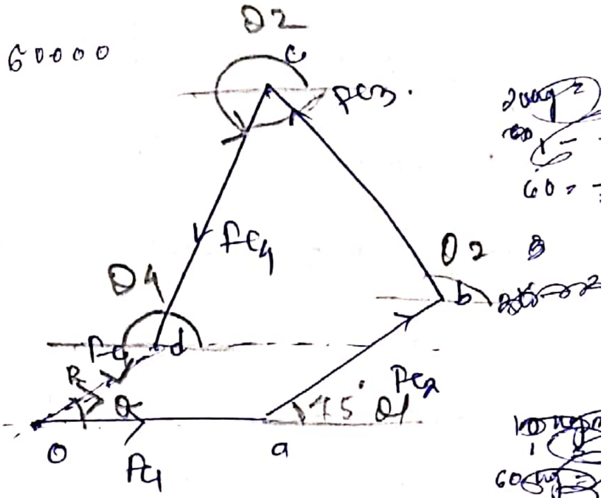


Od → Resultant of all the masses.

$Fc_1 = 60$ kg m = 3cm

$Fc_2 = 67.5 = 3.37$

$Fc_3 = 90 = 4.5$

$Fc_4 = 117 = 5.85$

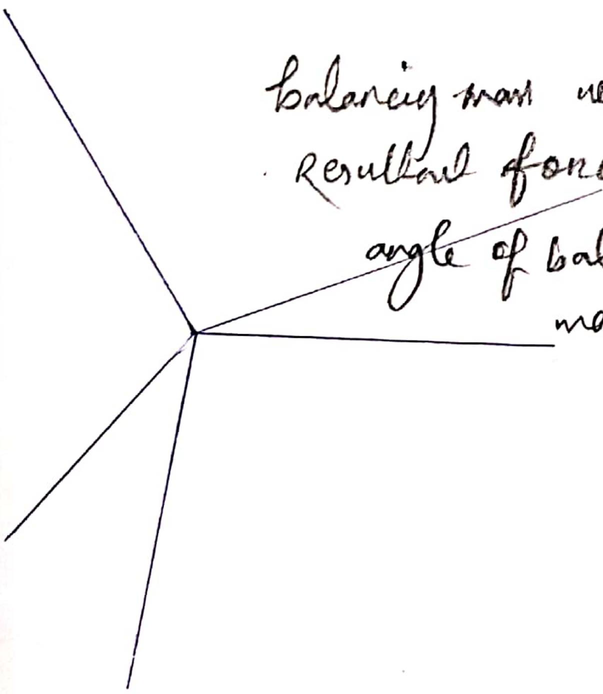
ii) Cal. the centrifugal force.

Fc_1, Fc_2, Fc_3, Fc_4.

$F_c = m \times r = 300 \times 200 = 600$ kg m

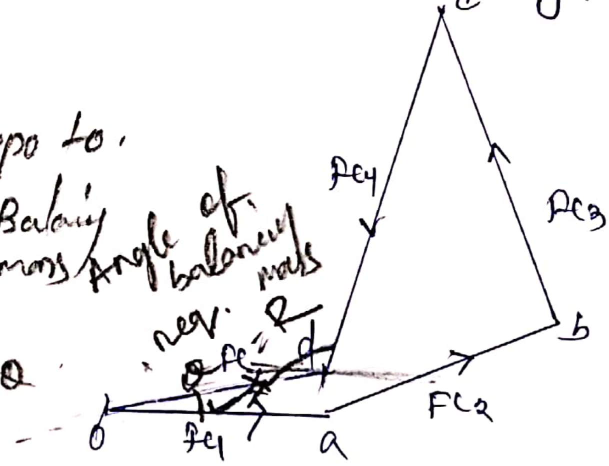
iv) take suitable scale.

v) take any pt from O & draw $Oa = Fc_1 = m_1 r_1$ parallel to Fc_1, from a draw ab, ll to Fc_2. From b, draw Fc_3 ll to Fc_3. From c draw cd ll to Fc_4. The closing side will represent the resultant force. measure od = 34.8 kg.



balancing mass will act appo to. Resultant force. R = Balancing mass Angle of balancing mass

angle of balancing mass = 180+θ

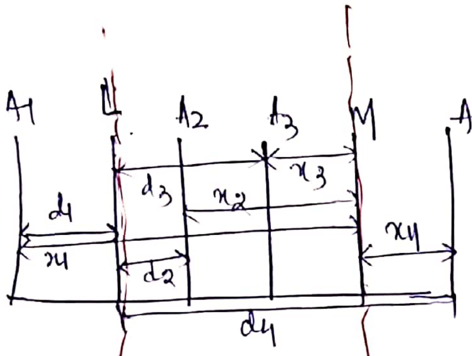


1cm = 20.

3.1cm = 20×3.

OD = 34.8

Balanceing of several masses rotating in different plane



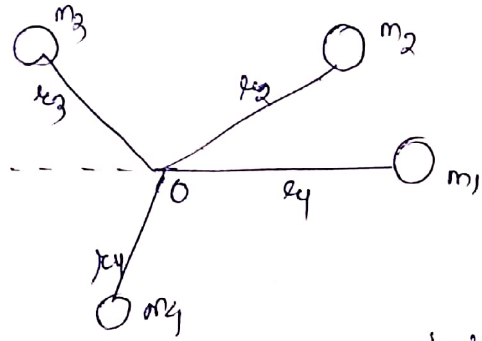


Fig shows several masses (m_1, m_2, m_3 & m_4) are rotating in 4 diff plane (A_1, A_2, A_3 & A_4) & raddi of rotation (r_1, r_2, r_3, r_4) respectively

Suppose the balancing masses are in plane L & M , so it is req. to find the masses & their angular position.

plane	mass	radius	centrifugal force $\div \omega^2$	Distance from plane L	Distance from plane M	balancing force $\div \omega^2$ L	balancing force $\div \omega^2$ M
A_1	m_1	r_1	$m_1 r_1$	d_1	x_1	$-\frac{m_1 r_1 x_1}{d}$	$\frac{m_1 r_1 d_1}{d}$
A_2	m_2	r_2	$m_2 r_2$	d_2	x_2	$-\frac{m_2 r_2 x_2}{d}$	$-\frac{m_2 r_2 d_2}{d}$
A_3	m_3	r_3	$m_3 r_3$	d_3	x_3	$-\frac{m_3 r_3 x_3}{d}$	$-\frac{m_3 r_3 d_3}{d}$
A_4	m_4	r_4	$m_4 r_4$	d_4	x_4	$+\frac{m_4 r_4 d_4}{d}$	$+\frac{m_4 r_4 d_4}{d}$

Disturbing mass m_1 is in plane A_1.

The plane A_1 is left to " L & M.

The baling force of plane L will be opposite to the centrifugal force on plane A_1 & M

If we assume the force on A_1 is +ve, then consicutively the forces on L will be -ve & M will be +ve.

As follows.

The sign convention is as follows

1. Let 1st disturbing mass is A1 & it is placed left to both L & M so the balancing forces on plane L must be opposite to the centrifugal force on outer 2 masses i.e. plane A1 & M. So if we assume centrifugal force on A1 is +ve, then balancing force L will be -ve & balancing force on plane M is +ve.

2. for mass m_2, it is bet^n L & M. Fc at m_2 should be opposite to balancing forces on L & M. As we consider centrifugal force as +ve, hence balancing forces on L & M will be -ve.

3. At m_3 is also bet^n L & M & same condition will be applied.

4. m_4 it is place right to L & M & same procedure will be followed.

Q cal. the mini^m speed, max^m speed & range of speed of porter governor, which has equal arms each 200mm long & pivoted on the axis of rotation. The mass of each ball is 4 kg & the central mass on the sleeve is 20 kg. The radius of rotation of the ball is 100mm when the governor begins to lift & 130mm when the governor is at max^m speed.

Q four masses $m_1 = 200$ $r_1 = 270 = \cdot 27m$

$m_2 = 300$ $r_2 = 210$.

$m_3 = 240$ $r_3 = 300$.

$m_4 = 260$. $r_4 = 360$.

distance betn L & M = 500 = d.

A_1 & L = 120 = d_1

A_4 & M = x_4 = 100 mm

radius of balancing mass 72 mm.

Find m_L & m_m & θ_L & θ_m.

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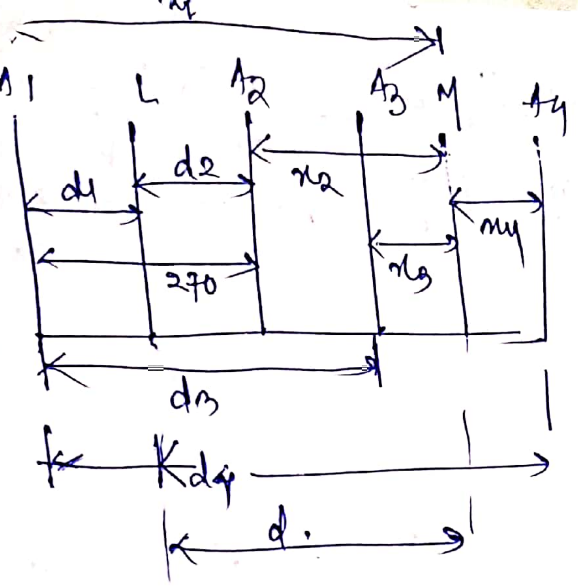


distance betn A1 & A2

= 270mm

A1 & A3 = 420 mm

A1 & A4 = 720mm.

Soln

$d_1 = 120 mm$

$d_2 = 270 - 120 = 150 mm$

$d_3 = 420 - 120 = 300 m$

$d_4 = 500 + 100$

$= 600 mm.$

$d = 500 mm$

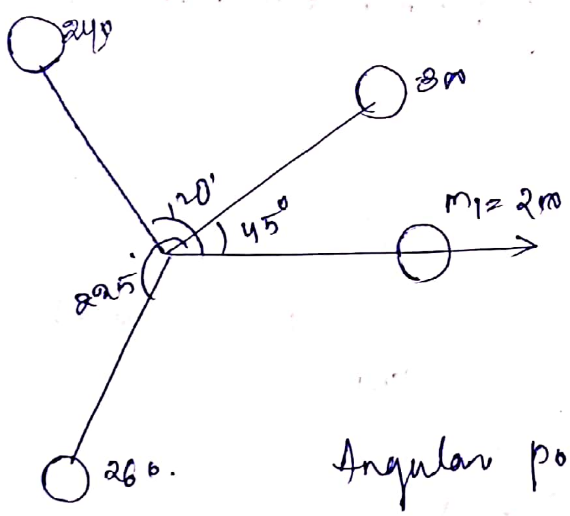
$x_1 = 620 mm$

$x_2 = 620 - 270 = 350$

$x_3 = 500 - 300 = 200$

$x_4 = 100 mm.$

r_L & r_M = 72 cm = .72 m

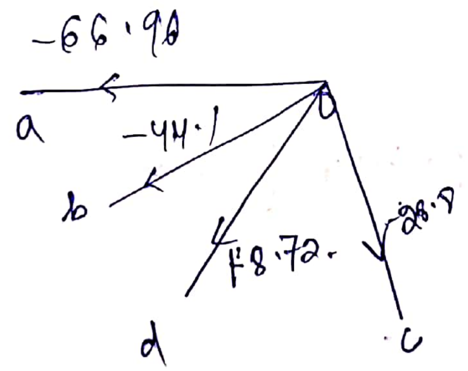


Angular positions of masses.

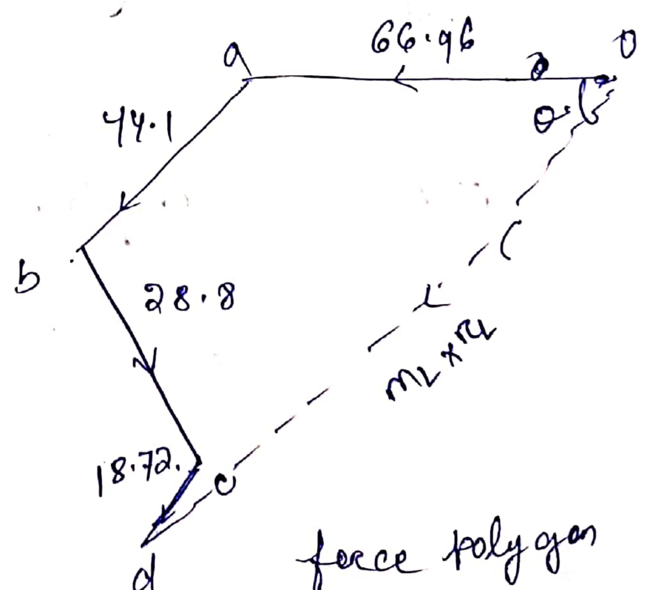
planes. A	mass (m) (in kg)	Radius r (in m)	centrifugal force ÷ ω^2 $\frac{mr\omega^2}{\omega^2}$	Distance from plane L	plane M	Balancing force to plane L $\frac{m \times r \times x}{d}$	plane M $\frac{m \times r \times d}{d}$
A_1	200	.27	54 kgm	.12	.62	−66.96	12.96
A_2	300	.21	63	.15	.35	−44.1	−18.9
A_3	240	.30	72	.30	.20	−28.8	−43.2
A_4	260	.36	93.6	.60	.10	18.72	−112.32

Resultant force for plane L.

If the balancing force due to disturbing mass is +ve is column, then the direction of balancing force is taken in same direction or if −ve taken in opposite direction.



balancing forces for plane L



force polygon for plane L

Taking suitable scale draw the force polygon for plan L.

m_L = balancing mass for plane L.

r_L = Radius of balancing mass in plan L = .72m

66.96 →

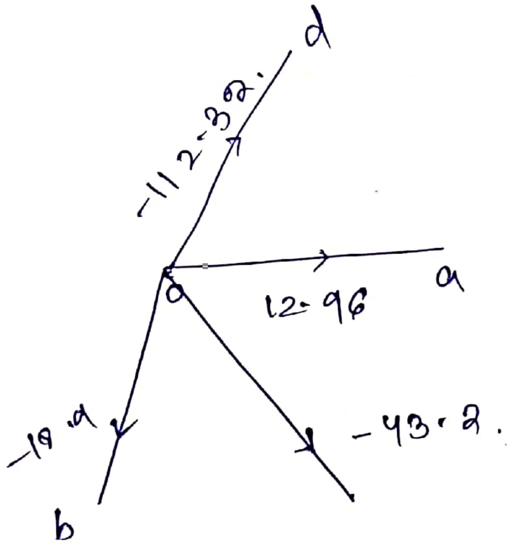
Measure od, $od = m_L \times r_L$

$\Rightarrow m_L \times r_L = od$

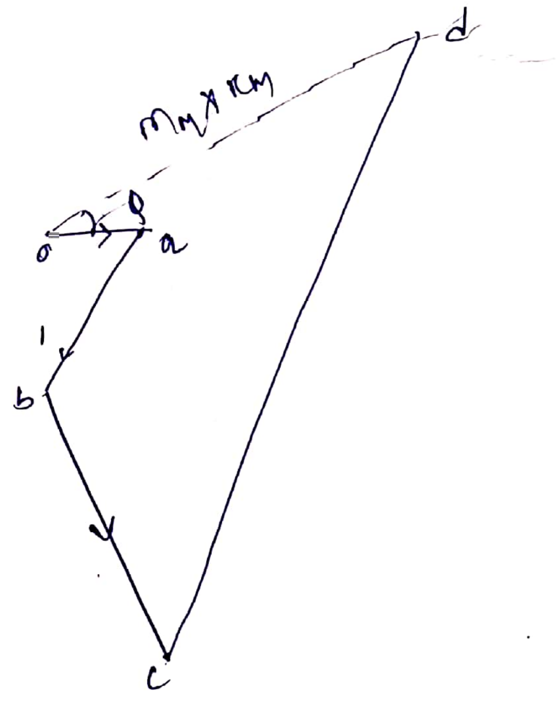
$\Rightarrow m_L = \frac{od}{r_L} = (\ )$

measure angle θ → from the polygon.

Resultant force for plane M.



balancing forces for plane M.



force polygon for plane M.

Now measure $od = m_M \times r_M$

$\Rightarrow m_M = \frac{od}{r_M} = (\ )$

measure angle ϕ.

Vibration <CHAPTER-06>

(Longitudinal & transverse)

Vibrations are due to internal elastic forces within the body. When an elastic body like shaft & springs, which are fixed at one end & displaced at the other end from its equilibrium by the application of an external force. The body starts to move to & fro or up & down, then the body is said be vibrating. & or said to be in vibration.

Types of vibration

1) free or natural vibration

2) force vibration.

3) Damped vibration.

1) Free vibration – A vibration in which no. ext force acts on the body, after giving a initial displacement & the motion is maintained by internal elastic forces (when friction & other resistances are neglected) is known as free or natural vibration.

* The frequency of free vibration is called natural frequency.

2) Forced vibration – A vibration in which ext. force is applied on the body & the vibrations have the same freq. as the applied force is known as force vibration.

3) Damped vibration – A vibration in which there is a reduction in amplitude over every cycle of vibration is known as damped vibration. After removing the external force, the energy possed by the body is gradually dissipated in overcomming the internal & external resistance of the body So that the amplitude goes on decreasing.

Important definations for vibrating motion

1. Period of vibration or time period – It is the time taken by motion to repeat itself. It is measured in seconds.

2. cycle – It is the motion completed during one time period.

3. Frequency – No of cycles completed in one sec. denot unit is Hertz
i.e 1 cycle / 1 sec.

4. Resonance – when freq of external force is same as that of the natural freq. of the system, resonance takes place. Resonance results in large amplitude of vibration & this may be dangerious.

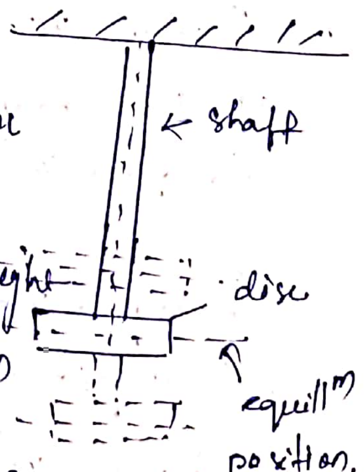
Free vibration

In free vibration there is no ext. force is there. It is divided in to 3 types
1) Longitudinal
2) Transverse.
3) Torsional

1) Longitudinal

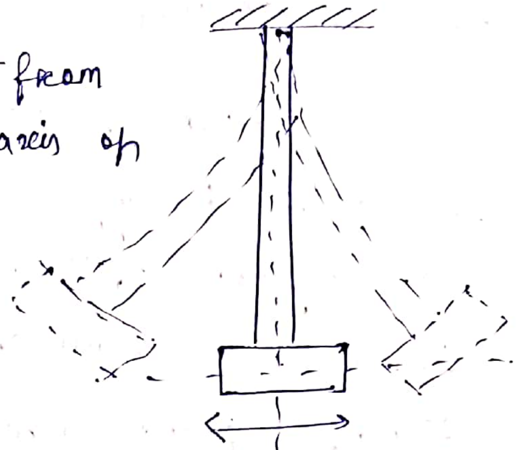
The shaft is asumed to be weight less. The disc is moving up & down as shown in the fig. All the particles of the disc will vibrate along straight path to the axis of the shaft. This type of vibration is known as longitudinal vibration.

In longitudinal vibration the shaft elongated & shortened alternately resulting in compressive & tensile stress in shaft.



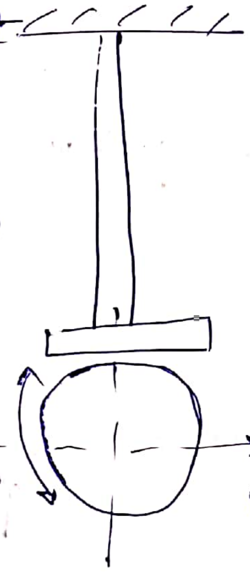
Transverse Vibration

The disc may be given initial displacement from equilm position by external force ⊥ to the axis of the shaft i.e towards left or right)
This type of vibration is known as transverse vibration. In transverse vibration, the shaft is alternately bent & straight resulting in bending stress in shaft.



Torsional vibration

The disc may be given initial angular displacement from the equilm position by external torque. i.e it is twisted in a circular manner and then released.
All the particles of the disc will vibrate along the circular arc whose centre lies on the axis of shaft.
In torsional vibration, the shaft is alternatively twisted & untwisted resulting in torsional vibration.

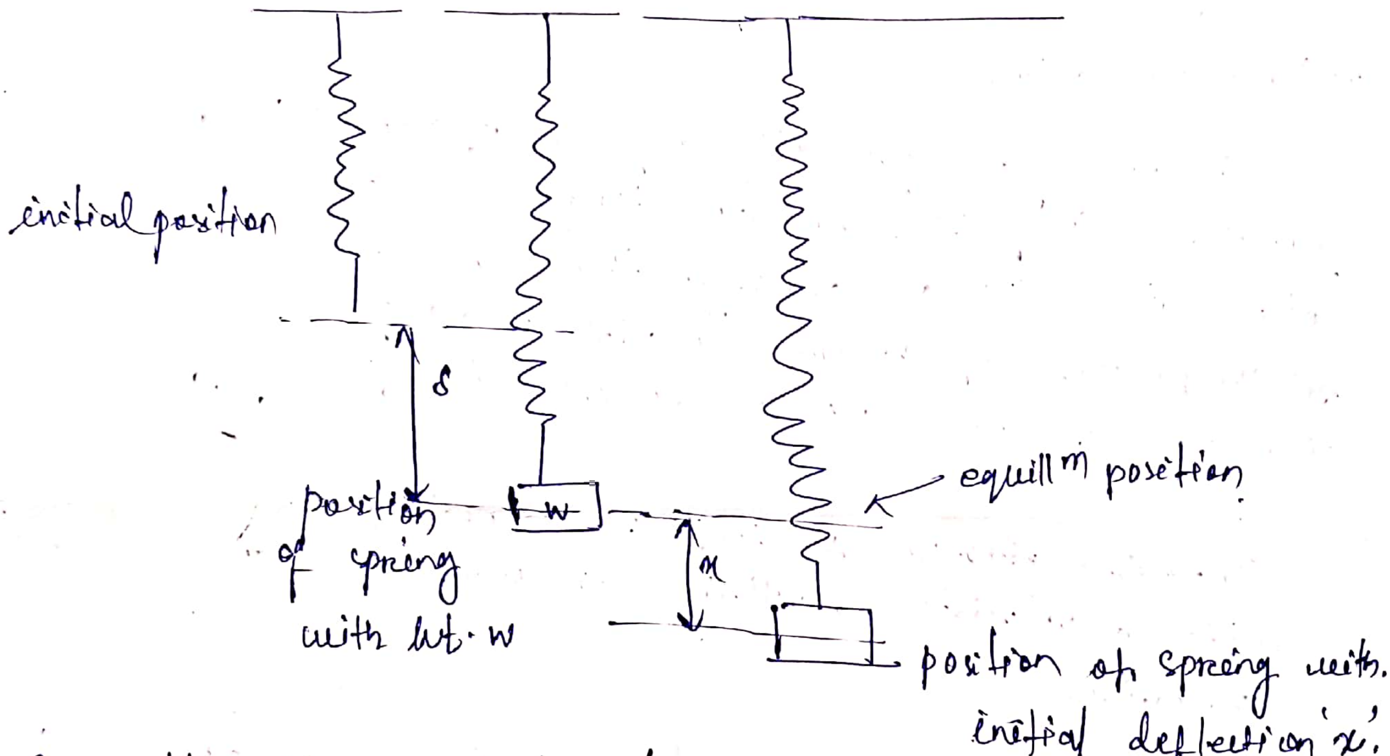


Methods of finding the natural frequency of free longitudinal vibration

- Equilm
- Energy
- Rayleigh's methode.

Equilibrium Method -

Consider a spring of negligible mass suspended vertically from a rigid support. The other end of spring is free. If weight W is suspended from the free end, the spring is stretched by a distance δ as shown in fig. The distance δ is known as static deflection of spring under wt. W.



S → stiffness of the spring. / spring constant
or k   i.e the force req. to produce unit deflection.

m → mass of wt. suspended $W = mg$.

For equill^m position, wt. suspended = upward force of spring.

$$mg = S \times \delta$$

Now the wt. W given a initial displacement x & then released as shown in fig.

the weight w is moving downward & is at a distance of x from equill^m position, the net force acting on the weight.

$= $ Down ward force − upward force.

$= W - S(\delta + x)$

$= mg - S\delta - Sx$

$= S.\delta - S\delta - Sx.$

Spring force $= -Sx$ ——— ①. Spring force
$= Sx(\uparrow)$

The net force is equal to the product of mass & accl^n.

\# Another method
Acc. to D'alembert's principle
Spring force $= Sx(\uparrow)$
→ sum of internal & external force is zero in any dire^n.

$m\ddot{x} + Sx = 0$

$\Rightarrow \ddot{x} + \frac{S}{m}x = 0$

$\Rightarrow \ddot{x} + w_n^2 x = 0$

$w_n^2 = \frac{S}{m}$

$w_n = \sqrt{S/m}$

Net force $= m \times a$ (↓) +ve
internal force $= m \times \frac{d^2x}{dt^2}$ ——— ②

inertia force $= m\ddot{x}(\uparrow)$

ve $\frac{md^2x}{dt^2} = -Sx$ ——— ③

$\Rightarrow m\frac{d^2x}{dt^2} + Sx = 0.$ ——— ③a

$\Rightarrow \frac{d^2x}{dt^2} + \left(\frac{S}{m}\right)x = 0.$ ——— ④

This equ^n is similar to fundamental equ^n of simple harmonic.

$$\frac{d^2x}{dt^2} + \omega^2 . x = 0. \quad ——— ⑤$$

from equ^n ③ & ④

$\omega^2 = \frac{S}{m}$

$\Rightarrow \omega = \sqrt{S/m}$

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where ω is known as the natural angular velo, & denoted by ω_n

$\Rightarrow \omega_n = \sqrt{s/m}$ —— (5)

→ Hence the time period $t = \frac{2\pi}{\omega_n} = \frac{2\pi}{\sqrt{s/m}} = 2\pi\sqrt{m/s}$ —— (6)

→ Natural freq $f_n = \frac{1}{t}$

$$f_n = \frac{1}{2\pi}\sqrt{\frac{s}{m}}$$ —— (7)

The natural freq. can also be expressed by static deflection δ, by substituting the value of s in equn (7)

$m \cdot g = s \cdot \delta$

$\Rightarrow s = \frac{mg}{\delta}$ $\quad f_n = \frac{1}{2\pi}\sqrt{\left(\frac{mg}{\delta}\right) \times \frac{1}{m}}$

$$f_n = \frac{1}{2\pi}\sqrt{g/\delta}$$ —— (8)

$$f_n = \frac{0.4985}{\sqrt{\delta}} \text{ Hz}$$

$E = \frac{\text{Stress}}{\text{strain}} = \frac{W/A}{\delta/L}$

$E = \frac{W}{A} \times \frac{L}{\delta}$.

$\Rightarrow$ ~~$\delta = \frac{E \times A}{WL}$~~

$\Rightarrow \delta = \frac{W \times L}{EA}$

Energy Methode : Energy Methode

In free vibrations, the total energy of the system means the sum of P.E & K.E remains const. P.E is taken w.r.t to some certain datum position. Datum position is taken as equilibm position in case of vibration.

$$K.E + P.E = const.$$

or

$$\frac{d}{dt}[K.E + P.E] = 0. \quad \text{——— (1)}$$

$$K.E = \frac{1}{2}mv^2$$

$$= \frac{1}{2}m\left(\frac{dx}{dt}\right)^2 = \frac{1}{2}m\dot{x}$$

P.E = mean force × displacement from equilibrium position.

$$= \left(\frac{0+s.x}{2}\right)\times x$$

$$= \frac{sx^2}{2}$$

$$\frac{d}{dt}\left[\frac{1}{2}m\dot{x}^2 + \frac{kx^2}{2}\right] = 0.$$

$$\Rightarrow \frac{1}{2}m\, 2\dot{x}.\ddot{x} + \frac{1}{2}k\, 2x.\dot{x} = 0$$

$$\Rightarrow m\ddot{x} + kx = 0$$

Now equn (1) becomes as $\frac{d}{dt}\left[\frac{1}{2}m\left(\frac{dx}{dt}\right)^2 + \frac{sx^2}{2}\right] = 0$

$$\Rightarrow \frac{1}{2}m \times 2.\frac{dx}{dt} \times \frac{d^2x}{dt^2} + \frac{1}{2}\times s \times 2x \times \frac{dx}{dt} = 0.$$

$$\Rightarrow 2.\frac{dx}{dt}\left[\frac{1}{2}m.\frac{d^2x}{dt^2} + \frac{1}{2}s\times x\right] = 0$$

$$\Rightarrow \boxed{m.\frac{d^2x}{dt^2} + sx = 0}$$

This equn is same as. equn is same as equn no. 2(a).
Hence in this case also the time period & natural freq. will be same as given in equilibm methode.

Methode for Natural freq. of free Transverse vibration.

Consider a cantilever shaft with one end is fixed & other end is free. Let it is of negligible mass. A wt. w is attached at the free end, due to wt w the shaft got deflected by δ.

The distance δ → static deflection under the wt. W.

S → stiffness of the shaft i.e force req to produce unit deflec^n in the shaft

S.δ → total force req. to produce δ deflec^n.

Again δ is produced due to wt. w

so $W = S.\delta \Rightarrow mg = S.\delta$ —— (1)

The net force acting on the body, when the body is at a dist. of x below the equilm position.

= Wt. of body − upward resistant force

$= W - S.(x+\delta)$

$= mg - S.x - S.\delta$

$= -Sx$

again Net force = m. a.

$$-Sx = m.\frac{d^2x}{dt^2}$$

$$\Rightarrow m.\frac{d^2x}{dt^2} + Sx = 0.$$

$$\text{or} \quad \frac{d^2x}{dt^2} + \left(\frac{S}{m}\right)x = 0.$$

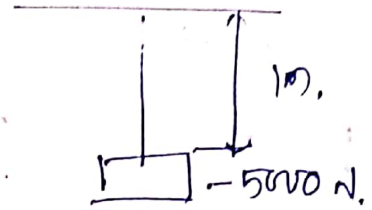
Hence the time period & natural freq. of transverse vibration will be same as that of longitudinal vibrations.

$$t = 2\pi\sqrt{m/S}$$

$$f_n = \frac{1}{2\pi}\sqrt{S/m} \quad \text{or} \quad \frac{1}{2\pi}\sqrt{g/\delta}$$

for a cantilever shaft loaded at free end, the static deflection $\delta = \frac{WL^3}{3EI}$ ——

A vertical shaft 100 mm in dia & 1m in length has its upper end fixed at top. Lower end carries a ~~[illegible]~~ wt. 2000N, the $E = 2\times10^{5}\ N/mm^2$. Neg. wt. of shaft, determine fn for longitudinal & transverse vibrations



Sol^n

$d = 100\ mm$

$L = 1m$

$W = 5000$

$E = 2\times10^{5}\ N/mm^2$

$= 2\times10^{11}\ N/m^2$

i)

$$f_n = \frac{1}{2\pi}\sqrt{g/\delta}$$

$$\delta = \frac{W\times L}{AE}$$

$$= \frac{5000\times1}{\pi/4(\cdot1)^2\times2\times10^{11}}$$

$$= 3.183\times10^{-6}\ m.$$

$$f_n = 279.5\ hz.$$

ii)

$$f_n = \frac{1}{2\pi}\sqrt{g/\delta}.$$

$$\delta = \frac{WL^3}{3EI}$$

$$= \frac{5000\times1^3}{3\times2\times10^{11}\times\frac{\pi}{64}(d^4)}$$

$$= 1.7\times10^{-3}\ m$$

$$f_n = 12\ hz.\ \underline{\underline{Ans}}$$

Causes of vibration

1) unbalanced reciprocating m/c pairs.
2) unbalanced rotating m/c pairs.
3) Incorrect alignment of the transmission elements like coupling etc.
4) use of simple spur gears for power transmission.
5) Worn out teeth of the gears for power transmission.
6) Loose transmission belts & chains.
7) Loose fastening of the moving parts.
8) vibration due to improper isolation of the m/c.
9) Due to more material contact eg. base plates on the foundations for pedesal bearing.
10) Non - rigid m/c foundations due to lack of compact soil below which causes misalignment of m/c components.

Remedies

Vibrations can not be eliminated but can be reduced by,

→ partial balancing of reciprocating masses.
→ Balancing of unbalanced rotating masses.
→ using helical gears instead of spur gears.
→ proper tightening & locking of parts.
→ correcting the misalignments of rotating components & checking it time to time.
→ Timely replacement of worn-out moving parts, slides & bearings with excessive clearance.
→ providing vibration pads in m/c foundations.
→ Making strong foundations.

Tool Materials

Syllabus:

1.1 Composition of various tool materials
1.2 Physical properties & uses of such tool materials.

Manufacturing technology:

It is defined as a field of study focused on process techniques or equipments, cost reduction, increased efficiecy, enhanced reliability, security safety and anti-polution measures are it's objects.

Tool Material:

The characteristic of the ideal cutting tool material are-

(a) Hot hardness
(b) Wear resistance
(c) Toughness
(d) Cost and easiness in fabrication

Hot hardness:

The material must remain hander than the the work material at elevated operating temperatures.

Wear resistances:

The material must withstand excessive were even through the relative hardness of the tool-work materials changes.

Toughness:

The term toughness actually implies a combination of strength and ductility. The material must have sufficient toughness to withstand shocks and vibrations and to prevent breakage.

Cost and easiness in fabrication:

The cost and easiness of fabrication should have within reasonable limits.

State the composition of various tool material

The cutting tool materials are-:

1. **Carbon steels**
2. **Medium alloy steel**
3. **High speed steels**
4. **Stellites**
5. **Cemented carbides**
6. **Ceramics**
7. **Diamonds**
8. **Abrasives**
9. **Cubic boron nitridw(CBN)**

Composition of carbon steels:

Carbon steels contain carbon in amounts ranging fron 0.008 to 1.5%

Composition of medium alloy steel:

The high carbon medium alloy steels have a carbon content akin to plain carbon steels,but in addition there is ,say up to 5% alloy content consisting there of tungsten,molybdenum,chromium and vanadium.

Composition of high speed steel:

High speed steel is the general pupose metal for low and medium cutting speed owing to its soperior three type of high speed steel

1. **High tungsten**
2. **High molybdenum**
3. **High cobalt**

Actually these three named modify as following

1. 18-4-1 high speed steel (T-series)
2. Molybdenum high speed steel(M-series)
3. Cobalt high speed steel

Composition of 18-4-1 high speed steel (T-series)-

This steel containing 18% tungsten ,4% cr & 1% vanadium, is considered to be one of the best of all purpose o f tool steel.

Composition of molybdenum high speed steel (M-series):

This steel containing 6% molybdenum,6%w,4% cr % & 2% vanadium.

Composition of cobalt high speed steel:

This is sometimes called super high speed steel. Cobalt is added from 2 to 15% io incrise of this steel contains 20% tungston 4%cr,2% v & 12% cobalt.

Composition of satellites:

Satellites is the trade name of a nonferrous cost alloy cobalt, chromium and tungsten. The ranges of elements in these alloys is40 to 48%, 30 to 35% Cr & 12 to 19% tungsten.

Composition of cemented carbides:

A typical analysis of a carbide suitable for steel machining is 82% tungsten carbide,10% titanium carbide and 8% cobalt.

Composition of ceramics:

The latest development in the metal cutting tools use Al oxide generally referred to as ceramics

Tools are made by composing aluminium oxide powder in a mould at about 280 kg/cm^2 or more.

Composition of diamonds:

The diamonds are used for cutting tools are industrial diamonds, which are naturally occurring diamonds.

Composition of abrasive:

Abrasive grains in various forms, loose, bonded into wheels and extended in papers and story and extended in paper s and cloths find wide application in industry. They are mainly used for grinding harder materials and where a superior finish is desired on hardened or unhardened materials.

Composition of Cubic Boron Nitride (CBN):

This material consisting atoms of boron and nitrogen is considered as the hardest tool material available.

1. **Carbon steel**
2. **Medium alloy steel**
3. **High speed steel**
4. **Cast alloy satellites**
5. **Cemented carbide tool material**
6. **oxide or ceramic tool material**
7. **diamonds**
8. **abrasives**
9. **cubic boron nitride(CBN)**

Carbon steel:

Properties

I. **low hot hardness**
II. **poor hardenability**
III. **can be withstand cutting temperature 200^0c**
IV. **carbon tool steel are harder then many hss**

uses: It can be used most economically under these condtion.

(a) The carbon steels are used for making certain taps and drills.
(b) For making wood working tools

Medium alloy steel:

Properties

i) Better hardenability.
ii) Higher wear resistance.
iii) Higher hardness.

Uses

i) Used for making drills
ii) Used for making taps, etc
iii) It can aut effectively up to temperature 250 to 300^0c.

High speed steel (HSS):

Properties

i) **High hot hardness**
ii) **Cutting tools retain the cutting ability upto 600^0 c.**
iii) **High wear resistance.**
iv) **The hardenability is good.**

Uses

i) **Drills**
ii) **Broaches**
iii) **Milling cutters**
iv) **Lathe cutting tools**
v) **Taps,etc.**

Cast alloy satellite:

Properties:

i) Material is not so hard at room temperature
ii) Hardness above 1000^0F is greater then high speed steels.
iii) Hat hardness is higher then H.S.S at higher temprature.
iv) This material is very brittle

Uses

These material are used extensively in some non metal cutting application such as rubbers, plastics.

Cemented Carbide:

Properties:

i) High hardness
ii) High heat resistance
iii) High wear resistance

Uses:

These tool materials are used for machining cast iron, alloy steels.

Oxides ceramic tool material:

Properties:

I) The ceramic has extremely high compressive strength. It is quietly brittle.

II) Heat conductivity is very low. So generally no coolant is required while machining

III) The ceramic tools can retain strength and hardness upto 1200^0c.

Uses:

These tool materials are used for turning boring, etc operations at high speed.

Diamonds are cutting tools:

Properties:

i) It has a low co-efficient of friction

ii) Hardness of the diamond is incompressible.

Uses:

Diamonds are suitable for cutting very hard material such as glass, plastics, ceramics.

Abrasive:

Uses:

For most grinding operations there are two kinds of abrasives in general use namely aluminium oxide and silicon carbide. The aluminium oxide abrasive are used for grinding all high tensile materials, where as Silicon Carbide abrasives are more stable for low tensile materials.

Chapter-2

Cutting Tools

Syllabus:

2.1 Cutting action of various hand tools such as Chisel, hack saw blade, dies and reamer
2.3 Turning tool geometry and purpose of tool angle
2.5 Machining process parameters (Speed, feed and depth of cut)
2.6 Coolants and lubricants in machining and purpose

<u>Cutting tools:</u>

In machining a cutting tool or cutter is any tool which is used to remove the material from the W/P by means of shear difference

Cutting tool must be made of a material harder than the material which is to be cut and the tool must be to withstand the heat generated in the metal cutting process

The angle of cutting facer is also important, also the tool must have a specific geometry and clearance angles designed so that the cutting edge can contact the W/P surface .

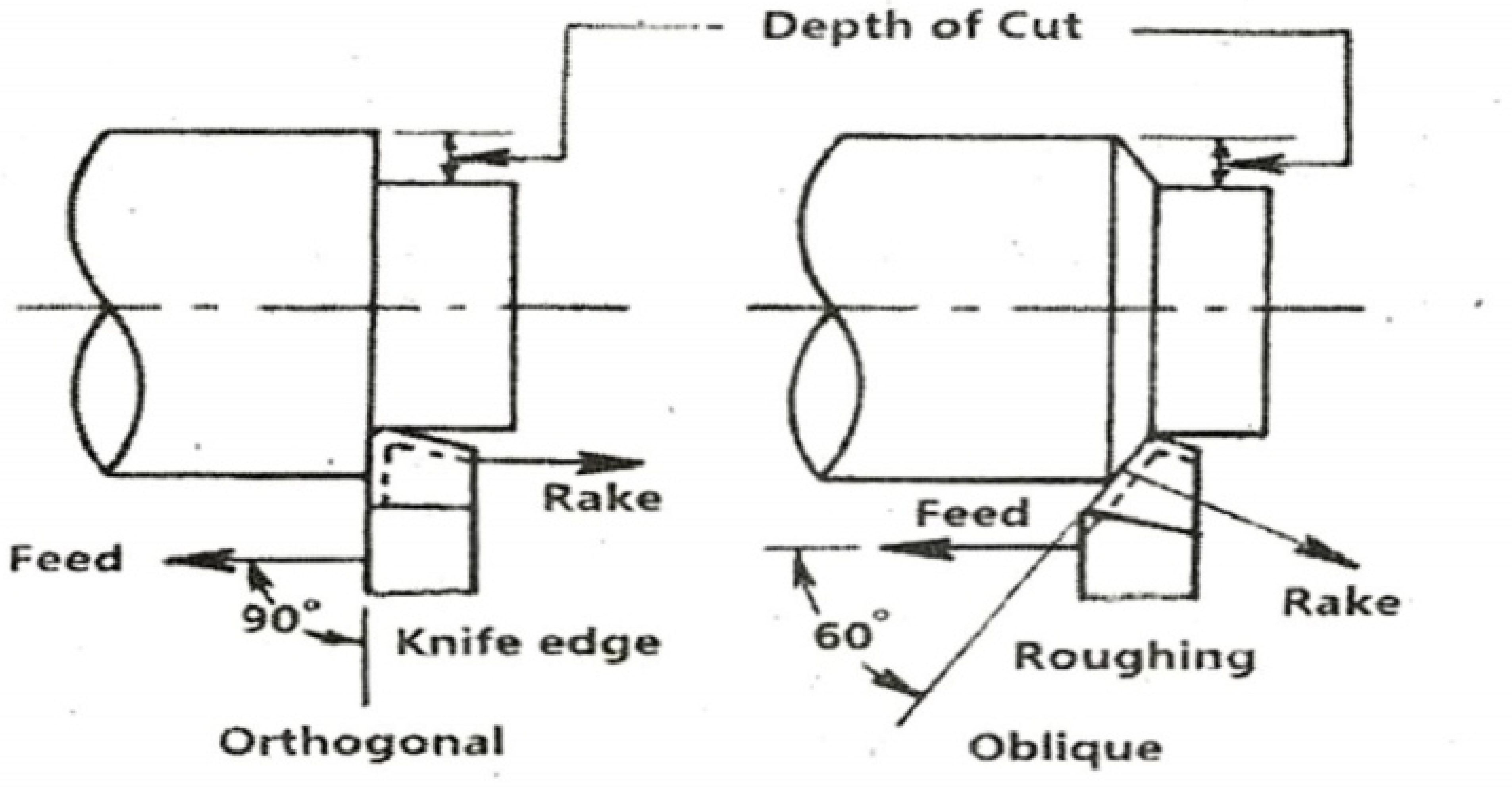


Figure Orthogonal and oblique cutting

Single point cutting tool

This type of cutting tools have only one cutting edge. These used for wide application of lathe, shaper planner, slitter, boring M/C

Multi point cutting tools

This type cutting tools have more than cutting edge. These are employed for wide application in twist drills, Reamers, tapes, milling cutters etc.

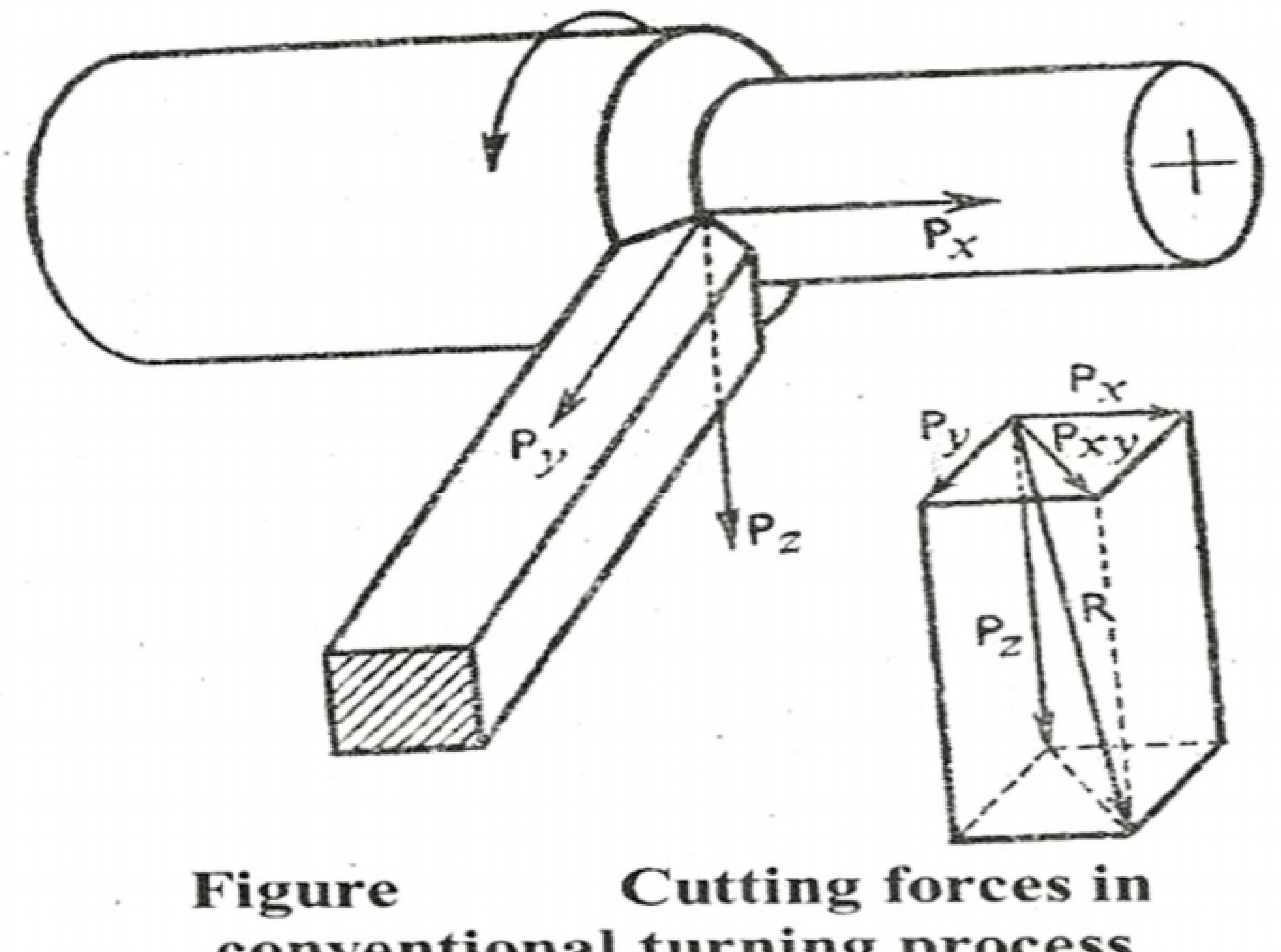


Figure Cutting forces in conventional turning process

<u>**Cutting action of hand tools**</u>

Chisel:

A chisel is a hand cutting tools which is shaped cutting edge of blade on its end, forcarving, cutting a hard material such as wood, stone, metal by hand with the help of mechanical power.

In used the chisel are forced in to the material to linear relative motion.

The driving forced into the material may be manually applied by using a hammer.

In industrial use, a hydraulic ram or falling weight drives the chisel into the material to be cut .

Chisel is employed to use in wood work, metal working etc.

In wood & stone working used for carving, cutting, shaving, shaping, trimming.

In metal working process chisel use divided into two categories:

Cold chisel:

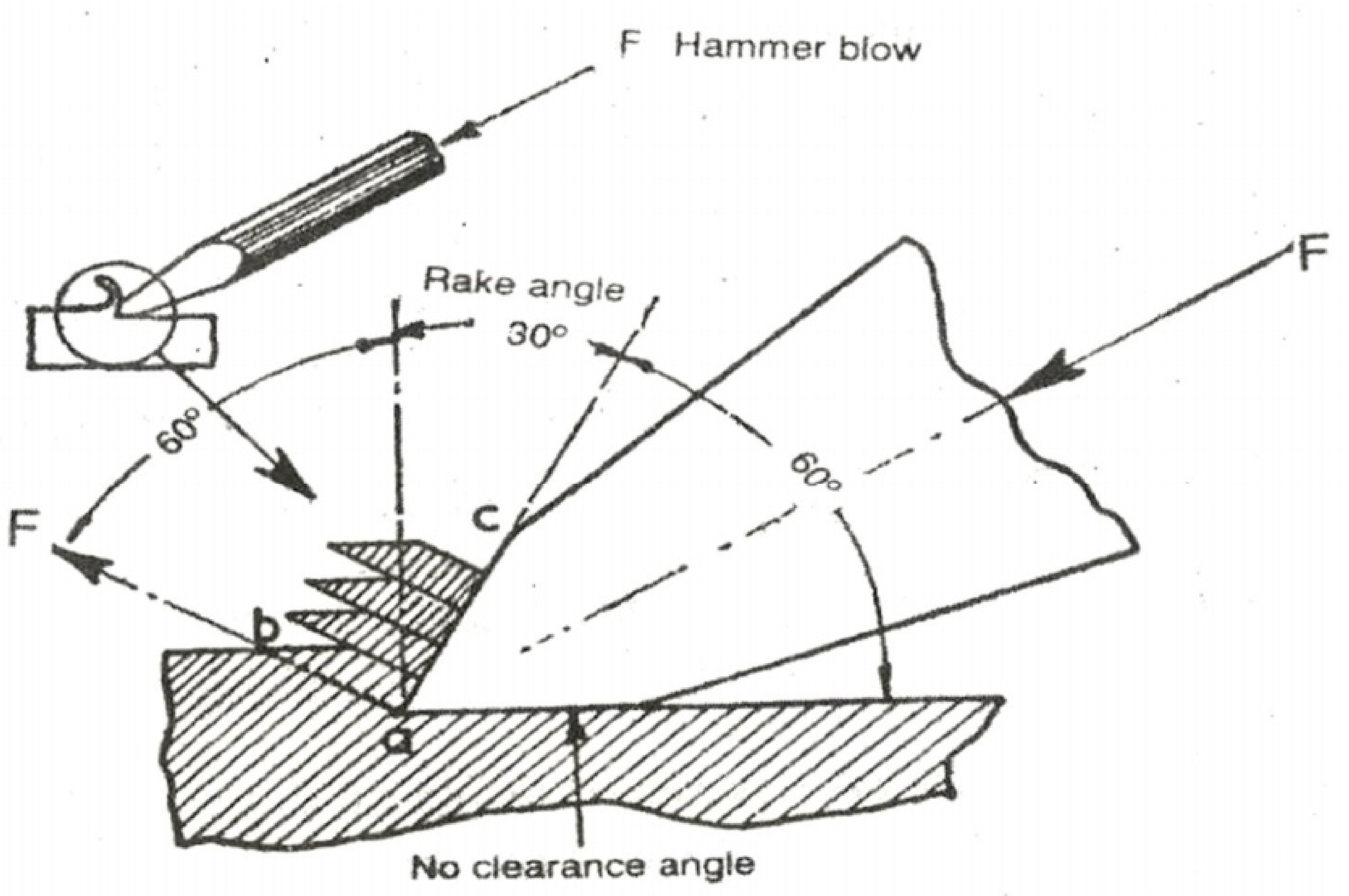


Figure Shearing action of a cold chisel

It is made of from tempered steel.

Use for cutting cold metal.

Used to remove waste metal in the situation where a smooth finish is not necessary or when other tools such as file, hacksaws cannot be used .

Hot chisel:

A hot chisel is used to cut metaln that has been heated in a force to sustain the metal.

Used to smooth the metals.

Hacksaw blade

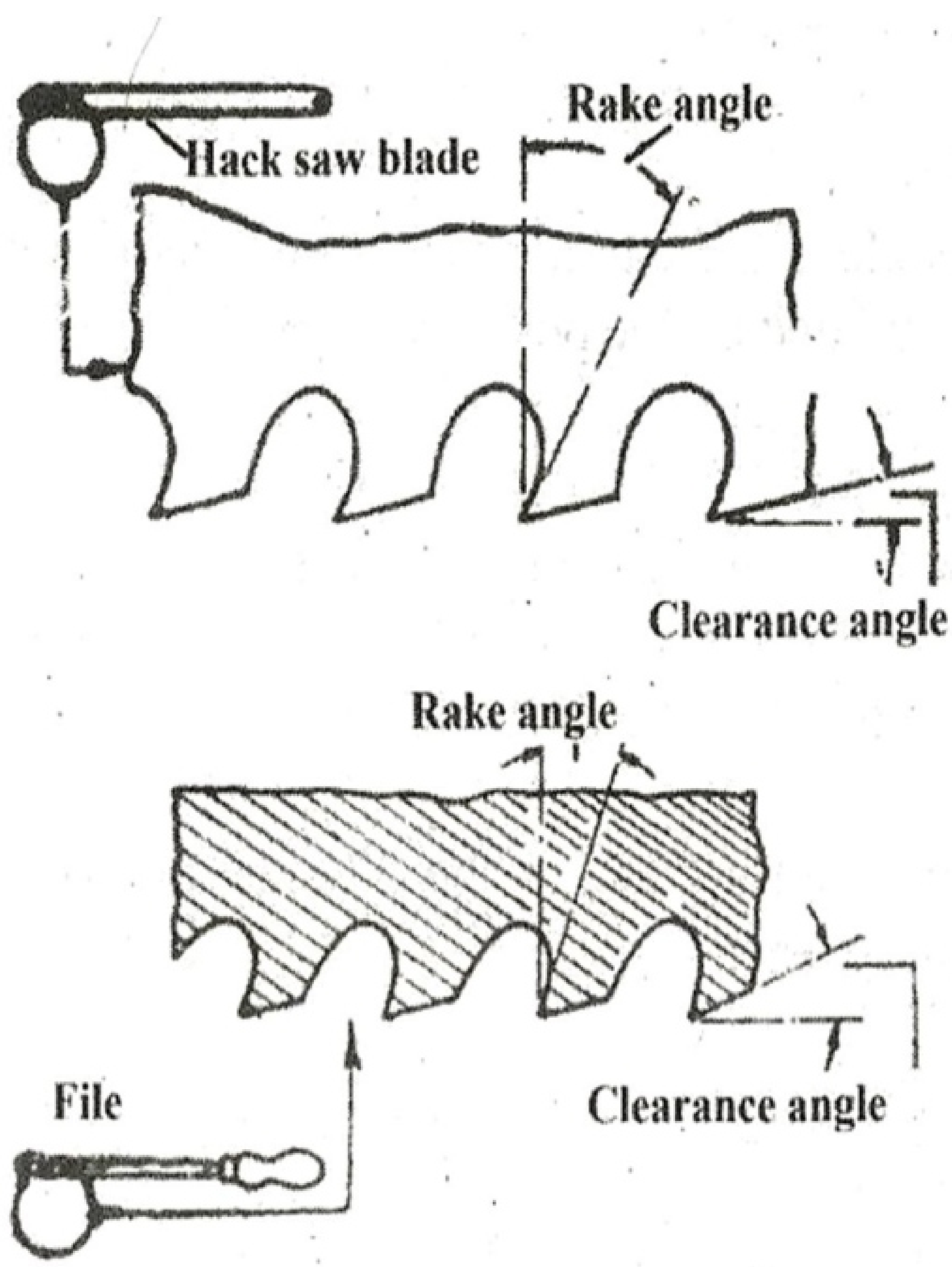


Figure Rake and clearance angles on hack saw blade and file

When attached to a C-shaped frame which holds a blade under tension.

The frames may be adjustable to accommodate blades of different sizes.

Blades are available in standardized lengths, usually 10^{11} or 12^{11} for a standard hand hack-saw.

The pitch of the teeth can be anywhere from 14 to 32 per inch for a hand blade & for large power hack saw blade there are 3 tpi

As hack-saw teeth are so small, they are set in a wave set.

As the blades are normally quite brittle, so proper care should be taken to prevent fracture of the blade.

Blades are made of carbon steel or low alloy steel.

But for several decades now, hack-saw blades have used HSS for their teeth, giving great improved cutting & tooth life.

On hack-saw the blade can be mounted with the teeth facing toward or away from the handle

Resulting and cutting action on either pushes or pull stroke.

In normal use, cutting vertically downwards with work held in a bench, vice, the saw blade Should be set to be face forward.

<u>Die</u>:

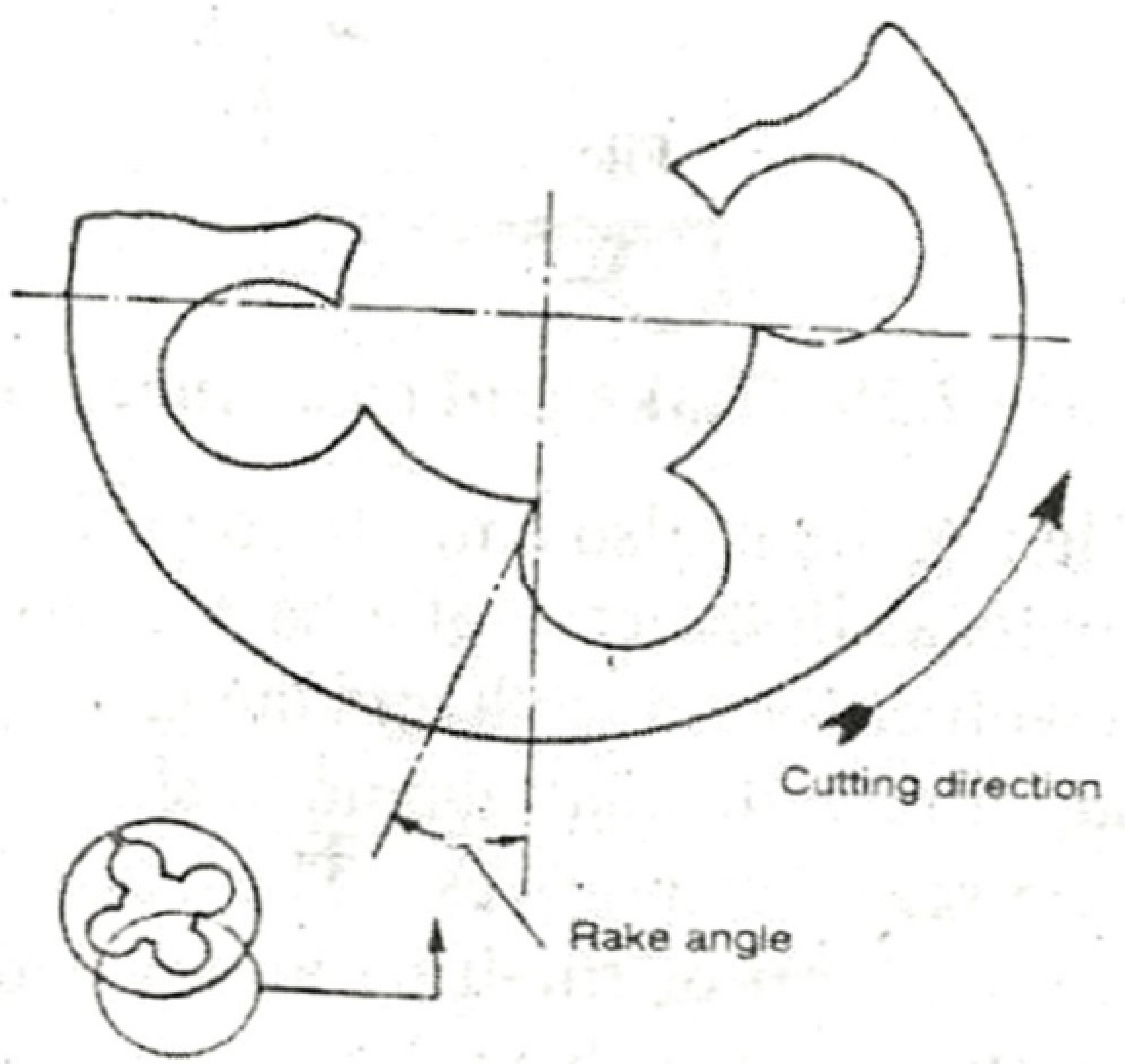


Figure Rake angle on a die

Die cutting is the posses of using die to shear weds of low strength material such as rudder, tidier, cloth, plastic, sheet metal etc.

Die cutting can be done on either flat bed or by rotary process .

Rotary dry cutting is die cutting using a cylindrical die or a rotary processes .

Dies are used to cut the external thread or the rod or pipe end .

Dies are made of high carbon steel or HSS .

The process of cutting external thread by dies is called dieing .

Sharing is also known as die cutting, is a prosses which cuts stock without formation of chips or the off during or melting.

The die cutting action can be controlled by electric, hydraulic, pressurized or manual surfaces.

Reamer:

- It is a multiple edge cutting tools.
- The process of enlarging the hole is called reaming.
  - There are many different types reamer and there may be designed for used as a hand tool oir in a M/C tool such as milling M/C or drill press.
  - A typical reamer consists of a set of parallel straight or helical cutting edge along the length of a cylindrical body
  - Each cutting edge is grounded at a slightangle and with slight under cut below the cutting edge
  - This may be used to remove small amount of material.
  - Reamers are made of high Carbon or Plain Carbon Steel

Reamers ar of two types

- Hard Reamers
- Machine Reamers

Machining Process Parameters:

Factors affecting tool life:

The life of a tool is affected by many factors such as: cutting speed, feed, depth of cut, chip thickness tool geometry, material of cutting fluid, and rigidity of the machine

Cutting Speed:

The cutting speed can be defined as the relative surface speed between the tool and the job or the amount of length that will pass the cutting edge of the tool per unit of time.

It may be defined as the speed which the cutting edge pass over the material. It is expressed in meters per min (mpm).

Feed:

It is defined as the relation by small movement per cycle of the cutting tool, relative to the workpiece in a direction which is usually to the cutting speed direction.

It is he distances the tools advances into or along the work piece. Each time the tool point passes a certain position in its travel over the surface. It is expressed as mm\tooth.

Depth of cut:

The depth of cut is the thickness of the layer of metal removed in one cut or pass, measured in a dir^n **1** to the machined surface.

It is the vertical distance the tool advances into the work piece during one revolution of job it is expressed in mm.

Selection of cutting speed, feed & depth of cut:

- Hard and strong materials require a lower cutting speed, soft & ductile material require higher cutting speeds.
- For light finishing cut – fine feed & higher speed roughing cut – low feed & lower cutting speed.
- Large depth of cut – roughing operation
- Small depth of cut – finishing operation
- Cemented carbide, ceramics, satellite &
- Hss – high cutting speed tool
- Alloy or carbon steel tools – lower cutting speed.

Coolants & lubricants:

Cutting fixed sometimes referred to at lubricants or coolants are liquids and gases applied to the tool and work piece to assist in the cutting operations.

Purpose of cutting fixed:

- To cool the tool
- To cool the work piece
- To lubricate and reduce friction
- To improve surface finish
- To protect the finished surface from corrosion
- To cause chips break up into small parts
- To wash the chips away from the tool

Properties of cutting fluids:

1. High heat absorption for readily absorbing heat developed.
2. Goo+d lubricating qualities to produce low-cofficient of friction.
3. High flash point so as to eliminate the hazard of fire
4. Stability so as not to oxide in the air
5. Neutral so as notr to react chemically
6. Colorless so as not to p[roduce any bad smell even when heated.
7. Harmless to the bearings.
8. Harmless to the skin of the operators
9. Non-corrosive to the work or the machine
10. Transparency so that the cutting action of the tool may be observed.
11. Low viscosity to permit frac flow of the liquid

1. Type of operation
2. The rate of metal removal
3. Material of the work piece
4. Material of the tool
5. Surface finish requirements
6. Cost of cutting fluid.

Type of cutting fluids:

Water:

Pure water is the best cutting fluid available because of its highest heat carrying capacity. But water corrodes the material very quickly so water containing alkali, salt or water-soluble additive but little or no oil or soap are some times used as coolant.

Soluble oils:

These are emulsions composed of around 80% or more water, soap & mineral oil. The soap acts as an emulsifying agent which breaks the oil into minute particles to dispose them throughout the water. The water increase the cooling effect and the oil provide the lubricating properties.

Straight oils:

The straight oils may be

a) Straight mineral oils, kerosene, low-viscosity petroleum fraction such as mineral seal, or higher viscosity mineral oils
b) Straight fixed or fatty oils consisting animal, vegetable or synthetic equivalent, lard oil etc.
c) They have both cooling and lubricating properties

Mixed oils:

This is a co0mbination of strength mineral and strength fatty oil. This makes oil excellent lubricant and coolant for anosmatic screw-machine work.

Chemical additive oil: straight oil or mixed oil when mixed- up with sulphur or chorine is known as chemical additive oil. Sulphur and chloral are used to increase both lubricating and cooling qualities. These oils used for machining tough, stivgy7 low carbon steels.

Chemical compounds: these compounds consists mainly of a rust inhibitor, such as sodium nitrate, mixed with a high percentage of water.

Solid lubricants: stick waxes. And bar soaps are sometimes useel as lubricants.

Metal cutting and cutting tools : in the metal working industry the various working processes fall into groups.

Not-cutting shaping – forgery, pressing, drawing

Cutting shaping – turning, dralling, milling.

Cutting tools

A cutting tool may be used either for cutting a part or for removing chips.

Cutting tools are mainly divided into two groups.

- Single point cutting tool
- Multipoint cutting tool

A single poiunt cutting tool consists of a sharpened cutting part called its point.
Ex: lathes, slotting machines

Multipoint cutting tools hame arrangement of two or more single point tools as a unit.

Ex – milling cutting, broaching tool,twist drill.

It means schematic naming of the various parts and angles of a cutting tool.

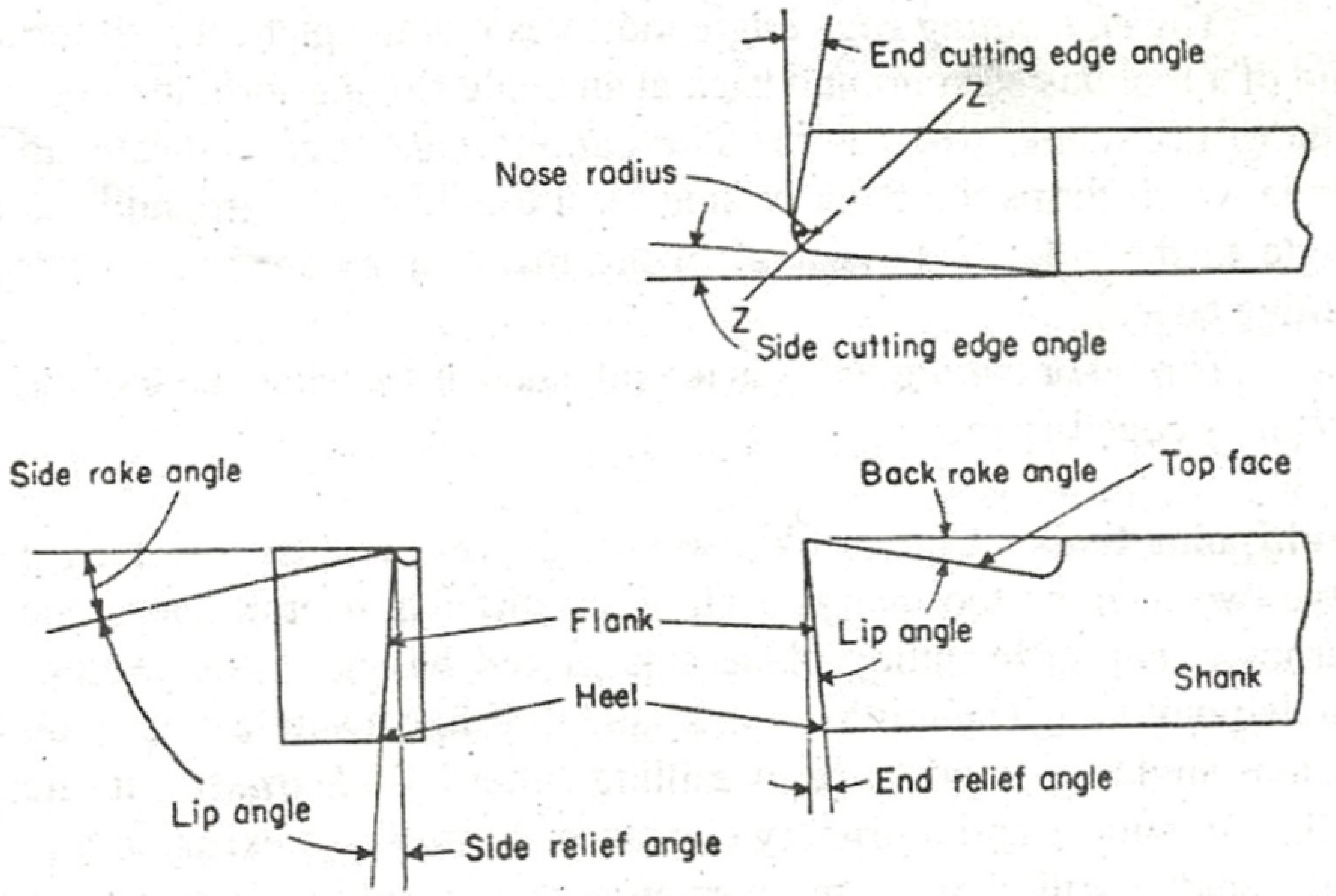


Figure **Tool nomenclature and tool angles**

Shank:

It is the main body of the tool.

Flank:

The surface or surfaces below amd adjacent to the cutting edge is called flank of the tool.

Heel:

It is the intersectuion of the flank and the base of the tool.

Nose:

It is the point where the side cutting edge and end cutting edge intersection.

Cutting edge :

It is the edge on the face of the tool which removes the metarial from the work piece. The total cutting edge consists edge (major), end cutting edge (minor) and the nose.

Face:

The surface against which the chip slides upward.

Base:

Tt is the undersice of the shank.

Rake:

It is the slope of the tap away from the cutting edge. Larger the rake angle, the cutting force and power reduce.

Designation of cutting tools: there are two system to designate the tool shape

1. **American standards assouiation system** (AsA)

Or

American national standards institute (ANSI)

2. **Orthogonal rake system**. (ORS)

The various tool angles are:

1. **Side cutting edge angle (Cs): (Lead angle)**

The angle between the side cutting edge and side of the tool shank

2. **End cutting edge angle (Ce):**

This is the angle between the end cutting edge and a line normal to the tool shank

Side relief angle:

It is the anglew between the portion of the side flank immediately below the side cutting edge and a line perpendicular top the base of the tool measured at right angle to the side flank.

End relief angle

It is the anglew between the portion of the end flank immediately below the side cutting edge and a line perpendicular to the base of the tool measured at right angle to the end flank.

Back rake angle:

It is the angle between the face of the tool and s line parallel tio the base of the tool and measured in a plane perpendicular to the side of the cutting edge. The angle is +ve – If side cutting edge slopes downwards from the point towards the shank.

-ve – if the slope of the side cutting edge is reverse.

Side rake angle :

It is the angle between the tool faxce and a lione parallel to the base of the tool and measaured in a planer perpendicular to the basr and side cutting edge. This angle gives slope of the face of the tpol from the cutting edge.

The angle is – ve – if the slope is towards the cutting edge

+ve - If the slope is away from the cutting edge

Chapter-3

Lathe Machine

Syllabus:

3.0 Lathe Machine
3.1 Construction and working of lathe Major components□ of a lathe and their function
Operations carried□ out in a lathe (Turning, thread cutting, taper turning, internal machining, parting off, facing, knurling)
Safety measures□ during machining
3.2 Capstan lathe
Difference with□ respect to engine lathe
Major components□ and their function
Define multiple□ tool holders
3.3 Turret Lathe
Difference with□ respect to capstan lathe
Major components□ and their function
3.6 Draw the tooling lay out for preparation of a hexagonal bolt & bush

Lathe machine:

The lathe machine is the one of the oldest machine tools and came the early tree lathe which was a device for rotating and machining a piece of lathe between two adjacent trees.a rope iwould round the work with its one end attached to a flexible branch of trees and end is pulled by a man to rotate the job hard tools are used them.

Function of lathe machine:

The main function of lathe machine is to remove metal from apiece of work to give it the required shape and size. the work is held securely and rigidly on the machine and then turn against the cutting tools which is remove metal from the work in the forms of chips.

Types of lathe:

- **speed lathe:**
  - **Wood working**
  - **Centering**
  - **Polishing**
  - **Spinning**
- **Engine lathe:**
  - **belt drive**
  - **Individual motor drive**
  - **Gear head lathe**
- **Bench lathe:**
- **Tool room lathe**
- **Caps & tureet lathe**
- **Special purpose:**
  - **Wheel lathe**
  - **Gap bed lathe**
  - **Turrete lathe**
  - **Duplicating lathe**
- **Automatic lathe:**

The speed lathe:

- It is the simplest of all types of lathe.
- It consists of a bed, headstock, a tailstock and a too post mounted on an adjusted slide.
- There is a no feed box , lead screw or conventional type carriage.
- The tool is mounted on the adjustable slide and is fed into work purely by hard control.
- Spindle speed is very high.(range from 1200 to 3600 rpm).
- This is used for word working, spinning, centering, polishing.

The engine lathe or centre lathe:

- The engine lathe in the early ware driven by steam engines
- It consists of bed, head stork, and tail stork.
- More robust head stock and contains mechanism for driving the spindle at multiple speeds.
- Belt driving lathe – receives power from an overhead live shaft
- Individual motor drive- receiving power from an individual motor
- Gear head lathe –gets power from a constant speed motor.

The bench lathe:

- The small lathe mounted on a bench
- It consists of all the parts but small in size.
- It is used for small & precision work.

The tool room lathe:

- It is similar to engine lathe.
- It has spindle speeds ranging from very low to high upto 2500 rpm.
- It consists of chuck, taper turning attachment, thread charing dial, steady rest, coolant etc.
- This is used for precision work on tools, dies, gasges & for accuracy works

multiple tools are fitted

- Several operations can be done on a work piece with out resetting of work or tools & a no. of identical parts can be produced in minimum time.

Special propose lathe:

- They are used for special proposes.
- The Wheel lathe – for finishing journals &turning the thread on rail road car and locomotive wheels gap bed lathe- to swing extra large diameter pieces.
- T-lathe – for machining of motor for jet engines the axis of the lathe bed is right angles to the axis of the head store spade.
- Duplicating lathe – for duplicating the shape of a flat or round template on the work piece

Automatic lathe:

- These are high speed, heavy duty, mass production lathes with complete automatic control.
- After the tools are set and the machine is started is performs automatically all the operations to finish the job.
- The changing of tools, speed s and feeds are done automatically.
- After the job is complete, the machine will continue to repeat the cycles producing identical parts.

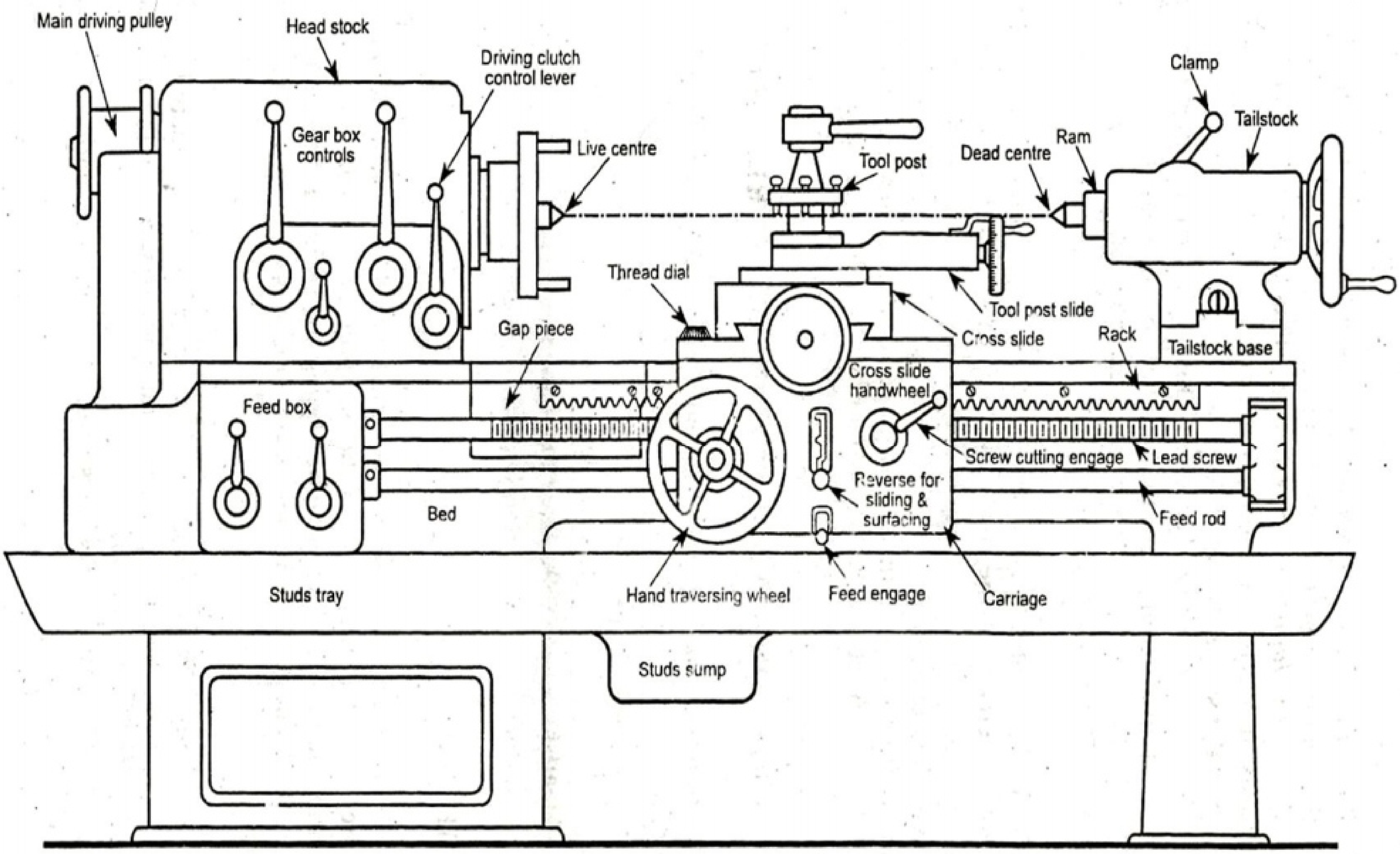


Figure 3.2 Lathe parts

1. **Bed**
2. **Head stock**
3. **Tail stock**
4. **Carriage**
5. **Feed mechanism**
6. **Screw cutting mechanism**

BED:

The bed is the base or foundation of the lathe. It is made of cast iron. It is a massive and rigid casting made in one piece to resist deflection and vibrations. It supports the head stock, tail stock and carriage. On the top of the bed, there are two sets of slides or guide ways. The outer ways for carriage and inner ways for the tail stock. The guide ways may be flat and inverted –v having included angle of 90^0

Head stock:

The head stock assembly is permanently fastened to the left hand end of the lathe. It provides mechanical means of rotating the work at multiple speeds.

The spindle of head stock is made of carbon or nickel chrome steel. It protrudes from gear box and contains means for fast ending work holding derives like chuck, face plate, dog plats, live centred spindle nose is turned so that face plate or chuck can be mounted on it hold and rotate the work piece. Hollow spindle is tapered at the nose to receive the live centre.

Tail stock or loose head stock:

The tail stock is located at on the inner ways at the right hand end of the bed and it is a non-rotating part which slides and can be clamped to it. Any position to accommodate different lengths of work pieces.

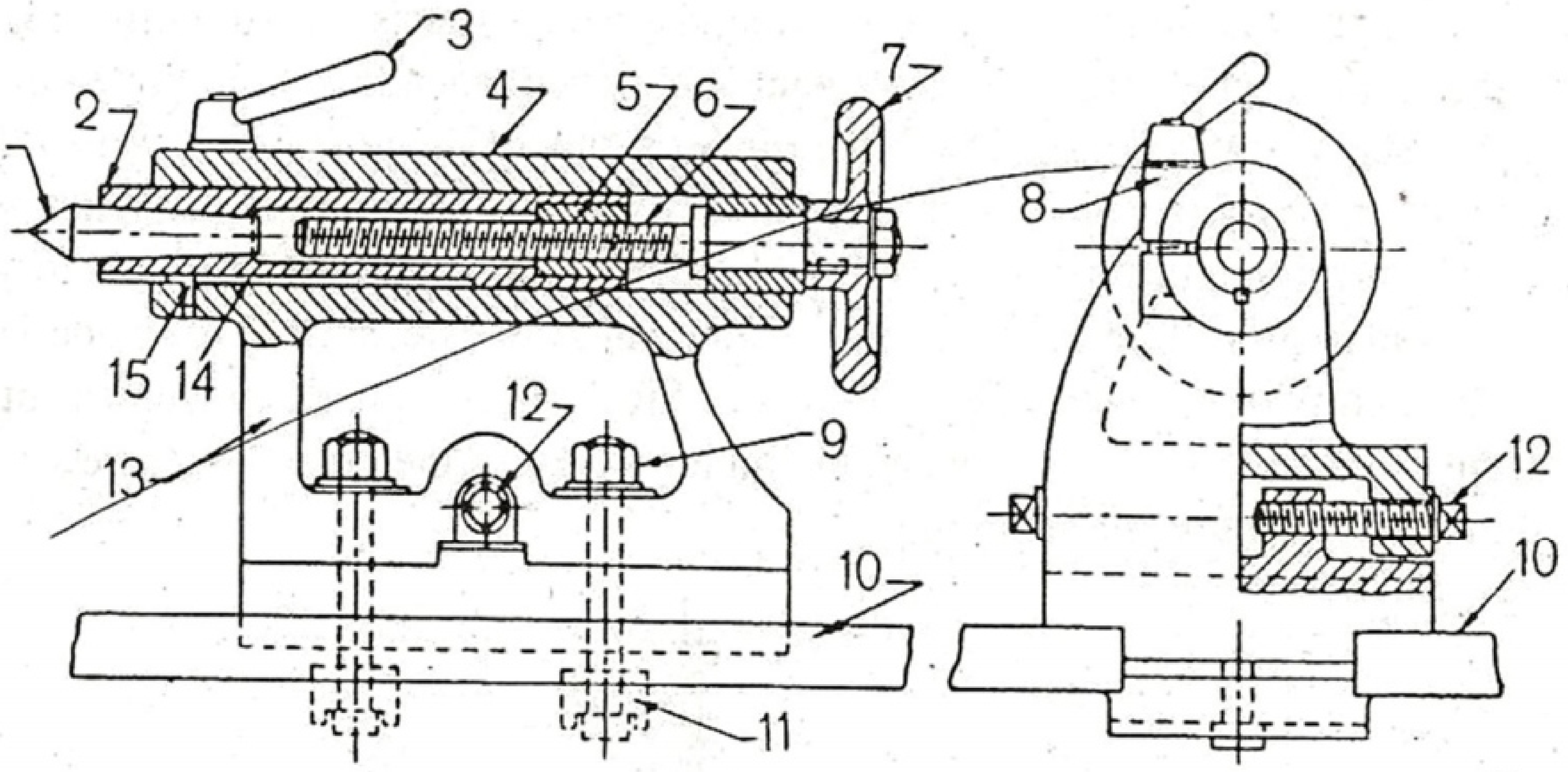


Figure Tailstock

1. Dead centre, 2. Spindle, 3. Spindle clamp, 4. Barrel, 5. Bush, 6. Square threaded screw, 7. Hand wheel, 8. Split lug, 9, Tailstock clamping bolt, 10. Lathe bedways, 11. Clamping plate, 12. Setover screw, 13. Body, 14. Keyway, 15. Key.

It has two uses:

1. Supports the other end of the work when it is machined between two centres.
2. To hold a tool for per forming operations such as drilling, reaming, tapping etc.

CARRIAGE:

In between the head stock and tail stock is the carriage. It is movable on the bed ways and its purpose is to hold the cutting tool and to impart to it either longitudinal or cross feed. It consists of the following parts:

1. **Saddle:**

   It is an H-shaped cashing that fits over the outer ways of the bed. It carries the corss-slide and tool post.

2. **Cross slide:**

   It is mounted on saddle. It provides cutting tool motion which is to the centre like of the lathe. This is known as cross slide can be moxed by means of feed screw, which is controlled by a small hand wheel or by power feed.

3. **Compound rest:**

   It is monted on the top of the cross slide. It supports the tool post. It has a graduated base and can be surivelled around a vertical axis. It can be swivelled around a vertical axis. It can be moved by means of a screw which is contoolled by a small hand wheel and graduated dia & not by power feed.

4. **Tool post:**

   It is mounted onthe top of the compound rest to hold the tool. The tool post can be moved on the compound rest and can be clamped in any position. It can be rotate also to hold the cutter in desired angle.1. single tool post 2. Four bolt 3. Open side 4. Four way

Lathe operation:

Lathe operations are performed by following methods.

Operations which are performed in a lathe either by holding the work piece between centers or by a chuck:

1. **Straight turning**
2. **Shoulder turning**
3. **Chamfering**
4. **Thread cutting**
5. **Facing**
6. **Knurling**
7. **Filling**
8. **Taper turning**
9. **Eccentric turning**
10. **Polishing**
11. **Grooving**
12. **Spinning**
13. **Spring winding**
14. **Forming**

, using a torved gauge the do is given by compound slide and the to read is finished in the usual manner.

Safety measures during machining:

Some safety precautions should be needed while working on lathe.

- Before operating the machine ,one should fully understand its operations controls and how to stop it .
- All gears and gear ends of the lathe should be properly guarded .
- Safety goggles are preferred to avoid damage to eyes by flying chips.
- Avoid wearing rings, bracelet or watch.
- Machine should not be left running and opperater should be alert during a job.
- Before starting a lathe spindle by power , spindle should be rotated by one revolution by hand to make it sure that no fouling is there.
- Safe distance from revolving chuck should be maintained.
- Tools and instruments should not be placed over lathe bed.
- Sliding parts of the lathe should be cleaned and lubricated periodically.
- Chips should never be removed by hand. It can be removed by brush.
- Before starting the machine, the work should be clamped properly.
- Before moving the carriage, the carriage clamping screw should be unlocked.
- On hearing unusual noise, machine should be stopped immediately and should not be operated till the fault is clear.

Capstan & Turret lathes:

A capstan or a turret lathe is a production lathe used to manufacture any number of identical pieces in the minimum time. The main feature is the six sided block mounted on one end of the bed replacing the normal tailstock six tools can be mounted at on cross slide two tool posts are mounted, one in the font and the other in the rear. Each one can hold four tools .Thus the total carrying capacity is a maximum 14 tools

Difference between CAPSTAN &TURRET and an ENGINE LATHE

CAPSTAN &TURRET	ENGINE LATHE
1. The head stock possesses wider range of speeds and in heavier in construction it require 15 hp power to drive the spindle.	1. It requires 3hp to drive the spindle.
2. The tool post mounted or the cross slide is a four way & a rear tool post is mounted on the rear side which also holds 4 tools.	2. In engine lathe one tool can be mounted at one time for different operation.
3. In turret lathe, the tail stock is replaced by a turrt which is a hexagonal block which contains 6 tools on each face.	3. It can accommodate one tool of limited size.
4. The feed movement of each tool set on square or hexagonal turret is regularity by stops & feed strips.	4. The feed movement is given by hand.
5. Combination cuts can be taken by mountiy two or more tools on the same face of the turret.	5. Combination cuts can not be done.
6. The labour cost is less.	6. Ladour cost is more.

7. The threads are cut by dieheads & taps.	7. The threads are cut by lead screws Centre lathe is suitable for odd jobs having different shapes & sizes.
8. Turret lathes are suitrable for producing large no. Of identical pieces.	8. The threads are cut by lead screws.

Difference between capstan & turret lathe:

Capstan lathe	Turret lathe
1. Its turret head is mounted in slide, which moves on the guide ways produced on the saddle. 2. For feeding the tool to the work, the saddle is fixed at convenient distance from the work. 3. It is suitable for smaller size & lighter jobs. It is not suitable for heavy cutting condition. 4. It is suitable to work for smaller bar upto 60 mm dia. 5. The turret head may hexagonal or circular. 6. It is smaller in size compound to turret lathe. 7. The tool traverse is faster and offer less fatigue to the hands of the operator.	1. Its turret to head is mounted directly on the saddle. 2. For feeding the tool to the work, the entire saddle unit is moved. 3. It is suitable for long and heavy work and severe cutting condition.\ 4. It is used to work for large size bar upto 200mm dia. 5. Turret head is hexagonal. 6. It is large in size as compared to capstan lathe. 7. The tool feeding is relatively slower and provide more fatigue to operator hands.

Parts of capstan and turret lathe:

Bed:

The bed is longer box like casing provided with accurate guide ways on which the carriage and turret slid are mounted. It is designed to ensure strength, rigidity and permanency of alignment under heavy duty services.

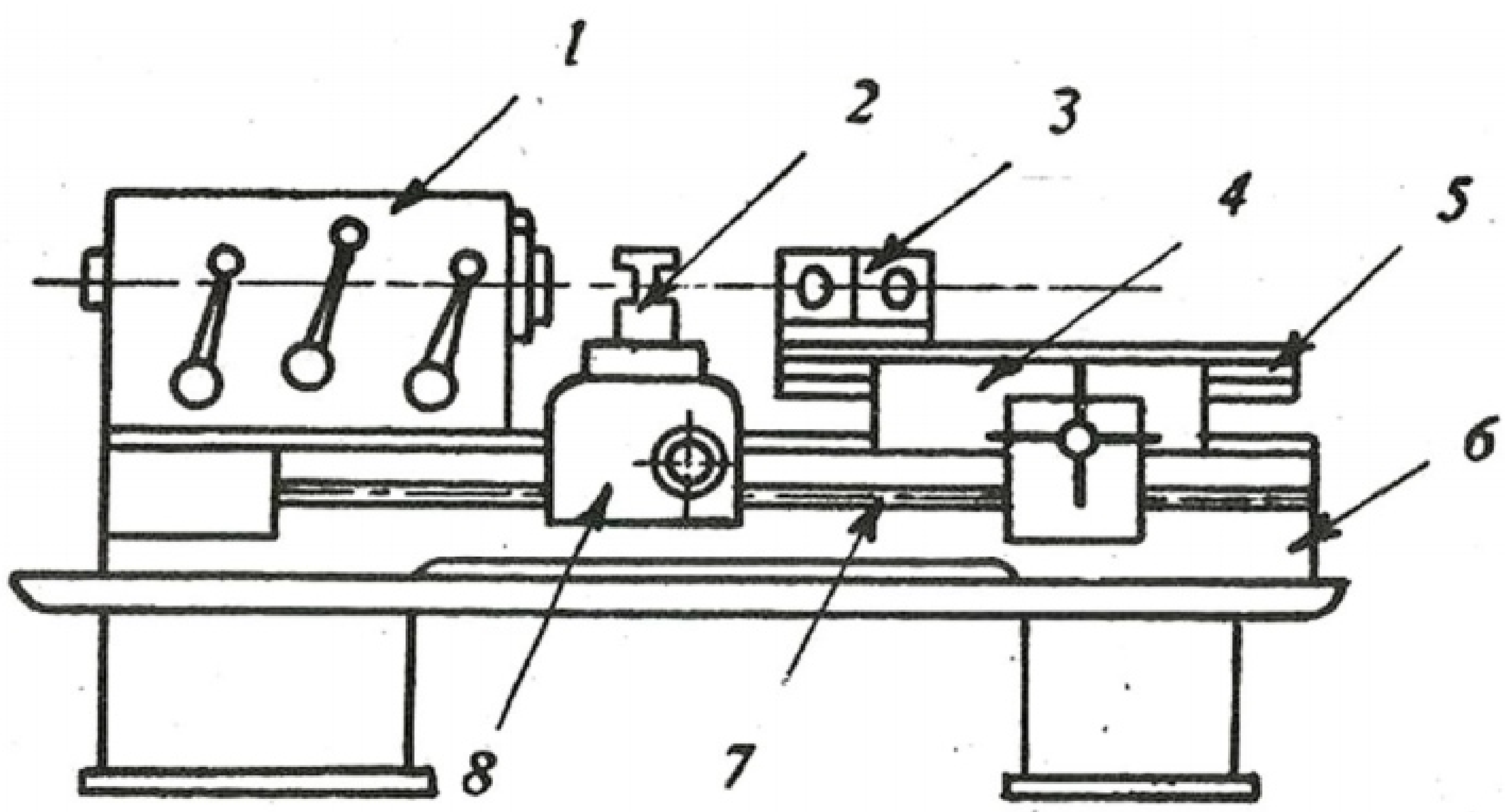


Figure 4.3 Capstan lathe parts

1. Headstock, 2. Cross-slide toolpost, 3. Hexagonal turret, 4. Saddle for auxiliary slide, 5. Auxiliary slide, 6. Lathe bed, 7. Feed rod, 8. Saddle for cross-slide.

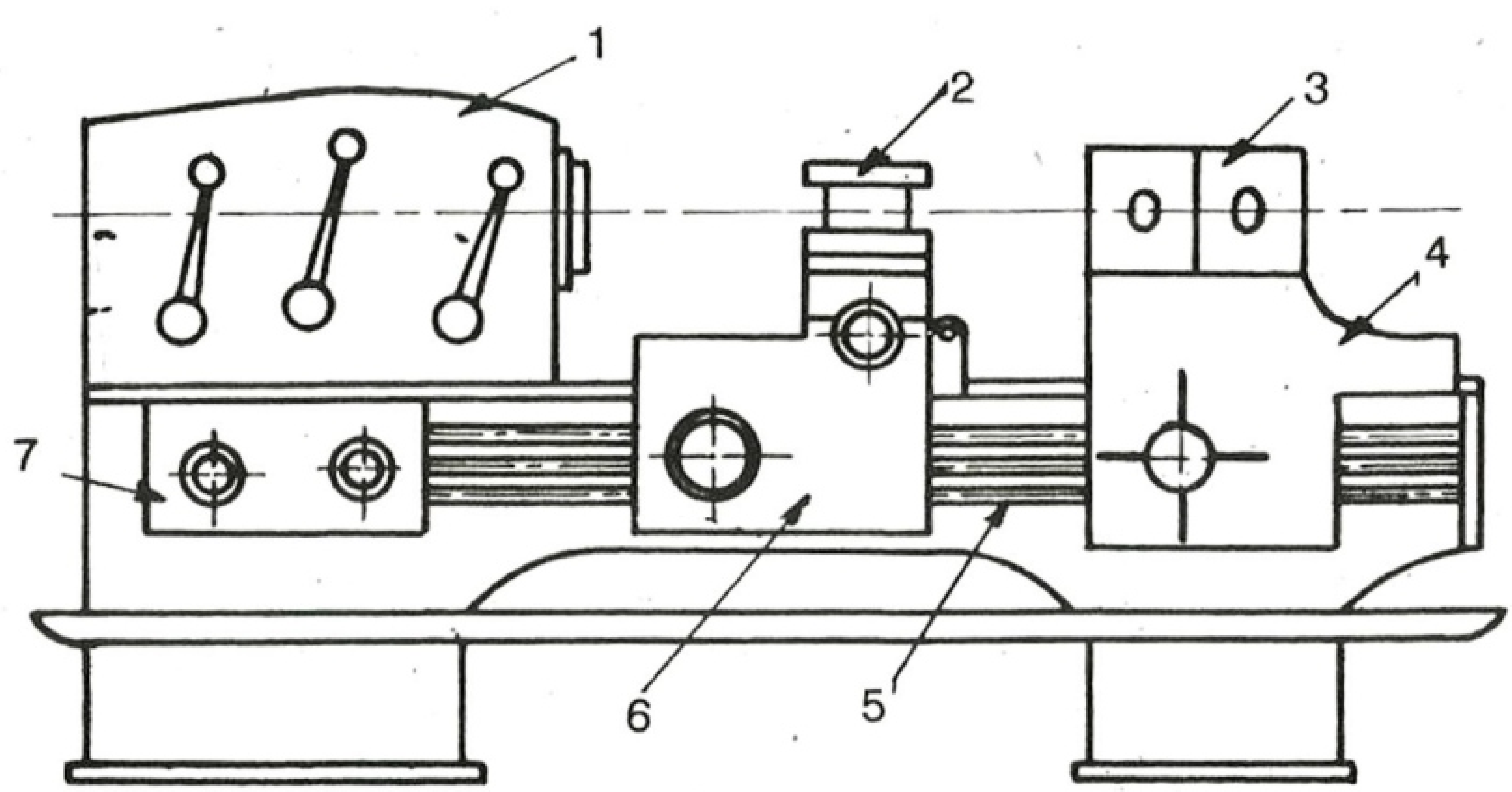


Figure 4.4 Turret lathe parts

1. Headstock, 2. Cross-slide toolpost, 3. Hexagonal turret, 4. Turret saddle, 5. Feed rod, 6. Saddle for cross-slide.

Headstock:

It is similar to engine lathe in construction . It is larger & heavier in construction and wider range of speeds speed may rang form 30 to 2000rpm two types of headstocks .

a) Electric head - variable speed motor is maunted .
b) All geared heads - wider range of speeds

The spindle is hollow and bar stock can be fed thorough a colletr chuck .

Gross slide & saddle:

There are two types of slides used in turret lathe

- Conventional type
- Slide hunk type

The conventional type of carriage bridge the gsp between the front and rear bed wage

The slide hunk type carriage is generally fitted with heavy duty turret lathe. Large diameter of work pieces can be swing over bed. The longitudinal movement of each tool may be regulated by using stop bars or shafts set against the stop fitted on the bed and carriage. The stops are set so the each tool will feed into the work to desired length the stop bars are indexed by hand

The turret saddle and auxiliary slide :-

The turret saddle bridges the gap between two bed ways. The hexagonal turret is mounted o9n the auxiliary slide. In turret lathe, the turret is directly mounted on the top of the saddle.

The turret is a hexagonal shaped tool harder intended for six or more tools. The centre line of each hole is coincides with the axis of the lathe. Six stop bars are mounted on the saddle which restricts the movement of each tool mounted on each face of turret to be fed predetermined amount. After one operation the turret is brought backward from the spindle nose the turret indexes automatically.

Capstan and turret lathe mechanism:-

Turret head indexing mechanism:-

This is an inverted plan of turret assembly. The turret is mounted on the spindle. The index plate , the, bevel gear and an indexing ratchet are keyed to the spindle. The plunger fitted within the housing and mounted on the saddle locks the index plate by spring pressure and prevents any rotary movement of the turret as the tool feeds into the work.

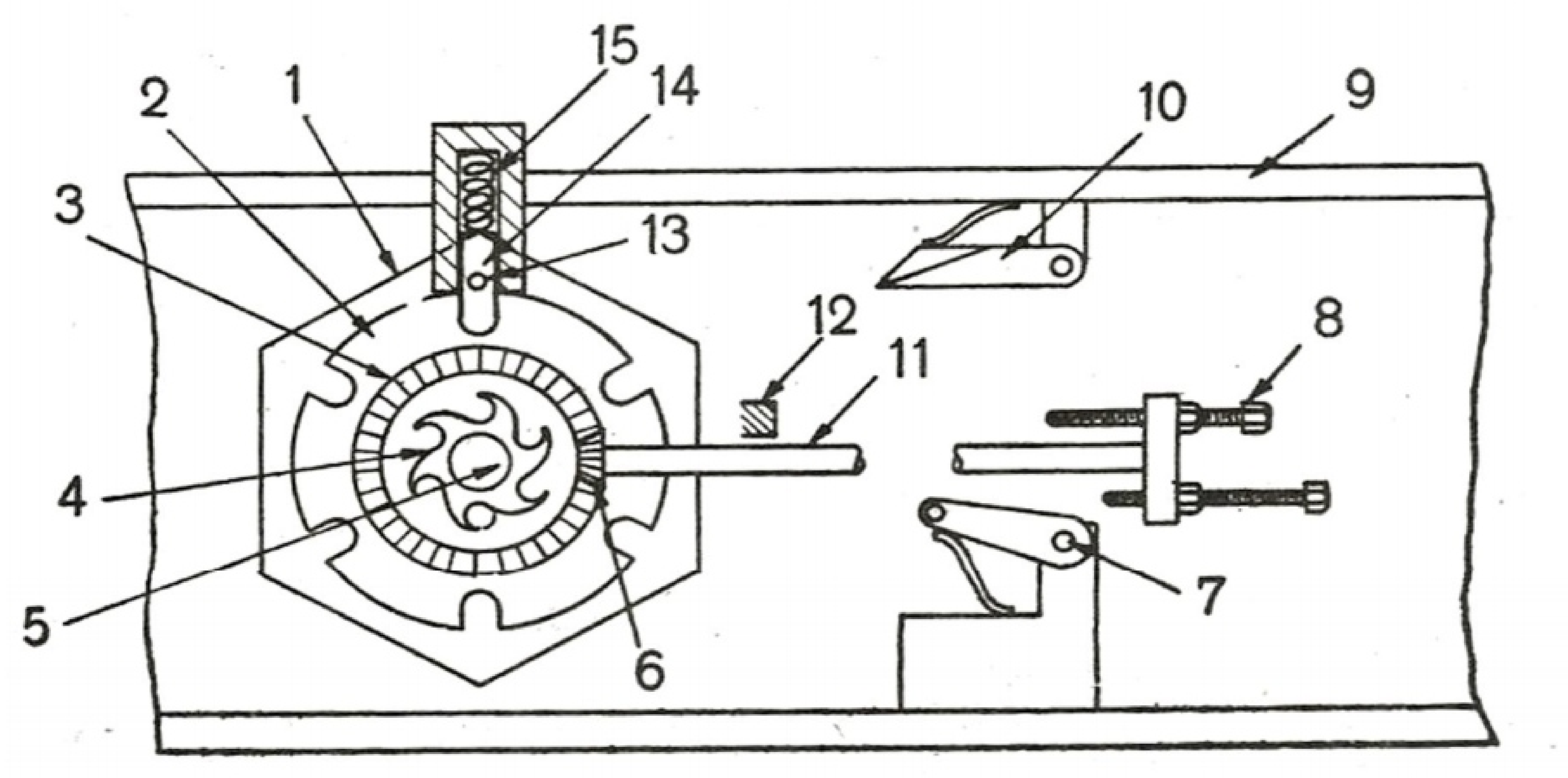


Figure 4.5 Turret indexing mechanism

1. Hexagonal turret, 2. Index plate, 3. Beveled gear, 4. Indexing ratchet, 5. Turret spindle, 6. Beveled pinion, 7. Indexing pawl, 8. Screw stop rods, 9. Lathe bed, 10. Plunger actuating cam, 11. Pinion shaft, 12. Stop, 13. Plunger pin, 14. Plunger, 15. Plunger spring.

A pin is fitted on the plunger projects out of the housing. An actuating cam and the indexing pawl are attached to the lathe bed at desired positions. Both the cam and the pawl are spring loaded. As the turret reaches the backward position , the attaching cam lifts the plunger out of the groove in the index plate due to the riding of the pin on the bevelled surface of the cam and thus unlocks the index plate.

The spring loaded pawl which by this time engages with a groove of ratchet plate, causes the ratchet to rotate as the turret head moves backward.

When the index plate or turret rotates through one sixth of revolution , the pin and the plunger drops out of the cam and the plunger locks the index plate at the next groove.

The turret is thus indexed by one sixth of revolutions and again backed into the next position automatically. The turret holds the next tool is now fed forward and the pawl is released from the ratchet plate by the spring pressure.

The bevel opinion meshes with the bevel gear mounted on the turret spindle. The extension of the pinion shaft carries a plate holding six adjustable stop rods. As the turret rotates through one sixth of the revolution , the bevel gear causes the plate to rotate.

The ratio of the teeth between the pinion and the gear are so chosen that when the tool mounted on the face of the turret is indexed to bring it to the cutting position, the particular stop rod for controlling the longitudinal travelling of the tool is aligned with the stop.

The setting of the stop rods for limiting the feed of each operation may be adjusted by unscrewing the lock nuts and rotating the stop rods on the plate. Thus, six stop rods may be adjusted for controlling the longitudinal travel of tools mounted on six faces of the turret.

Bar feeding mechanism:-

On the capstan and turret lathes , some arrangements is need to be feed the bar stock through the collet or chuck after each finished work piece is parted off. Bar may be fed by hand also but has a safety measure one has to stop the machines first for every feeding of bar. It also wastes lot of time.

Chapter-4

Shaper

Syllabus:

4.1 Potential application areas of a shaper machine
4.2 Major components and their function
4.3 Explain the automatic table feed mechanism
4.4 Explain the construction & working of tool head
4.5 Explain the quick return mechanism through sketch
4.6 State the specification of a shaping machine.

Shaper:-

The shaper is a reciprocating type of machine tool intended to produce flat surfaces. The surface nay be horizontal, vertical or inclined

Working principle:-

The job is fixed rigidly in a suitable vice or directly clamped on the machine table. The tool is held in the tool post mounted on the ram of the machine. This ram reciprocates to and fro , and in doing so , makes the tool to cut the material in the forward stroke. No cutting takes place during the return stroke of the ram. It is called idle stroke. The job is given an intended feed, in a direction normal to the line of action of the cutting tool.

Types of shapers:-

1. According to the type of mechanism used for giving reciprocating motion to the ram.
   a. Crank type
   b. Geared type
   c. Hydraulic type
2. According to the position and travel of ram .
   a. Horizontal type
   b. Vertical type
   c. Travelling head type
3. According to the type of design of the table
   a. Standard shaper
   b. Universal shaper
4. According to the type of cutting stroke
   a. Push type
   b. Draw type

Specification of shaper:-

1. Maximum length of stroke(175-900mm)
2. Maximum horizontal travel of table
3. Maximum vertical travel of table
4. Maximum distance from table to ram
5. Tool box, vertical adjustment
6. Length and width of the table
7. Numbers and range speeds available
8. Numbers and range feeds available
9. Horse power and speed of driving motor
10. Weight of the machine and floor space required

DIFFERENT PARTS OF A SHAPER:-

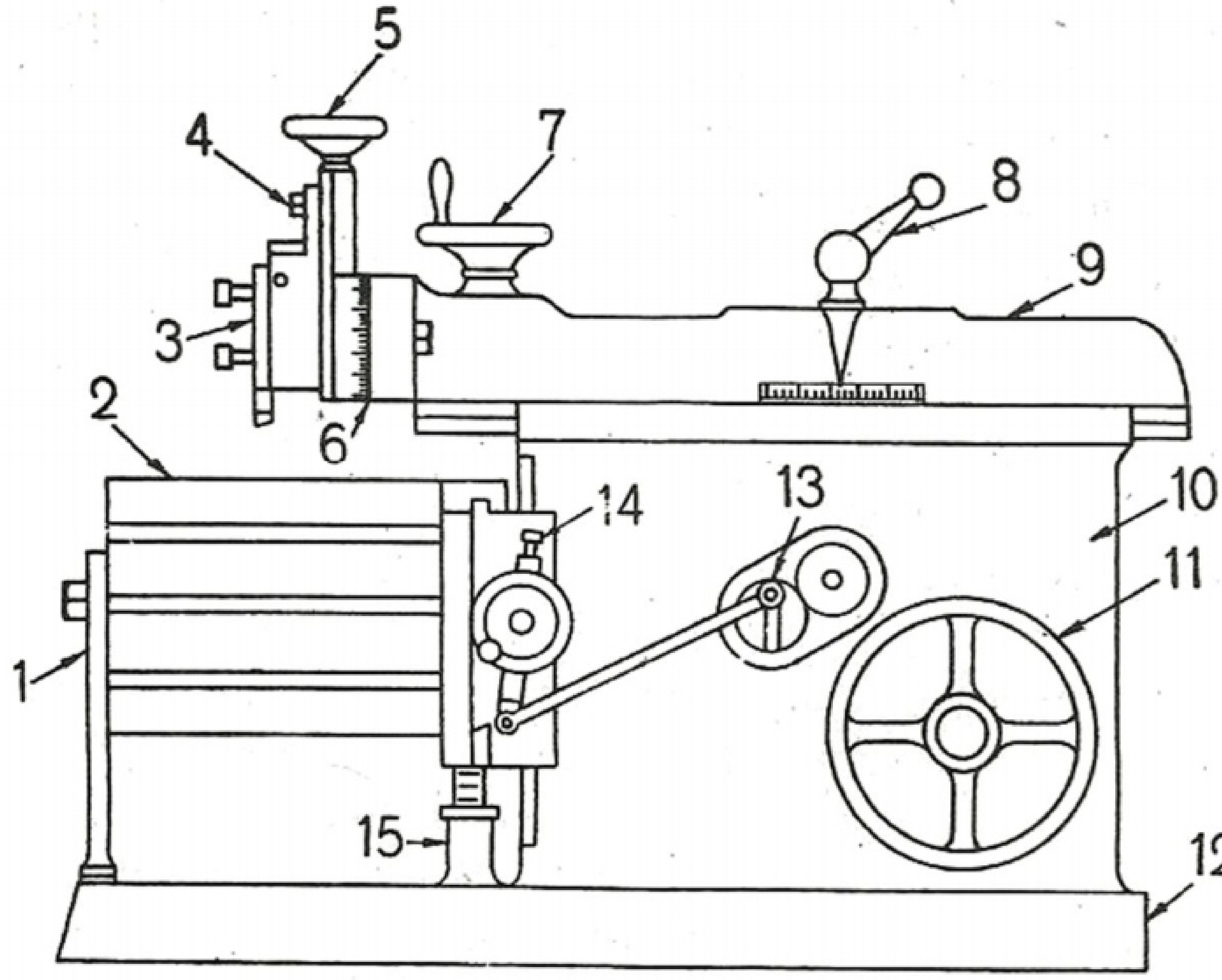


Figure 7.1 Parts of a standard shaper
1. Table support, 2. Table, 3. Clapper box, 4. Apron clamping bolts, 5. Downfeed hand wheel, 6. Swivel base degree graduations, 7. Position of stroke adjustment handwheel, 8. Ram block locking handle, 9. Ram, 10. Column, 11. Driving pulley, 12. Base, 13. Feed disc, 14. Pawl mechanism, 15. Elevating screw.

BASE:-

The base provides stability for the shaper as it supports all other equipments present as well as absorb the forces coming due to the cutting . it is made of cast iron and have a necessary arrangements of bolts so that it can be bolted to the factory floor.

Column(housing):-

The column of the shaper is a hollow casting and is mounted on the base. It houses the ram driving mechanism. For the ram and table, on the top of the column, necessary guide ways are provided for the linear movement of the ram and the front vertical face is for cross rail.

Cross rail:-

The cross rail is mounted on the front vertical guideways of the column. It has two parallel guide ways on its top vertical plane that are perpendicular to the ram axis. The table may be raised or lowered to accommodate different sizes of job by rotating elevating screw.

Saddle:-

The saddle is mounted on the cross rail which holds the table . on its top crosswise movement of the table is powered by rotating cross feed screw.

Table:-

The work table of a shaper is fastened to the front of the column. The table is provided T-slots for mounting the work pieces. The table can be moved up and down and crosswise by cross rail and saddle. Jobs can be held by vice.

Ram:-

The ram is a reciprocating member of the shaper. It is semicylindrical in form and heavily ribbed inside to make more rigid. It slides on the guideways of the column. A single point cutting tool is fastened in the tool post.

Tool head:-

The single point cutting tool is held in the tool post. The tool head holds the tool provides vertical and angular feed movement and allows the tool to have an automatic relief during return stroke. The vertical side of the tool head has a swivel base which is held on a circular seat on the room.

The swivel base is graduated in degrees so that the vertical slide may be set perpendicular to the work surface at any desired angle. By rotating the down feed screw handle, the vertical slide carrying the tool executes down feed or angular feed movement while machining vertical or angular surface.

The amount of feed or depth of cut may be adjusted by a micrometer dial on the top of the down feed screw. Apron consisting of clapper box, clapper block and tool post is clamped upon the vertical slide by a screw. By releasing the clamping screw , the apron may be swivelled upon the apron swivel pin either towards left or towards right w.r.t the vertical slide. This arrangements is necessary to provide relief to the tool while making vertical or angular cuts.

The two vertical walls on the apron called clapper box houses the clapper block which is connected to it by means of a hinge pin. The tool post is mounted upon the clapper block.

On the forward cutting stroke the clapper block fits securely to the clapper box to make a rigid tool support on the return stroke a slight frictional drag of the tool on the work lifts the block out of the clapper box a sufficient amount preventing the tool cutting edge from dragging and consequent wear. The work surface is also prevented from any damage due to dragging.

Shaper mechanism:-

The metal is removed in the forward cutting stroke, while the return stroke no matal is removed during this period.

To reduce the total machining time it is necessary to reduce time taken by the return stroke. The shaper mechanism should be so designed that it can allow the ram holding the tool to move at comparatively slower speed during the forward cutting stroke and during the return stroke the ram move faster rate to reduce the idle return time. The mechanism is called quick return mechanism.

1. **Crank and slotted mechanism**
2. **Whitworth quick return mechanism**
3. **Hydraulic shaper mechanism**

Crank and slotted link mechanism:-

The motion or power is transmitted to the bull gear through a pinion which receives is motion from an individual motor or overhead line shaft through speed control mechanism. Speed can be changed by shifting gears.

A radial slide is bolted to the centre of the bull gear , carries a sliding block into which the crank pin is fitted . rotation of the bull gear causes the clapper block and tool post is clamped upon the vertical slide by a screw. By releasing the clamping screw , the apron may be swivelled upon the apron swivel pin either towards left or towards right w.r.t the vertical slide. This arrangements is necessary to provide relief to the tool while making vertical or angular cuts.

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A radial slide is bolted to the centre of the bull gear , carries a sliding block into which the crank pin is fitted . rotation of the bull gear causes the crank pin to rotate at a uniform speed. Sliding block which is invented on the crank pin is fitted within the slotted link. The slotted link is pivoted at its bottom end attached to the frame of the column. The upper end is forked and connected to the ram block by a pin.

As bull gear rotates causes the crank pin to rotate, the sliding block fastened to the crank pin will rotate on the crank pin circle, and at same time will move up and down in the slot giving a rocking movement which is communicated to the ram. The rotary motion of the bull gear converted to reciprocating movement of the ram.

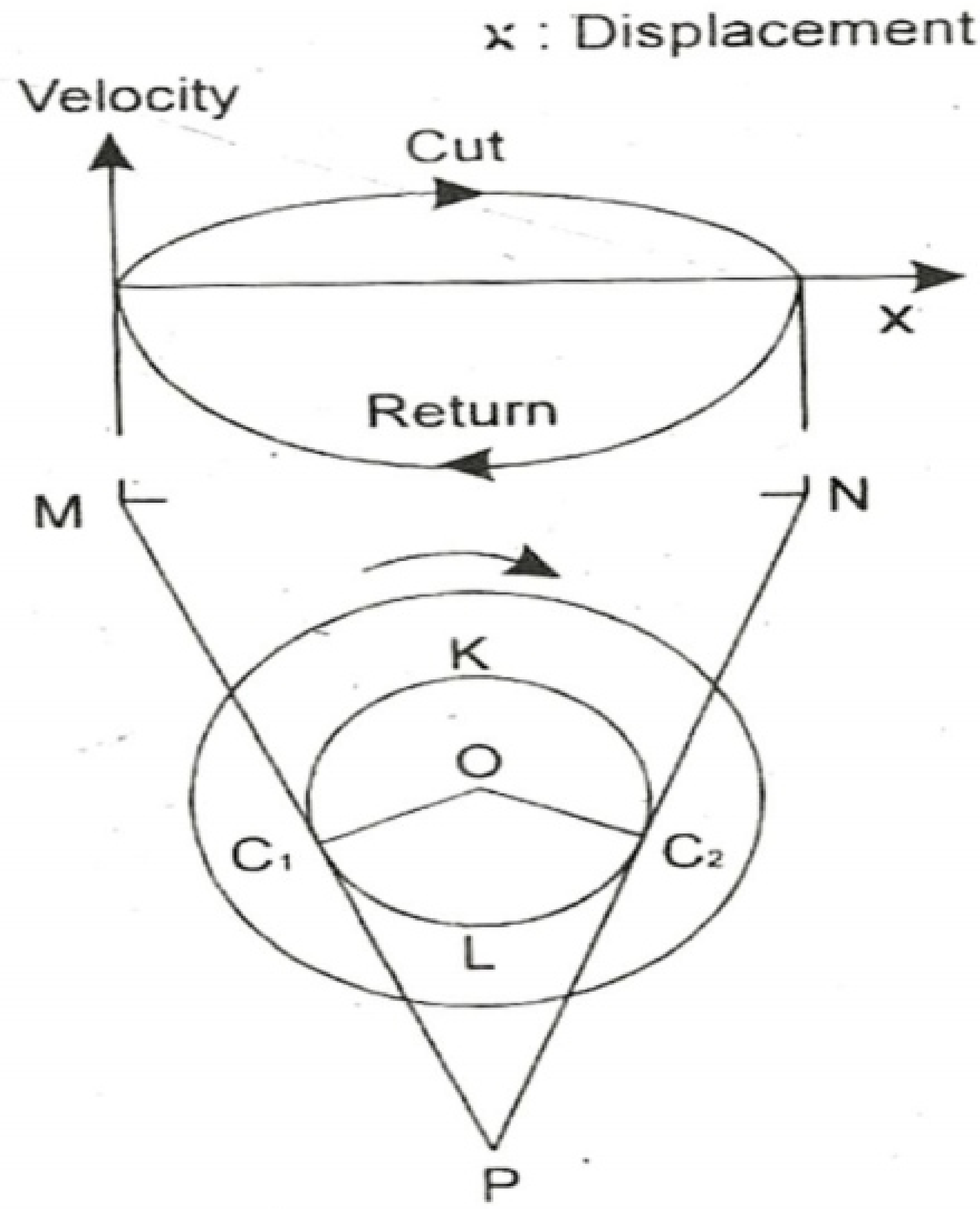


Figure 7.4 Principle of quick return mechanism

When the link is in the position PM.ram will be at the extreme backward of its stroke.

When at PN – extreme forward position

PM &PN are tangent to the crank pin circle.

$C_1 \hat{k} C_2$ ⇨ forward cutting stroke

$C_2 \hat{L} c_1$ ⇨ return stroke

It is clear that the angle made by the forward stroke> return stroke. The angular velocity is constant ⇨ rotated by speed metre . crank rotates at uniform speed.

$$\frac{time\ taken\ in\ cutting\ stroke}{time\ taken\ in\ return\ stroke} = \frac{C1\ \hat{k}\ C2}{C2\ \hat{L}\ c1} = \frac{\propto}{\beta} = \frac{\propto}{360-\propto}$$

Generally varies 2:1 and practical 3:1

Whitworth quick return mechanism:-

A bull gear is mounted on a large fixed pin a upon which it is free to rotate. The crank plate is pivoted eccentrically upon the fixed pin at 5.fitted on the face of the bull gear is the crank pin 2 on top of which sliding block is mounted. Sliding block fits into the slot provided on the crank plate. ,a connecting rod connects the crank plate by a pin and the ram by a pin.

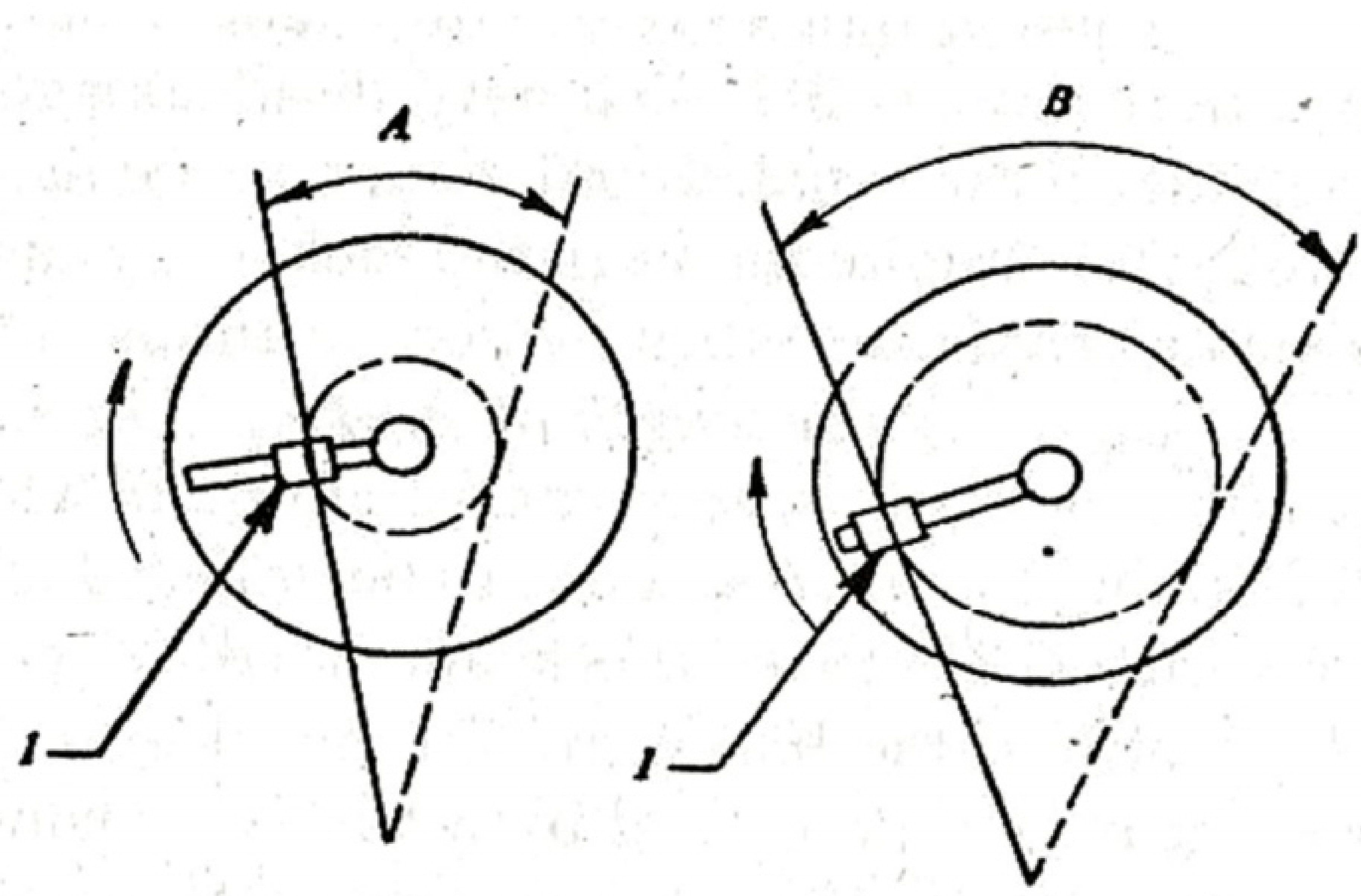


Figure Stroke length adjustment
1. Position of crankpin, A. Short stroke length, B. Long stroke length.

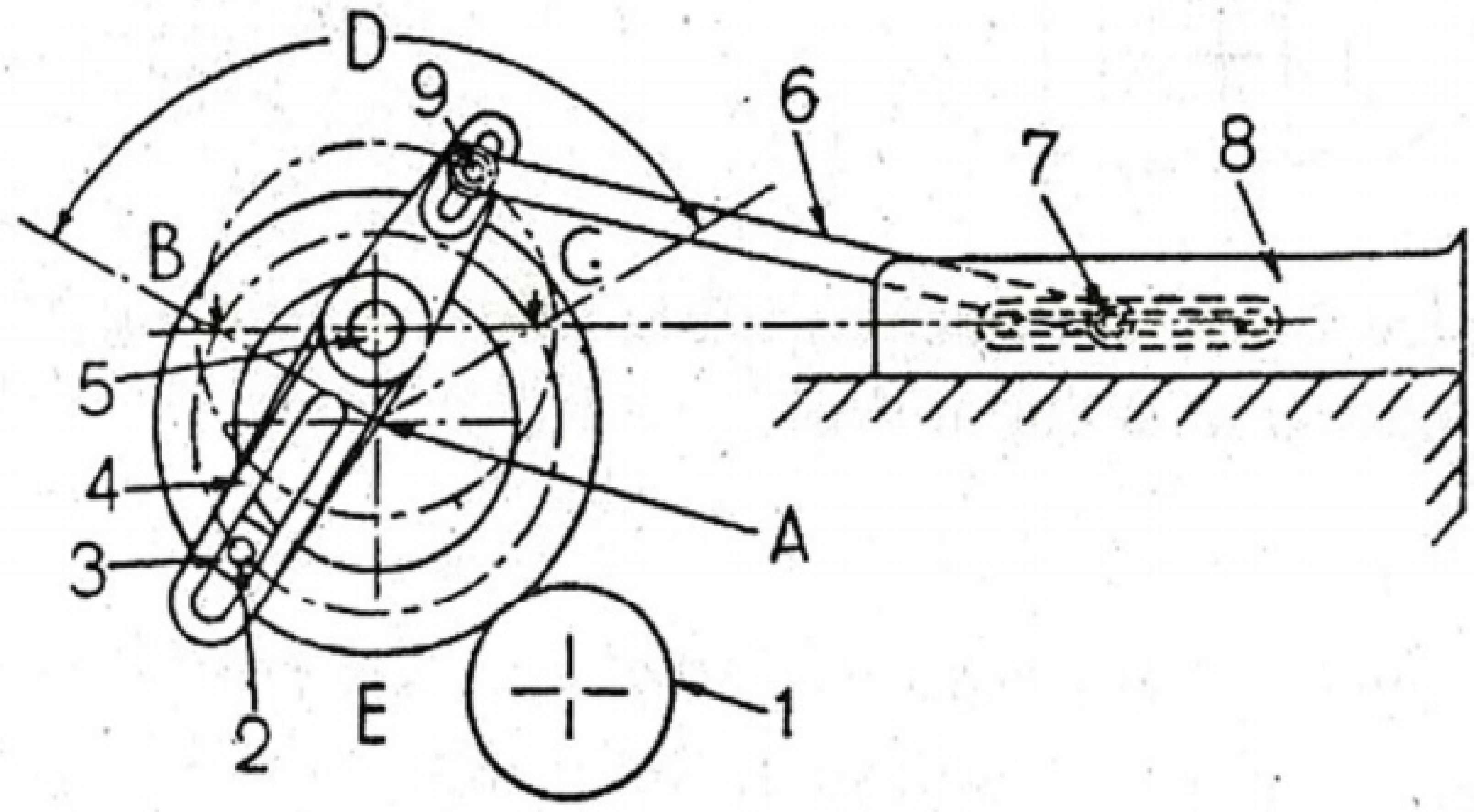


Figure Whitworth quick return mechanism

1. Driving pinion, 2. Crank pin, 3. Sliding block, 4. Crank plate, 5. Pivot for crank plate, 6. Connecting rod, 7. Connecting pin for ram, 8. Ram, 9. Pin, A. Fixed pin.

When the bull gear will rotate at constant speed the crank pin with the sliding block will rotate on a crank pin with the sliding block will rotate on a crank circle of radius A2 and the sliding block will cause the crank plate to rotate about the point 5 with a variable angular velocity.

Pin fitted on the other end of the crank plate will rotate in a circle and the rotary motion of the pin will be converted into reciprocating movement in the ram. Similar to crank and connecting rod mechanism. The axis of reciprocating of the ram passes through the pin and normal to the line A3.

When the pin cutting stroke is at position C ⇨ extreme backward position

When the pin cutting stroke is at position B ⇨ forward position

C$\hat{E}$B = cutting stroke (backward to forward)

B$\hat{D}$C = return stroke(forward to backward)

As angular velocity of the crank pin is uniform for the time taken i.e,

$$\frac{time\ taken\ in\ cutting\ stroke}{time\ taken\ in\ return\ stroke} = \frac{\widehat{CEB}}{B\hat{D}C} = \frac{\propto}{\beta} = \frac{\propto}{360-\propto}$$

Chapter-5

Planning Machine

Syllabus:

5.1 Application area of a planar and its difference with respect to shaper
5.2 Major components and their functions
5.3 The table drive mechanism
5.4 Working of tool and tool support
5.5 Clamping of work through sketch.

The planner like a shaper is a machine tool to produce plane and flat surfaces by a single point cutting tool

Difference between shaper & planner

The work is stationary; the tool along with ram reciprocates against the work

The work which is supported on the table reciprocates and the tool is stationary

Principal parts of a planner:

BED:

- The bed of a planner is a box like casting cross ribs.
- It is a very large in size and heavy in weight and it supports the column and all other moving parts of the machine.
- The guides ways are provided on the bed for the movement of the table.
- The hollow space within the box like structure of the bed home the driving mechanism for the table.

Table:

- The table supports the job and reciprocates along the ways of the bed.
- The planner table is heavy rectangular casting and is made of cast iron.
- The top face of the table is accurately finished in order to hold the job correctly.
- The top face of the table is 'T' slotted for clamping the job and job holding devices.
- At each end of the table or hollow space is left for collecti9ng chips.
- A groove is cut on the side of the table for clamping planner revising dugs at different position.

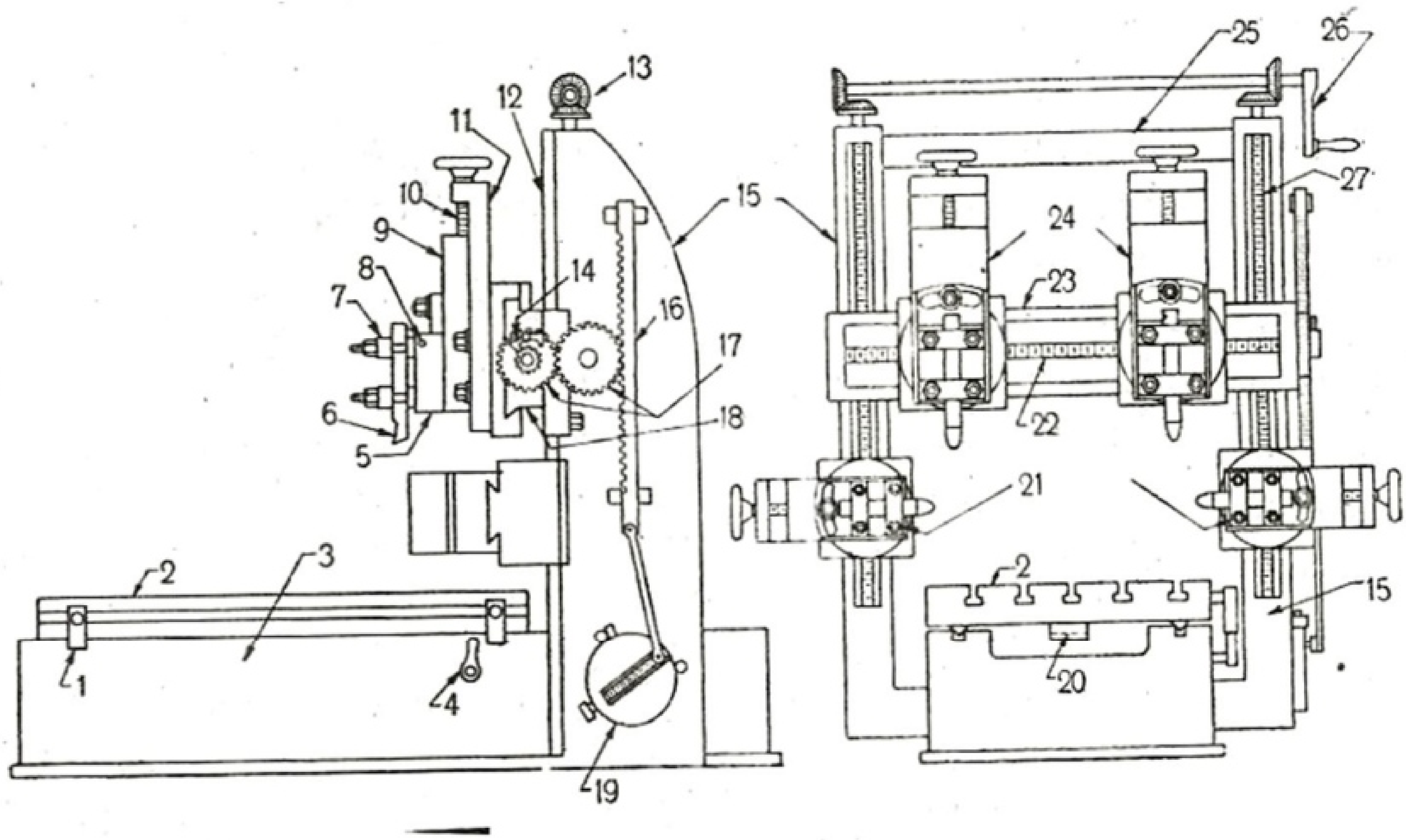


Figure 8.1 Standard double housing planer

1. Trip dog, 2. Table, 3. Bed, 4. Reversing lever, 5. Clapper box, 6. Tool, 7. Tool Post, 8. Hinge pin, 9. Vertical slide, 10. Downfeed screw, 11. Slide, 12. Guideways on column face, 13. Feed screw for elevating crossrail, 14. Pawl, 15. Column or housing, 16. Rack, 17. Feed gears, 18. Saddle, 19. Feed disc, 20. Table rack, 21. Slide toolhead, 22. Feed screw, 23. Crossrail, 24. Vertical toolheads, 25. Crossmember, 26. Crossrail, elevating handle, 27. Cross elevating screw.

Column:

- It is a rigid vertical box like structure.
- The front face of each housing is accurately machines to provide guide ways on which the crosier may be slipped up and down for accommodating the different suitable heights job.
- The housing is enclosed with vertical elevating screw and cross feed screws for tool heads and counter balanced the weight of the cross rail.

CROSS RAIL:

- It is a rigid box like casting connecting the two housings.
- The cross rail can be raised or lowered on the face of the housing and can be clamped at any desired position.
- The cross rail when clamped showed remain parallel to the top surface of the table.

- The two elevating screws in two the housing are rotated by an equal horizontal any in position.
- The two tool heads are mounted upon the cross rail.
- The cross rail has screws for vertical and cross flew of the tool heads and a screw for elevating the rail.

TOOL HEAD:

- The tool head of the planer is similar to that of a shaper in construction and operation.

CLAMPING OF JOB:

- There are three important points to be hoted while clamping the job on the planer table.
- The work should be connected rigidly to the table so that it may not be shifted out of its position while cutting progresses.
- Proper clamping should be done all round the job.
- The job should be so held that the surface planed should remain in proper position with other sur face.
- The job may be located on the planning machine table by the following methods.
- By standard clamping devices.
- By special fixtares.
- The standard clamping devices are t-bolts, stops, planer jacks, heavy duty vises, angle plates & planner centres etc.

PLANER TOOLS:

- The cutting tools which are uses in planer are single point cutting tool which are used in lathe and shaper.
- Planer tools may be solid for get type or bit type.
- The bit may be brazed, welded or mechanically held on a m.s bar.
- As a planer tool has to take up heavy cuts, the tools are made fevaier and larger in cross section.

Chapter-6

Milling Machine

Syllabus:

6.1 Types of milling machine and operations performed by them
6.2 Explain work holding attachment
6.3 Construction & working of simple dividing head, universal dividing head
6.4 Procedure of simple and compound indexing
6.7 Illustration of different indexing methods

<u>Milling m/c:</u>

A milling m/c is a type of metal cutting device which remove metal with a fast rotating multi-touch cutter.

As this m/c yield high production of different varities of jobs, in choice for production m/c, comes after the lathe.

Generally smaller jobs are employed for machining in milling m/c. If larger jobs are handled, then the m/c will perhaps be slower.

Because of using multi tooth cutters & various forms of cutters, a milling m/c can be economically employed for generating varties of surfaces quite speedily.

Types of milling m/c:

Milling m/c are available in various besings covering a wide range of work & capacities. The choice for a particular m/c depends on the nuture & size of the work to be undertaken.

a) column & knee type. Milling m/c.
   a. Hand milling m/c
   b. Plain milling m/c
   c. Universal milling m/c
   d. Omniversal milling m/c
   e. Vertical milling m/c

b) manufacturing/ fixed bed type. Milling m/c

c) planer type milling m/c

d) special type milling m/c.
   a. Rotary table machine.
   b. Drum milling m/c.

Milling attachment:

It is a rotary table types work holding device bolted on the table. It provides a rotary motion to the w/p in addition to longitudinal, cross & vertical motions.

Dividing head/indexing head:

Indexing is an operation of dividing a periphery of a cylindrical w/p into equal no. Of divisions by the help of index crank & index plate.

Indexing is accomplished by using a special attachment known as dividing head/indexing head.

Dividing heads are 3 types

1. **Plain/simple deviding head:**
2. **Universal deviding head**

Plain/ simple dividing head:

- It has a spindle which carries job holdering devices such as three jaw chuck, face plate with centre carrier
- A worm wheel is rigidly fixed on spindle. While an indexing crank is mounted on the worn shaft such that the rotation of index crank finally results in the rotation of the spindle.
- In a plane dividing head, its spindle rotates only around horizontal axis.
- The index plate remains fixed & does not rotates only around horizontal axis.
- The index plate remains fixed & does not rotate while performing simple indexing operation.

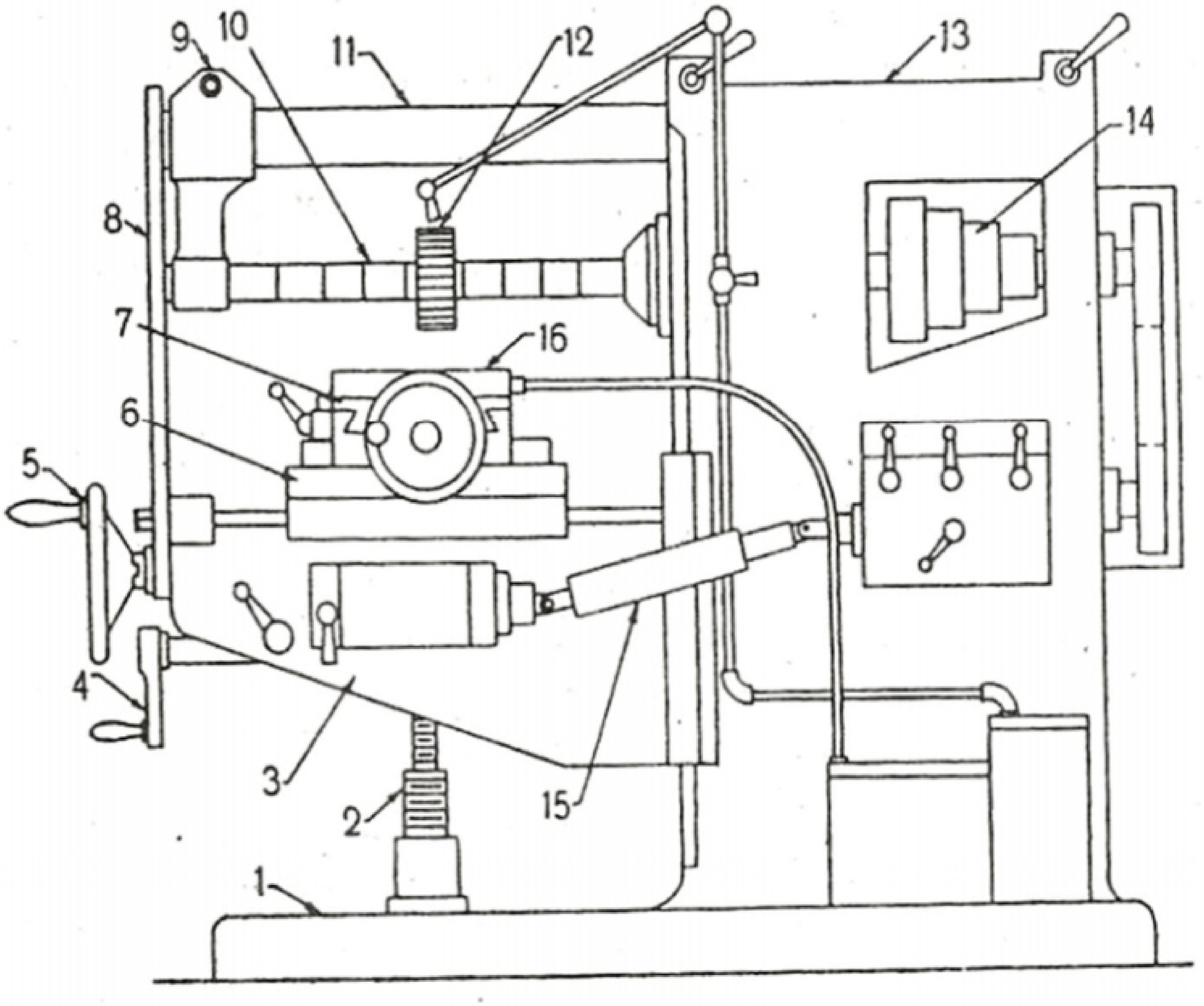


Figure 11.1 Column and knee type milling machine

1. Base, 2. Elevating screw, 3. Knee, 4. Knee elevating handle, 5. Crossfeed handle, 6. Saddle, Table, 8. Front brace, 9. Arbor support, 10. Conepulley, 15. Telescopic feed shaft.

The amount of the spindle relative to the worm depends on the ratio between the relations of worm & the worm wheel.

The most common ratio is 40:1, which means 40 revolutions of index crank or worm will move the worm wheel or spindle through one complete revolution.

Universal dividing head:

- It is the most commonly used type of attachment on the milling m/c.
- It is used for the following purposes.
- Setting the w/p in horizontal, vertical & inclined positions relative to the milling m/c table.
- Turning the work periodically through a given angle per forming indexing of the work.
- Imparting a continuous rotary motion to the w/p for milling helical grooves.
- Dividing head spindle is connected with the table feed screw through a gear train attachment to impart a continuous rotary motion to the w/p for helical milling.
- Working mechanism of an universal dividing head is the crank which is regidlr fixed at one end of the work shaft, while the bevel gear runs free on the worm shaft.
- The index plate is bloted with gear & can be locked aginst the rotation of lock pin.

Optical dividing head:

It is used for high precision angular indexing of the job with respect to the cutter.

For reading the angle, on optical system is built into the deviding head.

Splidle:

Splindle is located in the upper part of the column.

It gets driving power from motor to transmit it to the abrod.

The front end of the spindle just projects from the column face & is provided with a tapered hole to accommodate various cutting tools & arbors.

Arbour:

The arbour is connected with a splindle through a bolt, which serves as an extension of the m/c spindle on which milling cutters are safely mounted & rotated

It is taper shank for proper alingnment with the splindle having tapered hole at its nose.

Work holding devices:

Work holding device used on a milling m/c includes the following: Vices which may be plain vice, swivel vice & tool maker's universal vice.

- **Angle plates.**
- **v-blocks**
- **special fixtures.**

Work holding attachment:

Special attachment are used on miiling m/c for performing different typical operations. Common attachments include:

a. vertical milling attachment: used for facilitating the horizontal spindle milling m/c to do facing on horizontal surface or for making grooves.
b. universal milling attachment: similar to vertical attachment with added features for swivelling the spindle about two mutually perpendicular axis.

slitting attachment :

used for converting rotational motion of the horizontal splindle m/c into up & down vertical reciprocating motins. The slotting head is fitted to the spindle & is used for cutting slats. The attachment can be swivelled to any angular positions.

high speed milling attachment:

it is a gearing system used for increasing the splindle speed by four to six times. The attachment is bolted to the face of the column.

rack milling attachment:

It is bolted to the face of the column. Used for cutting rake teeth.

Differential Indexing :

Available no. Of index plates with different hole circles sometimes limit the range of plate indexing. In such case differential indexing is found useful. In this process, the indexing polate rotates itself in relation to the cranck during the process of indexing. For making necessary calculation to find the change gears to be placed between the spindle and the power shaft use the following relation

Where N = no. Of divisions to be indexed

N is a no. Opf slightly or less than N. After simplification, the above relation n will give the gear ratio between the gears to be placed on the spindle (driver) amd the own shaft (driver).

Gears may be arrabged in a simple train or in a compound train as the case may be.

When (n – N) is possotive, the index plate must rotate in the direction in which the crank is rotated.

If (n – N) is negative the index plate rotates in the opposite direction to that of the cranck.

Dividing head attachment:

A dividing head attachment is also a special work holding de3cvice which is bolted on the machine plate. The work may be mounted on a chuck fitted on the dividing head spindle or may be supported between alive or dead centre.

The dead centre is mounted on a foot stock as in a klathe tail stock that is bolted on the machine table after after correctly aligning its spindle axis with the dividing heads. spindle

universal dividing head:

The attachment nis similar to the vertical attachment but it has an added arrangement for swivelling the spindle about two mutually perpendicular axes . This feature of the attachment permits the cutting spindle axis to swivel at practically any angle and machine any compound angle surface of the work. The attachment is supported by the over-ram and operates at either the same speed or at higher speed than the scope of machine.

Chapter-7

Slotter

Syllabus:

7.1 Major components and their function
7.2 Construction and working of slotter machine
7.3 Tools used in slotter

SLOTTER

It is used for cutting grooves, key ways and slots of various shapes for making regular and irregular surfaces both internal and external.

Difference between slotter and shaper:

SLOTTER	SHAPER
The ram holds the tool and reciprocates in a vertical axis	The ram holds the tool and reciprocates in a horizontal axis.

SLOTTING MACHINE PARTS:

Base/bed:

The base of the machine is rigidly built to withstand all cutting forces and entire load of the machine.

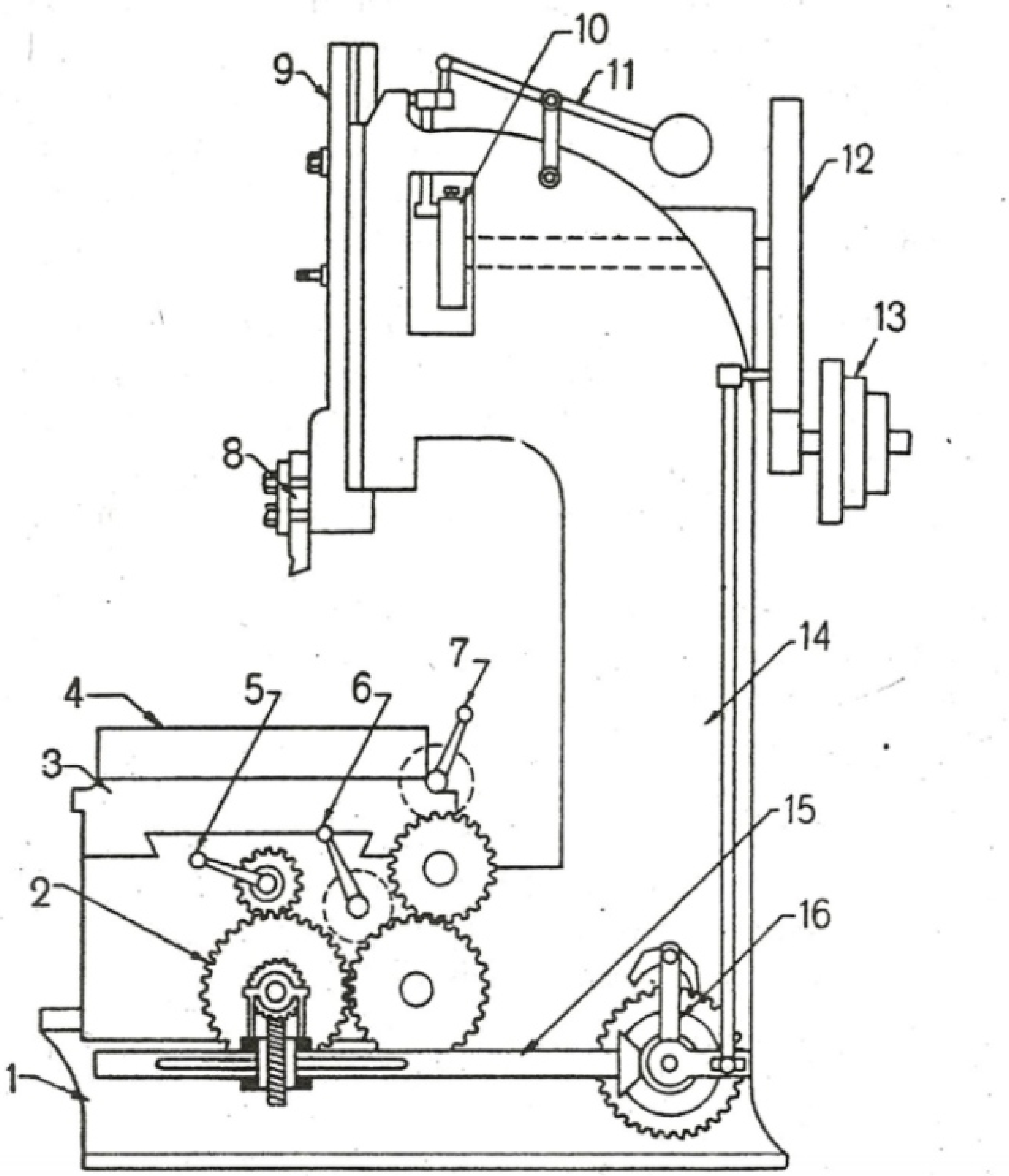


Figure 9.1 Slotting machine

1. Base, 2. Feed gear, 3. Cross-slide, 4. Table, 5. Crossfeed handle, 6. Longitudinal feed handle, 7. Circular feed handle, 8. Tool, 9. Ram, 10. Crank disc, 11. Lever for conterbalance weight, 12. Bull gear, 13. Cone pulley, 14. Column, 15. Feed shaft, 16. Pawl actuating crank.

COLUMN:

- The column is the vertical member which is cast integral with the base.
- Driving mechanism and feeding mechanism are inside the column.
- The front vertical face of column is accurately finished for providing ways onwhich the ram reciprocates.

SADDLE:

- The saddle is mounted upon the guideways and may be moved towards or away from the column either by power/ manual control to supply longitudinal feed to the work.
- The top surface of the saddle is accurately finished to provide guideways for the cross slide.
- These guideways are perpendicular to the guideways on the base.

CROSS SLIDE:

- The cross slide is mounted upon the guideways of the saddle and may be moved parallel to the face of the column. The movement of the slide may be controlled either by head or power to supply cross feed.

ROTATING TABLE:

- The rotating table is a circular table which is mounted on the top of the cross slide. The table may be rotated by rotating a worn which meshes with a worm glar connected to the under side of the table.
- In same machines the table is graduated in degrees that enables the table to be rotated for indexing.
- T-slots are cut on the top face of the table for holding the work by different clamping devices.
- The rotary table enables a circular or contoured surface to be generated on the work piece.

RAM & TOOTHED ASSEMBLY:

- The ram is the reciprocating member of the machine mounted on the guide ways of the column.
- It supports the tool at it's bottomend on toolhead.

RAM DRIVE MECHANISM:

- A slotter removes metal during downward cutting stroke only wherlas during upward return stroke no metal is removed.
- To reduce the idler time quick return mechanism is incorporated in the machine.

FEED MACHANISM:

- The teed is given by the table.
- A slotting machine table have 3 types of feed movements.

LONGITUDINAL:

- If the table is fed perpendicular to the column towards or away from face the feed movement is termed as longitudinal.

CROSS: If the table is feed parallel to the face of the column the feed movement is termed as cross.

CIRCULAR: If the table is rotated on a vertical axis the feed movement is circular.

SLOTTER TOOLS:

α = top rake angle

β = from clearance angle

- In a slotter the pr. Acts along the length of the tool.
- In slotter tool the angles are provided for better cutting.
- The nose of the tool projects slightly beyond the shank to provide clearance.
- The slotter tools are robust in cross section and usually of torged type.
- Bit type tools are fitted in heavy duty tool holders.
- Key way cutting tools are thinner at the cutting edges.
- Round nose tools are used for machining circular/ contoured surfaces.
- Square nosed tools are used for machining flat surfaces.

Chapter-8

Grinding

Syllabus:

8.1 Significance of grinding operations
8.2 Manufacturing of grinding wheels
8.3 Criteria for selecting of grinding wheels
8.4 Specification of grinding wheels with example
Working of
Cylindrical Grinder□
Surface Grinder□
Centre less Grinder□

Griding M/C:

- Grinding is the process of removing material from workpiece. The removing of material from the W/P is either two brings its dia metre within very closed tolerance (0.02mm) or to give a fine finish or the work surface.
- The grinding machine supports and rotates the grinding wheel for smooth operation. Grinding machine is used for roughing and finishing flat, cylindrical and conical surface.

- The grinding wheel is made of fine grains of abrasive materials. The grains during the rotation of the wheels remove very small chip[s .
- As the selection of chips remove is very small and high cutting speed are involved, the grinding operation results into a very good finish or the work surface and high accuracy in work dimensions.

<u>Types of Grinding:</u>

Oftainly used to grind casting and weldments using portable grinders or pedestal; grinder

Fine Grinding :

- It is applied for finishing of thoseer material which are too hard to be machined by opther methopds of metal cutting.
- It is also used for producing surface on the job to attain higher dimensional accuracy andc finish

<u>BED/BASE</u>

- It is a heavy cast iron construction and support s other parts of the slotting machine such as column, ram and its driving mechanism, table etc.
- The top of the base is accurately finished to provide guide ways for mounting of the saddle. The cross-slide guide ways are perpendicular to the column face.

<u>Column</u>

- It is a vertical structure cast integral with the base.
- It houses the mechanism for driving ram and feeding mechanism.
- The front vertical face of the column cdarries guide ways for ram to reciprocating upon it

<u>Saddle:</u>

- It is mounted upon guide ways and can be moved towards or away from the column
- The saddle caries guide ways for cross-slide
- The feed is given by manual or power.

Cross-slide:

- It is mounted upon guide wayus made at the top of the saddle and can be moved parallel top the front face of the column.
- Feed is given manual or by power.
- Table
- It is a circular rotary table mounted on the top of the cross-slide
- A circular feed handle for the table is provided
- Rotation of the table is effected by hand or by power
- The table carries T-slots to help mounting of jobs on the tabloe
- Ram and tool head
- They reciprocates up and down on the guide ways made on the front face on the column.
- The ram carries a tool head at its bottom end.
- In some mechanism special tool head is provided to releave the tool during its return stroke
- A quick return mechanism is given with the machine which enables the return or ideal stroke to be completed faster than the cutting stroke

Methods of grinding:

According to type surface to be grounded main kinds of grinding methods are as follow:

External cylindrical grinding: produces a straight or tappered surface on a w/p when it is rotated about its own axis between centres as it passes lengthwise across the face of a revolvingrinding wheel.

Internal cylindrical griding: it produces internal cylindrical holes & tapers. The work is chucked & rotated on its axis, while the grinding wheel rotates agest the work.

Surface grinding:

It produces flat surfaces & the work may be grounded either by periphery or by end face of the grinding wheel.

Face grinding:

It is a method of grinding vertical flat surface & the wheel spindle may be vertical or horizontal.

From grinding:

It is done by specially shaped grinding wheels to grind formed surfaces as gearteeth, theards, shaft, dovetails etc.

Set wheel grinding:

It is a method of grinding short w/p without changing the grinding wheel.

Centre less grinding:

It is a method of grinding external & internal cylindrical surfaces in which the work is supported among a regulating wheel, a grinding wheel & a work rest blade.

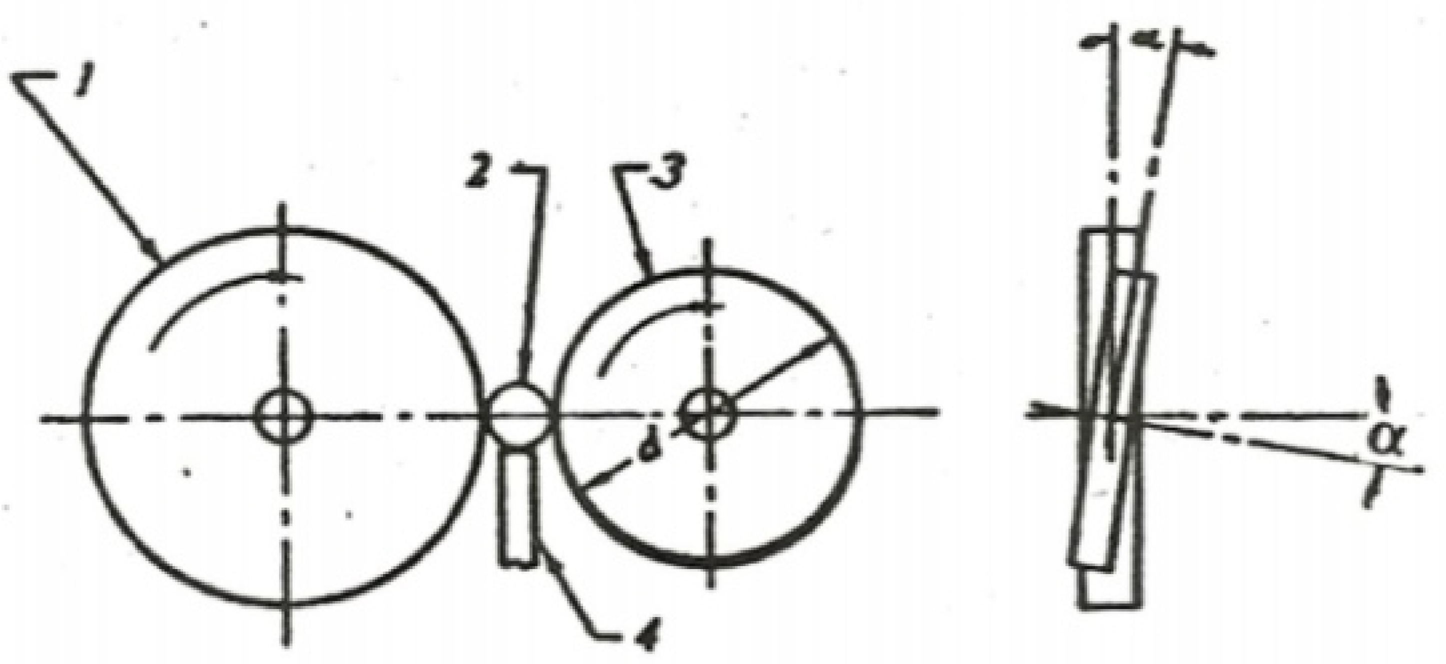


Figure External centreless grinding
1. Grinding wheel, 2. Work, 3. Regulating wheel, 4. Work-rest.

Off-hand grinding:

It is rough grinding method in which work is held in hand and pressed

Against the rotating grinding wheel. For example grinding a chisel on pedestal grinder

Types of grinding machine:

Grinding machine may be broadly classified as follows

1. **Surface grinder**
2. **Cylindeical grinder**
3. **Center-less grinder**
4. **Portable grinder**
5. **Pedestal grinder**
6. **Cutter and tool grinder**
7. **Internal grinder**
8. **Flexible shaft grinder**

Surface grinder :

a. It is used for grinding flat surfaces
b. Surface grinding effective for removing hard spots and sets from the work surface
c. Surface grinding machine differs according the shyape of grinding wheel and motion givren to the work table during working.
d. Some common type surface grinding machine are prescribed in the following

Horizontal spindle surface grinding machine:

It is used for the circumferemce of a straight grinding wheel and are able to handle a wide range of work with super finish and externally fine limits of accuracy

Vertical spindle flat grinding machine:

These are strongly built machine. They yield more out put with cup type wheel rather than using of straight wheels.

Disc grinding machine:

These are used for rough semi precision grinding rapid removal of metal is done by this type of machine.

Chapter-9

Internal Machining operations

Syllabus:

Classification of drilling machines
9.1 Working of
Bench drilling machine
Pillar drilling machine
Radial drilling machine
9.2 Boring
Basic Principle of Boring
Different between Boring and drilling
9.3 Broaching
Types of Broaching (pull type, push type)
Advantages of Broaching and applications

Introduction

The drilling machine is one of the most important machine tools in a workshop. As regards its importance it is second only to the lathe. Although it was primarily designed to originate a hole, it can perform a number of similar operations. In a drilling machine holes may be drilled quickly and at a low cost. The hole is generated by the rotating edge of a cutting tool known as the drill which exerts large force on the work clamped on the table. As the machine tool exerts vertical pressure to originate a hole it is loosely called a "drill press".

Holes were drilled by the Egyptians in 1200 B.C. about 3000 years ago by bow drills. The bow drill is the mother of present day metal cutting drilling machine.

TYPES OF DRILLING MACHINE

Drilling machines are made in many different types and sizes, each designed to handle a class of work or specific job to the best advantage. The different types of drilling machines are :

1. Portable drilling machine.
2. Sensitive drilling machine.
   (a) Bench mounting, (b) Flour mounting
3. Upright drilling machine.
   (a) Round column section, (b) Box column section
4. Radial drilling machine.
   (a) Plain (b) Semiuniversal
   (c) Universal
5. Gang drilling machine.
6. Multiple spindle drilling machine.
7. Automatic drilling machine.
8. Deep hole drilling machine.
   (a) Vertical (b) Horizontal

PORTABLE DRILLING MACHINE

As the name implies this type of drilling machine can be operated with ease any where in the workshop and is used for drilling holes in workpieces in any position which can not be drilled in a standard drilling machine. Some of the portable machines are operated by hand power, but most of the machines are driven by individual motor. The entire drilling mechanism including the motor is compact and small in size. The motor is usually of universal type which may be driven by both A.C. and D.C. The maximum size of the drill that it can accommodate is not more than 12 to 18 mm. The machine is operated at high speed as smaller size drills are only used. Some of the portable machines are driven by pneumatic power.

SENSITIVE DRILLING MACHINE

The sensitive drilling machine is a small machine designed for drilling a small holes at high speed in light jobs, The base of the machine may be mounted on a bench or on the floor. It consists of a vertical column, a horizontal table, a head supporting the motor and driving mechanism, and a vertical spindle for driving and rotating the drill. There in no arrangement for any automatic feed of the drill spindle. The drill is fed into the work by purely hand control. High speed and hand feed are necessary for drilling small holes. High speeds are necessary to attain required cutting speed by small diameter drill. Hand feed permits the operator to feel or sense the progress of the drill into the work, so that if the drill becomes worn out or jams on any account, the pressure on the drill may be released immediately to prevent it from

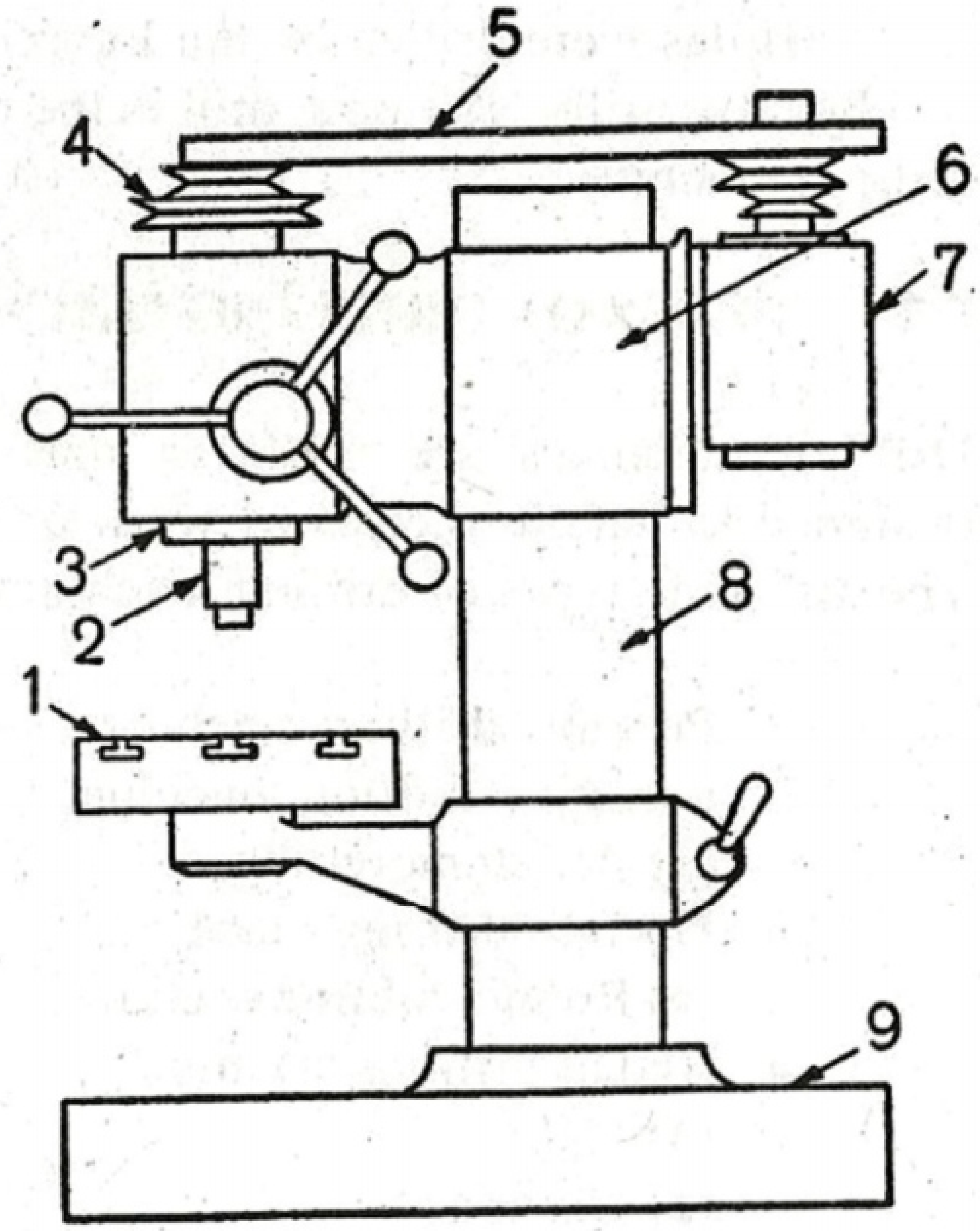


Figure Sensitive drilling machine
1. Table, 2. Vertieal drill spindle, 3. Sleeve, 4. Cone pulley, 5. V-belt, 6. Head, 7. Driving motor, 8. Vertical column, 9. Base.

breaking. As the operator senses the cutting action, at any instant, it is called sensitive drilling machine. Sensitive drilling machines are capable of rotating drills of diameter from 1.5 to 15.5 mm. Super sensitive drilling machines are designed to drill holes as small as 0.35 mm in diameter and the machine is rotated at a high speed of 20,000 r.p.m. or above. Fig.5.1 illustrates a sensitive drilling machine.

UPRIGHT DRILLING MACHINE

The upright drilling machine is designed for handling medium sized workpieces. In construction the machine is very similar to a sensitive drilling machine for having a vertical column mounted upon the base. But this is larger and heavier than a sensitive drill and is supplied with power feed arrangement. In an upright drilling machine a large number of spindle speeds and feeds may be available for drilling different types of work. The table of the machine also have different types of adjustments. There are two general classes of upright drilling machine:

1. Round column section or pillar drilling machine.
2. Box column section.

Round column section or pillar drilling machine : The round column section upright drilling machine or pillar drilling machine consists of a round column that rises from the base which rests on the floor, an arm and a round table assembly, and a drill head assembly.

The arm and the table have three adjustments for locating workpieces under the spindle. The arm and the table may be moved up and down on the column for accommodating workpieces of different heights. The table and the arm may be moved in an arc upto 180° around the column and may be clamped at any position. This permits setting of the work below the spindle. Moreover, heavy and odd-size work may be supported directly on the base of the machine and drilled after the arm is swung out of the way. The table may be rotated 360° about its own centre independent of the position of the arm for locating workpieces under the spindle.

The construction of the machine being not very rigid and the table being supported on a horizontal arm, this is particularly intended for lighter work. The maximum size of holes that the machine can drill is not more than 50 mm.

Box column section upright drilling machine : The upright drilling machine with box column section has the square table fitted on the slides at the front face of the machine column. Heavy box column gives the machine strength and rigidity. The table is raised or lowered by an elevating screw that gives additional support to the table. These special features permit the machine to work with heavier workpieces, and holes more than 50 mm in diameter can be drilled by it.

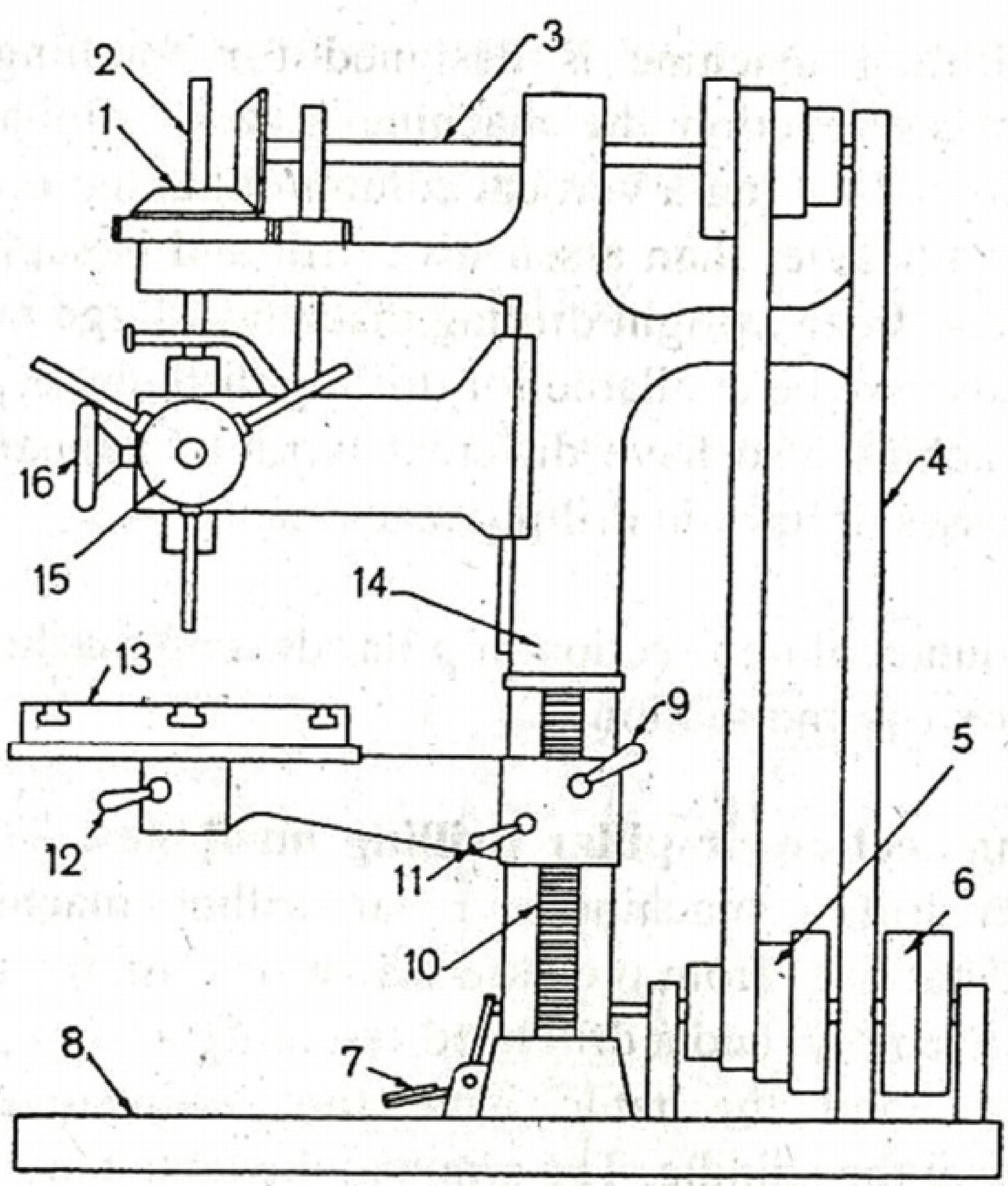


Figure Upright pillar drilling machine

1. Bevel gear drive to spindle, 2. Spindle, 3. Overhead shaft, 4. Back stay, 5. Counter shaft cone pulley, 6. Fast and loose pulley, 7. Table elevating handle, 8. Foot pedal, 9. Base, 10. Rack on column, 11. Table elevating clamp handle, 12. Table clamp, 13. Table, 14. Column, 15. Handwheel for quick hand feed, 16. Handwheel for sensitive hand feed.

RADIAL DRILLING MACHINE

The radial drilling machine is intended for drilling medium to large and heavy workpieces. The machine consists of a heavy, round, vertical column mounted on a large base. The column supports a radial arm which can be raised and lowered to accommodate workpieces of different heights. The arm may be swung around to any position over the work bed. The drill head containing mechanism for rotating and feeding the drill is mounted on a radial arm and can be moved horizontally on the guide-ways and clamped at any desired position. These three movements in a radial drilling machine when combined together permit the drill to be located at any desired point on a large workpiece for drilling the hole. When several holes are drilled on a large workpiece, the position of the arm and the drill head is altered so that the drill spindle may be moved from one position to the other after drilling the hole without altering the setting of the work. This versatility of the machine allows it to work on large workpieces. The work may be mounted on the table or when the work is very large it may be placed on the floor or in a pit. Fig.5.3 illustrates a radial drilling machine.

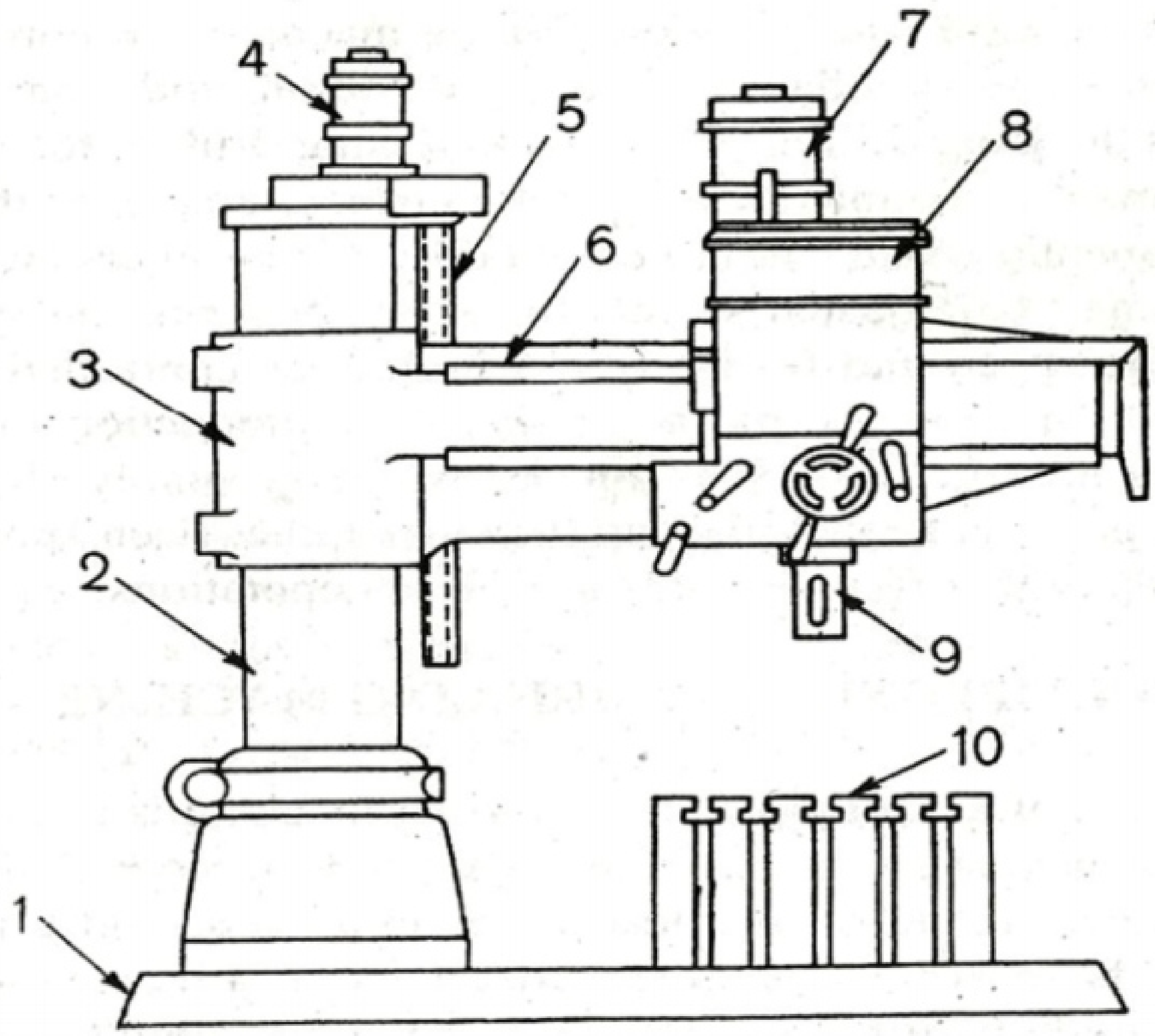


Figure Radial drilling machine

1. Base, 2. column, 3. Radial arm, 4. Motor for elevating the arm, 5. Elevating screw, 6. Guide ways, 7. Motor for driving the drill spindle, 8. Drill head, 9. Drill spindle, 10. Table

Plain radial drilling machine : In a plain radial drilling machine provisions are made for vertical adjustment of the arm, horizontal movement of the drill head along the arm, and circular movement of the arm in horizontal plane about the vertical column.

Semiuniversal machine : In a semiuniversal machine, in addition to the above three movements, the drill head can be swung about a horizontal axis perpendicular to the arm. This fourth movement of the drill head permits drilling hole at an angle to the horizontal plane other than the normal position.

Universal machine : In a universal machine, in addition to the above four movements, the arm holding the drill head may be rotated on a horizontal axis. All these five movements in a universal machine enables it to drill on a workpiece at any angle.

The boring machine is one of the most versatile machine tools used to bore holes in large and heavy parts such as engine frames, steam engine cylinders, machine housings, etc. which are practically impossible to hold and rotate in an engine lathe or a drilling machine. Boring machines have, therefore, been developed primarily to do this. In addition to its primary purpose of boring the range of speeds and feeds provided to the various traversing components allow drilling, milling and facing to be performed with equal facility. By the fitting of simple attachments, the use of the machine can be extended still further to include screw cutting, turning, planetary grinding, or gear cutting.

TYPES OF BORING MACHINES

The boring machines may be classified under the four headings :

1. Horizontal boring machine.
   - (a) Table type.
   - (b) Floor type.
   - (c) Planer type.
   - (d) Multiple head type.
2. Vertical boring machine.
   - (a) Vertical turret lathe.
   - (b) Standard vertical boring machine.
3. Precision boring machine.
4. Jig boring machine.
   - (a) Vertical milling machine type.
   - (b) Planer type.

HORIZONTAL BORING MACHINE

In a horizontal boring machine, the work is supported on a table which is stationary and the tool revolves in a horizontal axis. A horizontal boring motion. The machine essentially consists of a bed, headstock supporting column, end supporting column, headstock, saddle and table, and boring bar. The table, saddle and headstock may be adjusted by leadscrews using micrometer dials. This type of machine is suitable for general purpose work where other operations, in addition to boring, are required to be performed. A block diagram of a table type machine is shown in Fig.6.2.

Floor type horizontal boring machine : The floor type horizontal boring machine having no table uses a stationary floor-plate on which T-slots are provided to hold the work. The headstock supporting column and the end supporting column and the end supporting column are mounted on the runways which are placed at right angles to the spindle axis. Thus any crosswise adjustment or cross-feed movement is provided by the spindle itself and not by the work. This is so designed for holding very large and heavy workpieces which are difficult to be mounted and adjusted on a table. A block diagram of a floor-type machine is shown in Fig.6.3.

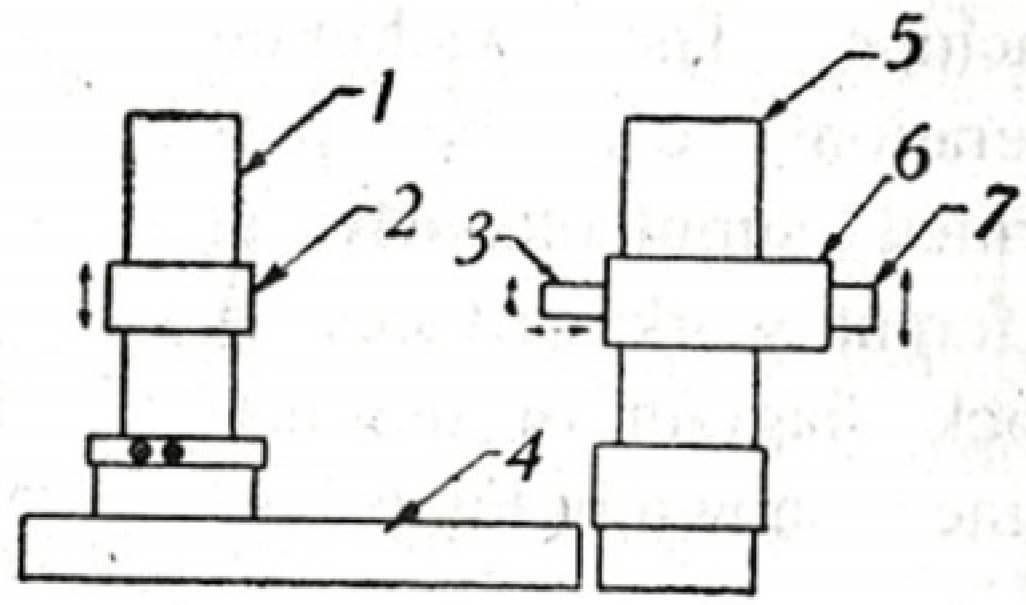


Figure Floor type horizontal boring machine

1. End supporting column, 2. Column base, 3. Spindle, 4. Floor plate, 5. Headstock, 7. Motor.

Planer type horizontal boring machine : The planer type horizontal boring machine resembles the table type but table slides directly on the bed instead of on a saddle and reciprocates at right angles to the spindle similar to a planer. The end supporting column and headstock supporting column may be adjusted towards or away from the table for accommodating different widths of work. This type of machine is suitable for supporting a long work. A block diagram of a planer type machine shown in Fig.6.4.

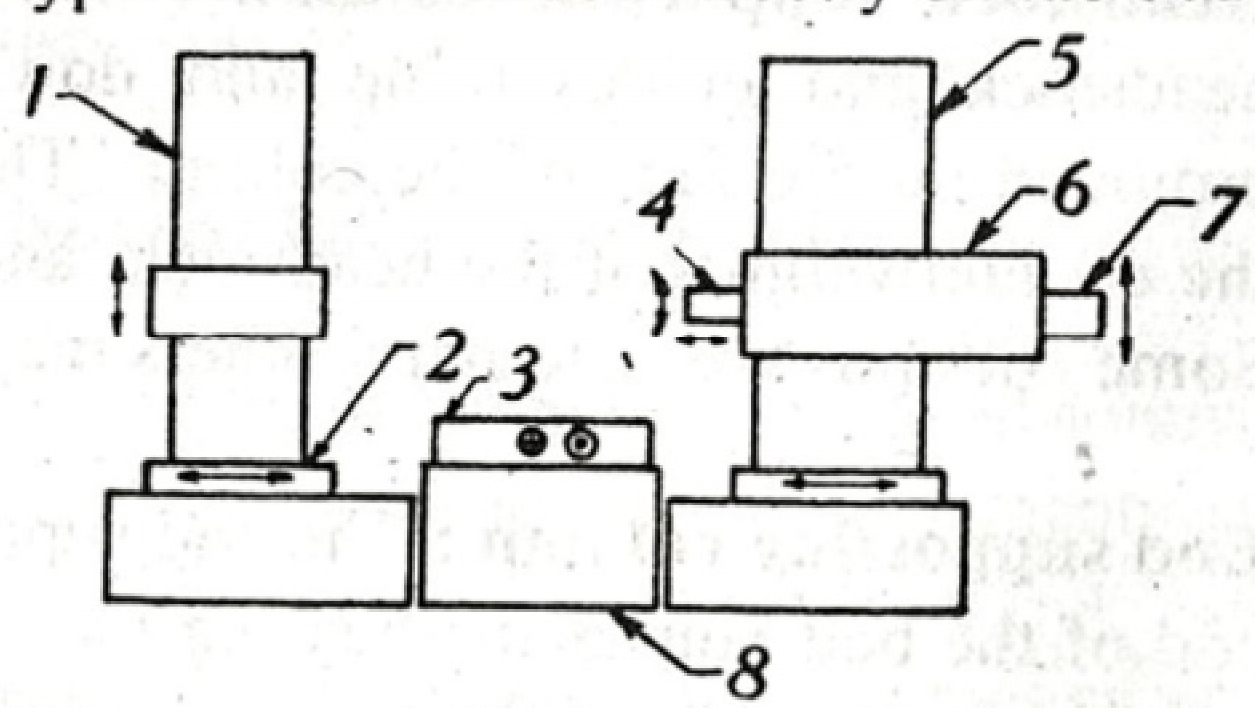


Figure Planer type horizontal boring machine

1. End supporting column, 2. Column base, 3. Table, 4. Spindle 5. Headstock supporting column, 6. Headstock, 7. Motor, 8. Bed.

Multiple head type horizontal boring machine : The machine resembles a double housing planer or a plano-miller. The table is supported on a long bed on which it reciprocates. There are two vertical columns at two sides of the bed, nearly at the middle of the bed. The two columns are bridged by a crossrail. The machine may have two, three or four headstocks. This type of machine may be used both as a horizontal and vertical machine. The machining operations can be performed simultaneously at different work surfaces. A block diagram of the machine is shown in Fig.6.5.

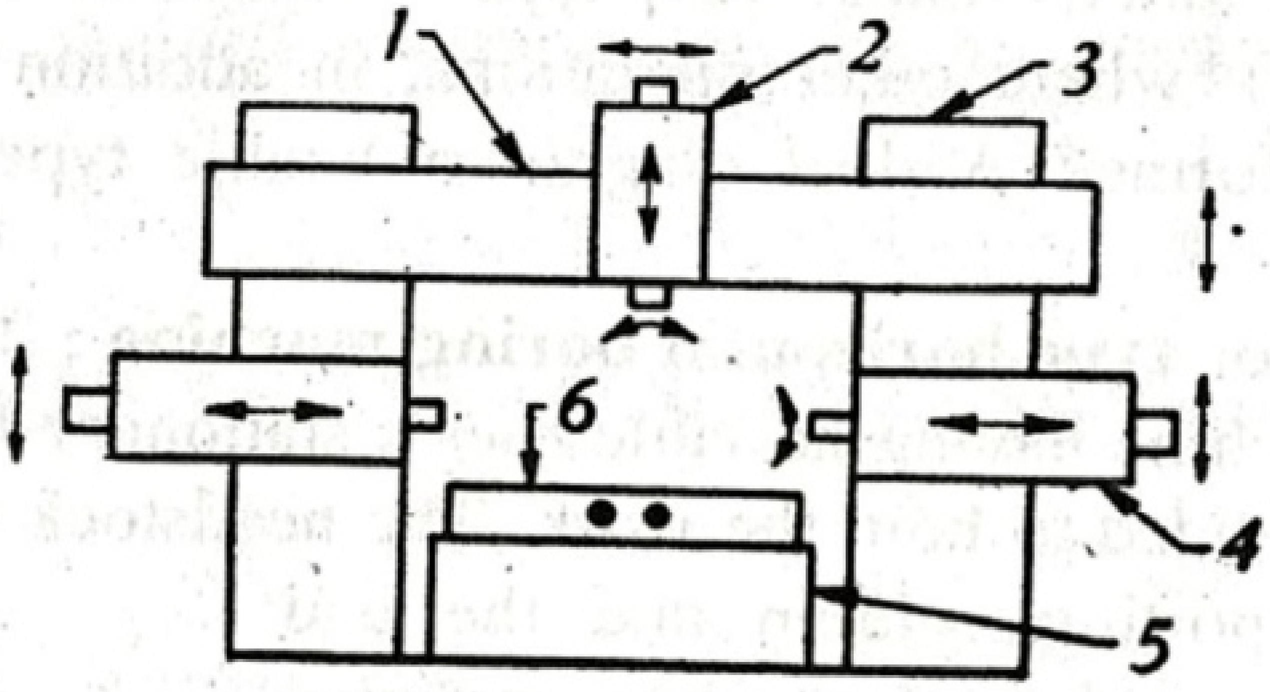


Figure Multiple head type horizontal boring machine
1. Crossrail, 2,4. Headstocks, 3. Column, 5. Bed, 6. Table.

PART OF A HORIZONTAL BORING MACHINE

The different parts of a horizontal; boring machine are illustrates in Fig.

Bed : The bed is that part of the machine which is fitted on the floor of the shop and has a box like casting. The bed supports the columns, tables and other parts of the machine.

Headstock supporting column : The column provides support to the headstock and guides it up and down accurately by the guide ways provided on the face of the column. The column which is hollow houses the counterweights of the headstock, and is heavily ribbed to add rigidity. Some columns are stationary, others may be made to slide along the bed.

End supporting column : The end supporting column situated at the other end of the bed houses the bearing block for supporting a long boring bar. The column may be adjusted on the sideways of the bed towards or away from the spindle for supporting different lengths of boring bars or it may be moved at right angles to the spindle as in the case of a floor type machine.

Headstock : The headstock mounted on the column supports, drives, and feeds the tool. The spindle revolves within a quill. The spindle provides

The teeth of a gear or splint may be broached altogether or one or a few at a time. A comparatively simple broach can be made to cut one or a few tooth spaces, After one pass, the gear blank is indexed, and more of its teeth are cut. Successive passes are made until all the teeth are finished.

ADVANTAGES AND LIMITATIONS OF BROACHING

Broaching has been adopted for mass production work because of the following outstanding features and advantages :

1. Rate of production is very high. With properly applied broaches, fixtures, and machines, more pieces can be turned out per hour by broaching than by any other means,
2. Little skill is required to perform a broaching operation. In most cases the operator merely loads and unloads the workpiece.
3. High accuracy and a high class of surface finish is possible. A tolerance of ± 0.0075 mm and a surface finish of about 0.8 microns (1 micron = 0.001mm) can be easily obtained in broaching.
4. Both roughing and finishing cuts are completed in one pass of the tool.
5. The process can be used for either internal or external surface finishing.
6. Any form that can be reproduced on a broaching can be machined.
7. Cutting fluid may be readily applied where it is most effective because a broach tends to draw the fluid into the cut.

Certain reasons, however, limit the application of the broaching process. They are :

1. High tool cost. A broach usually does only one job and is expensive to make and sharpen.
2. Very large workpieces cannot be broached.
3. The surfaces to be broached cannot have an obstruction.
4. Broaching cannot be used for the removal of a large amount of stock.
5. Parts to be broached must be capable of being rigidly supported and must be able to withstand the forces that set up during cutting.

Chapter-10

Surface finish, lapping

Syllabus:

10.1 Definition of Surface finish
Define super finishing
10.2 Description of lapping & explain their specific cutting.

Introduction:

In a manufacturing plant, a product may be shaped, turned, milled or drilled, and left in that condition as being satisfactory for use. However, if a better finish is desired, for looks, for accuracy, for wearing qualities, or for any other reasons, one of the micro finished that include lapping, honing, super finishing, polishing, buffing, may be employed. In some cases other operations are done only to get durable finishes.

LAPPING:

Lapping is an abrading process that is used to produce geometrically true surfaces, correct minor surface imperfection, improve dimensional accuracy, or provide a very close fit between two contact surfaces. Very thin layers of metal(0.005 to 0.01mm)are removed in lapping and it is therefore, evident that is unable to correct substantial error in the form and size of surface, it is however low efficiency process is used only when specified accuracy and surface finish cannot be obtained by other method. Abrasive powders (floors such as emery, corundum ion oxide, chromium oxide mixed with oil is mixed with oil or special paste with some carrier are used in lapping.

Most lapping is done by means of lapping shoes or quills called laps that are robbed against the work. The face of a lap becomes 'charged' with abrasive particle. Charging a lap means to embed the abrasive grains into surface. Laps may be made of almost of any material soft enough to receive and retain the abrasive grains. They are made of soft iron, brass, copper, lead or soft steel.

The method of charging a lap depends upon the shape of lap. When the lap is once charged it should be used without applying more abrasive until it ceases to cut. Lap may be operated by hand or machine, the motion being rotary or reciprocating.

Cylindrical work may be lapped by rotating the work in the lathe or drill press and reciprocating the lap over the work in an ever-changing path. Small flat surfaces may be lapped by holding the work against a rotating disc, or the work may be moved by hand in an irregular path over a stationary face plate lap. In equalising lapping the work and lap mutually improve each other surfaces as they slide on each other.

There are three important types of lapping machines. The vertical axis lapping machine laps flat or round surfaces between two oppose laps on vertical spindle. The centre-less lapping machine is designed for continuous production of round parts such as piston pins, bearing races and cups, valve tappets and shafts.

The centre less lapping machine on the same principle as centre less grinding. The abrasive belt lapping machine lapps bearings and cam surfaces by means of abrasive coated clothes.

Fluid Mechanics

Chapter – I (Properties of fluid)

Any substance which flows is called as fluid. For example: oil, water, gas. Mechanics deals with the rest and motion of any substance. So fluid mechanics is the study of either rest or motion of any fluid. In this subject we will deal with only liquids. We know that liquid possesses many properties out of which some are described below.

Properties:

Density or Specific mass or Mass Density:—

It is defined as the ratio of mass with volume at standard pressure and temperature.

Mathematically, $\text{Density} = \frac{\text{mass}}{\text{Volume}}$.

It is denoted by 'ρ'. Both S.I. and M.K.S. units are kg/m^3. The density of water is $1000\ kg/m^3$.

Specific weight or weight density:—

It is defined as the ratio of weight with volume at standard pressure and temperature. It is denoted by 'w'. Mathematically, $\text{specific weight} = \frac{\text{Weight}}{\text{Volume}}$

The S.I. unit is N/m^3, while MKS unit is kgf/m^3.

The specific weight of water is $9800\ N/m^3$.

Specific Gravity:—

It is defined as the ratio of the specific weight of any liquid with the specific weight of a standard substance at the standard temperature. For liquids, the pure water at 4°C is taken as the standard substance.

Mathematically, $\text{specific Gravity (any liquid)} = \frac{\text{Specific weight of the liquid}}{\text{Specific weight of pure water at } 4^\circ C}$

It is denoted by 's'. It is unitless.

Mathematically, $S_{liquid} = w_{liquid} / w_{water}$

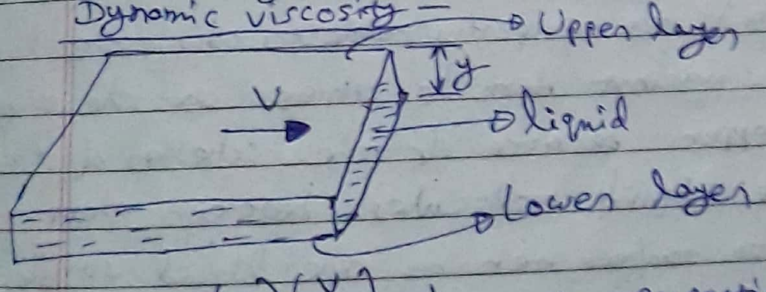
The specific gravity of water is 1, while for Hg (Mercury) it is 13.6.

Specific volume:–
It is defined as the ratio between volume with mass. Mathematically, specific volume = $\frac{\text{volume}}{\text{mass}}$
It is the reciprocal of density.

Viscosity:–
It is defined as the property which resist the movement of one layer of liquid on the other layer (adjacent). It is also the resistance offered against the flow of the liquid.

Newton's law of viscosity:
It states that the shear stress on a layer of fluid is directly proportional to the rate of shear strain. Mathematically, $\tau \propto \frac{v}{y}$
where; τ = shear stress,
v = velocity of fluid or liquid
y = thickness of the liquid layer
$\frac{v}{y}$ = Rate of shear strain or velocity gradient

Dynamic viscosity –



$\therefore \tau = (\mu)\left(\frac{v}{y}\right)$ where; μ = proportionality constant or coefficient of viscosity or coefficient of absolute viscosity or coefficient of dynamic viscosity.
In S.I. system, the unit of 'μ' is poise.
Also unit of 'μ' is $N\text{-}s/m^2$ (S.I.).
1 poise = $0.1\ N\text{-}s/m^2$.
Centipoise (cP) is the smaller unit used.
1 centipoise = $\frac{1}{100}$ of poise.

$\mu = \tau \times \left(\frac{y}{v}\right)$

'μ' is called as the dynamic viscosity.

Kinematic viscosity :-

It is the ratio of the absolute viscosity with the density of the liquid. It is denoted by 'ν' and is the modified form of viscosity.

Mathematically, $\nu = \frac{\mu}{\rho}$

where; μ = absolute viscosity, ρ = density

In S.I., the unit is stoke and also $\frac{m^2}{s}$.

1 stoke = 10^{-4} m^2/s

The smaller unit is centistoke and

1 centistoke = $\frac{1}{100}$ of stoke.

Compressibility :-

It is the property due to which the volume changes with change in pressure. But with change in pressure, the change in volume of water is very small and can be neglected. So, for practical purposes, the water is considered to be incompressible.

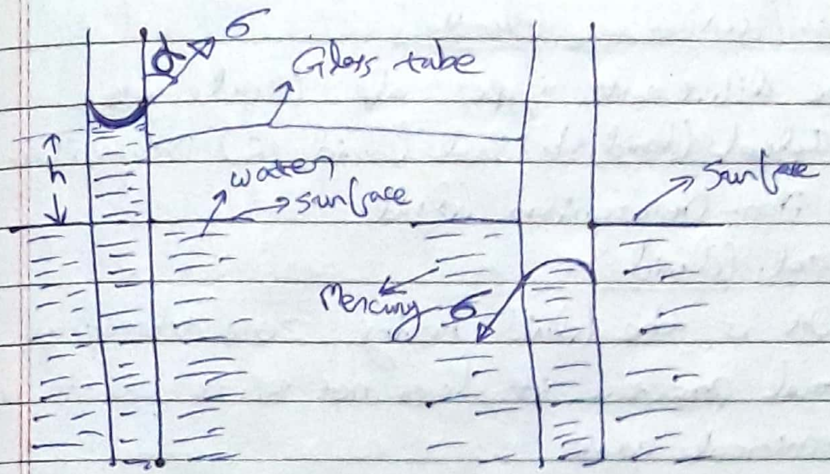
Surface Tension :-

It is the property due to which the liquid resists against tensile stress at the surface. It happens because of the cohesion of the surface liquid molecules between them.

Due to surface tension, the liquid surface tries to reduce its surface as small as possible. Due to this, the rain water drops falling on the earth are of spherical shape. The water surface inside a small glass tube dipped in water becomes concave due to it. It also makes the mercury surface convex when mercury is taken in the glass tube instead of water. It is also used to produce the spherical lead shots.

It is denoted by 'σ' and S.I. unit is N/mm

Capillary :-



When we dip any small diameter glass tube in water, then water rises in the tube having upward concave surface. Here the adhesion between the glass tube and water molecules is more than the cohesion between the water molecules. While taking mercury in the glass tube in place of water, the mercury falls in the tube having downward convex surface. Here the adhesion between glass and mercury molecules is less than the cohesion between mercury molecules. Thus there is either rise or fall of liquid inside the glass tube. This rise or fall is called capillary rise or capillary fall. This property of liquid is called as capillarity.

We know that,

Downward weight of water column in the glass tube = Vertical component of force of surface tension

or, $(wh) \times \frac{\pi}{4} d^2 = (\sigma)(\pi d)(\cos\alpha)$

where; w = specific weight of water,

h = height of capillary rise of water,

d = Diameter of the glass tube

α = angle of contact of water surface with tube

σ = Force of surface tension / unit length of tube or, $h = \frac{4\sigma \cos\alpha}{wd}$

Classification of fluids:

The different types of fluids are;
(a) Ideal fluid, (b) Real fluid, (c) Newtonian fluid, (d) Non-Newtonian fluid.

Ideal fluid:-

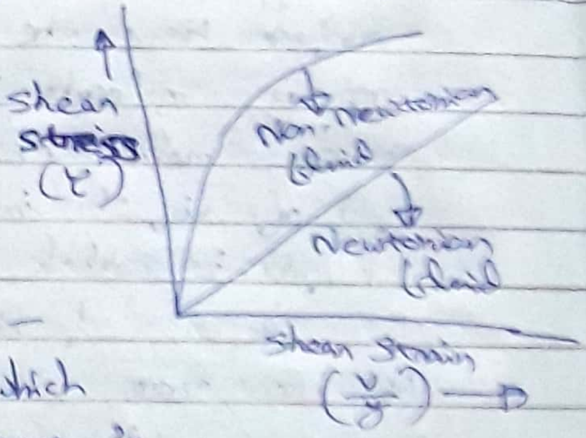
It is the fluid having zero viscosity. In actual practice it does not exist. So it is theoritical case.

Real fluid:-

It is the fluid which possesses some viscosity. Practically all fluids are real fluids.

Newtonian fluid:-

It is the fluid which obeys the Newton's law of viscosity. It is the fluid having no change in viscosity with the rate of deformation. It is represented by the straight line as shown in the side graph.



Non-Newtonian fluid:-

It is the fluid, which does not obey the Newton's law of viscosity.
Here, the viscosity value changes with the rate of deformation or shear strain. In the graph, the Non-Newtonian fluid is shown by a curve.

Problem - 1

The weight of 2.5 m^3 of a liquid was found to be 18.75 KN. Calculate the specific weight and density of the liquid.

Solution

Volume, $V = 2.5 m^3$; weight, $W = 18.75 KN = 18750 N$

Specific weight of liquid, $w = \frac{W}{V} = \frac{18750}{2.5} = 7500 \frac{N}{m^3}$.

Mass of liquid, $m = \frac{W}{\text{Acceleration due to gravity } (g)}$

$= \frac{18750}{9.81} = 1.91 \times 10^3$ Kg.

Density of liquid, $\rho = \frac{m}{V} = \frac{1.91 \times 10^3}{2.5} = 764 \text{ Kg/m}^3$.

Problem - 2

A container having volume of 4 m^3 contains oil having weight equal to 30.2 KN. Calculate the specific gravity of the oil.

Solution

Volume, $V = 4 m^3$; Weight, $W = 30.2 KN = 30200 N$.

Specific weight of oil, $w_{oil} = \frac{W}{V} = \frac{30200}{4} = 7550 \frac{N}{m^3}$

Specific gravity of oil, $S_{oil} = \frac{w_{oil}}{w_{water}} = \frac{7550}{9810} = 0.77$

Problem - 3

The space between two parallel square plates each of side 0.8 m is filled with an oil of specific gravity 0.8. If the space between the plates is 12.5 mm and the upper plate moves with velocity of 1.25 m/s needs force equal to 51.2 N, then calculate both dynamic and kinematic viscosities of oil.

Solution

Side of each square = 0.8 m; $S_{oil} = 0.8$;

~~distance between plates~~

$y = 12.5$ mm $= 0.0125$ m; $V = 1.25$ m/s (velocity);

Force $= 51.2$ N.

Area of square plate $=$ side $\times$ side $= 0.8 \times 0.8 = 0.64 m^2$

Shear stress, $\tau = \frac{Force}{Area} = \frac{51.2}{0.64} = 80$ N/m^2

Again, $\tau = (\mu)\left(\frac{V}{y}\right)$ → Dynamic viscosity

or, $\mu = \frac{(\tau)(y)}{V} = \frac{(80)(0.0125)}{1.25}$

or, $\mu = 0.8 \frac{Ns}{m^2} = 8P$, where $P =$ poise.

Density of oil, $\rho_{oil} = S_{oil} \times \rho_{water}$

$= 0.8 \times 1000 = 800$ kg/m^3

Kinematic viscosity, $\nu = \frac{\mu}{\rho_{oil}} = \frac{0.8}{800}$

or, $\nu = 10^{-3}$ m^2/s $= 10$ stokes.

Problem - 4

Find out the capillary effect for a glass tube of 4mm diameter when immersed in water and in mercury. The surface tension for water and mercury in contact with air are 0.0735 N/m and 0.51 N/m respectively. The contact angle for water and mercury are $0°$ and $130°$ respectively.

Solution

Diameter of tube $d = 4$mm $= 0.004$m;

$\sigma_w = 0.0735$ N/m; $\sigma_{Hg} = 0.51$ N/m; $\alpha_w = 0°$; $\alpha_{Hg} = 130°$

Specific weight of water, $w_w = 9800$ N/m^3

Capillary rise of water, $h_w = \frac{4 \sigma_w \cos\alpha_w}{(w_w)(d)}$

or, $h_w = \frac{4 \times 0.0735 \times \cos 0°}{9800 \times 0.004} = 0.0075$ m

$= 7.5$ mm

Capillary fall of mercury, $h_{Hg} = \frac{4 \times \sigma_{Hg} \times \cos\alpha_{Hg}}{(w_{Hg})(d)}$

$= \frac{4 \times 0.51 \times \cos 130°}{132800 \times 0.004} = -0.00247$ m

$= -2.47$ mm.

Question Bank:

1. Define about fluid mechanics.
2. What do you mean by mass density?
3. Define specific weight with unit (S.I.).
4. Define about specific gravity.
5. What is specific volume of liquid?
6. What do you understand by viscosity?
7. Write down the law of viscosity (Newton's).
8. Define about Dynamic viscosity.
9. Define Kinematic viscosity.
10. Define about compressibility.
11. Write down about surface tension in one sentence.
12. In a single sentence write down about capillarity.
13. What do you mean by ideal fluid?
14. What is real fluid?
15. Define about Newtonian fluid.
16. Define Non-Newtonian fluid.

Long Questions –

17. Write short notes about density, specific weight and specific gravity of liquid.
18. Write briefly about both dynamic and kinematic visosity.
19. Explain briefly about the surface tension and capillarity of liquid.
20. Classify the different types of fluids and write brief notes about them.

Chapter - 2

Fluid Pressure and its measurement

Fluid Pressure :-

Whenever any fluid is kept in a container, then it exerts force at all points of all sides of the vessel. This force acting per unit area is called as fluid pressure. It is measured in Pascal (Pa) and in N/m^2 (SI), in kgf/m^2 (MKS) and also in bar.

Intensity of Pressure :-

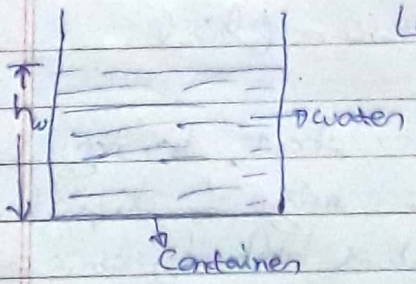
It is the ratio of the force of fluid with the area on which it is acting. It is denoted by 'p'. Mathematically, $p = \frac{F}{A}$

where, F - Force acting and A = Area

The intensity of pressure always acts at right angles to the surface on which fluid supplies force. It is also called as Pressure. It is measured in bar, pascal, N/m^2 and kgf/m^2

$1\ Pa = 1\ N/m^2$

Pressure Head :-



Let the container as shown in figure containing water. This water will produce pressure on all sides and on bottom of the container.

w_w = specific weight of water

h_w = height of water in the container

A = Area of base of the container

The water will exert pressure on the base of the container due to its weight (of the water).

Hence, pressure, $p = \frac{\text{Weight of water}}{\text{Area of container base}}$

or, $p = \frac{w \times h \times A}{A}$

or, $\boxed{p = wh}$ or, $\boxed{h_w = \frac{p}{w}}$

Thus we know that the intensity of pressure is proportional to the height of water above the base, So the pressure can be expressed in terms of depth of water and this height of water is called as pressure head. So hw = Pressure head of water. Both MKS and S.I. units are mt.

Pascal's Law:-

It states that the intensity of pressure at any point in a fluid (which is at rest), is same in all the directions.

Atmospheric pressure:-

It is the pressure of the atmosphere or atmospheric air on the earth surface. As air is compressible, hence its density varies with height temperature and humidity, So, it cannot be calculated like the liquids. But it can be measured by finding the liquid column height which it can support. At the sea level, the pressure exerted by 1m² cross-sectional area air column is 103 KN. So atmospheric pressure at sea level is 103 KN or 103 KPa or 10.3 mt. of water column or 760 mm. of mercury column.

Gauge Pressure:-

The pressure which is measured by using any pressure measuring instrument by taking the atmospheric pressure as datum is called as gauge pressure, Generally the atmospheric pressure is marked as zero on the gauge scale. This gauge pressure is of two types like (a) positive gauge pressure and (b) negative gauge pressure.

Positive gauge pressure:-

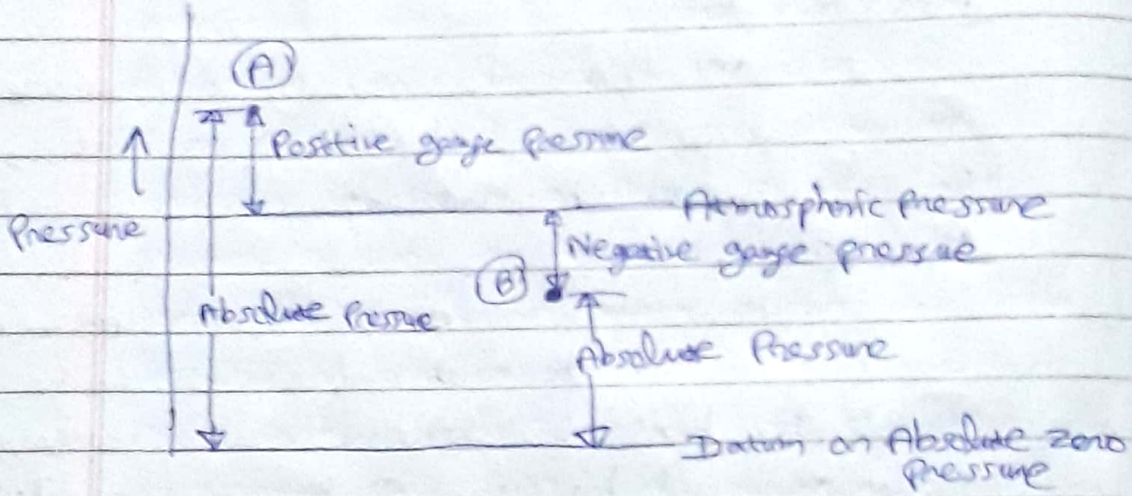
The value of it is positive and it is

above the atmospheric pressure.

Negative Gauge Pressure or Vacuum pressure —

It has negative value and measured below the atmospheric pressure. It is either having unit as N/m^2 or kgf/m^2 or mt.

Absolute Pressure :—



Absolute pressure is the pressure equal to the algebraic sum of atmospheric pressure and gauge pressure. Let 'A' is a point; Then pressure at 'A' from Absolute zero pressure is the absolute pressure at A. Absolute pressure at A = Gauge Pressure at A (positive gauge pressure) + Atmospheric pressure. But Absolute pressure at B = Atmospheric Pressure — Gauge Pressure at B (negative gauge pressure). So, absolute pressure can also be defined as the total pressure measured from the absolute zero pressure.

Mathematically, $P_{Abs.} = P_{atm.} \pm P_{gauge}$

where; P_{Abs} = Absolute Pressure

$P_{atm.}$ = Atmospheric Pressure

P_{gauge} = Gauge Pressure

Hence, $P_{Abs.} = P_{atm.} + P_{gauge}$ (for positive gauge pressure)

and $P_{Abs.} = P_{atm.} - P_{gauge}$ (for vacuum gauge pressure)

Pressure Measurement :-

It can be measured in 2 ways.

(1) By balancing one liquid column whose pressure is to be measured with another liquid column. These are called as tube gauges.

(2) By balancing the liquid column with spring force or dead weight. These are called as mechanical gauges.

Tube gauges -

These are of two types.

(1) Piezometer
(2) Manometer

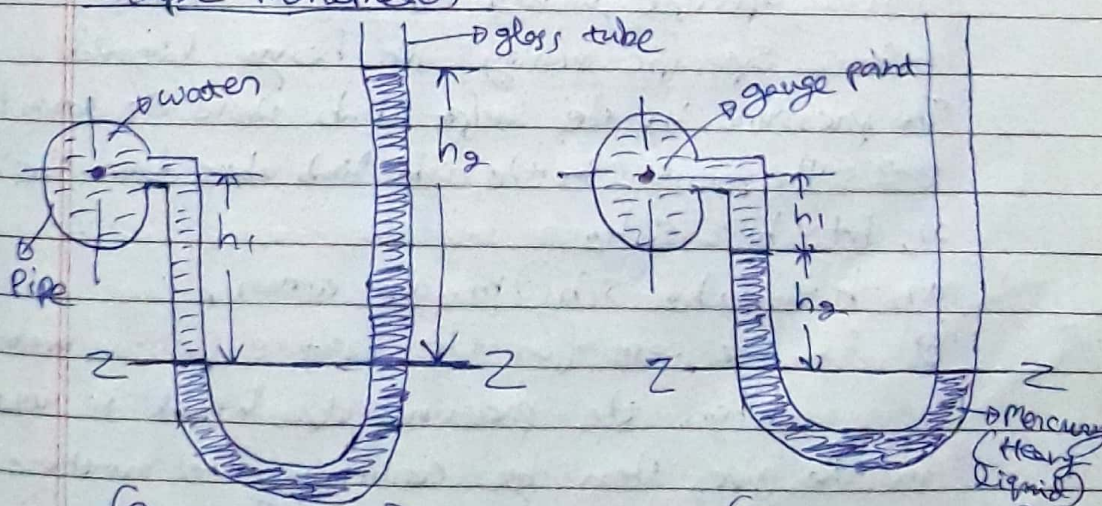
Piezometer -

It is a L-shaped glass tube used to measure positive gauge pressure only.

Manometer -

It is the improved version of piezometer and can measure both positive and negative gauge pressures. The different types are;
Simple manometer, Differential manometer.

Simple manometer -



(Positive Pressure) (Negative Pressure)

The simple manometer is a U-shaped bent glass tube attached to the gauge point for measuring both positive and negative gauge pressure.

and also high pressure. It is also called as U-tube manometer. In the figure the manometer is connected to a pipe containing light liquid (water here) at one end and other end is free to atmosphere. Another heavy liquid (Mercury here) is taken in the U-tube. When connected, the high pressure light liquid will force the heavy liquid in the left limb of U-tube to move downward. Due to this the heavy liquid will rise in the right limb. The datum line or common surface is the line where both heavy and light liquid will meet in the left limb. The Z-Z is the datum line.

h_1 = height of light liquid above the datum line in the left limb in m

h_2 = height of the heavy liquid above the datum line in the right limb in m

h = Pressure of water in the pipe in terms of water head in m

S_1 = Specific gravity of light liquid

S_2 = Specific gravity of heavy liquid

The pressure in the left limb above the datum line Z-Z = The pressure in the right limb above datum line Z-Z

or, $h + S_1 h_1 = S_2 h_2$

or, $h = (S_2 h_2 - S_1 h_1)$ m. of water.

It is the case for the positive pressure measurement.

When the pressure of liquid is negative in the pipe, then by connecting the manometer in the pipe, the heavy liquid (mercury here) will rise in the left limb. The heavy liquid will fall in the right limb. The datum line may be taken as the meeting line of both light and heavy liquid in the left limb or the height of the heavy liquid in the right limb. Here second case is taken as 2-2 line due to simple in calculation.

h_1 = height of light liquid in the left limb above the meeting line of light and heavy liquid

h_2 = height of heavy liquid in the left limb above the datum line 2-2

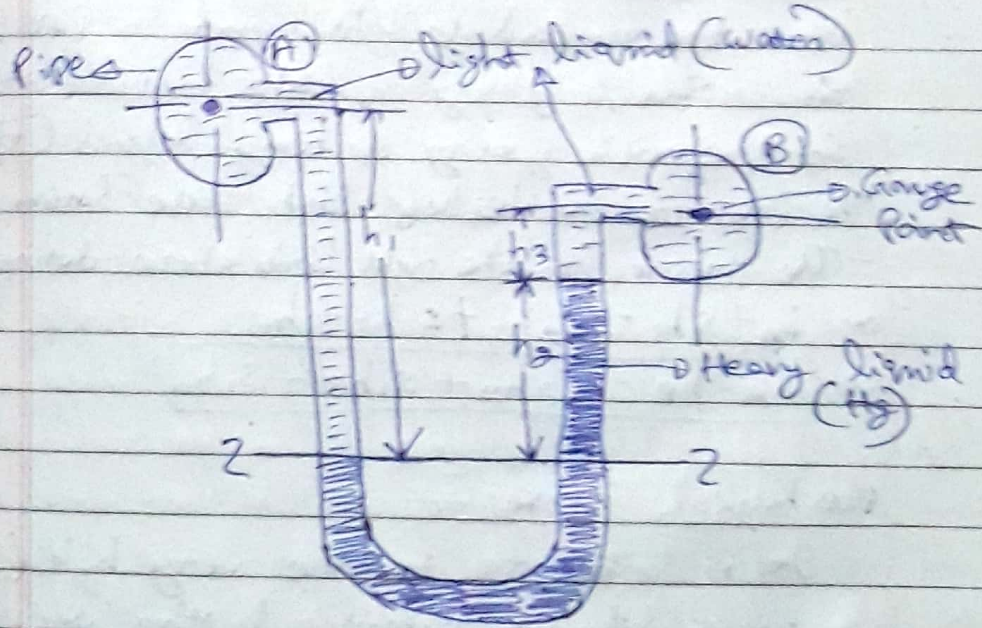
So, Pressure in the left limb above datum line (2-2)
= Pressure in the right limb above datum line (2-2)

or, $h + s_1h_1 + s_2h_2 = 0$

or, $h = -s_1h_1 - s_2h_2 = -(s_1h_1 + s_2h_2)$ m of water

Thus it measures the negative gauge pressure.

Differential manometer —



It is used to measure pressure difference between any two points or between different pipes. The manometer containing heavy liquid (Hg here) is connected with two different pipes having different gauge points named as A and B by means of its two ends. The pipes contain light liquid (water here), where the pressure of liquid at A is more than the pressure of liquid at B. So, the high pressure liquid at A will force the heavy liquid to move downwards in the left limb, while there will be corresponding rise of heavy liquid in the right limb. The meeting line of light and heavy liquid in the left limb is taken as datum line Z-Z here.

h_1 = Height of light liquid in left limb above Z-Z

h_2 = Difference in height of heavy liquid in both left and right limb or reading of differential manometer or manometer reading

h_3 = height of liquid (light) in the right limb above Z-Z

h_A = Pressure head of liquid (light) in Pipe A

h_B = Pressure head of light liquid in Pipe B

S_1 = Specific gravity of light liquid (water)

S_2 = Specific gravity of heavy liquid (Hg)

The pressure in the left limb above datum Z-Z = The pressure in the right limb above datum Z-Z

or, $h_A + S_1 h_1 = S_2 h_2 + S_1 h_3 + h_B$

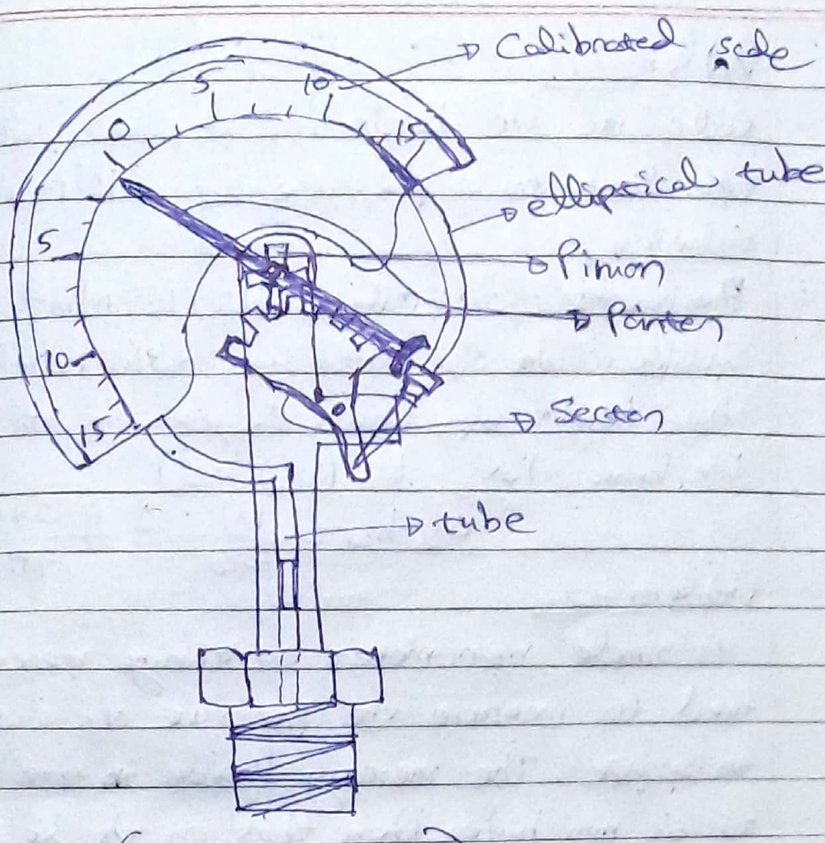
or, $\boxed{h_A - h_B = S_2 h_2 + S_1 h_3 - S_1 h_1}$

Mechanical Gauges —

It is used to measure very high fluid pressures like in boilers and other high pressure equipments (Compressor). The Bourdon's tube pressure gauge is one of the commonly used type.

Bourdon's tube Pressure gauge —

It is used to measure both positive and negative gauge pressure. It consists of an elliptical tube which is called as Bourdon tube.



(Bourdon Tube)

The elliptical tube is encased in a circular cover. The elliptical tube is connected with a tube containing fluid under pressure at the bottom side. So the fluid under pressure enters the elliptical tube and the elliptical tube tries to straighten itself. As it is inside circular cover, so the tube becomes circular. Due to this elastic deformation the sector attached with one end of Bourdon's tube moves. Then the pinion attached with sector also moves. So finally the pointer attached with the pinion rotates over a calibrated scale and shows directly the pressure reading. Thus we can measure the pressure of the fluid directly and get the numerical value of it. This type is most commonly used.

Problem – 1

Calculate the height of a water column equivalent to a pressure of 0.15 MPa.

Solution

Pressure, $p = 0.15$ MPa $= 0.15 \times 10^6$ N/m^2

Specific weight of water, $w_w = 9810$ N/m^3

h_w = height of water column in mt.

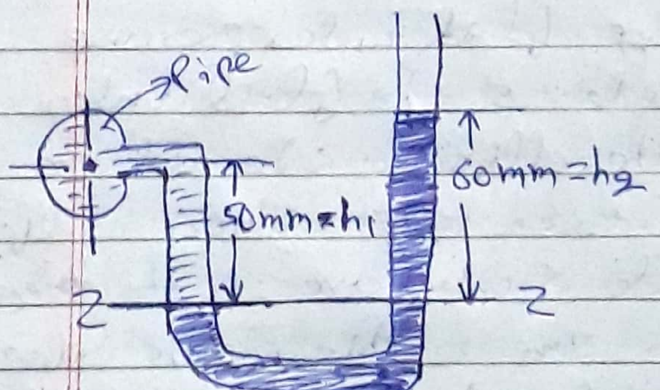
We know that; $p = (w_w)(h_w)$

or, $h_w = \frac{p}{w_w} = \frac{0.15 \times 10^6}{9810} = 15.3$ m

Problem – 2

A simple manometer containing mercury is used to measure the pressure of water flowing in a pipe. The mercury level in the open tube is 60 mm higher than that on the left tube. If the water height in the left tube is 50 mm, then calculate the pressure in the pipe in terms of water head.

Solution



The height of water in the left tube, $h_1 = 50$ mm. The height of mercury in the right tube above the datum line Z-Z, $h_2 = 60$ mm.

h = Pressure in the pipe in terms of water head.

Pressure in the left tube above datum Z-Z
= Pressure in the right tube above datum Z-Z

or, $h + s_1 h_1 = s_2 h_2$; where, s_1 = specific gravity of water, and s_2 = specific gravity of Hg.

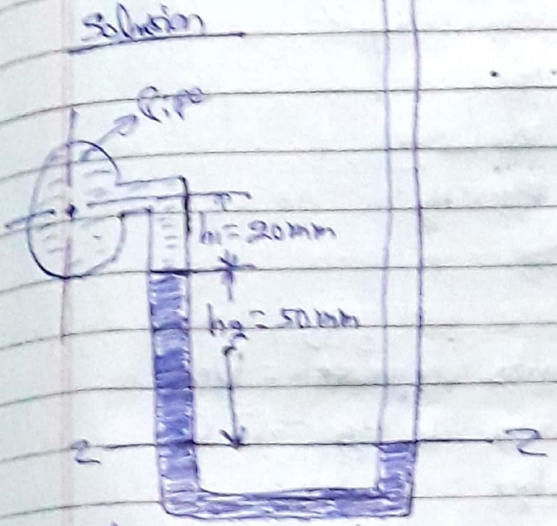
or, $h = h_2 s_2 - s_1 h_1 = 60 \times 13.6 - 1 \times 50 = 766$ mm. of water.

Problem – 3

A simple manometer having mercury was used to

Find the negative pressure in the pipe containing water. The mercury level in the left side above datum line is 50 mm and water level in the left side from the mercury meeting line upto the pipe centre line is 20 mm. Calculate the negative pressure below the atmosphere in the pipe.

Solution



h_1 = height of water from the upper level of Hg upto the centre line of pipe = 20mm (in left side)

h_2 = height of Hg from Datum line 2-2 upto the meeting line of water and mercury in the left tube = 50mm

h = water pressure in the tube in terms of head of water.

Pressure in the left tube above datum 2-2 = Pressure in the right tube above datum 2-2

or, $h + h_1 S_1 + h_2 S_2 = 0$

where, S_1 = specific gravity of water = 1

and S_2 = specific gravity of mercury = 13.6

or, $h = -h_1 S_1 - h_2 S_2 = -20 \times 1 - 50 \times 13.6 = -700mm$

or, $h = -7$ m. of water

Gauge pressure in the pipe, $P = w_w \times h$

where, w_w = specific weight of water

or, $P = 9810 \times (-7) = -68670 \, N/m^2 = -68670$ Pa

$= 68670$ Pa (Vacuum).

Problem-4

A differential manometer connected at the two points A and B at the same level in a pipe

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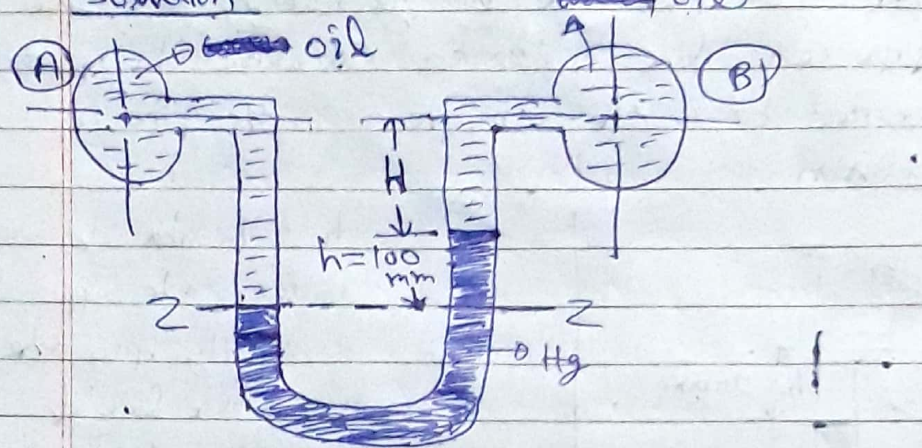
containing an oil of specific gravity 0.8, shows a difference in mercury level as 100 mm. Find out the difference in pressures at the two points.

Solution



S_1 = Specific gravity of oil = 0.8
S_2 = Specific gravity of Hg = 13.6
h = manometer reading = 100 mm
H = Height between upper level of mercury in right tube and pipe centre named as B.

Pressure head in the left limb above datum Z-Z
= Pressure head in the right limb above Z-Z

or, $h_A + S_1H + S_1h = h_B + S_2h + S_1H$

where; h_A = pressure head in pipe having point A,
h_B = Pressure head in pipe having point B.

or, $h_A + 0.8 \times 100 = h_B + 13.6 \times 100$

or, $h_A - h_B = 13.6 \times 100 - 0.8 \times 100 = 1280$ mm. of oil

∴ Pressure difference, $P_A - P_B = w_o (h_A - h_B)$

where, w_o = specific weight of oil
$= w_w \times S_1 = 9810 \times 0.8 = 7848 \ N/m^3$

where, w_w = specific wt. of water

or, $P_A - P_B = 7848 \left(\frac{1280}{1000}\right)$
$= 7848 (1.28)$
$= 10045.44 \ N/m^2$

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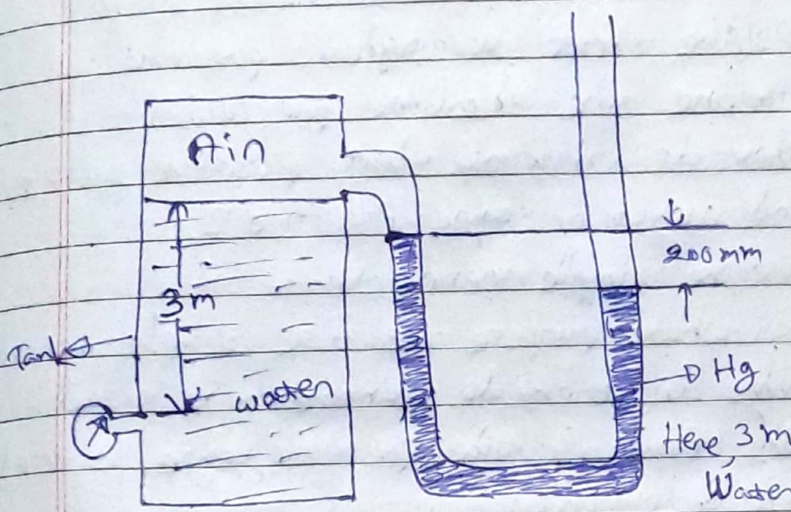
Problem - 5

A closed tank fitted with a gauge and a manometer contains water as shown in figure. Find the gauge reading if the manometer, containing mercury shows a reading of 200 mm.



Here 3m = the available Water head in tank

Manometer reading = 200 mm = 0.2m.

As air is connected to the manometer, so the air pressure will be equal to the manometer reading. As the right side of manometer shows a lower level than the left side, so the air pressure is negative.

Pressure of air (in terms of water head) = -0.2×13.6

$= -2.72$ m (specific gravity of mercury = 13.6).

Gauge reading = water head in tank + Pressure of air

$= 3m + (-2.72) = 0.28$ m. of water.

$\therefore$ Gauge reading (in terms of pressure intensity)

= Specific wt. of water × water head

$= 9810 \times 0.28$

$= 2750$ N/m^2

$= 2750$ Pa.

($\because$ Pressure intensity, $p = w \times h$)

Question Bank (short questions) :-

1. Define fluid pressure and write its S.I. unit
2. What is intensity of pressure ?
3. What do you mean by pressure head and write down the unit ?
4. State the "Pascal's law"
5. Define about atmospheric pressure.
6. Define the absolute pressure.
7. What do you know about positive gauge and negative gauge pressure ?
8. Define simple manometer.
9. For what purpose we use simple manometer?
10. Why differential manometer is used ?
11. Why Bourdon's tube pressure gauge is used ?

Long Questions

12. Write briefly about fluid pressure, intensity of pressure and pressure head of any fluid.
13. Write a short note about atmospheric pressure, positive gauge pressure and negative gauge pressure
14. Explain about the absolute pressure of any fluid in detail
15. Explain about simple manometer, draw the line diagram and derive mathematical derivation to find out both positive and negative gauge pressure heads by using it.
16. Explain the differential manometer with proper diagram and also derive the mathematical derivation for the pressure difference.
17. Explain in detail about the Bourdon's tube pressure gauge with proper diagram

Chapter - 3

Hydrostatics

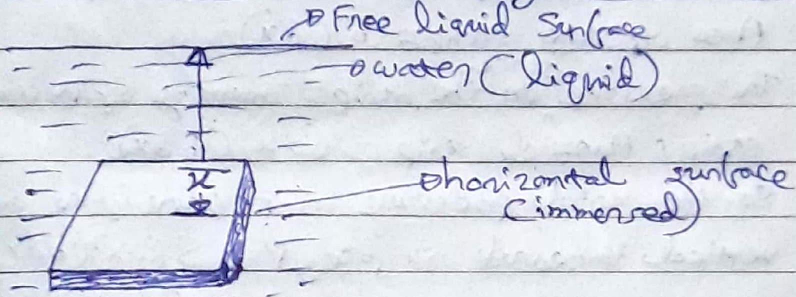
Hydrostatic Pressure:-

It is the pressure exerted by the liquid at rest on any body which is immersed in it. The direction of this pressure is always at right angles with the immersed surface.

Total Pressure:-

It is defined as the total pressure force exerted by the liquid on the immersed surface. The immersed surface may be either in horizontal or vertical position.

Total pressure on horizontally immersed surface -



The plane horizontal surface is immersed in water as shown in the figure.

w = specific weight of the liquid (water)

A = Top area of the immersed surface

$\bar{x}$ = Depth of the horizontal surface from liquid surface

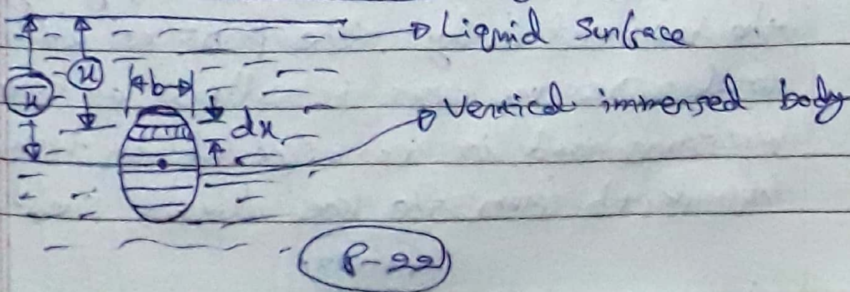
Total pressure on the surface, P = weight of the liquid (water) above the horizontally immersed surface

= specific wt. of the liquid × Area of surface × liquid Depth

Or, $\boxed{P = wA\bar{x}}$

The S.I. unit is N.

Total Pressure on vertically immersed surface -



The plane surface is vertically immersed in the liquid and it is divided into a number of small parallel strips.

Let us take; ω = specific weight of the liquid

A = Total area of the immersed surface

$\bar{x}$ = Depth of Centre of Gravity of the immersed surface from liquid surface

Now take a small strip having width 'b'; thickness as 'dx' and at a depth of 'x' from the free liquid surface.

The intensity of pressure on the strip (small) = $(\omega)(x)$

Area of the strip = $(b)(dx)$

The pressure (force) on the strip = Intensity of pressure on the strip × Area of strip = $(\omega x)(b\,dx)$.

So, the total pressure or pressure force on the vertical immersed surface, $P = \int(\omega x)(b\,dx)$

$= (\omega)\int(x)(b\,dx)$

But, $\int(x)(b\,dx)$ = The moment of the total surface area of immersed body about the liquid level

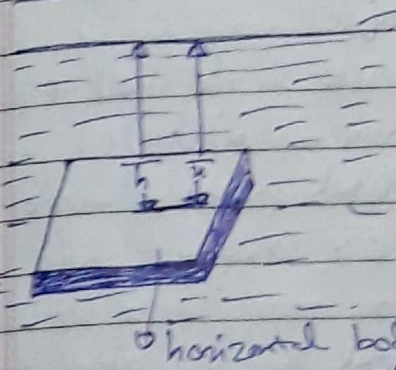
$= (A)(\bar{x})$

So, $\boxed{P = (\omega)A(\bar{x})}$

Centre of Pressure —

The intensity of pressure increases when the depth of the liquid increases, hence the pressure is more over the lower part of the immersed body than the upper part. Hence the resultant force (total pressure) will act at some point below the centre of gravity of the immersed body. The point at which the total pressure acts is called as centre of pressure and it is expressed in terms of its depth from the free liquid surface.

Centre of Pressure for horizontally immersed body—



The horizontal body (rectangular) is immersed in the liquid.

w = specific weight of the liquid

A = Area of the immersed surface

$\bar{x}$ = Depth of C.G. of immersed surface from free surface

$\bar{h}$ = Depth of centre of pressure from free surface

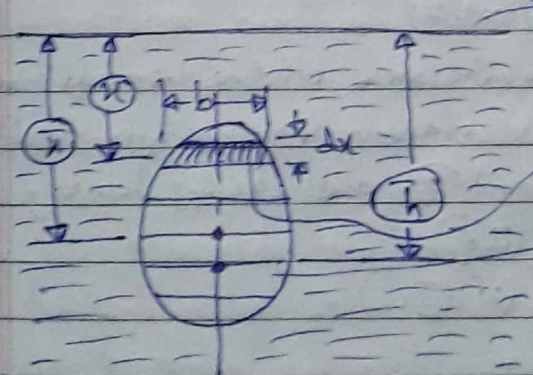
Total Pressure, P = specific weight × Volume of liquid

or, $P = w \times (A)(\bar{x}) = (w)(A)(\bar{h})$

here; $\bar{x} = \bar{h}$

So, $\boxed{\bar{h} = \frac{P}{wA}}$

Centre of pressure of vertically immersed surface—



The plane surface shown above is vertically immersed in liquid and it is divided into a number of small parallel strips.

Let us take, w = specific weight of the liquid

A = Area of the vertical immersed surface

$\bar{x}$ = Depth of centre of gravity of the vertical immersed surface from free surface

Now consider a small strip having breadth "b", thickness 'dx' and having a depth of 'x' from the free liquid surface.

The intensity of pressure on the small strip $= (\omega)(x)$

Area of the small strip $= (b)(dx)$

The pressure force or total pressure on the small strip

$=$ Intensity of Pressure $\times$ Area of strip

$= (\omega)(x)(b\,dx)$

The moment of this total pressure about the liquid surface $= (\omega x)(b\,dx)(x) = (\omega x^2)(b\,dx)$

The sum of moments of all the total pressure about the liquid surface, $M = S(\omega x^2)(b\,dx)$

$= (\omega) S(x^2)(b\,dx)$

But, $S(x^2)(b\,dx) = I_o$ (Moment of Inertia of the vertical immersed surface about the liquid surface or the second moment of area)

Hence, $M = (\omega)(I_o)$ — ①

Again, the sum of the moments of the pressure

$= (P)(\bar{h})$ — ②

where, $P =$ Total Pressure on the vertical immersed surface

$\bar{h} =$ Depth of centre of pressure from liquid surface

As equations ① and ② are equal; hence,

$(P)(\bar{h}) = (\omega)(I_o)$

or, $(\omega A \bar{x})(\bar{h}) = (\omega)(I_o)$

or, $\bar{h} = \dfrac{I_o}{A(\bar{x})}$

Again from the Parallel Axis Theorem;

$I_o = I_G + A h^2$

where, $I_G =$ Moment of Inertia of the vertical immersed surface about the horizontal axis through its centre of gravity and

$h =$ Distance between the liquid surface and centre of gravity of the vertical immersed surface $= \bar{x}$

So, $\bar{h} = \frac{I_G + Ah^2}{A(\bar{x})} = \frac{I_G}{A(\bar{x})} + \frac{A(\bar{x})^2}{A(\bar{x})}$

or, $$\boxed{\bar{h} = \frac{I_G}{A(\bar{x})} + (\bar{x})}$$

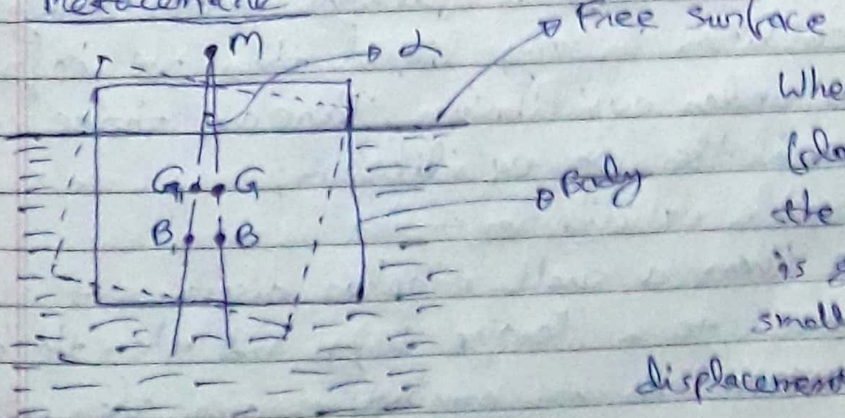
Archimedes' Principle —

It states that when a body is immersed fully or partly in a fluid, then it is buoyed up by a force equal to the weight of the liquid (fluid) displaced by the body. So, when a body is immersed, then the resultant force acting on it is equal to the difference between the downward force due to gravity and upward force of fluid at the bottom of the body.

Buoyancy —

It is the property of the fluid to lift a submerged body in the upward direction due to the upward force of the fluid. The upward force is called as force of buoyancy. It is equal to the weight of the fluid displaced by the submerged body. When the force of buoyancy is more than the body weight (submerged) then the body will float. When the buoyant force is less than the body weight, then the body will sink down.

Metacentre —



When a body floating in the liquid is given small angular displacement, then it starts oscillating about some point and that point is called as metacentre. It is mentioned in the figure as point 'm'. It is also the point of intersection of the line passing through original centre of Buoyancy (B) and centre of gravity of the body and the vertical line through the new centre of Buoyancy (B1).

Metacentric Height —

It is the distance between the centre of gravity of a floating body and the metacentre of the body. Here, GM = Metacentric Height as shown in the figure.

Floatation —

Whenever a body is placed in a liquid, then two forces like gravitational force and upthrust of liquid acts on the body. Both the mentioned forces are opposite in direction to each other. When the gravitational force is less than the upthrust, then the body will float. But if the gravitational force is more than the upthrust of liquid, then the body will sink down in the liquid.

Conditions of equilibrium (Floating Body):—

When a body is floating under steady condition in any liquid then the body is under equilibrium. There are three conditions available for equilibrium;

(a) Stable equilibrium —

When a small angular displacement is given to a floating body and then the body returns to its original position, then only the body is under stable equilibrium.

(b) Unstable equilibrium —

When a small angular displacement is given and the body instead of returning to original position moves further away, then the body is under unstable equilibrium.

(c) Neutral equilibrium —

When a small angular displacement is given and the body achieves a new position of rest then the body is under neutral equilibrium.

Problem-1

A tank 3m × 4m contains 1.2 m deep oil of specific gravity 0.8. Calculate the intensity of pressure at the base of the tank and total pressure on the base of the tank.

Solution

Given data,

size of the tank, $A = 3m \times 4m = 12\ m^2$;

Depth of oil, $\bar{x} = 1.2\ m$;

Specific gravity of oil, $S_o = 0.8$;

Specific weight of oil, $w_o = S_o \times w_w$

$= 0.8 \times 9810$

$= 7850\ N/m^3$

where, w_w = specific weight of water

$= 9810\ N/m^3$

Intensity of pressure at the base of the tank,

$p = w_o \times h$

$= 7850 \times 1.2 = 9420\ N/m^2$

where, h = depth of oil.

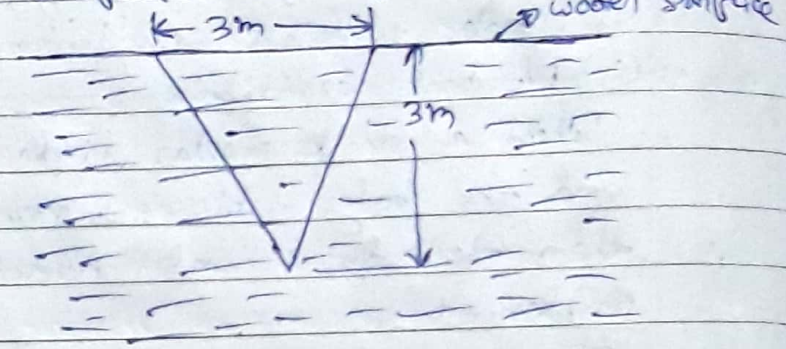
Total pressure on the base of the tank,

$P = w_o A \bar{x}$

$= 7850 \times 12 \times 1.2 = 113040\ N$.

Problem – 2

An isosceles triangular plate of base 3m and altitude 3m is immersed vertically in water as shown in the figure. Calculate the total pressure and centre of pressure of the plate.



Solution

Given data; Width of the base, $b = 3m$;

Altitude of the triangle, $h = 3m$.

Surface area of the triangular plate,

$$A = \frac{bh}{2} = \frac{3 \times 3}{2} = 4.5 \, m^2$$

Depth of centre of gravity of the triangular plate from the water surface, $\bar{x} = \frac{3}{3} = 1m$.

Total pressure on the plate, $P = w_o A \bar{x}$

$= (9810)(4.5)(1) = 44100 N$

where; w_o = specific weight of water

Moment of Inertia of the triangular plate about its centre of gravity and parallel to the water surface (free surface),

$$I_G = \frac{bh^3}{36} = \frac{3(3)^3}{36} = 2.25 \, m^4$$

The depth of centre of pressure from the water surface, $\bar{h} = \frac{I_G}{A\bar{x}} + \bar{x}$

$$= \frac{2.25}{(4.5)(1)} + 1$$

$= 1.5 m$

Question Bank

Short questions;

1. Define about hydrostatic pressure.
2. Define total pressure of liquid on immersed body.
3. Define the term centre of pressure on immersed body in the liquid.
4. Write down the mathematical equation for total pressure on a horizontal immersed body.
5. Write down the mathematical formula for total pressure on a vertical immersed body.
6. Define Archimede's principle.
7. Define about the term buoyancy.
8. What do you mean by metacentre?
9. What is metacentric height?
10. What do you understand by floatation?

Long Questions

11. Derive the mathematical equation for finding the total pressure on a horizontally immersed surface.
12. Derive the mathematical expression for finding out the total pressure on a vertical immersed surface in liquid.
13. Derive the mathematical equation to find out the centre of pressure for a horizontal immersed surface in any liquid.
14. Find out the mathematical equation by deriving for the centre of pressure when a vertical body is immersed in liquid.
15. Write short notes about the buoyancy and floatation.

Chapter-4

Kinematics of Flow

Types of Fluid Flow:-

There are many types or ways in which the fluid particles may flow and they are as follows

① Uniform flow –

When the velocities of different fluid particles are equal at all sections of any conduit through which the particles flow, then the type of flow is called as uniform flow.

② Non-uniform flow –

If the velocities of different fluid particles are different at all sections of any conduit, then the type of flow is called as non-uniform flow.

③ Steady flow –

When the quantity of fluid flowing per time period is constant, then the type of flow is called as steady flow.

④ Unsteady flow –

When the quantity of fluid flowing per time period is not constant, then the type of flow is called as unsteady flow.

⑤ Streamline flow –

When each fluid particle in a fluid flow has a particular path and the paths of different particles donot cross with each other, then the flow is called as streamline flow.

⑥ Turbulent flow –

When each fluid particle does not possess a particular path and the paths of different particles cross with each other, then the flow is called as turbulent flow.

⑦ Rotational flow –

When the fluid particles while flowing also rotate about their own axis, then the flow is called as rotational flow.

⑧ Irrotational flow —

If the fluid particles at the time of flowing, donot rotate about their own axis, then the flow is called as irrotational flow.

⑨ Compressible flow —

If the density of the fluid changes during flow, then it is called as compressible flow.

⑩ Incompressible flow —

If the density of the fluid doesnot change during the flow, then it is called as incompressible flow.

⑪ One-dimensional flow —

When the streamlines of flowing particles are represented by a straight line and as straight line has only one dimension, then the flow is called as one-dimensional flow.

⑫ Two-dimensional flow —

When the streamlines of flowing particles are represented by a curve and as curve possesses two mutually perpendicular directions, then the flow is called as two-dimensional flow.

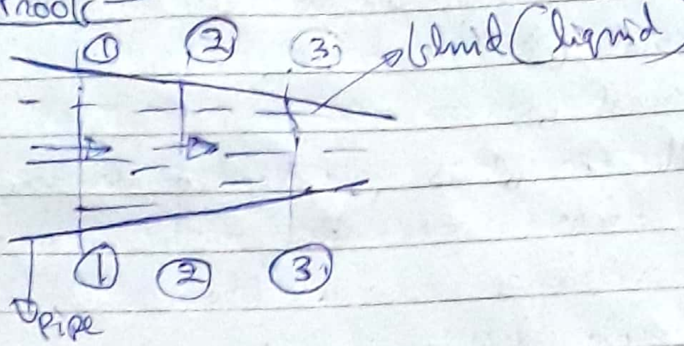
⑬ Three-dimensional flow —

When the streamlines of flowing particles are represented in space and as space has three mutually perpendicular directions, then the flow is called as three-dimensional flow.

Continuity Equation :—

It states that when any incompressible fluid is flowing continuously through a conduit, then the quantity of fluid passing per time period is same at all the sections of the conduit.

Proof:—



Let us take a tapered pipe as shown in above, through with liquid is flowing.

Let us assume; a_1 = area of cross-section of pipe at 1-1,

V_1 = velocity of liquid at section 1-1,

a_2 = area of cross-section of pipe at section 2-2,

V_2 = velocity of liquid at section 2-2,

a_3 = area of cross-section of pipe at 3-3

V_3 = Velocity of liquid at section 3-3

Total quantity of liquid passing at section 1-1,

$Q_1 = (a_1)(V_1)$

Total quantity of liquid passing at section 2-2,

$Q_2 = (a_2)(V_2)$

Total quantity of liquid passing at section 3-3,

$Q_3 = (a_3)(V_3)$

According to the law of conservation of matter the total quantity of liquid flowing through all the sections must be same.

So, $Q_1 = Q_2 = Q_3$

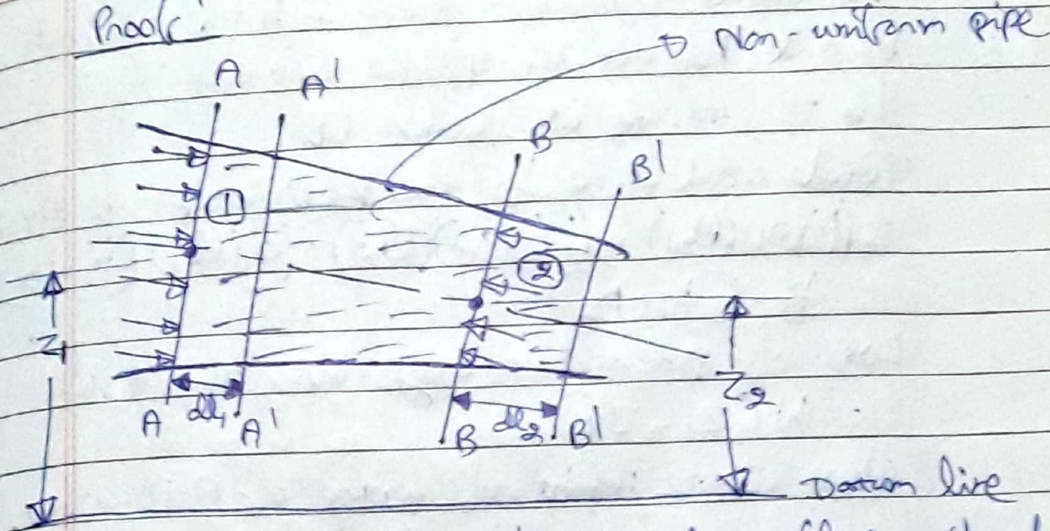
or, $a_1V_1 = a_2V_2 = a_3V_3$

or, $Q_1 = a_1V_1 = Q_2 = a_2V_2 = Q_3 = a_3V_3$.

Bernoulli's Equation:—

It states that when a perfect, incompressible liquid is flowing continuously in a conduit, then the total energy possessed by liquid particles remains same at all sections of the conduit.

Proof:



The perfect, incompressible liquid is flowing through the tapered pipe as shown in the figure both continuously and fully. The AA and BB are two sections of the pipe. The liquid available between sections AA and BB is assumed to move to sections A'A' and B'B' through very small distances of dl_1 and dl_2. Thus the liquid (equivalent) between AA and A'A' is moved to the section between BB and B'B', while liquid between A'A' and BB remains unaffected.

Suppose, W = weight of the liquid between AA and A'A'

or, $W = wa_1 dl_1 = wa_2 dl_2$

where; a_1 = area of cross-section of pipe at AA

a_2 = area of cross-section of pipe at BB

w = specific weight of liquid flowing

or, $a_1 dl_1 = a_2 dl_2 = \frac{W}{w}$

or, $a_1 dl_1 = a_2 dl_2$

Now, the work done by pressure for moving the liquid from section AA to section A'A'

= Force × distance $= (p_1)(a_1)(dl_1)$

where p_1 = pressure of liquid at AA

Work done by pressure for moving the liquid from section BB to section B'B'

$= (-p_2)(a_2)(dl_2)$

The minus sign is given with p_2 as both p_1 and p_2 act in opposite directions.

p_2 = pressure at section BB

Total work done by the pressure of the liquid

$= (p_1)(a_1)(dl_1) - (p_2)(a_2)(dl_2) = (a_1)(dl_1)(p_1 - p_2)$

$= \frac{W}{\omega}(p_1 - p_2)$

Loss of potential energy of the liquid

$= W(Z_1 - Z_2)$

where, Z_1 = Height of centre of A-A section from the datum line

Z_2 = Height of centre of B-B from datum

Gain in kinetic energy $= W\left(\frac{V_2^2}{2g} - \frac{V_1^2}{2g}\right)$

$= \frac{W}{2g}(V_2^2 - V_1^2)$

where, V_1 = velocity of liquid at section A-A

V_2 = velocity of liquid at section B-B

g = acceleration due to gravity

Again; Work done by pressure of liquid + Loss of Potential energy of liquid = Gain in kinetic energy of the liquid

or, $\frac{W}{\omega}(p_1 - p_2) + W(Z_1 - Z_2) = \frac{W}{2g}(V_2^2 - V_1^2)$

or, $$\boxed{\frac{p_1}{\omega} + Z_1 + \frac{V_1^2}{2g} = \frac{p_2}{\omega} + Z_2 + \frac{V_2^2}{2g}}$$

Limitations of Bernoulli's equation:-

(1) In Bernoulli's theorem, it is assumed that the velocity of every liquid particle at any cross-section of the pipe is uniform. But the velocity of liquid particles at the centre of the pipe is maximum and reduces towards the pipe wall because of friction. So, actually mean velocity is taken.

(2) It is also assumed that except the gravitational force, there is no other external

force acting on the liquid. But actually external force like pipe friction is available.

(3) The other assumption is that there is no loss of energy from the liquid particles. But in actual practice, some energy losses occur.

(4) When the liquid is flowing in a curved path, then we have to consider the energy due to centrifugal force.

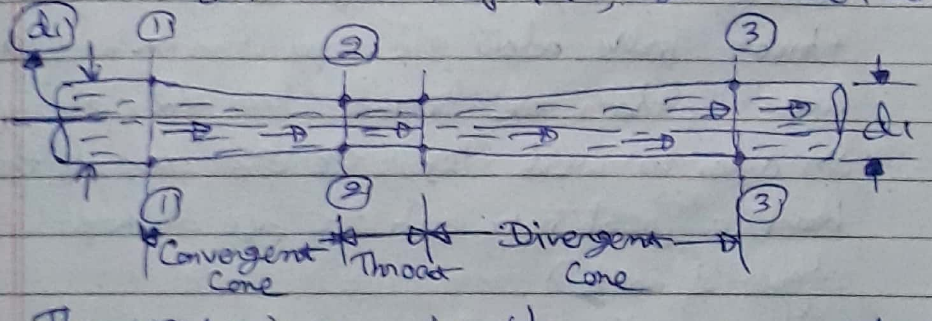
(5) It is also assumed that the liquid is perfect. But in actual practice, there is no perfect liquid which means that all liquids are real.

Applications of Bernoulli's theorem:-

This theorem is generally applied in hydraulics and applied hydraulics. The other practical applications are;

(a) Venturimeter —

d_1 = larger diameter of pipe, d_2 = smaller diameter.



The venturimeter is the apparatus used to find out the discharge (Q) of a liquid flowing in a pipe by applying Bernoulli's equation. It has three main parts like; (i) Convergent part, (ii) Throat, (iii) Divergent Part.

Convergent part —

It is the part of the pipe which gradually reduces from pipe diameter (d_1) to a smaller diameter of pipe (d_2). It is also called as the inlet of the venturimeter. The slope of the convergent cone generally varies from 1 in 4 to 1 in 5.

Throat –

It is the part having the smaller diameter of the pipe (d_2).

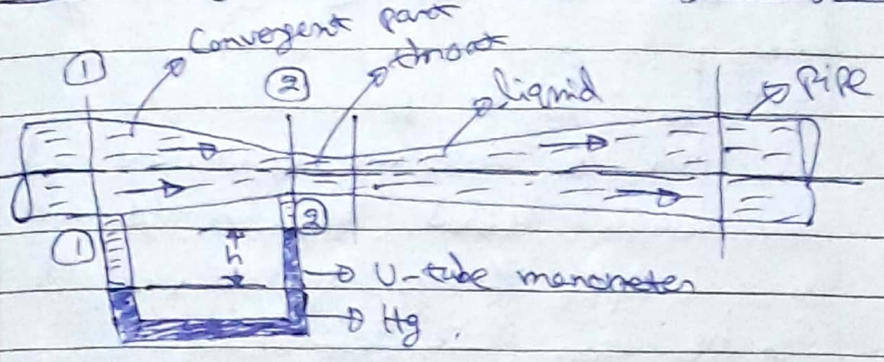
Divergent part –

It is the part having gradual increase in diameter from lower diameter (d_2) upto the higher diameter (d_1). It is also called as the outlet part. The length of this part is 3 to 4 times more than convergent part.

As the liquid gets accelerated while flowing from convergent part to throat (section 1 to section 2), so velocity at the throat becomes higher than velocity of liquid at section 1, so the pressure at the throat is reduced as compared to the convergent part. If the pressure head at throat falls below the separation head (2.5 m of water), then the liquid flow tends to separate. In order to avoid this, the diameter of throat bears a fixed ratio with the pipe diameter (Generally $\frac{d_2}{d_1} = \frac{1}{3}$ to $\frac{1}{2}$).

The liquid when flows through the divergent part, deacceleration occurs and hence the pressure at the outlet of divergent part becomes more. When the increase in pressure becomes quick, then liquid particles break away from the wall because of boundary layer effect. To avoid this and also to minimise the losses due to friction, the divergent part length is made more than the length of the convergent part.

Equation for calculation of discharge through Venturimeter



The liquid is flowing in the venturimeter as shown in the figure and an U-tube manometer is connected between the convergent part and throat. The U-tube manometer contains heavy liquid mercury and shows the manometer reading of h.

p_1 = pressure at section 1

V_1 = velocity of liquid at section 1

Z_1 = Datum head at section 1

a_1 = area of the venturimeter at section 1

p_2 = pressure at section 2

V_2 = velocity of liquid at section 2

Z_2 = Datum head at section 2

a_2 = area of the venturimeter at section 2

Applying Bernoulli's equation, we get,

$$\frac{p_1}{w} + Z_1 + \frac{V_1^2}{2g} = \frac{p_2}{w} + Z_2 + \frac{V_2^2}{2g}$$

where, w = specific weight of the liquid

As the pipe is horizontal, so both datum heads are equal. Hence, $Z_1 = Z_2$.

So, $$\frac{p_1}{w} + \frac{V_1^2}{2g} = \frac{p_2}{w} + \frac{V_2^2}{2g}$$

or, $$\frac{p_1}{w} - \frac{p_2}{w} = \frac{V_2^2}{2g} - \frac{V_1^2}{2g} \quad \text{--- (1)}$$

As per continuity equation,

$$a_1 V_1 = a_2 V_2 \text{ or, } V_1 = \frac{a_2 V_2}{a_1}$$

Putting the value of V_1 in equation (1);

$$\frac{p_1}{w} - \frac{p_2}{w} = \frac{V_2^2}{2g} - \left(\frac{a_2}{a_1}\right)^2 \left(\frac{V_2^2}{2g}\right)$$

or, $\frac{p_1}{w} - \frac{p_2}{w} = \frac{V_2^2}{2g}\left(1 - \frac{a_2^2}{a_1^2}\right) = \frac{V_2^2}{2g}\left(\frac{a_1^2 - a_2^2}{a_1^2}\right)$

Let $\frac{p_1}{w} - \frac{p_2}{w} = h_l$

where, h_l = Difference of pressure head of liquid flowing in the venturimeter between convergent part and throat.

So, $h_l = \frac{V_2^2}{2g}\left(\frac{a_1^2 - a_2^2}{a_1^2}\right)$

or, $V_2^2 = (2g)(h_L)\left(\frac{a_1^2}{a_1^2 - a_2^2}\right)$

or, $V_2 = \sqrt{2g(h_L)} \times \frac{a_1}{\sqrt{a_1^2 - a_2^2}}$

Discharge through the venturimeter,

$Q = C_v \times a_2 V_2$

or, $Q = C_v \times \frac{a_1 a_2}{\sqrt{a_1^2 - a_2^2}} \times \sqrt{2gh}$

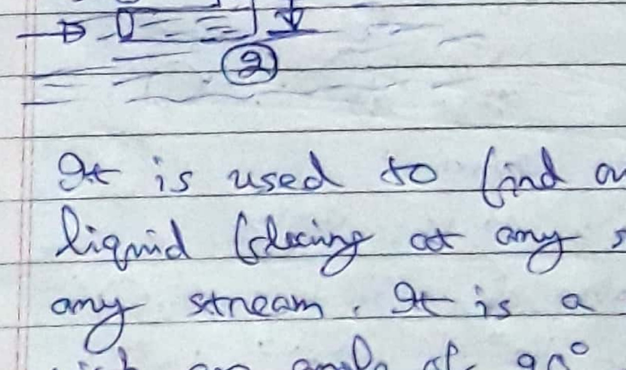
where, C_v = Coefficient of Venturimeter

Also, $h_l = h\left(\frac{S_{Hg} - S_l}{S_l}\right)$

where, S_{Hg} = Specific gravity of Hg

S_l = Specific gravity of liquid

Pitot Tube –



It is used to find out the velocity of liquid flowing at any required point in any stream. It is a glass tube bent with an angle of 90°. The lower end of tube faces the direction of flow and liquid rises in the tube because of the pressure of liquid (flowing).

h = height of liquid in the tube above free surface of liquid

H = Depth of the tube inside the flowing liquid

v = velocity of the flowing liquid

Applying Bernoulli's equation between section ① and ②

$$\frac{p_1}{\omega} + z_1 + \frac{v_1^2}{2g} = \frac{p_2}{\omega} + z_2 + \frac{v_2^2}{2g}$$

For section ① and ② ; $z_1 = z_2$

So, $\frac{p_1}{\omega} + \frac{v_1^2}{2g} = \frac{p_2}{\omega} + \frac{v_2^2}{2g}$

where, z_1 = Datum head at section 1;

z_2 = Datum head at section 2;

p_1 = Pressure at section 1;

p_2 = pressure at section 2;

ω = specific wt. of the liquid

But, $\frac{p_1}{\omega} = H$ and $\frac{p_2}{\omega} = H+h$

Hence, $H + \frac{v_1^2}{2g} = H+h+0$

because, $v_2 = 0$ as the velocity of liquid in the tube becomes zero at section 2 and then liquid rises

v_1 = velocity of liquid at section 1 = v

v_2 = velocity of liquid at section 2

So, $H + \frac{v^2}{2g} = H+h$

or, $\frac{v^2}{2g} = h$

or, $v^2 = 2gh$

or, $v = \sqrt{2gh}$

Problem-1

Water is flowing through a pipe of 100mm diameter with an average velocity of 10 m/s. Calculate the rate of discharge of water and the velocity of water at the other end of the pipe. The diameter of the pipe is gradually changed to 200mm.

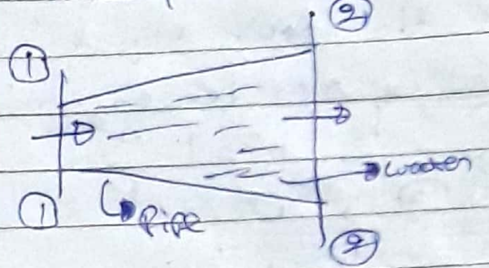
Solution

Given data; $d_1 = 100mm = 0.1m$, $V_1 = 10m/s$,

$d_2 = 200mm = 0.2m$.

Cross-sectional area of pipe at point 1 (section 1),

$a_1 = \frac{\pi}{4} d_1^2 = \frac{\pi}{4} \times (0.1)^2 = 0.007854 \; m^2$



Rate of discharge,

$Q = a_1 V_1$

$= (0.007854)(10)$

$= 0.07854 \; m^3/s$.

Cross-sectional area of pipe at section 2,

$a_2 = \frac{\pi}{4} (d_2)^2 = \frac{\pi}{4} (0.2)^2 = 0.03142 \; m^2$

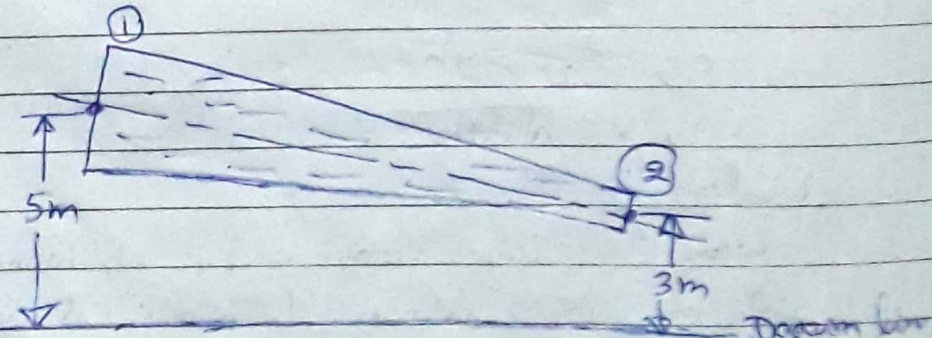
Velocity of water at section 2, $V_2 = \frac{Q}{a_2}$

$= \frac{0.07854}{0.03142} = 2.5 \; m/s$.

Problem-2

The diameter of a pipe changes from 200mm at a section 5m above datum to 50mm at a section 3m above datum. The pressure of water at 1st section is 500 KN/m^2, the velocity of flow at the same section is 1m/s, calculate the pressure intensity at the second section.

Solution



Given data; $d_1 = 200mm = 0.2m$,

$z_1 = 5m$, $d_2 = 50mm = 0.5m$,

$Z_2 = 3m$, $P_1 = 500\ KN/m^2$, $V_1 = 1m/s$

P_2 = pressure at section 2, V_2 = velocity at section 2

Area of pipe at section 1, $a_1 = \frac{\pi}{4}(d_1)^2 = \frac{\pi}{4}(0.2)^2$
$= 0.03142\ m^2$

Area of pipe at section 2, $a_2 = \frac{\pi}{4}(d_2)^2 = \frac{\pi}{4}(0.05)^2$
$= 0.001964\ m^2$

Applying continuity equation; $a_1V_1 = a_2V_2$

or, $V_2 = \frac{a_1V_1}{a_2} = \frac{(0.03142)(1)}{0.001964} = 16\ m/s$.

Applying Bernoulli's equation,

$$\frac{P_1}{w} + Z_1 + \frac{V_1^2}{2g} = \frac{P_2}{w} + Z_2 + \frac{V_2^2}{2g}$$

or, $\frac{500}{9.81} + 5 + \frac{(1)^2}{2 \times 9.81} = \frac{P_2}{9.81} + 3 + \frac{(16)^2}{2 \times 9.81}$

or, $51 + 5 + 0.05 = \frac{P_2}{9.81} + 3 + 13.05$

or, $\frac{P_2}{9.81} = 40$ or, $P_2 = 40 \times 9.81 = 392.4\ KN/m^2$

Problem-3

A venturimeter with a 150 mm diameter at inlet and 100 mm at throat is laid with its axis horizontal and is used for measuring the flow of oil having specific gravity 0.9. The oil-mercury differential manometer shows a gauge difference of 200 mm. The coefficient of venturimeter is assumed to be 0.98. Calculate the discharge of oil.

Solution

Given data; $d_1 = 150mm = 0.15m$; $d_2 = 100mm = 0.1m$,

Specific gravity of the oil, $S_o = 0.9$;

Gauge difference, $h = 200mm = 0.2m$ of Hg,

Coefficient of Venturimeter, $C_v = 0.98$

Area at the inlet, $a_1 = \frac{\pi}{4}(d_1)^2$
$= \frac{\pi}{4}(0.15)^2$
$= 0.01767\ m^2$

Area at the throat, $a_2 = \frac{\pi}{4}(d_2)^2 = \frac{\pi}{4}(0.1)^2$
$= 0.007854\ m^2$

Difference of pressure head of oil flowing through the venturimeter between section ① and section ②, $h_2 = h\left(\frac{S_{Hg} - S_o}{S_o}\right)$

$$= (0.2)\left(\frac{13.6 - 0.9}{0.9}\right)$$

$$= 2.82 \text{ m of oil}$$

Discharge through the venturimeter,

$$Q = \frac{(C_v)(a_1 a_2)}{\sqrt{a_1^2 - a_2^2}}\left(\sqrt{2gh}\right)$$

$$= \frac{(0.98)(0.01767)(0.007854)}{\sqrt{(0.01767)^2 - (0.007854)^2}}\left(\sqrt{2\times 9.81\times 2.82}\right)$$

or, $Q = 0.0639 \text{ m}^3/\text{s}$.

Problem-4

A pitot tube was inserted in a pipe to measure the velocity of water in it. If the water rises in the tube is 200 mm, find the velocity of water.

Solution

Given data; $h = 200 \text{ mm}$

$= 0.2 \text{ m}$

Velocity of water in the pipe,

$$V = \sqrt{2gh}$$

where, g = acceleration due to gravity

$= 9.8 \text{ m/sec}^2$

or, $V = \sqrt{2\times 9.81\times 0.2}$

or, $V = 1.98 \text{ m/s}$.

Question Bank

Date ______
Page ______

Short Questions

(1) Define Uniform fluid flow.
(2) Define about Non-uniform fluid flow.
(3) What is steady fluid flow?
(4) What do you mean by unsteady fluid flow?
(5) What is streamline flow?
(6) Define about turbulent fluid flow.
(7) What do you understand by rotational flow?
(8) What is irrotational flow?
(9) Define about compressible flow.
(10) Define incompressible fluid flow.
(11) What is one-dimensional flow?
(12) Define about the two-dimensional flow.
(13) What is three-dimensional flow?
(14) State Continuity equation for one-dimensional flow.
(15) State Bernoulli's equation.
(16) Why Venturimeter is used?
(17) For what purpose pitot tube is used?

Long Questions

(18) State and proove the continuity equation for one-dimensional fluid flow.
(19) State and proove the Bernoulli's equation for fluid flow.
(20) Write in brief the limitations of Bernoulli's equation.
(21) Write a short note about Venturimeter.
(22) Derive the equation to find out the discharge of flowing fluid through venturimeter.
(23) Explain in brief about Pitot tube.

Chapter-5

Orifices, Notches, Weirs

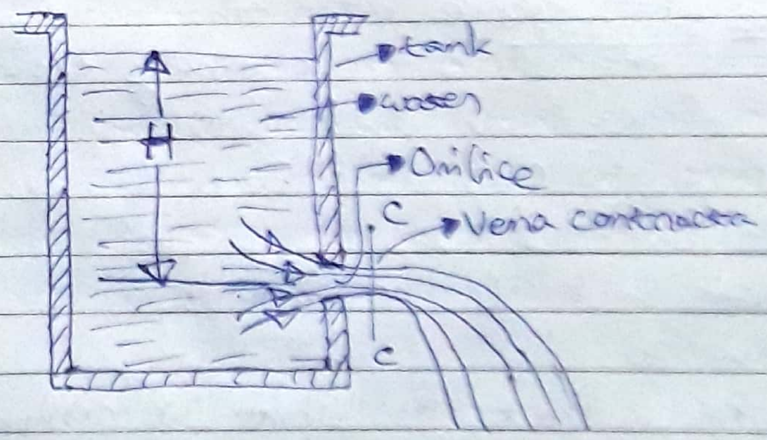
Orifice:-

Orifice is defined as an opening in a vessel through which liquid comes out and the liquid level on the upstream side is above the top of the orifice. It is used to measure the discharge of liquid. It may be provided in the vertical side or along the base.

Types of Orifice:-

1. According to size;
(a) Small orifice, (b) Large orifice
2. According to shape
(a) Circular orifice, (b) Rectangular orifice, (c) Triangular orifice
3. According to the type of discharge
(a) Fully submerged orifice, (b) Partially submerged orifice

Flow through Orifice:-



The tank as shown above contains water and fitted with an orifice at one side. The water flows out through the orifice. The water particles above the orifice taking a turn in order to pass through the orifice. By making this turn the water particles lose some of the energies possessed by them. So the water jet (water coming out of orifice) becomes contracted after leaving the orifice. The maximum contraction of water jet occurs at a particular section on the downstream side of the orifice. At this section the water particles become parallel with each other. This section is called as vena contracta and in the figure it is shown by section C-C. The position of this section is generally at a distance of $\frac{d}{2}$ from the orifice in the downstream side (d = diameter of the orifice). After venacontra the water particles are attracted by the gravitational pull force of the earth, so the cross-section of water jet increases after venacontracta and the water jet moves in the downward direction.

Velocity of the water jet (theoritical), $v = \sqrt{2gH}$

where, H = Head of water available in the upstream side of the orifice in the tank

So, theoritical Discharge, $Q_{th} = (a)\sqrt{2gH}$

where, a = area of cross-section of the orifice

Hydraulic coefficients :-

The orifice has four types of hydraulic coefficients.

① Coefficient of Contraction —

It is defined as the ratio of area of water jet at the vena-contracta with the area of orifice. It is denoted by C_c. Mathematically,

$$C_c = \frac{\text{Area of jet (water) at vena-contracta}}{\text{Area of the orifice}}$$

The average value of C_c is 0.64. The value of C_c depends on the head available, size and shape of orifice.

② Coefficient of velocity —

It is defined as the actual velocity of the water jet at the vena-contracta with the theoritical velocity of water jet, It is denoted by Cv. Mathematically,

$$C_v = \frac{\text{Actual jet velocity at vena contracta}}{\text{Theoritical jet velocity}}$$

The average value is 0.97. It depends upon the different shapes of orifice edges and also on the orifice size.

③ Coefficient of dischage —

It is defined as the ratio between the actual discharge through the orifice with the theoritical discharge through the orifice. It is denoted by Cd, Mathematically,

$$C_d = \frac{\text{Actual dischage}}{\text{Theoritical dischage}}$$

The average value of it varies from 0.6 to 0.64, It also depends upon shape and size of the orifice.

④ Coefficient of resistance —

It is defined as the ratio between loss of head in the orifice with the available head of water at the orifice exit. It is denoted by Cr, Mathematically,

$$C_r = \frac{\text{head loss in the orifice}}{\text{Head of water available at orifice exit}}$$

As the value is very less, hence the value of it is neglected while solving problems.

Relation between Hydraulic coefficients —

$$C_d = \frac{\text{Actual discharge of water jet}}{\text{Theoritical discharge of water jet}}$$

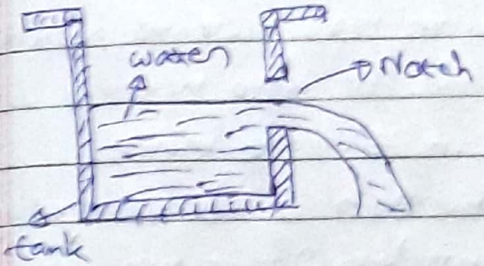
$$= \frac{\text{Actual velocity} \times \text{Actual area}}{\text{Theoritical velocity} \times \text{Theoritical area}}$$

$$= \frac{\text{Actual velocity}}{\text{Theoritical velocity}} \times \frac{\text{Actual area}}{\text{Theoritical area}}$$

$$= C_v \times C_c$$

or, $\boxed{C_d = (C_v)(C_c)}$

Notch:-

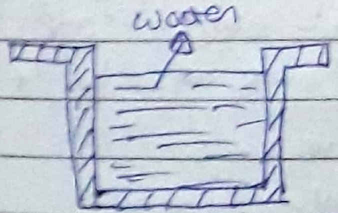


The notch is defined as the opening provided in one side of the tank when the upstream liquid level is below the top edge of the opening. So, notch only has working sides and bottom edge. The notch is used to measure the discharge of liquid and generally made of metal. The bottom edge of the notch is called as crest or sill. The sheet of water flowing over the notch is called as vein or nappe.

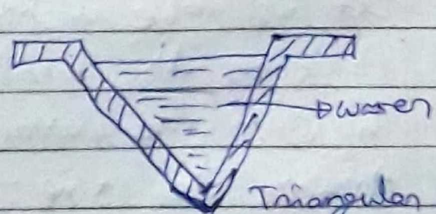
Classification of notch:-

The different types are;

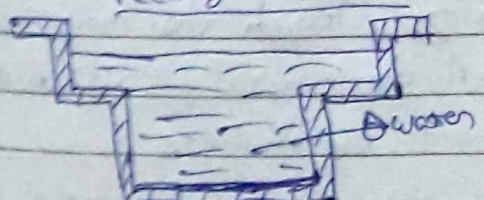
(a) rectangular notch, (b) Triangular notch, (c) Stepped notch, (d) Trapezoidal notch



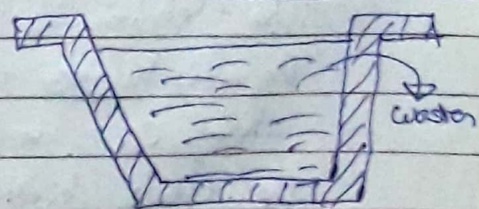
Rectangular notch



Triangular notch



Stepped notch



Trapezoidal notch

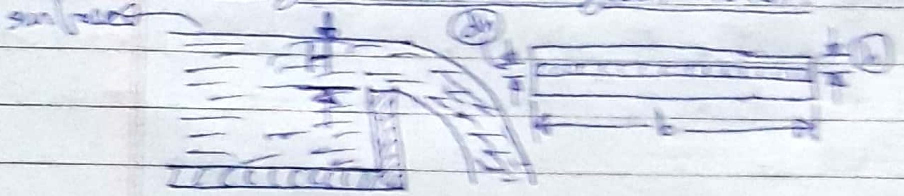
The rectangular notch is of having rectangular shape. It gives more accurate results for high discharges.

The triangular notch is having the shape of a triangle. It is also called V-notch. The triangular notch gives more accurate results for low discharge and it also measures wide range of flows in accurate manner.

The stepped notch is the combination of many rectangular notches. It is used for higher discharges.

The trapezoidal notch is the combination of one rectangular notch and two triangular notches. So it combines both the advantages of rectangular and triangular types.

Discharge over Rectangular Notch:—



The above shown rectangular notch is fitted on the side of the tank. The water is flowing over the rectangular notch.

Let us take a horizontal water strip having thickness 'dh', breadth 'b' and at a height of 'h' from the water surface.

Area of the strip $= (b)(dh)$

The theoretical velocity through the strip $= \sqrt{2gh}$

The discharge through the strip, $dq = C_d \times (b\,dh) \sqrt{2gh}$

where, C_d = Coefficient of discharge

∴ The total discharge over the whole notch, Q

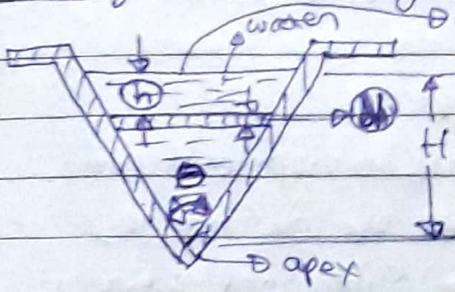
$$= \int_0^H dq = \int_0^H (C_d)(b\,dh)\sqrt{2gh}$$

H = height of water above the bottom of the notch on the upstream side

or, $Q = (C_d)(b)(\sqrt{2g}) \int_0^H (\sqrt{h})\, dh = (C_d)(b)(\sqrt{2g}) \left[\frac{h^{3/2}}{(3/2)} \right]_0^H$

or, $Q = \frac{2}{3} (C_d)(b)(\sqrt{2g})(H)^{3/2}$

Discharge over Triangular notch :-



The above figure shows a triangular notch over which water is flowing.

H = height of the water above the apex of the notch

θ = angle of the notch

Cd = coefficient of discharge

Let us consider a small water strip having thickness "dh" and at a height of "h" from water surface

The width of the notch at the water surface $= 2H \tan\left(\frac{\theta}{2}\right)$

Area of the small strip $= \left[2(H-h)\tan\frac{\theta}{2}\right](dh)$

Theoritical velocity of water through the strip $= \sqrt{2gh}$

The discharge over the small strip, dq

$= (C_d)(2)(H-h)\left(\tan\frac{\theta}{2}\right)(dh)(\sqrt{2gh})$

The discharge over the full triangular notch,

$Q = \int_0^H (C_d)(2)(H-h)\left(\tan\frac{\theta}{2}\right)(dh)\sqrt{2gh}$

$= \tan\left(\frac{\theta}{2}\right)(2C_d)(\sqrt{2g})\int_0^H (H-h)(\sqrt{h})(dh)$.

$= (2)(C_d)(\sqrt{2g})\left(\tan\frac{\theta}{2}\right)\int_0^H \left[H h^{\frac{1}{2}} - (h)^{3/2}\right] dh$

$= (2)(C_d)(\sqrt{2g})\left(\tan\frac{\theta}{2}\right)\left[\frac{H (h)^{3/2}}{(3/2)} - \frac{h^{5/2}}{5/2}\right]_0^H$

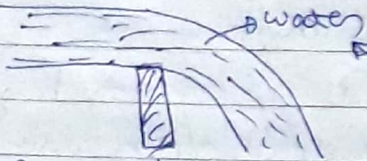
or, $Q = \left(\frac{8}{15}\right)(C_d)(\sqrt{2g})\left(\tan\frac{\theta}{2}\right)(H)^{5/2}$

Weir:-

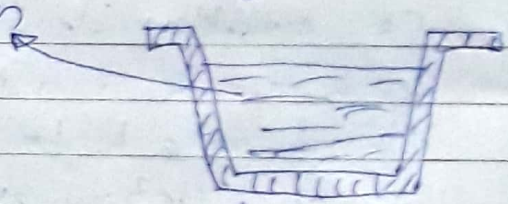
It is a structure made to reserve or contain river water, over which the water flows. It is similar to notch but bigger in size. It is made of concrete or masonry.

Classifications:-

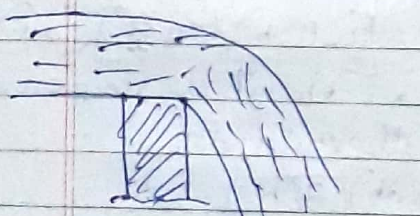
① According to shape;
(a) Rectangular weir, (b) Cippoletti weir
② According to type of discharge;
(a) Ordinary weir, (b) Submerged weir
③ According to Crest width
(a) Narrow-crested weir, (b) Broad-crested weir
④ According to the nature of crest
(a) Sharp-crested weir, (b) Ogee weir



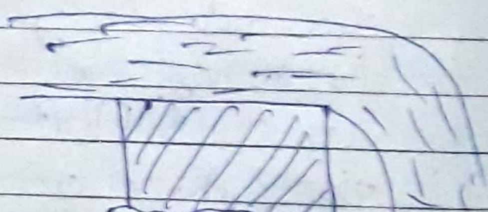
Rectangular weir



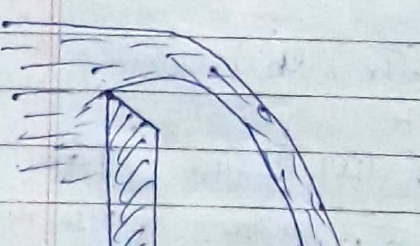
Cippoletti weir



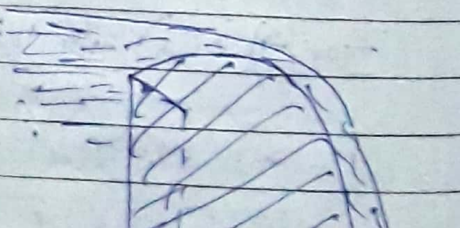
Narrow Crested weir



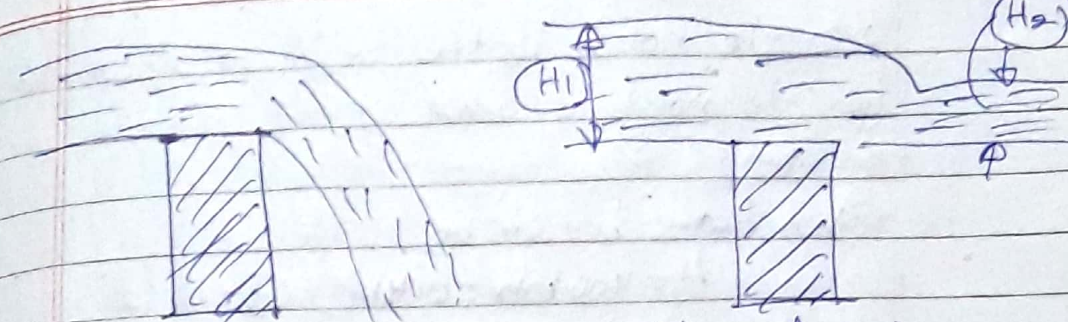
Broad crested weir



Sharp-crested weir



Ogee weir



Ordinary weir   Submerged weir

Problem – 1

A 60 mm. diameter orifice is discharging water under a head of 9m. Calculate the actual discharge through the orifice and actual velocity of the jet at vena contracta. Given, $Cd = 0.625$ and $C_v = 0.98$. Also find out C_c.

Solution

Given data; $d = 60\ mm = 0.06\ m$,
$H = 9m$,
$Cd = 0.625$, $C_v = 0.98$

The cross-sectional area of the orifice, $a = \frac{\pi}{4}(d)^2$
$= \frac{\pi}{4}(0.06)^2 = 0.00283\ m^2$

The theoritical discharge through the orifice,
$Q_{th.} = (a)(\sqrt{2gh}) = (0.00283)\sqrt{2\times9.81\times9}$
$= 0.0376\ m^3/s$.

Actual discharge through the orifice, $Q_{ac.} = (Cd)(Q_{th})$
$= (0.625)(0.0376) = 0.0235\ m^3/s$,

Theoritical velocity of the jet, $V_{th} = \sqrt{2gh}$
$= \sqrt{2\times9.81\times9} = 13.3\ m/s$

Actual velocity of the jet, $V_{ac.} = (C_v)(V_{th.})$
$= (0.98)(13.3) = 13\ m/s$,

We know that, $Cd = (C_c)(C_v)$.

or, $C_c = \frac{Cd}{C_v} = \frac{0.625}{0.98} = 0.6377$.

Problem – 2

A rectangular notch of 0.5 m wide has a constant head of 400 mm. Find the discharge over the notch, if the coefficient of discharge for the notch is 0.62.

Solution

Given data; $b = 0.5m$,

$H = 400mm = 0.4m$, $C_d = 0.62$

The discharge over the rectangular notch,

$Q = \frac{2}{3}(C_d)(b)(\sqrt{2g})(H)^{3/2}$

$= \left(\frac{2}{3}\right)(0.62)(0.5)(\sqrt{2\times9.81})(0.4)^{3/2}$

$= 0.231\ m^3/s$.

Problem - 3

A right angled V-notch was used to measure the discharge. The depth of water at V-notch is 200mm. Calculate the discharge over the notch. Assume; coefficient of discharge = 0.62

Solution

Given data; $\theta = 90°$, $H = 200mm = 0.2m$, $C_d = 0.62$

Discharge over the triangular notch,

$Q = \left(\frac{8}{15}\right)(C_d)(\sqrt{2g})\left(\tan\frac{\theta}{2}\right)(H)^{5/2}$

$= \left(\frac{8}{15}\right)(0.62)(\sqrt{2\times9.81})\times\left(\tan\frac{90}{2}\right)(0.2)^{5/2}$

$= 0.026\ m^3/s$.

Problem - 4

A rectangular weir of 4.5 m long has a 300mm head of water. Determine the discharge over the weir if coefficient of discharge is 0.6

Solution

Given data; $L = 4.5m$, $H = 300mm = 0.3m$, $C_d = 0.6$

The discharge over the weir,

$Q = \left(\frac{2}{3}\right)(C_d)(L)(\sqrt{2g})(H)^{3/2}$

$= \left(\frac{2}{3}\right)(0.6)(4.5)(\sqrt{2\times9.81})(0.3)^{3/2}$

$= 1.31\ m^3/s$.

Question Bank

Short Questions

1. Define about orifice.
2. What do you mean by vena-contracta?
3. Define about the coefficient of contraction.
4. What is the coefficient of velocity?
5. What do you understand by coefficient of discharge?
6. Define the term coefficient of resistance.
7. Define about the notch.
8. Why rectangular notch is preferably used?
9. For what advantages we use triangular notch?
10. Define about the weir.
11. What is nappe of notch?
12. What do you mean by crest of notch?
13. Write down the materials used for making weir.

Long Questions

14. Write a short note about the flow through orifice.
15. Derive the mathematical relation between the three hydraulic coefficients of orifice.
16. Derive the mathematical equation for the discharge of liquid over the rectangular notch.
17. Derive the mathematical equation to find out the discharge of liquid over the triangular notch.
18. Briefly classify the different types of weirs.

Chapter-6

Flow through Pipe

Pipe:-

The pipe is defined as the closed conduit generally having circular cross-section and carries liquid or fluid. A pipe when running full is said to be pipe flow under pressure.

Loss of energies in Pipes:-

Whenever any liquid or fluid flows through the pipe, then it experiences resistance to its flow. Due to the resistance, the velocity and head of liquid are reduced. The losses are of generally two types, like (a) major loss and (b) minor loss.

Major loss-

The major loss is because of the frictional resistance of the pipe. The frictional resistance generally depends on the inside surface roughness of the pipe. With increase in roughness the frictional resistance also increases. This friction is also called as fluid friction.

Mr. Froude conducted many experiments on fluid friction and found out that,

(a) The frictional resistance changes approximately with the square of the velocity.

(b) The frictional resistance also changes according to the nature of the surface.

Minor losses-

There are energy losses at the entrance of the pipe. There are also energy losses because of the liquid velocity at the pipe mode. In actual cases, the minor losses are neglected such that the mathematical equations and calculations become simple. Also the minor losses are small when compared with major losses.

Darcy's formula for frictional head loss in pipe:-

The mathematical equation is;

$$h_f = \frac{4(f')(l)(v^2)}{(w)(d)}$$

where, h_f = Loss of head because of friction

f' = Frictional resistance per unit area per unit velocity

l = length of the pipe

v = velocity of liquid in the pipe

w = specific weight of the liquid

d = diameter of the pipe

Again; $f' = \frac{(f)(w)}{(2g)}$

where, f = Darcy's coefficient or friction coefficient

Again, $f = 0.005\left(1+\frac{1}{12d}\right)$ for smooth and new pipe

$f = 0.01\left(1+\frac{1}{12d}\right)$ for rough and old pipe

So, $h_f = 4 \times \frac{(f w)}{(2g)} \times \frac{(l v^2)}{w d} = \frac{4 f l v^2}{2gd}$

Again; $Q = \frac{\pi}{4} d^2 \times v$ or, $v = \frac{4Q}{\pi d^2}$

So; $h_f = \frac{4fl}{2gd} \times \frac{16Q^2}{\pi^2 d^4} = \frac{32 f l Q^2}{\pi^2 g d^5}$

where, Q = discharge of liquid.

Chezy's formula for head loss:-

The mathematical equation is;

$v = C\sqrt{mi}$

where, v = velocity of liquid in the pipe

C = Chezy's constant

$C = \sqrt{\frac{w}{f'}}$

where, w = specific weight of the liquid
f' = Frictional resistance per unit area per unit velocity

Again, $m = \frac{A}{P}$

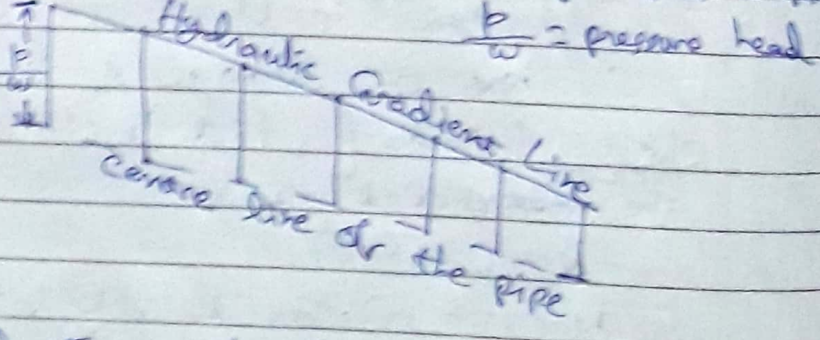
where, m = hydraulic mean depth
A = Area of the pipe
P = Wetted perimeter $= \pi d$
d = diameter of the pipe

Again, $i = \frac{h_f}{L}$

where, i = loss of head per unit length
h_f = Loss of head due to friction
L = length of the pipe

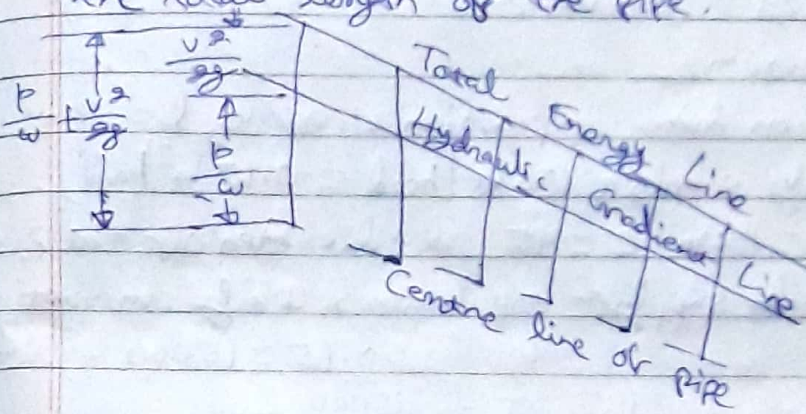
Hydraulic gradient line :-

When the pressure heads of the liquid flowing through the pipe are plotted as the vertical ordinates on the centre line of the pipe, then the line joining the tops of all the vertical ordinates is called as hydraulic gradient line. In short it is called as H.G.L. From this line we are able to know how the pressure head changes along the length of the pipe and also gives us idea about the flow pattern of liquid in pipe.



Total Energy Line :-

When the sum of pressure heads and velocity heads of the liquid are plotted as vertical ordinates on the centre line of the pipe, then the line joining the tops of all the vertical ordinates is called as Total Energy Line, In short it is also called as T.G.L. This line maintains constant velocity head above the H.G.L. and lies above it. It also provides information about total energy along the total length of the pipe.



Problem - 1

Find the loss of head, due to friction, in a pipe of 500 mm diameter and 1.5 km. long. The velocity of water in the pipe is 1m/s. Take coefficient of friction as 0.005.

Solution

Given Data; $d = 500\,mm = 0.5\,m$,

$l = 1.5\,km = 1500\,m$,

$v = 1\,m/s$,

$f = 0.005$

$1000d = 1000 * 0.5 = 500\,m$.

As, length of pipe 1500m is more than 500m, so it is a long pipe and hence all the minor losses are neglected. The only loss is frictional loss. According to Darcy's equation, head loss due to friction;

$$h_f = \frac{4flv^2}{2gd} = \frac{4(0.005)(1500)(1)^2}{2*9.81\times0.5} = 3.01\,m.$$

Problem - 2

A town having a population of 100000 is to be supplied with water from a reservoir at 5 km. distance. The one-half of the daily supply of 150 lit/head are delivered within 8 hours. Find the size of the pipe to furnish the supply, if the head available is 12m. Take, C = 45 in the Chezy's formula.

Solution

Given data: population = 100000, $l = 5\,km = 5000m$

Daily supply = 150 lit/head = $0.15\ m^3/head$,

$h_f = 12m$, $C = 45$, d = diameter of the pipe.

Total supply = population × Daily consumption

$= 100000 \times 0.15 = 15000\ m^3/day$.

Maximum flow, $Q = \frac{15000}{2 \times 8 \times 3600}$

$= 0.26\ m^3/sec$.

Hydraulic mean depth of pipe;

$m = \frac{d}{4}$

Loss of head per unit length,

$i = \frac{h_f}{l} = \frac{12}{5000} = 0.0024$.

Velocity of water, $V = C\sqrt{mi}$

$= 45\sqrt{\frac{d}{4} \times 0.0024}$

$= 45\sqrt{0.0006d}$

Discharge through the pipe, $Q = a \times V$

where, a = area of pipe $= \frac{\pi}{4}d^2$

or, $Q = \frac{\pi}{4}d^2 \times V$

or, $0.26 = \frac{\pi}{4}(d)^2 \times 45\sqrt{0.0006d}$

or, $0.0676 = \left(\frac{\pi^2}{16}\right) \times d^4 \times 2025 \times 0.0006d$

(squaring both sides)

or, $0.0676 = 0.7495\,d^5$ or, $d = 0.618m$.

Question Bank

Date ______
Page ______

Short questions

(1) Define about the pipe.
(2) Define about the frictional resistance in pipe flow.
(3) Write down the findings of Mr. Froude.
(4) Why minor losses are not considered as compared with the major losses when any fluid is flowing through the pipe.
(5) Write down the mathematical formula for the Darcy's in case of fluid flow in pipe.
(6) Write the mathematical equations for friction coefficient in both new and old pipes when liquid is flowing through it.
(7) What is Chezy's constant ?
(8) What do you mean by hydraulic mean depth ?
(9) Write the mathematical equation for head loss per unit length.
(10) Define about H.G.L.

Long Questions

(11) Write down in details about the energy losses in pipes when fluid is flowing through it.
(12) Write both Darcy's and Chezy's formula and elaborate the different terms in the formula.
(13) Write short note about Hydraulic Gradient line and Total Energy Line for pipe flow.

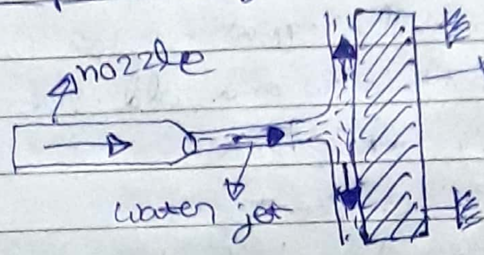
Chapter - 7

Impact of Jets

Impact of jet :-

The liquid jet when strikes on a fixed plate, then it produces force on the plate. According to Newton's 2nd law of motion, the force produced is equal to the rate of change of momentum of the water jet. When the plate is not fixed, then the plate moves in the direction of the liquid jet due to the force.

Impact of jet on a vertical fixed plate :-



A liquid jet is making impact on the fixed vertical plate.

V = velocity of liquid (water) jet.

a = cross-sectional area of the water jet.

Mass of water flowing/sec. = $\frac{waV}{g}$ kg

where, w = specific weight of the water,
g = acceleration due to gravity

The velocity of jet after impact with the vertical plate is zero in the direction of water jet or in the horizontal direction.

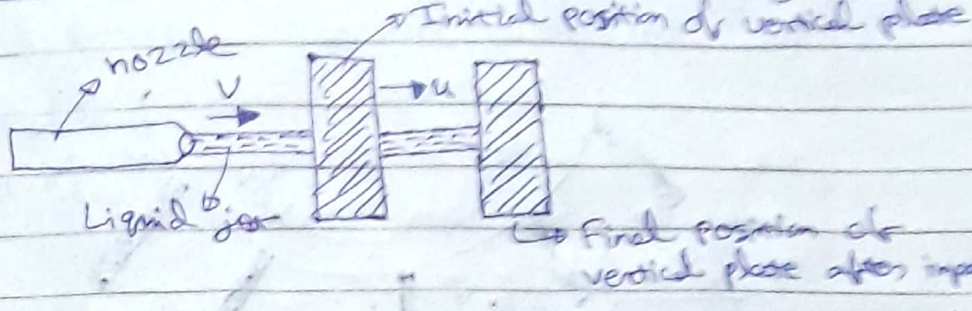
The force exerted by the water jet on the plate,

F = mass of water flowing/sec × Velocity change

$= \left(\frac{waV}{g}\right)(V-0)$

or, $\boxed{F = \frac{waV^2}{g}}$

Impact of jet on a vertical moving plate :-



The liquid jet is making impact on the vertical plate. After impact the vertical plate moves in the direction of liquid jet.

V = velocity of liquid jet

a = Cross-sectional area of the liquid jet

u = velocity of the vertical plate after impact of the liquid jet

$V-u$ = Relative velocity of the liquid jet with respect to the vertical plate

Hence, initially the jet of liquid is moving with the relative velocity of $(V-u)$. After impact the relative velocity becomes zero in the direction of impact.

The Force exerted by the liquid jet on the plate,

F = mass of water flowing per sec. × velocity change

$$= \left[\frac{wa(V-u)}{g}\right]\left[(V-u)-0\right]$$

where, w = specific weight of the liquid,

g = acceleration due to gravity

or, $$F = \frac{wa(V-u)^2}{g}$$

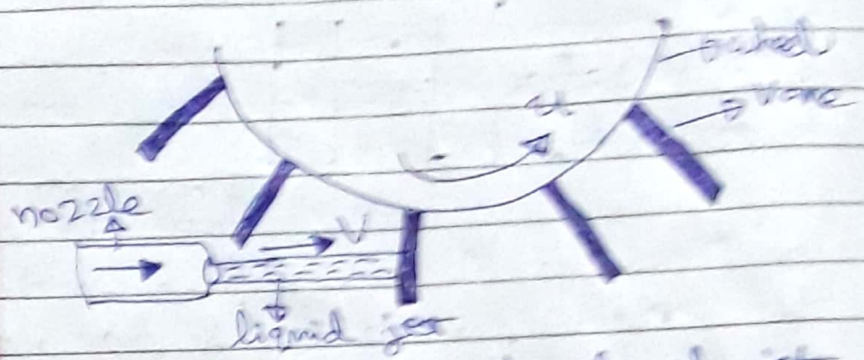
The work done by the liquid jet on the plate/sec,

W = Force exerted by the liquid jet × the distance travelled by the plate/sec.

$$= \left[\frac{wa(V-u)^2}{g}\right](u)$$

or, $$W = \frac{(wa)(u)(V-u)^2}{g}$$

Impact of jet on a series of vanes:-



In actual practice, the liquid jet commonly becomes unable to give impact on the moving vertical flat planes (one plate). So, practically the liquid jet impacts on a series of vanes on plates which are mounted on the circumference of a wheel. As shown in the above figure, the liquid jet strikes on the vanes with a velocity 'V' and due to it the vanes move with a velocity 'u'.

V = Velocity of liquid jet

a = cross-sectional area of liquid jet

u = velocity of the series of vanes after impact

Force exerted by the jet on the vanes,

F = Mass of liquid flowing/sec × Velocity change

$= \left(\frac{waV}{g}\right)(V-u)$

where, w = specific wt. of the liquid

or, $F = \frac{waV(V-u)}{g}$

Work done by the jet/sec,

W = Force exerted by the jet × Distance moved by the vanes/sec

$= \frac{waV(V-u)}{g} \times (u)$

Energy of the liquid jet = Kinetic energy of jet

$= \frac{1}{2} \times$ mass of jet $\times$ velocity of jet

$= \frac{1}{2} \times \left(\frac{waV}{g}\right)(V)^2$

The efficiency, $\eta = \dfrac{\text{Work done by the jet}}{\text{Energy of the jet}}$

$$= \frac{\left(\frac{waV}{g}\right)(V-u)(u)}{\left(\frac{1}{2}\right)\left(\frac{waV}{g}\right)(V^2)}$$

or, $\eta = \dfrac{2(V-u)u}{V^2}$

Maximum efficiency –

The efficiency to be maximum;

$\frac{d\eta}{du} = 0$

or, $\frac{d}{du}\left[\frac{2(V-u)u}{V^2}\right] = 0$

or, $\frac{d}{du}\left(\frac{2Vu - 2u^2}{V^2}\right) = 0$

or, $\left(\frac{1}{V^2}\right)\left(\frac{d}{du}\right)(2Vu - 2u^2) = 0$

or, $\left(\frac{d}{du}\right)\left[2Vu - 2u^2\right] = 0$

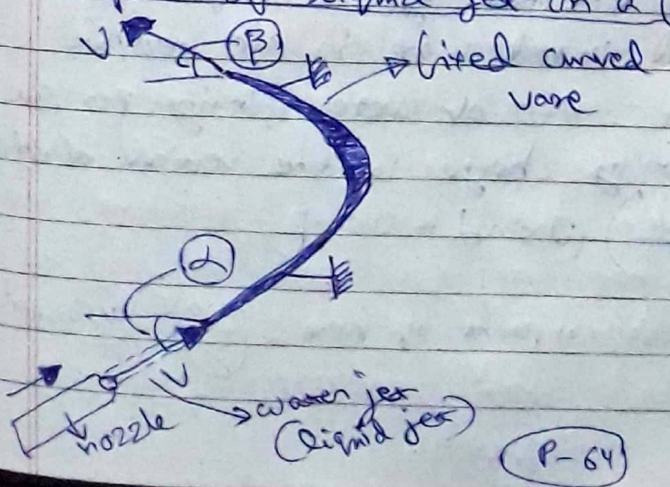
or, $2V - 4u = 0$

or, $2V = 4u$

or, $V = \frac{4u}{2} = 2u$

So, the condition is; $\boxed{V = 2u}$ for maximum efficiency

Impact of liquid jet on a fixed curved vane:-



The liquid jet is entering and leaving the fixed curved vane in the tangential direction. The liquid jet produces force on the fixed curved vane. This force has two components out of which one component is acting in the horizontal direction and other one is acting in the vertical direction.

V = Velocity of the liquid jet

a = cross-section area of the liquid jet

α = Inlet angle of the liquid jet

β = outlet angle of the liquid jet

The force exerted by the jet on the curved fixed vane in the direction normal to the vane or in the horizontal direction

= mass of liquid flowing/sec × change in velocity in the horizontal direction

$$= \left(\frac{waV}{g}\right)\left[V\cos\alpha - (-V\cos\beta)\right]$$

$$= \left(\frac{waV}{g}\right)(V\cos\alpha + V\cos\beta)$$

where, w = specific weight of the liquid,

g = acceleration due to gravity.

$V\cos\beta$ is negative as it acts in opposite direction that of $V\cos\alpha$.

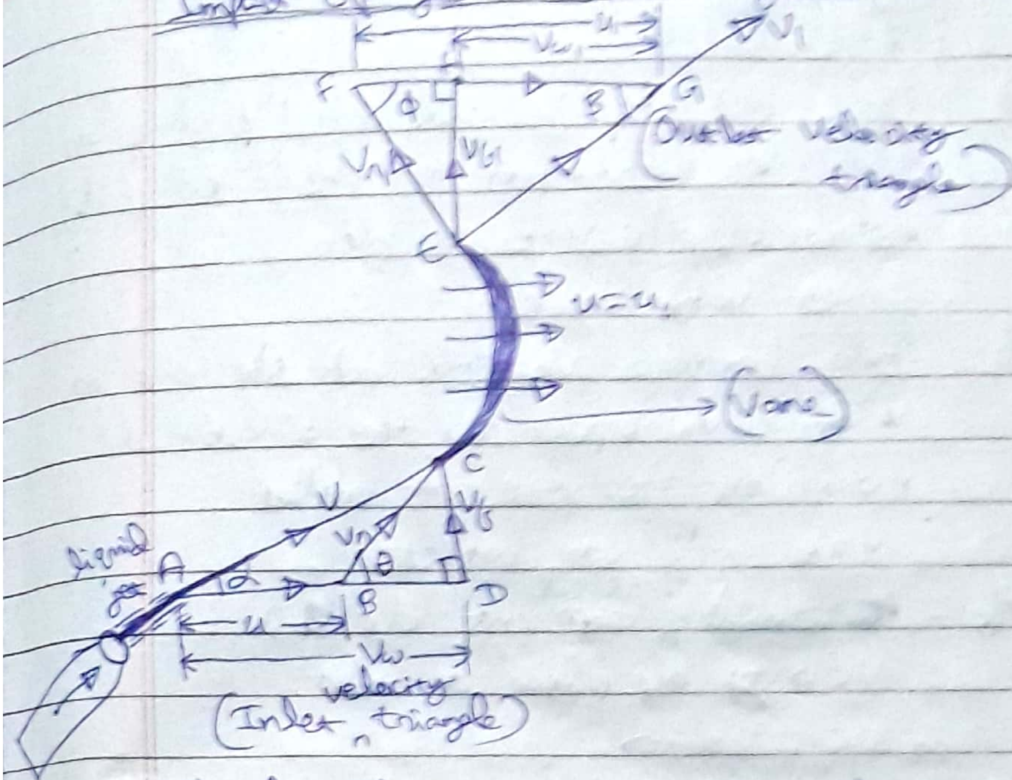
$\longrightarrow V\cos\alpha$ and $\longleftarrow V\cos\beta$

The force exerted by the liquid jet on the fixed curved vane in the vertical direction = mass of water flowing per sec. × velocity change in the vertical direction

$$= \left(\frac{waV}{g}\right)(V\sin\alpha - V\sin\beta)$$

or, Vertical component of force $= \left(\frac{waV}{g}\right)(V\sin\alpha - V\sin\beta)$

Impact of jet on a moving curved vane :-



The liquid jet is entering the moving curved vane tangentially and also leaving the vane tangentially.

V = velocity of liquid jet entering the vane = AC

V_1 = velocity of liquid jet leaving the vane = EG

u = velocity of vane at inlet = AB

u_1 = velocity of vane at outlet = FG

V_r = relative velocity of the liquid jet with the vane at the entry = BC

V_{r1} = relative velocity of the liquid jet with the vane at the outlet = EF

V_w = Horizontal component of the velocity 'V'
= Velocity of whirl at inlet
= AD = $V\cos\alpha$

α = Liquid jet entry angle with the vane with respect to the horizontal axis

β = Liquid jet outlet angle with the vane with respect to the horizontal axis

V_{w1} = Horizontal component of the velocity 'V_1'

= velocity of whirl at the outlet
= HG = $V_1 \cos\beta$

θ = Angle between V_r and with the vane at the inlet with respect to the direction of motion of the vane at inlet
= Inlet vane angle

ϕ = Angle between V_{r1} and with the vane at outlet with respect to the direction of motion of the vare at outlet
= Vane angle at outlet

V_f = ~~Horizontal~~ Vertical component of V
= velocity of flow at inlet
= DC = $V \sin\alpha$

a = cross-sectional area of the liquid jet

V_{f1} = Vertical component of V_1
= velocity of flow at the outlet
= EH = $V_1 \sin\beta$

The liquid jet must enter and leave the curved vane in tangential manner in order to reduce impact of jet and friction. The inner surface of the curved vane must also be very smooth in order to reduce friction. The ABDC in the inlet velocity triangle. First of all it is to be drawn as per given data. Then the vane is drawn in such a manner that the both V_r and V_{r1} will be tangent to the vane. Then the outlet velocity triangle (EFHG) is drawn. Both the triangles represent mainly the different velocity components of the jet and hence so named. As both the impact load and friction losses are very less, so we can assume the following for both the velocity triangles

The $u = u_1$

and $V_r = V_{r_1}$

The force exerted by the liquid jet in the direction of motion of the vane or in the horizontal direction;

F_x = Mass of water (liquid) flowing / sec. × the velocity change (Horizontal components)

= mass of liquid jet × change in velocity of whirl

$$= \left(\frac{waV}{g}\right)(V_w - V_{w_1})$$

where, w = specific weight of the liquid

g = acceleration due to gravity

Work done by the liquid jet in the direction of motion of the vane or in the horizontal direction / sec.

= Force in the horizontal direction × Distance covered by the vane in the horizontal direction per second

$$= \left(\frac{waV}{g}\right)(V_w - V_{w_1})(u)$$

Energy of the jet of liquid

= Kinetic energy of the jet of liquid

= $\frac{1}{2}$ × mass of jet of liquid × (Velocity of liquid)^2

$$= \left(\frac{1}{2}\right)\left(\frac{waV}{g}\right)(V)^2$$

$$\text{Efficiency}, \eta = \frac{\text{Work done by the liquid jet}}{\text{Energy of the liquid jet}}$$

$$\text{or, } \eta = \frac{\left(\frac{waV}{g}\right)(V_w - V_{w_1})(u)}{\left(\frac{1}{2}\right)\left(\frac{waV}{g}\right)(V^2)} = \frac{2(V_w - V_{w_1})(u)}{(V^2)}$$

Date ____
Page ____

Problem - 1

A jet of water of 50 mm diameter is discharging water under a constant head of 70 m. Calculate the force exerted by the water jet on a fixed plate. Assume, $C_v = 0.9$

Solution

Given data; $d = 50\,mm = 0.05\,m$,

$H = 70\,m$,

$C_v = 0.9$

Area of cross-section of the jet,

$$a = \frac{\pi}{4}(d)^2 = \frac{\pi}{4}(0.05)^2 = 0.001964\ m^2$$

Velocity of the jet,

$$V = C_v\sqrt{2gH} = (0.9)\sqrt{2\times9.81\times70} = 33.4\ m/s$$

Force exerted by the jet on the plate,

$$F = \frac{w a V^2}{g} = \frac{9810\times0.001964\times(33.4)^2}{9.81}$$

$= 2190\ N$.

Problem - 2

A water jet having 50 mm diameter moving with a velocity of 26 m/s is impinging normally on a plate. Calculate the pressure on the plate when it is moving with a velocity of 10 m/s in the direction of the jet. Also find out the work done per second by the jet.

Solution

Given data, $d = 50\,mm = 0.05\,m$,

$V = 26\ m/s$,

$u = 10\ m/s$.

Pressure on the plate when it is moving

$$= \frac{w a (V-u)^2}{g} = \frac{9810\times\frac{\pi}{4}(0.05)^2(26-10)^2}{9.81}$$

where, a = area of the jet = $\frac{\pi}{4}(d)^2 = \frac{\pi}{4}(0.05)^2$

or, Pressure = 503 N (again, ω = specific weight of water = 9810 N/m³)

Work done per second by the jet

= Pressure force × (distance/sec)

= (503)(10) = 5030 N-m/sec.

Problem – 3

A jet of water 50 mm in diameter, moving with a velocity of 15 m/s, impinge on a series of vanes moving with a velocity of 6 m/s. Calculate the force exerted by the jet, work done per second by the jet and efficiency of the jet.

Solution

Given, d = 50 mm = 0.05m,

V = 15 m/s,

u = 6 m/s.

Cross-section area of the jet, $a = \frac{\pi}{4}(d)^2$

$= \frac{\pi}{4}(0.05)^2 = 0.001964\ m^2$

Force exerted by the jet,

$$F = \frac{(waV)(V-u)}{g}$$

$$= \frac{(9810)(0.001964)(15)(15-6)}{9.81} = 265\ N$$

where, w = specific weight of water = 9810 N/m³

Work done per second by the jet/sec.

= Force × Distance moved/sec.

$= 265 \times 6 = 1590\ \frac{N\text{-}m}{sec}$.

Efficiency of the jet;

$$\eta = \frac{2(V-u)u}{V^2} = \frac{2(15-6)(6)}{(15)^2}$$

or, $\eta = 0.48 = 48\%$.

Problem – 4

A jet of water 40 mm diameter enters a fixed curved vane with a velocity of 50 m/s at an angle of 20° to the horizontal. Find the normal and tangential forces exerted by the jet, if it leaves the vane at angle of 15° to the horizontal.

Solution

Given data, $d = 40mm = 0.04m$,

$V = 50 m/s$,

$\alpha = 20°$,

$\beta = 15°$.

Area of cross-section of the jet,

$a = \frac{\pi}{4}(d)^2 = \frac{\pi}{4}(0.04)^2 = 0.001257 m^2$.

Normal force exerted by the jet,

$F_n = \left(\frac{waV}{g}\right)(V\cos\alpha + V\cos\beta)$

where, w = specific weight of water = $9810 N/m^3$

or, $F_n = \frac{9810 \times (0.001257)(50)}{(9.81)}(50\cos 20° + 50\cos 15°)$

$= (1000)(0.063)(50 \times 0.9397 + 50 \times 0.9659)$

$= 6000 N$.

Tangential force exerted by the jet,

$F_t = \left(\frac{waV}{g}\right)(V\sin\alpha - V\sin\beta)$

$= \frac{9810 \times (0.001257)(50)}{(9.81)}(50\sin 20 - 50\sin 15)$

$= (63)(50 \times 0.3420 - 50 \times 0.2588)$

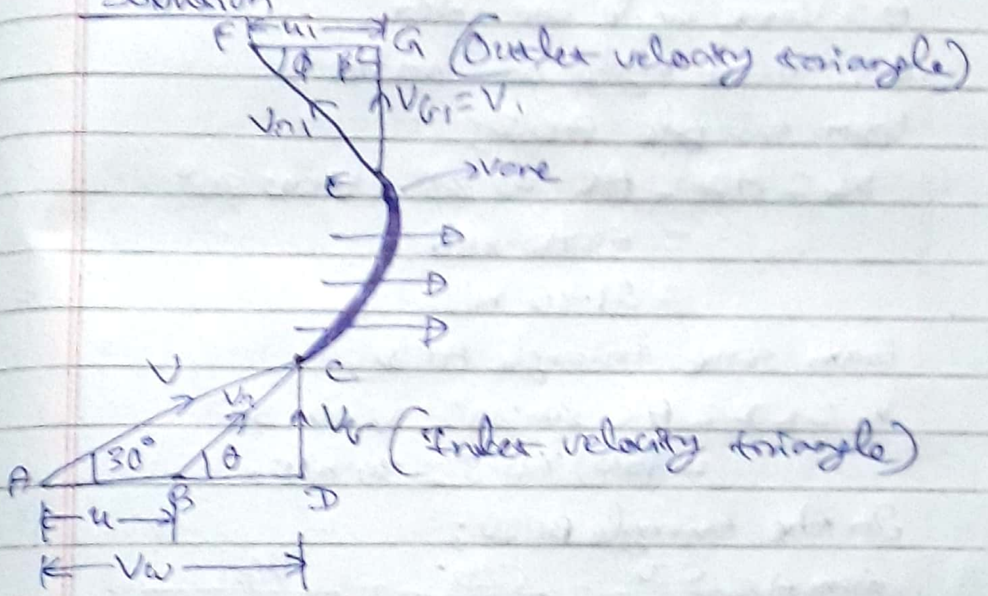
$= 262 N$.

Problem – 5

A jet of water having a velocity of

60 m/s impinges on a curved vane and vane is moving at 25 m/s. The water jet enters the vane at 30° with the direction of jet. The water leaves the blade normally to the motion of the vanes. Draw both inlet and outlet velocity triangles and find the vane angles for no shock at entry and exit. The relative velocity at the outlet to be 0.85 of the relative velocity at the inlet.

Solution



Given data; $V = 60$ m/s, $u = 25$ m/s, $\alpha = 30°$, $V_{r1} = 0.85 V_r$

(a) Draw a horizontal line and cut it as AB equal to 25 m/s as per any suitable scale. So AB = u.

(b) Draw a line at an angle of 30° at point A and cut it equal to 60 m/s as per the same scale as AC. So, AC = V

(c) Then join B with C and BC = V_r.

(d) Now draw a perpendicular from the point C on the AB line extended such that it cut at point D. So CD = V_f and AD = V_w.

(e) Then draw a curved vane such that V_r is tangential at the inlet tip of vane.

(f) Now draw a line EF tangential at the point of outlet 'E' of the vane by taking EF = 0.85 (BC) by the same scale taken. $EF = V_{r_1} = 0.85\, V_r$.

(g) Draw a horizontal line from point 'F' towards right and draw a perpendicular on it from point 'E' to meet both at point 'G'. Hence the outlet velocity triangle is completed.

$FG = u_1$, $EG = V_{f_1}$ and $\angle FGE = \angle B = 90^\circ$.

θ = Vane angle at inlet,

ϕ = Vane angle at outlet,

From triangle ACD;

$V_w = AD = AC \cos 30^\circ = V \cos 30^\circ$

$= 60 \times 0.866$

$= 51.96$ m/s.

From same triangle ACD;

$V_f = CD = AC \sin 30^\circ = V \sin 30^\circ$

$= (60) \times 0.5 = 30$ m/s.

In the triangle BCD;

$$\tan\theta = \frac{CD}{BD} = \frac{CD}{AD - AB} = \frac{V_f}{V_w - u}$$

$$\text{or, } \tan\theta = \frac{30}{51.96 - 25} = 1.1128$$

or, $\theta = 48.1^\circ$.

In the same triangle BCD;

$$V_r = BC = \frac{CD}{\sin\theta} = \frac{V_f}{\sin 48.1^\circ} = \frac{30}{0.7447}$$

or, $V_r = 40.31$ m/s.

In the outlet triangle EFG;

$V_{r_1} = EF = 0.85 (BC) = 0.85 (V_r) = (0.85)(40.31) = 34.26$ m/s

In the triangle EFG;

$$\cos\phi = \frac{FG}{EF} = \frac{u_1}{V_{r_1}} = \frac{25}{34.26} = 0.7297$$

or, $\phi = 43.1^\circ$.

Question Bank

Short questions

1. Define about impact of jet of liquid.
2. Write down the mathematical equation for the force exerted by liquid jet on the fixed vertical plate.
3. Write down the mathematical equation of work done per second by the liquid jet on the moving vertical plate.
4. What is the condition for the maximum efficiency of impact of jet on series of vanes.
5. Write down the mathematical equation for the horizontal force exerted by the liquid jet on the fixed curved vane.
6. Write the mathematical equation for the efficiency of jet when liquid jet impinges on the moving curved vane.

Long Questions

7. Derive the equation for the force exerted by the liquid jet on a moving vertical plate.
8. Derive the formula for efficiency of the liquid jet when the liquid jet impacts on a series of vanes.
9. Derive the equation for the force exerted in the vertical direction when liquid jet enters the fixed curved vane.
10. Draw both inlet and outlet velocity triangles and derive the equation for work done when liquid jet impinges on a moving curved vane.

Chapter-1

Performance of I.C engine

Engine →
It is a device which transform one form of energy into another form.

Internal combustion engine →
It is a machine which converts chemical energy of fuel into mechanical energy.

Fuel is burnt in the combustion chamber, which releases its chemical energy in the form of heat, & it converts mechanical energy with the help of reciprocating piston & crank mechanism. Two types of reciprocating IC engines are used. 1> Otto cycle engine
2> Diesel " "

Performance of Internal combustion engines →
Engine is selected for a particular application on the basis of its power o/p & rated speed. Some performance parameters are

1. Indicated power
2. Brake "
3. Frictional "
4. Fuel consumption
5. Air "
6. Brake thermal efficiency
7. Indicated " "
8. Mechanical "
9. Volumetric "
10. Air-fuel ratio

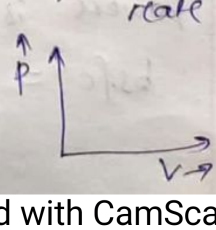
1> Indicated power (IP) →

→ It is defined as the rate of work done on the piston by burning of charge inside the cylinder.
→ It is obtained from the indicated diagram obtained from the engine.
→ It is the gross power produced by the engine.

IP = Indicated mean effective pressure × Swept volume rate

$$= \frac{PLAnk}{60} \text{ (KW)}$$

where ~~n = No. of cyli~~



where P = Indicated mean effective pressure (in kPa)
L = stroke length (in m)
A = cross-sectional area of cylinder bore
$= \frac{\pi}{4} d^2$
$n = N$ (for 2-stroke engine) K → No. of cylinders
$= \frac{N}{2}$ (for 4-stroke ")
n → No. of working strokes per minute, when engine has a speed of N rpm.

2) Brake power (BP) →
It is the net power available at the engine shaft for external use. It is measured by brake or dynamometer.

BP = brake load × velocity of brake drum $P = F \times V$

$= F \times \frac{2\pi RN}{60}$

$= \frac{2\pi N(FR)}{60} = \frac{2\pi NT}{60}$ kW

where F = braking force in N
R = effective radius of the brake drum
$= \frac{\text{Dia of brake drum} + \text{Dia of rope}}{2}$
T = Torque acting = F×R
N = speed of the engine in rpm

3) Friction power (FP) →
It is the part of the indicated power which is used to overcome the frictional effects within the engine.

FP = IP − BP

4) Specific fuel consumption (sfc) →
It is defined as the ratio of the mass of fuel consumed per hour per unit power o/p (BP).
It is of 2 types → bsfc
→ Isfc

Bsfc (Brake Specific fuel Consumption) →
The specific fuel consumption based on the indicated power is called bsfc.

$bsfc = \frac{\dot{m}_f\ (kg/h)}{BP\ (kW)}$ kg/kW-h

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Isfc (Indicated Specific fuel Consumption)
It is the sfc based on the indicated power.

$$Isfc = \frac{\dot{m}_f\ (kg/h)}{IP\ (kW)}\ kg/kWh$$

5) Air-Fuel Ratio (A/F) →
It is defined as the ratio between the mass of the air & mass of the fuel supplied to the engine.

$$A/F = \frac{\dot{m}_a}{\dot{m}_f}$$

Theoritically correct (stoichiometric) A/F is 15.
A/F is 12 to 19 for petrol engine
A/F is 20 to 60 " diesel "

Efficiencies of IC engines :→

i) Brake thermal efficiency (η_{bth}) →
It is defined as the ratio between brake power to the heat supply rate.

$$\eta_{bth} = \frac{BP}{\text{energy supply rate}} = \frac{BP}{\dot{m}_f \times CV}$$

where $\dot{m}_f$ = mass flow rate of fuel (kg/s)
CV = Calorific value of fuel (KJ/kg)

ii) Indicated thermal efficiency (η_{ith}) →
It is defined as the ratio between indicated power to input fuel energy.

$$\eta_{ith} = \frac{IP}{\dot{m}_f \times CV}$$

iii) Mechanical Efficiency (η_{mech}) →
It is defined as the ratio between brake power to indicated power.

$$\eta_{mech} = \frac{BP}{IP}$$

$$\text{or } \eta_{mech} = \frac{\eta_{bth}}{\eta_{ith}}$$

$$\text{or } \eta_{mech} = \frac{Bmep}{Imep}$$

(Bmep → brake; Imep → Indicated)

iv) Relative efficiency →
It is the ratio between actual thermal efficiency to air standard efficiency of the engine. It is also called as efficiency ratio.

$$\eta_{relative} = \frac{\eta_{Brake\ thermal}}{\eta_{air\ standard}}$$

It varies from 75 % to 95%.

v) Volumetric efficiency → (η_{vol})
It is defined as the ratio of mass or volume of actual charge inducted into the cylinder to the mass/volume of the charge ~~core~~ displaced by the system.

$$\eta_{vol} = \frac{V_{act}}{V_{swept}}$$

vi) Calorific Value of fuel (CV) →
It is defined as the amount of heat energy liberated by complete combustion of unit quantity of fuel. The quantity of heat energy liberated by combustion at const. pressure & under normal condition.
Unit → KJ/kg

v. Mean effective pressure →
It is the theoritical parameter used to measure the performance of an engine. It is the average pressure in the cylinder.
It is a hypothetical average pressure, which if acted on the piston during the entire power stroke, will produce the same power o/p as produced during the actual cycle.

$$P_{mep} = \frac{W_{net}}{V_{swept/displacement}}$$

* It is used to compare the o/p of similar engines of different sizes.

Q-1 A 4 cylinder, 4S petrol engine develops indicated power of 14.7 KW at 1000 rpm. The mean effective pressure is 5.5 bar. Calculate the bore & stroke of the engine, if the stroke is 1.5 times the bore.

Sol^n Given $K = 4$

$IP = 14.7$ KW

$P_m = 5.5$ bar $= 550$ KPa

$L = 1.5d$

$n = \frac{N}{2}$

$N = 1000$ rpm

$$IP = \frac{P_m L A n K}{60} \Rightarrow 14.7 = 550 \times \frac{1.5d}{60} \times \left(\frac{\pi}{4} d^2\right) \frac{1000}{2} \times 4$$

$$\Rightarrow d^3 = 6.806 \times 10^{-4}\ m^3 \Rightarrow d = 0.08796\ m = 87.96\ mm$$

So, $L = 1.5d = 131.94$ mm

Q-2 The following results were obtained from a test on a single cylinder, 4S diesel engine. Dia of cylinder is 30cm, stroke of the piston is 45 cm, indicated mean eff. P is 540KPa & engine speed is 240rpm. Calculate the IP of the engine.

Sol^n Given $K = 1$ $\quad L = 45$ cm $= 0.45$ m

$d = 30$ cm $= 0.3$ m $\quad N = 240$ rpm

$P_m = 540$ KPa $\quad n = \frac{N}{2} = 120$ working stroke/minute

$$A = \frac{\pi}{4} d^2 = \frac{\pi}{4} 0.3^2 = 0.07068\ m^2$$

$$IP = \frac{P_m L A n K}{60} = \frac{540 \times 0.45 \times 0.07068 \times 120 \times 1}{60} = 34.353\ KW$$

Q-3 In a single cylinder 4 stroke diesel engine indicated mean effective pressure = 755 KPa, cylinder dia = 10 cm, Piston stroke = 15 cm, engine speed = 480 rpm. Brake wheel dia = 62.5 cm, net load on brake wheel = 170 N, find IP, BP, η_{mech}.

Sol^n Given data $P_m = 755$ KPa, $D = 62.5$ cm $= 0.625$ m

$d = 10$ cm, $F = 170$ N

$L = 15$ cm

$N = 480$ rpm

$T = F \times r = 170 \times \frac{0.625}{2} = 53.125$ N-m

$B.P = \frac{2\pi N T}{60{,}000} = \frac{2\pi \times 480 \times 53.125}{60{,}000} = 2.67$ KW

$IP = \frac{P_m L A N K}{60{,}000} = \frac{755 \times 0.15 \times \frac{\pi}{4} 0.1^2 \times \frac{480}{2} \times 1}{60} = 3.54$ K

$\eta_{mech} = \frac{BP}{IP} = \frac{2.67}{3.54} = 0.75 = 75\%$

Q-4 In a 4 cylinder 2S petrol engine 30 KW power is generated at 2500 rpm. The P_m on each piston is 8 bar & $\eta_{mech} = 80\%$. Calculate the dia & stroke of each cylinder if the stroke to bore ratio is 1.5. Also calculate the fuel consumption of the engine if the $\eta_{bth} = 28\%$. The CV of fuel is 43900 KJ/kg.

Sol^n Given $K = 4$, $n = N =$

$BP = 30$ KW, $d = ?$

$N = 2500$ rpm, $L = ?$

$P_m = 8$ bar $= 800$ KPa, $\frac{L}{d} = 1.5 \Rightarrow L = 1.5d$

$\eta_{mech} = 0.8$, sfc $= ?$

$\eta_{bth} = 0.28$

$CV = 43900$ KJ/kg

$\eta_{mech} = \frac{BP}{IP}$

$\Rightarrow 0.8 = \frac{30}{IP} \Rightarrow IP = 37.5$ KW

$\eta_{bth} = \frac{BP}{\dot{m}_f \times CV} \Rightarrow 0.28 = \frac{30}{\dot{m}_f \times 43900} \Rightarrow \dot{m}_f = 2.44 \times 10^{-3}$ $= 8.78$ kg/h

$IP = \frac{P_m L A n K}{60} = \frac{800 \times 1.5d \times \frac{\pi}{4} d^2 \times 2500 \times 4}{60} = 37.5$

$\Rightarrow d = 0.062$ m $= 62$ mm

$L = 1.5d = 93\ mm$

sfc for BP $= \frac{\dot{m}_f}{BP} = \frac{2.44\times10^{-3}}{30} = 8.13\times10^{-5}$ kg/kW-H

sfc for IP $= \frac{\dot{m}_f}{IP} = \frac{2.44\times10^{-3}}{37.50} = 6.50\times10^{-5}$ kg/kW-H

Q-5 Bsfc $= \frac{\dot{m}_f\ (kg/h)}{BP\ (kW)} = \frac{8.78}{30} = 0.293$ kg/kWH

Q-5 The following results found from a petrol engine test. IP = 30 kW, BP = 26 kW, engine speed = 1000 rpm. Bsfc = 0.35 kg/kW-H, CV of fuel = 43900 kJ/kg. calculate a) Indicated thermal efficiency

b) brake " "

c) Mech. "

Sol^n Given IP = 30 kW

BP = 26 kW

N = 1000 rpm

bsfc = 0.35 kg/kW-H

a) $\eta_{ith} = ?$

b) $\eta_{bth} = ?$

c) $\eta_{mech} = ?$

Fuel consumption rate $= \dot{m}_f =$ bsfc × BP

$= 0.35 \times 26 = 9.1$ kg/h

$= 2.53\times10^{-3}$ kg/s

a) $\eta_{ith} = \frac{IP}{\dot{m}_f \times CV}$

$= \frac{30}{2.53\times10^{-3}\times43900} = 0.27 = 27\%$

b) $\eta_{bth} = \frac{BP}{\dot{m}_f \times CV} = \frac{26}{2.53\times10^{-3}\times43900} = 0.234 = 23.4\%$

c) $\eta_{mech} = \frac{BP}{IP} = \frac{26}{30} = 0.867 = 86.7\%$

Q-6 The mechanical efficiency of a single cylinder, 4S engine is 80%. The friction power is estimated to be 26 kW. calculate the indicated power & brake power developed by the engine.

Sol^n Given data $\eta_{mech} = 80\% = 0.8$ IP = ?

FP = 26 kW BP = ?

$\eta_{mech} = \frac{BP}{IP} \Rightarrow 0.8 = \frac{BP}{IP} \Rightarrow BP = 0.8\ IP$

$FP = IP - BP \Rightarrow 26 = IP - 0.8\ IP \Rightarrow IP = \frac{26}{0.8} = 130$ kW

$BP = IP - FP = 130 - 26 = 104$ kW

Q.7 A 2 stroke, diesel engine develops a brake power of 420 KW. The engine consumes 195 kg/h of fuel and air-fuel ratio is 22:1. CV of fuel is 42000 KJ/kg. If 76 KW of power is required to overcome the frictional losses, calculate a) η_{mech}
b) air consumption
c) η_{bth} (brake thermal efficiency)

Sol^n^ Given data $n = N$

$BP = 420\ KW$

$\dot{m}_f = 195\ kg/h$

$A/F = 22:1$

$CV = 42000\ KJ/kg$

$FP = 76\ KW$

a) $IP = BP + FP = 420 + 76 = 496\ KW$

$$\eta_{mech} = \frac{BP}{IP} = \frac{420}{496} = 0.8467 = 84.67\%$$

b) Fuel consumption rate

$$\dot{m}_a = \dot{m}_f \times \frac{A}{F} = 195\ kg/h \times \frac{22}{1} = 4290\ kg/h = 71.5\ kg/min$$

c) $$\eta_{bth} = \frac{BP}{\dot{m}_f \times CV}$$

$$= \frac{420}{\frac{195}{3600} kg/s \times 42000\ KJ/kg} = 0.1846 = 18.46\%$$

Q.8 Calculate the brake mean effective pressure of a 4 cylinder, 2S engine of 100 mm bore, 125 mm stroke, when it develops a torque of 490 N-m.

Sol^n^ Given data $P_{mep} = ?$

$K = 4$

$n = N$

$d = 100\ mm = 0.1\ m$

$L = 125\ mm = 0.125\ m$

$T = 490\ N\text{-}m$

$$BP = \frac{2\pi NT}{60{,}000} = \frac{PLAnK}{60} = \frac{P \times 0.125 \times \frac{\pi}{4} 0.1^2 \times N \times 4}{60}$$

$\Rightarrow P = 784\ KPa = 7.84\ bar$

Q. A single cylinder, CI engine with a brake thermal efficiency of 30% uses diesel oil having a CV of 42000 kJ/kg. If its $\eta_{mech} = 80\%$, calculate
a) BSfc c) ISfc c) η_{ith}

Sol^n Given $\eta_{bth} = 0.3$ $\eta_{mech} = 0.8$
$CV = 42000$ kJ/kg

a) $\eta_{bth} = \frac{BP}{\dot{m}_f \times CV}$

$\Rightarrow 0.3 = \frac{BP}{\dot{m}_f \times 42000} \Rightarrow \frac{BP}{\dot{m}_f} = 0.3 \times 42000$ kJ/kg.

$bsfc = \frac{sfc}{BP} = \frac{\dot{m}_f \times 3600}{BP} = \frac{1}{0.3 \times 42000} \times 3600$

$= 0.286$ kg/kW-H

b) $\eta_{mech} = \frac{Isfc}{bsfc}$

$\Rightarrow 0.8 = \frac{Isfc}{0.286} \Rightarrow Isfc = 0.8 \times 0.286 = 0.229$ kg/kW-h

c) $\eta_{mech} = \frac{BP}{IP} = \frac{\eta_{bth}}{\eta_{ith}}$

$\Rightarrow \eta_{ith} = \frac{\eta_{bth}}{\eta_{mech}} = \frac{0.3}{0.8} = 0.375 = 37.5\%$

Q For a single cylinder, 2-S cycle engine
$P_{mep} = 550$ KPa.
cylinder dia = 21 cm
piston stroke = 28 cm
engine speed = 360 rpm
brake torque = 628 N-m
fuel consumption = 8.16 kg/h
CV of fuel = 42700 kJ/kg
Calculate a) η_{mech} b) η_{ith} c) η_{bth} d) bsfc in kg/kW-h

Sol^n Given data
$P = 550$ KPa
$d = 21$ cm $= 0.21$ m
$L = 28$ cm $= 0.28$ m
$N = 360$ rpm
$T = 628$ N-m
$\dot{m}_f = 8.16$ kg/h
$CV = 42700$ kJ/kg
$K = 1$

Scanned with CamScanner

$A = \frac{\pi}{4} d^2 = \frac{\pi}{4} \times 0.21^2 = 0.0346\ m^2$

$IP = \frac{P L A n K}{60}$

$= \frac{550 \times 0.28 \times 0.0346 \times 360 \times 1}{60} = 32.0\ kW$

$BP = \frac{2\pi NT}{60,000} = \frac{2\pi \times 360 \times 628}{60,000} = 23.675\ kW$

a) $\eta_{mech} = \frac{BP}{IP} = \frac{23.675}{32} = 0.7397 = 74\%$

b) $\eta_{ith} = \frac{IP}{\dot{m}_f\ CV} = \frac{32\ kW}{\left(\frac{8.16}{3600}\ kg/s\right) \times (42700\ kJ/kg)}$

$= 0.330 = 33\%$

c) $\eta_{bth} = \frac{BP}{\dot{m}_f \times CV}$

$= \frac{23.675\ kW}{\left(\frac{8.16}{3600}\ kg/s\right) \times (42700\ kJ/kg)}$

$= 0.244 = 24.4\%$

d) $bsfc = \frac{\dot{m}_f\ (kg/h)}{BP\ (kW)} = \frac{8.16\ kg/h}{23.675\ kW} = 0.3446\ kg/kWh$

Q A single cylinder 4S diesel engine works on the following data.

cylinder bore = 15 cm
Stroke = 25 cm
Speed = 250 rpm
Area of Indicator diagram = 6 cm²
Length " = 7.9 cm
Spring const = 7.5 bar/cm
bsfc = 0.24 kg/kWh

CV = 42000 kJ/kg
dia of brake wheel = 70 cm
Rope dia = 3.5 cm
brake load = 40 kg = 392.4 N

Calculate a) B.P b) P_{mep} c) IP d) η_{mech} e) η_{ith}

Sol^n Given data

$n = \frac{N}{2}$
$K = 1$
$d = 15\ cm$
$L = 25\ cm$
$N = 250\ rpm$

$A_i = 6\ cm^2$
$l = 9\ cm$
Sp. const = 7.5 bar/cm
bsfc = 0.24 kg/kWh
CV = 42000 kJ/kg
D = 70 cm
W = 392.4
$d_r = 3.5\ cm$

Scanned with CamScanner

Effective brake radius $= R_{brake} = \frac{D_{brake} + d_{rope}}{2} = \frac{70 + 3.5}{2}$

$= 36.75$ cm $= 0.3675$ m

$T =$ Load × eff. brake radius

$= W_{brake} \times R_{brake} = 392.4 \times 0.3675 = 144.2$ N-m

a) $BP = \frac{2\pi NT}{60} = \frac{2\pi \times 250 \times 144.2}{60} = 3775$ W

b) $P_{mi} = \frac{\text{Area of Indicator diagram}}{\text{Length of " "}} \times$ spring. const.

$= \frac{6\text{ cm}^2}{9\text{ cm}} \times 7.5$ bar/cm

$= 5$ bar $= 500$ kPa

c) $IP = \frac{PLANK}{60} = \frac{500 \times 0.25 \times \pi \times 0.15^2 \times 250 \times 1}{4 \times 60 \times 2}$

$= 4.6$ KW

d) $\eta_{mech} = \frac{BP}{IP} = \frac{3.775}{4.6} = 0.820 = 82\%$

e) $bsfc = \frac{\dot{m}_f}{BP} \Rightarrow 0.24 = \frac{\dot{m}_f}{3.775} \Rightarrow \dot{m}_f = 0.906$ kg/h

$= 2.516 \times 10^{-4}$ kg/s

$\eta_{ith} = \frac{IP}{\dot{m}_f \times CV}$

$= \frac{4.6}{2.516 \times 10^{-4} \times 42000} = 0.435 = 43.5\%$

Q. A single cylinder CI engine with a brake thermal efficiency 30%. Diesel fuel has CV = 42000 KJ/kg. $\eta_{mech} = 80\%$. Calculate bsfc, isfc & η_{ith}.

Sol^n K = 1 bsfc = ?

$\eta_{bth} = 0.3$ isfc = ?

CV = 42000 KJ/kg $\eta_{ith} = ?$

$\eta_{mech} = 0.8$

$\eta_{bth} = \frac{BP}{\dot{m}_f \times CV} \Rightarrow \frac{\dot{m}_f}{BP} = \frac{1}{\eta_{bth} CV} = \frac{1}{0.3 \times 42000}$ kg/kWh

$= \frac{3600}{0.3 \times 42000}$ kg/kW-s

$\eta_{mech} = \frac{isfc}{bsfc}$

$\eta_{mech} = \frac{\eta_{bth}}{\eta_{ith}} \Rightarrow 0.8 = \frac{0.3}{\eta_{ith}} \Rightarrow \eta_{ith} = \frac{0.3}{0.8} = 0.375 = 37.5\%$

$bsfc = \frac{\dot{m}_f}{BP} = \frac{3600}{0.3 \times 42000}$

Now $\eta_{mech} = \frac{isfc}{bsfc}$

$\Rightarrow 0.8 = \frac{isfc}{\frac{3600}{0.3 \times 42000}}$ $\Rightarrow isfc = 0.228$ kg/kw-h

Q. In a petrol engine indicated power = 30 kW, BP = 26 kW, N = 1000 rpm. sfc = 0.35 kg/kw-h, CV = 43000 kJ/kg. Calculate indicated thermal η, η_{bth}, η_{mech}.

Sol^n Given IP = 30 kW
BP = 26 kW
N = 1000 rpm
sfc = 0.35 kg/kw-h
$= \frac{0.35}{3600}$ kg/w-s

CV = 43000 kJ/kg
$\eta_{ith} = ?$
$\eta_{bth} = ?$
$\eta_{mech} = ?$

$\eta_{mech} = \frac{BP}{IP} = \frac{26}{80} = 86\%$

$sfc = \frac{\dot{m}_f}{BP}$

$\Rightarrow \frac{0.35}{3600} = \frac{\dot{m}_f}{30}$

$\Rightarrow \dot{m}_f =$

$sfc = \frac{\dot{m}_f}{IP}$

$\Rightarrow 0.35 = \frac{\dot{m}_f}{30}$

$\Rightarrow \dot{m}_f =$

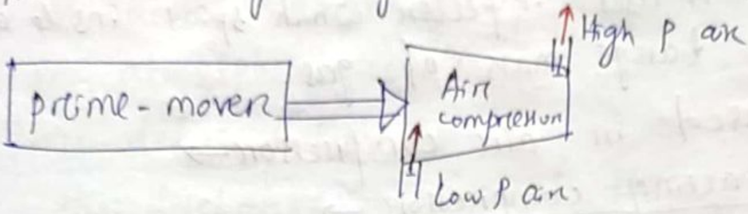
$\eta_{ith} = \frac{IP}{\dot{m}_f \times CV}$

$\eta_{bth} = \frac{BP}{\dot{m}_f \times CV}$

Chapter-2

Reciprocating Air Compressor

Air compressor is a machine which takes atmospheric air with the help of mechanical energy & delivers it at high pressure. It is also called as air pump. It increases pressure of air by decreasing its specific volume by using some mechanical means.



Use of compressed air →

1. In air refrigeration & cooling of large buildings.
2. In driving pneumatic tools in shops like drills, rivettes, screw drivers etc.
3. In blast furnaces
4. In spray painting & spraying fuel in diesel engines
5. Operating of air brakes in buses, trucks & trains.
6. In inflating automobile & aircraft tyres.
7. In supercharging of internal combustion engines.
8. In driving air motors in mines, where electric motor & IC engines cannot be used due to fire risks as imflammable gases are present there.
9. In operation of lifts, hoists, cranes, pumps.
10. In automobile suspension system.
11. Cleaning purposes.

Classification of air compressor →

- compressor
  - Positive displacement type
    - Reciprocating
      - Single acting
      - Double acting
    - Rotary
      - Roots blower
      - Vane type
  - Dynamic compressor
    - Centrifugal
    - Axial

→ Reciprocating compressor is used to produce high pressure gas. It uses displacement of piston in the cylinder for compression. It handles low mass of gas & a high pressure ratio.

→ Rotary compressors are used for low & medium pressures. It uses impeller which spins inside a housing. It handles large mass of gas.

Terms used in air compressor →

1> Single acting compressor →

Here suction, compression & delivery of gas takes place only on one side of the piston during a cycle of one revolution of crank shaft.

2> Double acting compressor →

Here suction, compression & delivery of gas takes place on both sides of the piston & 2 cycles takes place during one revⁿ of crankshaft.

3> Single stage compressor →

Here compression of gas to final delivery pressure is done in one cylinder only.

4> Multi stage compression →

Here compression of gas is done in more than one cylinder in series.

5> pressure ratio →

Ratio between absolute discharge pressure to absolute suction pressure.

6> Free air →

It is the air existing under atmospheric condition.

7> Compressor displacement volume →

The volume created when piston travels a stroke.

$$V = \frac{\pi}{4} d^2 L$$

8> Induction volume rate / flow rate →

It is expressed in m^3/s.

$\dot{V}$ = volume inducted per cycle × No. of inductions per revolution × No. of revolutions per sec.

$$\dot{V} = \frac{\pi}{4} d^2 L \frac{N}{60} \quad \text{(for single acting compression)}$$

$$\dot{V} = \frac{\pi}{4} d^2 L \left(\frac{2N}{60}\right) \quad \text{(" double " ")}$$

9) Capacity of a compressor →

It is the actual quantity of air delivered per unit time at atmospheric condⁿ.

10) Free Air delivery (FAD) →

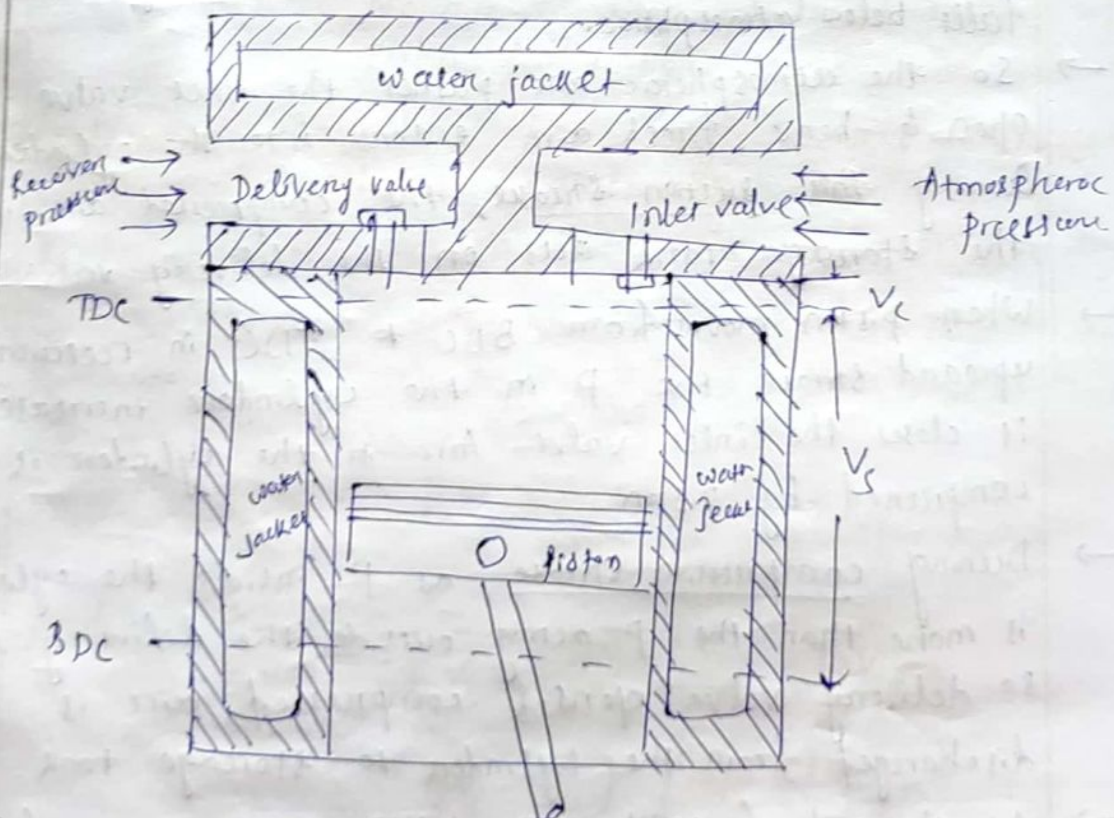
It is the discharge volume of the compressor corresponding to ambient conditions.

11) Piston speed →

It is the linear speed of the piston measured in m/min.

$$V_{piston} = 2LN$$

Construction of air compressor →



It consists of a piston, cylinder with cooling arrangement, connecting rod, crank, inlet & delivery valves.

Piston, which is fitted with piston rings, reciprocates in the cylinder.

The prime mover (an engine or electric motor) drives

the crank shaft. The crank shaft rotates &
converts rotary motion into reciprocating motion
of piston with the help of connecting rod.

→ The cylinder head consists of spring loaded inlet & delivery valves, which are operated by small pressure difference across them.

→ The piston rings seal the gap between the piston & cylinder wall.

→ The cylinder is surrounded by a water jacket or metallic fin for proper cooling of air during compression.

Working →

→ When piston moves from TDC to BDC in downward stroke, any residual compressed air left in the cylinder from previous cycle expands first.

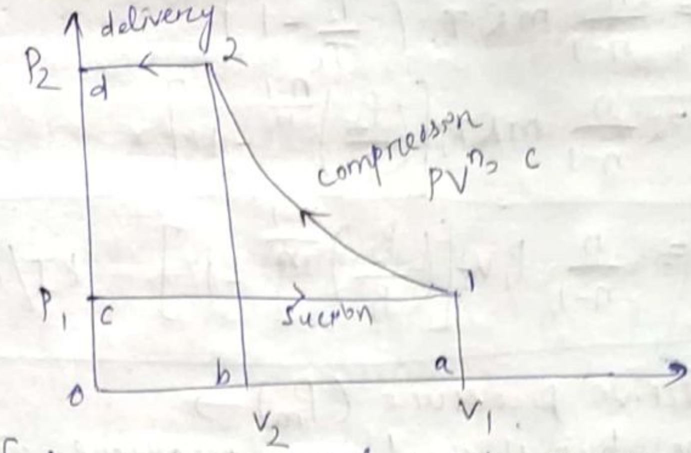
→ When piston moves further, P inside the cylinder falls below atmospheric.

→ So the atmospheric air pushes the inlet valve to open & hence fresh air enters into the cylinder. During this suction stroke, the compressed air in the storage tank acts on the delivery valve.

→ When piston moves from BDC to TDC in return/upward stroke, the P in the cylinder increases & it closes the inlet valve. Air in the cylinder is compressed by piston.

→ During compression stroke, as P inside the cylinder is more than the P acting outside the delivery valve, so delivery valve opens & compressed air is discharged from the cylinder to storage tank.

→ At the end of compression, piston again moves from TDC to BDC & the cycle repeats.



[P-V diagram of single stage compressor without clearance]

process c-1 → Suction stroke → Inlet valve opens & air enters the compressor at const P, (P_1)

" 1-2 → Polytropic compression of air from P_1 to P_2.

" 2-d → Discharge of compressed air through delivery valve at P (P_2).

" d-c → No air in the cylinder & return of piston for suction stroke.

Indicated work done for single acting reciprocating compressor without considering clearance →

Net workdone = area ~~under~~ behind the curve on P-V diagram

W_{in} = Area c-1-2-d-c

= Area 2-d-0-b-2 + Area 1-2-b-a-1 − Area 1-c-0-a-1

$= P_2V_2 + \left(-\int P\,dV\right) - P_1V_1$ (for compression process)

$PV^n = C$
so, $W = -\int P\,dV = \frac{P_2V_2 - P_1V_1}{n-1}$

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

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

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

$= \frac{n}{n-1}(P_2V_2 - P_1V_1)$ KJ/cycle

from characteristic gas equ^n $PV = mRT$

so, $W_{in} = \frac{n}{n-1} mR(T_2 - T_1)$

$$\Rightarrow W_{in} = \frac{n}{n-1} mRT_1 \left(\frac{T_2}{T_1} - 1 \right)$$

$$\Rightarrow W_{in} = \frac{n}{n-1} mRT_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

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

mean effective pressure (P_m) →

It is the hypothetical avg. pressure, which if acted on the piston during the entire compression stroke will require the same power I/P as required during actual cycle.

Net work input in a cycle = $W_{in} = P_m \times$ (Swept volume)

$$\Rightarrow W_{in} = P_m \times V_s$$

$$\Rightarrow \boxed{P_m = \frac{W_{net}}{V_s}}$$

* Again $P_m = \frac{\text{Area of indicator diagram } (mm^2)}{\text{Length of " " } (mm)} \times$ spring const. (KPa/mm)

Power & η_{mech} :→

1) **IP** → The workdone on air per unit time is called indicated power input to the compressor.

Power required by an air compressor, running at N rpm is = IP = work I/P per cycle × No. of cycles per unit of time

$$\Rightarrow IP = \frac{W_{in} N K}{60} \ (KW)$$

from indicated diagram, $IP = P_m \times V_s$

$$= \frac{P_m L A N K}{60} \quad (KW)$$

K ⇒ No. of suction per revolution of crank shaft
= 1 for single acting reciprocating compressor
= 2 " double " " "

2) **BP** → The actual power (shaft power) I/P to the compressor is more than IP as some work is required to overcome the irreversibilities & mechanical frictional effects.

BP = IP + FP

3) $\eta_{mech} = \frac{IP}{BP}$ (for compressor)

~~BP~~ motor power / engine power $= \frac{\text{Shaft power (or BP)}}{\eta_{mech} \text{ of motor \& drive}}$

Q. A single stage reciprocating air compressor takes in 1.4 kg of air per minute at 1 bar & 17°C & delivers it at 6 bar. Assuming compression process follows the law $PV^{1.35} = C$, calculate IP input to compressor.

Sol^n Given data $\dot{m}_a = 1.4$ kg/min

$P_1 = 1$ bar $\qquad PV^{1.35} = C$

$P_2 = 6$ bar

$T_1 = 17°C = 290K$

$n = 1.35$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} \Rightarrow T_2 = 290\left(\frac{6}{1}\right)^{\frac{1.35-1}{1.35}} = 461.46K$$

$$W_{in} = \frac{n}{n-1}\dot{m}_a R(T_2 - T_1)$$

$$= \frac{1.35}{1.35-1}(1.4 \text{ kg/min})(0.287 \text{ kJ/kg-K})(461.46-290)$$

$$= 265.72 \text{ kJ/min}$$

$$IP = \frac{W_{in}}{60} = \frac{265.72 \text{ kJ/min}}{60} = 4.43 \text{ kW}$$

Q=2) A single acting, single cylinder reciprocating air compressor has a cylinder dia of 200 mm & a stroke of 300 mm. Air enters the cylinder at 1 bar, 27°C. It is then compressed polytropically to 8 bar acc^n to $PV^{1.3} = C$. If the speed of the compressor is 250 rpm, calculate the mass of air compressed per minute & power required in kW for driving the compressor.

Sol^n Given data $d = 200$ mm $= 0.2$ m $\qquad L = 300$ mm $= 0.3$ m

$P_1 = 1$ bar $= 100$ KPa $\qquad P_2 = 8$ bar

$N = 250$ rpm $\qquad T_1 = 27°C = 300K$

$n = 1.3$

$$V_s = V_1 = \frac{\pi}{4}d^2L = \frac{\pi}{4}\times 0.2^2 \times 0.3 = 9.424 \times 10^{-3} \text{ m}^3$$

$P_1V_1 = m_a R T_1$

$\Rightarrow m_a = \frac{P_1 V_1}{R T_1} = \frac{100 \text{ kPa} \times 9.424 \times 10^{-3} m^3}{0.287 \text{ KJ/kg-K} \times 300 \text{ K}} = 0.0109 \text{ kg}$

$\dot{m}_a$ = mass of air × no. of suction / min

$= 0.0109 \times 250 = 2.74 \text{ kg/min}$

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

$\Rightarrow T_2 = 300 \times \left(\frac{8}{1}\right)^{\frac{1.3-1}{1.3}} = 484.73 \text{ K}$

$W_{in} = \frac{n}{n-1} \dot{m}_a R (T_2 - T_1)$

$= \frac{1.3}{1.3-1}$ 2.74 kg/min × 0.287 KJ/kg-K (484.73-300)

$= 629.56$ KJ/min

$= 10.49$ KW

Q-3 A single acting, single cylinder reciprocating air compressor is compressing 20 kg/min of air from 110 KPa, 30°C to 600 KPa & delivers it to a receiver. Law of compression is $PV^{1.25} = C$. $\eta_{mech} = 80\%$. find the power I/P to compressor, neglecting losses due to clearance, leakage & cooling.

Sol^n Given data $\dot{m}_a = 20$ kg/min $PV^{1.25} = C$

$P_1 = 110$ kPa $\eta_{mech} = 0.8$

$T_1 = 30°C = 303K$

$P_2 = 600$ kPa

$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} \Rightarrow \frac{T_2}{303} = \left(\frac{600}{110}\right)^{\frac{0.25}{1.25}} \Rightarrow T_2 = 425.4K$

IP input to compressor = IP $= \frac{n}{n-1} \dot{m}_a R (T_2 - T_1)$

$= \frac{1.25}{0.25} \left(\frac{20}{60} \text{ kg/s}\right) 0.287 (425.4 - 303)$

$= 58.55$ kW

The motor (brake) power

$BP = \frac{IP}{\eta_{mech}} = \frac{58.55}{0.8} = 73.18$ kW

Q-4 A single cylinder, double acting reciprocating air compressor receives air at 1 bar, 17°C, compresses it to 6 bar acc^n to the law $PV^{1.25} = C$. The cylinder dia is 300 mm. The avg. piston speed is 150 m/min at 100 rpm. Calculate the power required in KW for driving the compressor. Neglect clearance.

Sol^n Given data $P_1 = 1$ bar $= 100$ kPa, $PV^{1.25} = C$, $N = 100$ rpm

$T_1 = 17°C = 290K$, $d = 300mm = 0.3m$, $K = 2$

$P_2 = 6$ bar, $V_{piston} = 150$ m/min, $n = 1.25$

$V_{piston} = 2LN$

$\Rightarrow L = \frac{V_{piston}}{2N} = \frac{150 \text{ m/min}}{2 \times 100 \text{ rpm}} = 0.75 \text{ m}$

$V_s = V_1 = \frac{\pi}{4} d^2 L = \frac{\pi}{4} 0.3^2 \times 0.75 = 0.053 \text{ m}^3$

Indicated work i/p to compressor

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

$$= \frac{1.25}{0.25} 100 \times 0.053 \left[\left(\frac{6}{1}\right)^{\frac{0.25}{1.25}} - 1 \right]$$

$$= 11.42 \text{ KJ/cycle}$$

For double acting reciprocating compressor,

$$IP = \frac{W_{in} N K}{60} (KW) = \frac{11.42 \times 100 \times 2}{60} = 38.1 \text{ KW}.$$

Clearance volume in a compressor →

It is the space left in the cylinder when piston reached TDC. It is provided

→ to avoid the piston striking the cylinder head &

→ to accomodate valve's position inside the cylinder.

* compressor should have smallest clearance volume, as compressed air left here, first re-expands in the cylinder during suction, which reduces suction capacity.

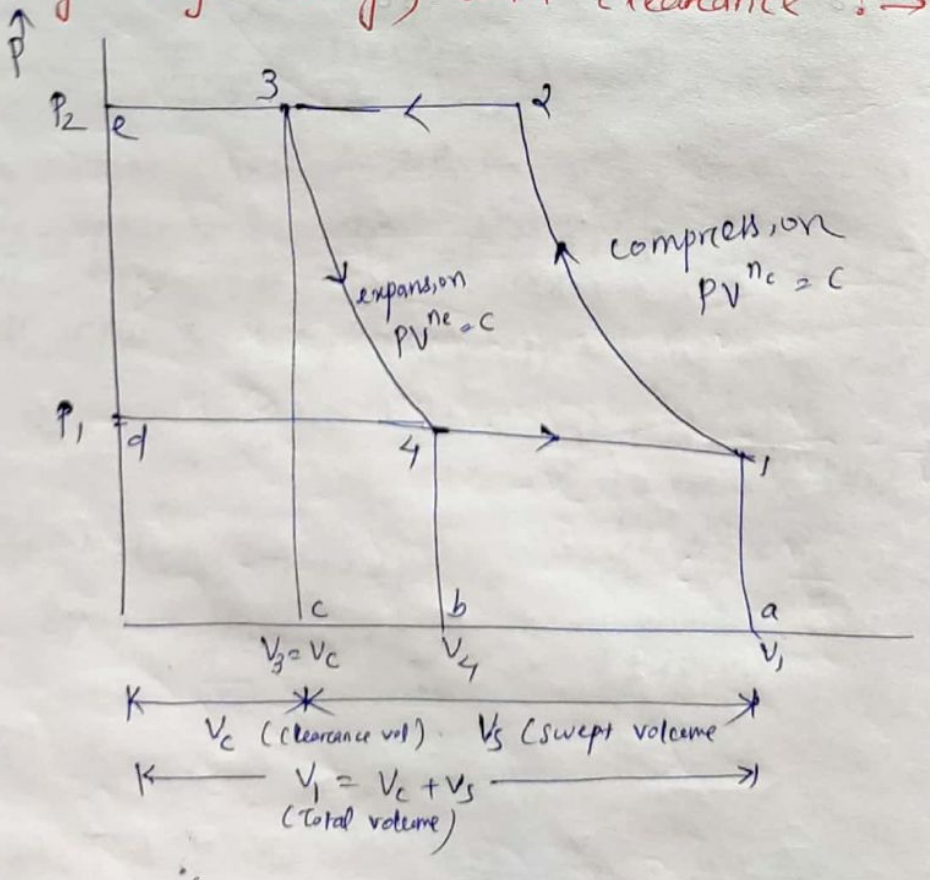
* clearance ratio = $\frac{\text{clearance volume}}{\text{swept volume}}$

It varies from 2 to 10 %.

Effect of clearance volume →

1. The volume of air taken in per stroke is less than the swept volume, thus the volumetric efficiency decreases.
2. More power i/p is required to drive the compressor for same pressure ratio, due to increase in volume to be handled.
3. The max^m compression pressure is controlled by clearance volume.

Indicated work input to the compressor (single stage single acting) with clearance :→



Here after delivery of compressed air, the air remaining in the clearance volume at P, P_2 expands, when the piston proceeds for the next suction stroke. As soon as the P, P_1 reaches at state 4, the induction of fresh charge starts & continues upto state 1.

Indicated work done = Area of 1-2-3-4-1 on the P-V diagram

$\Rightarrow W_{in}$ = (Area of 1-2-e-d) − (Area of 3-e-d-4)

Area of 1-2-e-d = $W_{comp} = \frac{n_c}{n_c-1} P_1V_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n_c-1}{n_c}} - 1\right]$

Area of 3-e-d-4 = $W_{exp} = \frac{n_e}{n_e-1} P_4V_4\left[\left(\frac{P_3}{P_4}\right)^{\frac{n_e-1}{n_e}} - 1\right]$

Now $P_4 = P_1$ & $P_3 = P_2$

So, $$W_{in} = \frac{n_c}{n_c-1} P_1V_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n_c-1}{n_c}} - 1\right] - \left\{\frac{n_e}{n_e-1} P_1V_4\left[\left(\frac{P_2}{P_1}\right)^{\frac{n_e-1}{n_e}} - 1\right]\right\}$$

If $n_c = n_e = n$

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

Q. A single stage, single acting reciprocating air compressor has a displacement volume of 14 ltr & a clearance volume of 0.7 ltr. It receives the air at a pressure of 1 bar & delivers it at a pressure of 7 bar. The compression is polytropic with an index of 1.3 & re-expansion is isentropic with an index of 1.4. Calculate the net indicated work of a cycle.

Soln Given V_s = 14 ltr = $14 \times 10^{-3}\ m^3$

V_c = 0.7 ltr = $0.7 \times 10^{-3}\ m^3$

P_1 = 1 bar = 100 KPa

P_2 = 7 bar = 700 KPa

$n_c = 1.3$

$n_e = 1.4$

$W_{in} = ?$

Total volume = $V_1 = V_s + V_c$ = 14 + 0.7 = 14.7 ltr = $14.7 \times 10^{-3}\ m^3$ = $0.0147\ m^3$

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

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

$$\Rightarrow V_4 = V_c \left(\frac{P_2}{P_1}\right)^{\frac{1}{n_e}}$$

$$= 0.7 \times 10^{-3} \left(\frac{7}{1}\right)^{1.4} = 0.00281 \ m^3$$

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

$$= \frac{1.3}{1.3 - 1}\left[100 \times 0.0147 \left(\frac{7}{1}\right)^{\frac{0.3}{1.3}} - 1\right] - \left\{\frac{1.4}{1.4 - 1} 100 \times 0.00281 \left[\left(\frac{7}{1}\right)^{\frac{.4}{1.4}} - 1\right]\right\}$$

$$= 3.61 - 0.731$$

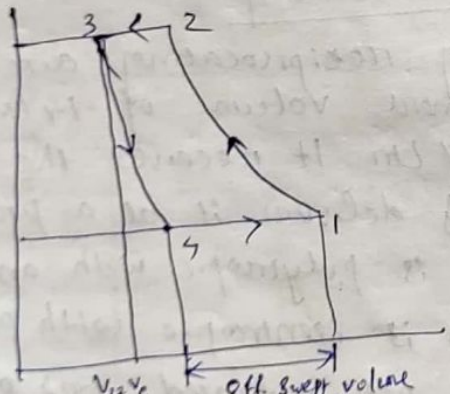
$$= 2.88 \ KJ/cycle.$$

* Volumetric efficiency →

It is the ratio between actual volume of air sucked into the compressor (measured at atmospheric P & T) to the piston displacement volume.

$$\eta_{vol} = \frac{\text{Actual mass sucked}}{\text{mass corresponding to swept volume at atmospheric P \& T}}$$

$$= \frac{\text{effective swept volume}}{\text{piston displacement "}}$$



$V_s = V_1 - V_3$ (piston displacement volume)

$$\eta_{vol} = \frac{V_1 - V_4}{V_1 - V_c} = \frac{V_s + V_c - V_4}{V_s + V_c - V_c} = 1 + \frac{V_c}{V_s} - \frac{V_4}{V_s}$$

$$= 1 + C - C\left(\frac{V_4}{V_3}\right) \quad \text{where } C = \frac{V_c}{V_s}$$

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

$$\Rightarrow \eta_{vol} = 1 + C - C\left(\frac{P_2}{P_1}\right)^{\frac{1}{n_e}}$$

If $n_c = n_e = n$, $\left(\frac{P_2}{P_1}\right)^{\frac{1}{n_e}} = \left(\frac{P_2}{P_1}\right)^{\frac{1}{n}} = \frac{V_1}{V_2}$

$$\Rightarrow \boxed{\eta_{vol} = 1 + C - C\left(\frac{V_1}{V_2}\right)}$$

Q-1 A single stage, single acting reciprocating air compressor receives air at 1.013 bar, 27°C & delivers it at 9.5 bar. The compressor has a bore = 250 mm & stroke = 300mm & it runs at 200 rpm. mass flow rate of air is 200 kg/h. Calculate η_{vol}.

Sol:

$P_1 = 1.013$ bar $d = 250$ mm $= .25$ m $\dot{m}_a = 200$ kg/h

$T_1 = 27°C$ $L = 300$ mm $= .3$ m

$P_2 = 9.5$ bar $N = 200$ rpm

$$V_1 = \frac{\pi}{4} d^2 L = \frac{\pi}{4} 0.25^2 \times 0.3 = 0.0147 \text{ m}^3$$

$$m_a = \frac{P_1 V_1}{RT_1} = \frac{101.3 \times 0.0147}{0.287 \times 300} = 0.0173 \text{ kg/cycle}$$

mass flow rate per hour $= \dot{m}_a =$ mass per cycle × No. of suction/rev^n × No of rev^n/hour

$= 0.0173 \times 1 \times (200 \times 60)$

$= 207.6$ kg/h

$$\eta_{vol} = \frac{200}{207.6} = 0.963 = 96.3\%$$

Limitations of single stage compression →

Pressure ratio for a single stage reciprocating air compressor is limited to 7.

Increase in pressure ratio causes the following effects

i) Greater expansion of clearance air in the cylinder. Hence decreases effective suction volume, which decreases fresh air induction.

ii) With high delivery p, delivery T increases. It increases specific volume of air in the cylinder, so more compression work is needed.

iii) For high p ratio, the cylinder size should be large, strong & heavy working parts of compressor are needed. It will increase balancing problems & high torque fluctuation will need heavier flywheel.

Multistage compression :→

The compression of air in two or more cylinders in series is called multi-stage compression. The limitations of single stage compression can be reduced by using multi stage compression.

* compressor needs min^m work input with isothermal compression. But the delivery tempr T_2 increases with pressure ratio & the η_{vol} decreases as pressure ratio increases.

Air cooling between stages provides the means to achieve appreciable reduction in compression work & maintaining the air tempr within safe operating limits.

Advantages of Multi-stage compression →

1. The gas can be compressed to a sufficiently high pressure.
2. Cooling of air is more efficient with inter coolers & cylinder wall surface.
3. By multistaging, the pressure ratio of each stage is lowered.
4. Low pressure ratio in a cylinder improves η_{vol}.
5. The size of the two cylinders (i.e. High pressure & low pressure) may be adjusted to suit the volume & pressure of air.
6. It reduces leakage loss considerably.
7. It gives more uniform torque, so smaller size flywheel is required.
8. It reduces cost of compressor.
9. It provides effective lubrication due to lower tempr range.

Q. A single stage, single acting reciprocating air compressor has a bore of 200mm & a stroke of 300mm. It receives air at 1 bar & 20°C & delivers it at 5.5 bar. If compression follows $pV^{1.3} = C$ & $V_c = 5\%$ of V_s. Find i) P_{mep} ii) power required to drive the compressor, if it runs at 500 rpm.

Soln Given data $d = 200\,mm = 0.2\,m$ $\quad PV^{1.3} = C$

$L = 300\,mm = 0.3\,m$ $\quad V_c = 5\%$ of V_s

$P_1 = 1$ bar $\quad N = 500$ rpm.

$P_2 = 5.5$ bar

$T_1 = 20^\circ C = 293K$

$V_s = \frac{\pi}{4} d^2 L = \frac{\pi}{4} 0.2^2 \times 0.3 = 0.00942\,m^3$

$V_c = 5\%$ of $V_s = 0.05 \times 0.00942 = 0.00047\,m^3$

Now, $V_1 = V_c + V_s$

$= 0.00942 + 0.00047 = 0.00989\,m^3$

Again $V_4 = V_c \left(\frac{P_2}{P_1}\right)^{\frac{1}{n}} = 0.00047 \left(\frac{5.5}{1}\right) = 0.00174\,m^3$

effective swept volume $= V_1 - V_4 = 0.00989 - 0.00174$

$= 0.00815\,m^3$

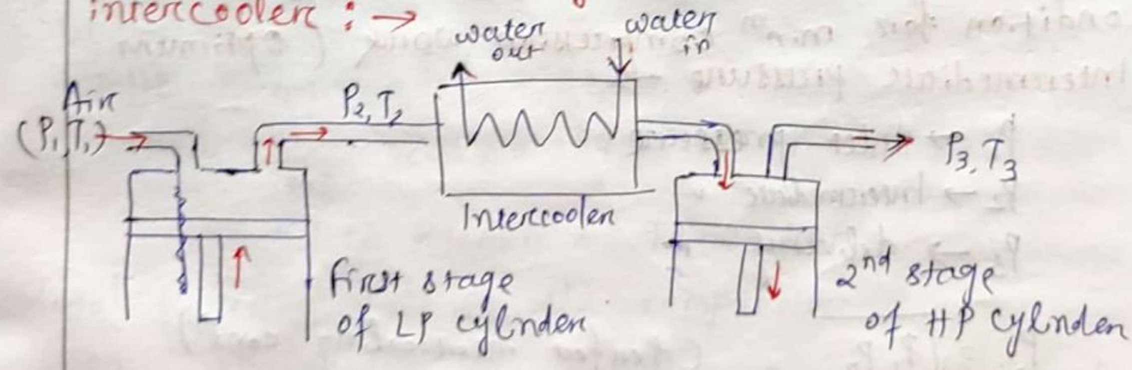
$W_{in} = \frac{n}{n-1} P_1 (V_1 - V_4)\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$

$= \frac{1.3}{1.3-1} 1 \times 10^5 \times 0.00174 \left[\left(\frac{5.5}{1}\right)^{\frac{0.3}{1.3}} - 1\right]$

$= 1702$ N-m

$P_{mep} = \frac{W_{in}}{V_s} = \frac{1703}{0.00942} = 180700\,N/m^2$

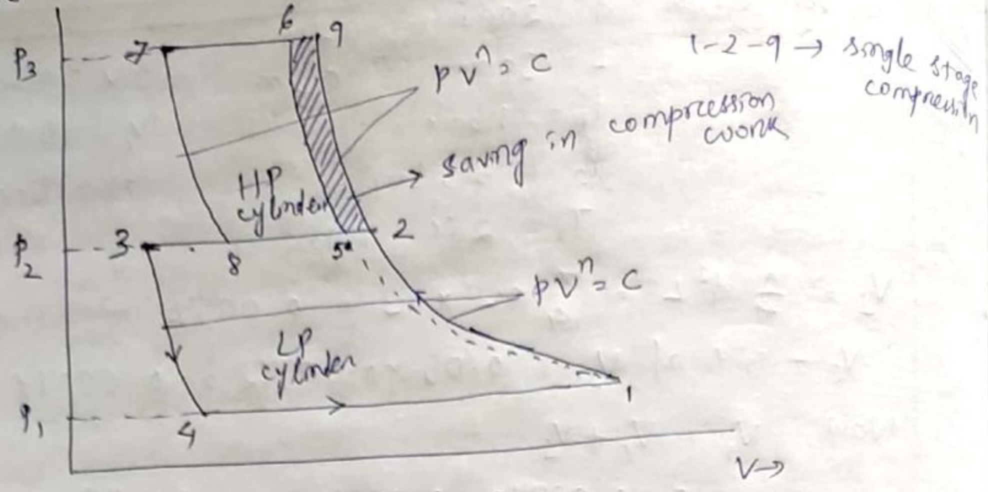
Workdone in Multi stage compression with intercooler :→



→ Here air at P_1 & T_1 is first drawn into 1st stage or Low pressure (LP) cylinder

→ It is partially compressed to some intermediate pressure P_2 & temp^n T_2 & then discharged to intercooler (cools air to its initial temp^n T_1)

→ The cooled air then enters the 2nd stage or high pressure (HP) cylinder & is compressed to a delivery pressure P_3 & temp^n T_3.



$$W_{in} = W_{LP} + W_{HP}$$

$= \text{Area of } 1\text{-}2\text{-}3\text{-}4\text{-}1 + \text{Area of } 5\text{-}6\text{-}7\text{-}8\text{-}5$

$$= \frac{n}{n-1} P_1 (V_1 - V_4)\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] + \frac{n}{n-1} P_1 (V_5 - V_8)\left[\left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 1\right]$$

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

Here $m_a = \frac{P_f V_f}{R T_f} = \frac{P_1 (V_1 - V_4)}{R T_1} = \frac{P_2 (V_5 - V_8)}{R T_1}$

& suffix f → free air cond^n.

For given mass flow rate $\dot{m}_a$ (kg/s),

$$IP = \frac{n}{n-1} \dot{m}_a R T_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 2\right]$$

Condition for min^m compression work (Optimum Intermediate pressure →

P_1 → Inlet pressure
P_2 → Intermediate "
P_3 → delivery "

$P_2 = \sqrt{P_1 P_3}$ (Perfect intercooling cond^n) when $T_3 = T_1$

<u>cond^n</u>

→ Pressure ratio of each stage should be same.
→ " " of any stage is the square root of overall pressure ratio, for a 2 stage compression.
→ Air after compression in each stage should be cooled to initial temp^n of air intake.
→ Work i/p to each stage is same.

Q. Calculate the power required to compress 25 m^3/min atmospheric air at 101.3 KPa, 20°C to a pressure ratio of 7 in an LP cylinder. Air is then cooled at const. P to 25°C in an intercooler, before entering HP cylinder, where air is again compressed to a pressure ratio of 6. Assume polytropic compression with n = 1.3 & R = 0.287 KJ/kg.K.

Sol Given $\dot{V}_1 = 25\ m^3/min$ $T_3 = 25°C = 298K$

$P_1 = 101.3\ KPa$ $\frac{P_4}{P_2} = 6$

$T_1 = 20°C = 293K$ $R = 0.287\ KJ/kg\text{-}K$

$\frac{P_2}{P_1} = 7$

$$\dot{m}_a = \frac{P_1\dot{V}_1}{RT_1} = \frac{(101.3\ KPa) \times (25\ m^3/min)}{(0.287\ KJ/kg\text{-}K) \times (293K)} = 30.11\ kg/min$$

Temp^n of air after 1st stage compression

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} \Rightarrow T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} = 293(7)^{\frac{.3}{1.3}} = 459.08K$$

$$W_{in_{LP}} = \frac{n}{n-1}\dot{m}_a R(T_2 - T_1)$$

$$= \frac{1.3}{0.3} 30.11 \times 0.287(459.08 - 293)$$

$$= 6219.24\ KJ/min = 103.65\ KW$$

Temp^n of air after 2nd stage compression,

$$T_4 = T_3\left(\frac{P_4}{P_3}\right)^{\frac{n-1}{n}} = 298(6)^{\frac{.3}{1.3}} = 450.59\ K$$

$$W_{in_{HP}} = \frac{n}{n-1}\dot{m}_a R(T_4 - T_3)$$

$$= \frac{1.3}{0.3} 30.11 \times 0.287(450.59 - 298)$$

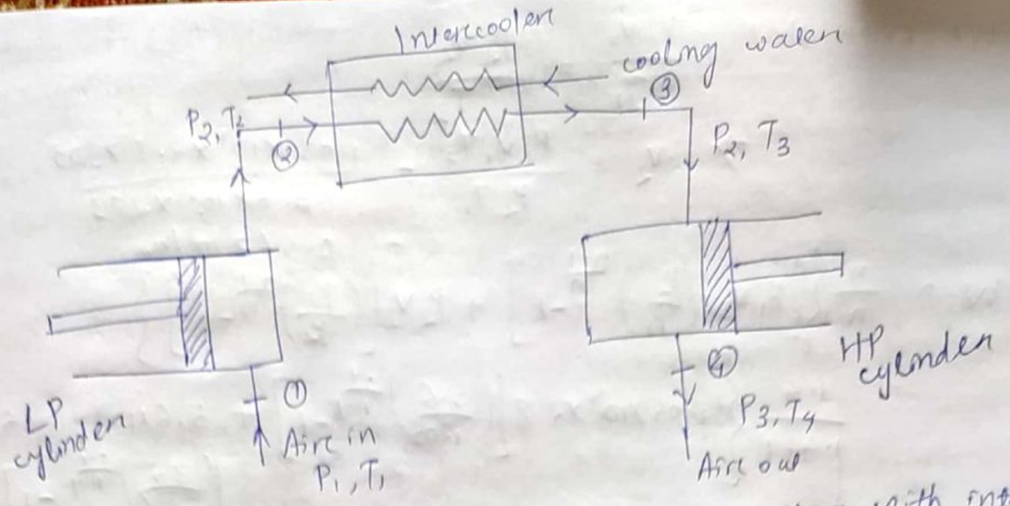
$$= 5714\ KJ/min = 95.23\ KW$$

Total power input to the compressor

$$IP = IP_{LP} + IP_{HP}$$

$$= 103.65 + 95.23 = 198.88\ KW$$

Q.2 The LP cylinder of a 2 stage double acting reciprocating air compressor running at 120 rpm has a 50 cm dia & 75 cm stroke. It draws air at a P of 1 bar & 20°C & compresses it adiabatically to a P of 3 bar. The air is then delivered to the intercooler, where it is cooled at const. pressure to $35^\circ C$ & is then further compressed polytropically ($n = 1.3$) to 10 bar in HP cylinder. Determine the power required to drive the compression if $\eta_{mech\ compression} = 90\%$ & $\eta_{motor} = 86\%$.



2-stage reciprocating air compressor with intercooler

Work-done

P_1 = pressure of air entering LP cylinder
V_1 = volume of " "
P_2 = pressure of air leaving LP & entering HP cylinder
V_2 = volume of HP cylinder
P_3 = pressure of air leaving the HP cylinder.

i) when inter cooling is incomplete (Imperfect intercooling i.e. $T_3 \neq T_1$)

Workdone per cycle in LP cylinder = $W_1 = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$

" " in HP " = $W_2 = \frac{n}{n-1} P_2 V_2 \left[\left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 1\right]$

Total $W = W_1 + W_2$

$$= \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] + \frac{n}{n-1} P_2 V_2 \left[\left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 1\right]$$

ii) when intercooling is complete (perfect intercooling) i.e. $T_3 = T_1$

Here $P_1 V_1 = P_2 V_2$

$$\text{so, } W = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 2\right]$$

$$= \frac{n}{n-1} mRT_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 2\right]$$

Q. Find workdone by a 2 stage reciprocating single acting air compressor to compress 2.8 m³ of air per minute at 1.05 bar & 10°C to a final pressure of 35 bar. The intermediate receiver cools the air to 30°C & 5.6 bar pressure. For air take $n = 1.4$

Soln Given $V_1 = 2.8\ m^3/min$
$P_1 = 1.05$ bar $= 1.05 \times 10^5$ Pa
$T_1 = 10°C = 283$ K
$P_3 = 35$ bar
$T_3 = 30°C = 303$ K

$P_2 = 5.6$ bar $= 5.6 \times 10^5$ Pa
$n = 1.4$

we know that $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_3}$

$\Rightarrow V_2 = \frac{P_1 V_1 T_3}{P_2 T_1} = \frac{1.05\times10^5 \times 2.8 \times 303}{5.6\times10^5 \times 283}$

$= 0.562 \ m^3/min$

$$W = \frac{n}{n-1}\left\{\left[P_1 V_1 \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] + P_2 V_2\left[\left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 1\right]\right\}$$

$$= \frac{1.4}{1.4-1}\left\{1.05\times10^5\times2.8\left[\left(\frac{5.6}{1.05}\right)^{\frac{.4}{1.4}} - 1\right] + 5.6\times10^5\times0.562\left[\left(\frac{35}{5.6}\right)^{\frac{.4}{1.4}} - 1\right]\right\}$$

$= 13.7\times10^5$ N-m/min.

* Power required to drive a two-stage reciprocating air compressor $= P = \frac{W \times N}{60}$ watt.

N → No. of working strokes per minute

Q Calculate min^m work required to compress 1kg of air from 1 bar, 27°c to 16 bar in two stages, if $pv^{1.25} = c$ & the inter cooling is perfect. R = 287 J/kg-K

Sol

m = 1kg

$P_1 = 1$ bar $= 10^5$ Pa

$T_1 = 27°C = 300K$

$P_3 = 16$ bar

$n = 1.25$

$R = 287$ J/kg-K

For perfect intercooling, $P_2 = \sqrt{P_1 P_3} = \sqrt{1\times16} = 4$ bar

(can be derived) $W = 2\times\frac{n}{n-1} mRT_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$

$= 275090$ J.

Q A two-stage single acting reciprocating air compressor draws in air at 1 bar & 17°c & compresses to 60 bar. After compression in LP cylinder, the air is cooled at const. P of 8 bar & to 37°C. The LP cylinder has dia 150 mm & both cylinders have 200 mm stroke. If compression is $PV^{1.35} = c$, find power of the compressor when it runs at 200 rpm. Take R = 287 J/kg-K

Soln Given $P_1 = 1$ bar $= 10^5$ Pa

$T_1 = 17°C = 290K$

$P_3 = 60$ bar

$P_2 = 8$ bar

$T_3 = 37°C = 310K$

$d = 150$ mm $= 0.15$ m

$L = 200$ mm $= 0.2$ m

$n = 1.35$

$N = 200$ rpm

R = 287 J/kg...

V_1 = Volume of LP cylinder

$$V_1 = \frac{\pi}{4} d^2 L = \frac{\pi}{4} 0.15^2 \times 0.2 = 0.0035\ m^3$$

V_2 = volume of HP cylinder

we know $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_3}$

$$\Rightarrow V_2 = \frac{P_1 V_1 T_3}{P_2 T_1} = \frac{10^5 \times 0.0035 \times 310}{8 \times 10^5 \times 290} = 0.00047\ m^3$$

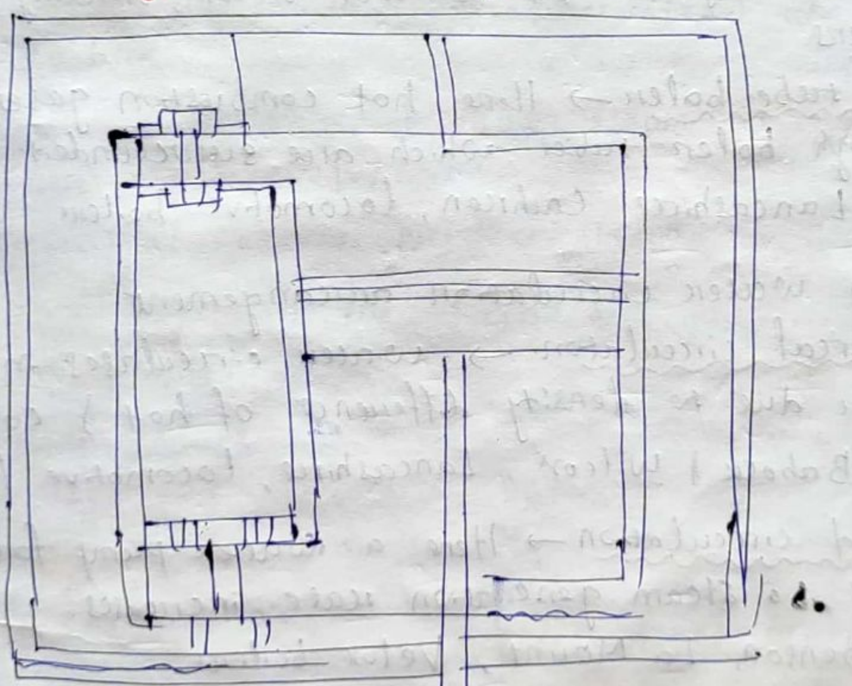
$$W_{in} = \frac{n}{n-1}\left[P_1 V_1 \left\{\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right\} + P_2 V_2 \left\{\left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 1\right\}\right]$$

$$= \frac{1.35}{1.35-1}\left[10^5 \times 0.0035 \left\{\left(\frac{8}{1}\right)^{\frac{.35}{1.35}}\right\} + 8 \times 10^5 \times 0.00047 \left\{\left(\frac{60}{8}\right)^{\frac{.35}{1.35}} - 1\right\}\right]$$

$$= 3.86\,(250 + 258) = 1961\ N\text{-}m$$

$$P = \frac{W_{in} \times N}{60} = \frac{1961 \times 200}{60} = 6540\ W$$

Double acting reciprocating air compressor →



construction of double acting air compressor is similar to single acting air compressor, except two inlet & two delivery valves on two ends of the cylinder are present to allow air entry & delivery on two sides of the piston.

→ when piston compresses the air on its one ~~end~~ side, it creates suction on the other side. So suction & compression of air takes place on two sides of the piston simultaneously.

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Chapter-4

Steam Generators

- A steam boiler or steam generator is a closed vessel in which water is heated, vapourised & converted into steam at a pressure higher than the atmospheric pressure.
- Heat energy required for steam generation is produced by burning fuel in the furnace.
- Steam generated in boiler can be used for producing power or for heating purposes.

Classification of boiler →

1> Accⁿ to relative passage of water & hot gases

a) water tube boiler → Here water flows through a no. of small tubes which are surrounded by hot combustion gases. Ex- Bobcock & Wilcox, Stirling, Benson boilers.

b) Fire tube boiler → Here hot combustion gases pass through boiler tubes which are surrounded by water. Ex- Lancashire, Cochran, locomotive boilers.

2> Accⁿ to water circulation arrangement

a) Natural circulation → water circulates in the boiler due to density difference of hot & cold water. Ex- Babock & Wilcox, Lancashire, locomotive boilers.

b) Forced circulation → Here a water pump forces the water so steam generation rate increases. Ex- Benson, La Mount, Velox boilers.

3> Accⁿ to use

a) Stationary boiler → Used for power generation in thermal power plants or process steam plants.

b) portable boiler → These are mobile boilers used for temporary uses at the sites.

c) Locomotive boiler → Specially designed boilers. It produces steam to drive railway engines.

d) Marine boiler → Used on ships.

4> Accⁿ to position of furnace
a) Internally fired → Furnace is located inside the shell. Ex- Cochran, Lancashire boiler
b) Externally fired → Furnace is located outside the boiler shell. Ex- Babcock & Wilcox, Stirling boiler

5> Accⁿ to position of boilers
a) Horizontal
b) Vertical
c) Inclined

6> Accⁿ to pressure of steam generated
a) Low pressure boiler → produces steam at pressure of 15-20 bar. This steam is used for process heating.
b) Medium pressure boiler → It produces steam from 20 bar to 80 bar. This steam is used for power generation & process heating.
c) High pressure boiler → It produces steam at pressure above 80 bar.
i) Sub-critical boiler → produces steam at pressure < $P_{critical}$ i.e. 221.1 bar.
ii) Supercritical " → produces steam " > $P_{critical}$

7> Accⁿ to charge in the furnace
a) Pulverised fuel
b) Supercharged "
c) Fluidised bed combustion boiler

Parts of boiler :→

1> Drum / Shell
It consists of one or more steel plates bent into the cylindrical form & riveted or welded together. Ends of the shell are closed by flat or curved plates called as boiler head.

2> Setting
Also called as foundation & is constructed of bricks. It supports boiler drum & other components. It forms the wall of the furnace, combustion chamber & passage to flue gases.

3> Grate
It is the space located below the furnace & consists of

cast iron bars upon which fuel is burned. The air can pass through the spaces between the bars & can support the combustion process, the ash can fall down through these spaces.

4) Furnace
It is the space above the grate & below the boiler shell. Here combustible gases are burnt & flue gases are generated.

5) Flue gases
It is the hot mixture of products of combustion generated in the furnace.

6) Flue
The hot gas passage in the boiler is called flue. It provides the drum to the hot gases to pass around the boiler.

7) Heating surface
It is the surface of the boiler which is exposed to hot flue gases on one side, water on other side.

8) Stocker
It is a mechanical system for charging of coal to the furnace & keep the firing continued.

9) Water wall
The closely spaced water tubes arranged near the furnace wall form a layer like a wall, called as water wall. The tube surface in the water wall receives the heat by radiation.

10) Water space
Space of the boiler shell occupied by water. Its level can be seen by water level indicator.

11) Steam space
Entire space of boiler shell not occupied by water.

12) Feed water
The water supplied to the boiler is called feed water. The pump supplying water is called feed pump.

13) Working pressure
P of steam generated in boiler & superheater.

14) Economiser
Feed water supplied by feed pump is heated by waste heat of flue gases before leaving to atmosphere

through chimney. It ↑ η.

15) Air preheater

Fresh air going to the furnace is preheated, which increases combustion efficiency. It also uses waste heat of flue gases.

16) Superheater

Used to heat saturated steam generated in the boiler to superheated steam. They are located above the furnace & ↑ η of the system.

17) combustion chamber

It is the space, generally, below the boiler shell used for burning fuel to produce steam from the water contained in the shell.

18) Boiler mountings

These are the fittings which are mounted on the boiler for its proper functioning. Ex- pressure gauge, water level indicator, steam stop valve, feed check valve, blow off cock, boiler safety valve.

Boiler can't function safely without mountings.

19) Boiler accessories

These are integral part of the boiler but not mounted on it. These are auxiliary parts of boiler. Ex- superheater, economiser, air preheater, ESP, feed pump etc.

Characteristics of a good boiler →

→ Should have max^m steam generation rate with min^m fuel consumption.

→ can be started or stopped quickly.

→ initial cost, running & maintenance cost should be low.

→ should have control & safety appliances.

→ " high rate of heat transfer & better combustion efficiency.

→ Should occupy less floor space.

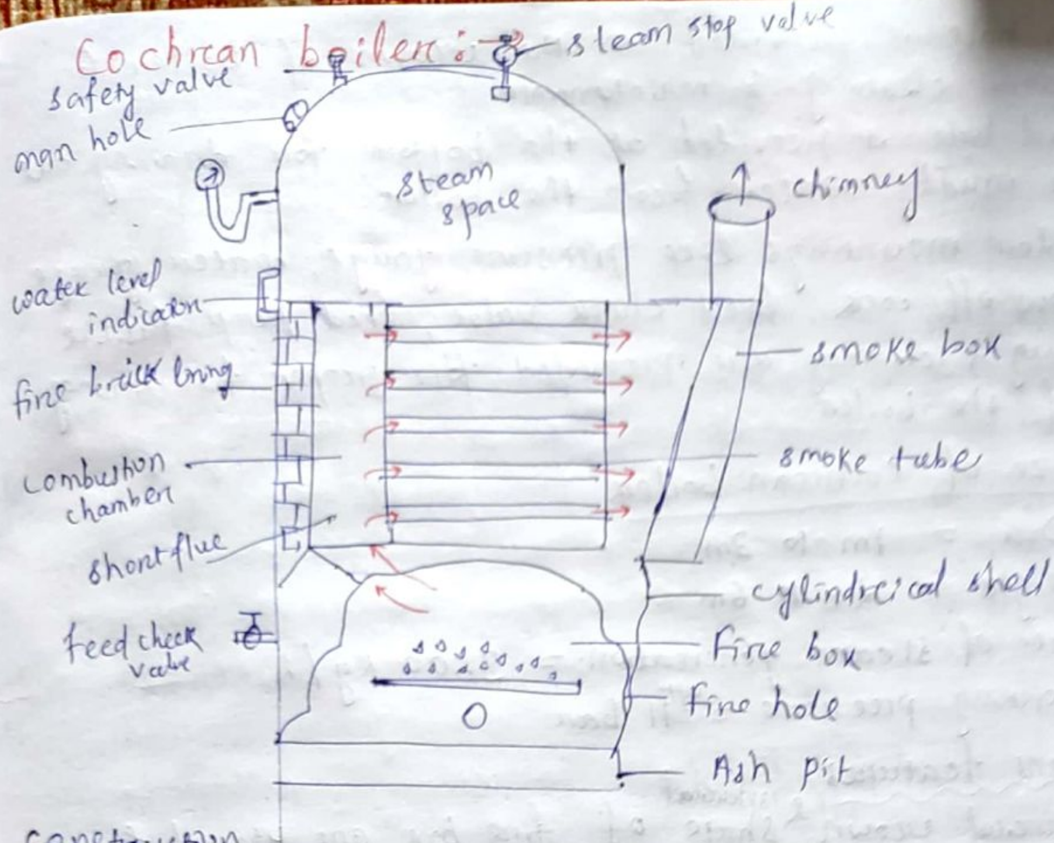
→ All parts of boiler should be accessible for cleaning & inspection.

→ Should obey IBR act

Comparision between fire tube & water tube boilers

Fire Tube	Water Tube
i) Hot flue gases passes through tubes & water surrounds them.	i) water passes through tubes & hot flue gases surrounds them.
ii) Operated at low Pressure upto 20 bar.	ii) upto 250 bar in supercritical boiler
iii) Rate of steam generation & quality of steam are low. So not suitable for power generation.	iii) ... better. So suitable for power generation.
iv) Load fluctuations can not be handled.	iv) ... are easily handled.
v) Requires more floor area for a given o/p.	v) .. less floor area
vi) Bulky & difficult to transport.	vi) Light in weight. So easy to transport.
vii) Overall η is upto 75%.	vii) overall η with economiser is upto 90%.
viii) water does not circulate in a definite dirn	viii) Dirn of water circulation is well defined.
ix) Less initial cost but cost per unit is more.	ix) Initial cost is high but cost/unit is less.
x) Simple in design, easy to erect & low maintenance cost.	x) complex design, difficult to erect & high maintenance cost.
xi) Less skill required for operⁿ.	xi) Skilled operators are required.
xii) Used in process industry.	xii) Used in large power plants.

Cochran boiler :



Construction

→ It is a vertical, coal or oil fired, fire tube boiler.

→ Here the flue gases from the furnace passes through a number of small tubes surrounded by water.

Construction

→ It consists of a cylindrical shell with a hemi-spherical crown, grating, fire box, chimney & different mountings.

→ The grate is placed at the bottom of the hemispherical furnace. Coal is feed into the grate through fire door & the ash formed is collected by ash pit which is present below the grate & removed manually.

Working

→ The fuel is burnt on grate.

→ Now the hot flue gases passes to combustion chamber through short flue, small horizontal smoke tubes & then collected in smoke box, from this it is disposed to atmosphere via chimney.

→ Here the heat is transferred to water by radiation through the dome of the fire place & by convection from the walls of the smoke tubes.

→ During heating water is vapourised & converted to steam. This steam is collected in the steam space above the water.

→ Now this steam is taken for use via main steam stop valve.

→ Man hole is provided in the crown of boiler for periodic cleaning & maintenance.

→ Mud hole is provided at the bottom for draining out the muddy water from the boiler.

→ Boiler mountings like pressure gauge, water gauge, blow off cock, feed check valve, feed pump, fusible plug & chimney are provided for proper functioning of the boiler.

Size of Cochran boiler

Dia = 1m to 3m

height = 2m to 6m

Rate of steam generation = 3600 kg/h

working pressure = upto 11 bar

Salient features :

→ Spherical crown & spherical shape of fire box are special features as these shapes require least material for a given volume.

→ It is very compact & requires less floor area.

→ Any type of fuel can be burnt.

→ well suited for small industries.

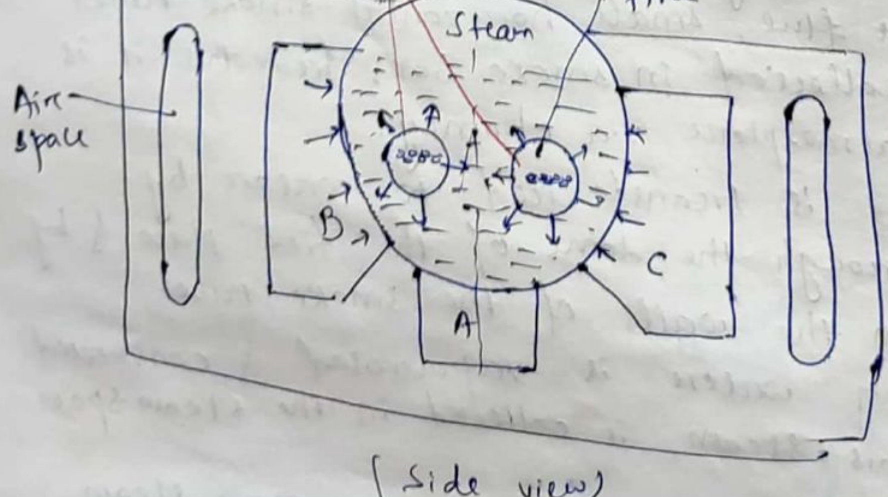
→ gives about 70 % of $\eta_{thermal}$ with coal firing.

Lancashire boiler :→

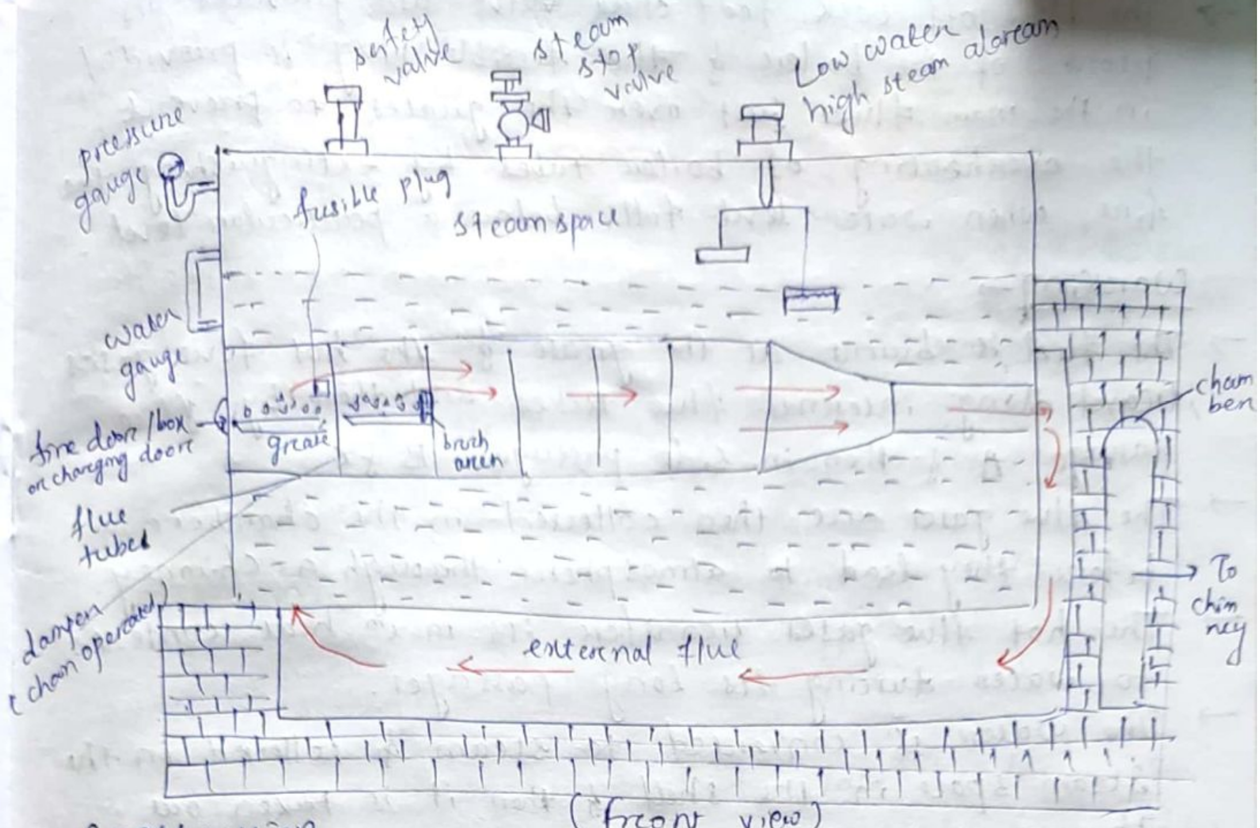
→ It is a horizontal, internally fired, fire tube, natural circulation, stationary boiler.

→ It is used widely due to capacity of good steam generation.

→ It is also used for power generation at moderate steam pressure of 15 bar.



(Side view)



<u>Construction</u>

→ It consist of a large shell supported by refractory brick masonary.
→ The cylindrical shell is 2-3 m dia & 7-9 m long.
→ Two large, horizontal & parallel flue gas tubes passe through shell. (its dia 0.4 times dia of shell)
→ The fire place is located in front of the flue tubes.
→ In brick work, a flue passage A below the boiler shell, & two flue passages B & C at the sides of boiler are formed.
→ The flue passages B & C are connected to a chamber & then to the chimney.
→ The dampers in the form of sliding doors are located at the end of side flues to control the flow of gases. It regulates rate of combustion and rate of steam generation.
→ Boiler is also provided with mountings like pressure gauge, water level indicator, steam stop valve, safty valve, low water & high steam safety valve, man hole etc on the top of the shell.

It gives an audio signal for low water level & high steam pressure.

'Brick arc → Deflect the flue gases upward

→ The blow off cock, feed check valve are provided in front of the boiler & the fusible plug is provided in the main flues just over the grates to prevent the overheating of boiler tubes by extinguishing the fire, when water level falls below a particular level

Working →

→ The fuel is burnt at the grate & the hot flue gases travel along internal flue tubes and then by flue passage A & then in side passages B & C.

→ The flue gases are then collected in the chamber, before they lead to atmosphere through a chimney.

→ The hot flue gases transfer its max^m heat contents to water during its long passages.

→ The water is converted to steam & collected in the steam space in the shell & then it is taken out through steam stop valve for use.

Special feature

→ Its heating surface area per unit volume is large.

→ Maintenance is easy.

→ can be handled easily fluctuations of load.

→ Highly suitable for process industries.

Shell dia → 2m

" height → 8 - 10 m

fire tube dia → 80 cm - 100 cm (2 NOS)

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Babcock & Wilcox boiler :→

→ It is a horizontal water tube ~~boiler~~, straight tube, externally fired natural circulation stationary type boiler.

components

welded steel drum

uptake & down take header

water tubes inclined at about 15° (dia 10cm) — 2/3 of boiler shell is filled with water.

externally fired furnace

mountings & accessories.

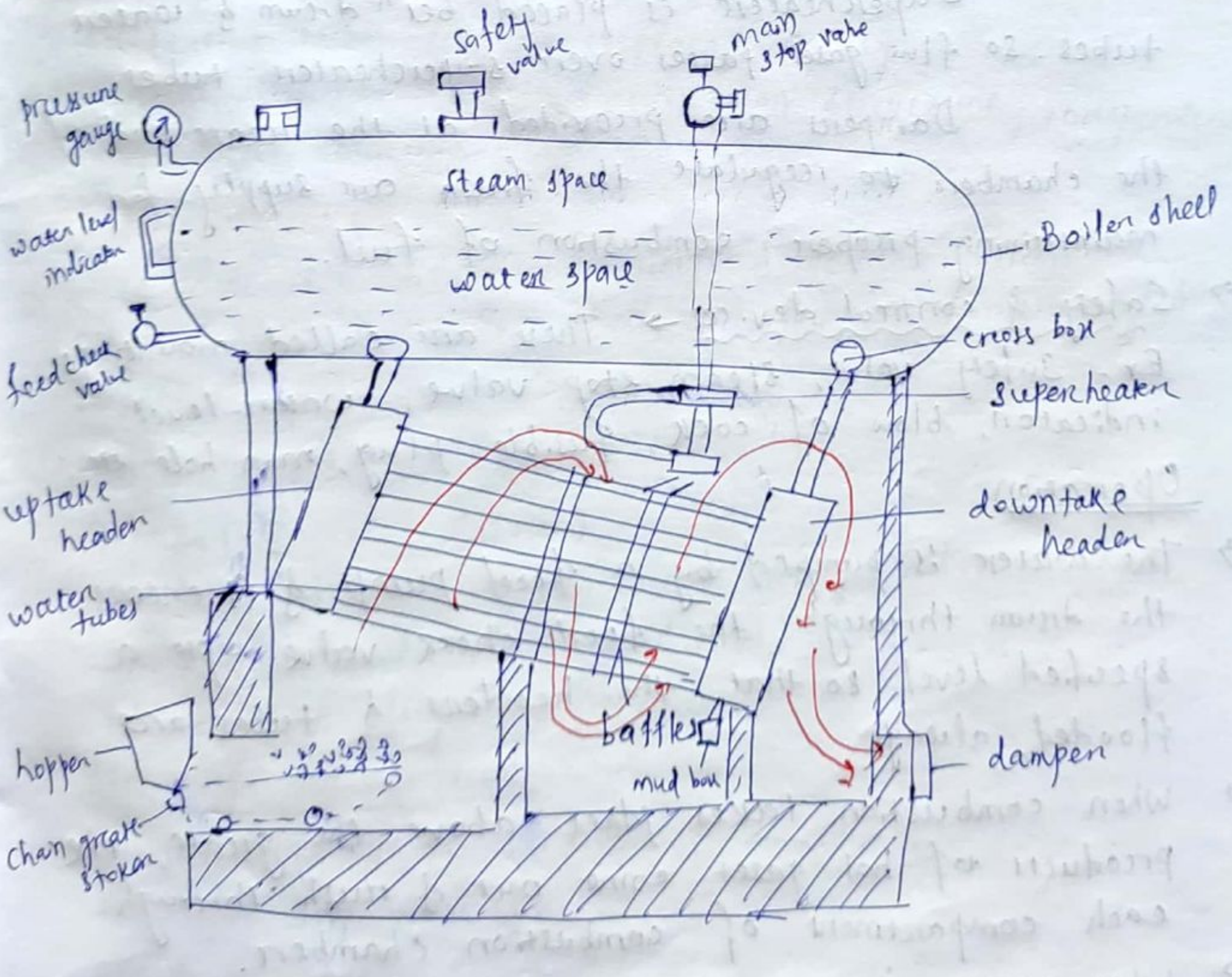
baffles = deflector (deflects flue gas travel to ↑ surface area for heat conduction)

Anti priming pipe → removes/reduces moisture content of wet steam & send it to superheater.

grate → where fuel is burnt. made of C.I. & have gap for air passage.

mud box is located at bottom of downtake header.

blow off pipe → used to blow the muddy water from mud box.



Construction

→ horizontal boiler shell → It is the main part of boiler. It is supported by a steel structure at certain height & independent of brick works. All safety & control devices are mounted on it.

→ bundle of steel tubes → They connect uptake header & downtake header. They are fitted at an angle of 5° to 15° with horizontal to promote water circulation.

→ combustion chamber – It is the space above the grate & below the front end of the drum where combustion of fuel takes place. It is enclosed by brickwork & lined with fire bricks from inside. Doors are provided for cleaning, inspection & repairing.

It is divided into 3 separate chambers by baffles. 1st is hottest & the last is having lowest tempr of flue gases.

Superheater is placed betn drum & water tubes. So flue gases passes over superheater tubes.

Dampers are provided at the rear end of the chamber to regulate the fresh air supply for maintaining proper combustion of fuel.

→ Safety & control devices → These are called mountings. Ex- safety valve, steam stop valve, water-level indicator, blow of cock, fusible plug, man hole etc.

Operation

→ The water is pumped by a feed pump & it enters the drum through the feed check valve upto a specified level so that the headers & tubes are flooded always.

→ When combustion takes place above the grate, the products of hot gases come out & rush through each compartment of combustion chamber.

→ When water inside the tube comes in contact with outside hot flue gases, heat transfer takes place.

→ When water is heated inside the tubes, it becomes lighter & rises up in the tube.

→ Due to continuous heat supply, some of the water gets vapourised into steam & the mixture of steam & water enters the boiler drum through uptake header.

→ The cold water from boiler drum comes down through downtake header & enters the lower end of water tubes for further heating.

→ This natural circulation of water remains continuous due to difference in tempr.

→ The steam generated gets collected in steam space. To remove moisture on water particles, it is further passes over superheater. Now superheated steam is available for use.

Special feature

→ Operating capacity = 20,000 to 40,000 kg/h

→ " pressure = 11.5 to 17.5 bar

→ draught losses mmm.

→ defective tubes can be replaced easily.

→ entire structure rests on an iron structure, independent of brick structure.

Boiler Mountings →

These are the different fittings & devices which are mounted on the boiler shell for proper functioning & safety.

1) Mountings for safety

i) Safety valve (2 nos)
ii) High pressure & low water safety valve (1)
iii) water level Indicator (2 nos)
iv) Fusible plug (1 nos)

2) Mountings for control

i) pressure gauge (1 nos)
ii) Steam stop valve (")
iii) Feed check " (")
iv) Blow off cock (")
v) man hole (")
vi) Mud box (")

Boiler Mountings :→

These are those mechanical appliances which are considered essential for smooth & safe operation of boiler. These are usually mounted on the surface of a boiler.

Example of boiler mountings are

i) water level indicator
ii) pressure gauge
iii) Safety valve
iv) fusible plug
v) steam stop valve
vi) Blow off valve or blow down cock
vii) feed check valve
viii) man hole & mud box

1> water level indicator / water gauge

It is used to indicate the level of water present in the boiler. If level goes below the fixed mark so that corrective action can be taken to avoid accident.

2> Pressure gauge

It is used to indicate the gauge pressure of a fluid. It indicates the gauge pressure of steam with in the boiler. Ex- bourdon tube pressure gauge

3> Safety valve

It is a relief valve and it prevents the raising of boiler pressure above its normal working pressure by automatically opening when boiler pressure exceeds the normal working pressure & thus allows excess steam to escape into atmosphere until the pressure comes down to its normal value. It also provides safety to a pipe or vessel containing water at high pressure.

types of safety valve

a) Lever type S.V
b) Dead weight S.V
c) High steam & low water S.V
d) Spring-loaded S.V

4> Fusible plug

It is used to put off fire in the furnace of the boiler when the water level in the boiler falls below an unsafe level and thus avoids explosion which may take place due to overheating of the tubes and shells.

This plug is usually fitted over the crown (head) of the furnace or over the combustion chamber.

5> Steam stop valve

Also called as main stop valve.

Used to control the flow of steam from within the boiler and to stop it completely when required.

6> Blow-off valve / blow-down cock / Block-off cock

Its function is

a) To empty the boiler when necessary for cleaning, repair and inspection.
b) To discharge the mud and sediments carried with the feed water and accumulated at the bottom of the boiler.

→ It is fitted to the lowest part of the boiler either directly with the boiler shell or to a pipe connected with the boiler.

→ When blow-off cock is opened, the water which is under the pressure of steam, rushes out with tremendous velocity & thus carry out the sediments along with it.

7> Feed check valve

Used to control the flow of water from the feed pump to the boiler and to prevent the back flow of water from the boiler to the pump when the pump pressure is less than the

boiler pressure on when ...
work.

→ It is placed at the boiler end of the delivery pipe of the feed pump.

Boiler accessories: →

These are the auxilliary parts required to increase the overall efficiency of the boiler & to improve the operating conditions.

Difference betn mountings & accessories

→ Boiler mountings is an essential apparatus without which a boiler cannot be operated, but boiler accessories is not an essential part, used only to

→ mountings are mounted on the boiler but accessories are not generally mounted on the boiler but installed within or near the boiler

→ mountings occupy less floor space but accessory occupy more floor space.

Example

i) Economiser
ii) Feed water heater
iii) Superheater
iv) Steam separator
v) Steam trap
vi) Feed pump
vii) Injectors
viii) Air preheater

Electro static precipitator

Air preheater →

→ It recovers some portion of the waste heat of the flue gases. Air supplied to the combustion chamber is preheated by using heat of waste flue gases.

→ These are placed after the economiser & before the gases enter the chimney.

→ Preheating of air results the following advantages

- waste heat from the flue gases is recovered for heating air & reduces the fuel consumption by about 1.5% for each 100°C drop in gas temp.

- Inferior grades of coal can be burnt efficiently with preheated air
- Combustion can be more efficient & an intense flame can be achieved in the furnace. So ↑ evaporation rate of the boiler.

Economiser →

It is a heat exchanger.

It extracts the waste heat of the chimney gases to preheat the water before it is fed to the boiler. It ensures economy of fuel. So it is called economiser.

advantages of preheating of boiler feed water

→ Saving of fuel as waste heat of flue gas is utilised to heat feed water

→ Dissolved gases as air & CO_2 are removed by preheating feed water & reduces corrosion & pitting.

→ Less temp strain in boiler plates as feed water enters the boiler at high temp

→ circulation of H_2O is well maintained as quick evaporation is possible due to hot feed water

→ ↑ overall η by ↓ fuel consumption.

Types of economiser

1> Independent type

Installed in chamber upset from the boiler setting. Installed in chamber situated at passage of the flow of the flue gases from the boiler or boiler to chimney.

2> Integral type.

part of the boiler heating surface & is installed within the boiler setting.

→ Water moves from top to bottom pipe & then to boiler.

→ The gases move around the pipes in dirn opposite to flow of water & consequently heat transfer through the surface of pipe takes place & water is thereby heated.

→ Blow-off cock is provided at back end of vertical pipes to remove sediment deposit in bottom boxes.

→ To remove soot of flue gases on pipe of economiser scrapper are used which move up & down to keep it clean.
→ By pass arrangement enables to isolate or include the economiser in path of flue gases.

Advantages
→ temp. range betn various parts of boiler is reduced which results in reduction of stresses due to unequal explosion.
→ evaporative capacity of boiler ↑.
→ $\eta_{overall}$ of plant ↑
→

Air preheater →
→ Used to ↑ the temp. of air before it enters the furnace. It is generally placed after economiser. So flue gases pass through economiser & then the to air preheater.
→ It consists of plates or tubes with hot gases on one side & air on other. Preheated air accelerates the combustion & facilitates the burning of coal.
→ Degree of pre-heating depends on
- type of fuel
- " " " burning equipment
- Rating at which boiler & furnace are operated.

→ Types of air preheater
- Tubular
- plate
- Storage

→ After leaving boiler or economiser, flue gas preheats the air & is supplied to furnace.
Finally the gases escape to the atmosphere through stack (chimney). Temp of gases leaving the chimney should be kept as low as possible to minimize losses.

Superheater →
Used to increase temp of saturated steam into superheated steam after it comes from the boiler.
Advantages
→ Steam consumption of turbine is reduced
→ Saving in fuel consumption (about 15 – 20%).

→ $\eta \uparrow$

→ Losses due to condensation in cylinders & steam pipe is reduced.

→ Superheaters are located in path of furnace gases so that heat is recovered by the superheater from the hot gases.

→ Types of super-heater

1> convective → uses heat of the flue gases by convective mode to superheater surface

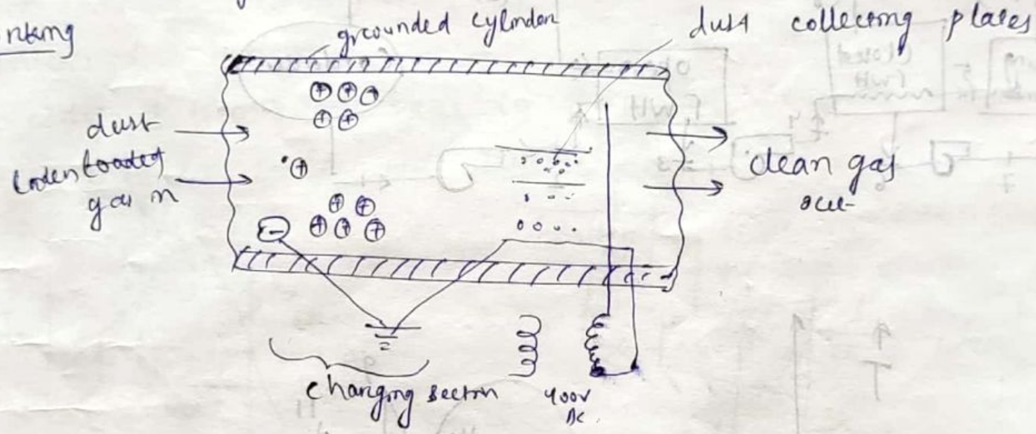
2> Radiant → placed in furnace & wall tubes receives heat from burning fuel through radiation (used where high temp. requirement)

3> combination type → heat is transferred by both mode.

ESP →

→ Used for removal of dust & ash particle carried with exhaust gases of thermal power plants.

Working



When dust laden gas is passed betn oppositely charged conductors it becomes ionised as voltage applied betn the conductors. particles get charged +vely & -vely. The collecting unit collect the dust which has metal plates arranged that are alternatively charged.

advantage

→ Remove very small particles

→ η 99.5 %

→ ease of operation

→ maintenance of charge is easier

Disadvantage

→ DC current not available directly

→ running cost is high

→ space required is large

→ velocity of gas is not maintained η is affected.

→

Boiler Draught :→ (draft)
It is defined as the pressure difference which causes continuous flow of gases inside the boiler.

Function of draught →

→ Forces sufficient quantity of air into the furnace for proper combustion of fuel.

→ Circulates the hot flue gases through the flue tubes, superheater, economiser, air preheater etc.

→ Discharges the hot flue gases to the atmosphere through the chimney.

Classification of boiler draught →

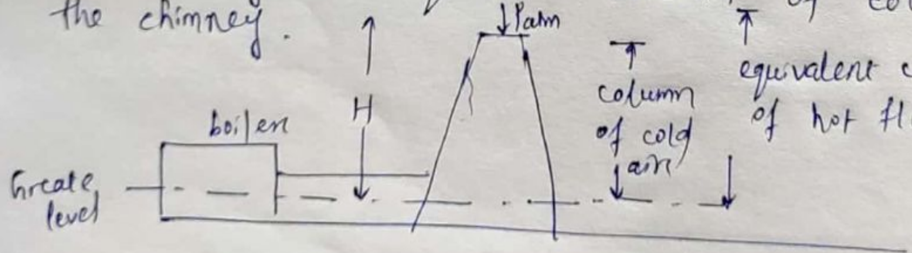
- Draught
  - Natural / Chimney
  - Artificial
    - mechanical
      - Induced
      - Forced
      - balanced
    - steam jet
      - Induced
      - forced

Natural draught →

→ It is produced by using chimney.

→ Chimney is a vertical long cylindrical structure made of brick masonary, RCC or steel.

→ The draught produced by chimney is due to density difference betn the column of hot flue gases inside the chimney and equivalent column of cold air outside the chimney.



Pressure at grate level in combustion chamber

$P_1 = P_{atm} + \rho_g g H$

Pressure at grate level outside the chimney

$P_2 = P_{atm} + \rho_a g H$

$\rho_g < \rho_a$

$\Delta P = P_2 - P_1 = (\rho_a - \rho_g) g H$

* The pressure difference causing the flow of gases is called static draught & is very small. So measured by water manometers.

Advantages

→ easy to construct
→ No power is required for producing draught
→ Long life of chimney
→ No maintenance required

Disadvantages

→ Tall chimney required
→ poor η.
→ η ↓ with ↑ in outside tempⁿ.
→ No flexibility to create more draught to take peak loads

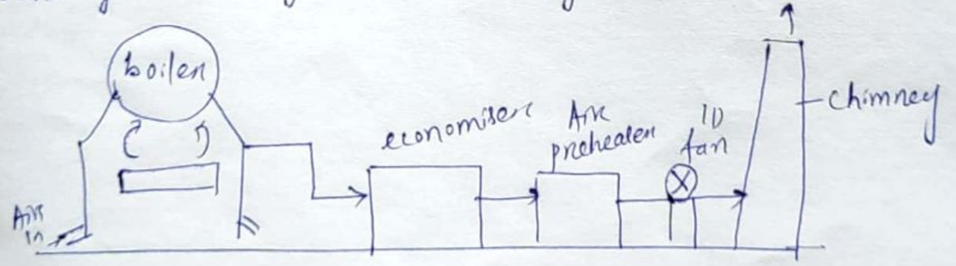
Artificial Draught →

Draught produced by any artificial means.
when artificial draught is produced by fan or blower it is called mechanical draught & that produced by steam jet is called steam jet draught.

Mechanical draught →

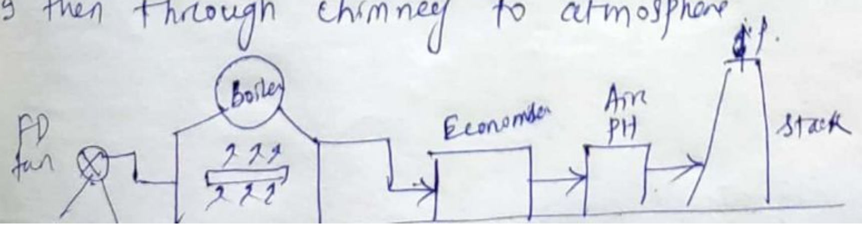
1) Induced draught →

Here fan is placed near the base of the chimney. The fan draws the flue gases from the furnace. So the pressure above the fuel bed is reduced below the atmospheric pressure. The fresh air rushes to the furnace & after combustion, the flue gases get discharged through the chimney in the atmosphere.



2) Forced draught →

- Here fan or blower is located near or at the base of the boiler grate to force atmospheric air on to the furnace under pressure. This pressure helps in circulation of flue gases through components of boiler & then through chimney to atmosphere.



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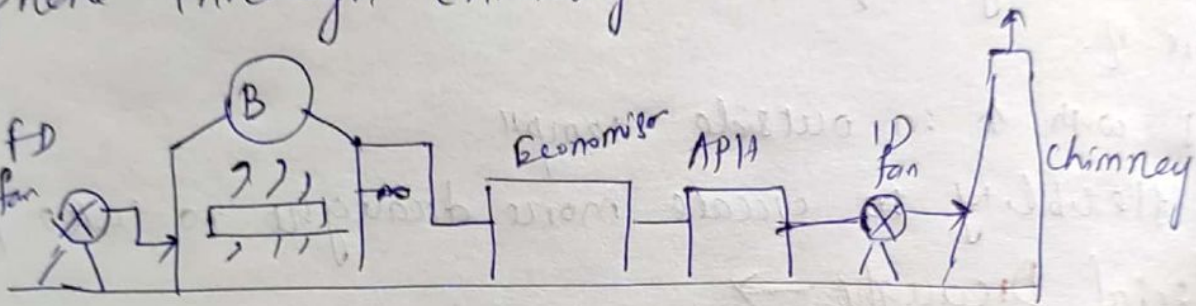
Balanced draught →

It is the combination of induced & forced draught. A forced draught fan located near the grate supplies air under pressure through the furnace & an ID fan located near the chimney base, draws in flue gases through the economiser, APH etc & discharges to atmosphere through chimney.



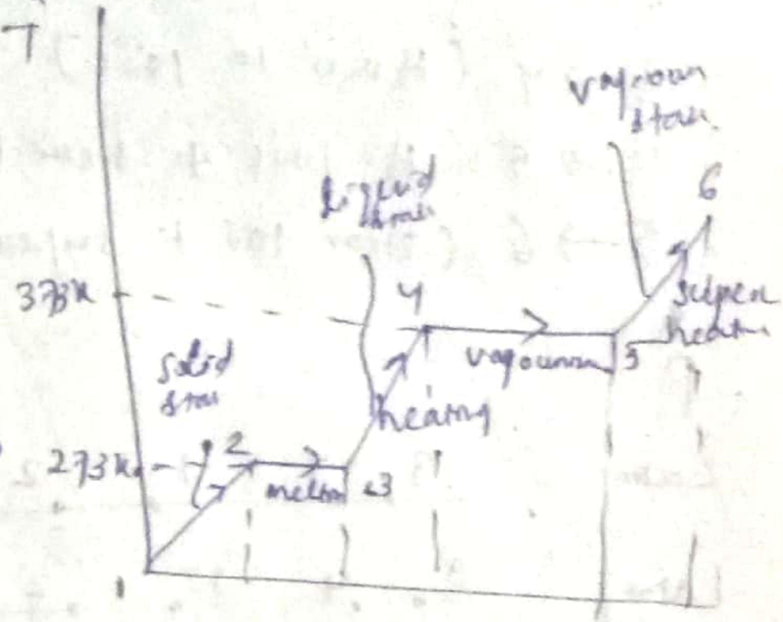
Advantages of artificial draught over natural draught →

i) Forced draught has better control on combustion.
ii) Low grade fuel can be efficiently burnt.
iii) overall η of a thermal powerplant ↑ as better heat recovery from the exhaust flue gases in economiser & APH.
iv) Height of chimney can be reduced.
v) smoke formation is less.
vi) Tendancy for air leakage in the furnace is less.

Working Substance — Chapter-5

Pure substance →
It is a substance of fixed chemical composition throughout its mass. It is one component system & exists in one or more phases. Ex- O_2, N_2, air, steam etc.

Formation / Generation of steam →
Consider 1 kg of ice at pressure P & at temp 0°C is contained in a vessel. Now it is heated by keeping P const. The following changes occur.



i) temp of ice ↑ gradually till it reaches 0°C at atm p. (1→2)

ii) By ↑ heat further, ice starts melting by absorbing Latent heat of fusion at const P & T. (2→3)

iii) Further adding heat, liquid H_2O absorbs heat till it reaches its boiling point. (3→4)

iv) Again heating water at 100°C will be converted to steam at 100°C by absorbing Latent heat of vapourisation at const P & T. (4→5)

v) Further heating called superheating & the steam follows all gas laws. increases its T.

Terms used in steam :-

1) **Wet steam →** when the steam contains moisture or particles of water. It contains partly vapour & partly liquid.

2) **Dry saturated steam →** when wet steam is further heated, it does not contain any suspended particles of water called as dry saturated steam.

3) **Superheated steam →** when dry saturated steam is further heated at const P and thus raising its tempⁿ, is called superheated steam. The process is called superheating.

degree of superheat = $t_{superheat} - t_s$ ← saturation temp

4) **Quality or dryness fraction →**
Defined as ratio between mass of actual dry steam to the total mass of steam. denoted by x.

mathematically $x = \dfrac{m_g}{m_g + m_f} = \dfrac{m_g}{m}$ (m_g ← mass of dry saturated vapour, m ← mass of mixture)

5) ~~Specific~~ Sensible heat of water →

sensible heat = mass × sp. heat × rise in temp

= 1 × 4.2 (1° − 0°)

6) Enthalpy or total heat of steam →

enthalpy = sensible heat + latent heat.

P–V diagram for pure substance →

(1) −10°C ice → (2) 0°C ice → (3) 0°C water → (4) 100°C water → (5) 100°C steam → (6) 110°C steam

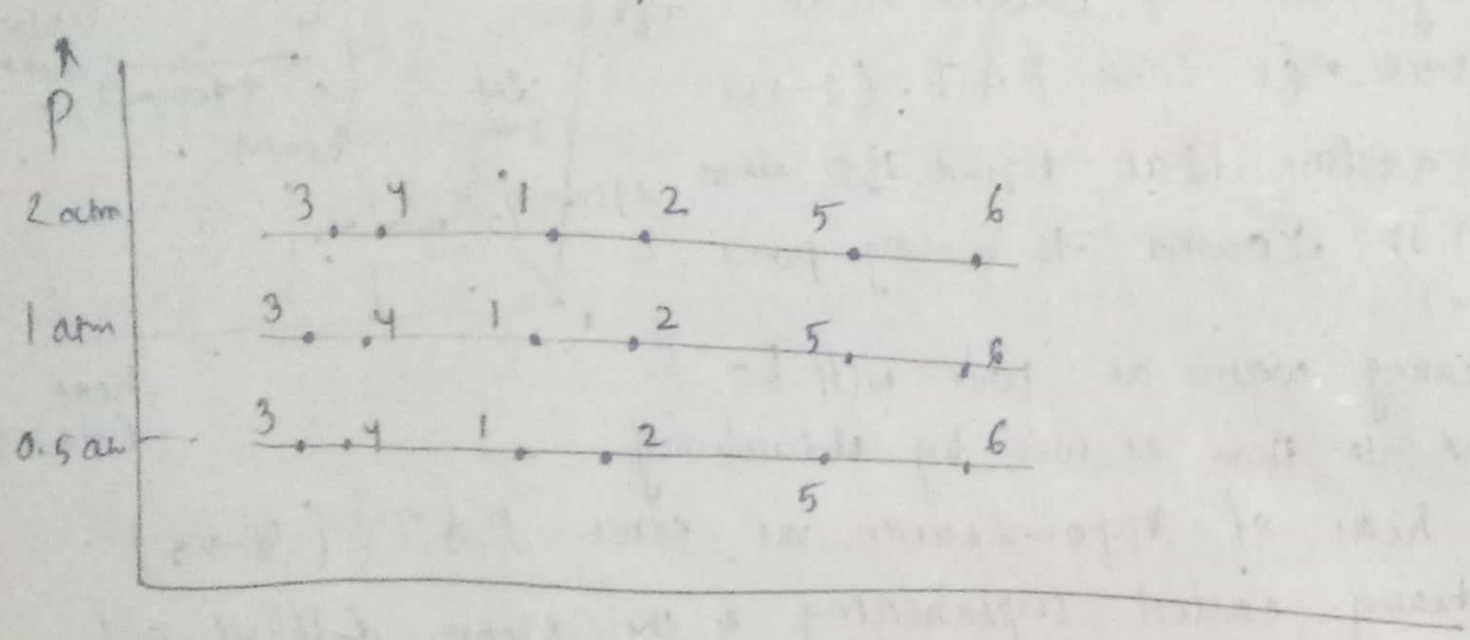
1 → 2 (ice −10°C to 0°C)

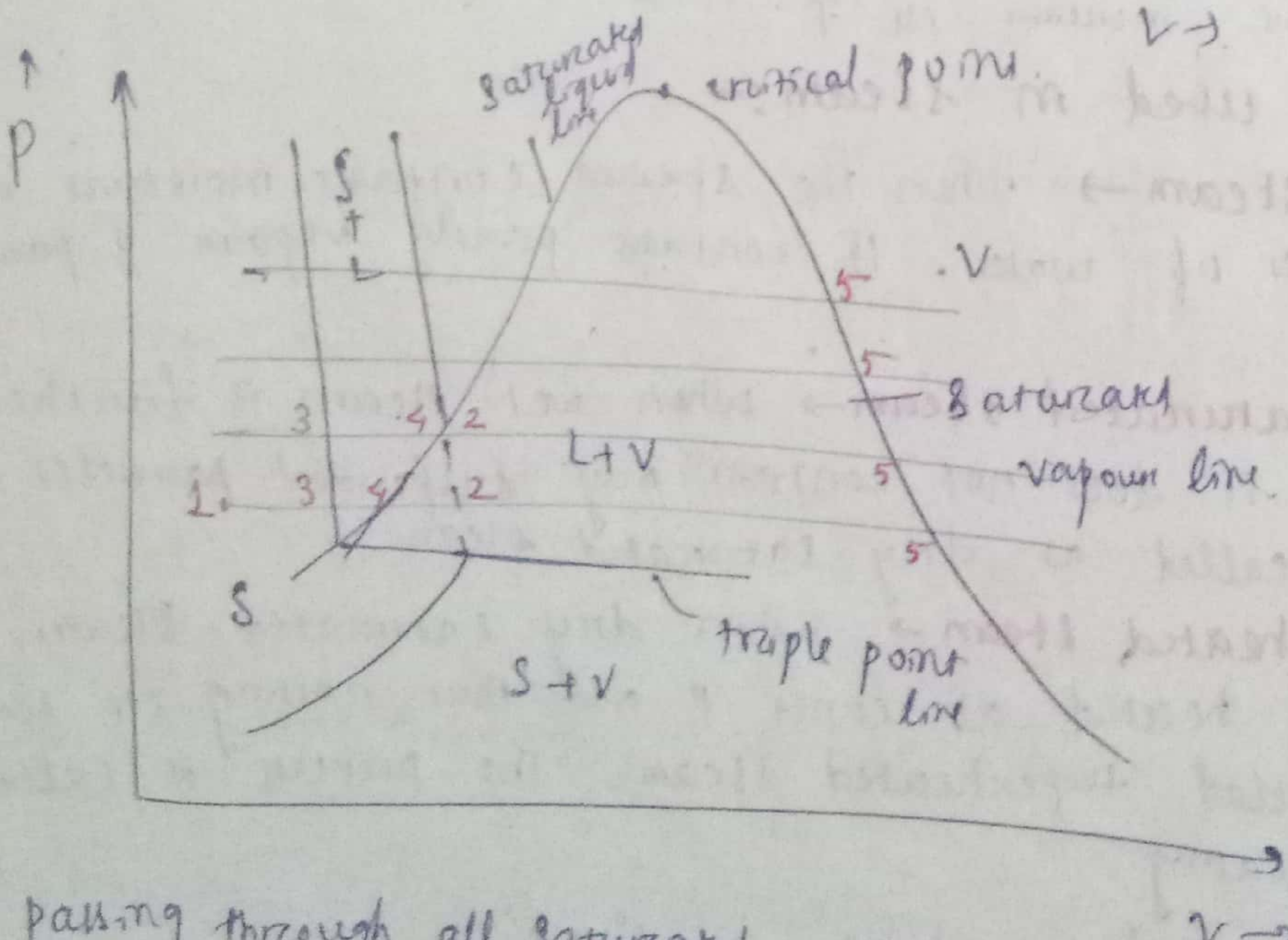
2 → 3 (ice 0° to H_2O 0°)

3 → 4 (H_2O 0° to 100°C)

4 → 5 (H_2O 100°C to steam 100)

5 → 6 (steam 100 to superheated steam at > 100)



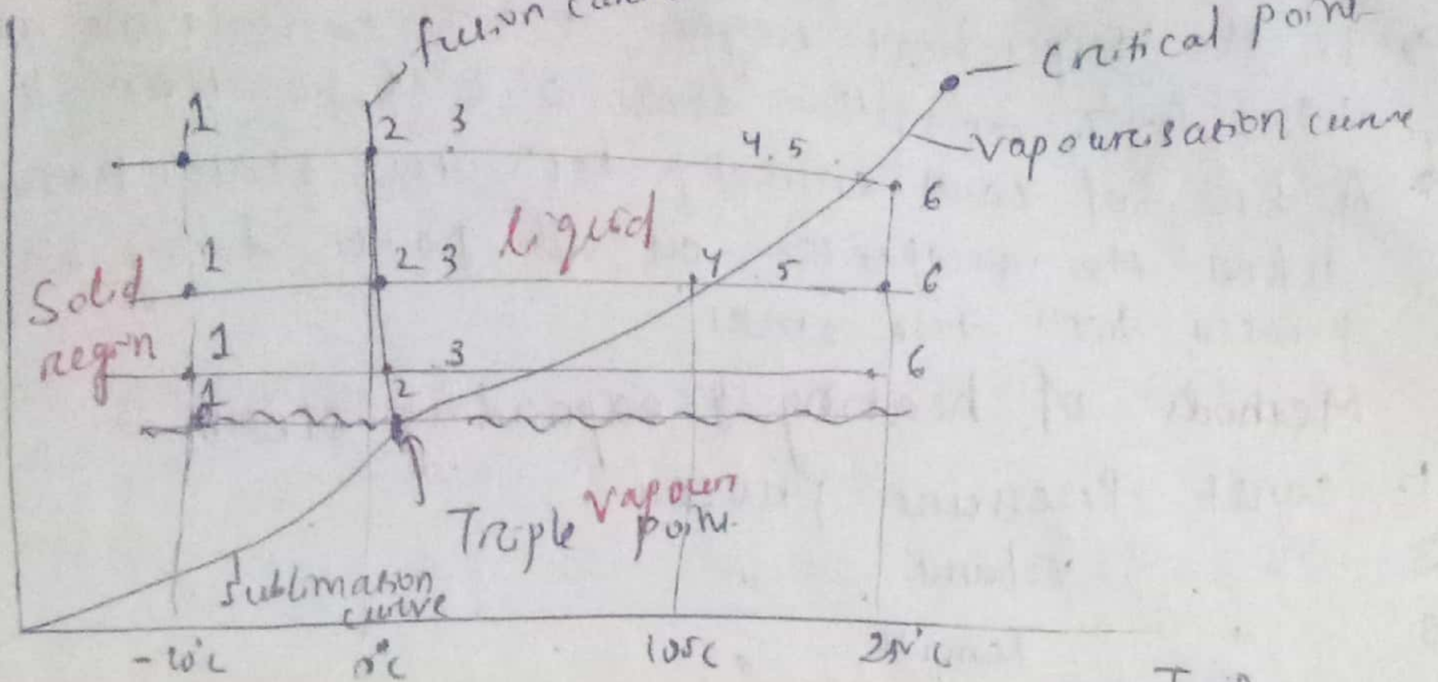


line passing through all saturated solid state 2 → saturated solid line

" " " liquid 3 → " liquid line

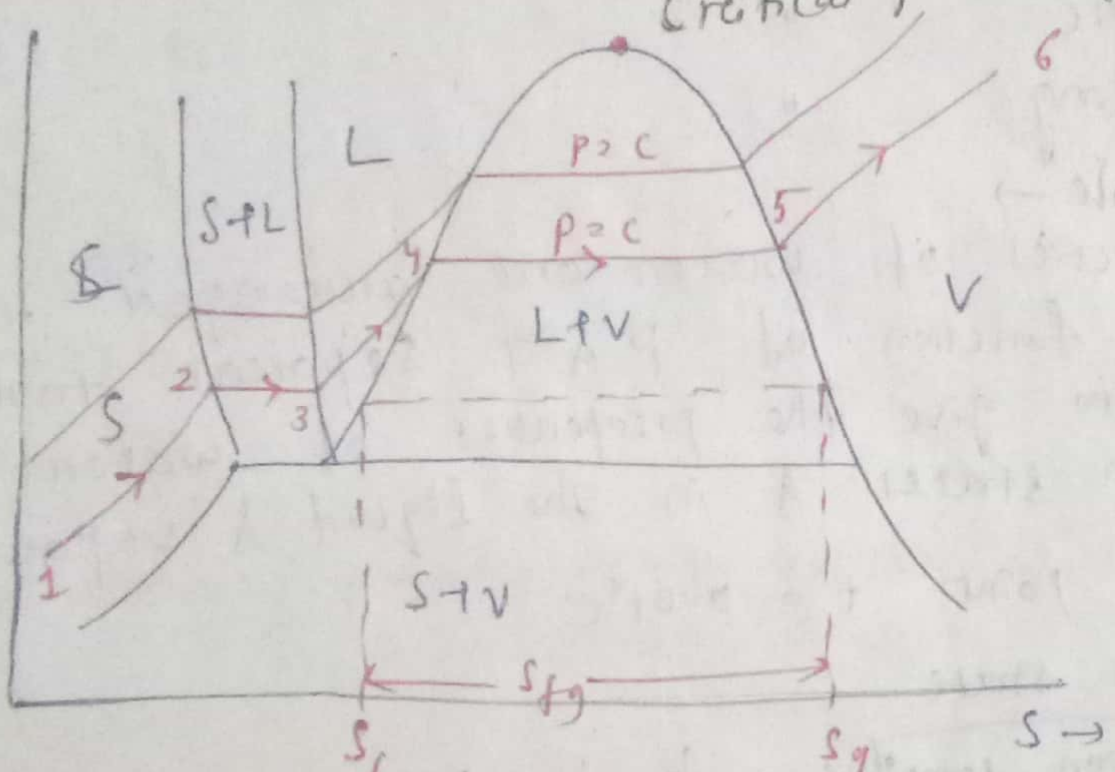
" " " 5 → " vapour "

P-T diagram for pure substance →

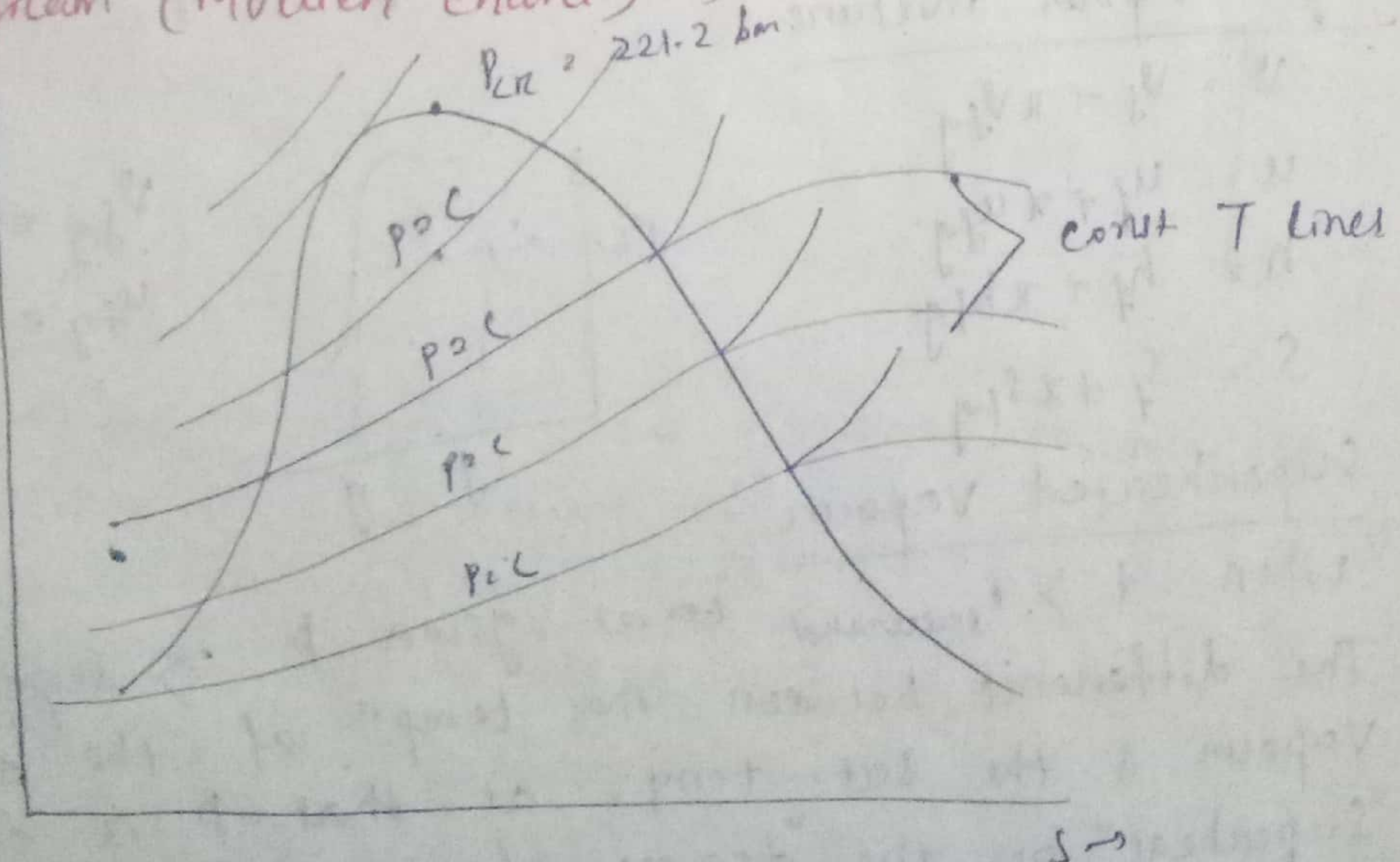


T-S diagram for pure substance →

Critical point ($P_c = 221.2$ bar, $T_c = 374.15°C$)



H-S diagram (Mollier chart) →



Here vertical coordinate represents enthalpy & base represents entropy.

Lines of const P, are indicated by P_1, P_2 ... etc & lines of const T by T_1, T_2, ... etc.

Any two independent properties which appear on the chart are sufficient to define the state. e.g. 1st P_1 &

T_1 are known. Then from state 1, h_1 can be found out.

→ In the superheat region, P & T can define the state e.g. P_3, T_4 can define state 2 & from them h_2 can be found.

→ A line of const entropy betn two state points 2 & 3 defines the properties at all points during an isentropic process betn two states.

Methods of heating & expanding steam →

1. const Pressure process
2. " volume "
3. " Tempr "
4. Adiabatic "
5. polytropic "
6. Throttling "

Steam table →

The properties of water are arranged in the steam tables as function of P & T. Separate tables are provided to give the properties of water in the saturation states & in the liquid & vapour phase.

* At triple point $t = 0.01°C$

Saturation state

At saturation tempr $t°C$, $h_f, h_g, v_f, v_g, s_f, s_g, u_f, u_g$ etc.

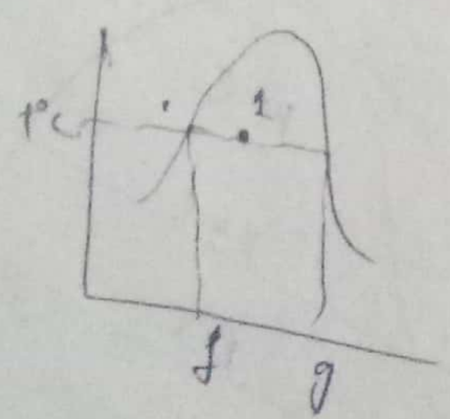
Liquid-vapour mixture

$v = v_f + x v_{fg}$

$u = u_f + x u_{fg}$

$h = h_f + x h_{fg}$

$s = s_f + x s_{fg}$



$v_{fg} = v_g - v_f$

$u_{fg} = u_g - u_f$

Superheated vapour

when $t > t_{saturated}$ at given p ⇒ superheated vapour

* The difference between the tempr of the superheated vapour & the sat. temp. at that p is called "superheat" or the "degree of superheat".

$t_1 - t_{sat} =$ superheat

compressed or subcooled liquid

When temp. of liquid is less than $t_{saturation}$, at given P then the liquid is sub-cooled.

* As its properties varies slightly, so saturation temp. table data

are taken.

Q.1 Find the saturation temp, change in specific volume & entropy of steam during evaporation at 1 MPa.

Sol. t_{sat} = S_{fg} =

v_{fg} =

Q.2 Find the enthalpy & entropy of steam when P is 2 MPa & sp. volume is 0.09 m^3/kg.

Sol. At P = 2 MPa, v_f = 0.001177 m^3/kg & v_g = 0.09963 m^3/kg.

$v = v_f + x v_{fg}$

$\Rightarrow 0.09 = 0.001177 + x(0.09963 - 0.001177)$

$\Rightarrow x = 0.904$

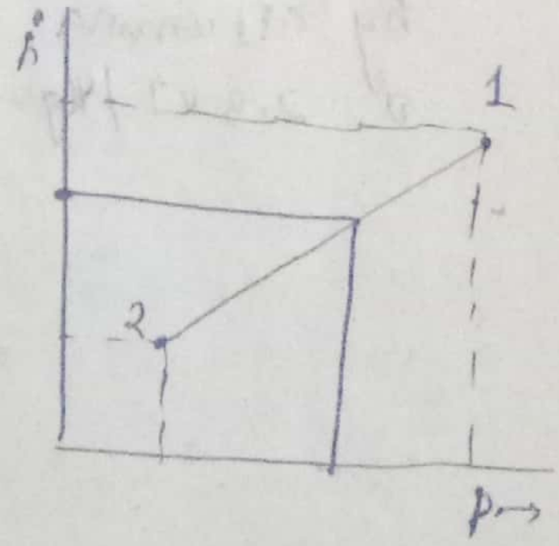
At 2 MPa, h_f = h_g =

S_f = S_g =

$h = h_f + x h_{fg}$ =

$S = S_f + x S_{fg}$ =

Find the enthalpy, entropy & volume of steam at 1.4 MPa, 380°C.



Determine the quantity of heat required to produce 1 kg of steam at a pressure of 6 bar & at a temp. of 25°C, under the following cond's
i) When steam is wet having x = 0.9
ii) " dry saturated
iii) " superheated at a constant p at 250°C.
assuming mean sp. heat of superheated steam to be 2.3 kJ/kg-K

From S.S.T.

P|6 bar, 25°C = h_f = 670.4 kJ/kg, h_{fg} = 2085 kJ/kg, t_{sat} = 158.8°C

$h = h_f + x h_{fg}$

$= 670.4 + (0.9 \times 2085) = 2546.9$ kJ

A) water is at temp.^n of 25°, so heat already in water = $4.2 \times 25 = 105$ kJ

∴ Heat actually required = $2546.9 - 105 = 2441.9$ kJ

ii) $h_g = h_f + h_{fg} = 670.4 + 2085 = 2755.4$ kJ

Heat actualy required = ~~2965.16 - 10~~ $2755.4 - 105$

$= 2650.4$ kJ

iii) $h_{sup} = h_g + C_p(t_{sup} - t_{sat})$

$= 2755.4 + 2.3(250 - 158.8) = 2965.16$ kJ

Heat actualy required = $2965.16 - 105 = 2860.16$ kJ.

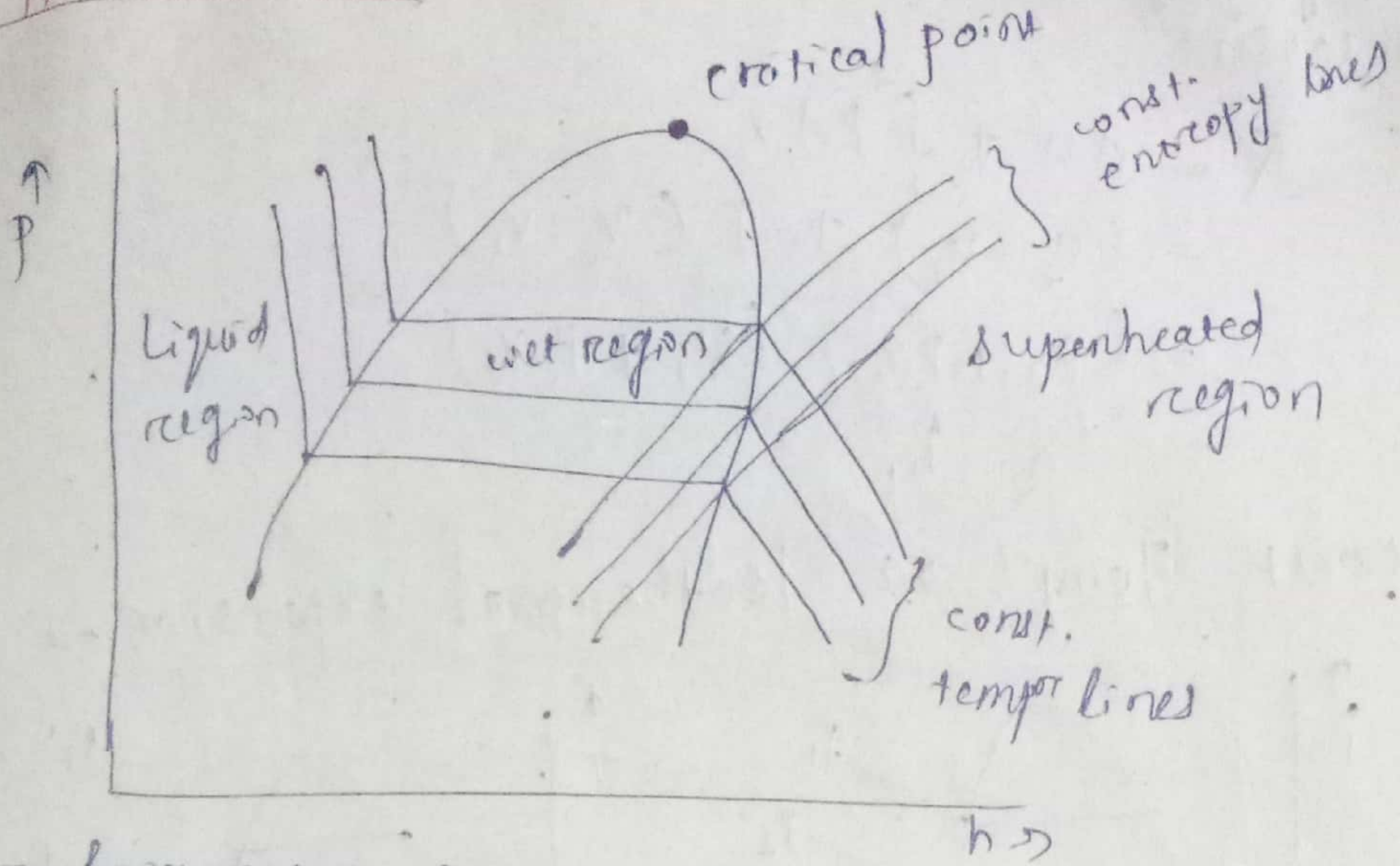
Q Determine the quantity of heat required to produce 1kg of steam at pressure of 6 bar at a temp^n of 25°C. under the following cases.

i) steam is wet having 95% quality

ii) steam is dry saturated

iii) steam is superheated at cast-process at 250°C by assuming: mean sp. heat of superheated steam is 2.3 kJ/kg-K.

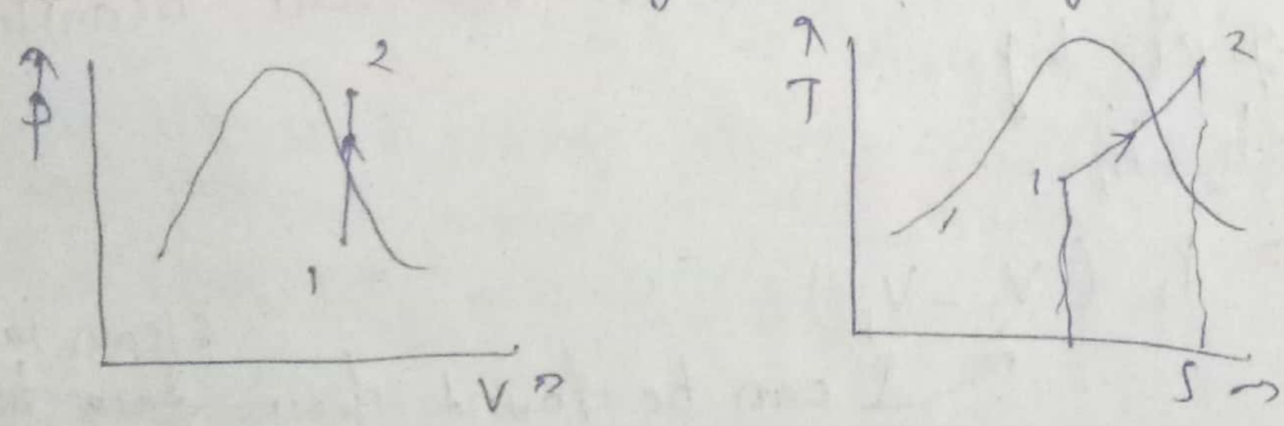
P-H chart



- In refrigeration system P-h chart is used
- It is useful in locating const. enthalpy lines & const. entropy lines starting from saturated liquid conditions

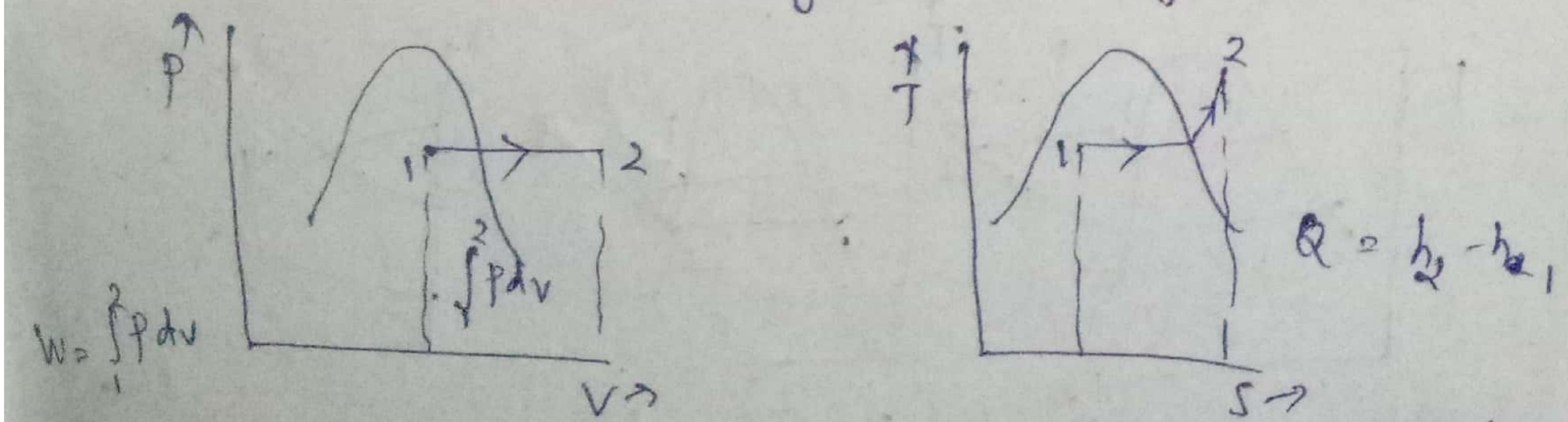
Different flow & non-flow processes of vapour →

1) Const. volume heating or cooling →



Steam is in wet condn before heating at P, P_1 & becomes superheated after heating at P, P_2. mass of steam remains const during the process. Data can be extracted from the steam table.

2) Const. pressure heating or cooling →

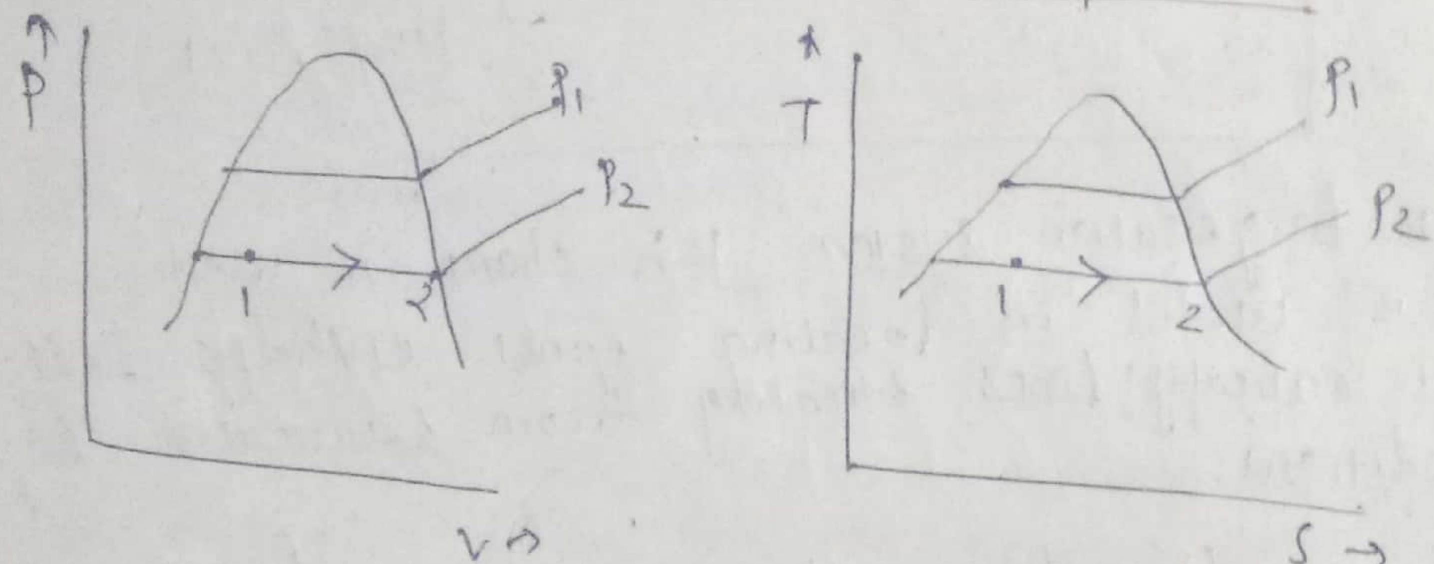


Ex - generation of steam in boiler [const. P heating]

Applying 1st law of TD for const. P. non-flow process

$$Q = \Delta u + \int_1^2 P dv$$
$$= (u_2 - u_1) + P(V_2 - V_1)$$
$$= (u_2 + PV_2) - (u_1 + P \cdot V_1)$$
$$= h_2 - h_1$$

3> Const Temp^n or Isothermal expansion →



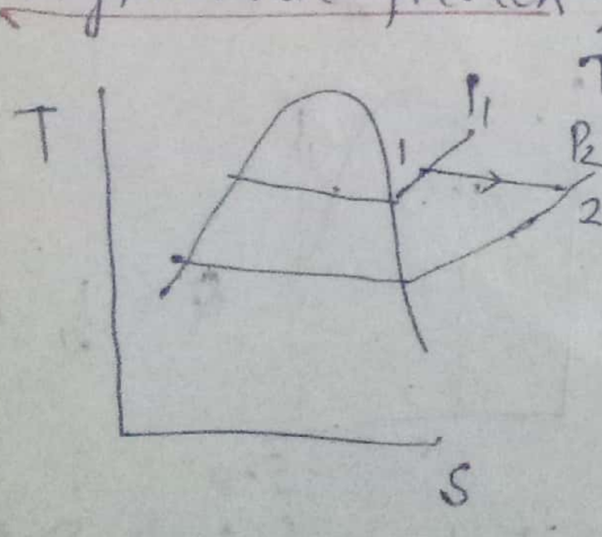
When wet steam is heated at const. temp^n till it becomes dry saturated, then heat transfer Q is given by

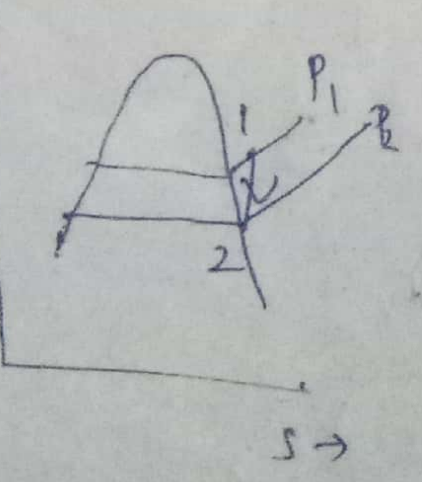
$$Q = h_2 - h_1$$
& $$W = P_1 (V_2 - V_1)$$

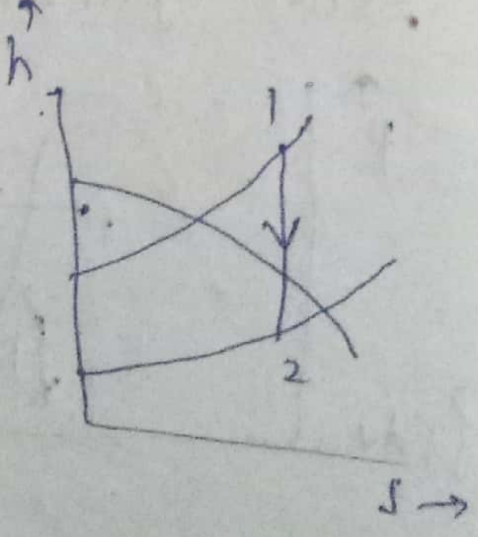
↖ can be found from ~~data book~~ steam table.

* In wet region const P = const T process. In superheated region steam will behave like a gas & const T process in superheated region become hyperbolic ($PV = C$).

4> Hyperbolic process →







process $PV = C$. It is also an isothermal process in superheated region.

$$W = \int_1^2 p\,dv$$

$$Q = \Delta u + \int_1^2 p\,dv$$

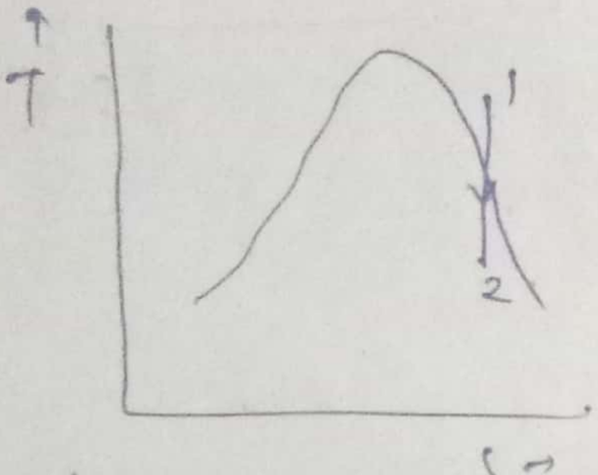
$= ~~(h_2 - h_1) + p_1 v_1 \ln\left(\frac{v_2}{v_1}\right)~~$

$= (u_2 - u_1) + p_1 v_1 \ln\left(\frac{v_2}{v_1}\right)$ $\quad \because p_2 v_2 = p_1 v_1$

$= (h_2 - p_2 v_2) - (h_1 - p_1 v_1) + p_1 v_1 \ln \frac{v_2}{v_1}$

$= (h_2 - h_1) + p_1 v_1 \ln \frac{v_2}{v_1}$

5> Reversible adiabatic or Isentropic process



By applying 1st law, $Q = \Delta u + \int_1^2 p\,dv$

$\Rightarrow Q = u_2 - u_1 + W$

If the process is steady flow reversible adiabatic, then as per 1st law applied to this process

$$u_1 + p_1 v_1 + Q - W = u_2 + p_2 v_2$$

$$h_1 + 0 - W = h_2$$

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

6> Polytropic process →

$$pv^n = c$$

Workdone, $W = \frac{p_1 v_1 - p_2 v_2}{n-1}$ N-m/kg.

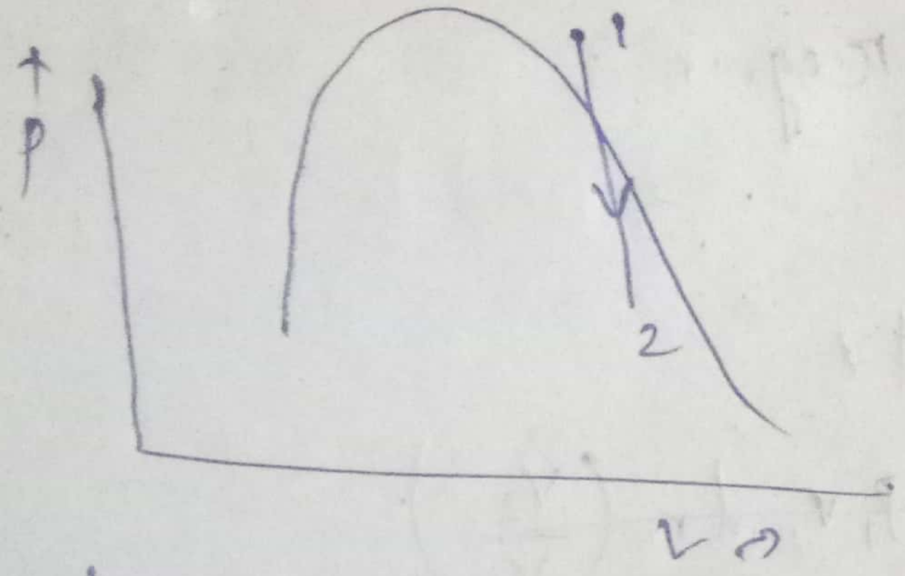
Applying 1st law, $Q = \Delta u + W$ $\quad h = u + pv$

$= u_2 - u_1 + \frac{p_1 v_1 - p_2 v_2}{n-1}$

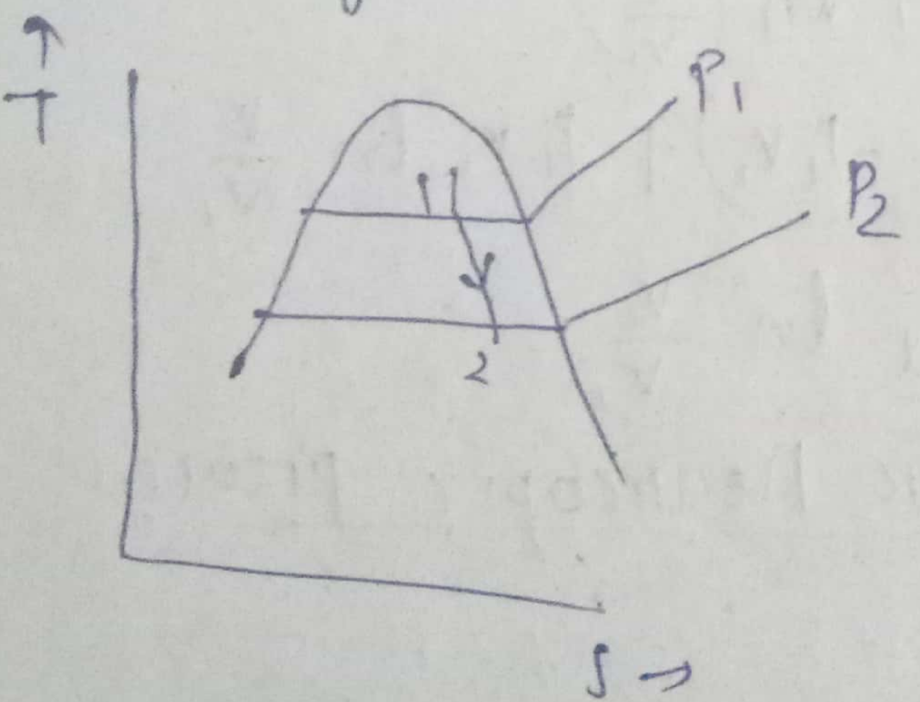
$= (h_2 - p_2 v_2) - (h_1 - p_1 v_1) + $ "

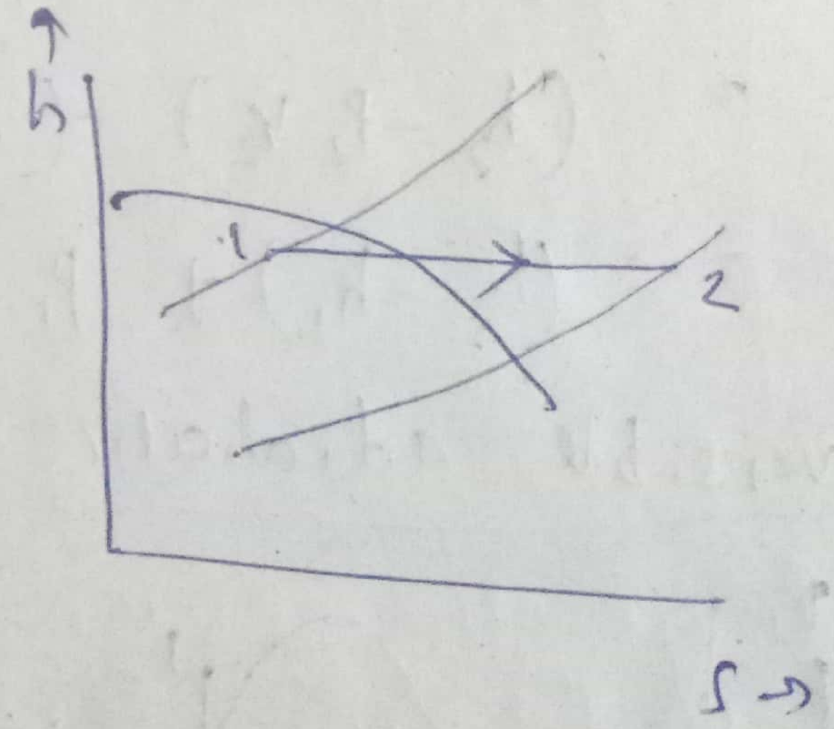
$= (h_2 - h_1) + (p_1 v_1 - p_2 v_2)\left(1 + \frac{1}{n-1}\right)$

$= (h_2 - h_1) + \frac{n}{n-1}(p_1 v_1 - p_2 v_2)$



7) Threottling preocess →





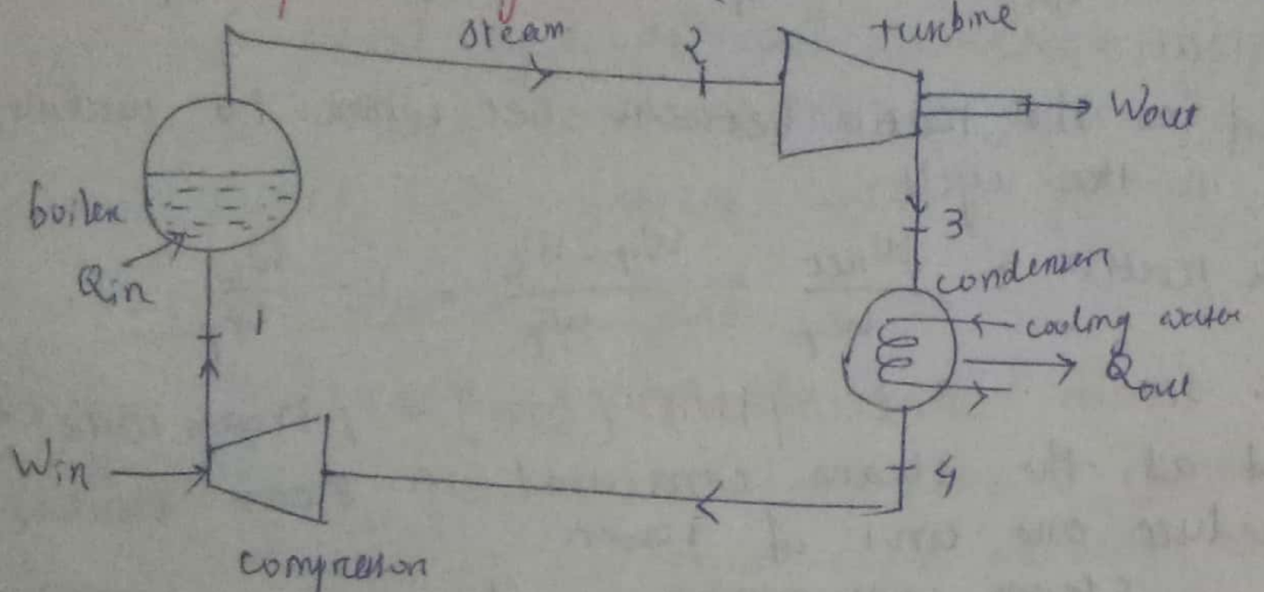
$h_1 = h_2$

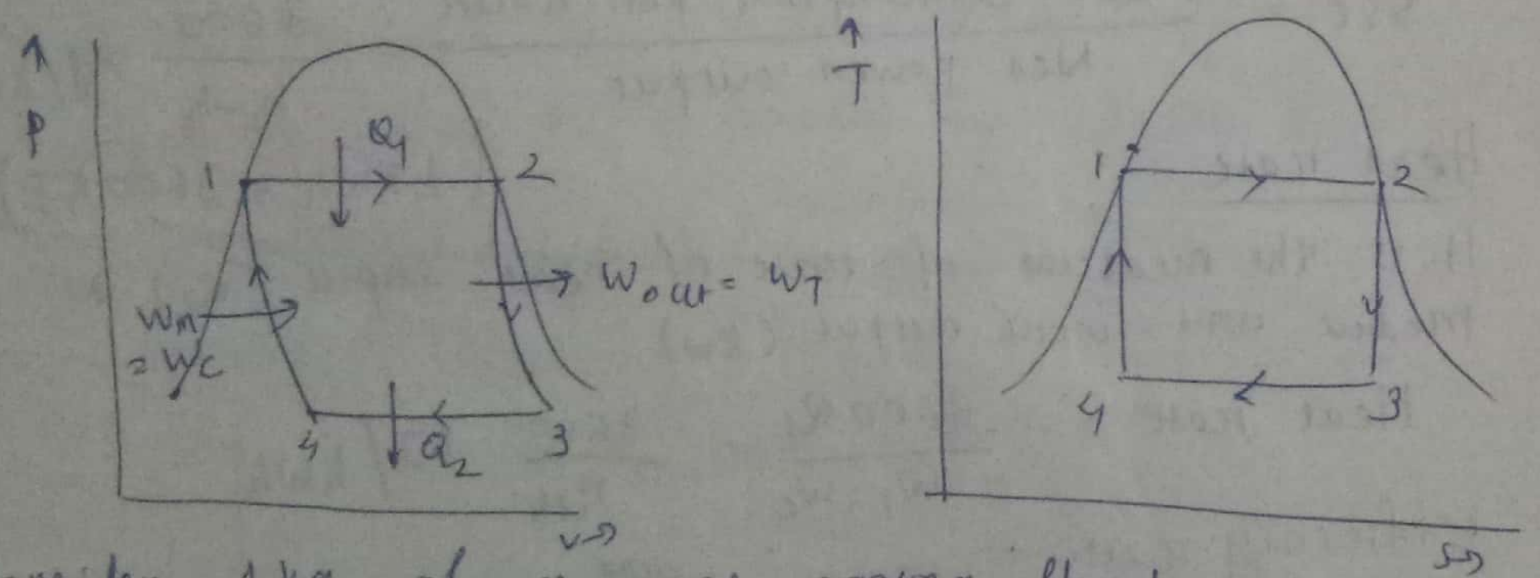
1.2 Vapour Power Cycle [Steam power plant cycle]

Here working fluid is alternately vapourised & condensed. working fluid is essential to convert heat into work in any thermodynamic process. If steam is used as the working fluid then it is called vapour power cycle ~~Steam~~

Steam, mercury, potasium etc can be used as working fluid but steam is widly used due to its low cost, easy availability & high enthalpy of vapourisation.

1.3 Carnot vapour cycle → (with steam as working fluid)





Consider 1 kg of steam as working fluid

Process 1-2 (reversible isothermal heat addition)

Heat water is heated ~~isothermally in a boiler~~ at const temp & pressure to convert saturated steam by addition of heat in the boiler

Amount of heat added $= Q_1 = h_2 - h_1$ (or) $Q_1 = T_1(\Delta S)$
$= T_1(S_2 - S_1)$

Process 2-3 (reversible Isentropic expansion)

Here dry saturated steam is expanded isentropically in a turbine & work is done by the system.

$W_{out} = h_2 - h_3$

process 3-4 (reversible isothermal heat rejection)

Here steam is condensed reversibly & isothermally in a condenser at const pressure

Heat rejected $= Q_2 = h_3 - h_4$

Process 4-1 (reversible , isentropic compression)

The vapour (wet steam) is compressed isentropically by a compressor to its initial state. Thus the cycle completes.

$W_c = h_1 - h_4$

Performance criteria of thermodynamic vapour cycle →

1) Thermal efficiency →

Defined as the ratio between net work done to net heat supplied

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_1} = 1 - \frac{h_3 - h_4}{h_2 - h_1}$$

2) Work ratio →

Defined as the ratio between net work to turbine work done in the cycle

$$\text{Work ratio} = \frac{W_{net}}{W_T} = \frac{W_T - W_c}{W_T} = 1 - \frac{W_c}{W_T}$$

3) Specific steam consumption (SSC) → / Steam rate / Specific rate of flow of steam

Defined as the steam consumed in steam turbine to produce one unit of power.

$$SSC = \frac{\text{Steam consumption per hour}}{\text{Net power output}} = \frac{3600}{h_2 - h_3} \text{ kg/kWh} = \frac{3600}{W_{net}}$$

Heat rate

$(1\,kWh = 3600\,kJ)$

It is the measure of rate of heat input (Q_1) to produce unit work output (kW)

$$\text{Heat rate} = \frac{3600\,Q_1}{W_T - W_c} = \frac{3600}{\eta_{th}} \text{ kJ/kWh}$$

4) Efficiency ratio →

ratio of actual thermal efficiency to rankine efficiency (ideal)

$$E.R = \frac{\eta_{th}}{\eta_{rankine}}$$

Limitations of carnot cycle →

1) Theoritically a carnot cycle is most efficient. However the following difficulties are associated with it when steam is used as working fluid.

i) It is difficult to compress wet vapour ie 2 phase mixture, isentropicaly ie process (4-1).

ii) It is difficult to control the quality of the condensate coming out of the condenser so that state 4 can be exactly obtained

iii) The vapour has large specific volume, so to accomodate this compressor size has to be quite big.

iv) Carnot cycle has high SSC & low work ratio as isentropic compression of vapour requires more work.

v) η of carnot cycle is greatly affected by the upper limit temp T_1. As critical temp of steam is only 374°c, so cycle has to be operated within two phase region only which limit the max^m η.

vi) Difficult to operate with superheated steam as superheated steam has to be supplied at const temp instead of const P.

1.9 Rankine cycle :→

It is a modified form of carnot cycle. It is the simplest or ideal cycle of all reversible vapour power cycles. Here condensation is allowed upto the saturated liquid line unlike carnot cycle.

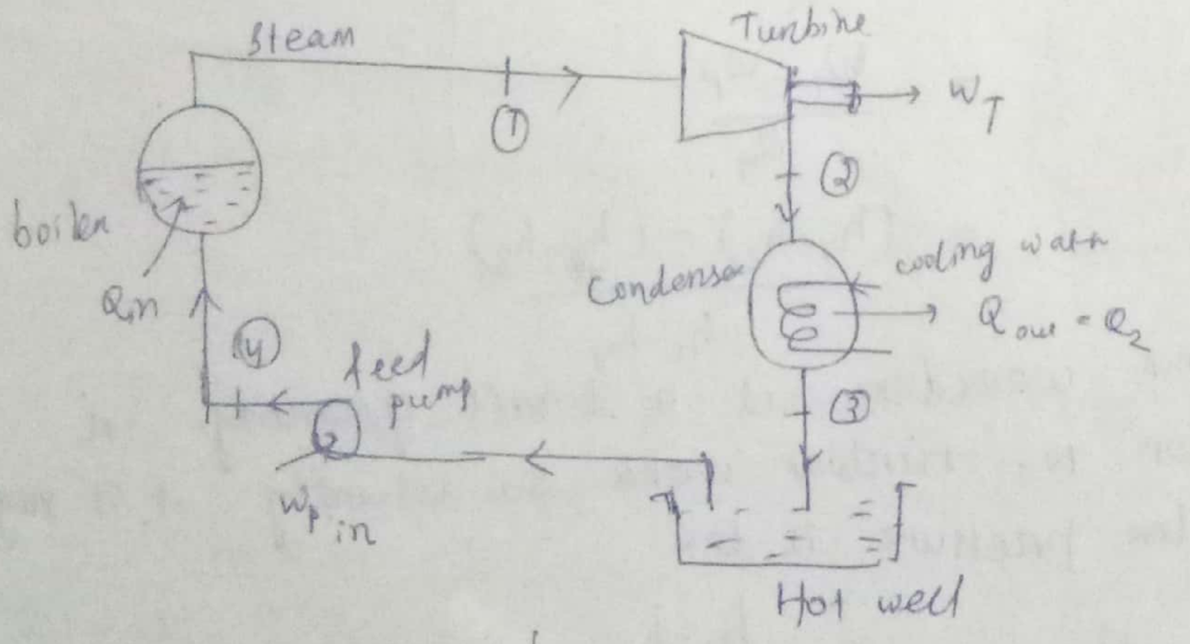
Elements of rankine cycle

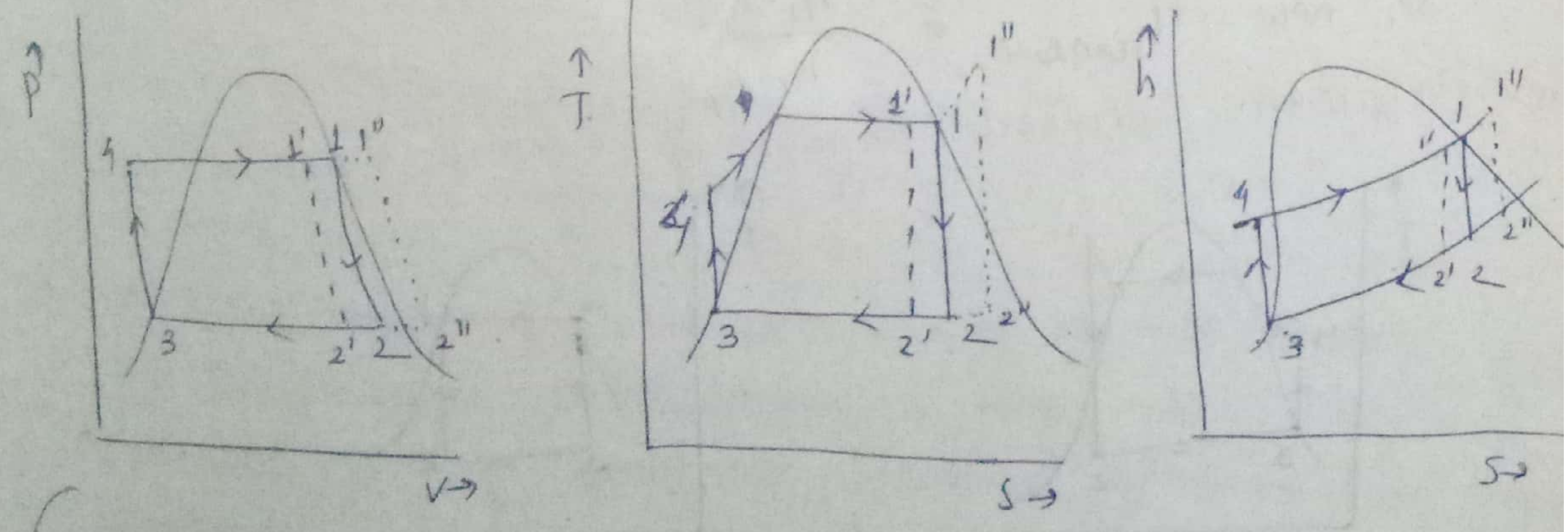
1> Boiler → generates steam at const P.

2> Turbine → Steam expands isentropically & work is produced

3> condenser → heat is rejected from exhaust steam at const P & converted to sat liquid water

4> pump → Increases P of water upto boiler P.





It consists of the following processes →

1-2 → Dry saturated steam at exit of boiler

1'-2' → wet steam at the end of boiler

1''-2'' → superheated " " "

Process 1-2 (reversible adiabatic expansion)

Steam is expanded in the turbine from boiler P, P_1 to condenser P, P_2. Workdone is determined by enthalpy as, $h_1 = W_T + h_2$

Turbine work = $W_T = h_1 - h_2$

Process 2-3 (reversible const P heat rejection)

Steam from turbine is condensed at const P & T to water.

$Q_{rej} = Q_2 = h_2 - h_3$

Process 3-4 (~~reversible adiabatic compression~~) / pump work)

pumping of condensate occurs isentropically from condenser p to boiler pressure

~~$W_p = h_{3'} - h_3 = V_f (P_1 - P_2) = v_3 (P_1 - P_2)$~~

$h_3 + W_p = h_4 \Rightarrow W_p = h_4 - h_3 = v_3 (P_1 - P_2)$

Process 4-1 (const P heat addition)

heat is added in boiler at const P

$Q_{in} = Q_1 = h_1 - h_4$

$dQ = dU + PdV$

& $h = U + PV$

$\Rightarrow dh = du + Pdv + vdP$

Now, $\eta_{rankine} = \frac{W_{net}}{Q_{in}}$

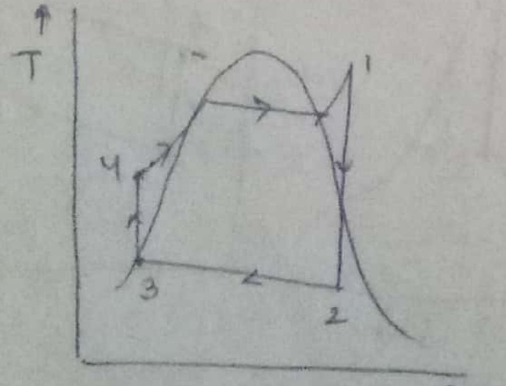
$= \frac{W_T - W_P}{Q_1}$

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

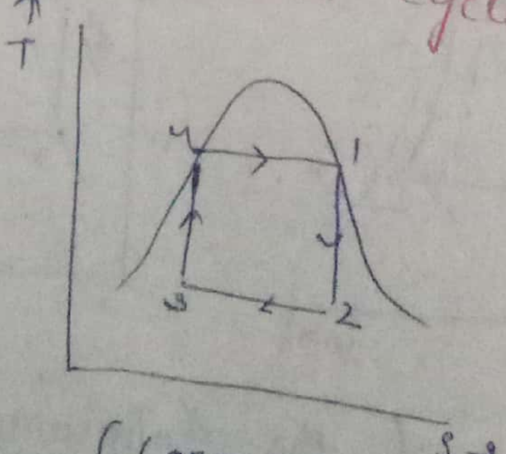
* The Feed pump workdone is a small quantity in comparision to turbine work so usually it is neglected when boiler pressure is low.

So, now $\eta_{rankine} = \frac{h_1 - h_2}{h_1 - h_4}$

Comparision between Rankine & Carnot cycle →



(Rankine cycle)



(Carnot cycle)

i) Betn same tempn limit rankine cycle provides a higher specific work o/p than a carnot cycle. rankine cycle requires smaller SSC so ...

It requires higher grades of heat transfer in the boiler & condenser.

ii) Here only a part of heat is supplied isothermally at T_1 ⇒ its η is lower than carnot cycle & its η approaches carnot if the degree of superheat is reduced.

iii) Advantages of using pump to feed liquid to the boiler instead of compressing a wet vapour is obvious because the work of compression is very large as compared to pump work.

Q. A steam power plant is supplied with dry saturated steam at a P of 12 bar & exhausts into a condenser at 0.1 bar. Calculate the $\eta_{rankine}$.

Sol^n At P = 12 bar

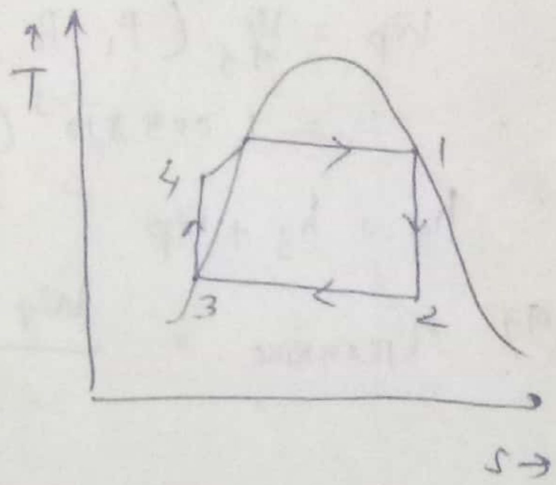
$h_f = 798.4$ KJ/kg, $h_{fg} = 1984.3$

$S_f =$ $\quad S_{fg} =$ $\quad S_g = 6.519$ KJ/kg.K

At P = 0.1 bar

$h_f = 191.8$ KJ/kg, $h_{fg} = 2393$ $\quad S_f = 0.649$ $\quad S_{fg} = 7.502$

$h_1 = h_g|_{12\,bar} =$



$S_1 = S_2$

$\Rightarrow 6.519 = S_{f_2} + x_2 S_{fg_2}$

$\Rightarrow 6.519 = 0.649 + x_2 \times 7.502$

$\Rightarrow x_2 = 0.783$

$h_2 = h_{f_2} + x_2 h_{fg_2}$

$= 191.8 + (0.783 \times 2393) = 2065.5$ kJ/kg

$h_3 = h_f|_{0.1\,bar} = 191.8$ KJ

$W_p = V_{f_3}(P_1 - P_2) =$

$h_4 = h_3 + W_p$.

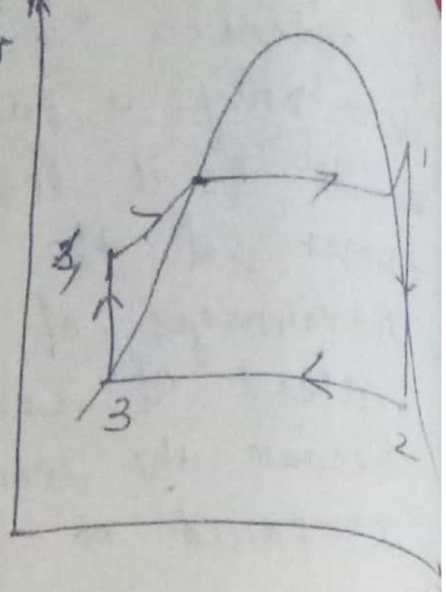
$$\eta_{rankine} = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)} = 27.7\%$$

Q. A steam power plant operates on rankine cycle, has steam at a P of 40 bar & temp 400°C & is exhausted into a condenser, where P of 0.05 bar is maintained. Determine
a) $\eta_{rankine}$
b) power developed
c) SSC
d) Heat rejected into the condenser
e) η_{carnot}

Take $\dot{m}$ of steam = 160 kg/s.

Sol^n

At 40 bar & 400°C (Superheated steam table)



$h = 3215.7 \ KJ/kg$

$S = 6.773 \ KJ/kg\text{-}K$

At 0.05 bar (Sat^n steam table)

$h_f = 137.8 \qquad S_f = 0.476$

$h_{fg} = 2423.7 \qquad S_{fg} = 7.919$

So, $h_1 = 3215.7 \ KJ/kg$

Again $S_1 = S_2$

$\Rightarrow 6.773 = 0.476 + (x_2 \times 7.919)$

$\Rightarrow x_2 = 0.795$

$h_2 = h_{f_2} + x_2 h_{fg_2} = 137.8 + (0.795 \times 2423.7) = 2064.64 \ kJ/kg$

$v_3 = 1.005 \times 10^{-3} \ m^3/kg$

$h_3 = 137.8 \ KJ/kg$

$W_p = v_{f_3}(P_1 - P_2)$

$= 1.005 \times 10^{-3} (4000 - 5)$

$h_4 = h_3 + W_p$

a) $\eta_{Rankine} = \dfrac{W_T - W_p}{Q_1} = \dfrac{(h_1 - h_2) - (h_4 - h_3)}{h_1 - h_4}$

$= 37\%$

b) Power developed $= m_s \times W_T$

$= 160(h_1 - h_2) = 184.256 \ MW$

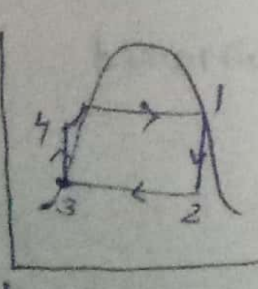
c) $SSC = \dfrac{3600}{h_1 - h_2} = 3.125 \ kg/kWH$

d) $Q_2 = m_s(h_2 - h_3) = 308294.4 \ kJ/s$

e) $\eta_{Carnot} = 1 - \dfrac{T_2}{T_1} = 1 - \dfrac{273 + 32.9}{273 + 400} = 54.5\%$

Q. In a steam power cycle, the steam is supplied at 15 bar & dry saturated. The condenser P is 0.4 bar calculate carnot & Rankine η of the cycle neglecting pump work

Sol^n $\eta_{Rankine} = \dfrac{h_1 - h_2}{h_1 - h_3}$



$\eta_{Carnot} = 1 - \dfrac{T_2}{T_1}$

Q. Steam at 150 bar (sat) enters a steam turbine & comes out to the condenser at 0.1 bar. calculate η_{th} of the cycle $\eta = 3?$

Actual Vapour Power Cycle :→

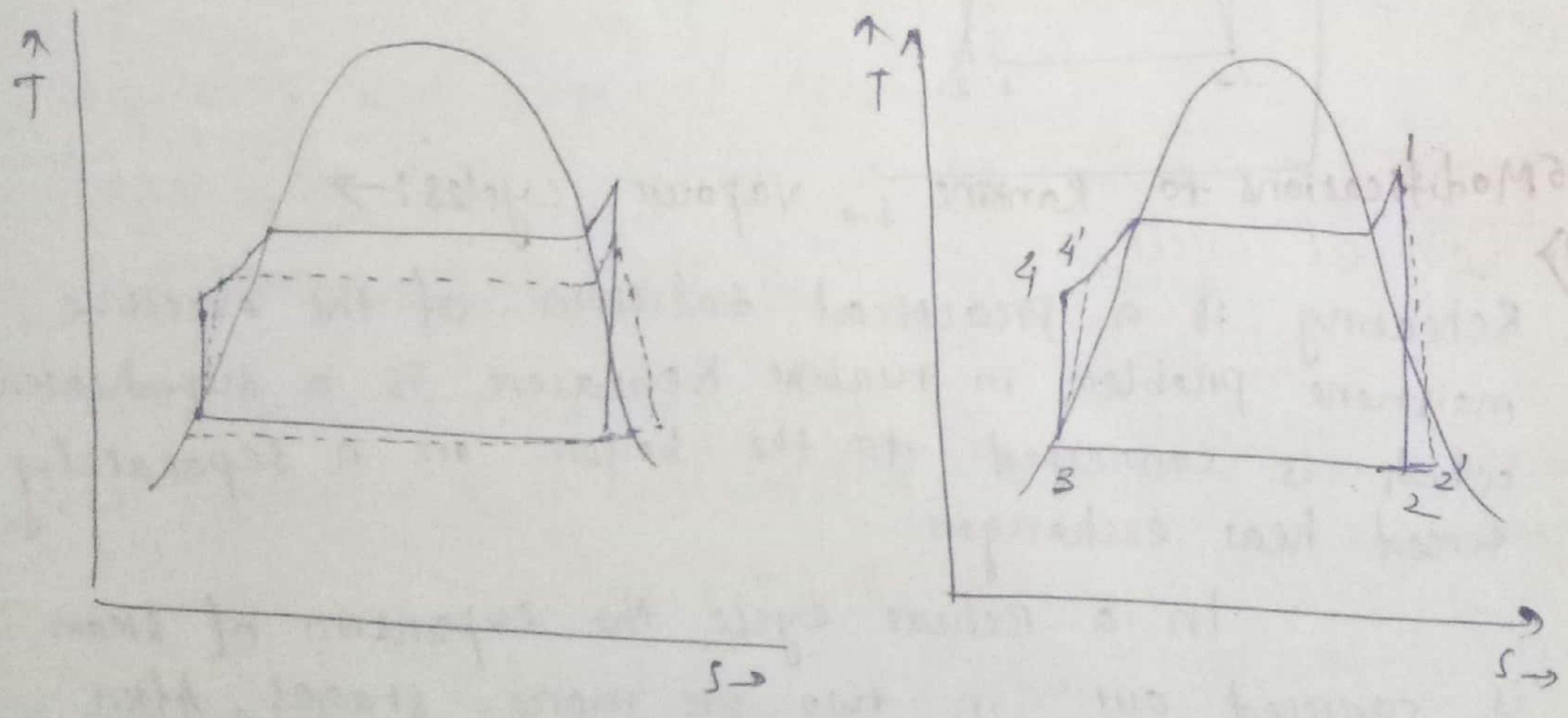
→ Actual vapour power cycle differs from ideal Rankine cycle due to irreversibilities in various components due to fluid friction & heat loss to the surrounding

→ Fluid friction causes pressure drops in boiler, condenser & piping betn various components. So steam leaves at lower P in boiler & P at turbine entrance is also lower (because of P drop). P drop in condenser is very small.

To compensate for these P drops, the water must be pumped to a sufficiently higher P than the ideal cycle. So requires a large pump with high I/P power

→ To compensate the heat losses, more heat requires to be transferred to the steam in the boiler.

→ So due to irreversibility pump requires greater work & turbine produces less work



$$\eta_p = \frac{h_4 - h_3}{h_{4'} - h_3} = \frac{\text{Isentropic work I/p}}{\text{Actual} \quad ''}$$

$$\eta_T = \frac{h_1 - h_{2'}}{h_1 - h_2} = \frac{\text{Actual turbine work}}{\text{Isentropic} \quad ''}$$

Improving the efficiency of Rankine cycle →

1) <u>By lowering the condenser pressure →</u>

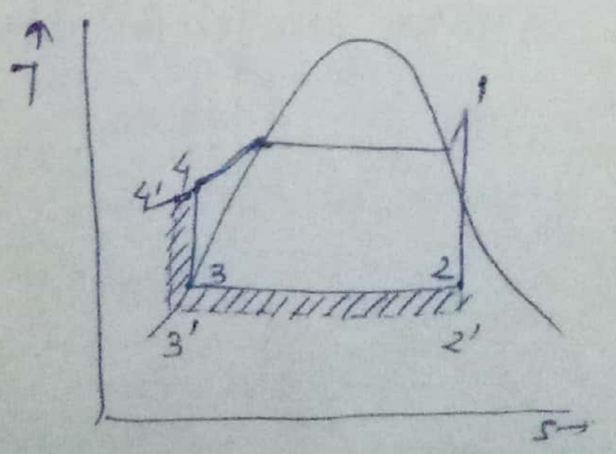
hatched area → ↑ of work o/p.

So, W_T ↑ (1 → 2')

& Q_1 also increase (4' → 1) instead of

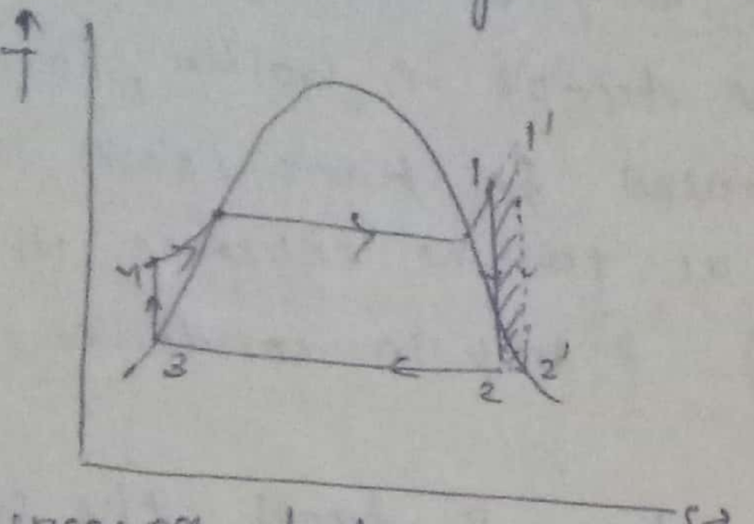
as P ↓ so satn temp ↓.

→ P is lowered not below the satn P corresponds to temp. of cooling medium.



2) Superheating the steam to high temp →

The avg. temp at which heat is transferred to the steam can be increased by superheating the steam to higher temp without increasing the boiler pressure.

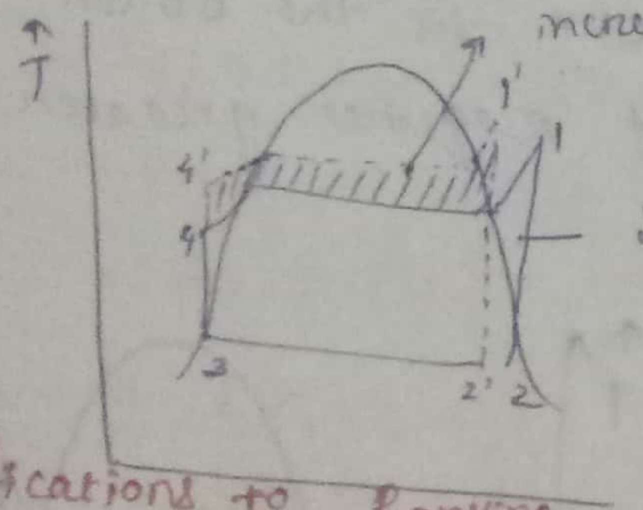


work o/p increases & shown by hatched area

⇒ $\eta \uparrow$

3) By increasing boiler pressure

By increasing boiler pressure, it automatically increases the operating temp at which water will boil. So ↑ avg. temp. at which heat is transferred to the steam & thus η_{th} increases.

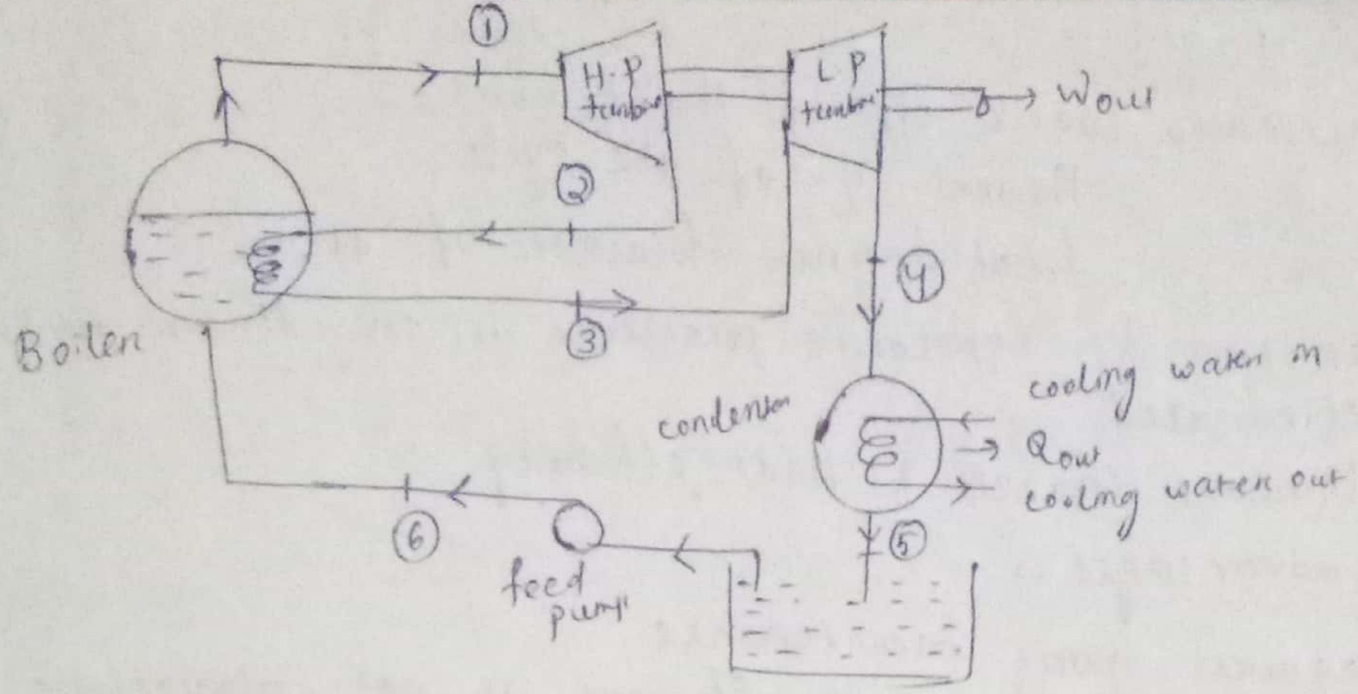


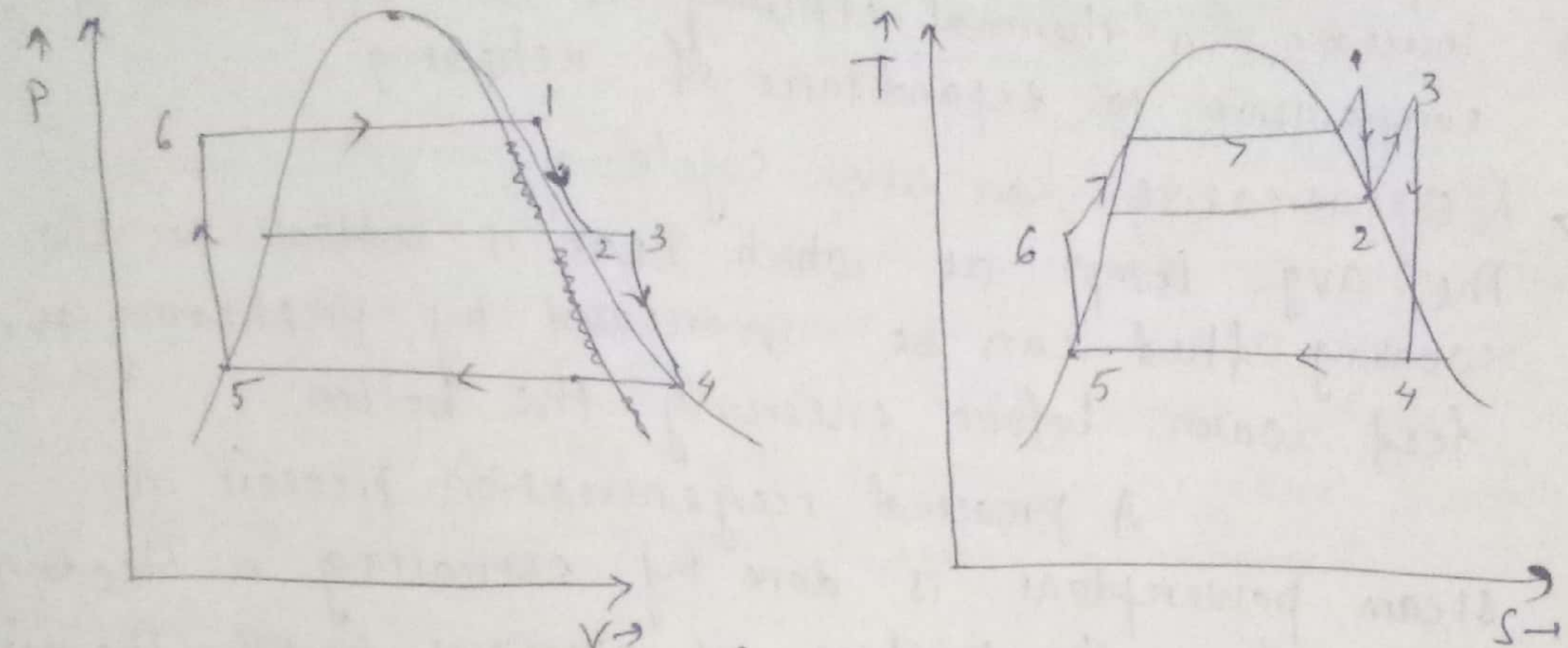
1.5 Modifications to Rankine vapour cycles:→

1) Reheat cycle :→

Reheating is a practical solution of the excessive moisture problem in turbine. Reheater is a superheater which is connected to the boiler or a separately fired heat exchanger.

In a reheat cycle, the expansion of steam is carried out in two or more stages. After partial expansion to an intermediate pressure in the high pressure turbine, the steam is withdrawn & reheated to the original temp^n at const. pressure. Steam is then expanded in the low pressure turbine





Considering unit mass of steam

Turbine work o/p = work done in H.P turbine + W.D in low P turbine

$\Rightarrow W_T = (h_1 - h_2) + (h_3 - h_4)$

Pump work $= W_p = h_6 - h_5$

Heat supplied $= Q_1 =$ heat supplied in boiler + heat supplied in superheater

$= (h_1 - h_6) + (h_3 - h_2)$

Rankine reheat cycle efficiency, $\eta = \dfrac{W_{net}}{Q_1} = \dfrac{W_T - W_p}{Q_1}$

$$\Rightarrow \eta = \frac{[(h_1 - h_2) + (h_3 - h_4)] - (h_6 - h_5)}{(h_1 - h_6) + (h_3 - h_2)}$$

* Avg temp^n during the reheat process can be increased by increasing the no. of expansion & reheat stages. But more than 2 stages are not practical.

Reheat cycle decreases the moisture content at low P turbine & thus erosion & corrosion in the turbine can be reduced. It also ↑ the o/p of turbine & thus ↑ overall η of the plant.

Scanned with CamScanner

Advantages →

i) Increases work o/p of the turbine

ii) " thermal η of the cycle

iii) " final dryness fraction of steam

iv) erosion & corrosion problems in the steam turbine are eliminated.

v) Increases nozzle & blade efficiency.

Disadvantages →

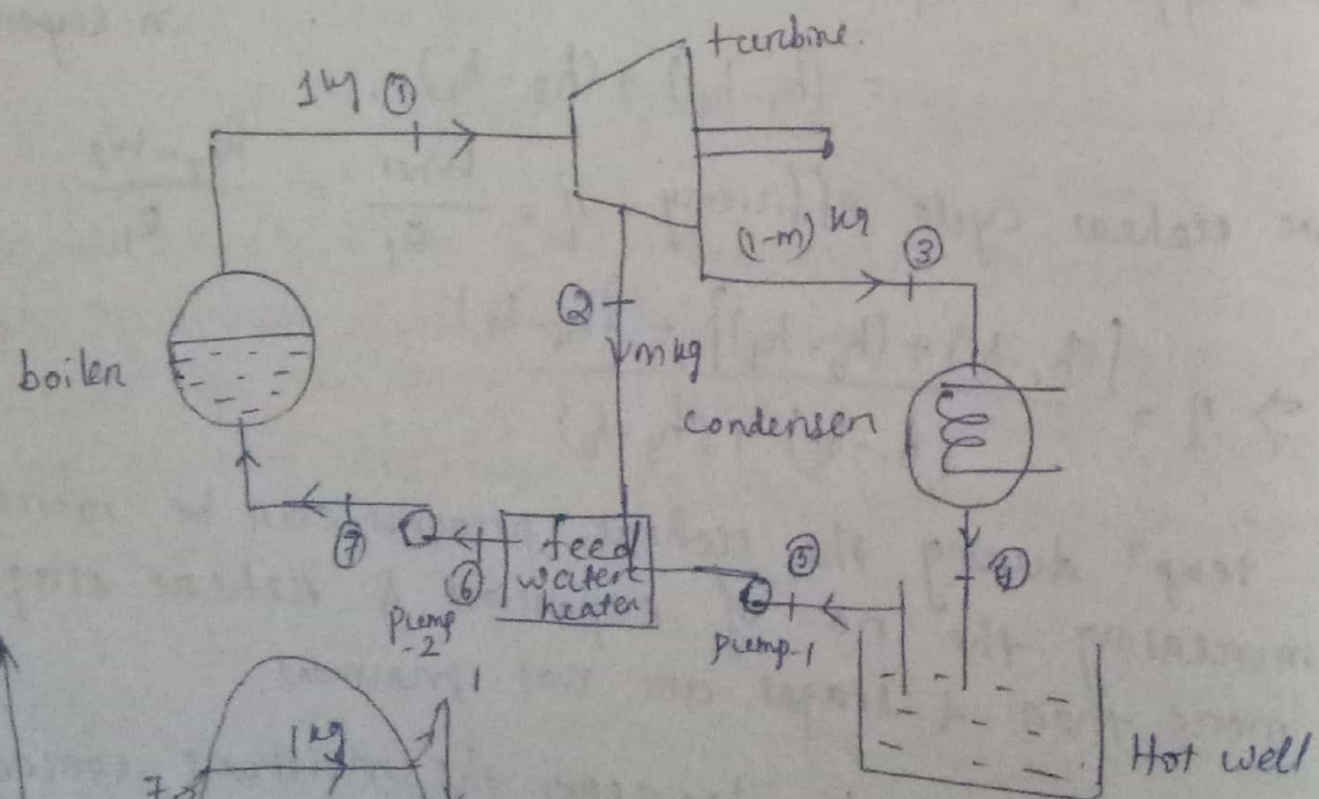
i) Requires more maintenance

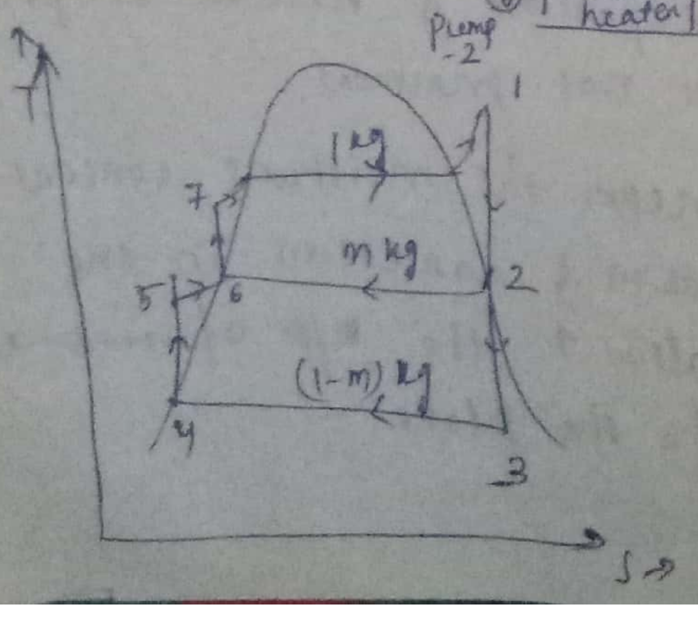
ii) Increase in thermal efficiency is not appreciable in comparision to expanditure of reheating.

2> Regenerative Rankine cycle →

The avg. temp^n at which heat is added to the working fluid can be increased by preheating the feed water before entering the boiler.

A practical regeneration process in steam powerplant is done by extracting a bleeding steam from the turbine at various points. The rest of the steam expands to the condenser pressure in the turbine. The steam thus extracted is mixed with feed water coming from the condenser. The device in which the feed water is heated by regeneration is called a regenerator or feed water heater.





For unit mass of steam

$W_T = 1(h_1 - h_2) + (1-m)(h_2 - h_3)$

pump work $W_P = W_{P_1} + W_{P_2}$

$= (1-m)(h_5 - h_4) + 1(h_7 - h_6)$

$= (1-m) v_{f_4}(P_5 - P_4) + 1\{v_{f_6}(P_7 - P_6)\}$

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

$$= \frac{(h_1 - h_2) + (1-m)(h_2 - h_3) - (\cdots)}{h_1 - h_7}$$

* Thermal efficiency of the cycle increases as a result of regeneration. This is due to increase in avg. tempⁿ at which heat is transferred to the steam in the boiler by raising the tempⁿ of feed water before it enters the boiler. The cycle efficiency increases further as the no. of feed water heater is increased.

Advantages :→

i) ↑ η_{th} as avg. temp of heat addition in boiler ↑.

ii) Thermal stresses in the boiler are minimised as the tempⁿ ranges in the boiler are reduced.

iii) Heating process in the boiler tends to become reversible.

iv) Size of the condenser is reduced.

v) Blade height of the turbine reduces due to reduced amount of stream passing through the low pressure stages.

Disadvantages :→

i) Greater maintenance is required for the addition of more heaters.

ii) Plant becomes complicated.

iii) For a given power a large capacity boiler is required.

* For one heater case

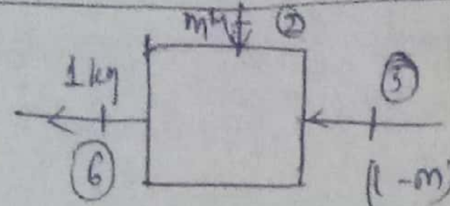
Heat supplied in the boiler, $Q_1 = h_1 - h_7$

Heat rejected in the condenser, $Q_2 = (h_3 - h_4)(1-m)$

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

- The η of ideal regeneration rankine cycle is equal to the carnot cycle. As it is practically infeasible so actual regeneration cycle is used.

Energy balance across heaters



Heat & mass balance across heater

For steam entry = for condensate entry

⇒ Heat ~~gained~~ lost by bleed steam = Heat gained by condensate

⇒ $m(h_2 - h_6) = (1-m)(h_6 - h_5)$

⇒ $\frac{1-m}{m} = \frac{h_2 - h_6}{h_6 - h_5}$

⇒ $\frac{1}{m} - 1 = \frac{h_2 - h_6}{h_6 - h_5}$

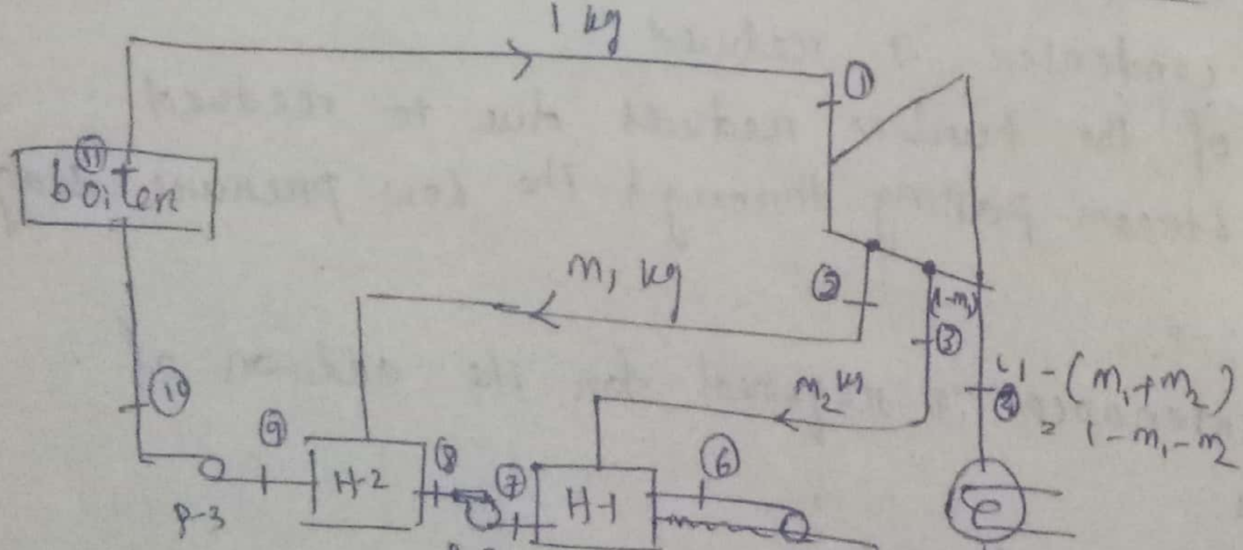
⇒ $\frac{1}{m} = \frac{h_2 - h_5}{h_6 - h_5}$

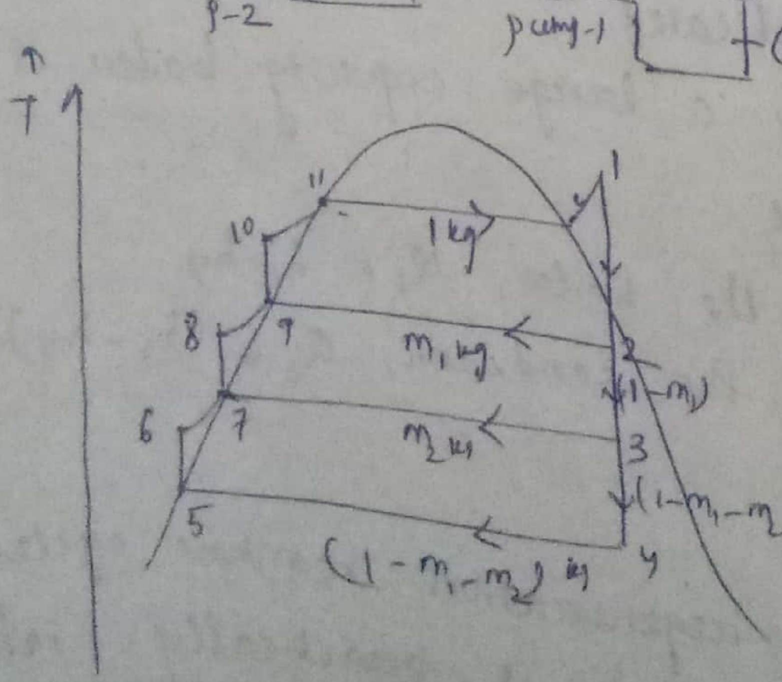
⇒ $m = \frac{h_6 - h_5}{h_2 - h_5}$

$\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{(h_3 - h_4)(1-m)}{(h_1 - h_7)}$

$= 1 - \frac{(h_3 - h_4)(h_2 - h_6)}{(h_1 - h_7)(h_2 - h_5)}$

Actual regeneration with two heaters



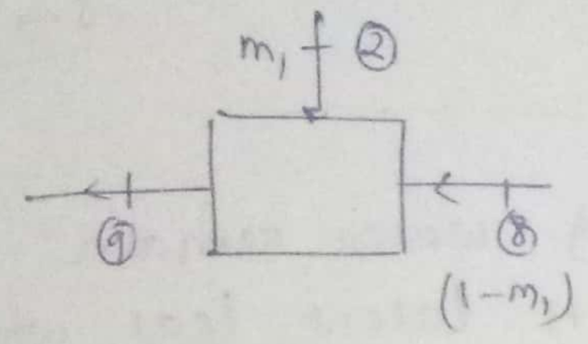


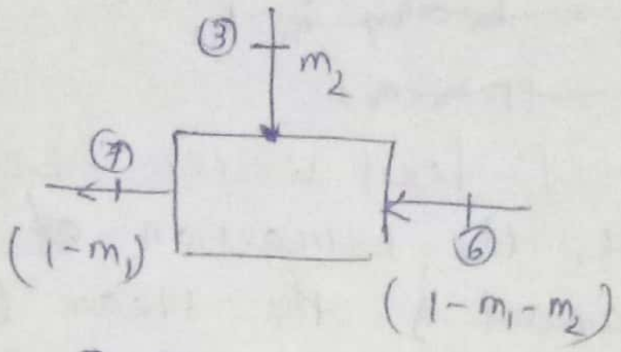
i) Heat rejected in condenser, $Q_2 = (1-m_1-m_2)(h_4-h_5)$

ii) Heat added in boiler, $Q_1 = h_1 - h_{10}$

iii) Work done by turbine, $W_T = (h_1-h_2) + (1-m_1)(h_2-h_3) + (1-m_1-m_2)(h_3-h_4)$

m_1 & m_2 can be found by





iv) Heat balance for heater across 8 - 9

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

$\Rightarrow$ $\boxed{m_1 = ?}$

v) Heat balance for heater across 6 - 7

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

$\Rightarrow$ $\boxed{m_2 = ?}$

vi) work done by pumps

$W_{P_1} = h_{10} - h_9$

$W_{P_2} = (h_8-h_7)(1-m_1)$

$W_{P_3} = (1-m_1-m_2)(h_6-h_5)$

Types of heater :→

1> Open or direct type feed heater

2> Closed or Indirect "

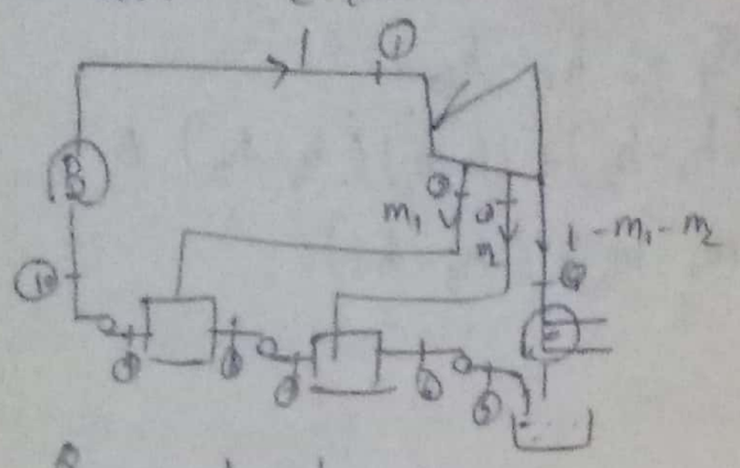
1> Open Feed water heater →

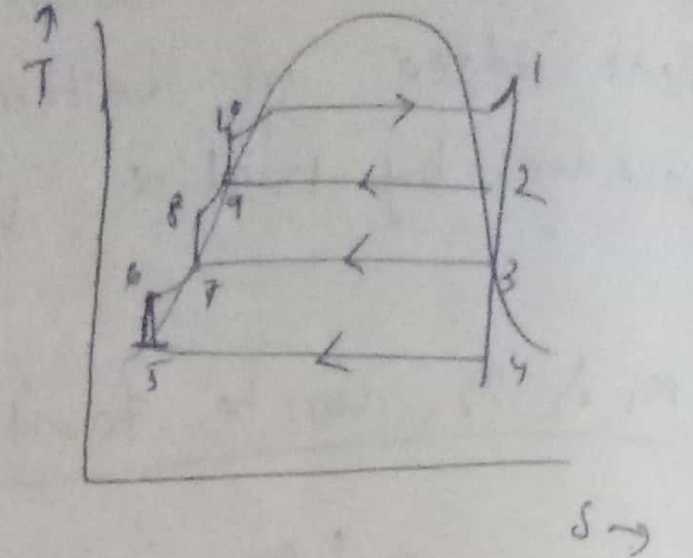
→ In an open heater, feed water & extraction steam are mixed together & the tempn of feed water reaches the saturation tempn corresponding to the extraction steam pressure

→ The latent heat of steam is used to increase the tempn of feed water

→ Here the no. of pumps required is one more than the no. of heaters. So power consumption in the pumps is higher

→ They are simple & inexpensive & have good heat transfer characteristics





$Q_1 = h_1 - h_{10}$

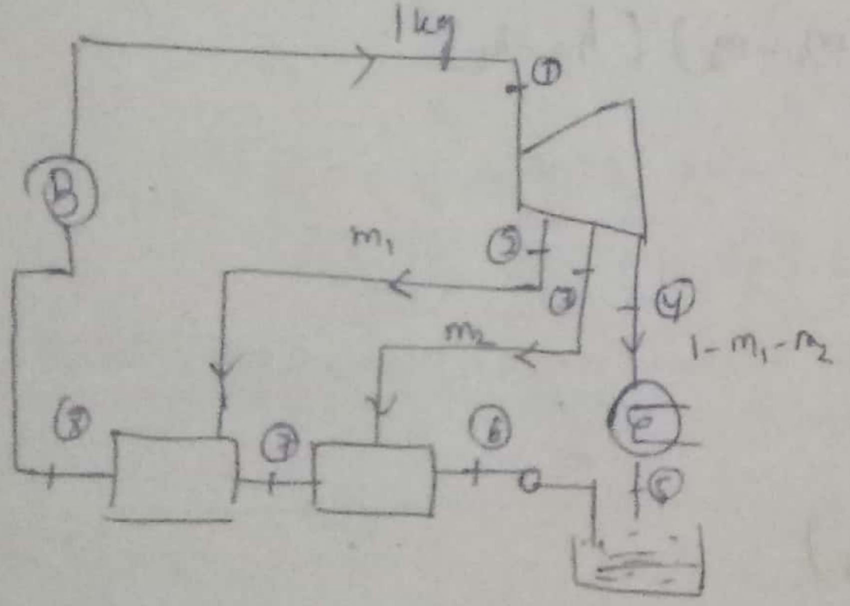
$Q_2 = (1-m_1-m_2)$

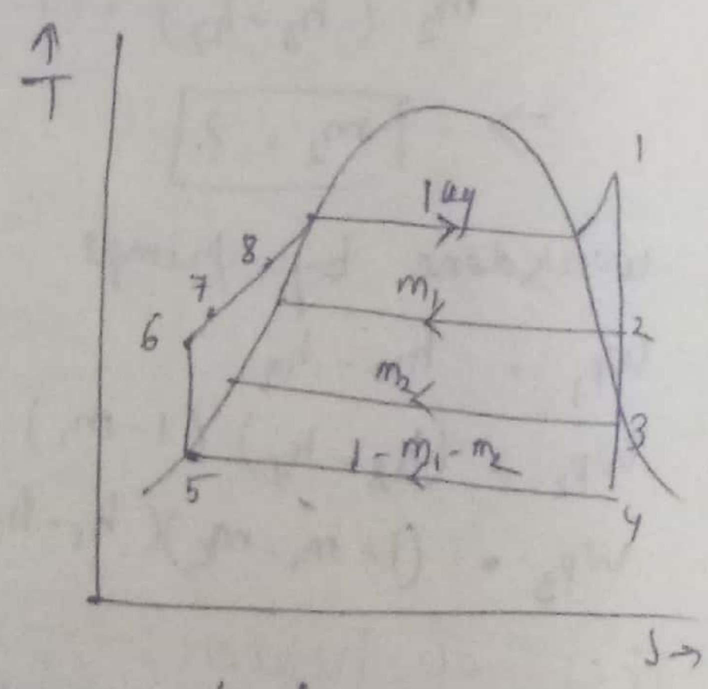
2) Closed feed water heater →

→ Here, the extraction of steam & water remain separated & the steam loses its latent heat which is used for increasing the temp^n of feed water

→ The condensate of extraction steam is called drip

→ Here only one pump is sufficient for sending the feed water to boiler. So power consumption in pumps is less than open feed water system.





* For indirect type heater, effectiveness of feed heater is always less than 100% & where as for direct heater it is 100%.

Q Dry sat steam at 150 bar enters a steam turbine & comes out at 1 bar. Calculate cycle efficiency

Q If reheating is done with pressure ratio (0.25) & HP turbine inlet parameters (150 bar, 540°c). Calculate cycle η if reheating is done upto 540°c.

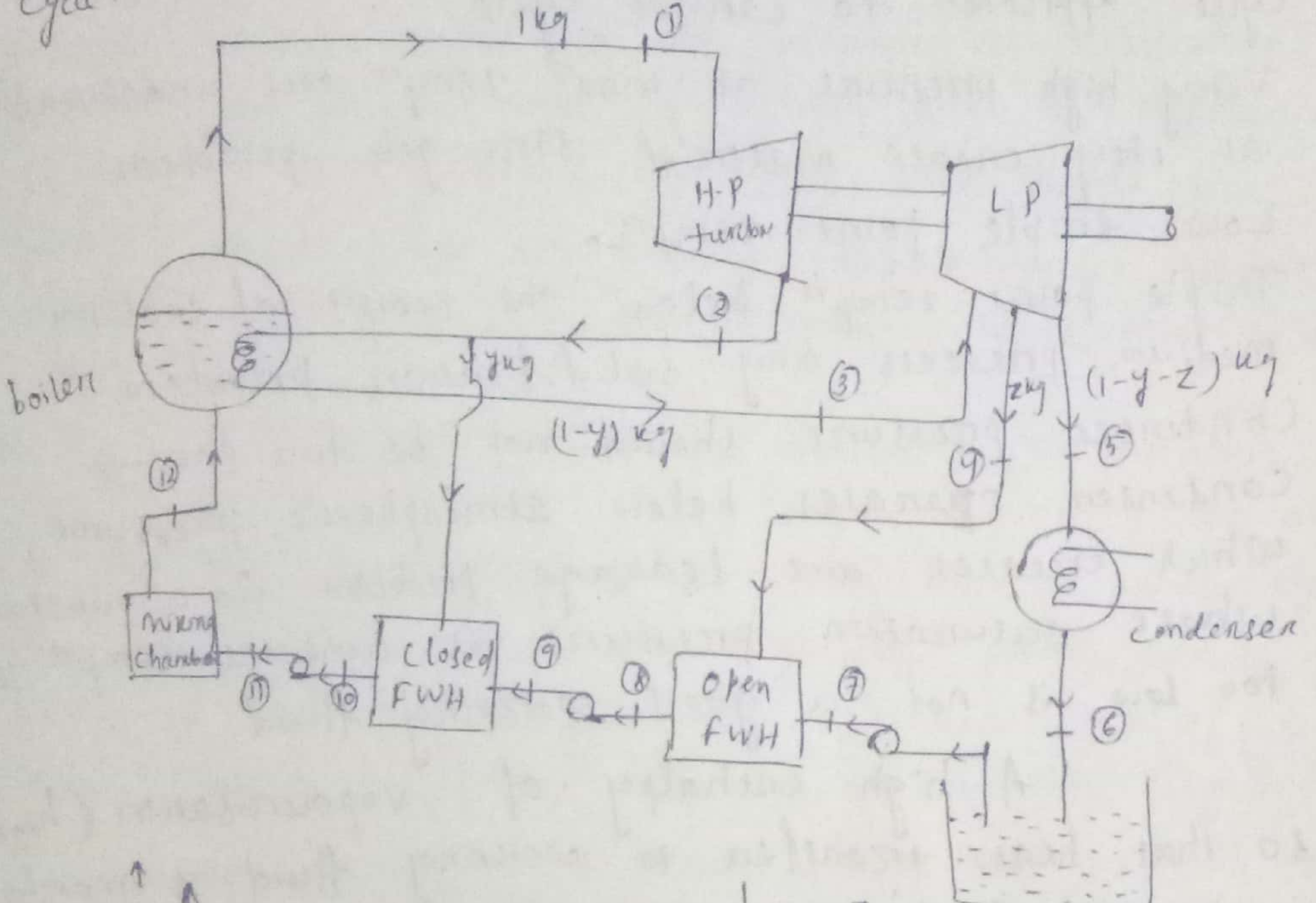
$\frac{P_2}{P_1} = 0.25$

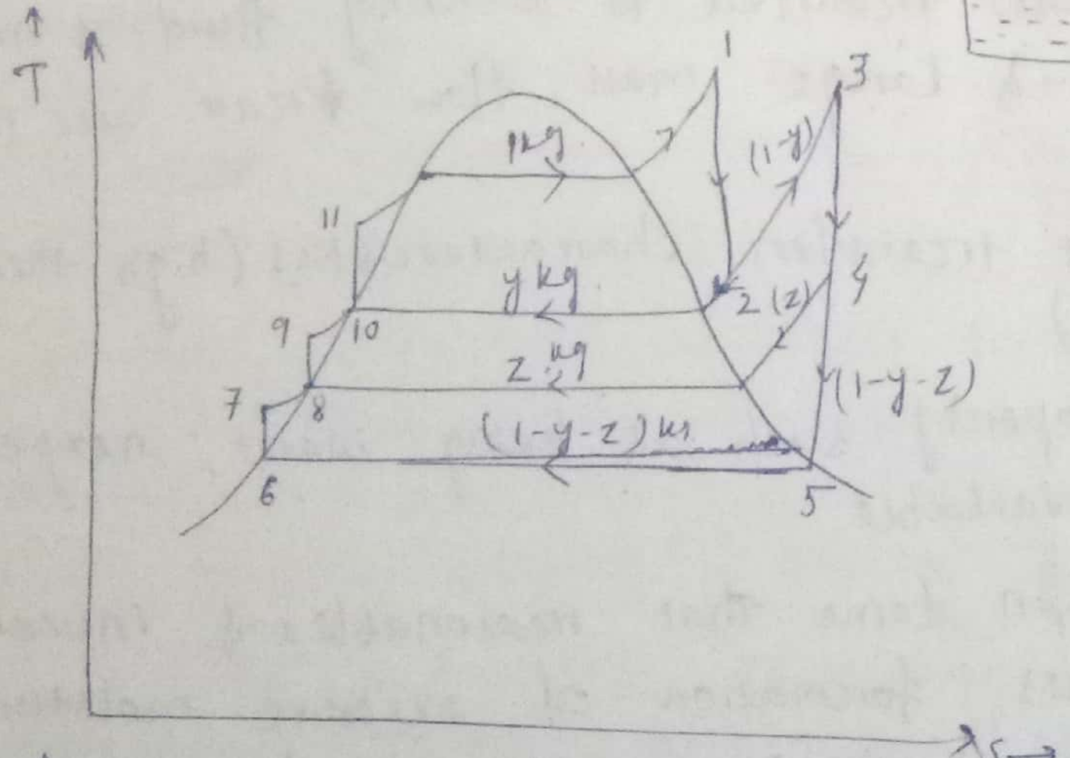
3) Reheat Regenerative Rankine cycle :→

→ Reheating is done with high T & p but gain in thermal η by reheating is rather small

→ But regeneration or heating up of feed water by steam extracted from turbine rewards a considerable gain in η_{th}

→ So modern power plant operate on reheat-regenerative cycle





considering unit mass of steam,

$Q_{add} = Q_1 = 1(h_1 - h_{11}) + (1-y)(h_3 - h_2)$

$Q_{out} = Q_2 = (1-y-z)(h_5 - h_6)$

$W_T = W_{T_1} + W_{T_2}$

$= 1(h_1 - h_2) + (1-y)(h_3 - h_4) + (1-y-z)(h_4 - h_5)$

$W_p = W_{p_1} + W_{p_2} + W_{p_3}$

$= (1-y-z)(h_7 - h_6) + (1-y)(h_9 - h_8) + 1(h_{11} - h_{10})$

HEAT TRANSFER Chapter-6

Heat transfer can be defined as the transmission of energy from one region to another as a result of tempn gradient.

1.) Modes of heat transfer →

1) conduction →

It is the transfer of heat from one part of a substance to another part of the same substance or from one substance to another in physical contact with it, without appreciable displacement of molecules forming the substance.

In solid, heat is conducted by two mechanisms

i) By Lattice vibration (faster moving molecules or atoms in the hottest part of a body transfer heat by impacts some of their energy to adjacent molecules).

ii) By transfer of free electrons (

In gas & liquid, K.E of a molecule is a function of tempn. It losses energy by collision.

2) convection →

→ It is the transfer of heat within a fluid by mixing of one portion of the fluid with another.

It is possible only in fluid medium & is directly linked with the transport of medium itself.

→ The heat flow depends on the properties of fluid & is independent of the properties of the material of the surface.

→ It is of 2 types

i) Free or natural convection – It occurres when the fluid circulates by virtue of the natural density difference of hot & cold fluids.

The densen portion of fluid move downward due to greater force of gravity as compared to less dense fluid.

ii) Forced convection – When work is done to blow or pump the fluid.

3) Radiation →

It is the transfer of heat through space or matter by means other than conduction & convection. It occurs due to emission of electromagnetic waves. It requires no medium & occurs mainly in infrared region.

4.2 Imp Heat transfer by conduction:→

1) Fourier's law of heat conduction →

It states that "The rate of flow of heat through a simple homogeneous solid is directly proportional to the area of the section at right angles to the dirn of heat flow, & to tempn gradient in the direction of heat flow".

tempn gradient → change of tempn w.r.t length of the path of heat flow.

mathematically,
$$Q \propto A$$
$$Q \propto \frac{dT}{dx}$$

So,
$$Q \propto A \frac{dT}{dx}$$
$$\Rightarrow Q = -KA\frac{dT}{dx}$$

where Q = Rate of heat transfer or amount of heat flowing through a body in unit time.

A = Surface area normal to dirn of heat flow.

dT = Tempn difference on the two faces of body.

dx = Thickness of the body through which heat flows. It is taken along the dirn of heat flow.

K = proportionality constant called as thermal conductivity of the body.

'–' sign is used to consider decreasing tempn alongwith the dirn of heat flow

$\frac{dT}{dx}$ is always –ve alonge positive x dirn, so Q will be +ve.

Assumption

1. conduction of heat takes place under steady state condn
2. The heat flow is unidirectional
3. Tempn gradient is const & tempn profile is linear.

4. There is no internal heat generation
5. The material is homogeneous & isotropic.

4.2) Thermal conductivity →

It is defined as the ability of a substance to conduct heat.

We know $Q = KA\frac{dT}{dx}$ Unit of K = $\frac{J}{m^2}\frac{m}{K} = J/m\text{-}K$

$\Rightarrow K = \frac{Q}{A}\frac{dx}{dT}$ or $\frac{W}{m\text{-}K}$

when Q = 1, A = 1 & $\frac{dT}{dx} = 1$, then K = 1

So, Thermal conductivity of a material is defined as
→ "The amount of energy conducted through a body of unit area, & unit thickness in unit time when the difference in tempr between the faces causing heat flow is unit".

→ materials with high thermal conductivity are good conductors & with low K are insulators.

→ It depends on
i) material structure
ii) moisture content
iii) Density of the material
iv) P & T

Q. Calculate the rate of heat transfer per unit area through a copper plate 45 mm thick, whose one face is maintained at 350°C & the other face at 50°C. Take K for Cu = 370 W/m°C

Soln
$dT = T_2 - T_1 = 50 - 350 =$
$L = 45\ mm = 0.045\ m$
$K_{cu} = 370\ W/m°C$

$$\boxed{q = \frac{Q}{A}}$$

We know $Q = -KA\frac{dT}{dx}$

$\Rightarrow q = -370 \times \frac{(50 - 350)}{0.045}$

$= 2.466 \times 10^6\ W/m^2$

Heat flux →

It is the quantity of heat transfer per unit time per unit area of isothermal substance.

$$q = \frac{Q}{A}$$

The greatest rate of heat flow will be along the lines normal to isothermal surface.

$$Q_x = -K_x A \frac{dT}{dx}$$

$$Q_y = -K_y A \frac{dT}{dy}$$

$$Q_z = -K_z A \frac{dT}{dz}$$

A material having $K_x = K_y = K_z = K$ is called an isotropic material.

Characteristics of thermal conductivity

→ K of a material is due to flow of free electrons.

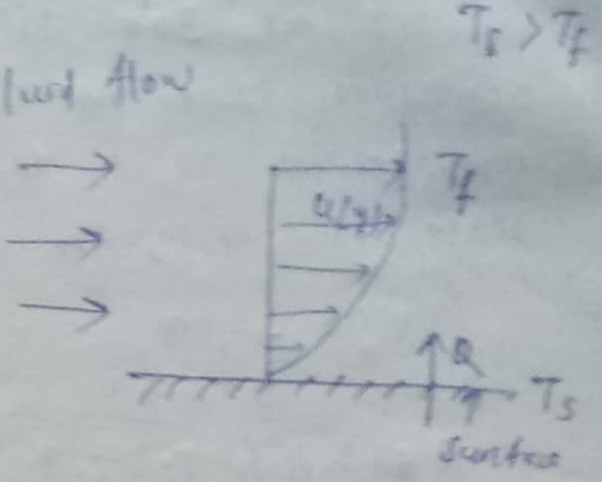
→ K for pure metal is highest & decreases with impurity.

→ K for most metals ↓ with ↑ in temp^n (Al & U are exception). In gas K ↑ with T ↑.

→ In solids & liquids, K weakly depends on P, but in gases K is independent of P.

Convective heat transfer →

For a fluid flowing at a mean tempⁿ (T_f) over a surface at a tempⁿ T_s, Newton proposed the following heat conduction eqⁿ called as Newton's law of cooling.



It states that "Heat transfer from a hot body to a cold body is directly proportional to surface area & difference of tempⁿ betⁿ the bodies".

$$Q \propto A$$

$$Q \propto T_s - T_f$$

$$\Rightarrow Q = hA(T_s - T_f)$$

where Q = Rate of conductive heat transfer
A = Area exposed to "
T_s = Surface tempⁿ
T_f = Fluid tempⁿ
h = co-efficient of convective heat transfer

Unit of h

$$h = \frac{Q}{A(T_s - T_f)} = \frac{W}{m^2 K} \text{ or } \frac{W}{m^2 \, ^\circ C}$$

* h can be defined as "the amount of heat transmitted for a unit tempⁿ difference between the fluid & unit area of the surface in unit time".

The value of h depends on
i) Thermodynamic & transport properties of fluid (e.g. viscosity, density, sp. heat etc.)
ii) Nature of fluid flow
iii) Geometry of the surface
iv) Prevailing thermal condition.

* At the surface, as viscosity is zero, so heat transfer occurs there by conduction only.
* It is possible only in fluid medium & directly linked with the transport of medium itself. The effectiveness of heat transfer by convection depends largely upon the mixing motion of the fluid.

Q. A flat plate of length 1m & width 0.5m is placed in air at 30°c flowing parallel to it. Calculate convective heat transfer coeff, if the plate is maintained at a tempr of 300°c & heat transfer rate is 4.05 KW.

Solⁿ Given $L = 1m$ $\quad T_f = 30°c$ $\quad Q = 4.05 KW$
$b = 0.5m$ $\quad T_s = 300°c$ $\quad = 4.05 \times 10^3 W$

$Q = hA [T_s - T_f]$

$\Rightarrow h = \dfrac{Q}{A(T_s - T_f)} = \dfrac{4.05 \times 10^3}{(1 \times 0.5)[300-30]} = 30 \ W/m^2 °c$

Q. A hot plate 1m×1.5m is maintained at 300°c. Air at 20°c blows over the plate. If the convective heat transfer coefficient is 20 W/m°c, calculate the rate of heat transfer.

Solⁿ $A = 1 \times 1.5 = 1.5 \ m^2$
$T_s = 300°C$
$T_f = 20°c$
$h = 20 \ W/m^2 °c$
$Q = hA(T_s - T_f)$
$= 20 \times 1.5 (300 - 20) = 8400 W = 8.4 KW$

4.5 Radiation heat transfer :→

→ It is defined as "The transfer of energy across a system boundary by means of an electromagnetic mechanism which is caused by tempr difference".

→ It does not require any medium & occures most effectively in vacuum.

→ Ex- furnaces, combustion chambers, nuclear explosions, & space application, solar energy incident or upon earth.

Electromagnetic waves → The energy which radiating surface releases is not continuous but in the form of discrete / separate packet or quanta of energy called photons, called EMW. It travels with velocity of light in straight path with same frequency.

When they approach receiving surface, the conversion of wave motion into thermal energy occures which is partly absorbed reflected or transmitted through the receiving surface.

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Stefan Boltzmann law of radiation →

States that " The emissive power of a black body is directly proportional to the fourth power of its absolute tempr ".

i.e $E_b \propto T^4$

$\Rightarrow E_b = \sigma T^4$

where E_b = Emissive power of a body

σ = Stefan Boltzmann constant

$= 5.67 \times 10^{-8}$ W/m² K⁴

$Q = F\sigma A (T_1^4 - T_2^4)$

F → A factor depending on geometry & surface properties.

Surface emission properties →

Rate of emission of radiation by a body depends on

i) tempr of surface
ii) nature "
iii) wavelength / frequency of radiation

Total emissive power (E)

Defined as total amount of radiation emitted by a body per unit area & time. unit = W/m²

* **Emissivity (ϵ)**

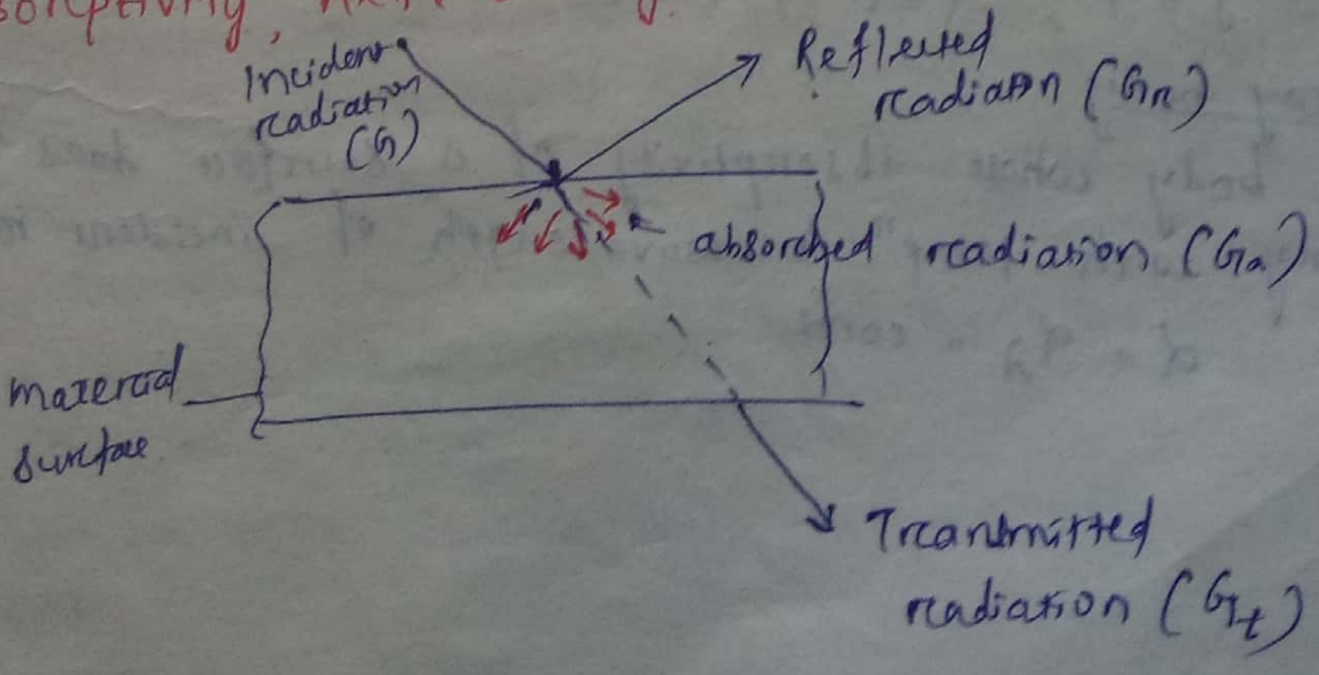
Ability of the surface of a body to radiate heat.

Also, $\epsilon = \frac{E}{E_b}$ — E → emissive power of any body. E_b → " of black body

For black body $\epsilon = 1$ $\quad 0 < E_b < 1$

" white " $\epsilon = 0$

Absorptivity, reflectivity & transmissivity →



When incident radiation also called irradiation (G) (defined as total incident radiation on a surface from all dir^n's per unit time & per unit area of surface) impinges on a surface, a part is reflected back (G_r), a part is transmitted (G_t) & the rest is absorbed (G_a).

By conservation of energy principle

$$G_a + G_r + G_t = G$$

$$\Rightarrow \frac{G_a}{G} + \frac{G_r}{G} + \frac{G_t}{G} = 1$$

$$\Rightarrow \alpha + \rho + \tau = 1$$

where α = absorptivity
ρ = reflectivity
τ = transmittivity.

Black body

→ For perfectly absorbing body $\alpha = 1$, $\rho = 0$, $\tau = 0$

→ So it is the body which neither reflects nor transmits any part of the incident radiation but absorbs all of it.

→ In real it does not exist.

Opaque body

When no incident radiation is transmitted through the body.

Here $\tau = 0$, so, $\alpha + \rho = 1$

Ex - Glass, liquid

White body

If all incident radiations are reflected back.

i.e. $\rho = 1$, $\alpha = 0$ & $\tau = 0$

Gray body

The body whose absorptivity of a surface does not vary with temp^n & wavelength of incident radiation.

$$\alpha = \alpha_\lambda = \text{const.}$$

concept of black body →

Black body is an object which absorbs all the radiant energy reaching its surface. So, $\alpha = 1$ & $\rho = \tau = 0$. The concept of it is important but does not exist practically.

Properties of black body

- → Absorbs all incident radiation irrespective of dirn.
- → Emits maxm amount of " at all wavelengths at any specified tempr.
- → It is a diffuse emitter (i.e. radiation emitted by a black body is independent of dirn).

4.8 Kirchhoff's law relating to spectral emissive power to absorptivity →

States that "At any tempr the ratio of total emissive power E to the total absorptivity α is a constant for all substances which are in thermal equm with their environment".

(or) States that, " Emissivity of a body is equal to its absorptivity when the body remains in thermal equm with its surroundings.

Planck's law →

It gives the spectral distribution of radiation intensity of black body & is given by

$$(E_\lambda)_b = \frac{2\pi c^2 h \lambda^{-5}}{e^{\left(\frac{ch}{\lambda K T}\right)} - 1} \quad \text{(Planck's law)}$$

where $(E_\lambda)_b$ = monochromatic emissive power of black body

c = velocity of light in vacuum = 3×10^8 m/s.

h = Planck's const = 6.625×10^{-34} J.s

λ = wavelength, μm

K = Boltzmann const = 1.3805×10^{-23} J/K

T = absolute tempr, K

Unit of $(E_\lambda)_b$ = $W/m^2(\mu m)$

4.6 Theories of radiation:→

Actual mechanism of radiation propagation is not fully understood till date. Still two theories are in use.

1> Maxwell's theory →

Accn to Maxwell's electromagnetic theory, the energy is transferred from a hot body to cold body in the form of electromagnetic waves. All electromagnetic waves travel with speed of light.

This concept is useful in prediction of the radiation properties of the surfaces & materials.

2> Max-Planck's theory →

Accn to Max Planck's concept, the propagation of thermal radiation takes place in the form of discrete quanta called photons.

Each quanta have energy $E = h\nu$

where h = planck's const

ν = frequency of photons

This concept is used to predict the magnitude of emitted energy by a body at a given tempn under ideal condn.