Date 26/11/20
Page

UNIT-1 INTRODUCTION TO MECHANICS OF SOLID

→ What is mechanic of solid?

1. Mechanics of Solids deals with study of various mechanical and physical properties related to mostly metal and their alloy for example - Steel, Al-alloy, Cu-alloy etc.

2. In Mechanics of solids we considered utilization pescribde material according to the need of system, properties required and also availibility and sustainibility.

→ Stress / Strain

1. STRESS -

a. Stress is that internal resistance applied by the material towards applied pressure or force.

b. Stress is the property of material which define certain mechanical properties such as, elasticity, ductility, malleability, toughness hardness etc.

c. After the stress is applied by the metal or

Date
Page

material it resists the strain developed till ultimate limit.

$$\text{Stress} = \sigma = \frac{\text{Resistive Force}}{\text{Area}}$$

$$\text{Pressure} = \frac{\text{External Force}}{\text{Area}}$$

There are two types of stress related to material which are-

1. Ultimate Stress (σu) - Ultimate stress is obtained for any material by performing various test on the material using UTM (Universal Testing Machine). It is the value after which sudden failure may occur.

2. Working Stress (σw) - Working stress or design stress is the value of any material that defines safe working for the system. It is obtained from FOS (Factor Of Safety).

$$FOS = \frac{\sigma u}{\sigma w} = \frac{\text{Ultimate stress in } N/mm^2}{\text{Working Stress in } N/mm^2}$$

According to forces, There are four types of stress which can be define as follow

Date
Page

...n developed till

...force

...orce

...s related to

...imate stress is
...ined for any
...ious test on
...niversal
...alue after
...ccur.

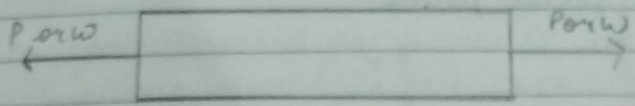
...king stress
...sign stress is
...at defines
... It is obtained
...y).

...tress in N/mm²
...tress in N/mm²

... four
...fine as follow

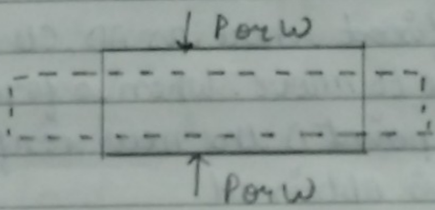
Date
Page

1. Tensile Stress (σT) -



As we can see in the above figure force P or W in Newton is stretching the bar therefore the applied stress for this condition is known as Tensile stress.
It is applicable mostly on ductile material.

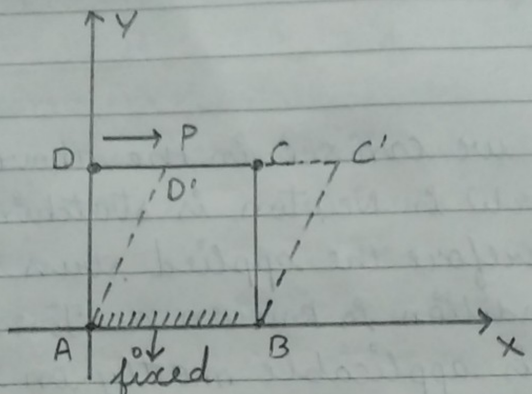
2. Compressive Stress (σC) -



In the above figure as we can see the block is being compressed or the transverse deformation is produced. Therefore, it is known as compressive stress. It is applied on Brittle material.

3. Shear Stress (σS) -

a Shear force is applied tangentially to the surface of given object. It tries to shear of the object either along a plane or a fixed point.



b. As shown in figure, we can see plain of side AB, BC, CD, AD. in which AB has been fixed where as AD, CD & BC sides are free to move. When a force P is applied on the point D the new configuration AD'BC' is obtained.

c. This shifting of the sides is known as shearing.

d. In components like stearing shaft of automobile, columns of buildings (known as Beam), key and shafts etc we can see shearing stress.

Date
Page

4. Thermal Stress -

a. Thermal stresses are a result of restrictions offered to free expansion and contraction in the material.
Example - Electric wires of high tension lines are made such that they can expand and contract as per environment without any thermal stress.

→ Loads And Its Types :-

It is the effort or applied force on a component. Load may be of three types-

1. Tensile Load
2. Compressive Load
3. Shear Load

→ Nature Of Loads -

The nature of load may be -

1. Gradually applied load
2. Sudden Load
3. Point Load
4. Uniformally Distributed Load
5. Uniformally Varying load

→ Material And Their Properties

1. In Engineering the materials are mostly classified under two categories [based on Loading Condition] -

a. Ductile	b. Brittle
* Live Load	* Dead Load
* Dynamic	* Static
* Yield more	* Yield less
* Better for Tenstile stress.	* Better for Compressive stress

2. On basis of composition they can be termed as -

a. Ferrous b. Non- ferrous.

3. While studying mechanics of solids the main area of focus is loading condition So the properties related to them will be :-

(a) Stiffness :- It is the ability of a material to resist deformation under stress The modulus of elasticity is the measure of stiffness.

(b) Strength :- It is the ability of a material to resist the externally applied force without breaking and yielding. The internal resistance offered by a part to an externally applied force is called stress.

(c) <u>Elasticity</u> :- It is the property of a material to regain its original shape after deformation when the external force are removed. This property is desirable for material used in tools and machines. It may be noted that steel is more elastic than rubber.

(d) <u>Plasticity</u> :- It is property of a material which retains the deformation produced under load permanently. This property of the material is necessary for forgings, in stamping on coins and in ornamental work.

(e) <u>Ductility</u> :- It is the property of a material enabling it to be drawn into wire with the application of a tensile force. The ductile material commonly used in engineering practice are mild steel, copper, aluminium, nickel, zinc, tin and lead.

Date ______
Page ______

(f) Brittleness :- It is the property of a material opposite to ductility. It is the property of breaking of a material with little permanent distortion. Brittle material when subjected to tensile loads, snap off without giving any sensible elongation. cast iron is brittle material.

(g) Malleability :- It is a special case of a ductility which permits material to be rolled or hammered into thin sheets. The malleable materials commonly used in engineering practice are lead, soft steel, wrought iron, copper and aluminium.

(h) Toughness :- It is the property of a material to resist fracture due to high impact loads like hammer blows. This property is desirable in parts subjected to shock and impact loads.

(i) Machinability :- It is the property of a material which refer to a relative case with which a material can be cut. It may be noted that brass can be easily machined than steel.

Date ______
Page ______

(j) **Resilience :-** It is the property of a material to absorb energy and to resist shock and impact load. This property is essential for spring materials.

(k) **Creep :-** When a part is subjected to a constant stress at high-temperature for a long period of time, it will undergo a slow and permanent deformation called creep. This property is considered in designing internal combustion engines, boilers and turbines.

(l) **Fatigue :-** When a material is subjected to repeated stresses, it fails at stresses below the yield point stresses Such type of failure of a material is known as fatigue

(m) **Hardness :-** It is the property of a material which helps scratching resistance, wearing of surface etc. while it is in working condition.

Date
Page

Q1 Which material is more elastic?
① Glass
② Cast iron
③ Rubber
④ Steel ✓

Note - In steel the mild steel is consider more elastic.

Q2 If we have to use brittle & Ductile material according to the working in a machinery [Example - Lathe Machine] Name the part which may be ductile as well as those are brittle.

Ans - 1. Headstock - Ductile
2. Tailstock - Brittle
3. Bed - Brittle
4. Chip-Pan - can be any
5. Lead Screw - Ductile
6. Compound Stress - Brittle
7. Feed Rod - Brittle
8. Tool Post - can be any
9. Hand Wheel - Brittle
10. Carriage - Brittle

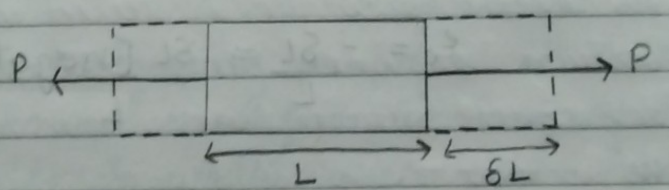
Date
Page

2. <u>STRAIN</u> -

a. Strain is the deformation produced due to applied load on the material

b. As we know load may be tensile in nature, compressive in nature and shearing in nature. Similarly the produced strain will also be respectively tensile, compressive, shearing in nature.

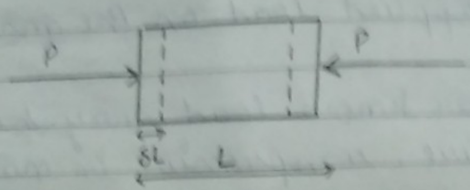
1. <u>Tensile Strain (ε_T)</u> -



In above diagram we can see a block which is being pulled from both ends. This result in elongation of length in the direction of applied force or load. Let us take L as original length in mm, δL as elongated length in mm. Then strain will be given by -

$$\varepsilon_T = \text{Tensile strain} = \frac{\delta L}{L}$$

2. Compressive strain



As we can see in the figure, Load P is compressing the given bar therefore the change in length will be negative. The formula or mathematical expression same as tensile But with negative sign.

$$\varepsilon_c = -\frac{\delta L}{L} = \frac{\delta L\ [\text{negative}]}{L}$$

3. Shearing strain -

In components such as Rivited Joint always shearing force is applied. As a result, the strained developed will be shearing strain. Mathematically, it will be given as $\tau / \varepsilon_{shear}$

$$\varepsilon_{shear} = \frac{\delta d}{d}$$

Date
Page

. Load P is
therefore the
egative. The
xpression same
ive sign.

gative]

ted Joint
pplied. As a
d will be
ically, it

Date
Page

very Imp → **Stress-Strain Diagram**

1. Stress-Strain Diagram provides a comparitive or graphical representation of the relation between σ i.e stress and ε i.e strain.

2. It is made for both ductile as well as brittle material.

→ **Stress-Strain Diagram for Ductile Material (Mild Steel)**

1. For designing purpose, it is necessary to know the functioning of material while in working condition. In general the material used for mechanical engineering practises in steel.

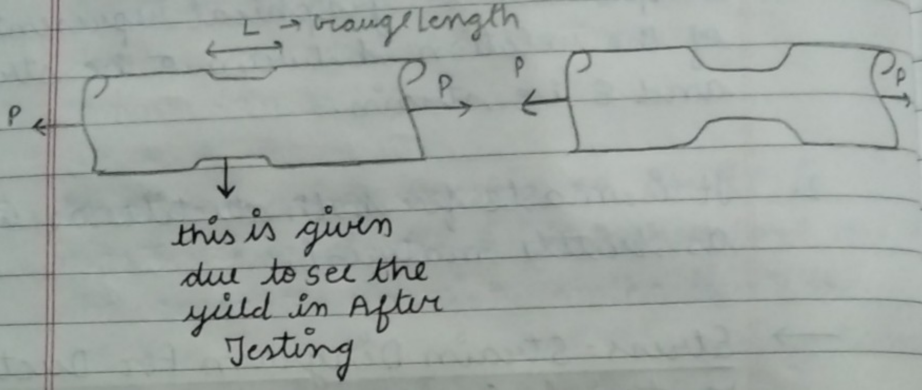
2. The standard tensile stress determine properties required by the material through a standard specimen test. So that the applied load and fracture due to it can be measure.

Due to strain hardening the curve decrease After point E.

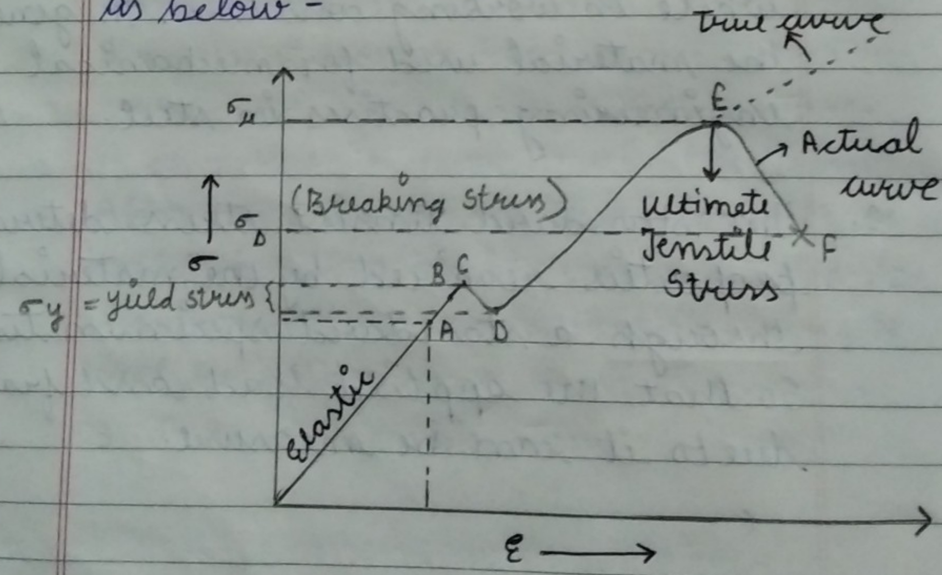
Date
Page

Standard Specimen Of Mild Steel

Before Testing — After Testing



The above specimen is tested on Universal Testing Machine [UTM] till it fracture. The curve obtain from this is shown as below -



a. Point A represent the proportional limit which will be obtained between stress and strain [it will be elastic limit]

b. After Point A till Point B the material is deformed plastically or we can say plastic deformation start.

c. After Point B the yielding of specimen starts which is ranged between Upper Yield Limit Point C and Lower Yield Limit Point D. This region is known as Yielding Region.

d. After Yielding when we further increase the stress, there is a significant increase till point E, which is known as Ultimate Tensile stress (U.T.S).

e. When we further increase the stress after Point E there is downfall of the curve resulting in fracture point F at the end of experiment.

Description Of Stress-Strain Curve for Mild Steel -

1. The point O in curve is starting point where no load has being appiled.

Gauge Length - length of the specimen on which we want to determine the mechanical properties.

Date

Page

2. The line OA represent the limit of proportionally between produced strain and applied stress. With point A representing limit of proportionally i.e if the load is removed the material will remain same

3. Point B is also known as limit of elasticity or elastic limit which represent the amount elasticity in the material.

4. After the point B [i.e elastic limit] the material starts yielding which means the Gauge length increases and its cross-section decreases. The point C represent Upper Yield Limit and point D represent Lower Yield Limit. The stress corresponding to them is Yield stress.

5. After point D, the material is further yielded till a limit represented by E known as Ultimate Tensile strength and corresponding stress is known as Ultimate Tensile stress.

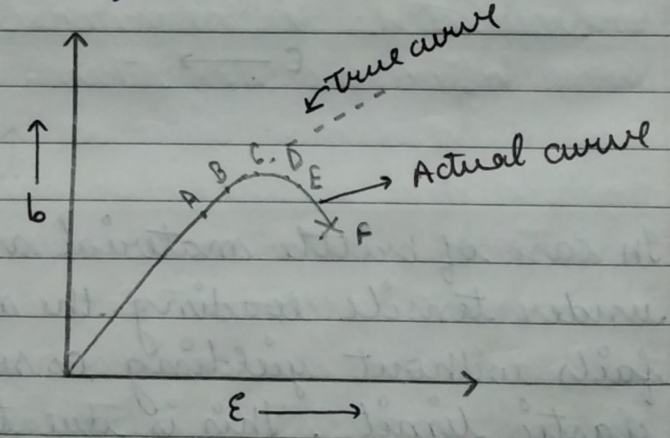
6. After this when further material is streched the limit of or we can say the value to stress decreases with increases

in strain till a point F known as fracture point and corresponding stress is known as breaking stress.

→ Relation Between True And Actual Curves for different ductile material.

a. In the case of mild steel we can see yielding region significantly, But in case of different material this may not be the condition.

b. For such material (only ductile) the curve may be as shown -



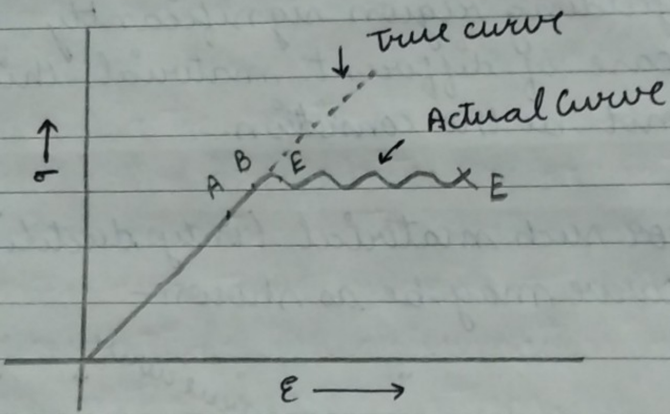
Ques What is the shape of broken cross-section in cases of ductile material.

Ans In case of ductile material the cross-section will be cup and cone structure

Ques What is the shape of cross-section obtained after yielding in cases of brittle material.

Ans In case of brittle material the cross-section will be pointed surface.

→ Stress-Strain Diagram For Brittle Material



In case of brittle material as we can see under tensile loading the material fails without yielding as soon as elastic limit. This is due to incapability of such material to resist Tensile loading.

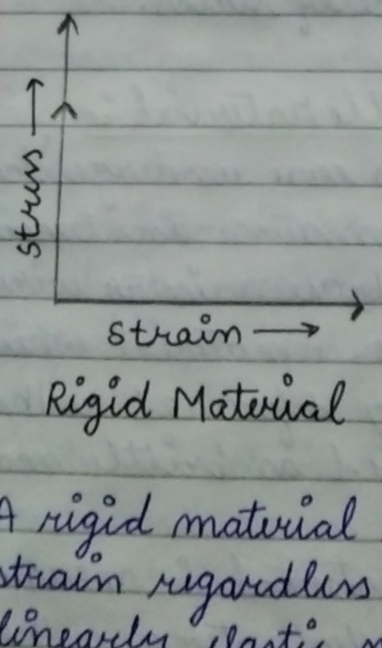
→ Material classification –

Materials are commonly classified as-

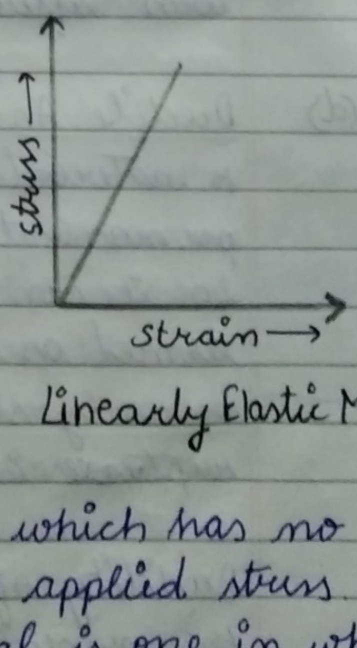
(a) Homogeneous And Isotropic Material :-

A homogeneous material implies that the elastic properties such as modulus of elasticity and Poisson's ratio of the material are same everywhere in the material system. Isotropic means that these properties are not directional characteristics i.e an isotropic material has same elastic properties in all direction at any one point of the body.

(b) Rigid and Linearly Elastic Material :-



Rigid Material

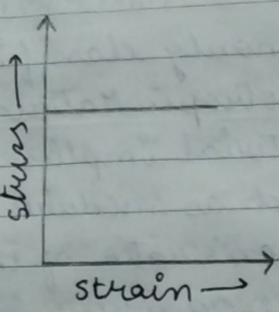


Linearly Elastic Mat.

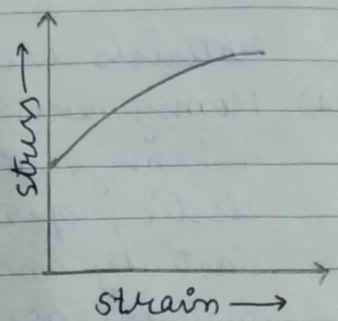
A rigid material is one which has no strain regardless of the applied stress. A linearly elastic material is one in which the strain is proportional to the stress.

Date ______
Page ______

(c) Plastic Material And Rigid-Plastic Material:-



Plastic Material



Rigid-Plastic Material

For a plastic material, there is definite stress at which plastic deformation starts. A rigid-plastic material is one in which elastic and time dependent deformation are neglected. The deformation remains even after release of stress.

(d) Ductile And Brittle Material:-

A material which can undergo 'large permanent' deformation in tension i.e. it can be drawn into wires is termed as ductile. A material which can be only slightly deformed without rupture is termed as brittle material.

Ductility of a material is measured by the percentage elongation of the specimen or the percentage reduction in cross-sectional area of the specimen when failure occurs. If l is the original length and l' is the final length then

$$\% \text{ increase in length} = \frac{l'-l}{l} \times 100$$

The length l' is measured by putting together two portion of the fractured specimen.

Similarly,

$$\% \text{ reduction in area} = \frac{A-A'}{A} \times 100$$

A = original area

A' = minimum cross sectional area.

A brittle material like cast iron or concrete has very little elongation and very little reduction in cross-sectional area. A ductile material like steel or Aluminium has large reduction in area and increase in elongation. An arbitary percentage elongation of 5% is frequently taken as the dividing lime between these two classes of the material.

Date ______
Page ______

→ Elastic Limit, Hook's Law And Young's Modulus.

→ Elastic Limit :-

1. When we perform elastic test or Tensile test [for Mild steel] in the curve of stress strain we can see their are 2 points before the actual yielding starts. These 2 point are known as limit of proportionality or Elastic Limit.
2. Elastic Limit shows the material is still maintaing its elastic i.e after removal of load. The material can regain its shapes.
3. Elastic Limit is the point through which we can justify or classify the provided material. i.e when we compare mild steel and say aluminium we will find mild steel is more elastic than aluminium.

→ Hook's Law -

1. After the Elastic Limit we will see that one more point is important i.e limit of proportionality. This is explained by Hook's Law which state that the stress and strain applied

on the m
one anoth

where, s
in natur
Modulus
Pascal

Ques-1 A steel
and 20
axial
extensi
0.9 mm
modul

Sol Given
Load
Length
Width
Thick
Exten

on the material are proportional to one another under elastic limit.

$$\sigma \propto \varepsilon$$
$$\sigma = E\varepsilon$$
$$E = \frac{\sigma}{\varepsilon}$$

where, stress and strain are linear in nature. And E is known as Young's Modulus. It unit will in N/mm^2 or Pascal

Ques-1 A steel bar 1.5 m long, 50 mm in width and 20 mm thickness is subjected to an axial tensile load of 120 KN. If the extension in length of the bar is 0.9 mm. Find intensity of stress, strain modulus of elasticity for the material.

Sol Given,

Load = 120 KN = 120×10^3 N

Length = 15 m = 1.5×10^3 mm

Width = 50 mm

Thickness = 20 mm

Extension length = 0.9 mm

$$\sigma = \frac{\text{Load}}{\text{Area}} = \frac{120\times10^3}{\text{width}\times\text{Thickness}}$$

$$= \frac{{}^{6}\cancel{12}\cancel{0}\times10^3}{50\times2\cancel{0}}$$

$$= 1.2\times10^2\ N/mm^2$$

$$\varepsilon = \frac{\delta l}{L} = \frac{0.9}{1.5\times10^{3}} = 6\times10^{-4}$$

$$E = \frac{120}{6\times10^{-4}} = 20\times10^{4}\ N/mm^2$$

$$= 200\ KN/mm^2$$

Ques-2 A hollow right circular cylinder is made of cast iron and has an outside diameter is 75mm and inner diameter is 60mm. The length of cylinder is 600mm and it is subjected to compression load of 50KN Neglect any possibility of lateral buckling of the cylinder. Find normal stress, shortening in length of cylinder due to this load. Taking E for cast iron as 100 GPa.

Sol Given.

$E = 100\ GPa = 1\times10^{8}\ N/mm^2$

$W = 50\ KN = 50\times10^{3}\ N$

$d_i = 60mm$

$d_o = 75mm$

$L = 600mm$

$\therefore$

$$Area = \frac{\pi}{4}\left[(75)^2 - (60)^2\right] = \frac{3.14}{4}\times[5625-3600]$$

$$= 1589.62\ mm^2$$

$$\text{Stress} = \frac{50\times10^3}{15.89.62} = 31.45\ N/mm^2$$

As we know,

$$E = \frac{\sigma}{\varepsilon} = \frac{\sigma}{\delta l/L} = \frac{\sigma L}{\delta l}$$

$$\Rightarrow \delta l = \frac{\sigma L}{E} = \frac{31.45\times 600}{100\times10^6}$$

$$\delta l = 0.000188$$

Ques 3 The wire working on a railway signal is 6mm in a diameter and 250 m Long. If the movement at signal is to be 15cm. Find the movement which must be given to the end of wire at signal box. Assuming a pull of 1500N on the wire for which modulus of Elasticity is taken as. $2\times10^5 N/mm^2$

Sol, Given

$E = 2\times10^5\ N/mm^2$

$W = 1500\ N$

diameter of wire = 6mm

Length = 250×10^3 mm

Movement at signal = 15cm

As we know,

$$E = \frac{\sigma}{\varepsilon}$$

Date
Page

$$E = \frac{WL}{A\,\delta l}$$

$$\delta L = \frac{WL}{AE}$$

$$= \frac{1500 \times 250 \times 10^3}{\frac{3.14 \times \cancel{36}^{\,18}}{\cancel{4}\,2} \times \cancel{2} \times 10^5}$$

$$= \frac{15 \times 25 \times 10^6}{3.14 \times 18 \times 10^5}$$

$$= \frac{375 \times 10^6 \times 10^{-5}}{56.52}$$

$= 66.348\,mm$

$= 66.3\,mm$

$= 6.63\,cm$

For getting movement of 15 cm at signal end we have to move the liver is equal ~~to~~ $[15 + 6.63]\,cm = 21.63\,cm$

Ques-4 A cast iron gurder is subject to axial compressive load the deflection due to this load is neglected if we take modulus of elasticity for cast iron as 115 MPascal, Length of the gurder is 1.3 m. The change in length due to load is 0.018 mm. Find the applied load if area of cross section $200\,mm^2$

Sol Given,
E = 115
Length =
change
area cr
as we k
E

Ques-5 A
m
w
of
e
c
s

$1 MPa = 1 N/mm^2$
$1 GPa = 10^3 N/mm^2$

Date
Page

Sol Given,
$E = 115$ Pascal $= 115\ N/mm^2$
Length $= 1.3 m = 1.3 \times 10^3 mm$
change Length $= 0.018 mm$
area cross section $= 225\ mm^2$
as we know

$$E = \frac{stress}{strain} = \frac{W/A}{\delta L/L}$$

$$E = \frac{WL}{A\delta L} \Rightarrow W = \frac{EA\delta L}{L}$$

$$W = \frac{115 \times 22.5 \times 0.018 \times 10}{1.3 \times 10^3 \times 10^3}$$

$$W = \frac{115 \times 22.5 \times 18 \times 10}{13 \times 10^6}$$

$$= \frac{465750 \times 10^{-5}}{13} N$$

$$= 0.358 N$$

$$\begin{array}{r} 225 \\ 115 \\ \hline 1125 \\ 225\times \\ 225\times\times \\ \hline 25875 \\ 18 \\ \hline 207000 \\ 25875\times \\ \hline 465750 \end{array}$$

Ques-5 A cluch wire is made of steel with modulus of elasticity as 200 GPascal when It is engaged a displacement of 3.5 cm is obtained at the cluch end. Find the length of wire if the displacement at liver end 0.5cm, diameter of the wire is 3mm. The applied force can be taken as 7N.

Date
Page

Sol Given,

$E = 200\, GPascal = 200 \times 10^3\, N/mm^2$

$\delta l = 0.5\, cm = 5\, mm$

diameter $= 3\, mm$

$W = 7N$

as we know

$$\sigma = \frac{W}{A} = \frac{7}{\frac{\pi d^2}{4}} = \frac{7 \times 7 \times 4}{22 \times 9}$$

$$= \frac{\cancel{196}^{98}}{\cancel{22}_{11} \times 9} = \frac{98}{99}\, N/mm^2$$

$$\begin{array}{r} 49 \\ \times 4 \\ \hline 196 \end{array}$$

Also,

$$E = \frac{\sigma}{\varepsilon}$$

$$\varepsilon = \frac{\sigma}{E} \Rightarrow \frac{\delta L}{L} = \frac{\sigma}{E} \Rightarrow L = \frac{\delta L\, E}{\sigma}$$

$$L = \frac{5 \times \cancel{2}00 \times 10^3 \times 99}{\cancel{98}\ 49}$$

$$\begin{array}{r} 99 \\ \times 5 \\ \hline 495 \end{array}$$

$$L = \frac{495}{49} \times 10^5\, mm$$

$$L = 10.1 \times 10^5\, mm$$

Ques 6 Make the calculation of diameter of a steel wire which is required to lift the load of 6 KN. Taking maximum sustainable stress as 120 M Pascal Length of the wire is 3m. Taking $E = 200\, GPascal$

Sol Given :

Load = 6 kN = 6×10^3 N

σ_{max} = 120 MPascal = 120 N/mm²

Length = 3×10^3 mm

E = 200 GPascal = 200×10^3 N/mm²

we know that

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

$$120 = \frac{6 \times 10^3}{\pi/4 \times d^2}$$

$$\frac{\pi}{4} \times d^2 = \frac{6 \times 10^3}{120}$$

$$d^2 = \frac{10^3 \times 4}{20 \times 5 \pi}$$

$$d = \sqrt{\frac{10^3 \times 7}{5 \times 22}} = 7.98 \text{mm}$$

Now, we have to find the induced stress in the wire due the obtained diameter

$$\sigma_{ind} = \frac{P}{A} = \frac{6 \times 10^3}{\frac{\pi}{4}(7.98)^2} = 119.9$$

Since, the value of induced is coming as 119.9, Therefore the dimension d = 7.98mm

Note - When we talk about failure in ductile material is called ductile fracture [with yielding] and in brittle material is called brittle fracture [without yielding]

Date

Page

Ques 7 A Tensile test was conducted on a mild steel bar and elastic material. Take following data from the test diameter of a steel bar 3 cm. gauge length is taken as 20 cm. Load up to elastic limit 250 KN. Extension at a load of 150 KN is 0.21 mm. Maximum Load 380 KN. Total extension 60 mm diameter the rod at failure 2.5 cm Find ① Young's Modulus ② Stress under elastic limit ③ precentage elongation ④ percentage decrease in in area.

Sol Given,

diameter of steel bar = 3 cm = 30 mm

Gauge length = 20 cm = 200 mm

Load up to elastic limit = 250×10^3 N

Extension at load 150×10^3 N = 0.21 mm

Maximum Load = 380×10^3 N

Total extension = 60 mm

Diameter at failure = 2.5 cm = 25 mm

Now

$$\text{Area} = \frac{\pi}{4} d^2 = \frac{\pi}{4} \times 30 \times 30$$

$$= 7.065 \times 10^2 \text{ mm}^2$$

① Stress at

Strain

Young'

② Stres

③ At

aft

Tot

...ure in ductile material
... [with yielding] and
...lled brittle fracture

Date
Page

...onducted on a
...d elastic material.
... from the test
... bar 3cm, gauge
...0cm. Load up to
...N. Extension at a
...1mm. Maximum
...xtension 60mm
... failure. 2.5cm
...dulus ② Stress
...rcentage elongation
... in in area.

$= 3cm = 30mm$

$= 200\ mm$

...it $= 250 \times 10^3\ N$

...$10^3 N = 0.21\ mm$

...$\times 10^3 N$

...m

...$5cm = 25mm$

...$\times 30$

...$10^2\ mm^2$

Date
Page

① Stress at elastic limit $= \dfrac{150 \times 10^3}{7.065 \times 10^2}$

$= 21.23 \times 10^1\ N/mm^2$

$\sigma = 212.3\ N/mm^2$

Strain at elastic limit $= \dfrac{\delta l}{L} = \dfrac{0.21}{200}$

$\varepsilon = 0.105 \times 10^{-2}$

Young's modulus at elastic limit $= \dfrac{\sigma}{\varepsilon}$

$= \dfrac{212.3}{0.105} \dfrac{\times 10^2 \times 10^3}{10}$

$= 20.219 \times 10^4$

$= 202.19 \times 10^3\ N/mm^2$

$= 202.19\ GPa$

② Stress under elastic limit $= \dfrac{W}{A} = \dfrac{250 \times 10^3}{7.065 \times 10^2}$

$= 35.38 \times 10^2$

$= 353.8\ N/mm^2$

③ At it is given total increase in length after the test is done $= 60mm$
Total length $= 20cm = 200mm$

% elongation $= \dfrac{l' - l}{l} \times 100 = \dfrac{\delta L}{L} \times 100$

Date ______
Page ______

$$= \frac{60}{200} \times 100 = 30\%$$

④ It is given after the test $d = 2.5\,cm$ or $25\,mm$

$$\%\text{ reduction area} = \frac{O.D^2 - F.D^2}{O.D^2} \times 100$$

$$= \frac{(30)^2 - (25)^2}{(30)^2} \times 100$$

$$= \frac{275 \times 100}{900}$$

$$= 30.56\%$$

→ **Poisson's Ratio -**

1. When we talk about stress and strain applied on a material their is certain amount of lateral strain produced when load is applied on a body.
2. Whenever we applied tensile load on any body their is increase in length But accompanied by certain amount of reduction in a form of decrease area. Thus we can say the body having axial deformation also deforms at the right angle due to the result of applied load. This is explain by

following te

(i) Lateral An

1. When a bo
or compres
produced
increase
known a
given by

2. The str
strain
of appl
Strain

F

J

It is
La

30%

...test $d = 2.5$ cm or

$\frac{...D^2 - F.D^2}{O.D^2} \times 100$

$\frac{(30)^2-(25)^2}{(30)^2} \times 100$

$\frac{275 \times 100}{900}$

0.56%

...s and strain
...ir is certain
... produced
a body.
...ile load on
...ase in length
...in amount
... decrease
body having
...forms at
...result of
...n by

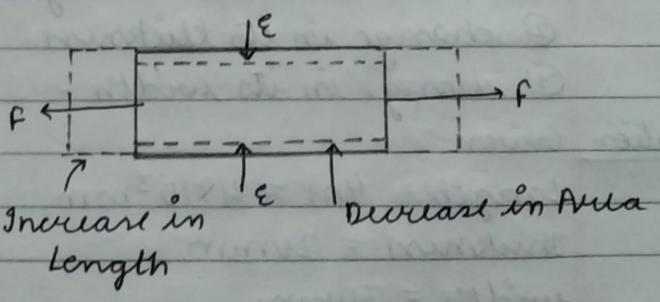
following term -

(i) Lateral And Longitudinal Strains -

1. When a body is subject to axial tention or compression loading. Then the strain produced in the body due to either increase or decrease of the length is known as longitudinal strain. It is given by

$$\varepsilon_L = \frac{\delta l}{L}$$

2. The strain is accompanied by a strain at right angle to the direction of applied load is called Lateral Strain



It is given by -

Lateral strain $= \frac{\delta b}{b}$ [in case of square or rectangle]

$= \frac{\delta d}{d}$ [in case of circular cross-section]

As discuss above about lateral and longitudinal strain the ratio by which they will be applied on a body is known as poisson's ratio.
Mathematically given as -

$$\mu = \frac{\text{Lateral strain}}{\text{Longitudinal strain}}$$

Ques-8 A steel bar having following dimension length is 4m, breadth is 30mm and thickness is 20mm. It is subject an axial pull of load 30KN which is applied in the direction of the length. Take $E = 2\times10^5\ N/mm^2$ and Poisson's ratio is 0.3. Find ① change in length ② change in its thickness and ③ change in its width.

Solution Given

Length = 4m = 4×10^3 mm

Thickness = 20mm

width = 30mm

load = 30×10^3 N

$E = 2\times10^5\ N/mm^2$

Poisson's Ratio = 0.3

Now.

Area = width x Thickness

$= 20 \times 30$

$= 600\,mm$

① $\text{Stress} = \dfrac{3\cancel{0} \times 10^3}{60\cancel{0}} = \dfrac{300\cancel{0}}{6\cancel{0}} = 50\ N/mm^2$

② $\text{Strain} = \dfrac{\text{Stress}}{\text{Young's Modulus}} = \dfrac{\cancel{50}\ 25}{\cancel{2} \times 10^5}$

$= 25 \times 10^{-5}$

$= 0.00025$

③ $\text{strain} = \dfrac{\delta l}{L}$

$\delta l = L \times \text{strain}$

$= 4 \times 10^3 \times 25 \times 10^{-5}$

$= 100 \times 10^3 \times 10^{-5}$

$= 1\,mm$

④ $\text{Poission ratio} = \dfrac{\text{Lateral strain}}{\text{Longitudinal strain}}$

$0.3 = \dfrac{\text{Lateral strain}}{0.00025}$

$75 \times 10^{-6} = \text{Lateral strain}$

$\text{Lateral strain} = 7.5 \times 10^{-5}$

⑤ change in thickness, $\delta t = \text{Lateral strain} \times t$

$= 7.5 \times 10^{-5} \times 20$

$= 150 \times 10^{-5}$

$= 1.50 \times 10^{-3}\,mm$

(6) change in width, δw = Lateral strain $\times w$

$= 7.5 \times 10^{-5} \times 30$

$= 225 \times 10^{-5}$

$= 2.25 \times 10^{-3}$ mm

Ques-9 A metallic bar of length 30 cm, width 4 cm & depth is 4 cm, is subjected to axial compressive load of 400 KN. The change in length is given as 0.075 cm, decrease in the width 0.003 cm. Find Young's modulus and Poisson's ratio.

Solution - Given

Length = 30 cm = 300 mm

Width = 4 cm = 40 mm

depth = 4 cm = 40 mm

Load = 400 KN = 400×10^3 N

change in length = 0.075 cm = 0.75 mm

decrease in width = 0.003 = 0.03 mm

Now

Area = 40×40

$= 1600 \text{ mm}^2$

(1) $\text{stress} = \dfrac{W}{\text{Area}} = \dfrac{\cancel{400} \times 10^3}{4\,\cancel{1600}} = \dfrac{1000}{4}$

$= 250 \text{ N/mm}^2$

(2) $\text{Strain} = \dfrac{0.\overset{25}{\cancel{75}}}{\cancel{3}0000} = 25 \times 10^{-4} = 0.0025$

(3) Young's M

(4) Lateral

(5) Poission

Note - When
alwa
since

③ Young's Modulus = Stress / Strain

$$= \frac{250}{0.00\cancel{25}} \times 10^4 \ N/mm^2$$

$$= 100 \times 10^3 \ N/mm^2$$

$$= 100 \ GPa.$$

④ Lateral strain $= \frac{\delta w}{w} = \frac{0.003 \times 1\cancel{0}}{4\cancel{0}}$

$$= 7.5 \times 10^{-4}$$

⑤ Poission ratio = Lateral strain / Longitudinal strain

$$= \frac{7.5 \cancel{\times 10^{-4}}}{25 \cancel{\times 10^{-4}}}$$

$$= 0.3$$

Note- When lateral strain is expressed it is always accompanied by negative sine

Date
Page

→ Working Stress And Factor Of Safety

① While designing any component we should always considered the strength for given material such that it is always below the value of ultimate strength [maximum allowable strength].

② To obtain this a minimum value is obtained which is known as working stress.

③ This stress is obtain by a factor know as Factor of Safety which defines the ratio between ultimate strength or stress to the working strength or stress [under tensile condition]

$$\text{Factor of Safety} - \frac{UTS}{WS}$$

UTS → Ultimate Tensile Stress and Strength
WS → Working stress or strength.

④ The factor of safety become very critical for components like shaft, rops of elevator, wheels etc. where cyclic loading is applied.

Date
Page

r Of Safety

nponent we
d the strength
that it is
f ultimate
owable

n value is
as working

factor know
defines the
trength or
gth or stress

s and Strength
ngth.

very critical
rops of
yclic

Date
Page

Ques-10 Find the internal diameter of a columne whose external diameter is 200 mm. The ultimate stress of this hollow steel columne carried load of 1.9 MN is 480 N/mm² Take FOS is 4.

Solution Given,

External diameter = 200 mm

Load = 1.9 MN = 1.9×10^6 N

External diameter = 200 mm

Ultimate stress = 480 N/mm²

Factor of Safety = 4

① As we know

$$FOS = \frac{U.S}{W.S}$$

$$W.S = \frac{U.S}{FOS} = \frac{480}{4} = 120\ N/mm^2$$

② As we know

$$\text{Working stress} = \frac{\text{Load}}{\text{Area}}$$

$$\text{Area} = \frac{\pi}{4}[d_o^2 - d_i^2]$$

$$120 = \frac{1.9 \times 10^6}{\pi/4[(200)^2 - d_i^2]}$$

$$(200)^2 - d_i^2 = \frac{1.9 \times 10^6 \times 4}{120 \times \pi}$$

Date

Page

$$(200)^2 - (di)^2 = \frac{7.6 \times 10^6}{376.8}$$

$$(200)^2 - (di)^2 = 0.0203 \times 10^6$$

$$40{,}000 - (di)^2 = 20300$$

$$(di)^2 = 40000 - 20300$$

$$= 19700$$

$$di = 140.3 \text{ mm}$$

B.TECH. 1ST YEAR

Sub- Fundamentals of Mechanical Engineering and Mechatronics [KME101T]

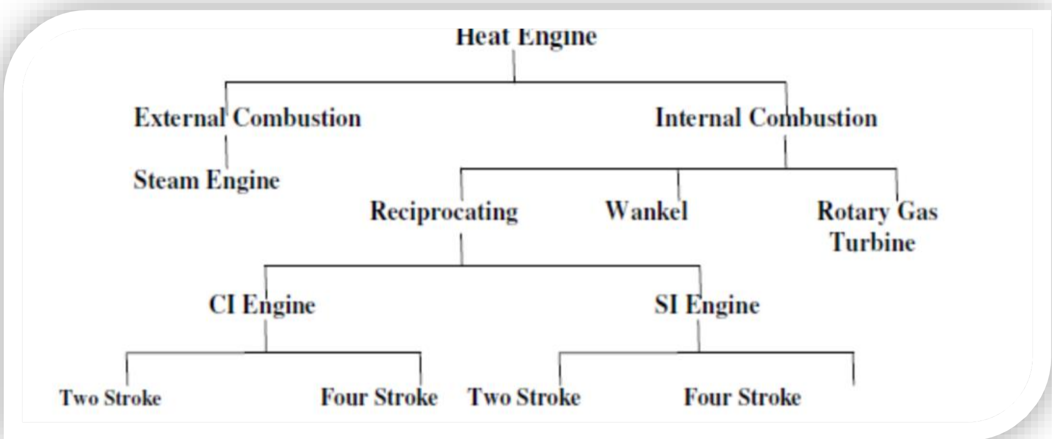
Theory Notes for Unit 2

Contents of UNIT 2

IC Engine: Basic Components, Construction and Working of Two stroke and four stroke SI & CI engine, merits and demerits, scavenging process; Introduction to electric, and hybrid electric vehicles.
Refrigeration: Its meaning and application, unit of refrigeration; Coefficient of performance, methods of refrigeration, construction and working of domestic refrigerator, concept of heat pump. Formula based numerical problems on cooling load.
Air-Conditioning: Its meaning and application, humidity, dry bulb, wet bulb, and dew point temperatures, comfort conditions, construction and working of window air conditioner.

IC Engine

- An Engine is a device which transforms the chemical energy of a fuel into thermal energy and uses this thermal energy to produce mechanical work. Engines normally convert thermal energy into mechanical work and therefore they are called heat engines.
  Heat engines can be broadly classified into:
  i) External combustion engines (E C Engines)
  ii) Internal combustion engines (I C Engines)



- External combustion engines are those in which combustion takes place outside the engine. For example, in steam engine or steam turbine the heat generated due to combustion of fuel and it is employed to generate high pressure steam, which is used as working fluid in a reciprocating engine or turbine, see figure 1.

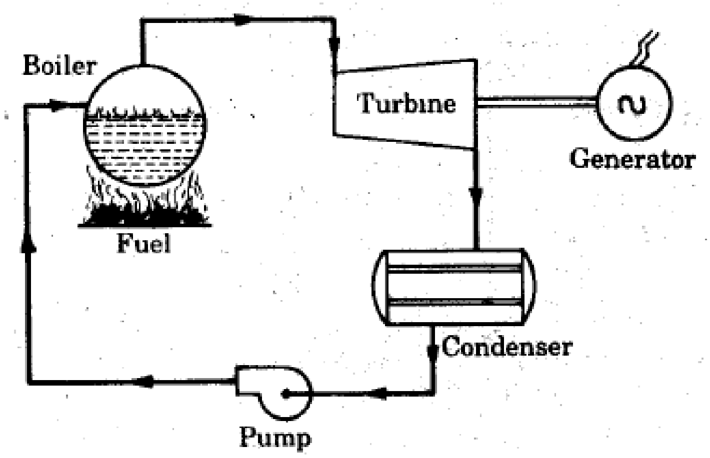


Figure 1 : External Combustion Engine

- Internal combustion engines are those in which the combustion of fuel is done inside a chamber which is an internal part of the engine. IC engine can be classified as: **Continuous IC engines and Intermittent IC engines.**
- In continuous IC engines products of combustion of the fuel enters into the prime mover as the working fluid. For example: In Open cycle gas turbine plant. Products of combustion from the combustion chamber enters through the turbine to generate the power continuously, see figure 2. In this case, same working fluid cannot be used again in the cycle.

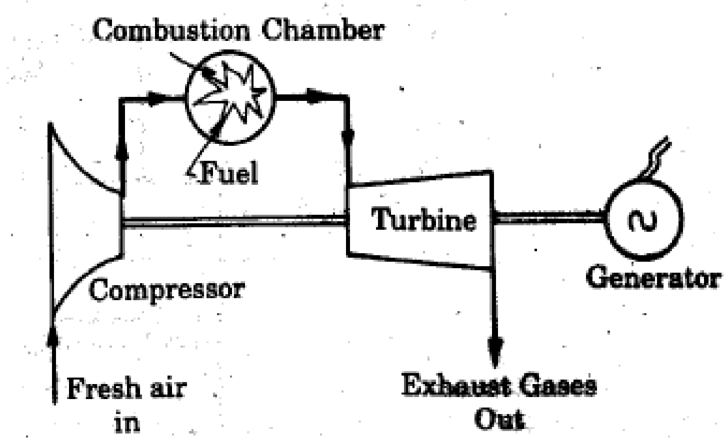
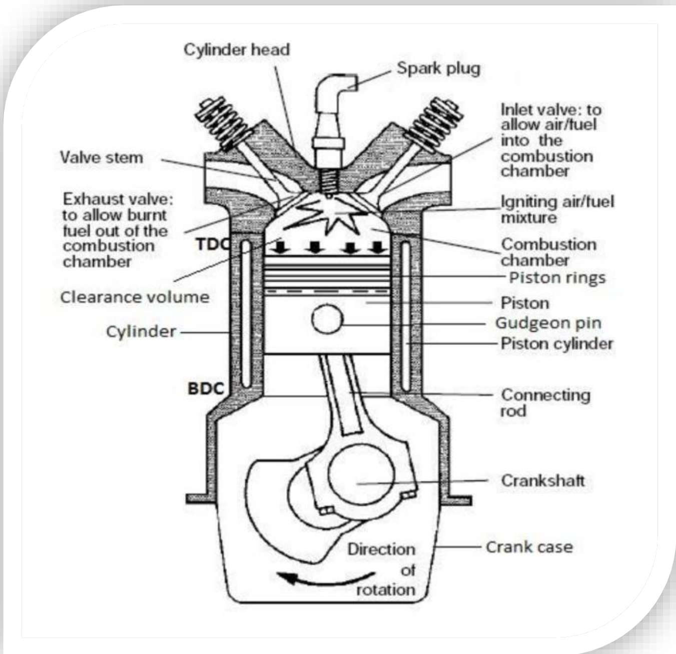
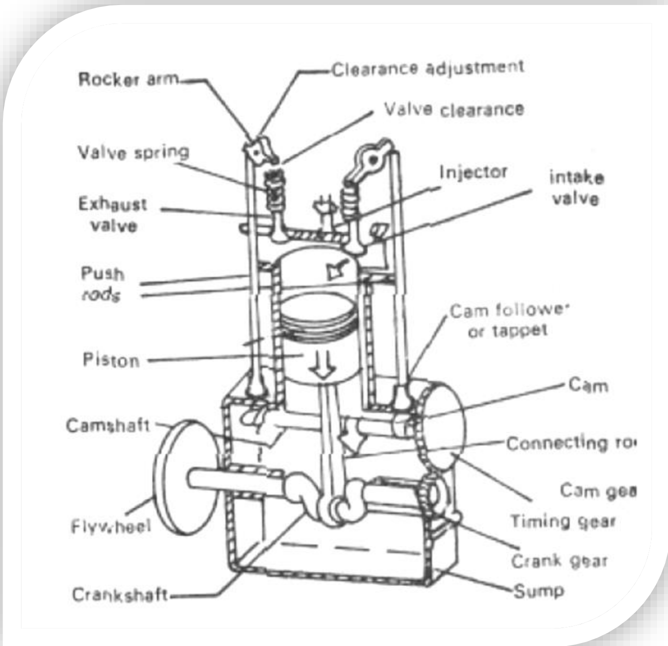


Figure 2: Continuous IC Engines

- In Intermittent internal combustion engine combustion of fuel takes place inside the engine cylinder. Power is generated intermittently (only during power stroke) and flywheel is used to provide uniform output torque. Usually these engines are reciprocating engines. The reciprocating engine mechanism consists of piston which moves in a cylinder and forms a movable gas tight seal. By means of a connecting rod and a crank shaft arrangement, the reciprocating motion of piston is converted into a rotary motion of the crankshaft. They are most popular because of their use as main prime mover in commercial vehicles, see figure 3.



CROSS-SECTION FOR PETROL ENGINE



CROSS-SECTION FOR DIESEL ENGINE

Figure 3: Intermittent Internal Combustion Engine

Comparison between external combustion engine and internal combustion engine:

External combustion engine	Internal combustion engine
*Combustion of air-fuel is outside the engine cylinder (in a boiler)	* Combustion of air-fuel is inside the engine cylinder (in a boiler)
*The engines are running smoothly and silently due to outside combustion	* Very noisy operated engine

*Higher ratio of weight and bulk to output due to presence of auxiliary apparatus like boiler and condenser. Hence it is heavy and cumbersome.	* It is light and compact due to lower ratio of weight and bulk to output.
*Working pressure and temperature inside the engine cylinder is low; hence ordinary alloys are used for the manufacture of engine cylinder and its parts.	* Working pressure and temperature inside the engine cylinder is very much high; hence special alloys are used
*It can use cheaper fuels including solid fuels	*High grade fuels are used with proper filtration
*Lower efficiency about 15-20%	*Higher efficiency about 35-40%
* Higher requirement of water for dissipation of energy through cooling system	*Lesser requirement of water
*High starting torque	*IC engines are not self-starting

Advantages of internal combustion engines:

1. Size of engine is very less compared to external combustion engines.
2. Power to weight ratio is high.
3. Very suitable for small power requirement applications.
4. Usually more portable than their counterpart external combustion engines.
5. Safer to operate.
6. Starting time is very less.
7. High efficiency than external combustion engine.
8. No chances of leakage of working fluids.
9. Requires less maintenance.
10. Lubricant consumption is less as compared to external combustion engines.
11. In case of reciprocating internal combustion overall working temperature is low because peak temperature is reached for only small period of time (only at detonation of fuel).

Disadvantages of internal combustion engines:

1. Variety of fuels that can be used is limited to very fine quality gaseous and liquid fuel.
2. Fuel used is very costly like gasoline or diesel.

3. Engine emissions are generally high compared to external combustion engine.
4. Not suitable of large scale power generation.
5. In case of reciprocating internal combustion noise is generated due to detonation of fuel.

Types and applications of internal combustion engines

1. Gasoline Engines: Automotive, Marine, Aircraft
2. Gas Engines: Industrial Power
3. Diesel Engines: Automotive, Railways, Power, Marine
4. Gas Turbines: Power, Aircraft, Industrial, Marine

CLASSIFICATION OF INTERNAL COMBUSTION ENGINES:

There are different types of IC engines that can be classified on the following basis:

1. According to thermodynamic cycle
i) Otto cycle engine or Constant volume heat supplied cycle.
ii) Diesel cycle engine or Constant pressure heat supplied cycle.
iii) Dual-combustion cycle engine.

2. According to the fuel used:
i) Petrol engine ii) Diesel engine iii) Gas engine

3. According to the cycle of operation:
i) Two stroke cycle engine ii) Four stroke cycle engine

4. According to the method of ignition:
i) Spark ignition (S.I) engine ii) Compression ignition (C.I) engine

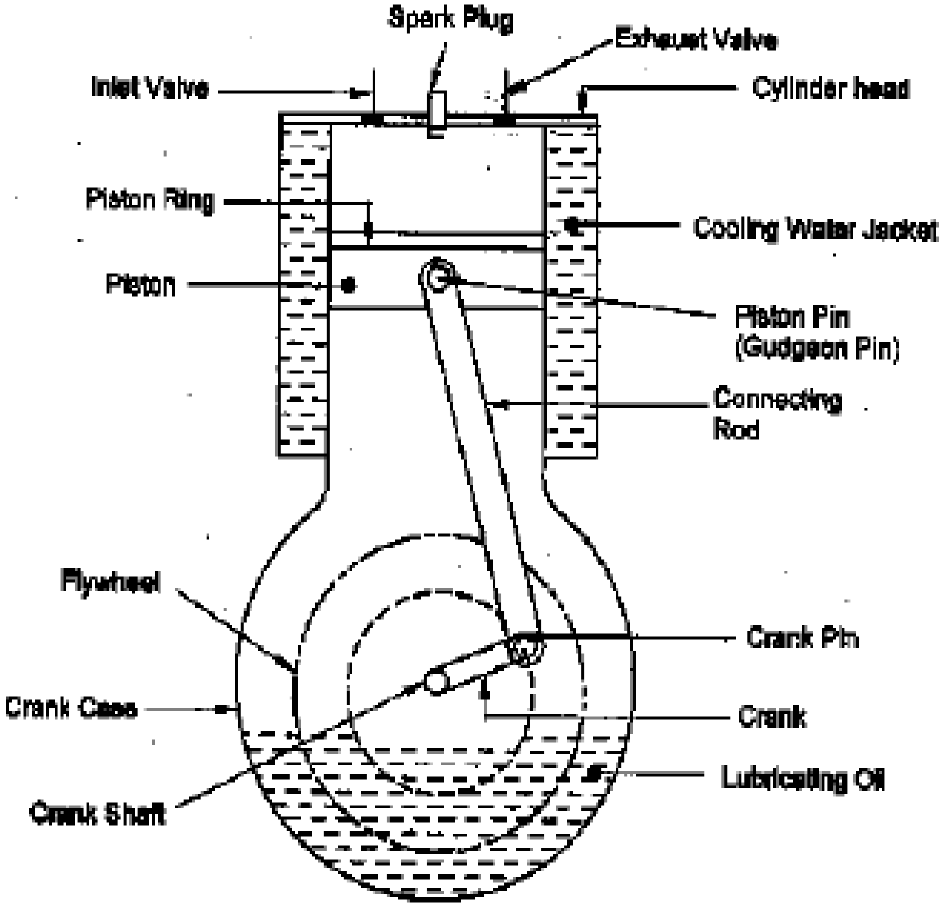
5. According to the number of cylinders.
i) Single cylinder engine ii) Multi cylinder engine

6. According to the arrangement of cylinder:
i) Horizontal engine ii) Vertical engine iii) V-engine
v) In-line engine vi) Radial engine, etc.

7. According to the method of cooling the cylinder:
i) Air cooled engine ii) Water cooled engine

8. According to their applications:
i) Stationary engine ii) Automobile engine iii) Aero engine iv) Locomotive engine v) Marine engine, etc.

Main components of reciprocating IC engines:



Cylinder: It is the main part of the engine inside which piston reciprocates to and fro. It should have high strength to withstand high pressure above 50 bar and temperature above 2000°C. The ordinary engine is made of cast iron and heavy duty engines are made of steel alloys or aluminum alloys. In the multi-cylinder engine, the cylinders are cast in one block known as cylinder block.
Cylinder head: The top end of the cylinder is covered by cylinder head over which inlet and exhaust valve, spark plug or injectors are mounted. A copper or asbestos gasket is provided between the engine cylinder and cylinder head to make an air tight joint.

Piston: Transmit the force exerted by the burning of charge to the connecting rod. Usually made of aluminium alloy which has good heat conducting property and greater strength at higher temperature.

Piston rings: These are housed in the circumferential grooves provided on the outer surface of the piston and made of steel alloys which retain elastic properties even at high temperature. 2 types of rings- compression and oil rings. Compression ring is upper ring of the piston which provides air tight seal to prevent leakage of the burnt gases into the lower portion. Oil ring is lower ring which provides effective seal to prevent leakage of the oil into the engine cylinder.

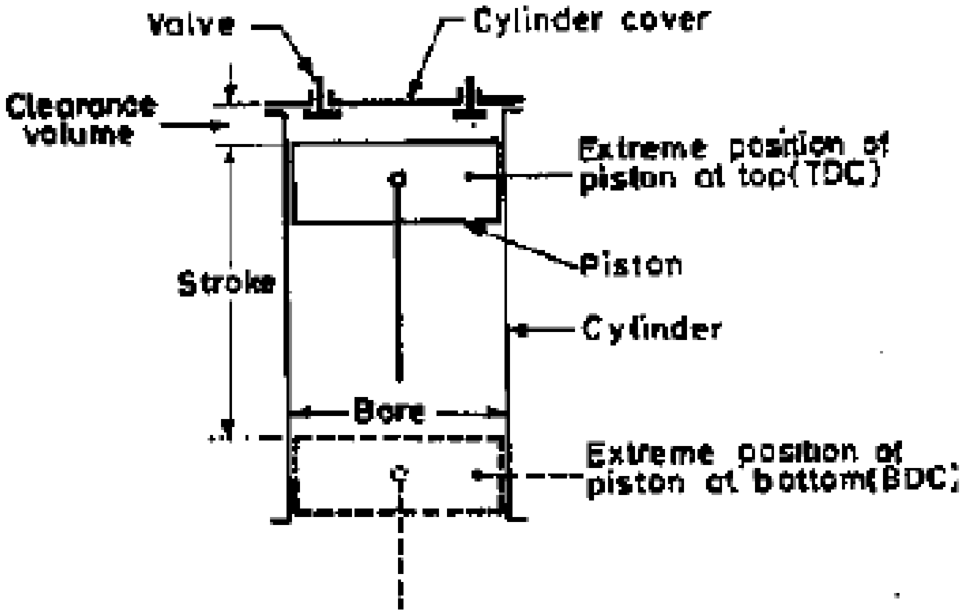
Connecting rod: It converts reciprocating motion of the piston into circular motion of the crank shaft, in the working stroke. The smaller end of the connecting rod is connected with the piston by gudgeon pin and bigger end of the connecting rod is connected with the crank with crank pin. The special steel alloys or aluminium alloys are used for the manufacture of connecting rod.

Crankshaft: It converts the reciprocating motion of the piston into the rotary motion with the help of connecting rod. The special steel alloys are used for the manufacturing of the crankshaft. It consists of eccentric portion called crank.

Crank case: It houses cylinder and crankshaft of the IC engine and also serves as sump for the lubricating oil.

Flywheel: It is big wheel mounted on the crankshaft, whose function is to maintain its speed constant. It is done by storing excess energy during the power stroke, which is returned during other stroke.

Terminology used in IC engine:



1. Cylinder bore (D): The nominal inner diameter of the working cylinder.
2. Piston area (A): The area of circle of diameter equal to the cylinder bore.
3. Stroke (L): The nominal distance through which a working piston moves between two successive reversals of its direction of motion.
4. Dead centre: The position of the working piston and the moving parts which are mechanically connected to it at the moment when the direction of the piston motion is reversed (at either end point of the stroke).
(a) Bottom dead centre (BDC): Dead centre when the piston is nearest to the crankshaft.
(b) Top dead centre (TDC): Dead centre when the position is farthest from the crankshaft.

5. Displacement volume or swept volume (V_S): The nominal volume generated by the working piston when travelling from the one dead centre to next one and given as: $V_S = A \times L$

6. Clearance volume (V_C): the nominal volume of the space on the combustion side of the piston at the top dead centre.
7. Cylinder volume (V): Total volume of the cylinder.

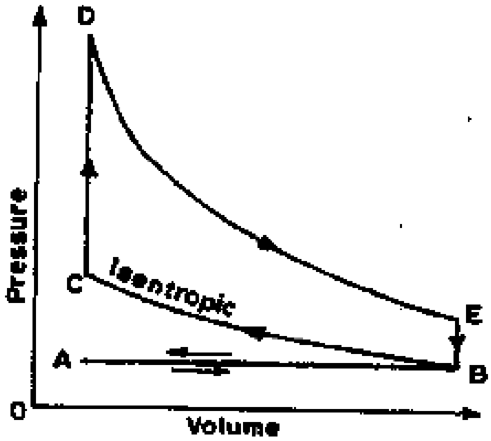
$$V = V_S + V_C$$

8. Compression ratio (r):

$$r = \frac{V_s}{V_c}$$

"Otto" engine:

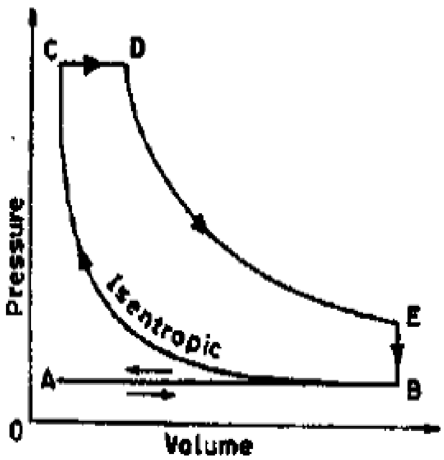
- Fuel and air mixture is produced outside the cylinder and the mixture of fuel and air flow into the cylinder mixture can produced by- carburettor or- injection system (to the inlet pipe) mixture in the cylinder is ignited by a spark-plug.
- That`s why these type of engines called "Spark Ignition" (SI) engines. Fuel can be petrol or gas (or alcohol and petrol mixture). That`s why these types of engines generally called petrol engine. Petrol engine can be two stroke, or four stroke type as well.
- Two stroke type engines generally used at low power rate. Compression ratio (e) can be maximum e=10-11, because at higher compression ratio the fuel air mixture ignited spontaneously, because of the heat produced by compression.



P-V diagram for Otto Cycle

"Diesel" engine:

- The piston in the cylinder is compressing pure air. The fuel is injected at the Top Dead Centre to the compressed air. The fuel-air mixture is produced inside the cylinder.
- The air became hot because of the compression, and has to be hot enough to ignite the fuel. That`s why it is called "Compression Ignition" (CI) engine.
- Fuel can be diesel oil, or fuel oil. Compression ratio (e) is at the range of e=15-30 at the difference type of diesel engines, because high compression ratio need the fuel ignition.
- That`s the main reason which produce higher efficiency of Diesel engines compared with petrol engines. For Diesel engine operation generally are made four stroke operation engines. Rarely, mainly at very large power rate, two stroke operation type engines are built as well.

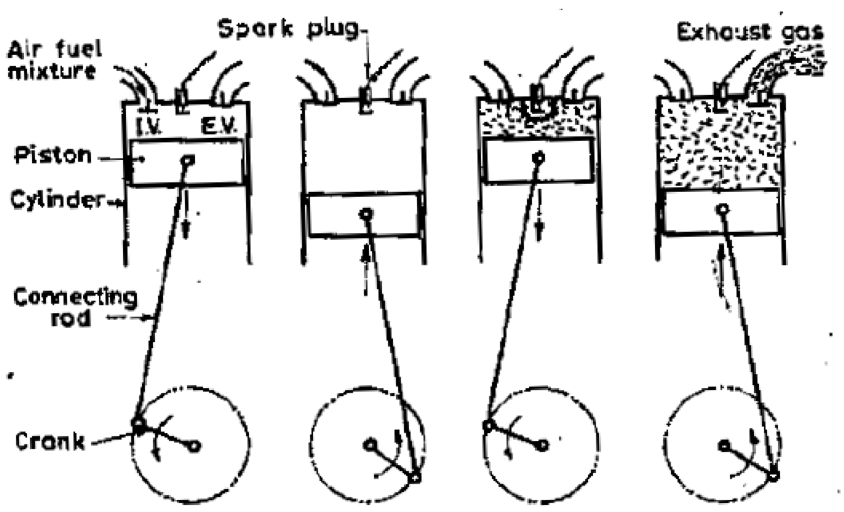


P-V diagram for Diesel Cycle

Four-Stroke Petrol Engine OR Four stroke Spark Ignition Engine (S.I. engine):

The four-stroke cycle petrol engines operate on Otto (constant volume) cycle shown in figure. Since ignition in these engines is due to a spark, they are also called spark ignition engines. The four different strokes are:
i) Suction stroke.
ii) Compression stroke.
iii) Working or power or expansion stroke.
iv) Exhaust stroke.

The construction and working of a four-stroke petrol engine is shown below:



- **Suction Stroke:** During suction stroke, the piston is moved from the top dead centre to the bottom dead centre by the crank shaft. The crank shaft is revolved either by the momentum of the flywheel or by the electric starting motor. The inlet valve remains open and the exhaust valve is closed during this stroke. The proportionate air-petrol mixture is sucked into the cylinder due to the downward movement of the piston. This operation is represented by the line AB on the P-V diagram.
- **Compression Stroke:** During compression stroke, the piston moves from bottom dead centre to the top dead centre, thus compressing air petrol mixture. Due to compression, the pressure and temperature are increased and is shown by the line BC on the P- V diagram. Just before the end of this stroke the spark - plug initiates a spark, which ignites the mixture and combustion takes place at constant volume as shown by the line CD. Both the inlet and exhaust valves remain closed during this stroke.
- **Working Stroke:** The expansion of hot gases exerts a pressure on the piston. Due to this pressure, the piston moves from top dead centre to bottom dead centre and thus the work is obtained in this stroke. Both the inlet and exhaust valves remain closed during this stroke. The expansion of the gas is shown by the curve DE.
- **Exhaust Stroke:** During this stroke, the inlet valve remains closed and the exhaust valve opens. The greater part of the burnt gases escapes because of their own expansion. The drop in pressure at constant volume is represented by the line EB. The piston moves from bottom dead centre to top dead centre and pushes the remaining gases to the atmosphere. When the piston reaches the top dead centre the exhaust valve closes and cycle is completed. This stroke is represented by the line BA on the P- V diagram.

The operations are repeated over and over again in running the engine. Thus a four stroke engine completes one working cycle, during this the crank rotate by two revolutions.

Four Stroke Diesel Engine (Four Stroke Compression Ignition Engine C.I. Engine):

The four stroke cycle diesel engine operates on diesel cycle or constant pressure cycle. Since ignition in these engines is due to the temperature of the compressed air, they are also called compression ignition engines. The construction and working of the four stroke diesel engine is shown in fig. 1, and fig. 2 shows a theoretical diesel cycle. The four strokes are as follows:

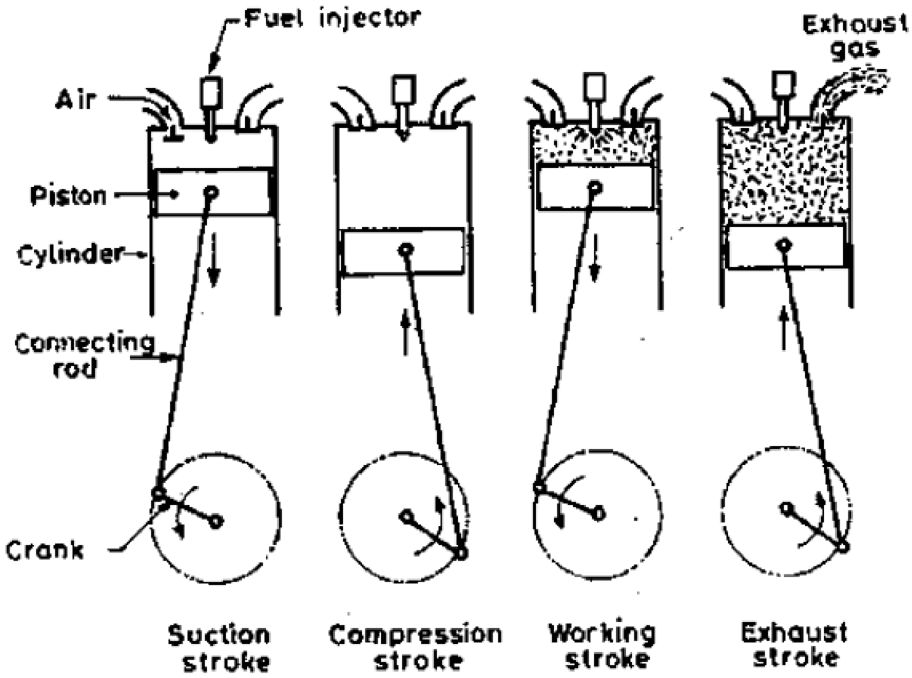


Fig: Construction and Working of the Four Stroke Diesel Engine

- **Suction Stroke:** During suction stroke, the piston is moved from the top dead centre to the bottom dead centre by the crankshaft. The crankshaft is revolved either by the momentum of the flywheel or by the power generated by the electric starting motor. The inlet valve remains open and the exhaust valve is closed during this stroke. The air is sucked into the cylinder due to the downward movement of the piston. The line AB on the P- V diagram represents this operation.
- **Compression Stroke:** The air drawn at the atmospheric pressure during suction stroke is compressed to high pressure and temperature as piston moves from the bottom dead centre to top dead centre. This operation is represented by the curve BC on the P- V diagram. Just before the end of this stroke, a metered quantity of fuel is injected into the hot compressed air in the form of fine sprays by means of fuel injector. The fuel starts burning at constant pressure shown by the line CD. At point D, fuel supply is cut off, both the inlet and exhaust valves remain closed during this stroke.

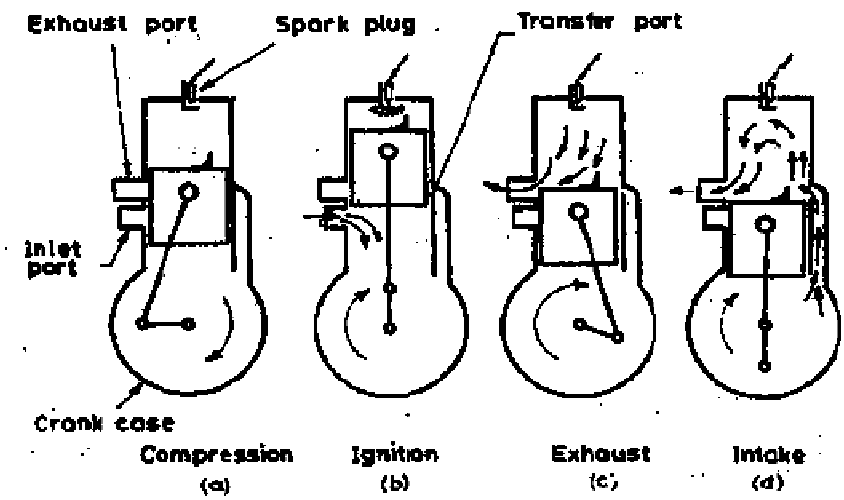
- **Working Stroke:** The expansion of gases due to the heat of combustion exerts a pressure on the piston. Under this impulse, the piston moves from top dead centre to the bottom dead centre and thus work is obtained in this stroke. Both the inlet and exhaust valves remain closed during this stroke. The expansion of the gas is shown by the curve DE.
- **Exhaust Stroke:** During this stroke, the inlet valve remains closed and the exhaust valve opens. The greater part of the burnt gases escapes because of their own expansion. The vertical line EB represents the drop in pressure at constant volume. The piston moves from bottom dead centre to top dead centre and pushes the remaining gases to the atmosphere. When the piston reaches the top dead centre the exhaust valve closes and the cycle is completed. The line BA on the F- V diagram represents this stroke.

Two Stroke Cycle Engine:

- In two stroke cycle engines, the suction and exhaust strokes are eliminated. There are only two remaining strokes i.e., the compression stroke and power stroke and these are usually called upward stroke and downward stroke respectively. Also, instead of valves, there are inlet and exhaust ports in two stroke cycle engines.
- The burnt exhaust gases are forced out through the exhaust port by a fresh charge which enters the cylinder nearly at the end of the working stroke through the inlet port. The process of removing burnt exhaust gases from the engine cylinder is known as scavenging.

Two Stroke Cycle Petrol Engine:

The principle of two-stroke cycle petrol engine is shown in Figure. Its two strokes are described as follows:

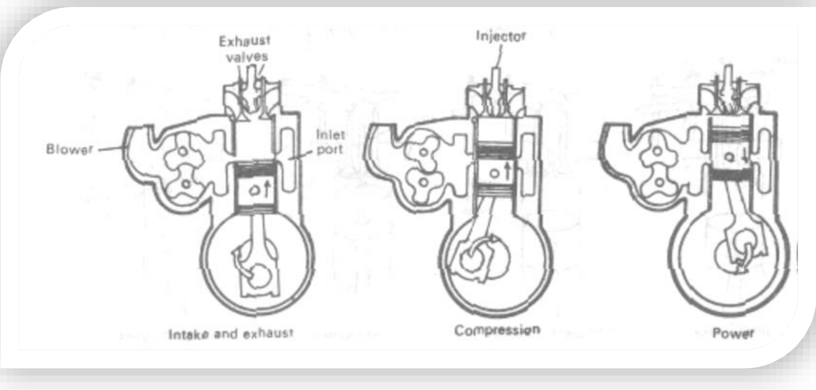


- **Upward Stroke:** During the upward stroke, the piston moves from bottom dead centre to top dead centre, compressing the air-petrol mixture in the cylinder. The cylinder is connected to a closed crank chamber. Due to upward movement of the piston, a partial vacuum is created in the crankcase, and a new charge is drawn into the crank case through the uncovered inlet port. The exhaust port and transfer port are covered when the piston is at the top dead centre position as shown in Figure (b). The compressed charge is ignited in the combustion chamber by a spark provided by the spark plug.

- **Downward Stroke:** As soon as the charge is ignited, the hot gases force the piston to move downwards, rotating the crankshaft, thus doing the useful work. During this stroke the inlet port is covered by the piston and the new charge is compressed in the crank case as shown in the Figure (c) Further downward movement of the piston uncovers first the exhaust port and then the transfer port as shown in Figure (d). The burnt gases escape through the exhaust port. As soon as the transfer port opens, the compressed charge from the crankcase flows into the cylinder. The charge is deflected upwards by the hump provided on the head of the piston and pushes out most of the exhaust gases. It may be noted that the incoming air-petrol mixture helps the removal of burnt gases from the engine cylinder. If in case these exhaust gases do not leave the cylinder, the fresh charge gets diluted and efficiency of the engine will decrease. The cycle of events is then repeated.

Two Stroke Cycle Petrol Engine:

The principle of two-stroke cycle diesel engine is shown in Figure. Its two strokes are described as follows:



- The cycle of the four-stroke of the piston (the suction, compression, power and exhaust strokes) is completed only in two strokes in the case of a two-stroke engine. The air is drawn into the crankcase due to the suction created by the upward stroke of the piston.
- On the down stroke of the piston it is compressed in the crankcase, The compression pressure is usually very low, being just sufficient to enable the air to flow into the cylinder through the transfer port when the piston reaches near the bottom of its down stroke. The air thus flows into the cylinder, where the piston compresses it as it ascends, till the piston is nearly at the top of its stroke.
- The compression pressure is increased sufficiently high to raise the temperature of the air above the self-ignition point of the fuel used. The fuel is injected into the cylinder head just before the completion of the compression stroke and only for a short period.
- The burnt gases expand during the next downward stroke of the piston. These gases escape into the exhaust pipe to the atmosphere through the piston uncovering the exhaust port.

Modern Two-Stroke Cycle Diesel Engine

The crankcase method of air compression is unsatisfactory, as the exhaust gases do not escape the cylinder during port opening. Also there is a loss of air through the exhaust ports during the cylinder charging process. To overcome these disadvantages blowers are used to pre-compress the air. This pre-compressed air enters the cylinder through the port. An exhaust valve is also provided which opens mechanically just before the opening of the inlet ports.

Comparison of Four-stroke and two-stroke engine:

S NO.	FOUR STROKE ENGINE	TWO STROKE ENGINE
1	Four stroke of the piston and two revolution of crankshaft	Two stroke of the piston and one revolution of crankshaft
2	One power stroke in every two revolution of crankshaft	One power stroke in each revolution of crankshaft
3	Heavier flywheel due to non-uniform turning movement	Lighter flywheel due to more uniform turning movement
4	Power produce is less	Theoretically power produce is twice than the four stroke engine for same size
5	Heavy and bulky	Light and compact
6	Lesser cooling and lubrication requirements	Greater cooling and lubrication requirements

7	Lesser rate of wear and tear	Higher rate of wear and tear
8	Contains valve and valve mechanism	Contains ports arrangement
9	Higher initial cost	Cheaper initial cost
10	Volumetric efficiency is more due to greater time of induction	Volumetric efficiency less due to lesser time of induction
11	Thermal efficiency is high and also part load efficiency better	Thermal efficiency is low, part load efficiency lesser
12	It is used where efficiency is important	It is used where low cost, compactness and light weight are important.
13	Ex-cars, buses, trucks, tractors, industrial engines, aero planes, power generation etc.	Ex-lawn mowers, scooters, motor cycles, mopeds, propulsion ship etc.

Comparison of SI and CI engine:

S NO.	SI ENGINE	CI ENGINE
1	Working cycle is Otto cycle.	Working cycle is diesel cycle.
2	Petrol or gasoline or high octane fuel is used.	Diesel or high cetane fuel is used.
3	High self-ignition temperature.	Low self-ignition temperature.
4	Fuel and air introduced as a gaseous mixture in the suction stroke.	Fuel is injected directly into the combustion chamber at high pressure at the end of compression stroke.
5	Carburettor used to provide the mixture. Throttle controls the quantity of mixture introduced.	Injector and high pressure pump used to supply of fuel. Quantity of fuel regulated in pump.
6	Use of spark plug for ignition system	Self-ignition by the compression of air which increased the temperature required for combustion
7	Compression ratio is 6 to 10.5	Compression ratio is 14 to 22

8	Higher maximum RPM due to lower weight	Lower maximum RPM due to higher weight
9	Maximum efficiency lower due to lower compression ratio	Higher maximum efficiency due to higher compression ratio
10	Lighter as compared to CI engine.	Heavier due to higher pressures as compared to SI engine.

Scavenging in 2-S and 4-S engines:

Scavenging is the process used in IC engines in which the burnt gases are forced or pushed to atmosphere from the engine cylinder by using the inlet pressure of fresh air. If the burnt gases inside the engine cylinder are not completely exhausted, then the following incidents will happen:

- Already burnt gases will be compressed again during the compression stroke if they are left inside the cylinder.
- This causes the temperature of air fuel mixture to exceed the maximum temperature as the burnt gases have already some temperature because of burning.
- Because of this maximum temperature, the fuel can burn before the power stroke, so this tends to abnormal combustion.
- We know that, the abnormal combustion causes the knocking phenomenon.
- A basic part of the cycle of an internal combustion engine is the supply of fresh air and removal of exhaust gases. This is the gas exchange process.
- Scavenging is the removal of exhaust gases by blowing in fresh air. Charging is the filling of the engine cylinder with a supply or charge of fresh air ready for compression.
- With supercharging a large mass of air is supplied to the cylinder by blowing it in under pressure. Efficient scavenging is essential to ensure a sufficient supply of fresh air for combustion.
- In the four-stroke cycle engine there is an adequate overlap between the air inlet valve opening and the exhaust valve closing.
- With two-stroke cycle engines this overlap is limited and some slight mixing of exhaust gases and incoming air does occur.
- A number of different scavenging methods are in use in slow-speed two-stroke engines.

- In each the fresh air enters as the inlet port is opened by the downward movement of the piston and continues until the port is closed by the upward moving piston.
- The flow path of the scavenge air is decided by the engine port shape and design and the exhaust arrangements.

Scavenging in 2 stroke engines:

Since one engine cycle in a two-stroke engine is completed in one crankshaft rotation, gas exchange has to occur while the piston is near BDC. There are two important consequences of this:

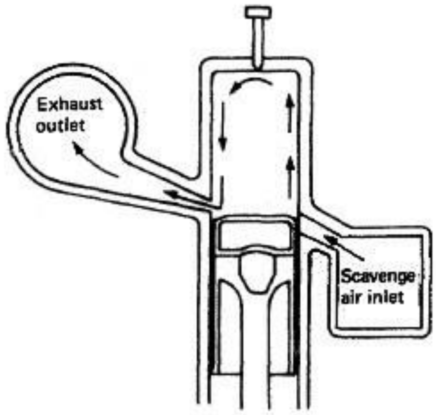
i. Since gas exchange commences before and ends after BDC, a portion of the expansion and compression stroke is unusable.

ii. Piston velocity is low during the entire gas exchange phase and is unable to provide a significant pumping effect on the cylinder charge. Hence, gas exchange can only occur when the intake pressure is sufficiently higher than the exhaust pressure to allow the incoming fresh charge to displace the burned gas in the time available. This process of simultaneously purging exhaust gas from the previous cycle and filling the cylinder with fresh charge for a new cycle is referred to as scavenging. To ensure adequate scavenging, two-stroke engines must be equipped with some form of intake air compression and the intake and exhaust ports and/or valves must be open simultaneously for a sufficient period of time.

iii. Both valves in the cylinder head and ports in the cylinder liner are applied as gas exchange control elements. In the case of ports, the piston also assumes the function of a control slide. For this the piston of 2 stroke engine is equipped with deflector on top to guide the exhaust gases through ports in 2-S engines.

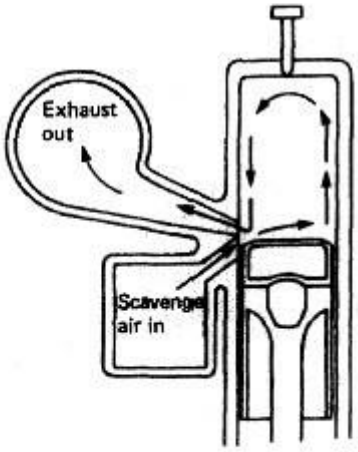
Three basic scavenging systems are: the cross flow, the loop and the uniflow. All modern slow-speed diesel engines now use the uniflow scavenging system with a cylinder-head exhaust valve.

- In cross scavenging the incoming air is directed upwards, pushing the exhaust gases before it. The exhaust gases then travel down and out of the exhaust ports. Figure below illustrates the process.



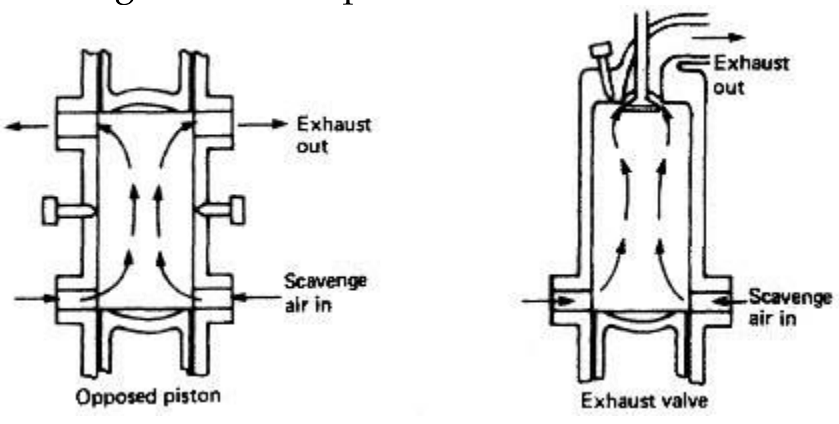
Cross flow scavenging

- In loop scavenging the incoming air passes over the piston crown then rises towards the cylinder head. The exhaust gases are forced before the air passing down and out of exhaust ports located just above the inlet ports. The process is shown in Figure below.



Loop scavenging

- With uniflow scavenging the incoming air enters at the lower end of the cylinder and leaves at the top. The outlet at the top of the cylinder may be ports or a large valve. The process is shown here.



Uni-flow scavenging

Scavenging in 4 stroke engines:

- Scavenging in a 4 stroke engine is achieved by careful header and exhaust design. The key is to keep a low pressure zone behind the escaping exhaust gasses in the header long enough to help remove more exhaust gasses (from the cylinder) to aid the exhaust stroke and to help draw in the next charge on the preceding intake stroke (valve overlap).
- This is achieved by keeping the primary header pipes an equal length. This allows the exhaust pulses to be evenly spaced down the exhaust system and not allowing the pulses to collide with each other avoiding a back pressure situation.
- To keep it simple. The low pressure zone behind the exhaust pulse helps to pull out exhaust gasses from the cylinder, and during valve overlap helps to draw in fresh fuel air mixture.
- The still expanding/mostly burnt fuel air mixture starts to leave the cylinder at very high speed during the power stroke as the exhaust valves open before bottom dead centre during the power stroke.
- As these very hot fast moving gasses travel down the header, this creates a low pressure zone behind it. This helps suck out the exhaust gasses during the exhaust stroke.
- Also as the inlet valves open before top dead centre on the exhaust stroke (valve overlap) the low pressure inside the cylinder helps draw in the next charge for the preceding power stroke.
- The low pressure zone also gives the piston less resistance to push against during the exhaust stroke as there is a partial vacuum in the cylinder making the engine more efficient.
- Whereas if the piston has to work on positive pressure also known as back pressure to push the exhaust gasses out of the cylinder, this saps energy from the engine that could be used to drive the wheels (power loss).

Introduction to Electric Vehicles:

- An electric vehicle, also called an electric drive vehicle, uses one or more electric motors or traction motors for propulsion. An electric vehicle may be powered through a collector system by electricity from off-vehicle sources, or may be self-contained with a battery, solar panels or a generator to convert fuel to electricity.

- EVs include road and rail vehicles, surface and underwater vessels, electric aircraft and electric spacecraft.
- EVs first came into existence in the mid-19th century, when electricity was among the preferred methods for motor vehicle propulsion, providing a level of comfort and ease of operation that could not be achieved by the gasoline cars of the time.
- The internal combustion engine has been the dominant propulsion method for motor vehicles for almost 100 years, but electric power has remained commonplace in other vehicle types, such as trains and smaller vehicles of all types.
- In the 21st century, EVs saw a resurgence due to technological developments and an increased focus on renewable energy.

Propulsion System Design:

Introduction:

- To reduce the severe problem of Air Pollution in this century caused by fuel emission from Automobiles, one answer has been developed called Zero Emission Vehicles (Electric Vehicles) which are powered by on board batteries and does not cause harmful tailpipe emissions. Fuel cell electric Vehicle has long term potential to be the vehicle of future.
- A design methodology is presented based on vehicle dynamics and is aimed at finding the optimal torque speed profile to meet the operational constraints with minimum power requirement. The more the motor can operate in constant power, the less the acceleration power requirement will be. Here, the components are designed in such a way that the motors are imparted maximum torque-speed characteristics. Simulation of electric vehicle propulsion system is done using drive cycle input and the performance is evaluated.

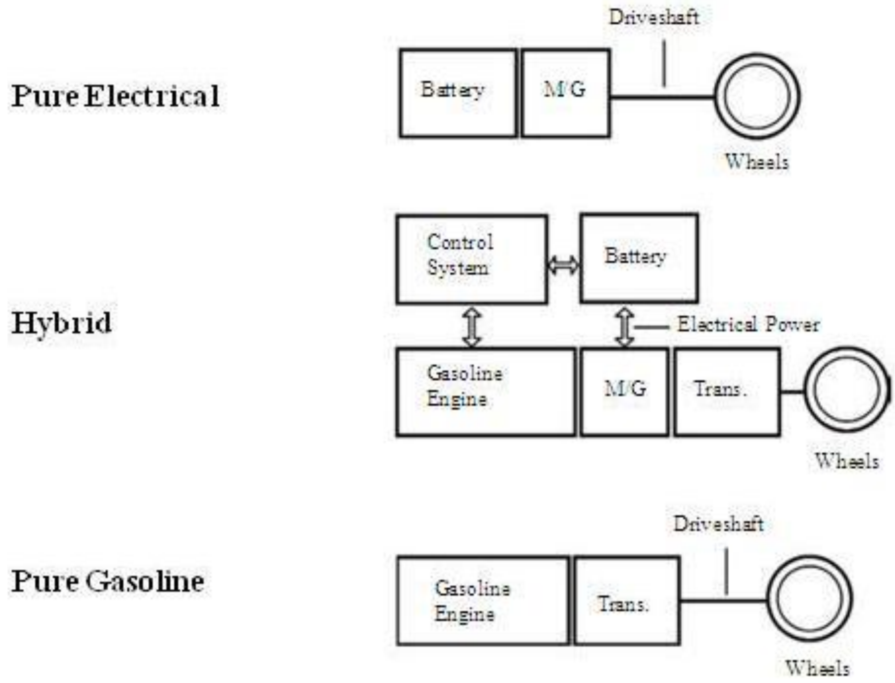
Electric Vehicle Structure:

An Electric Vehicle contains 3 main parts:

(1) Energy Source.
(2) Power Converter.
(3) Traction Motor.

Hybrid electric vehicle (HEV):

The hybrid electric vehicle combines a gasoline engine with an electric motor. An alternate arrangement is a diesel engine and an electric motor as shown in figure below:



Components of a hybrid Vehicle that combines a pure gasoline with a pure EV

- HEV is formed by merging components from a pure electrical vehicle and a pure gasoline vehicle. The Electric Vehicle (EV) has an M/G which allows regenerative braking for an EV; the M/G installed in the HEV enables regenerative braking. For the HEV, the M/G is tucked directly behind the engine. In Honda hybrids, the M/G is connected directly to the engine. The transmission appears next in line. This arrangement has two torque producers; the M/G in motor mode, M-mode, and the gasoline engine. The battery and M/G are connected together.
- HEVs are a combination of electrical and mechanical components. Three main sources of electricity for hybrids are batteries, FCs, and capacitors. Each device has a low cell voltage, and, hence, requires many cells in series to obtain the voltage demanded by an HEV.
- Difference in the source of Energy can be explained as:
    - The FC provides high energy but low power.
    - The battery supplies both modest power and energy.
    - The capacitor supplies very large power but low energy.

Hybrid Electrical Vehicles

Introduction

A hybrid electric vehicle (HEV) has two types of energy storage units, electricity and fuel.
Electricity means that a battery (sometimes assisted by ultracaps) is used to store the energy, and that an electromotor (from now on called *motor*) will be used as traction motor.
Fuel means that a tank is required, and that an Internal Combustion Engine (ICE, from now on called *engine*) is used to generate mechanical power, *or* that a fuel cell will be used to convert fuel to electrical energy. In the latter case, traction will be performed by the electromotor only. In the first case, the vehicle will have both an engine and a motor.

- Depending on the drive train structure (how motor and engine are connected), we can distinguish between parallel, series or combined HEVs. This will be explained in paragraph 1.
- Depending on the share of the electromotor to the traction power, we can distinguish between mild or micro hybrid (start-stop systems), power assist hybrid, full hybrid and plug-in hybrid. This will be explained in paragraph 2.
- Depending on the nature of the non-electric energy source, we can distinguish between combustion (ICE), fuel cell, hydraulic or pneumatic power, and human power. In the first case, the ICE is a spark ignition engines (gasoline) or compression ignition direct injection (diesel) engine. In the first two cases, the energy conversion unit may be powered by gasoline, methanol, compressed natural gas, hydrogen, or other alternative fuels.

Motors are the "work horses" of Hybrid Electric Vehicle drive systems. The electric traction motor drives the wheels of the vehicle. Unlike a traditional vehicle, where the engine must "ramp up" before full torque can be provided, an electric motor provides full torque at low speeds. The motor also has low noise and high efficiency. Other characteristics include excellent "off the line" acceleration, good drive control, good fault tolerance and flexibility in relation to voltage fluctuations.
The front-running motor technologies for HEV applications include PMSM (permanent magnet synchronous motor), BLDC (brushless DC motor), SRM (switched reluctance motor) and AC induction motor.
A main advantage of an electromotor is the possibility to function as generator. In all HEV systems, mechanical braking energy is regenerated.
The max. operational braking torque is less than the maximum traction torque; there is always a mechanical braking system integrated in a car.

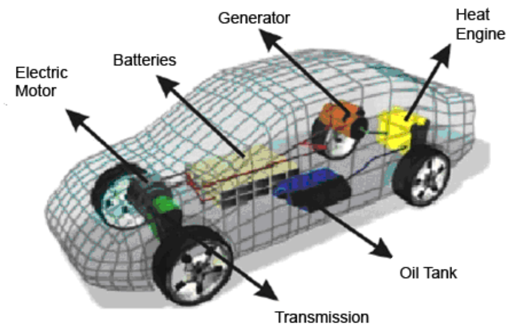
The battery pack in a HEV has a much higher voltage than the SIL automotive 12 Volts battery, in order to reduce the currents and the I^2R losses.

Accessories such as power steering and air conditioning are powered by electric motors instead of being attached to the combustion engine. This allows efficiency gains as the accessories can run at a constant speed or can be switched off, regardless of how fast the combustion engine is running. Especially in long haul trucks, electrical power steering saves a lot of energy.

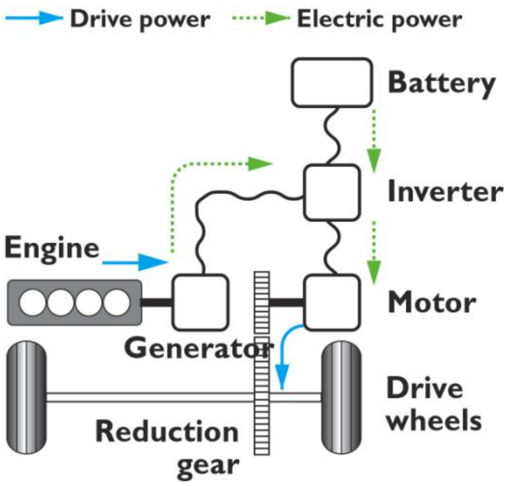
1. Types by drivetrain structure

1.1. Series hybrid

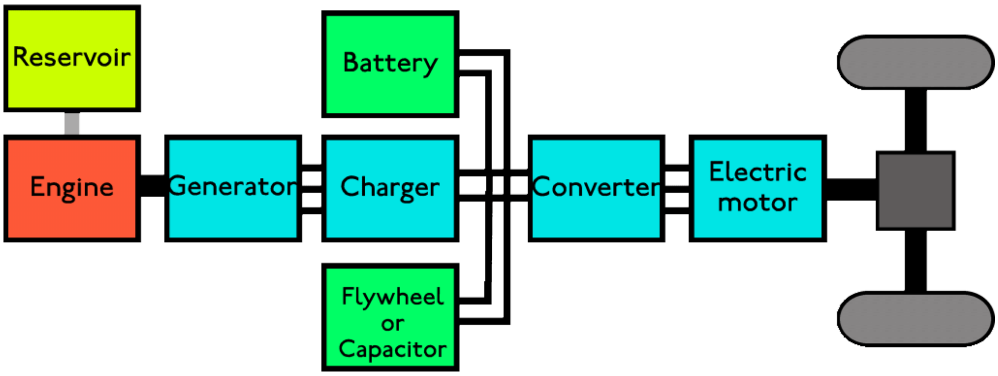
In a series hybrid system, the combustion engine drives an electric generator (usually a three-phase alternator plus rectifier) instead of directly driving the wheels. The electric motor is the only means of providing power to the wheels. The generator both charges a battery and powers an electric motor that moves the vehicle. When large amounts of power are required, the motor draws electricity from both the batteries and the generator.



Series hybrid configurations already exist a long time: diesel-electric locomotives, hydraulic earth moving machines, diesel-electric power groups, loaders.



Structure of a series hybrid vehicle
(below with flywheel or ultracaps as peak power unit)

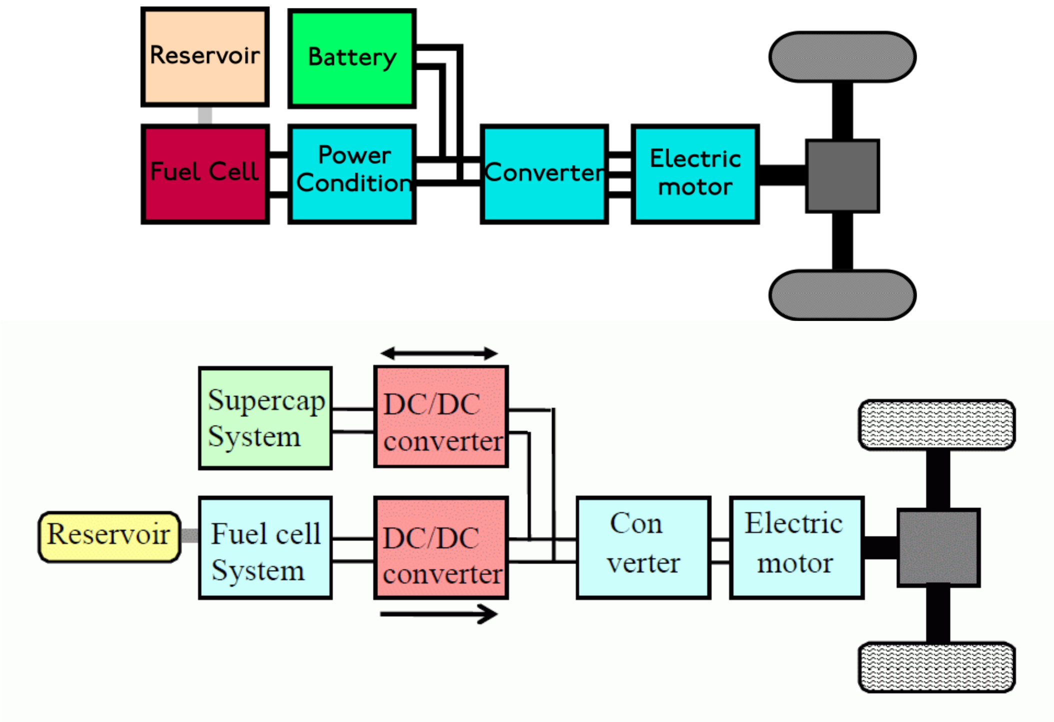


Series hybrids can be assisted by ultracaps (or a flywheel: KERS=Kinetic Energy Recuperation System), which can improve the efficiency by minimizing the losses in the battery. They deliver peak energy during acceleration and take regenerative energy during braking. Therefore, the ulracaps are kept charged at low speed and almost empty at top speed. Deep cycling of the battery is reduced, the stress factor of the battery is lowered.

A complex transmission between motor and wheel is not needed, as electric motors are efficient over a wide speed range. If the motors are attached to the vehicle body, flexible couplings are required.

Some vehicle designs have separate electric motors for each wheel. Motor integration into the wheels has the disadvantage that the unsprung mass increases, decreasing ride performance. Advantages of individual wheel motors include simplified traction control (no conventional mechanical transmission elements such as gearbox, transmission shafts, differential), all wheel drive, and allowing lower floors, which is useful for buses. Some 8x8 all-wheel drive military vehicles use individual wheel motors.

A fuel cell hybrid electric always has a series configuration: the engine-generator combination is replaced by a fuel cell.



Structures of a fuel cell hybrid electric vehicle

Weaknesses of series hybrid vehicles:

- The ICE, the generator and the electric motor are dimensioned to handle the full power of the vehicle. Therefore, the total weight, cost and size of the powertrain can be excessive.
- The power from the combustion engine has to run through both the generator and electric motor. During long-distance highway driving, the total efficiency is inferior to a conventional transmission, due to the several energy conversions.

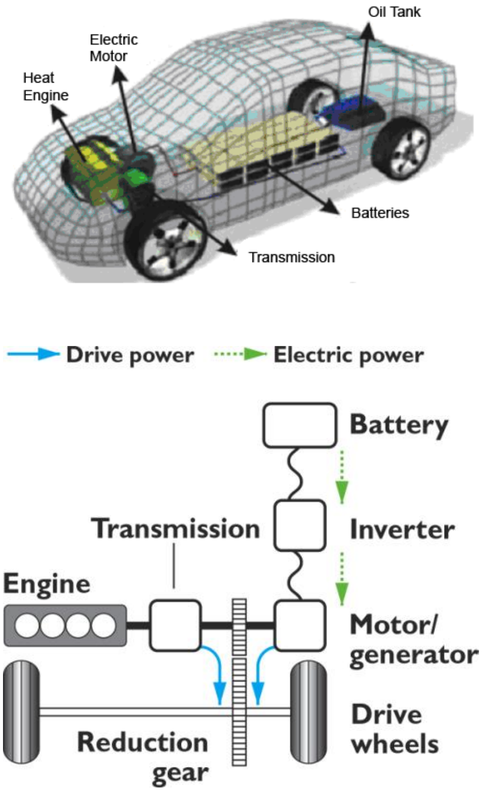
Advantages of series hybrid vehicles:

- There is no mechanical link between the combustion engine and the wheels. The engine-generator group can be located everywhere.
- There are no conventional mechanical transmission elements (gearbox, transmission shafts). Separate electric wheel motors can be implemented easily.
- The combustion engine can operate in a narrow rpm range (its most efficient range), even as the car changes speed.
- Series hybrids are relatively the most efficient during stop-and-go city driving.

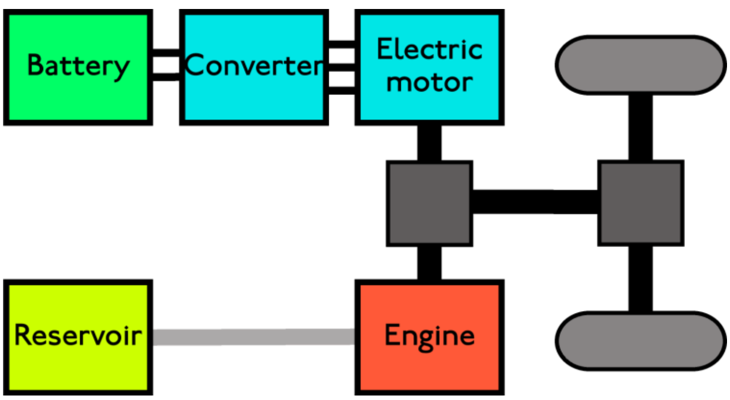
Example of SHEV: Renault Kangoo.

1.2. Parallel hybrid

Parallel hybrid systems have both an internal combustion engine (ICE) and an electric motor in parallel connected to a mechanical transmission.

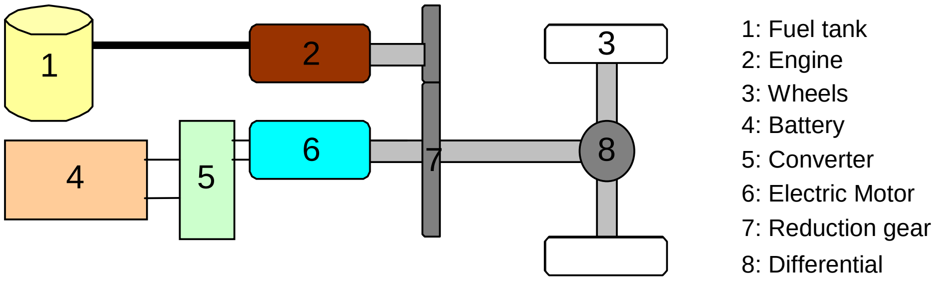


Structure of a parallel hybrid electric vehicle



Most designs combine a large electrical generator and a motor into one unit, often located between the combustion engine and the transmission, replacing both the conventional starter motor and the alternator (see figures above). The battery can be recharged during regenerative breaking, and during cruising (when the ICE power is higher than the required power for propulsion). As there is a fixed mechanical link between the wheels and the motor (no clutch), the battery cannot be charged when the car isn’t moving.

When the vehicle is using electrical traction power only, or during brake while regenerating energy, the ICE is not running (it is disconnected by a clutch) or is not powered (it rotates in an idling manner).

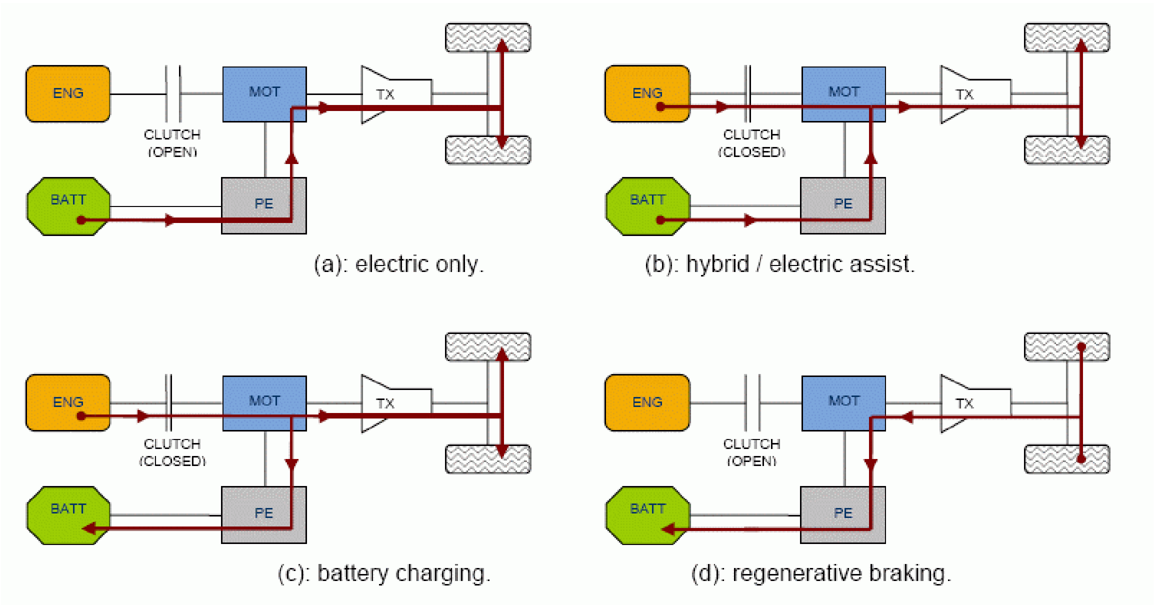


$$\omega_8 = \omega_6 = \omega_2 / x_2$$

$$T_8 = \frac{T_6}{\eta_6} + \frac{x_2 \cdot T_2}{\eta_2}$$

Operation modes:

The parallel configuration supports diverse operating modes:



Some typical modes for a parallel hybrid configuration
PE = Power electronics
TX = Transmission

(a) electric power only: Up to speeds of usually 40 km/h, the electric motor works with only the energy of the batteries, which are not recharged by the ICE. This is the usual way of operating around the city, as well as in reverse gear, since during reverse gear the speed is limited.

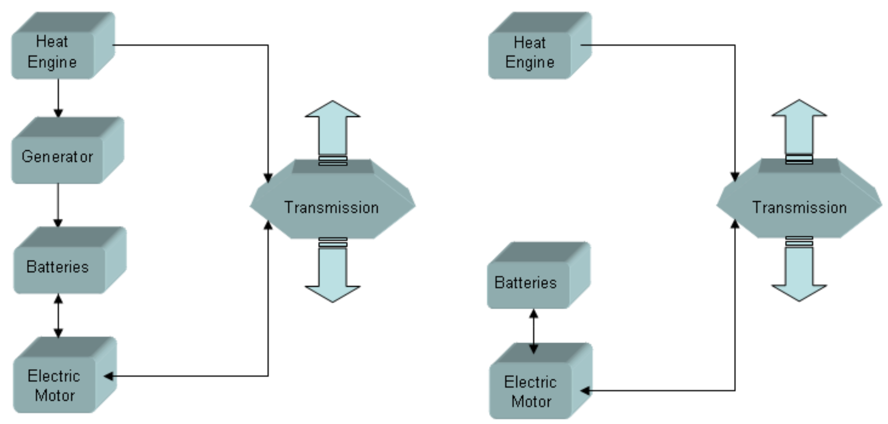
(b) ICE power only: At speeds superior to 40 km/h, only the heat engine operates. This is the normal operating way at the road.

(b) ICE + electric power: if more energy is needed (during acceleration or at high speed), the electric motor starts working in parallel to the heat engine, achieving greater power

(c) ICE + battery charging: if less power is required, excess of energy is used to charge the batteries. Operating the engine at higher torque than necessary, it runs at a higher efficiency.

(d) regenerative breaking: While braking or decelerating, the electric motor takes profit of the kinetic energy of the he moving vehicle to act as a generator.

Sometimes, an extra generator is used: then the batteries can be recharged when the vehicle is not driving, the ICE operates disconnected from the transmission. But this system gives an increased weight and price to the HEV.



A parallel HEV can have an extra generator for the battery (left)
Without generator, the motor will charge the battery (right)

Weaknesses of parallel hybrid vehicles:

- Rather complicated system.
- The ICE doesn't operate in a narrow or constant RPM range, thus efficiency drops at low rotation speed.
- As the ICE is not decoupled from the wheels, the battery cannot be charged at standstill.

Advantages of parallel hybrid vehicles:

- Total efficiency is higher during cruising and long-distance highway driving.
- Large flexibility to switch between electric and ICE power
- Compared to series hybrids, the electromotor can be designed less powerful than the ICE, as it is assisting traction. Only one electrical motor/generator is required.

Example of PHEV:

Honda Civic. Honda's IMA (Integrated Motor Assist) uses a rather traditional ICE with continuously variable transmission, where the flywheel is replaced with an electric motor.

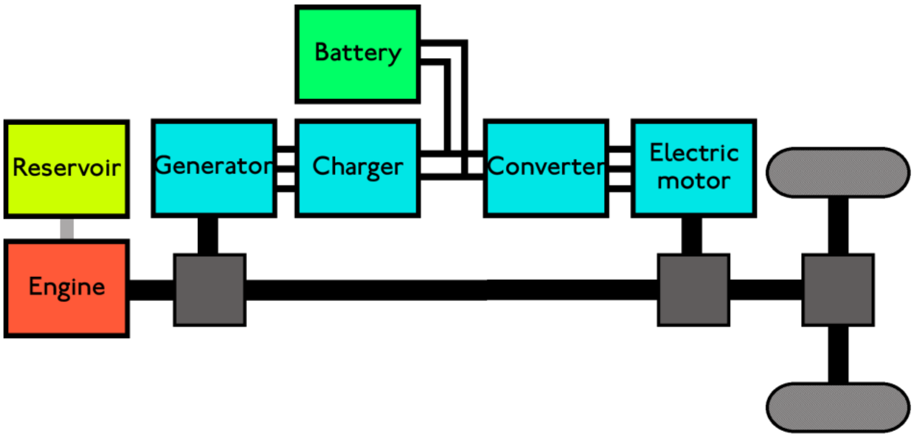
Influence of scale: a Volvo 26 ton truck (12 ton own weight, 14 ton max load) equipped with 200 kg of batteries can drive on pure electric power for 2 minutes only! Because of space constraints, it is not possible to build in more batteries.

BMW 7Series ActiveHybrid.

1.3. Combined hybrid

Combined hybrid systems have features of both series and parallel hybrids. There is a *double connection between the engine and the drive axle: mechanical and electrical*. This split power path allows interconnecting mechanical and electrical power, at some cost in complexity.

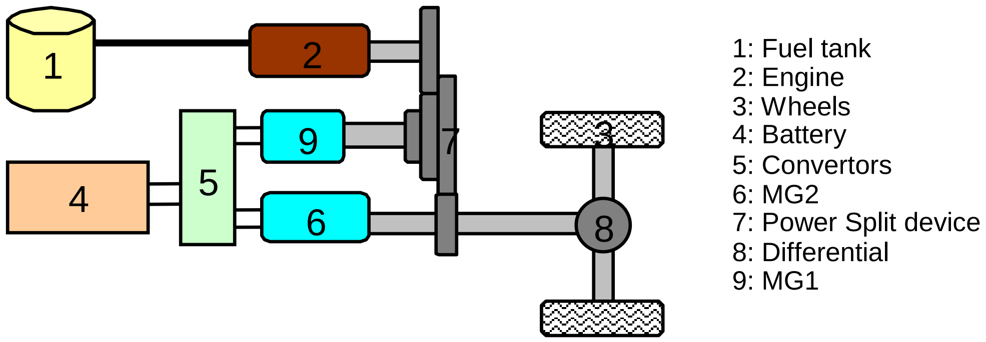
Power-split devices are incorporated in the powertrain. The power to the wheels can be either mechanical or electrical or both. This is also the case in parallel hybrids. But the main principle behind the combined system is the *decoupling of the power supplied by the engine from the power demanded by the driver*.

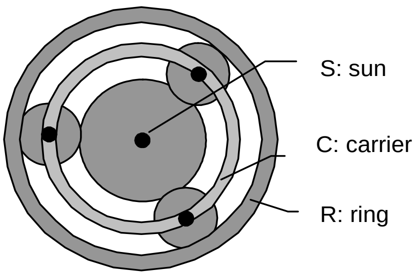


Simplified structure of a combined hybrid electric vehicle

In a conventional vehicle, a larger engine is used to provide acceleration from standstill than one needed for steady speed cruising. This is because a combustion engine's torque is minimal at lower RPMs, as the engine is its own air pump. On the other hand, an electric motor exhibits maximum torque at stall and is well suited to complement the engine's torque deficiency at low RPMs. In a combined hybrid, a smaller, less flexible, and highly efficient engine can be used. It is often a variation of the conventional Otto cycle, such as the Miller or Atkinson cycle. This contributes significantly to the higher overall efficiency of the vehicle, with regenerative braking playing a much smaller role.

At lower speeds, this system operates as a series HEV, while at high speeds, where the series powertrain is less efficient, the engine takes over. This system is more expensive than a pure parallel system as it needs an extra generator, a mechanical split power system and more computing power to control the dual system.

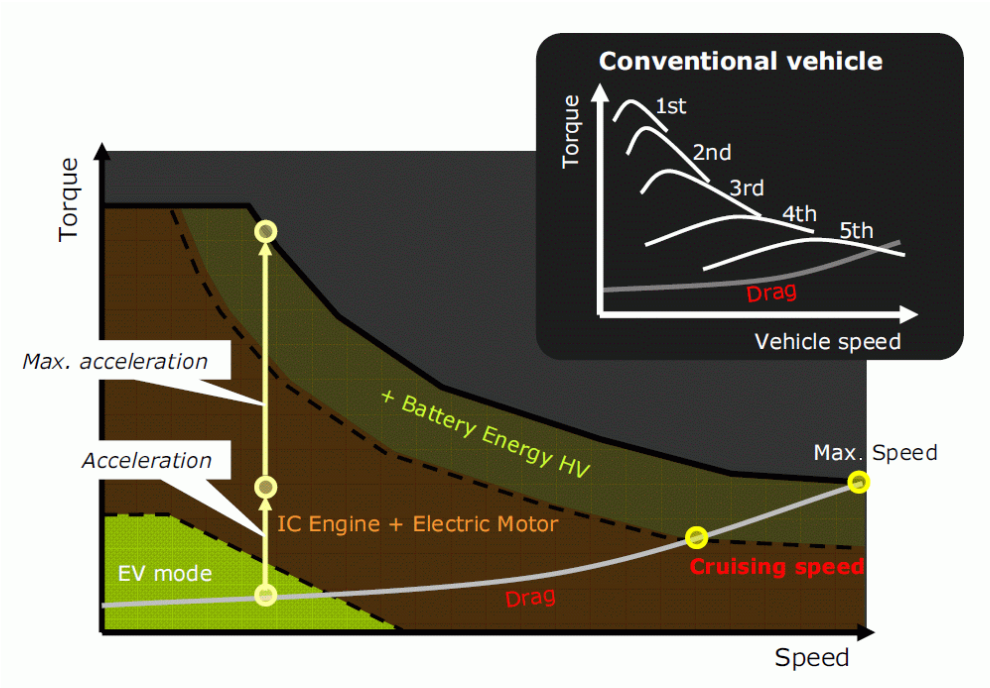




$$(1+\rho)\cdot\omega_C = \omega_S + \rho\cdot\omega_R$$

$$\rho = z_R / z_S$$

Combined HEV with planetary unit as used in the Toyota Prius



Combined hybrid drive modes

Weaknesses of combined hybrid vehicles:

- Very complicated system, more expensive than parallel hybrid.
- The efficiency of the power train transmission is dependent on the amount of power being transmitted over the electrical path, as multiple conversions, each with their own efficiency, lead to a lower efficiency of that path (~70%) compared with the purely mechanical path (98%).

Advantages of combined hybrid vehicles:

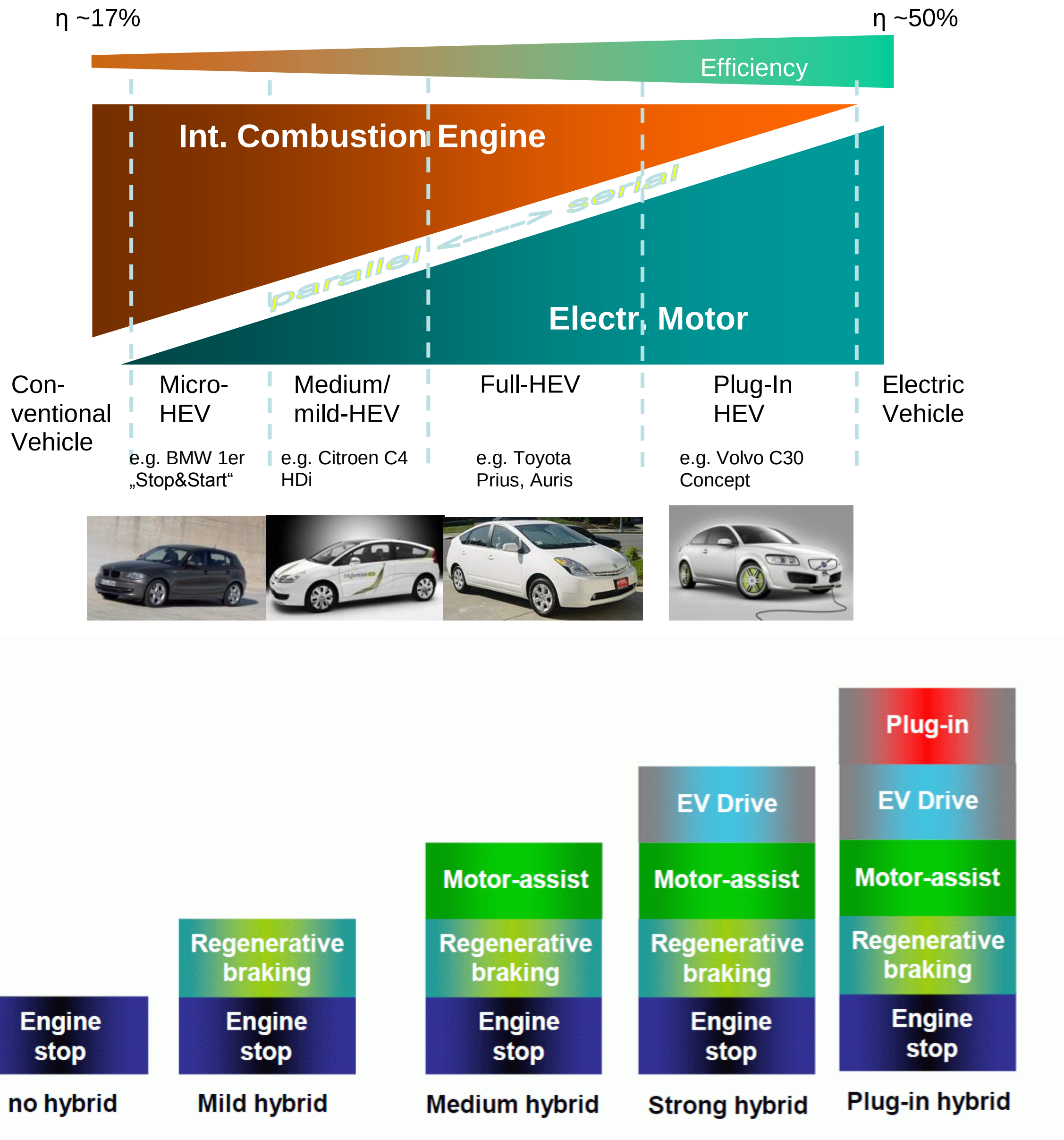
- Maximum flexibility to switch between electric and ICE power

- Decoupling of the power supplied by the engine from the power demanded by the driver allows for a smaller, lighter, and more efficient ICE design.

<u>Example of CHEV:</u> Toyota Prius, Auris, Lexus CT200h, Lexus RX400h.

2. Types by degree of hybridization

Parallel and combined hybrids can be categorized depending upon how balanced the different portions are at providing motive power. In some cases, the combustion engine is the dominant portion; the electric motor turns on only when a boost is needed. Others can run with just the electric system operating.



Overview of Hybrid-powertrain concepts

2.1. Strong hybrid (= full hybrid)

A full hybrid EV can run on just the engine, just the batteries, or a combination of both. A large, high-capacity battery pack is needed for battery-only operation.

Examples:

The Toyota Prius, Auris and Lexus are full hybrids, as these cars can be moved forward on battery power alone. The Toyota brand name for this technology is Hybrid Synergy Drive. A computer oversees operation of the entire system, determining if engine or motor, or both should be running. The ICE will be shut off when the electric motor is sufficient to provide the power.

2.2. Medium hybrid (= motor assist hybrid)

Motor assist hybrids use the engine for primary power, with a torque-boosting electric motor connected in *parallel* to a largely conventional powertrain. EV mode is only possible for a very limited period of time, and this is not a standard mode. Compared to full hybrids, the amount of electrical power needed is smaller, thus the size of the battery system can be reduced. The electric motor, mounted between the engine and transmission, is essentially a very large starter motor, which operates not only when the engine needs to be turned over, but also when the driver "steps on the gas" and requires extra power. The electric motor may also be used to re-start the combustion engine, deriving the same benefits from shutting down the main engine at idle, while the enhanced battery system is used to power accessories. The electric motor is a generator during regenerative breaking.

Examples:

Honda's hybrids including the Civic and the Insight use this design, leveraging their reputation for design of small, efficient gasoline engines; their system is dubbed Integrated Motor Assist (IMA). Starting with the 2006 Civic Hybrid, the IMA system now can propel the vehicle solely on electric power during medium speed cruising.

A variation on this type of hybrid is the Saturn VUE Green Line hybrid system that uses a smaller electric motor (mounted to the side of the engine), and battery pack than the Honda IMA, but functions similarly.

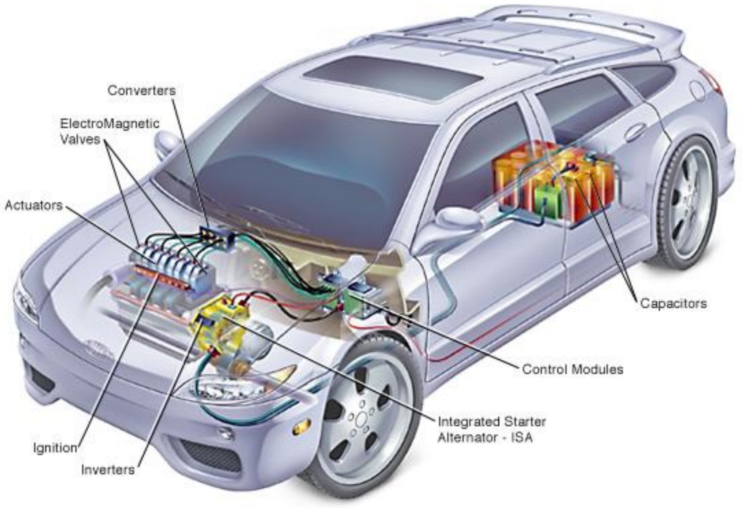
Another variation on this type is Mazda's e-4WD system, offered on the Mazda Demio sold in Japan. This front-wheel drive vehicle has an electric motor which can drive the rear wheels when extra traction is needed. The system is entirely disengaged in all other driving conditions, so it does not enhance performance or economy.

2.3. Mild hybrid / micro hybrid (= start/stop systems with energy recuperation)

Mild hybrids are essentially conventional vehicles with oversized starter motors, allowing the engine to be turned off whenever the car is coasting, braking, or stopped, yet restart quickly and cleanly. During restart, the larger motor is used to spin up the engine to operating rpm speeds before injecting any fuel. That concept is not unique to hybrids; Subaru pioneered this feature in the early 1980s, and the Volkswagen Lupo 3L is one example of a conventional vehicle that shuts off its engine when at a stop.

As in other hybrid designs, the motor is used for regenerative braking to recapture energy. But there is no motor-assist, and no EV mode at all. Therefore, many people do not consider these to be hybrids, since there is no electric motor to drive the vehicle, and these vehicles do not achieve the fuel economy of real hybrid models.

Some provision must be made for accessories such as air conditioning which are normally driven by the engine. Those accessories can continue to run on electrical power while the engine is off. Furthermore, the lubrication systems of internal combustion engines are inherently least effective immediately after the engine starts; since it is upon startup that the majority of engine wear occurs, the frequent starting and stopping of such systems reduce the lifespan of the engine considerably. Also, start and stop cycles may reduce the engine's ability to operate at its optimum temperature, thus reducing the engine's efficiency.



Powertrain of a mild HEV

Examples:

BMW succeeded in combining regenerative braking with the mild hybrid "start-stop" system in their current 1-series model.

Citroën proposes a start-stop system on its C2 and C3 models. The concept-car C5 Airscape has an improved version of that, adding regenerative breaking and traction assistance functionalities, and supercapacitors for energy buffering.

2.4. Plug-in hybrid (= grid connected hybrid = vehicle to grid V2G)

All the previous hybrid architectures could be grouped within a classification of *charge sustaining*: the energy storage system in these vehicles is designed to remain within a fairly confined region of state of charge (SOC). The hybrid propulsion algorithm is designed so that on average, the SOC of energy storage system will more or less return to its initial condition after a drive cycle.

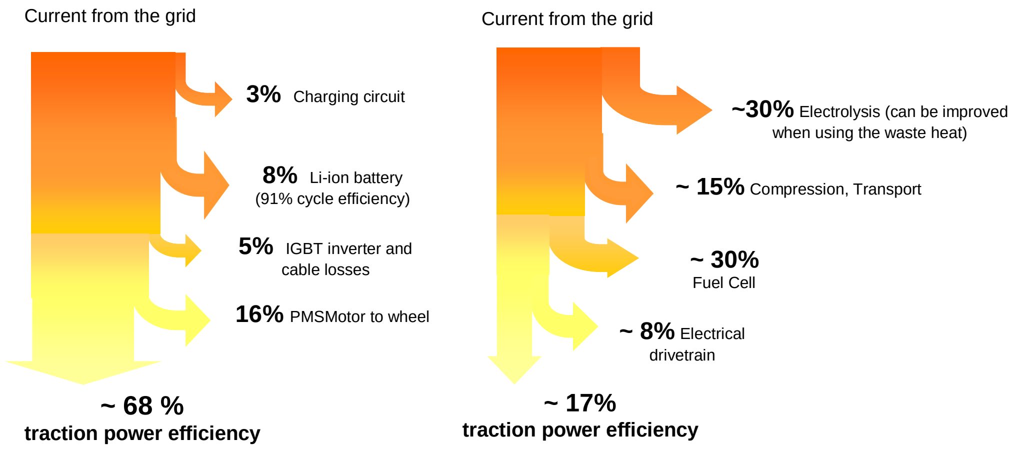
A plug-in hybrid electric vehicle (PHEV) is a *full hybrid*, able to run in electric-only mode, with larger batteries and the ability to recharge from the electric power grid. Their main benefit is that they can be gasoline-independent for daily commuting, but also have the extended range of a hybrid for long trips.

Grid connected hybrids can be designed as *charge depleting*: part of the “fuel” consumed during a drive is delivered by the utility, by preference at night. Fuel efficiency is then calculated based on actual fuel consumed by the ICE and its gasoline equivalent of the kWh of energy delivered by the utility during recharge. The "well-to-wheel" efficiency and emissions of PHEVs compared to gasoline hybrids depends on the energy sources used for the grid utility (coal, oil, natural gas, hydroelectric power, solar power, wind power, nuclear power).

In a serial Plug-In hybrid, the ICE only serves for supplying the electrical power via a coupled generator in case of longer driving distances. Plug in hybrids can be made multi-fuel, with the electric power supplemented by diesel, biodiesel, or hydrogen.

The Electric Power Research Institute's research indicates a lower total cost of ownership for PHEVs due to reduced service costs and gradually improving batteries.

Some scientists believe that PHEVs will soon become standard in the automobile industry. Plug-in vehicles which use batteries to store electric energy *outperform* cars which use hydrogen as carrier for the energy taken from the grid. The following figures indicate the efficiencies of a hydrogen fuel cell HEV and a battery powered EV.



Traction power efficiency of a plugged EV.
Left a battery powered plug in EV (Mitsubishi Lancer Evolution MIEV))
Right a Fuel Cell EV (Mercedes NECAR 3)

For typical driving cycles, the achieved efficiencies are lower. The battery powered EV achieves efficiencies in the range of 50 to 60%. The hydrogen powered EV has a total efficiency of about 13% only at those drive cycles.

<u>Examples:</u>

Mercedes BlueZERO E-CELL PLUS (concept car): series HEV.

Opel Ampera: series HEV.

Plug-in-Hybrid Opel Ampera

The Plug-in-Hybrid Volvo C30 (concept car) is a series HEV. It has a 1,6 liter gasoline/bio-ethanol ICE. A synchronous generator charges the Li-polymer battery (ca. 100 km autonomy) when the battery SoC is lower than 30%. There are four electric wheel-motors.

Plug-in-Hybrid Volvo C30

3. Types by nature of the power source

3.1. Electric-internal combustion engine hybrid

There are many ways to create an electric-internal combustion hybrid. The variety of electric-ICE designs can be differentiated by how the electric and combustion portions of the powertrain connect (series, parallel or combined), at what times each portion is in operation, and what percent of the power is provided by each hybrid component. Many designs shut off the internal combustion engine when it is not needed in order to save energy, see 2.3.

3.2. Fuel cell hybrid

Fuel cell vehicles have a series hybrid configuration. They are often fitted with a battery or supercapacitor to deliver peak acceleration power and to reduce the size and power constraints on the fuel cell (and thus its cost). See 1.1.

3.3. Human power and environmental power hybrids

Many land and water vehicles use human power combined with a further power source. Common are parallel hybrids, e.g. a boat being rowed and also having a sail set, or motorized bicycles. Also some series hybrids exist. Such vehicles can be tribrid vehicles, combining at the same time three power sources e.g. from on-board solar cells, from grid-charged batteries, and from pedals.

The following examples don't use electrical power, but can be considered as hybrids as well:

3.4. Pneumatic hybrid

Compressed air can also power a hybrid car with a gasoline compressor to provide the power. Moteur Developpement International in France produces such air cars. A team led by Tsu-Chin Tsao, a UCLA mechanical and aerospace engineering professor, is collaborating with engineers from Ford to get Pneumatic hybrid technology up and running. The system is similar to that of a hybrid-electric vehicle in that braking energy is harnessed and stored to assist the engine as needed during acceleration.

3.5. Hydraulic hybrid

A hydraulic hybrid vehicle uses hydraulic and mechanical components instead of electrical ones. A variable displacement pump replaces the motor/generator, and a hydraulic accumulator (which stores energy as highly compressed nitrogen gas) replaces the batteries. The hydraulic accumulator, which is essentially a pressure tank, is potentially cheaper and more durable than batteries. Hydraulic hybrid technology was originally developed by Volvo Flygmotor and was used experimentally in buses from the early 1980s and is still an active area.

Initial concept involved a giant flywheel (see Gyrobus) for storage connected to a hydrostatic transmission, but it was later changed to a simpler system using a hydraulic accumulator connected to a hydraulic pump/motor. It is also being actively developed by Eaton and several other companies, primarily in heavy vehicles like buses, trucks and military vehicles. An example is the Ford F-350 Mighty Tonka concept truck shown in 2002. It features an Eaton system that can accelerate the truck up to highway speeds.

Contents of UNIT 2

IC Engine: Basic Components, Construction and Working of Two stroke and four stroke SI & CI engine, merits and demerits, scavenging process; Introduction to electric, and hybrid electric vehicles.
Refrigeration: Its meaning and application, unit of refrigeration; Coefficient of performance, methods of refrigeration, construction and working of domestic refrigerator, concept of heat pump. Formula based numerical problems on cooling load.
Air-Conditioning: Its meaning and application, humidity, dry bulb, wet bulb, and dew point temperatures, comfort conditions, construction and working of window air conditioner.

RAC

Refrigeration

What is Refrigeration?

- **Refrigeration** is defined as the science of maintaining the temperature of a particular space lower than the surrounding space. Thermodynamically, when the body at certain temperature is kept in the atmosphere it tends to attain the temperature of the atmosphere. But with the process of refrigeration it can be kept at temperature much lower than the atmospheric temperature.
- In **refrigeration**, heat is pumped out from a lower temperature space to a higher temperature environment.
- A **refrigeration system** is a combination of components and equipment connected in a sequential order to produce the refrigeration effect. Refrigeration may also be defined as the process of achieving and maintaining a temperature below that of the surroundings, the aim being to cool some product or space to the required temperature.

Applications of refrigeration:

- Refrigeration has number of applications, one of the most common applications is household refrigerator and air conditioner. Other applications of refrigeration include making ice, ice cream, chilled water, frozen food etc.

- Some important applications are:

1. Ice making.
2. Transportation of foods above and below freezing.
3. Industrial air-conditioning.
4. Comfort air-conditioning.
5. Chemical and related industries.
6. Medical and surgical aids.
7. Processing food products and beverages.
8. Oil refining and synthetic rubber manufacturing.
9. Manufacturing and treatment of metals.
10. Freezing food products.
11. Industrial applications:
    - Laboratories
    - Printing
    - Manufacture of Precision Parts
    - Textile Industry
    - Pharmaceutical Industries
    - Photographic Material
    - Farm Animals
    - Vehicular Air-conditioning

Unit of refrigeration and COP :

- The standard unit of refrigeration is ton of refrigeration or simply ton denoted by TR.
- It is defined as the amount of refrigeration effect produced by the uniform melting of one tonne (1000 kg) of ice from and at 0ºC in 24 hours.
- Since latent heat of ice is 335kJ/kg, therefore one tone of refrigeration,

1 TR= 1000*335 kJ in 24 hours.

$$= \frac{1000 \times 335}{24 \times 60} = 232.6 kJ/min$$

- In actual practice one tone of refrigeration is taken as equivalent to 210 kJ/min or 3.5kW (i.e. 3.5 kJ/s).
- **Refrigeration effect** is an important term in **refrigeration** that defines the amount of cooling produced by a system. This cooling is obtained at the expense of some form of energy.
- It is defined as a term called **coefficient of performance (COP)** which is expressed as a ratio of the refrigeration effect to energy input.

- In other words we can say, **co- efficient of performance for refrigeration $(COP)_R$** can be defined as the ratio of heat absorbed by the refrigerant while passing through the evaporator to the work input required to compress the refrigerant in the compressor. In short it is the ratio between heat extracted and work done.
- While calculating $(COP)_R$, both refrigeration effect and energy input should be in the same unit.

$$\boxed{COP_R = \frac{\text{desired output}}{\text{required input}}}$$

Or

$$\boxed{COP = \frac{\text{Refrigeration effect}}{\text{Energy input}}}$$

Then, $\text{C.O.P.} = \dfrac{R_n}{W}$

and Relative $\text{C.O.P.} = \dfrac{\text{Actual C.O.P.}}{\text{Theoretical C.O.P.}}$

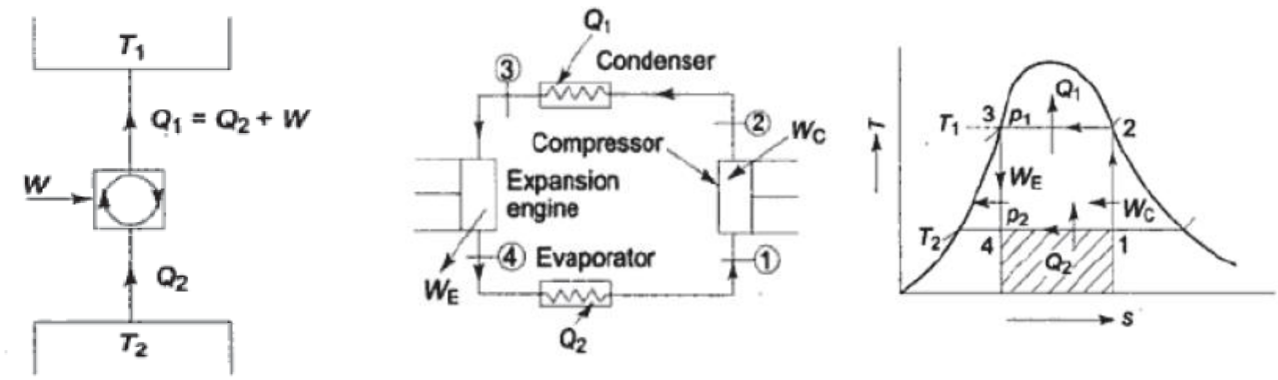
where, Actual C.O.P. = Ratio of R_n and W *actually measured during a test*

and, Theoretical C.O.P. = Ratio of *theoretical values of* R_n and W *obtained by applying laws of thermodynamics to the refrigeration cycle.*

- The performance of refrigerators and heat pumps are expressed in terms of **coefficient of performance(COP)**, as follows:

$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{net,in}}$$

$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{net,in}}$$



Refrigeration Cycle

- Most of the commercial refrigeration is produced by the evaporation of a liquid called **refrigerant**. Mechanical refrigeration depends upon the **evaporation of liquid refrigerant** and its circuit And its circuits includes the equipment naming **evaporator, compressor, condenser and expansion valve.**
- According to above figure, COP for heat pump and refrigerator can be expressed according to heat supplied and rejected (Q) and temperature (T)
- As an expression for heat rejected Q_1 and heat addition Q_2 $(COP)_R$ and $(COP)_{H.P.}$ can be expressed as:

$$\boxed{(COP)_{H.P.} = \frac{Q_1}{W} = \frac{Q_1}{Q_1 - Q_2}} \qquad \boxed{(COP)_{ref} = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2}}$$

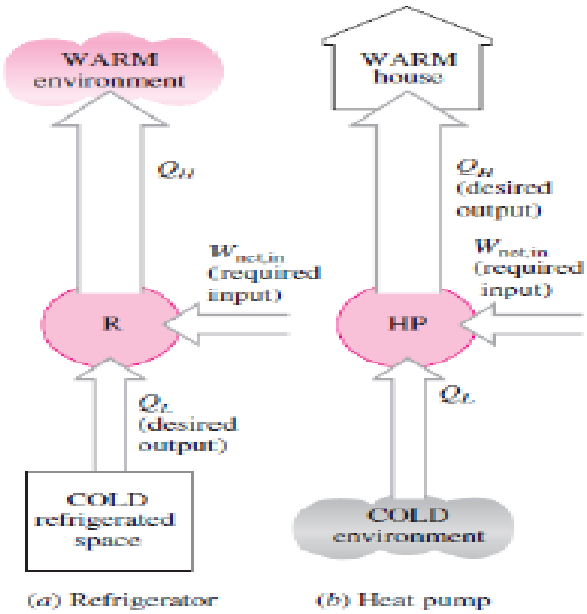
- As an expression for temperature of heat rejection T_1 and temperature of heat absorption T_2 $(COP)_R$ and $(COP)_{H.P.}$ can be expressed as:

$$\boxed{(COP_{H.P.})_{rev} = \frac{Q_1}{W_{net}} = \frac{T_1}{T_1 - T_2}} \qquad \boxed{(COP_{ref})_{rev} = \frac{Q_2}{W_{net}} = \frac{T_2}{T_1 - T_2}}$$

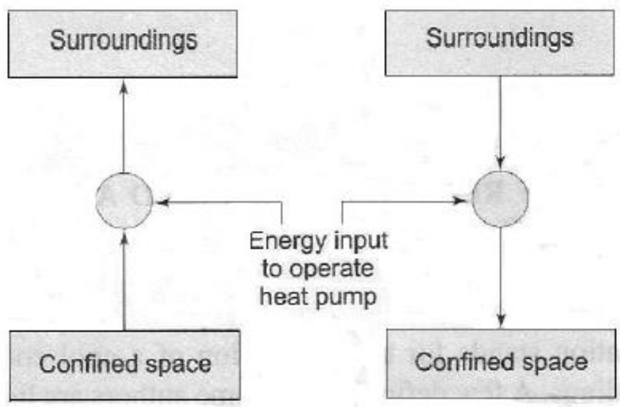
- For a vapour compression system, COPR is of the order of 3 for water-cooled and 2 for air-cooled air-conditioning applications and 1 for domestic refrigerators.

Refrigeration and Heat Pump:

- Generally heat flows in the direction of decreasing temperature i.e. from higher temperature regions to low temperature ones.
- This heat transfer process occurs in nature without requiring any devices.
- The reverse process, however, cannot occur by itself.
- The transfer of heat from a low temperature region to a high temperature one requires special devices called **Refrigerators/Heat pumps**.



Difference between Refrigeration and Heat Pump:



(a) (b)

(a) **Refrigeration** - pumping of heat out of the systems and production of cool confinement with respect to surroundings.

(b) **Heat Pump** – pumping of heat from the surroundings into the systems and does heating.

- **A refrigeration system can also be used as a heat pump, in which the useful output is the high temperature heat rejected at the condenser. Alternatively, a refrigeration system can be used for providing cooling in summer and heating in winter. Such systems have been built and are available now.**

❖ **For heating, which option is better: a heat pump or an electric heater?**

- If W is the energy consumed by an electric resistance heater, the heat released to the space will be at most equal to W only. But, if this energy is utilised in a heat pump, the heat pumped to the space will be

$$Q_H = COP_{HP} \cdot W = (1 + COP_{HP}) \cdot W$$

- Therefore, Q_H will always be greater than or equal to W. This means that it is better to use heat pump than an electric heater for heating.

Methods of Refrigeration:

- There are number of methods by which the refrigeration can be achieved. They are broadly classified into two categories: **Non-Cyclic and Cyclic methods of Refrigeration**. Firstly, let us see **non-cyclic methods.**
- The **non-cyclic methods of refrigeration** can be used only in places where small amount of refrigeration is required in places like laboratories, workshops, water coolers, small old drink shops, small hotels etc. In fact the ordinary ice and dry ice used for the refrigeration purposed have to be manufactured by the cyclic methods of refrigeration which we shall see in the next article. However, in the earlier days the ice used for the cooling purposes was usually harvested during the winter seasons from the ponds and lakes and stored in large insulated ice houses for the use throughout the year.
- In the **non-cyclic method of refrigeration** there is no thermodynamic cycle followed for creating the cooling effect. There are two methods of non-cyclic refrigeration process as described below:

1) Ice Refrigeration: In this method the ordinary ice is used for keeping the space at temperature below the surrounding temperature. The temperature of ice is considered to be 0 degree Celsius hence it can be used to maintain the temperatures of about 5 to 10 degree Celsius. To use the ice for refrigerating effect a closed and insulated chamber is required. On one side of the chamber ice is kept while on the other side there is a space which is to be cooled where some material to be cooled can be placed. If the temperature below 0 degree Celsius is required, then the mixture of ice and salt is used. This method of cooling is still being used for cooling the cold drinks, keeping the water chilled in thermos, etc.

2) **Dry ice refrigeration**: Dry ice is the solid carbon dioxide having the temperature of -78 degree Celsius. Dry ice converts directly from solid state to gaseous; this process is called as sublimation. Dry ice can be pressed into various sizes and shapes as blocks or slabs. Dry ice is usually packed in the frozen food cartons along with the food that has to be kept frozen for long intervals of time. When the dry ice gets converted into vapour state it keeps the food frozen. The process of dry ice refrigeration is now-a-days being used for freezing the food in aircraft transportation.

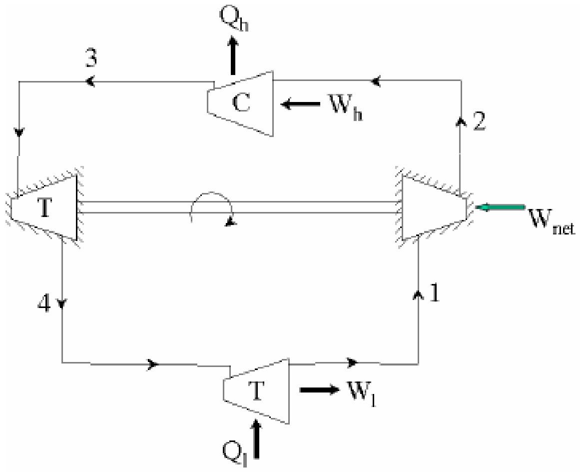
Cyclic Process of Refrigeration:

- In the **cyclic process of refrigeration** the heat is removed from the low temperature reservoir and is thrown to high temperature reservoir. As per the **second law of thermodynamics** the natural flow of heat is from the high temperature reservoir to low temperature reservoir. In the cyclic refrigeration process since the flow of heat is reversed, the external work has to be done on the system. The cyclic process of refrigeration is also **reverse of the thermodynamic power cycle or Carnot cycle** in which the heat flows from high temperature reservoir to low temperature reservoir; hence the cycle of refrigeration is also called as Reverse Carnot Cycle.
- There are two types of cyclic process of refrigeration: **vapour cycle and gas cycle**. The **vapour cycle is classified into vapour compression cycle and vapour absorption cycle**. Let us see all these processes one-by-one.

Reversed Carnot cycle employing a gas:

- Reversed Carnot cycle is an ideal refrigeration cycle for constant temperature external heat source and heat sinks. Figure 9.1(a) shows the schematic of a reversed Carnot refrigeration system using a gas as the working fluid along with the cycle diagram on T-s and P-v coordinates. As shown, the cycle consists of the following four processes:

Process 1-2: Reversible, adiabatic compression in a compressor
Process 2-3: Reversible, isothermal heat rejection in a compressor
Process 3-4: Reversible adiabatic expansion in a turbine
Process 4-1: Reversible, isothermal heat absorption in a turbine



Temperature Limitations of Carnot cycle:

- Carnot cycle is an idealization and it suffers from several practical limitations. One of the main difficulties with Carnot cycle employing a gas is the difficulty of achieving isothermal heat transfer during processes 2-3 and 4-1. For a gas to have heat transfer isothermally, it is essential to carry out work transfer from or to the system when heat is transferred to the system (process 4-1) or from the system (process 2-3). This is difficult to achieve in practice. In addition, the volumetric refrigeration capacity of the Carnot system is very small leading to large compressor displacement, which gives rise to large frictional effects. All actual processes are irreversible, hence completely reversible cycles are idealizations only.

Vapour Compression Cycle:

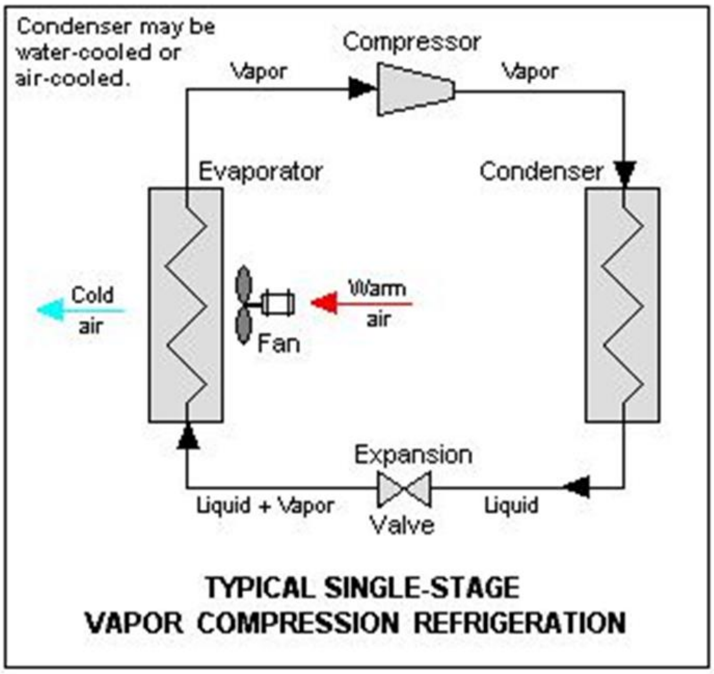
- The vapour compression cycle is the mostly widely used method of refrigeration in the modern applications. Your household refrigerator, water cooler, deep freezer, air-conditioner etc., all run on vapour compression cycle.

- The cycle is called as **vapour compression cycle**, because the vapour of refrigerant are compressed in the compressor of the refrigerator system to develop the cooling effect.
- A vapour compression refrigeration system is an improved type of air refrigeration system in which a suitable working substance, termed as refrigerant, is used. It condenses and evaporates at temperatures and pressures close to the atmospheric conditions.
- In evaporating, the refrigerant absorbs its latent heat from the brine (salt water) which is used for circulating it around the cold chamber. While condensing, it gives out its latent heat to the circulating water of the cooler. The vapour compression refrigeration system is, therefore a latent heat pump, as it pumps its latent heat from the brine and delivers it to the cooler.
- **The refrigerants, usually, used for this purpose are ammonia (NH_3), carbon dioxide (CO_2) and sulphur dioxide (SO_2).** The refrigerant used, does not leave the system, but is circulated throughout the system alternately condensing and evaporating.

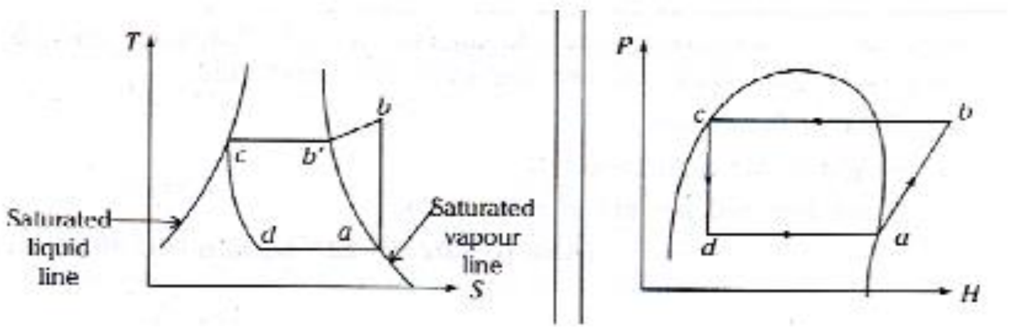
Here are the various processes of vapour compression cycle (refer the figure give below):

1) **Compression:** The vapour of refrigerant enter the compressor and get compressed to high pressure and high temperature. During this process the entropy of the refrigerant ideally remains constant and it leaves in superheated state.
2) **Condensation:** The superheated refrigerant then enters the condenser where it is cooled either by air or water due to which its temperature reduces, but pressure remains constant and it gets converted into liquid state.
3) **Expansion:** The liquid refrigerant then enters the expansion valve or throttling valve where sudden expansion of the refrigerant occurs, due to which its temperature and pressure falls down. The refrigerant leaves expansion valve in partially liquid state and partially in gaseous state.
4) **Evaporation or cooling:** The partially liquid and partially gaseous refrigerant at very low temperature enters the evaporator where the substance to be cooled is kept. It is here where the refrigeration effect is produced. The refrigerant absorbs the heat from the substance to be cooled and gets converted into vapour state. This low pressure refrigerant is then absorbed by the compressor where it is compressed again and the whole cycle of refrigeration repeats again. The vapour

compression cyclic process is used for refrigeration in domestic as well as commercial applications.



Compression Refrigeration System



Process diagrams for vapour compression refrigeration system

The various processes are:

- **Process ab:** The vapour refrigerant entering the compressor is compressed to high pressure and temperature in a isentropic manner.
- **Process bc:** This high pressure and high temperature vapour then enters a condenser where the temperature of the vapour first drops to saturation temperature and subsequently the vapour refrigerants condenses to liquid state.
- **Process cd:** This liquid refrigerant is collected in the liquid storage tank and later on it is expanded to low pressure and temperature by passing

it through the throttle valve. At point d we have low temperature liquid refrigerant with in small amount of vapour.

- **Process da:** This low temperature liquid then enters the evaporator where it absorbs heat from the space to be cooled namely the refrigerator and become vapour.

Components of A Vapour Refrigeration System

Compressors:

- The compressors are one of the most important parts of the refrigeration cycle. The compressor compresses the refrigerant, which flows to the condenser, where it gets cooled. It then moves to the expansion valve, and the evaporator and it is finally sucked by the compressor again. For the proper functioning of the refrigeration cycle, the refrigerant must be compressed to the pressure corresponding to the saturation temperature higher than the temperature of the naturally available air or water. It is the crucial function that is performed by the compressor. Compression of the refrigerant to the suitable pressure ensures its proper condensation and circulation throughout the cycle. The capacity of the refrigeration or air conditioning depends entirely on the capacity of the compressor.
- Types of compressors used are:
    - Reciprocating Compressors
    - Screw Compressors
    - Rotary Compressors
    - Centrifugal Compressor
    - Scroll Compressors

Evaporators:

- Different types of evaporators are used in different types of refrigeration applications and accordingly they have different designs. The evaporators can be classified in various ways depending on the construction of the evaporator, the method of feeding the refrigerant, the direction of circulation of the air around the evaporator, etc.
- Here we have classified the evaporators :

❖ According to their construction.

- Bare Tube Evaporators

- Plate Type of Evaporators
- Plate Type of Evaporators
- Finned Evaporators
- Shell and Tube types of Evaporators

❖ According to the manner in which liquid refrigerant is fed
- A flooded evaporator
- Dry expansion evaporator

❖ According to the mode of heat transfer
- Natural convection evaporator
- Forced convection evaporator

❖ According to operating conditions
- Frosting evaporator
- Non Frosting evaporator
- Defrosting evaporator

Expansion Devices:

- The basic functions of an expansion device are:

- Reduce pressure from condenser pressure to evaporator pressure,
- Regulate the refrigerant flow from the high-pressure liquid line into the evaporator at a rate equal to the evaporation rate in the evaporator.

- Types of Expansion Devices:
  - Capillary tube
  - Hand Operated Expansion Valve
  - Automatic or Constant Pressure Expansion Valve
  - Thermostatic Expansion valve
  - Low side float Valve
  - High side float valve

Condensers:

- The condenser is a heat exchanger that usually rejects all the heat from the system. The condenser accept all the hot, high-pressure refrigerant usually a super-heated gas, from the compressor. The condenser is usually air cooled by natural or forced convection to increase the cooling effect of the condenser. The function of condenser in the refrigeration system is to remove heat from the refrigerant vapour leaving the compressor (or generator in case of absorption system) so that the refrigerant will condense to its liquid state. This liquid refrigerant will then be able to achieve the refrigerating effect in the evaporator. In a typical refrigerant condenser, the refrigerant enters the condenser in a superheated state. It is first de- superheated and then condensed by rejecting heat to an external medium. The refrigerant may leave the condenser as a saturated or a sub- cooled liquid, depending upon the temperature of the external medium and design of the condenser.

- Types of Condensers:
    - Air Cooled Condensers
    - Water Cooled Condensers
    - Evaporative Condensers

Refrigerants:

- A refrigerant is a fluid in a refrigerating system that by its evaporating takes the heat of the cooling coils and gives up heat by condensing the condenser.
- **Identifying refrigerants by numbers**: The present practice in the refrigeration industry is to identify refrigerants by numbers. The identification system of numbering has been standardized by the American society of heating, refrigerating and air conditioning engineers (ASHRAE), some refrigerants in common use are

Refrigeration	*Name and Chemical Formula*	
R-11	Trichloromonofluoromethane	CCl_3F
R-12	Dichlorodifluoromethane	CCl_2F_2
R-22	Monochlorodifluoromethane	$CHClF_2$
R-717	Ammonia	NH_3
R114(R40)	Azeotropic mixture of 73.8%	
R-500	(R-22) and 26.2%	R-152a
R502	Azeotropic mixture of 48.8%	
	(R-22) and 51.2%	R-115
R-764	Sulphur Dioxide	SO2

Properties of Refrigerants:

- **Toxicity:** It obviously desirable that the refrigerant have little effect on people.

- **Inflammability:** Although refrigerants are entirely sealed from the atmosphere, leaks are bound to develop. If the refrigerant is inflammable and the system is located where ignition of the refrigerant may occur, a great hazard is involved.
- **Boiling Point:** An ideal refrigerant must have low boiling temperature at atmospheric pressure.
- **Freezing Point:** An ideal refrigerant must have a very low freezing point because the refrigerant should not freeze at low evaporator temperatures.
- **Evaporator and condenser pressure:** In order to avoid the leakage of the atmosphere air and also to enable the detection of the leakage of the refrigerant, both the Evaporator and condenser pressure should be slightly above the atmosphere pressure.
- **Chemical Stability:** An ideal refrigerant must not decompose under operating conditions.
- **Latent heat of Evaporation:** The Latent heat of Evaporation must be very high so that a minimum amount of refrigerant will accomplish the desired result; in other words, it increases the refrigeration effect
- **Specific Volume:** The Specific Volume of the refrigerant must be low. The lower specific volume of the refrigerant at the compressor reduces the size of the compressor.
- **Specific heat of liquid vapour:** A good refrigerant must have low specific heat when it is in liquid state and high specific heat when it is vaporized.
- **Viscosity:** The viscosity of the refrigerant t both the liquid and vapour state must be very low as improved the heat transfer and reduces the pumping pressure.
- **Corrosiveness:** A good refrigerant should be non-corrosive to prevent the corrosion of the metallic parts of the refrigerator.
- **Coefficient of performance:** The coefficient of performance of a refrigerant must be high so that the energy spent in refrigeration will be less.
- **Odour:** A good refrigerant must be odourless, otherwise some foodstuff such as meat, butter, etc. loses their taste.
- **Leakage:** A good refrigerant must be such that any leakage can be detected by simple test.
- **Oil solvent properties:** A good refrigerant must be not react with the lubricating oil used in the refrigerator for lubricating the parts of the compressor.

- **Cost:** The cost of the refrigerant is the major important, it will easily available and low cost.

Advantages and Disadvantages of vapour Compression Refrigeration System:

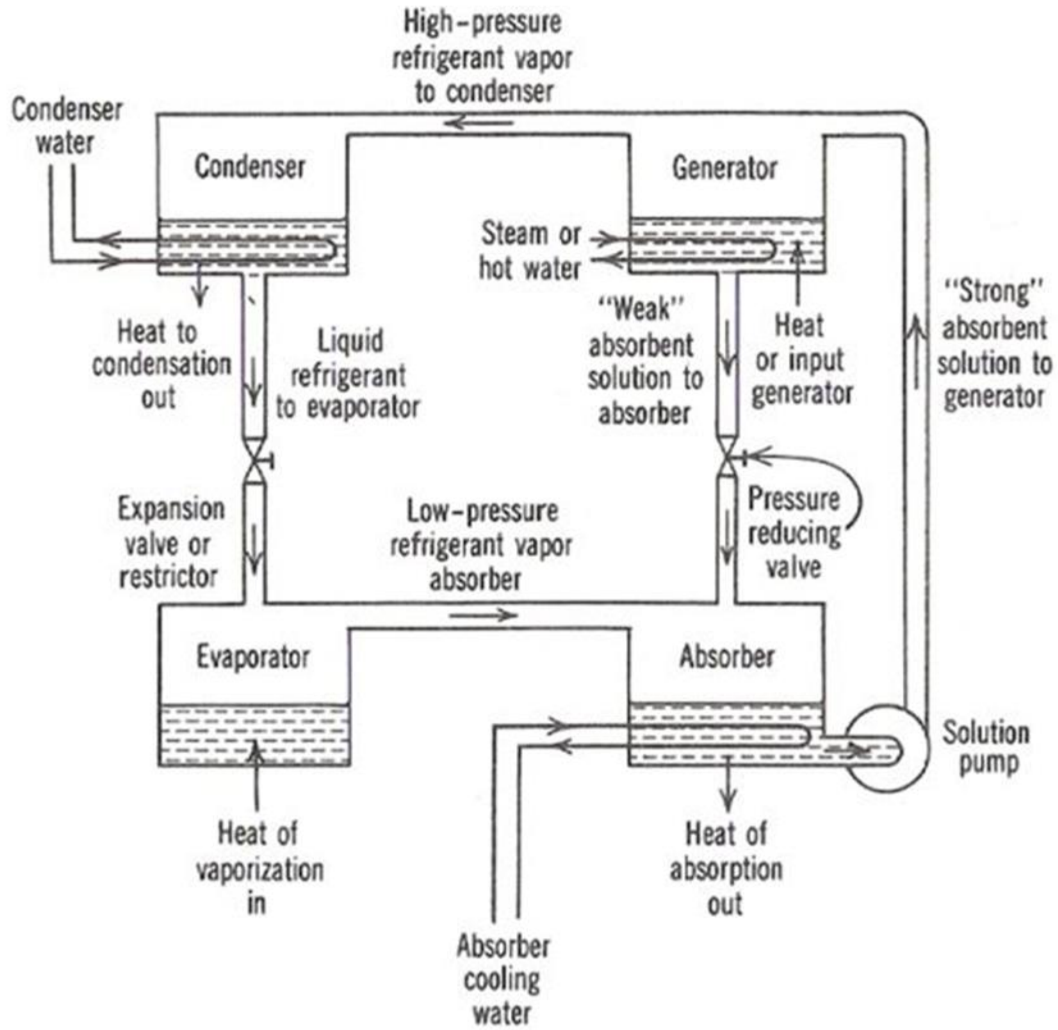
- **Advantages**
  - It has smaller size for the given capacity of refrigeration.
  - It has less running cost.
  - It can be employed over a large range of temperatures.
  - The coefficient of performance is quite high.
- **Disadvantages**
  - The initial cost is high.
  - The prevention of leakage of the refrigerant is the major problem in vapour compression system.

Vapour Absorption Cycle:

- Before the development of the vapour compression system of refrigeration, vapour absorption cycle was very widely used. The vapour compression system replaced vapour absorption system because it has high coefficient of performance (COP).
- The vapour absorption system requires very less amount of electricity but large amount of heat; hence it can be used very effectively in industries where very large stocks of excessive steam are available.
- In such cases there is not only effective utilization of steam, but also lots of savings in electricity costs.
- Of late the vapour absorption systems are being employed by a number of industries to save on their electric bills. However, the vapour absorption system is useful only where large scale refrigeration in excess of at least 20 tons is required.
- The various processes of the vapour absorption cycle are similar to the one in vapour compression cycle, only the method of compression of the refrigerant is different. In vapour absorption system ammonia is used as the refrigerant, which has very high affinity to dissolve in water.
- **Here are various processes of vapour absorption cycle:**

- **Compression or absorption of the refrigerant:** In vapour absorption system there is no traditional compressor, instead there is absorber. The absorber consists of water, called as absorbent, in which the refrigerant, ammonia, dissolves. This mixture of water and ammonia is then pumped and heated thus increase in temperature and pressure of the ammonia occurs. Ammonia leaves the absorber at high pressure and high temperature. Some work has to be provided to the pump and heating is carried out by the steam. The amount of electricity required by the pump is much lesser than that required by the compressor hence there is lots of saving of electricity, however, the additional source of heat in the form of steam has to be provided.
- **Condensation:** The refrigerant at pressure and temperature then enters condenser where it is cooled by water and its temperature and pressure reduces.
- **Expansion:** Thereafter the expansion of refrigerant occurs in throttling valve due to which the temperature and pressure of the ammonia refrigerant reduces drastically and suddenly.
- **Evaporation:** Finally the refrigerant enters the evaporator where it produces the cooling effect. It leaves the evaporator in vapor state and then enters absorber, where it is absorbed by absorbent, water and compressed by the pump. This process repeats again and cycle continues.

- There are different types absorbents like **water and lithium bromide that can be used with refrigerant ammonia**. These systems are called water absorption system or lithium bromide absorption system.



Vapour Absorption Refrigeration System

Vapour Absorption System components:

- **Condenser:** Just like in the traditional condenser of the vapour compression cycle, the refrigerant enters the condenser at high pressure and temperature and gets condensed. The condenser is of water cooled type.
- **Expansion valve or restriction:** When the refrigerant passes through the expansion valve, its pressure and temperature reduces suddenly. This refrigerant (ammonia in this case) then enters the evaporator.
- **Evaporator:** The refrigerant at very low pressure and temperature enters the evaporator and produces the cooling effect. In the vapour compression cycle this refrigerant is sucked by the compressor, but in the vapour absorption cycle, this refrigerant flows to the absorber that acts as the suction part of the refrigeration cycle.

- **Absorber:**

  - The absorber is a sort of vessel consisting of water that acts as the absorbent, and the previous absorbed refrigerant. Thus the absorber consists of the weak solution of the refrigerant (ammonia in this case) and absorbent (water in this case). When ammonia from the evaporator enters the absorber, it is absorbed by the absorbent due to which the pressure inside the absorber reduces further leading to more flow of the refrigerant from the evaporator to the absorber. At high temperature water absorbs lesser ammonia, hence it is cooled by the external coolant to increase it ammonia absorption capacity.
  - The initial flow of the refrigerant from the evaporator to the absorber occurs because the vapour pressure of the refrigerant-absorbent in the absorber is lower than the vapour pressure of the refrigerant in the evaporator. The vapour pressure of the refrigerant-absorbent inside the absorbent determines the pressure on low-pressure side of the system and also the vaporizing temperature of the refrigerant inside the evaporator. The vapour pressure of the refrigerant-absorbent solution depends on the nature of the absorbent, its temperature and concentration.
  - When the refrigerant entering in the absorber is absorbed by the absorbent its volume decreases, thus the compression of the refrigerant occurs. Thus absorber acts as the suction part of the compressor. The heat of absorption is also released in the absorber, which is removed by the external coolant.

- **Pump:** When the absorbent absorbs the refrigerant strong solution of refrigerant-absorbent (ammonia-water) is formed. This solution is pumped by the pump at high pressure to the generator. Thus pump increases the pressure of the solution to about 10bar.
- **Generator:** The refrigerant-ammonia solution in the generator is heated by the external source of heat. This is can be steam, hot water or any other suitable source. Due to heating the temperature of the solution increases. The refrigerant in the solution gets vaporized and it leaves the solution at high pressure. The high pressure and the high temperature refrigerant then enters the condenser, where it is cooled by the coolant, and it then enters the expansion valve and then finally into the evaporator where it produces the cooling effect. This refrigerant is then again absorbed by the weak solution in the absorber. When the vaporized refrigerant leaves the generator weak solution is left in it.

This solution enters the pressure reducing valve and then back to the absorber, where it is ready to absorb fresh refrigerant. In this way, the refrigerant keeps on repeating the cycle. The pressure of the refrigerant is increased in the generator, hence it is considered to be equivalent to the compression part of the compressor.

Difference between Vapour Compression and Vapour Absorption Refrigeration Systems:

S no.	Type of Difference Method	Vapour Compression	Vapour Absorption
1.	**The method of the suction and compression**	In the vapour compression system, the compressor sucks the refrigerant from evaporator and compresses it to the high pressure. The compressor also enables the flow of the refrigerant through the whole refrigeration cycle.	In the vapour absorption cycle, the process of suction and compression are carried out by two different devices called as the absorber and the generator. Thus the absorber and the generator replace the compressor in the vapour absorption cycle. The absorbent enables the flow of the refrigerant from the absorber to the generator by absorbing it.
2.	**The method in which the energy input is given to the system**	In the vapour compression system the energy input is given in the form of the mechanical work from the electric motor run by the electricity.	In the vapour absorption system the energy input is given in the form of the heat. This heat can be from the excess steam from the process or the hot water. The heat can also be

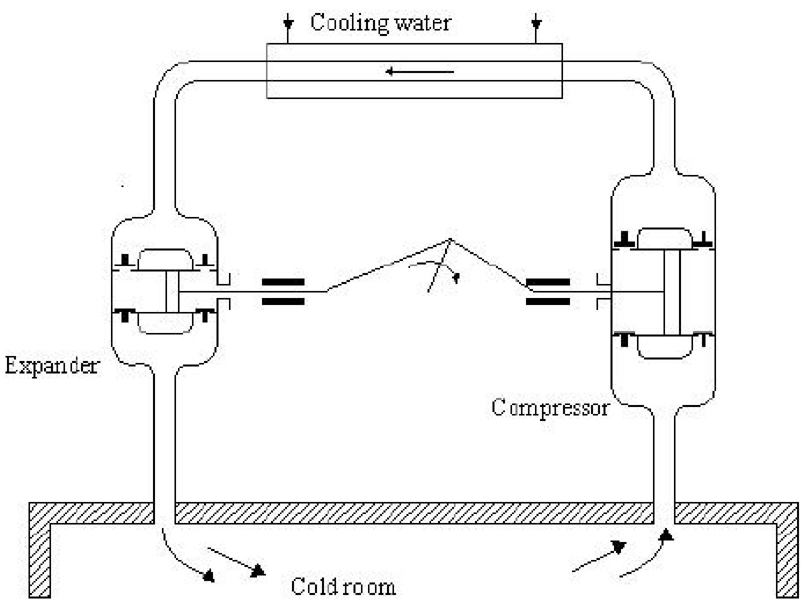
			created by other sources like natural gas, kerosene, and heater etc. Though these sources are used only in the small systems.
3.	**Moving part in the system**	The vapour compression system of the same capacity has more wear, tear and noise due to moving parts of the compressor.	The only moving part of the entire system is a pump which has a small motor. Thus, the operation of this system is essentially quiet and is subjected to little wear.
4.	**Energy used and cost effectiveness**	The vapour compression systems as electricity is must therefore, they can be used only where electricity is available properly and making this very expensive in terms of cost.	The vapour absorption systems are usually designed to use steam, either at high pressure or low pressure. The exhaust steam from furnaces and solar energy may also be used. Thus this system can be used where the electric power is difficult to obtain or is very expensive.
5.	**Working at reduced evaporator pressure**	The capacity of vapour compression system drops rapidly with lowered evaporator pressure.	The vapour absorption systems can operate at reduced evaporator pressure and temperature by increasing the steam pressure to the

			generator, with little decrease in capacity.
6.	**Load variation**	The performance of a vapour compression system at partial loads is poor.	The load variations does not affect the performance of a vapour absorption system. The load variations are met by controlling the quantity of aqua circulated and the quantity of steam supplied to the generator.
7.	**Condition of vapour after evaporator and effect on system**	• In the vapour compression system, it is essential to superheat the vapour refrigerant leaving the evaporator so that no liquid may enter the compressor. • Liquid traces in suction line may damage the compressor.	• In the vapour absorption system, the liquid refrigerant leaving the evaporator has no bad effect on the system except that of reducing the refrigerating effect. • Liquid traces of refrigerant present in Piping at the exit of evaporator constitute the compressor no danger.
8.	**Capacity of refrigeration**	• The vapour compression systems have very low and limited capacities due to increased size increases complex compressor units.	• The vapour absorption systems can be built in capacities well above 1000 tonnes of refrigeration each which is the largest

		• The COP decreases considerably with decrease in evaporator pressure.	size for single compressor units. • The system can work on lower evaporator pressures also without affecting the COP.
9.	**Space requirements**	With increased space requirement controlling of pressure becomes difficult as the evaporator temperature drops.	The space requirements and automatic control requirements favour the absorption system more and more as the desired evaporator temperature drops.
10.	**Form of energy used**	Uses high-grade energy like mechanical work.	Uses low grade energy like heat. Therefore, may work on exhaust systems from I.C engines, etc.

Gas Refrigeration Cycle:

- Just as the vapour is used for cooling in the vapour compression cycle and vapour absorption cycle, **the gas is used for cooling in gas refrigeration cycle**. When the gas is throttled from very high pressure to low pressure in the throttling valve, its temperature reduces suddenly while its enthalpy remains constant. This principle is used in gas refrigeration system.
- In this system instead of using **Freon or ammonia as the refrigerant**, the gas is used as the refrigerant. Throughout the cycle there are no phase changes of the gas, which are observed in the liquid refrigerants. **Air is the most commonly used gas, also called as refrigerant in this case, in the gas refrigeration cycles.**



Schematic diagram of the cold air system

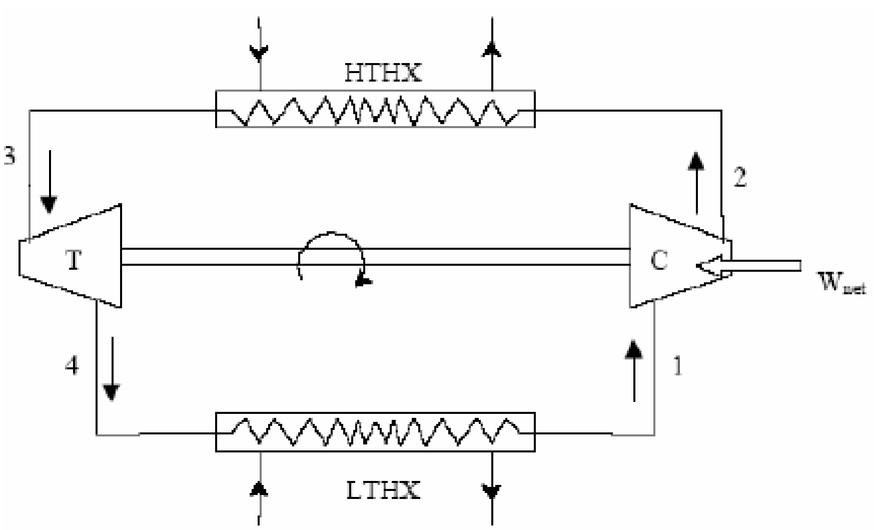
Components and Working of the Gas Refrigeration Cycle:

- The components of the gas refrigeration cycle are very similar to the vapour compression cycle. The gas flows through the compressor where its pressure and temperature becomes very high. It then flows into the heat exchanger, which performs the function similar to the condenser in the vapour compression cycle, except that there is no change in the phase of air or gas. In the heat exchanger the air gives up heat, but its pressure remains constant.
- The high pressure and medium temperature air then enters the throttling valve (also called expander), where its pressure is reduced suddenly and due to this its temperature also becomes very low. The low temperature and low pressure gas then enters the other heat exchanger (also called refrigerator) which performs the function similar to the evaporator in vapour compression cycle. The gas absorbs the heat from the substance to be cooled and becomes hotter, while the substance becomes cooler. There is no change in phase of the gas in this heat exchanger. The high pressure and high temperature gas then enters the compressor where the cycle repeats.
- When air is used as the refrigerant in the gas cycle, reverse Carnot cycle can be followed to achieve the refrigeration effect. However, the reverse Carnot cycle is an ideal cycle and is not useful for the practical applications. **Bell Coleman cycle** is a more practical cycle in which the isothermal processes are replaced by the constant pressure processes.

This is one of earliest types of refrigerators and was used for ships for transport of the food items.

- **The efficiency of the gas cycles is lesser than the vapour compression cycle. For absorbing the same amount of heat or producing the same refrigerating effect, the amount of gas required is very high compared to the amount of the liquid refrigerant required, hence the refrigeration systems with the gas cycles tend to be very large and bulky.**

Bell-coleman cycle



HTHX => High temperature Heat Exchanger.

LTHX => Low temperature heat exchanger.

C => Compressor

T => Turbine

- This is an important cycle frequently employed in gas cycle refrigeration systems. This may be thought of as a modification of reversed Carnot cycle, as the two isothermal processes of Carnot cycle are replaced by two isobaric heat transfer processes. This cycle is also called as Joule or Bell-Coleman cycle.
- As shown in the figure, the ideal cycle consists of the following four processes:

- **Process 1-2:** Reversible, adiabatic compression in a compressor
- **Process 2-3:** Reversible, isobaric heat rejection in a heat exchanger
- **Process 3-4:** Reversible, adiabatic expansion in a turbine
- **Process 4-1:** Reversible, isobaric heat absorption in a heat exchanger

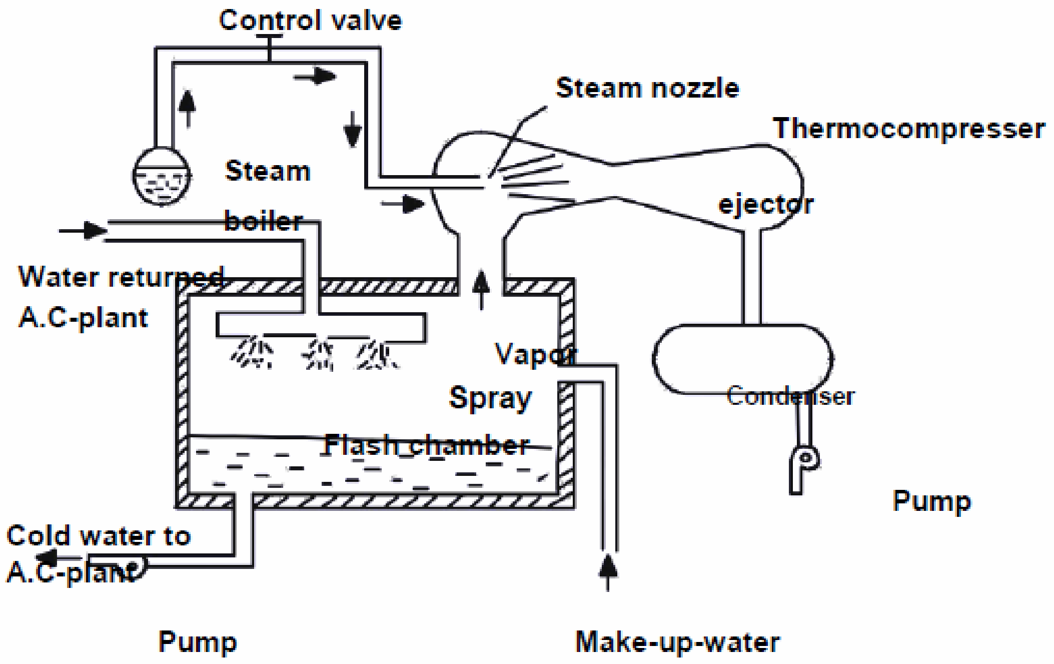
Comparison of Vapour Compression Cycle and Gas Cycle Refrigeration:

S No.	Parameters	Vapour Compression Cycle	Gas Cycle Refrigeration
1.	**Type of refrigerant used**	In vapour compression cycle liquids like Freon and ammonia are used as the refrigerant.	In the gas cycle the gas like air is used as the refrigerant.
2.	**Heat exchangers**	In the vapour compression refrigeration cycle condenser and evaporator are the two heat exchangers where the refrigerant gives up and absorbs heat respectively. The refrigerant undergoes change in phase in both the heat exchangers.	In the gas cycle the refrigerant exchanges heat in the heat exchangers, but there is no phase change of the gas.
3.	**Efficiency of the cycle**	The efficiency of the vapour compression cycle is more than that of the gas cycle.	For producing the same amount of refrigerating effect in the gas cycle, large volume of gas is required; hence the systems tend to become very large, bulky and expensive, which are not affordable for the domestic applications.
4.	**Cycle used**	The vapour compression cycle works on the reverse Brayton cycle.	The gas compression cycle works on reverse Rankine cycle.

5.	**Applications**	The vapour compression cycle is most widely used for the refrigeration purposes. It is used in household refrigerators, air-conditioners, water cooler, ice and ice cream makers, deep freezers, large industrial refrigeration and air-conditioning systems, etc.	Since the size of the gas compression systems is very large, they are not used for the domestic and industrial purposes. They are used widely in the aircraft air-conditioning systems since in aircrafts air at very high pressures is available readily and there won't be the need of air compressors. This makes the air-conditioning system in the aircraft light weight and less power consuming. The use of air as the refrigerant in aircraft prevents the dangers of fire of from the flammable refrigerants.

SOME MORE TYPES OF REFRIGERATION SYSTEMS

Steam Jet Refrigeration System:



Steam jet refrigeration system

- **In 1838, the Frenchman Pelletan** was granted a patent for the compression of steam by means of a jet of motive steam. **Around 1900, the Englishman Charles Parsons** studied the possibility of reduction of pressure by an entrainment effect from a steam jet. However, the credit for constructing the steam jet refrigeration system goes to the French engineer, **Maurice Leblanc** who developed the system in **1907-08**.
- Steam jet or Ejector refrigeration system uses water as refrigerant. It uses the basic principle of boiling of liquid at lower temperature by reducing pressure on its surface. Water boils at 6^0C, when the pressure on the surface is 5 cm of Hg and at 100^oC, when the pressure is 6.5 cm of Hg. The very low pressure or high vacuum on the surface of the water can be maintained by throttling the steam through jets or nozzles.
- This system employs a steam ejector or booster instead of mechanical compressor. The main components as shown in figure are flash chamber or evaporator, steam nozzles, ejector and condenser.

- The flash chamber is heavily insulated and is fitted with perforated pipes which spray warm water coming out of refrigerated space. Some of this water is converted into vapours after absorbing latent heat from the rest of the water, thereby cooling it. Loss of water through vapours is made up from make-up water line.
- High pressure steam from boiler is passed through steam nozzle thereby increasing its velocity. This entrains water vapours from flash chamber and results in further formation of vapours.
- The mixture of steam and water vapour passes through venturi-tube of ejector and gets compressed. This leads to rise in temperature and pressure of the mixture and then it is fed to the water cooled condenser.
- The condensate is again fed to boiler as feed water. Steam jet refrigeration system is widely used in paper mills, breweries, food processing plants, gas plants etc. Since water is the refrigerant, it cannot be used for applications below 0°C.

Advantages of Steam Jet Refrigeration System:

- It is flexible in operation; cooling capacity can be easily and quickly changed.
- It has no moving parts as such it is vibration free.
- It can be installed out of doors.
- The weight of the system per ton of refrigerating capacity is less.
- The system is very reliable and maintenance cost is less.
- The system is particularly adapted to the processing of cold water used in rubber mills, distilleries, paper mills, food processing plants, etc.
- This system is particularly used in air-conditioning installations, because of the complete safety of water as refrigerant and ability to adjust quickly to load variations and no hazard from the leakage of the refrigerant.

Disadvantages Steam Jet Refrigeration System:

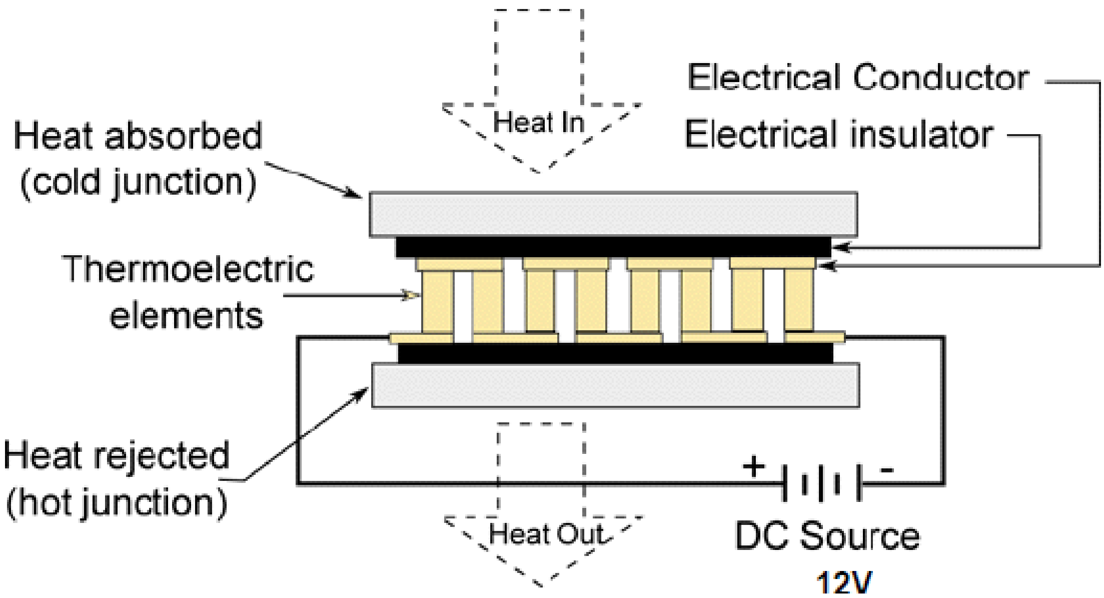
- The use of direct evaporation to produce chilled water is usually limited as tremendous volume of vapour is to be handled.
- About twice as much heat must be removed in the condenser of steam jet per ton of refrigeration compared with the vapour compression system.
- The system is useful for comfort air-conditioning, but it is not practically feasible for water temperature below 40°C.

Thermoelectric Refrigeration Systems:

- In 1821 the German physicist T.J. Seebeck reported that when two junctions of dissimilar metals are kept at two different temperatures, an electro motive force (emf) is developed, resulting in flow of electric current. The emf produced is found to be proportional to temperature difference.
- In 1834, a Frenchmen, J. Peltier observed the reverse effect, i.e., cooling and heating of two junctions of dissimilar materials when direct current is passed through them, the heat transfer rate being proportional to the current.
- In 1838, H.F.E. Lenz froze a drop of water by the Peltier effect using antimony and bismuth (it was later found that Lenz could freeze water as the materials used were not pure metals but had some impurities in them).
- In 1857, William Thomson (Lord Kelvin) proved by thermodynamic analysis that Seebeck effect and Peltier effect are related and he discovered another effect called Thomson effect after his name.
- According to this when current flows through a conductor of a thermocouple that has an initial temperature gradient in it, then heat transfer rate per unit length is proportional to the product of current and the temperature. As the current flow through thermoelectric material it gets heated due to its electrical resistance. This is called the Joulean effect, further, conduction heat transfer from the hot junction to the cold junction transfers heat.
- Both these heat transfer rates have to be compensated by the Peltier Effect for some useful cooling to be produced. For a long time, thermoelectric cooling based on the Peltier effect remained a laboratory curiosity as the temperature difference that could be obtained using pure metals was too small to be of any practical use. Insulating materials give poor thermoelectric performance because of their small electrical conductivity while metals are not good because of their large thermal conductivity.
- However, with the discovery of semiconductor materials in 1949-50, the available temperature drop could be increased considerably, giving rise to commercialization of thermoelectric refrigeration systems. Figure below shows the schematic of the thermoelectric refrigeration system based on semiconductor materials. The Russian scientist, A. F. Ioffe is one of the pioneers in the area of thermoelectric refrigeration systems

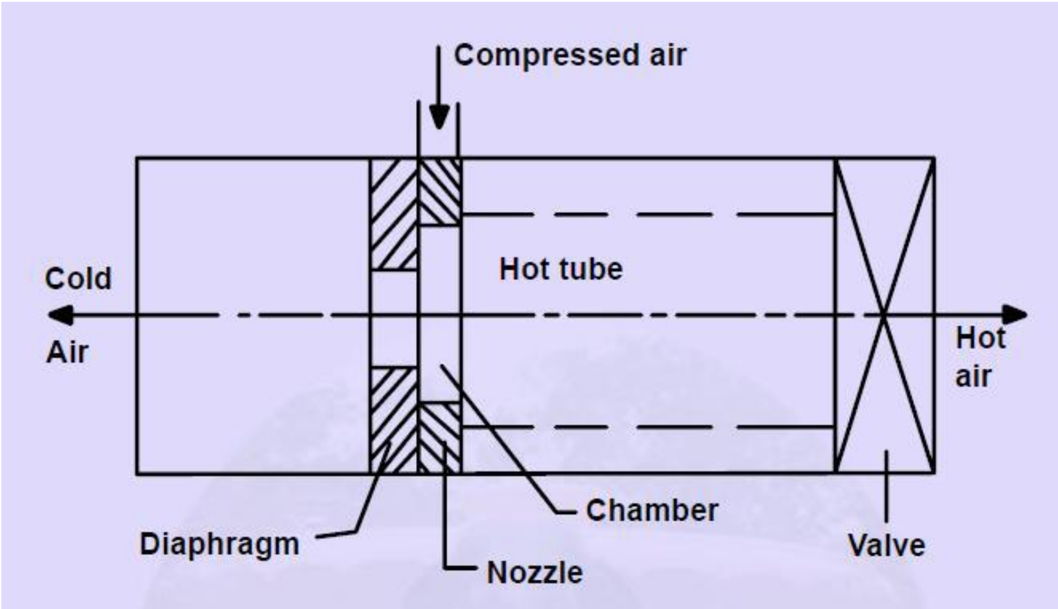
using semiconductors. Several domestic refrigerators based on thermoelectric effect were made in USSR as early as 1949.

- However, since 1960s these systems are used mainly used for storing medicines, vaccines etc and in electronic cooling. Development also took place in many other countries.
- In USA domestic refrigerators, air conditioners, water coolers, air conditioned diving suits etc. were made using these effects. System capacities were typically small due to poor efficiency. However some large refrigeration capacity systems such as a 3000 kcal/h air conditioner and a 6 tonne capacity cold storage were also developed. By using multi-staging temperatures as low as -145^{o}C were obtained. These systems due to their limited performance (limited by the materials) are now used only in certain niche applications such as electronic cooling, mobile coolers etc. Efforts have also been made to club thermoelectric systems with photovoltaic cells with a view to develop solar thermoelectric refrigerators.



Schematic of a thermoelectric refrigeration system

Vortex Tube Refrigeration:



- It is one of the non-conventional type refrigerating systems for the production of refrigeration. The schematic diagram of vortex tube is shown in the figure.
- It consists of nozzle, diaphragm, valve, hot-air side, cold-air side. The nozzles are of converging or diverging or converging-diverging type as per the design.
- An efficient nozzle is designed to have higher velocity, greater mass flow and minimum inlet losses.
- Chamber is a portion of nozzle that facilities the tangential entry of high velocity air-stream into hot side. Generally the chambers are not of circular form, but they are gradually converted into spiral form.
- Hot side is cylindrical in cross section and is of different lengths as per design. Valve obstructs the flow of air through hot side and it also controls the quantity of hot air through vortex tube.
- Diaphragm is a cylindrical piece of small thickness and having a small hole of specific diameter at the centre.
- Air stream traveling through the core of the hot side is emitted through the diaphragm hole. Cold side is a cylindrical portion through which cold air is passed.

Working:

- Compressed air is passed through the nozzle as shown in figure above. Here, air expands and acquires high velocity due to particular shape of the nozzle.

- A vortex flow is created in the chamber and air travels in spiral like motion along the periphery of the hot side. This flow is restricted by the valve. When the pressure of the air near valve is made more than outside by partly closing the valve, a reversed axial flow through the core of the hot side starts from high-pressure region to low-pressure region. During this process, heat transfer takes place between reversed stream and forward stream.
- Therefore, air stream through the core gets cooled below the inlet temperature of the air in the vortex tube, while air stream in forward direction gets heated up. The cold stream is escaped through the diaphragm hole into the cold side, while hot stream is passed through the opening of the valve. By controlling the opening of the valve, the quantity of the cold air and its temperature can be varied.

Advantages:

- It uses air as refrigerant, so there is no leakage problem.
- Vortex tube is simple in design and it avoids control systems.
- There are no moving parts in vortex tube.
- It is light in weight and requires less space.
- Initial cost is low and its working expenses are also less, where compressed air is readily available.
- Maintenance is simple and no skilled labours are required.

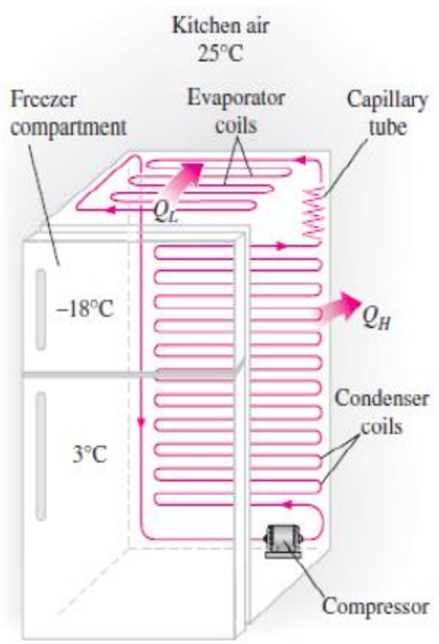
Disadvantages:

- Its low COP, limited capacity and only small portion of the compressed air appearing as the cold air limits its wide use in practice.

Applications:

- Vortex tubes are extremely small and as it produce hot as well as cold air. It may be of use in industries where both are simultaneously required.
- Temperature as low as –500C can be obtained without any difficulty, so it is very much useful in industries for spot cooling of electronic components.
- It is commonly used for body cooling of the workers in mines.

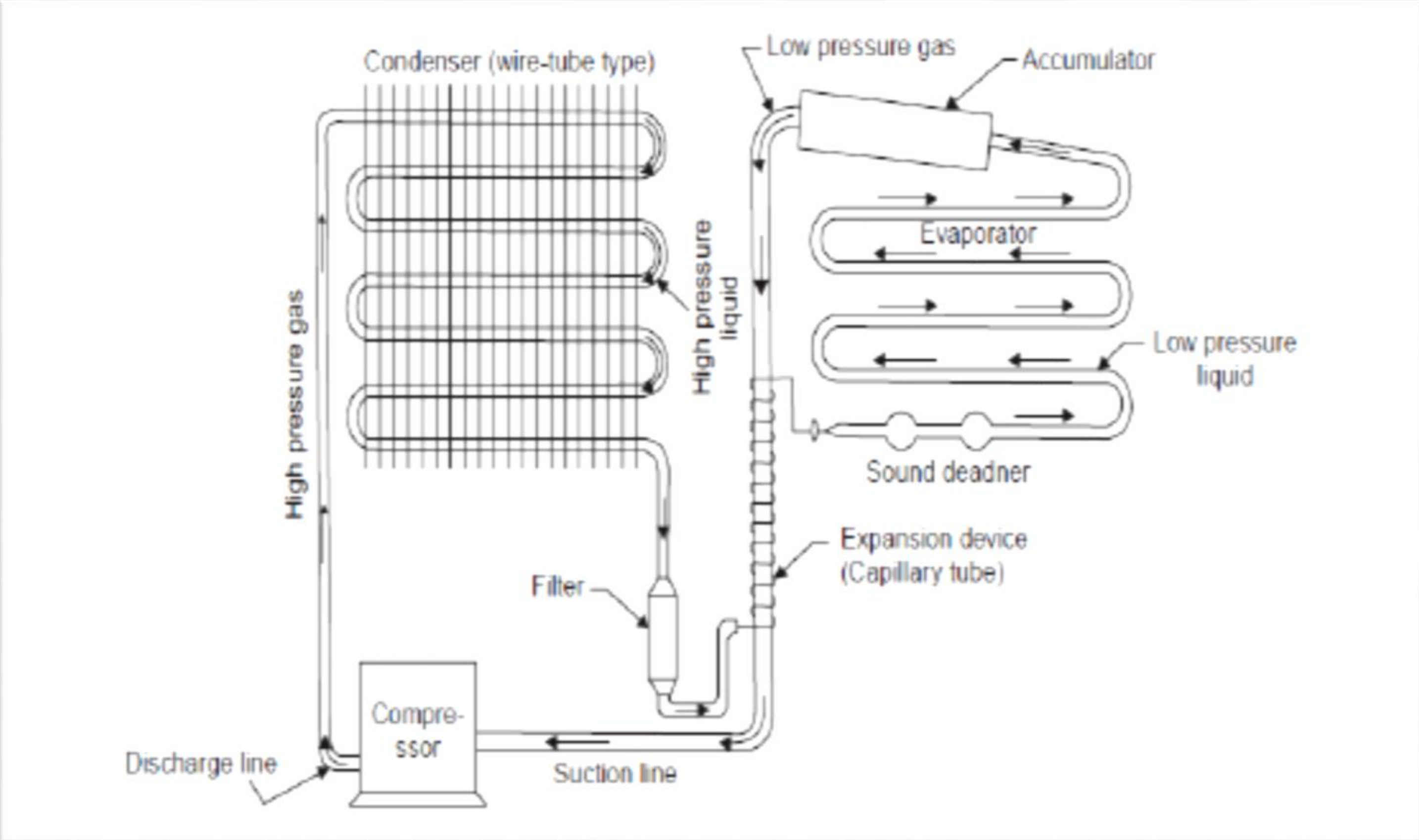
Domestic Refrigerator:



Domestic Refrigerator

- In a household refrigerator, the tubes in the freezer compartment where heat is absorbed by the refrigerator serves as the evaporator. The coils behind the refrigerator, where heat is dissipated to the kitchen air, serve as the condenser.
- Refrigerator, these days, are becoming the common items for house hold use, vendor's shop, hotels, motels, offices, laboratories, hospitals, chemists and druggists shops, studios etc. They are manufactured in different size to meet the needs of various groups of people. They are usually rated with internal gross volume and the freezer volume. The freezer space is meant to preserve perishable products at a temperature much below 0°C such as fish, meat, chicken, etc.

❖ Working of Domestic Refrigerator:

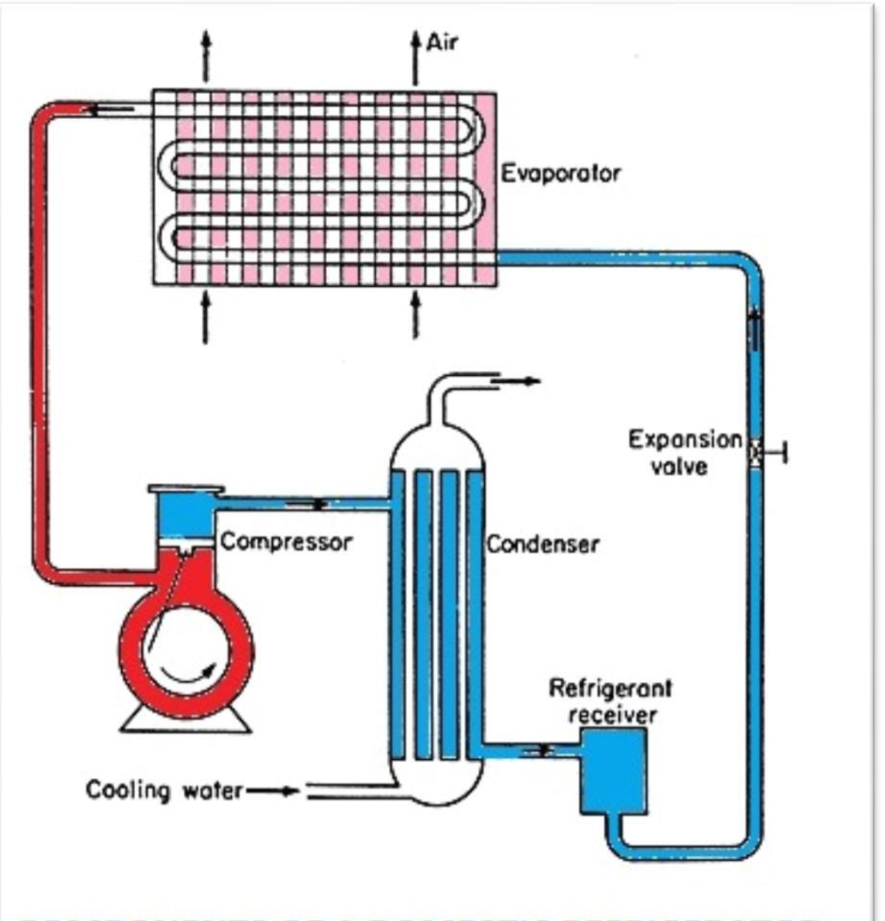


Layout of Domestic Refrigerator

- The refrigerator works on the vapour compression refrigeration cycle. The refrigerant vapour is first compressed in the compressor. The compressor is a special one known as the hermetic compressor. In this unit, the compressor is sealed casing along with an electrical motor to run. This sealing prevents leakage of refrigerant and lubrication oil.
- The pressure and temperature of the refrigerant increases after compression and is subsequently condensed in a condenser. In the condenser, the refrigerant rejects heat to a coolant and cools down and finally gets condensed.
- The condensate is then allowed to pass through capillary to reduce temperature and pressure by expansion of refrigerant. The refrigerant is filtered before entering the capillary tube.
- The pressure of the refrigerant, when it leaves the capillary, is maintained above atmospheric and temperature corresponds to saturation temperature so that the refrigerant can absorb heat in the evaporator.

- The refrigerant enters the evaporator and is heated by the heat absorbed from the body or space thereby producing the refrigeration effect. The vapour refrigerant enters the compressor again and the cycle is completed.
- When power to the compressor is switched on, a humming sound is heard and the refrigerator is functional. The refrigerant flows through its circuit and ice is produced in the freezer. Frost, i.e., moisture from ambient air, gets deposited on the evaporator coil. Defrosting removes this frost.
- The water from defrosting is collected in a tray to be removed manually. Articles to be refrigerated are placed on shelves. Fruits and vegetables, which contain moisture, are stored at the base. The temperature here is around 8°C.
- Thus there are **temperature gradients in the refrigerator, negative temperature in the freezer and positive temperature at the base**.

Components of a Domestic Refrigerator:



COMPONENTS OF A DOMESTIC REFRIGERATOR

Following are the components of a domestic refrigerator:

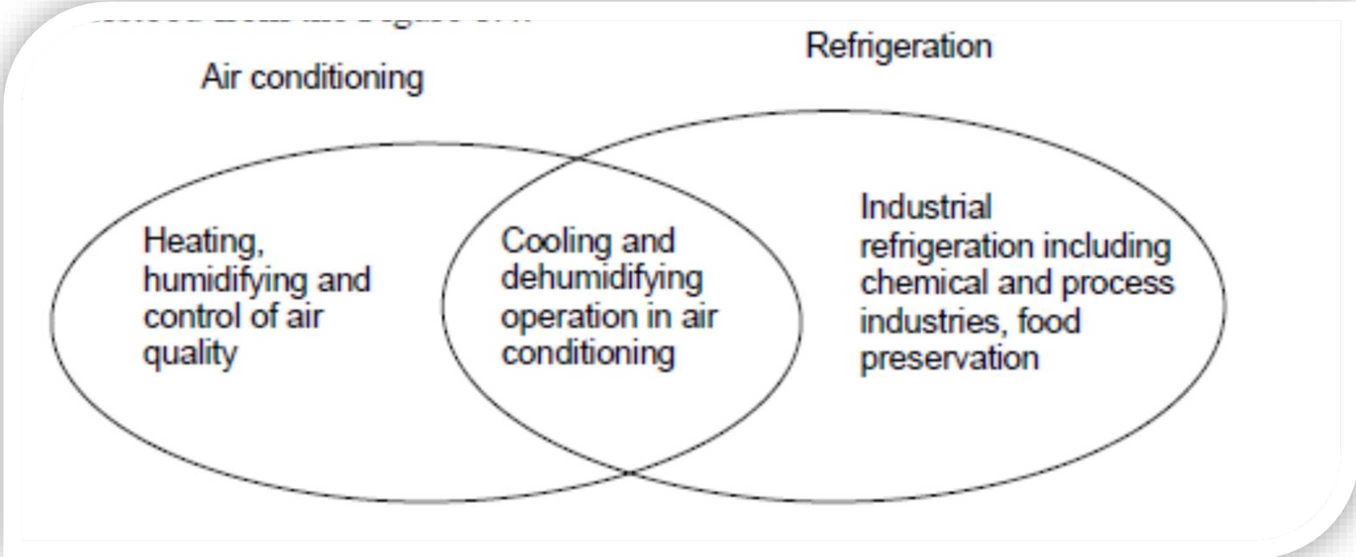
- **Evaporator:** The evaporator is located in a coil form on the freezer box. The liquid refrigerant is evaporated in the evaporator by absorbing heat from the contents of the domestic refrigerator in the cabinet. The evaporator consists of copper metal rubbing surrounding the freezing and cooling compartments.
- **Condenser:** The condenser is located as zigzag tubes behind the refrigerator on a mesh. In the condenser, the heat from the refrigerant at a higher temperature is rejected to the atmospheric air.
- **Compressor:** The compressor is located at the base at the rear end. It compresses the refrigerant vapour to a high pressure. Reciprocating compressor is used for low capacity domestic refrigerator.
- **Expansion Valve or Throttling Valve:** An expansion valve is used to reduce the temperature and pressure of the liquid refrigerant, before it passes to the evaporator. The expansion capillary is located inside the refrigerator body hear the wall. The capillary tube is small diameter tube used as an expansion device.
- **Refrigerator cabinet:** The refrigerator cabinet is thermally insulated to minimize heat flow from the atmosphere into the refrigerator. The insulation is glass fibre and the external body is of stainless steel.

Air-Conditioning: Meaning

- Merely lowering or raising the temperature does not provide comfort in general to the machines or its components and living beings in particular. In case of the machine components, along with temperature, humidity (moisture content in the air) also has to be controlled and for the comfort of human beings along with these two important parameters, air motion and cleanliness also play a vital role.
- **Air conditioning**, therefore, is a broader aspect which looks into the **simultaneous control all mechanical parameters** which are essential for the comfort of human beings or animals or for the proper performance of some industrial or scientific process. **The precise meaning of air conditioning can be given as the process of simultaneous control of temperature, humidity, cleanliness and air motion**. In some applications, even the control of air pressure falls under the purview of air conditioning. It is to be noted that refrigeration that is control of temperature is the most important aspect of air conditioning.

Air-Conditioning: Comfort Conditions

- **For comfort**, both **temperature and humidity** have to be in the specified range. This is true for both human beings and scientific processes. Apart from the above two, from intuition one can also say that purity or cleanliness of the air is an essential item for the comfort and it has been established that the air motion is also required for the comfort condition.
- Depending upon **the requirement**, air conditioning is divided into **the summer air conditioning and the winter air conditioning.**
- In **the summer air conditioning**, apart from cooling the space, in most of the cases, extra moisture from the space is removed, whereas in **the winter air conditioning**, space is heated and since in the cold places, normally the humidity remains low, moisture is added to the space to be conditioned. The summer air conditioning thus uses a refrigeration system and a dehumidifier. The winter air conditioning uses a heat pump (refrigeration system operated in the reverse direction) and a humidifier.
- Depending upon **the comfort** of the human beings and **the control of environment** for the industrial products and processes, air conditioning can also be classified as **comfort air conditioning** and **industrial air conditioning**.
- **Comfort air conditioning** deals with the air conditioning of residential buildings, offices spaces, cars, buses, trains, airplanes, etc. **Industrial air conditioning** includes air conditioning of the printing plants, textile plants, photographic products, computer rooms, etc.
- It has been mentioned above that the refrigeration and air conditioning are related. Even when a space has to be heated, it can be done so by changing the direction of flow of the refrigerant in the refrigeration system, i.e., the refrigeration system can be used as a heat pump.
- However, some section of the people, treat refrigeration exclusively the process that deals with the cooling of the space. They treat heating operation associated with the heat pump. The relationship between air conditioning and refrigeration fields can be understood from the Figure.



Relationship between the Refrigeration and Air Conditioning

Thermal comfort:

- Thermal comfort is defined as "**that condition of mind which expresses satisfaction with the thermal environment**". This condition is also sometimes called as "**neutral condition**", though in a strict sense, they are not necessarily same.
- A living human body may be likened to a heat engine in which the chemical energy contained in the food it consumes is continuously converted into work and heat. The process of conversion of chemical energy contained in food into heat and work is called as "**metabolism**". The rate at which the chemical energy is converted into heat and work is called as "**metabolic rate**".
- Knowledge of metabolic rate of the occupants is required as this forms a part of the cooling load of the air conditioned building. Similar to a heat engine, one can define thermal efficiency of a human being as the ratio of useful work output to the energy input.
- The thermal efficiency of a human being can vary from 0% to as high as 15-20% for a short duration. By the manner in which the work is defined, for most of the light activities the useful work output of human beings is zero, indicating a thermal efficiency of 0%.

- Irrespective of the work output, a human body continuously generates heat at a rate varying from about 100 W (e.g. for a sedentary person) to as high as 2000 W (e.g. a person doing strenuous exercise). Continuous heat generation is essential, as the temperature of the human body has to be maintained within a narrow range of temperature, irrespective of the external surroundings.
- A human body is very sensitive to temperature. The body temperature must be maintained within a narrow range to avoid discomfort, and within a somewhat wider range, to avoid danger from heat or cold stress. Studies show that at neutral condition, the temperatures should be:

Skin temperature, $t_{skin} \approx 33.7^{o}C$
Core temperature, $t_{core} \approx 36.8^{o}C$

- A tighter range for comfort, where almost 100% of people feel comfortable, is within;

Summer condition

30% to 70% of relative humidity

$23^{o}C$ ($73^{o}F$) and $25^{o}C$ ($77^{o}F$) of dry bulb temperature

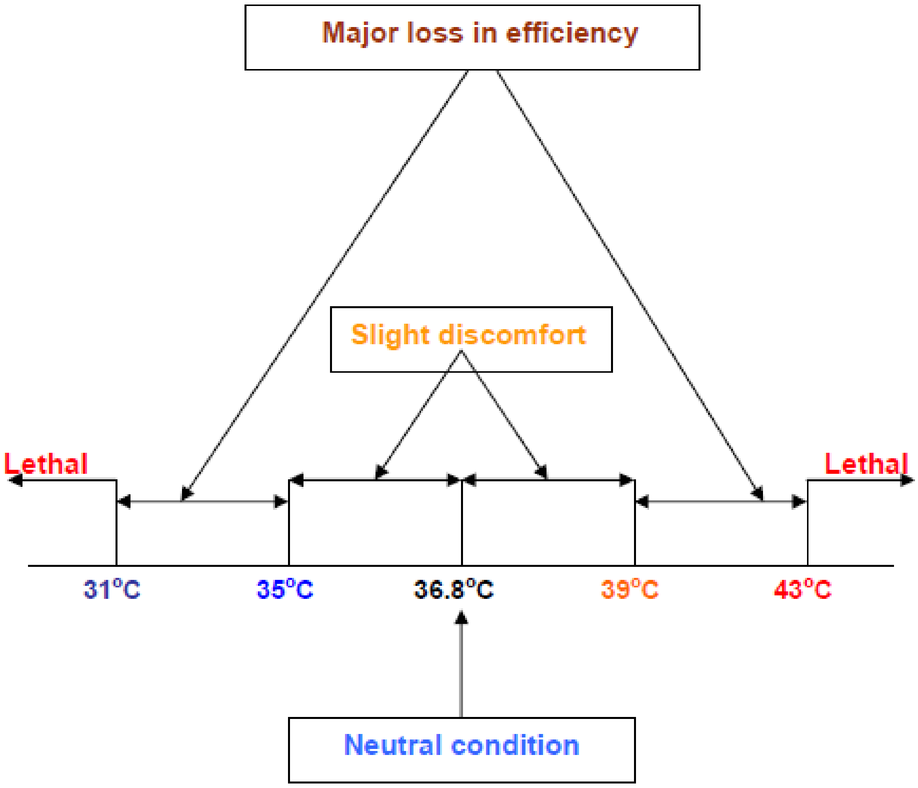
Winter condition

30% to 70% of relative humidity

$19^{o}C$ ($67^{o}F$) and $22^{o}C$ ($72^{o}F$) of dry bulb temperature

- Tight ranges are quite strict for air conditioning design and sizing. Therefore, more lenient and acceptable range provided earlier, is used.
- Humans generally feel comfortable between temperatures of 22°C to 27°C and a relative humidity of 40% to 60%.
- At other temperatures, the body will feel discomfort or it may even become lethal. It is observed that when the core temperature is between $35^{o}C$to $39^{o}C$, the body experiences only a mild discomfort. When the temperature is lower than $35^{o}C$ or higher than $39^{o}C$, then people suffer major loss in efficiency.

➢ It becomes lethal when the temperature falls below 31°C or rises above 43°C. This is shown in Figure.



Affect of the variation of core temperature on a human being

➢ **When the environment is colder than the neutral zone**, then body loses more heat than is generated. Then the regulatory processes occur in the following order:

1. **Zone of vaso-motor regulation against cold (vaso-constriction):** Blood vessels adjacent to the skin constrict, reducing flow of blood and transport of heat to the immediate outer surface. The outer skin tissues act as insulators.

2. **Zone of metabolic regulation:** If environmental temperature drops further, then vaso-motor regulation does not provide enough protection. Hence, through a spontaneous increase of activity and by shivering, body heat generation is increased to take care of the increased heat losses.

3. **Zone of inevitable body cooling:** If the environmental temperature drops further, then the body is not able to combat cooling of its tissues.

Hence the body temperature drops, which could prove to be disastrous. This is called as zone of inevitable body cooling.

- **When the environment is hotter than the neutral zone**, then body loses less heat than is generated. Then the regulatory processes occur in the following order:

1. **Zone of vaso-motor regulation against heat (vaso-dilation):** Here the blood vessels adjacent to the skin dilate, increasing the flow of blood and transport of heat to the immediate outer surface. The outer skin temperature increases providing a greater temperature for heat transfer by convection and radiation.

2. **Zone of evaporative regulation:** If environmental temperature increases further, the sweat glands become highly active drenching the body surface with perspiration. If the surrounding air humidity and air velocity permit, then increase in body temperature is prevented by increased evaporation from the skin.

3. **Zone of inevitable body heating:** If the environmental temperature increases further, then body temperature increases leading to the zone of inevitable body heating. The internal body temperature increases leading several ill effects such as heat exhaustion (with symptoms of fatigue, headache, dizziness, irritability etc.), heat cramps (resulting in loss of body salts due to increased perspiration) and finally heat stroke. Heat stroke could cause permanent damage to the brain or could even be lethal if the body temperature exceeds 43^{o}C.

- **Thus it is seen that even though human body possesses a regulatory mechanism, beyond certain conditions it becomes ineffective.** Hence it is essential to ensure that surrounding conditions are conducive for comfortable and safe living. The purpose of a comfort air conditioning system is to provide suitable conditions in the occupied space so that it is thermally comfortable to the occupants.
- A sedentary person at neutral condition loses about 40 % of heat by evaporation, about 30 % by convection and 30 % by radiation. However, this proportion may change with other factors. For example, the heat loss by evaporation increases when the DBT of the environment increases and/or the activity level increases.

Factors affecting thermal comfort:

Thermal comfort is affected by several factors, these are:

1. **Physiological factors**: such as age, activity, sex and health. These factors influence the metabolic rate. It is observed that of these factors, the most important is activity. Other factors are found to have negligible effect on thermal comfort.

2. **Insulating factor due to clothing:** The type of clothing has strong influence on the rate of heat transfer from the human body. The unit for measuring the resistance offered by clothes is called as "clo". 1 clo is equal to a resistance of about 0.155 m2.K/W. Typical clo values for different types of clothing have been estimated and are available in the form of tables. For example, a typical business suit has a clo value of 1.0, while a pair of shorts has a clo value of about 0.05.

3. **Environmental factors:** Important factors are the dry bulb temperature, relative humidity, air motion and surrounding surface temperature. Of these the dry bulb temperature affects heat transfer by convection and evaporation, the relative humidity affects heat loss by evaporation, air velocity influences both convective and evaporative heat transfer and the surrounding surface temperature affects the radiative heat transfer.

- Apart from the above, other factors such as drafts, asymmetrical cooling or heating, cold or hot floors etc. also affect the thermal comfort. The objective of a comfort air conditioning system is to control the environmental factors so that comfort conditions prevail in the occupied space. It has no control on the physiological and insulating factors. However, wearing suitable clothing may help in reducing the cost of the air conditioning system.

Applications of Air Conditioning:

- **Air Conditioning of Residential and Official Buildings:** Most of the air conditioning units are devoted for comfort air conditioning that is meant to provide comfortable conditions for people. Air conditioning of building is required in all climates. In the summer, living/working spaces have to be cooled and in the winter the same have to be heated. Even in places where temperature remains normal, cooling of the building is required to remove the heat generated internally by people, lights, mechanical and electrical equipment. Further in these buildings, for the comfort, humidity and cleanliness of air has to be maintained.

In hospitals and other medical buildings, conditions on cleanliness and humidity are more stringent. There ventilation requirements often specify the use of 100 percent outdoor air, and humidity limits.

- **Industrial Air Conditioning:** The term industrial air conditioning refers to providing at least a partial measure of comfort for workers in hostile environments and controlling air conditions so that they are favourable to processing some objects or materials. Some examples of industrial air conditioning are the following:

- **Spot Heating and Spot Cooling:** In a cold weather it may be more practical to warm a confined zone where a worker is located. One such approach is through the use of an infrared heater. When its surfaces are heated to a high temperature by means of a burner or by electricity, they radiate heat to the affected area. If a specific area has to be cooled, it will be unwise to cool entire room or factory. In this case, conditions may be kept tolerable for workers by directing a stream of cool air onto occupied areas.

- **Environmental Laboratories:** The role of air conditioning may vary from one laboratory to the other. In one laboratory, a very low temperature, say – 40^{o}C must be maintained to test certain equipment at low temperatures, and in another, a high temperature and humidity may be required to study behaviour of animals in tropical climates.

- **Printing:** In printing industries, control of humidity is a must. In some printing processes the paper is run through several different passes, and air conditioning must be maintained to provide proper registration. If the humidity is not properly maintained the problems of static electricity, curling or buckling of paper or the failure of the ink to dry arise.

- **Textiles:** Like paper, textiles are sensitive to changes in humidity and to a lesser extent changes in temperature. In modern textile plants, yarn moves at very high speeds and any changes in flexibility and strength of the yarn because of the change in humidity and temperature will thus affect the production.

- **Precision Parts and Clean Rooms:** In manufacturing of precision metal parts air conditioning helps to:-

(a) Keep the temperature uniform so that the metal will not expand & contract.
(b) Maintain a humidity so that rust is prevented.
(c) Filter the air to minimize dust.

- **Photographic Products:** Raw photographic materials deteriorate fast in high humidity and temperatures. Other materials used in coating film also require a careful control of temperature. Therefore, photographic-products industry is a large user of refrigeration and air conditioning.

- **Computer Rooms:** In computer rooms, air conditioning controls temperature, humidity and cleanliness of the air. Some electronic components operate in a faulty manner if they become too hot. One means of preventing such localized high temperature is to maintain the air temperature in the computer room in the range of 20 to 23 0C. The electronic components in the computer functions favorably at even lower temperatures, but this temperature is a compromise with the lowest comfortable temperature for occupants. A relative humidity of about 65% is maintained for comfort condition.

- **Air Conditioning of Vehicles:** For comfortable journey, planes, trains, ships, buses are air conditioned. In many of these vehicles the major contributor to the cooling load is the heat from solar radiation and in case of public transportation, heat from people.

- Apart from the above said applications air-conditioning have many direct and indirect applications combined with refrigeration.

Psychrometry:

- **Psychrometry** is the study of the properties of mixtures of air and water vapour.
- **Atmospheric air** makes up the environment in almost every type of air conditioning system. Hence a thorough understanding of the properties of atmospheric air and the ability to analyse various processes involving air is fundamental to air conditioning design.
- **Atmospheric air is a mixture** of many gases plus **water vapour** and a **number of pollutants**. The amount of water vapour and pollutants vary from place to place. **The concentration of water vapour and**

pollutants decrease with altitude, and above an altitude of about 10 km, atmospheric air consists of only dry air. The pollutants have to be filtered out before processing the air. Hence, what we process is essentially a mixture of various gases that constitute air and water vapour. This mixture is known as moist air.

- **The moist air** can be thought of as a mixture of dry air and moisture. For all practical purposes, the composition of dry air can be considered as constant. In 1949, a standard composition of dry air was fixed by the International Joint Committee on Psychrometric data. It is given in Table

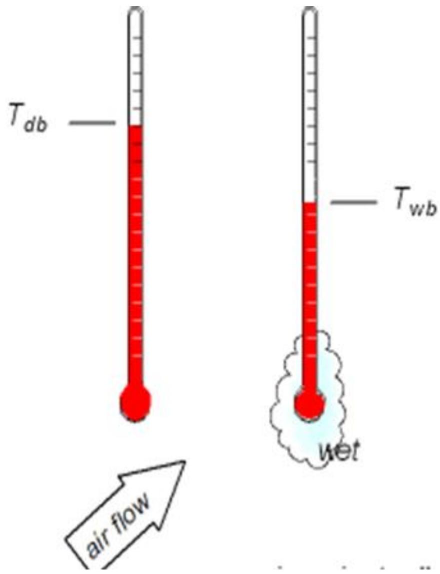
Constituent	Molecular weight	Mol fraction
Oxygen	32.000	0.2095
Nitrogen	28.016	0.7809
Argon	39.944	0.0093
Carbon dioxide	44.010	0.0003

- Based on the above composition the molecular weight of dry air is found to be **28.966** and the gas constant R is **287.035 J/kg.K.**
- As mentioned before the air to be processed in air conditioning systems is a mixture of dry air and water vapour. While the composition of dry air is constant, the amount of water vapour present in the air may vary from zero to a maximum depending upon the temperature and pressure of the mixture (dry air + water vapour).
- At a given temperature and pressure the dry air can only hold a certain maximum amount of moisture. When the moisture content is maximum, then the air is known as saturated air, which is established by a neutral equilibrium between the moist air and the liquid or solid phases of water.

- For calculation purposes, the molecular weight of water vapour is taken as **18.015** and its gas constant is **461.52 J/kg.K**.

Important Psychrometric Properties:

- **The Dry Bulb, Wet Bulb and Dew Point temperatures** are important to **determine the state of humid air**. The knowledge of only two of these values is enough to determine the state - **including the content of water vapour and the sensible and latent energy (enthalpy).**



Dry Bulb Temperature - T_{db}

- The Dry Bulb temperature, usually referred to as air temperature, is the air property that is most common used. When people refer to the temperature of the air, they are normally referring to its dry bulb temperature. The dry-bulb temperature is an indicator of heat content.
- The Dry Bulb Temperature refers basically to the ambient air temperature. It is called "Dry Bulb" because the air temperature is indicated by a thermometer not affected by the moisture of the air.
- Dry-bulb temperature - T_{db}, can be measured using a normal thermometer freely exposed to the air but shielded from radiation and moisture. The temperature is usually given in degrees Celsius (^oC) or degrees Fahrenheit (^oF). The SI unit is Kelvin (K). Zero Kelvin equals to -273^{o}C.

Wet Bulb Temperature - T_{wb}

- The Wet Bulb temperature is the temperature of adiabatic saturation. This is the temperature indicated by a moistened thermometer bulb exposed to the air flow.
- Wet Bulb temperature can be measured by using a thermometer with the bulb wrapped in wet muslin. The adiabatic evaporation of water from the thermometer and the cooling effect is indicated by a "wet bulb temperature" lower than the "dry bulb temperature" in the air.

- The rate of evaporation from the wet bandage on the bulb, and the temperature difference between the dry bulb and wet bulb, depends on the humidity of the air. The evaporation is reduced when the air contains more water vapour.
- The wet bulb temperature is always lower than the dry bulb temperature but will be identical with 100% relative humidity (the air is at the saturation line).

Dew Point Temperature - T_{dp}

- The Dew Point is the temperature at which water vapour starts to condense out of the air (the temperature at which air becomes completely saturated). Above this temperature the moisture will stay in the air.
  - **If the dew-point temperature is close to the dry air temperature - the relative humidity is high.**
  - **If the dew point is well below the dry air temperature - the relative humidity is low.**
- If moisture condenses on a cold bottle taken from the refrigerator, the dew-point temperature of the air is above the temperature in the refrigerator.
- The Dew Point temperature can be measured by filling a metal can with water and some ice cubes. Stir by a thermometer and watch the outside of the can. When the vapor in the air starts to condensate on the outside of the can, the temperature on the thermometer is pretty close to the dew point of the actual air.

Relative Humidity (f)

- It is defined as **the ratio of mass of water vapour in a certain volume of moist air at a given temperature (i.e. unsaturated air) to the saturated mass of water vapour in the same volume at the same temperature.**
- The relative humidity can also be defined as **the ratio of partial pressure of water vapour in an unsaturated moist air at a given**

temperature T to the saturation pressure of water vapour at the same temperature T.

$$f = m_v / m_{vs}$$

- Where, subscripts **v** and **s** stand for **unsaturated** and **saturated** conditions respectively.

Specific Humidity or Humidity Ratio (w)

- It is defined as the ratio of mass of water vapour to the mass of dry air in a given volume of the mixture.

$$w = m_v/m_a = (V/v_v)/(V/v_a) = v_a/v_v$$

- Where, subscripts **a** and **v** stand for **air** and **water vapour** respectively.
- Also, **the specific humidity is not a mass fraction of water vapour. Rather, it is the fraction of water vapour in dry air for a given volume of the mixture.**

Degree of Saturation (m)

- It is defined as the ratio of actual **w** to the specific humidity w_s of saturated air at the same temperature T and pressure p. degree of saturation represents the capacity of air to absorb moisture. Thus,

$$m = w/w_s$$

Enthalpy of Moist Air

- It is obtained by the summation of enthalpies of its constituents, i.e. dry air and the water vapour. Thus, Enthalpy of moist air (h) is equal to

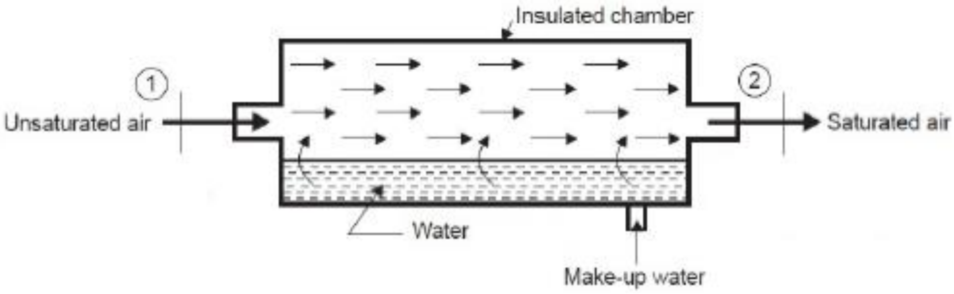
$$h = h_a + wh_v \text{, per kg of dry air}$$

- Where, h_a is the enthalpy of **dry air** and wh_v is the enthalpy of the **water vapour.**

Adiabatic Saturation Temperature (T*)

- When the unsaturated air flows over a long sheet of water, the water evaporates and the moisture content of air increases (as shown in the figure below). Because of the evaporation, both the water and the air are cooled the process continues till the thermal equilibrium, i.e. energy transferred from air to water is exactly same as the energy needed to vaporise the water When this condition is reached, air is saturated.

- **This equilibrium temperature is known as adiabatic saturation temperature or thermodynamic wet bulb temperature**. The adiabatic saturation temperature is taken equal to WBT for all practical purposes, i.e. **WBT = T*.**



Specific volume

- The specific volume is defined as **the number of cubic meters of moist air per kilogram of dry air**. From perfect gas equation since the volumes occupied by the individual substances are the same, the specific volume is also equal to the number of cubic meters of dry air per kilogram of dry air.

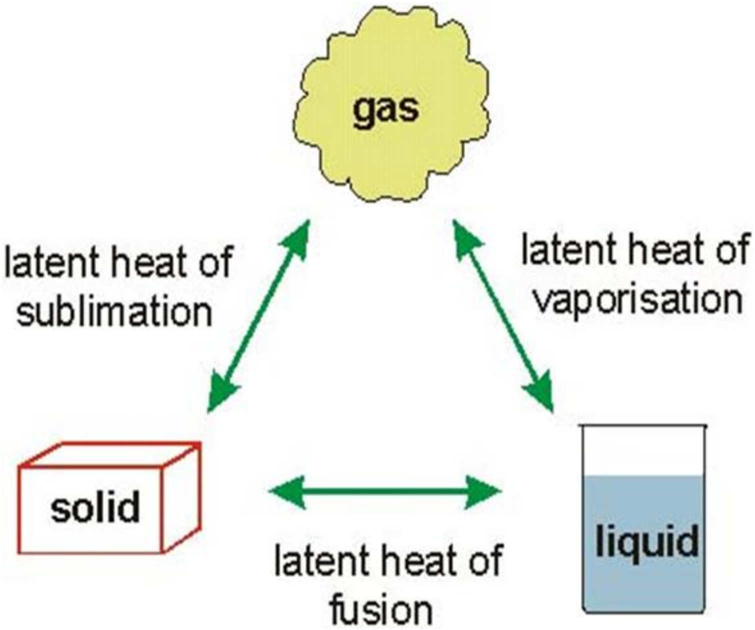
Sensible heat

- When an object is heated, its **temperature rises** as heat is added. The increase in heat is called **sensible heat addition**. Similarly, when heat is removed from an object and its **temperature falls**, the heat removed is also called **sensible heat of cooling**.
- Heat that causes a change in temperature in an object is called **sensible heat**.

Latent heat

- Latent heat is the **moisture content in the air**.
- All pure substances in nature are able to change their state. Solids can become liquids (ice to water) and liquids can become gases (water to vapour) but changes such as these require the addition or removal of heat. The heat that causes these changes is called latent heat.

- Latent heat however, does not affect the temperature of a substance - for example, water remains at 100°C while boiling. The heat added to keep the water boiling is latent heat. Heat that causes a change of state with no change in temperature is called latent heat.
- Appreciating this difference is fundamental to understanding why refrigerant is used in cooling systems. It also explains why the terms **'total capacity' (sensible & latent heat) and 'sensible capacity' are used to define a unit's cooling capacity.**
- During the cooling cycling, condensation forms within the unit due to the removal of latent heat from the air. Sensible capacity is the capacity required to lower the temperature and latent capacity is the capacity to remove the moisture from the air.



- There is water vapor in the air. If you want to take it out, you must condense it out by passing it across a surface which is cold enough (at or below dew point) to cause water to form (like the mirror in the bathroom when you take a shower, or a window on a winter day).

- This condensation occurs at 100 % relative humidity. When the air can no longer hold any greater concentration of water vapour, the vapour will change to a liquid. When a vapour changes to a liquid, it gives up heat. This is latent heat, because the energy came from changing vapour into liquid, not from lowering the temperature. All refrigeration units have some effect on both latent and sensible heat, assuming the evaporator is below dew point.

- The proportion will vary according to the amount that the coil temperature falls below dew point, and the time the air (with water vapour) gets to sit on that coil and lose energy.
- In other words, the temperature (sensible) does not change, but rather the energy is given up by the process of changing state from a gas to a liquid.

Application of Sensible and Latent heat in air-conditioning

- **Sensible heat is that heat which you can sense (standard temperature readings). Latent heat is that heat which you cannot sense (the heat energy that it took to turn that water into vapour in the first place), although the energy is still there.**
- **When you remove water from the air without changing the temperature, your RELATIVE humidity goes down. You have changed the RELATIVE amount of LATENT HEAT (moisture) to SENSIBLE HEAT (temperature).**
- **When you raise the (Sensible) temperature without adding water vapour (latent heat), your RELATIVE humidity goes down, because the RELATIONSHIP between temperature and water content has changed, in favour of temperature.**
- **If you add BOTH LATENT and SENSIBLE heat, your RELATIVE humidity may stay the same, if you have maintained the same proportions.**
- During the last few years, there has been an increase in the use of total heat evaporator selections offered for sale as a result of the globalization within the market. Global manufacturers, who have historically designed and rated their equipment for use in what is often referred to as the commercial refrigeration and light industrial markets, have been pursuing business in the industrial refrigeration market. Because evaporator coil capacity is strongly affected by entering air moisture content, it has become important to realize the potential consequences of a total heat evaporator selection.

What is "total heat"?

- **Total heat is the sum of the sensible heat and latent heat portions of the evaporator load** as shown in the equation:

$$Q_t = Q_s + Q_l$$

Where;

Q_t = Total heat load

Q_s = Sensible heat load

Q_l = Latent heat load

Sensible and latent heat loads

- The design cooling load (or heat gain) is the amount of heat energy to be removed from a house by the **HVAC (Heating Ventilation and Air-Conditioning)** equipment to maintain the house at indoor design temperature when worst case outdoor design temperature is being experienced.
- There are two types of cooling loads:
  - Sensible cooling load(Q_s)
  - Latent cooling load(Q_l)
- **The sensible cooling load refers to the dry bulb temperature of the building and the latent cooling load refers to the wet bulb temperature of the building.**
- **For summer conditions the humidity influence** on the selection of the HVAC equipment and the latent load as well as the sensible load must be calculated.

Factors that influence sensible cooling load

- Glass windows or doors
- Sunlight striking windows, skylights, or glass doors and heating the room
- Exterior walls
- Partitions (that separate spaces of different temperatures)
- Ceilings under an attic
- Roofs
- Floors over an open crawl space
- Air infiltration through cracks in the building, doors, and windows
- People in the building
- Equipment and appliances operated in the summer

- Lights

- Notice that below grade walls, below grade floors, and floors on concrete slabs do not increase the cooling load on the structure and are therefore ignored.
- Other sensible heat gains are taken care of by the HVAC equipment before the air reaches the rooms (system gains). Two items that may require additional sensible cooling capacity from the HVAC equipment are:
  - Duct work located in an unconditioned space.
  - Ventilation air (air that is mechanically introduced into the building).

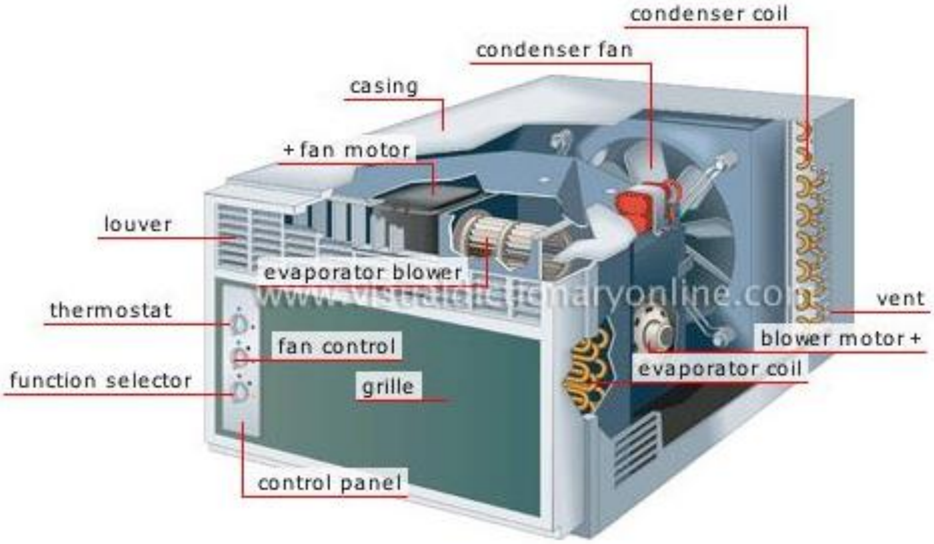
Air Conditioning systems

- In air conditioning it includes the cooling and heating of air, cleaning and controlling its moisture level as well as conditioning it to provide maximum indoor comfort.
- An air conditioner transfers heat from the inside of a building, where it is not wanted, to the outside. Refrigerant in the system absorbs the excess heat and is then pumped through a closed system of piping to an outside coil. A fan blows outside air over the hot coil, transferring heat from the refrigerant to the outdoor air. Because the heat is removed from the indoor air, the indoor area is cooled.
- An air conditioning system generally consists of five mechanical components: 1. Compressor 2. Fan 3. Condenser Coil (Hot) 4. Evaporator Coil (Cool) 5. Chemical Refrigerant

Window Air Conditioner

- Window air conditioner is sometimes referred to as room air conditioner as well. It is the simplest form of an air conditioning system and is mounted on windows or walls. It is a single unit that is assembled in a casing where all the components are located.

- This refrigeration unit has a double shaft fan motor with fans mounted on both sides of the motor. One at the evaporator side and the other at the condenser side. The evaporator side is located facing the room for cooling of the space and the condenser side outdoor for heat rejection. There is an insulated partition separating this two sides within the same casing.
- Schematic layout and components of a window air-conditioner are shown in figures below.



Window Air-Conditioner Unit

❖ Front Panel

- The front panel is the one that is seen by the user from inside the room where it is installed and has a user interfaced control be it electronically or mechanically. Older unit usually are of mechanical control type with rotary knobs to control the temperature and fan speed of the air conditioner.
- The newer units come with electronic control system where the functions are controlled using remote control and touch panel with digital display.
- The front panel has adjustable horizontal and vertical (some models) louvers where the direction of air flow are adjustable to suit the comfort of the users.
- The fresh intake of air called VENT (ventilation) is provided at the panel in the event that user would like to have a certain amount of fresh air from the outside.

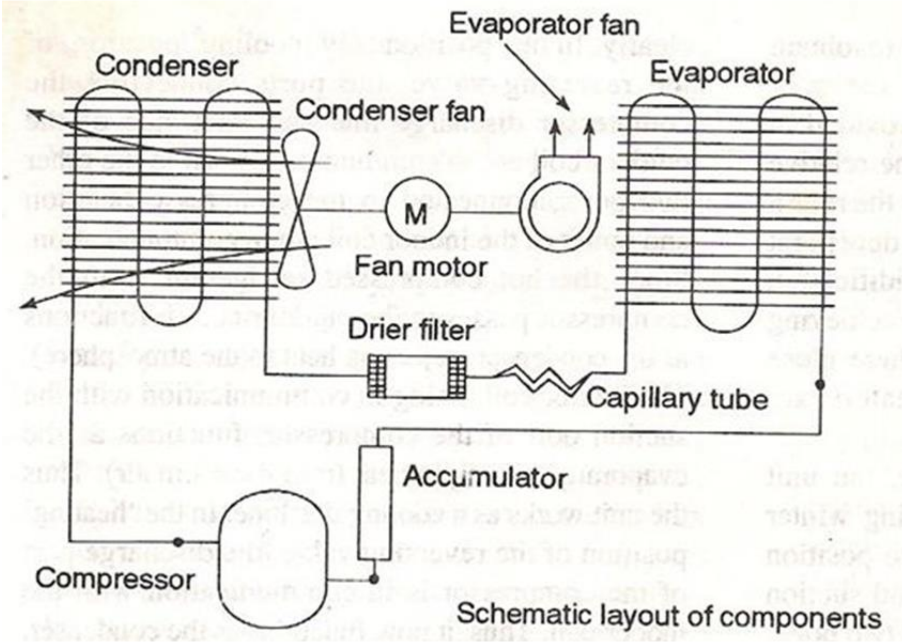
- The mechanical type is usually lower in price compared to the electronic type. If you just want to cool the room and are not too particular about aesthetic or additional functions, the mechanical type will do the work.

Indoor Side Components

- The indoor parts of a window air conditioner include:
  - **Cooling Coil** with an air filter mounted on it. The cooling coil is where the heat exchange happen between the refrigerant in the system and the air in the room.
  - **Fan Blower** is a centrifugal evaporator blower to discharge the cool air to the room.
  - **Capillary Tube** is used as an expansion device. It can be noisy during operation if installed too near the evaporator.
  - **Operation Panel** is used to control the temperature and speed of the blower fan. A thermostat is used to sense the return air temperature and another one to monitor the temperature of the coil. Type of control can be mechanical or electronic type.
  - **Filter Drier** is used to remove the moisture from the refrigerant.
  - **Drain Pan** is used to contain the water that condensate from the cooling coil and is discharged out to the outdoor by gravity.

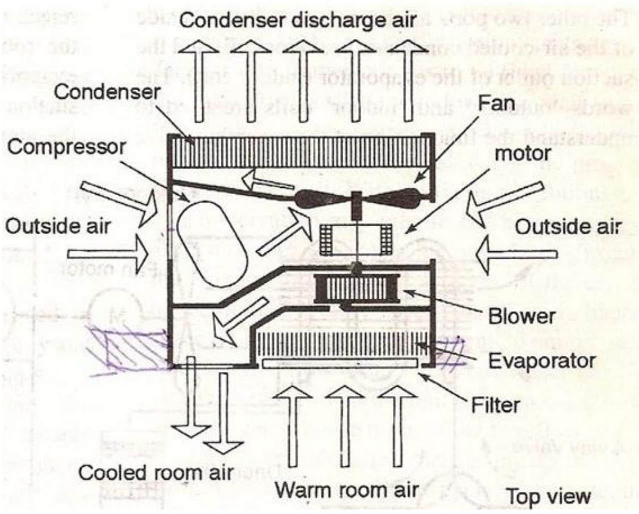
Outdoor Side Components

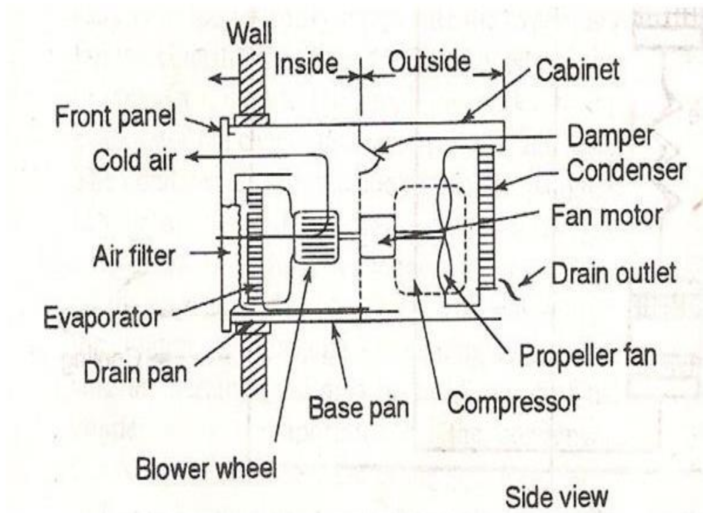
- The outdoor side parts include:
  - **Compressor** is used to compress the refrigerant.
  - **Condenser Coil** is used to reject heat from the refrigeration to the outside air.
  - **Propeller Fan** is used in air-cooled condenser to help move the air molecules over the surface of the condensing coil.
  - **Fan Motor** is located here. It has a double shaft where the indoor blower and outdoor propeller fan are connected together.



Operations

- Following figures show operation of a window air-conditioner with the help of top and side views:





- During operation, a thermostat is mounted on the return air of the unit. This temperature is used to control the on or off of the compressor. Once the room temperature has been achieved, the compressor cuts off.
- Usually, it has to be off for at least 3 minutes before turning on again to prevent it from being damaged. For mechanical control type, there is usually a caution to turn on the unit after the unit has turned off for at

least 3 minutes. For electronic control, there is usually a timer to automatically control the cut-in and cut-out of compressor.

- The evaporator blower fan will suck the air from the room to be conditioned through the air filter and the cooling coil. Air that has been conditioned is then discharge to deliver the cool and dehumidified air back to the room. This air mixes with the room air to bring down the temperature and humidity level of the room.
- The introduction of fresh air from outside the room is done through the damper which is then mixed with the return air from the room before passing it over the air filter and the cooling coil.
- The air filter which is mounted in front of the evaporator acts as a filter to keep the cooling coil clean to obtain good heat-transfer from the coil. Hence, regular washing and cleaning of the air filter is a good practice to ensure efficient operation of the air conditioner.

Humidification

- A **humidifier** is a device that increases humidity (moisture) in a single room or an entire building. In the home, point-of-use humidifiers are commonly used to humidify a single room, while whole-house or furnace humidifiers, which connect to a home's HVAC system, provide humidity to the entire house

Dehumidification

- A dehumidifier is an electrical appliance which reduces and maintains the level of humidity in the air, usually for health or comfort reasons, or to eliminate musty odor and to prevent the growth of mildew by extracting water from the air. It can be used for household, commercial, or industrial applications. Large dehumidifiers are used in commercial buildings such as indoor ice rinks and swimming pools, as well as manufacturing plants or storage warehouses.

Cycles in an Air-Conditioner

❖ COOLING CYCLE

- Refrigerant passes through the indoor coil, evaporating from a liquid to a vapour. As the liquid evaporates, it absorbs heat, cooling the air around the coil. An indoor fan pushes this cooled air through ducts inside the house. Meanwhile, the vaporized refrigerant laden with heat, passes through a compressor which compresses the vapour, raising its temperature and pressure. The reversing valve directs the flow of hot, high pressure vapour to the outdoor coil where the heat released during condensation is fanned into the outdoor air, and the cycle begins again.

❖ HEATING CYCLE

- During the heating cycle the refrigerant flows in reverse. Liquid refrigerant now flows to the outdoor coil picking up heat as it evaporates into a low pressure vapour. The vapour travels through the compressor where it is compressed into a hot, high pressure vapour, then is directed by the reversing valve to the indoor coil.

- Then vapour turns into liquid as it passes through the indoor coil, releasing heat that is pushed through the ducts by the indoor fan.

UNIT-3 FLUID MECHANICS & FLUID MACHINERY

LECTURE-19

Date..........

Fluid Mechanics:

It is that branch of science which deals with the behaviour of fluid (liquid or gas) at rest as well as in motion.

Properties of fluid:

1- Density or mass density:

It is defined as the ratio of the mass of a fluid to its volume.

It is denoted by ρ.

Its unit is kg/m^3.

Mathematically

$$\boxed{\rho = \frac{m}{V}}$$

mass per unit volume.

$\Rightarrow \rho = 1000 \ kg/m^3$ for water.

2- Specific weight or weight density:

It is the ratio of the weight of a fluid to its volume.

It is denoted by 'w'.

Its unit is N/m^3.

Mathematically, $w = \frac{W}{V} = \frac{m \cdot g}{V} = \rho \cdot g$

$$\boxed{w = \rho \cdot g}$$

3- Specific volume:

It is defined as the volume of a fluid occupied by a unit mass.

It is the reciprocal of mass density. It is expressed as m^3/kg.

$$\text{specific volume} = \frac{V}{m} = \frac{1}{m/V} = \frac{1}{\rho}$$

4- Specific gravity: It is defined as the ratio of weight density (density) of a fluid to the weight density (density) of a standard fluid.

For liquid: Standard fluid is water.

For gases: Standard fluid is air.

→ It is also called relative density.

→ It is denoted by S.

→ It is dimensionless quantity.

NOTE: 1 litre $= 10^{-3}\ m^3$

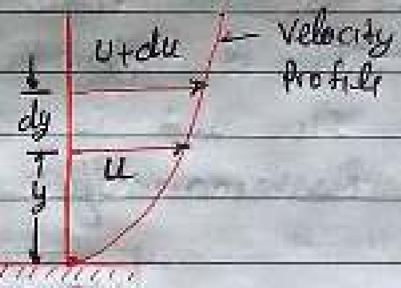
Density of water $= 1000\ kg/m^3$

Viscosity: It is defined as the property of a fluid which offers resistance to the movement of one layer of fluid to another adjacent layer of the fluid.

It is of two types:

1- Dynamic viscosity:

When two layers of fluid, a distance 'dy' apart, move one over the other at different velocities, say u and u+du,



The viscosity together with relative velocity causes a shear stress acting between the fluid layers.

This shear stress is proportional to the rate of change of velocity with respect to y. It is denoted by 'τ'.

Mathematically $\tau \propto \frac{du}{dy}$

$$\boxed{\tau = \mu \frac{du}{dy}}$$

Date..........................

The constant of proportionality (μ) is known as coefficient of dynamic viscosity or simply viscosity.

so,

$$\boxed{\mu = \frac{\tau}{du/dy}}$$

Dynamic viscosity is defined as the shear stress required to produce unit rate of shear strain.

It unit is $N \cdot s/m^2$. [SI unit]

Another unit of viscosity is Poise. [CGS unit]

$$\boxed{1 \text{ Poise} = \frac{1}{10} \ N\text{-}s/m^2}$$

Kinematic viscosity: It is defined as the ratio of dynamic viscosity to density of fluid.

It is denoted by 'ν'.

Its unit is m^2/s in SI and stoke in CGS.

$$\boxed{1 \text{ stoke} = 10^{-4} \ m^2/s.}$$

mathematically,

$$\boxed{\nu = \frac{\mu}{\rho}}$$

Newton's law of viscosity:

It state that the shear stress (τ) on a fluid element layer is directly proportional to the rate of shear strain. The constant of proportionality is called the coefficient of viscosity.

$$\tau \propto \frac{du}{dy}$$

$$\boxed{\tau = \mu \frac{du}{dy}}$$

Date.............

LECTURE: 20

Types of fluid:

Fluid may be classified into the following types.

1- Ideal fluid:

A fluid which is incompressible and is having no viscosity, is known as ideal fluid.

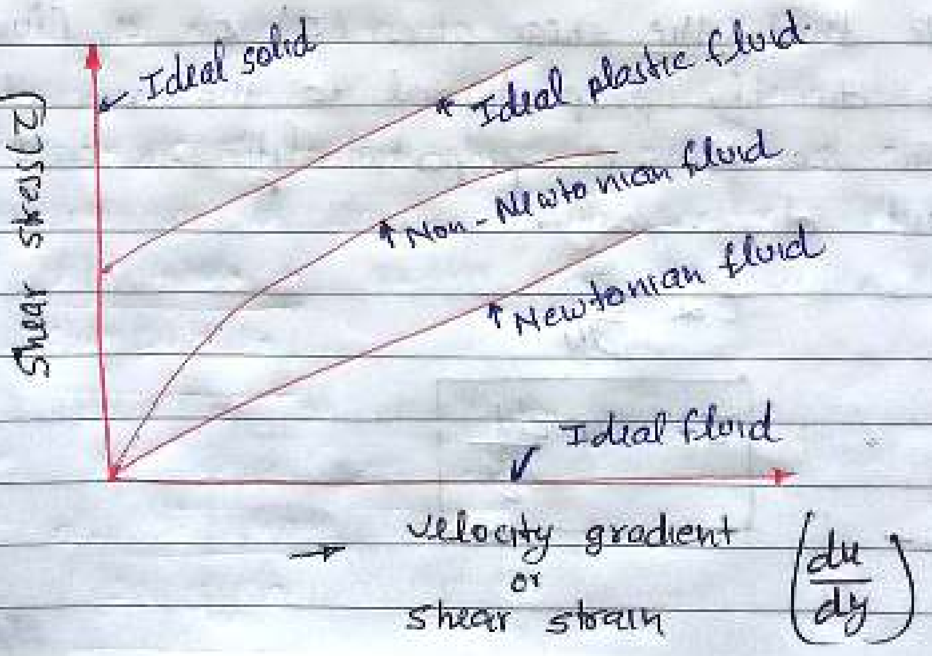
Ideal fluid is only an imaginary fluid as all the fluid which exist, have some viscosity.

2- Real fluid: A fluid which possesses viscosity, is known as real fluid.

All the fluid in actual practice are real fluid.

3- Newtonian fluid: A real fluid, in which the shear stress is directly proportional to rate of shear strain. i.e. fluids which obey Newton's law of viscosity, are known as newtonian fluid.

4- Non Newtonian fluid: A fluid, in which the shear stress is not directly proportional to rate of shear strain i.e. fluid which do not obey newton's law of viscosity, is known as non-newtonian fluid.



Spiral

Date..................

Fluid pressure at a point:

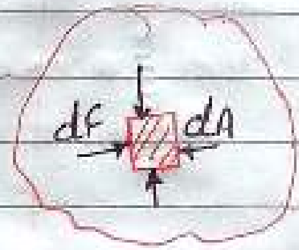
Consider a small area 'dA' in large mass of fluid, then the force exerted 'dF', by the surrounding fluid on 'dA' will always perpendicular to the surface dA.

Then the ratio of 'dF/dA' is known as intensity of pressure or simply pressure.

It is denoted by 'p'.

Mathematically,

$$\boxed{p = \frac{dF}{dA}}$$



If force (F) is uniformally distributed over the area(A) then

$$\boxed{p = \frac{F}{A}}$$

Unit of pressure is N/m^2 or Pascal (Pa)

$$\boxed{\begin{array}{c} 1\,Pa = 1\,N/m^2 \\ \hline 1\,MPa = 1\,N/mm^2 \end{array}}$$

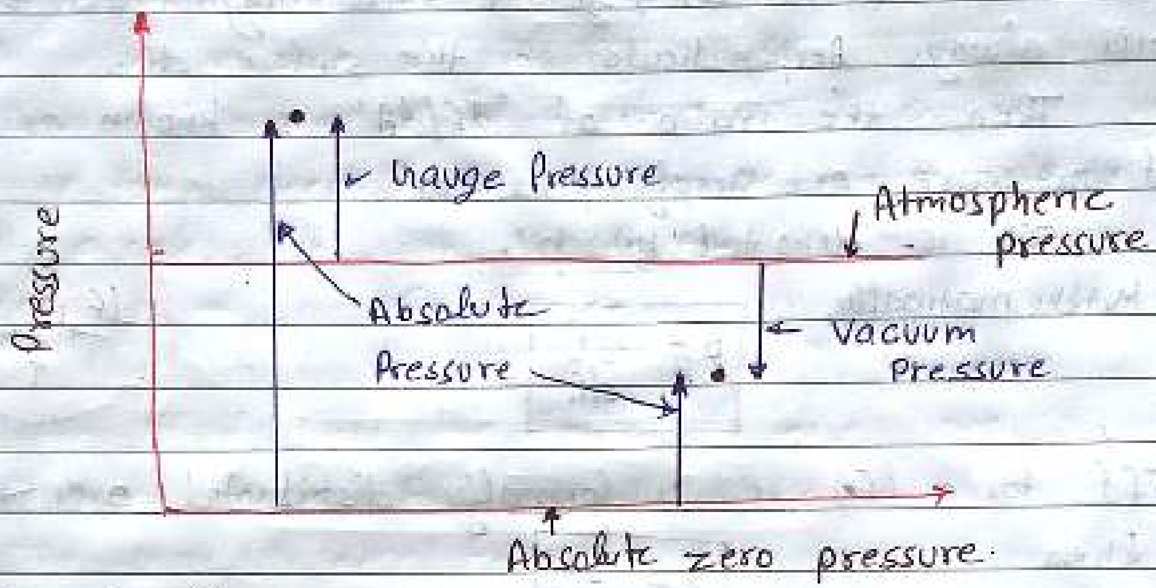
Measurement of Pressure [Absolute, Gauge, Atmospheric and vaccuum pressure]:

The pressure on a fluid is measured in two different systems. In one system, it is measured below atmospheric pressure (Vaccuum) & other is above atmospheric pressure.

1- Absolute pressure: It is defined as the pressure which is measured with reference to absolute vacuum pressure.

2- Gauge pressure: It is defined as the pressure which is measured with the help of a pressure measuring instrument in which the atmospheric pressure is taken as datum. The atmp pressure on the scale is marked as zero.

3- Vacuum pressure: It is defined as the pressure below the atmospheric pressure.



Mathematically,

Absolute pressure = Atmospheric pressure + Gauge Pressure

$$\boxed{P_{abs} = P_{atm} + P_{gauge}}$$

Vacuum pressure = Atmospheric pressure − Absolute pressure

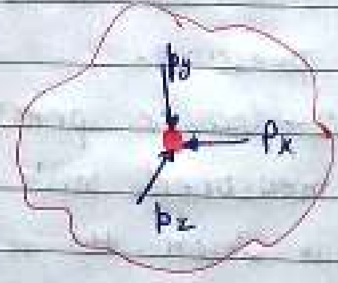
$$\boxed{P_{vac} = P_{atm} - P_{abs}}$$

→ Atmospheric pressure is taken as $101.3\ KN/m^2$ or $1.013 \times 10^5\ N/m^2$ or 1.013×10^5 Pa or $10.13\ N/cm^2$.

→ Atmospheric pressure ~~head~~ is 760 mm of Hg or 10.33 m of water.

Pascal's Law: It state that the pressure or intensity of pressure at a point in a static fluid is equal in all direction.

$$\boxed{p_x = p_y = p_z}$$



Pressure at any point 'A' at a height of 'h' from free surface

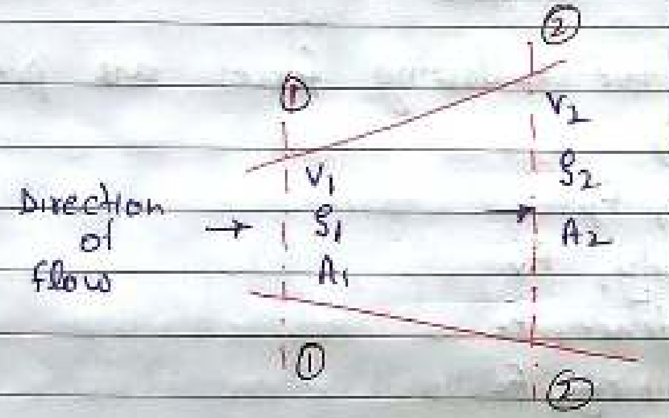
$$\boxed{p = \rho g h}$$

Continuity Equation:

Continuity equation is derived for kinematics of flow, which deals with motion of particles without considering the forces causing the motion. (study S, V, and a only)

The equation based on the principle of conservation of mass is called continuity equation.

Thus for a fluid flowing through the pipe at all the cross section, the quantity of fluid per second is constant.



Fluid kinematics
→ Lagrangian approach
(Video) observe motion of each particle wrt time from original position. $\vec{S} = f(x_0, y_0, z_0, t)$
→ Eulerian approach
(Picture) (Instantanious behaviour of fluid)

Consider two cross sections of a pipe as shown in fig

Let V_1 → Average velocity at cross section 1-1

ρ_1 → Density at section 1-1

A_1 → Area at section 1-1

and V_2, ρ_2, A_2 are corresponding values at section 2-2

Then rate of flow at section 1-1 $= \rho_1 A_1 V_1$

& rate of flow at section 2-2 $= \rho_2 A_2 V_2$

According to law of conservation of mass

Rate of flow at section 1-1 = Rate of flow at section 2-2

$$\boxed{\rho_1 A_1 V_1 = \rho_2 A_2 V_2}$$

This equation is applicable to the compressible as well as incompressible fluids & is called continuity equation.

If fluid is incompressible then $\rho_1 = \rho_2$, so

$$\boxed{A_1 V_1 = A_2 V_2}$$

Sairal

Dynamics of fluid flow:

It is the study of fluid motion with the forces causing flow. The fluid is assumed to be incompressible and non-viscous.

Dynamic behaviour of fluid flow is analysed by the newton's second law of motion, which relates the acceleration with the forces.

$$\boxed{F_x = m a_x}$$

In the fluid flow, the following forces are present.

(1) Gravity force, F_g
(2) The pressure force, F_p
(3) Force due to viscosity, F_v
(4) Force due to turbulence, F_t
(5) Force due to compressibility, F_c

Thus the net force.

$$\boxed{F_x = F_g + F_p + F_v + F_t + F_c}$$

NOTE: (A) If F_c, is negligible then resultant equations of motion are known as Reynold's equation of motion.

$$\boxed{F_x = F_g + F_p + F_v + F_t}$$

(B) If F_t is negligible then resultant equations of motion are known as Navier-stokes Equation.

$$\boxed{F_x = F_g + F_p + F_v}$$

(C) If the flow is assumed to be Ideal, F_v is zero then resultant equations of motion are known as Euler's equation of motion.

$$\boxed{F_x = F_g + F_p}$$

Differential form of Euler's eq. $\rightarrow \frac{dP}{\rho} + g\,dz + V\,dV = 0$

Date.........

Bernoulli's equation:

Assumptions

(i) The fluid is ideal ie viscosity is zero

(ii) The flow is steady

(iii) The flow is incompressible

(iv) The flow is irrotational

Bernoulli equation is drived using Euler's equation of motion. ie

$$\boxed{\frac{\delta P}{\rho} + g\,dz + v\,dv = 0}$$ Euler's equation.

Bernoulli's equation is obtain by integrating Euler's eq.

$$\int \frac{\delta P}{\rho} + \int g\,dz + \int v\,dv = \text{constant}$$

If flow is incompressible, ρ is constant then.

$$\frac{P}{\rho} + gz + \frac{v^2}{2} = \text{constant}$$

$$\boxed{\frac{P}{\rho g} + \frac{v^2}{2g} + z = \text{Constant}}$$

This is called ~~Euler's~~ Bernoulli's equation of motion. in which

$\frac{P}{\rho g}$ → Pressure energy per unit weight of fluid OR pressure head

work required to maintain the flow/weight

$\frac{v^2}{2g}$ → Kinetic energy per unit weight or kinetic head

z → Potential energy per unit weight or potential head.

So $\boxed{\text{Pressure head + Kinetic head + potential head = Constant}}$

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + Z_2$$

Spiral

Bernoulli's equation for real fluid:

The Bernoulli equation for real fluid between point 1 and 2 is given as

$$\boxed{\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + Z_2 + h_L}$$

where

$h_L \rightarrow$ loss of energy between point 1 and 2.

Practical applications of Bernoulli's equation:

Bernoulli equation is applied in all problems of incompressible fluid flow where energy considerations are involved.

Its practical application to the following measuring devices.

1- Venturimeter
2- Orifice meter
3- Pitot tube.

Cd, Cc and Cv are the coefficient of venturimeter, contraction or orifice meter and pitot tube respectively

$$(Cd)_{orific} << (Cd)_{venturi}$$

$$E_1 = E_2 + E_L$$

$$\frac{E_1}{\rho g} = \frac{E_2}{\rho g} + h_L$$

i.e. $\boxed{h_L = \frac{E_{in} - E_{out}}{\rho g}}$

Date..........

Ques.1: Calculate specific weight, density and specific gravity of one litre of a liquid which weights 7 N.

Ques 2: A flat plate of area 1.5×10^6 mm^2 is pulled with a speed of 0.4 m/s relative to another plate located at a distance of 0.15 mm from it. Find the force and power required to maintain this speed, if the fluid separating them is having viscosity as 1 Poise.

Ques.3 Calculate the pressure due to a column of 0.3m for
(a) water, take density of water $\rho = 1000 \, kg/m^3$
(b) an oil of specific gravity 0.8.
(c) mercury of specific gravity 13.6.

Ques.4. What are the gauge pressure and absolute pressure at a point 3m below the free surface of a liquid having a density of 1.53×10^3 kg/m^3. If the atmospheric pressure is equivalent to 750mm of mercury? The specific gravity of mercury is 13.6 and density of water is 1000 kg/m^3.

Ques.5 A 30cm diameter pipe, conveying water, branches into two pipes of diameters 20cm and 15cm respectively. If the average velocity in the 30cm diameter pipe is 2.5 m/s. find the discharge in this pipe. Also determine the velocity in 15cm pipe if the average velocity in 20cm diameter is 2 m/s.

Ques.6. The water is flowing through a pipe having diameters 20cm and 10cm at sections 1 and 2 respectively. The rate of flow through pipe is 35 liters/s. The section 1 is 6m above datum and section 2 is 4m above datum. If the pressure at section 1 is 39.24 N/cm^2, find the intensity of pressure at section 2.

Spiral

Hydraulic Machine:

Hydraulic machine are defined as those machines which converts either hydraulic energy (energy possed by water) into mechanical energy (which is further converted into electrical energy) or mechanical energy into hydraulic energy.

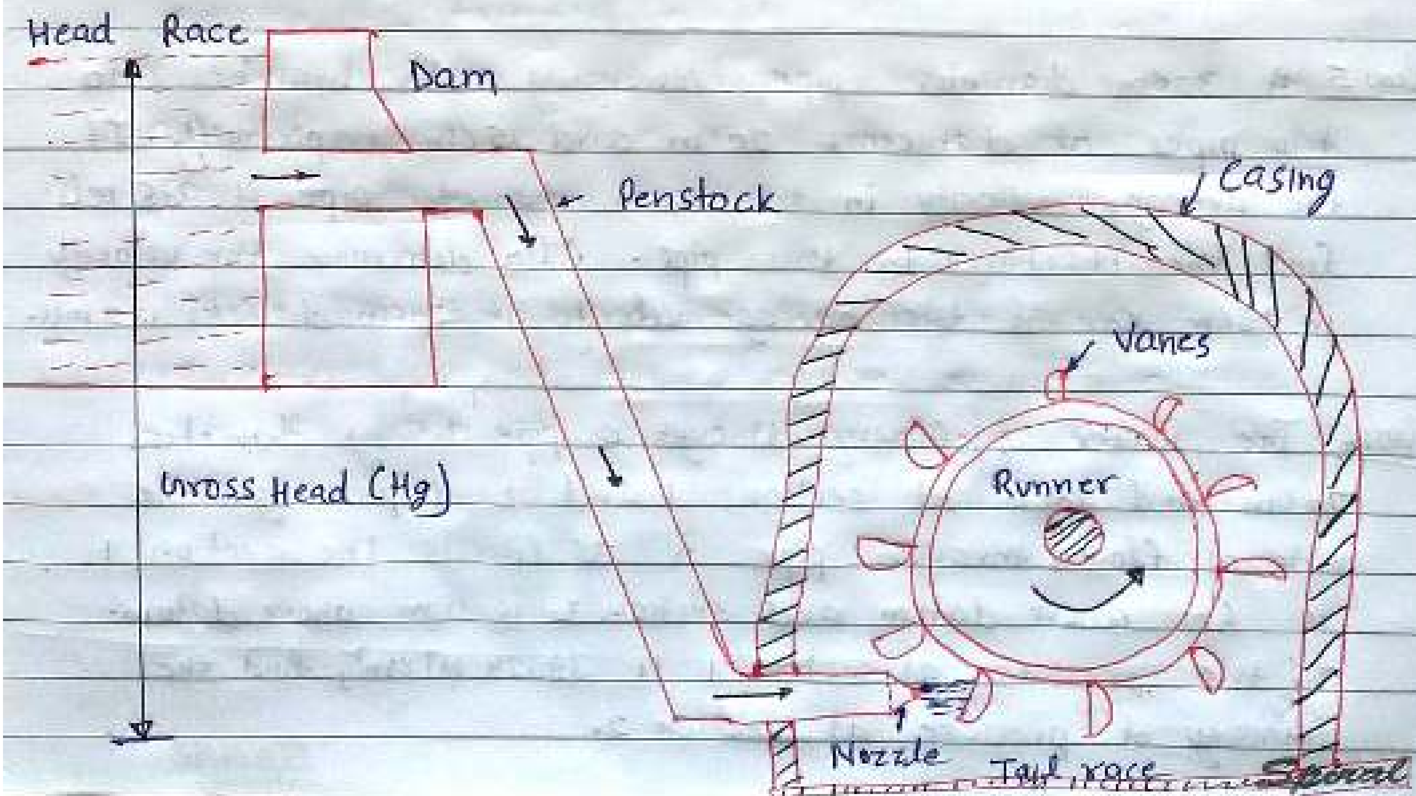
Turbines converts hydraulic energy into mechanical energy.

Pumps converts mechanical energy into hydraulic energy.

Turbines: Turbines are defined as the hydraulic machines which convert hydraulic energy into mechanical energy which is further converted into electrical energy.

The electric power which is obtained from the hydraulic energy (energy of water) is known as Hydro-electric power.

- Construction & working principle of turbine:



Date..........

Hydro-electric power plant consists of

(i) A dam constructed across a river to store water.

(ii) Pipes of large diameter called penstocks, which carry water under pressure from the storage reservoir to the turbines.

(iii) Turbines having different types of vanes fitted to the wheels.

(iv) Tail race, which is a channel carries water away from the turbines after the water has worked on the turbines.

Working Principle:

The liquid comes out in the form of a jet from the outlet of a nozzle through penstock, which is fitted to the dam through which the liquid is flowing under pressure. ~~Nozzle is fitted at the~~ vanes of the wheel are placed in the path of the jet, a force is exerted by the jet on the plate. This force is obtained from Newton's second law of motion or from Impulse-momentum equation.

If the vanes or wheel is stationary then work done by the jet is zero ie no work done on the vanes.

If wheel is moving then the work done on the wheel rotate it which is coupled with shaft. Thus hydraulic energy is converted into mechanical energy.

The force exerted by the jet on the vanes.

F = Rate of change of momentum in the direction of force

$$\boxed{F = \rho A V^2}$$

Work done per second by the jet on the vanes

$$\boxed{W = \rho A V^2 \cdot u}$$

Classification of Hydraulic turbines:
The following are the important classification of the turbines:

1- According to type of energy at inlet:

(a) Impulse turbine: Only kinetic energy available at the inlet of the turbine. Ex- Pelton wheel.

(b) Reaction turbine: If kinetic energy as well as pressure energy available at the inlet of the turbine. Ex- francis turbine, kaplan turbine

2- According to the direction of flow through runner:

(a) Tangential flow turbine: Water is flowing along the tangent of the runner.

(b) Radial flow turbine: If the water flows in the radial direction through the runner.
If the water is flows from outwards to inwards radially, the turbine is known as <u>inward radial flow turbine</u>. <u>Ex</u>: francis turbine.
If the water is flows radially inwards to outwards, the turbine is known as <u>outward radial flow turbine</u>.

(c) Axial flow turbine: If the water flow through the runner along the direction parallel to the axis of rotation of the runner. Ex: Kaplan turbine.

3- According to the head at the inlet of turbine:

(a) High head turbine: Above 250m. Ex: Pelton

(b) Medium head turbine: 60m - 250m. Ex: Francis

(c) Low head turbine: Below 60m. Ex: Kaplan

4- According to the specific speed of the turbine:

(a) Low specific speed turbine: Below 50, Ex - Pelton

(b) Medium specific speed turbine: 50 - 300, Ex - Francis

(c) High specific speed turbine: Above 300, Ex - Kaplan.

Efficiency:

Turbine converts hydraulic energy into mechanical energy.

Power supplied at inlet [Hydraulic power or water power] (W.P.)

→ Hydraulic efficiency $\boxed{(\eta_h) = \frac{R.P.}{W.P.}}$

Power delivered to runner [Runner power] (R.P.)

→ Mechanical efficiency $\boxed{(\eta_m) = \frac{S.P.}{R.P.}}$

Power at the shaft of the turbine [Shaft power] (S.P.)

$$\boxed{\eta_o = \eta_m \times \eta_h = \frac{S.P.}{W.P.}}$$

Electric power

Swinal

Date.........

LECTURE : 25

Pumps:

The hydraulic machines which convert the mechanical energy into hydraulic energy [Pressure energy] are called pumps.

Pumps converts mechanical energy [Shaft power] into impeller power, this impeller power is converted into manometric head ie water power.

Power is decreases from shaft of the pump to impeller and then to the water.

$$E.P. \longrightarrow S.P. \xrightarrow[\text{mechanical efficiency}(\eta_m)]{} I.P. \xrightarrow[\text{Manometric efficiency}(\eta_{man})]{} W.P.\ (\text{Head})$$

$$\boxed{\eta_{man} = \frac{W.P.}{I.P.}}$$

$$\boxed{\eta_m = \frac{I.P.}{S.P.}}$$

$$\boxed{\eta_o = \frac{W.P.}{S.P.}}$$

NOTE:

(i) For high head pumps are connected in series.

(ii) For obtaining high discharge the pump should be connected in parallel.

Date..........................

Classification of pumps:

- Dynamic pumps
  - Radial flow
  - Axial flow
  - Mixed flow
    - Centrifugal Pump
- positive displacement pumps
  - Reciprocating pump
    - Singl acting
    - Doubl acting

Here we discuss in detail construction and working principle of centrifugal pump and reciprocating pump.

Centrifugal pump:

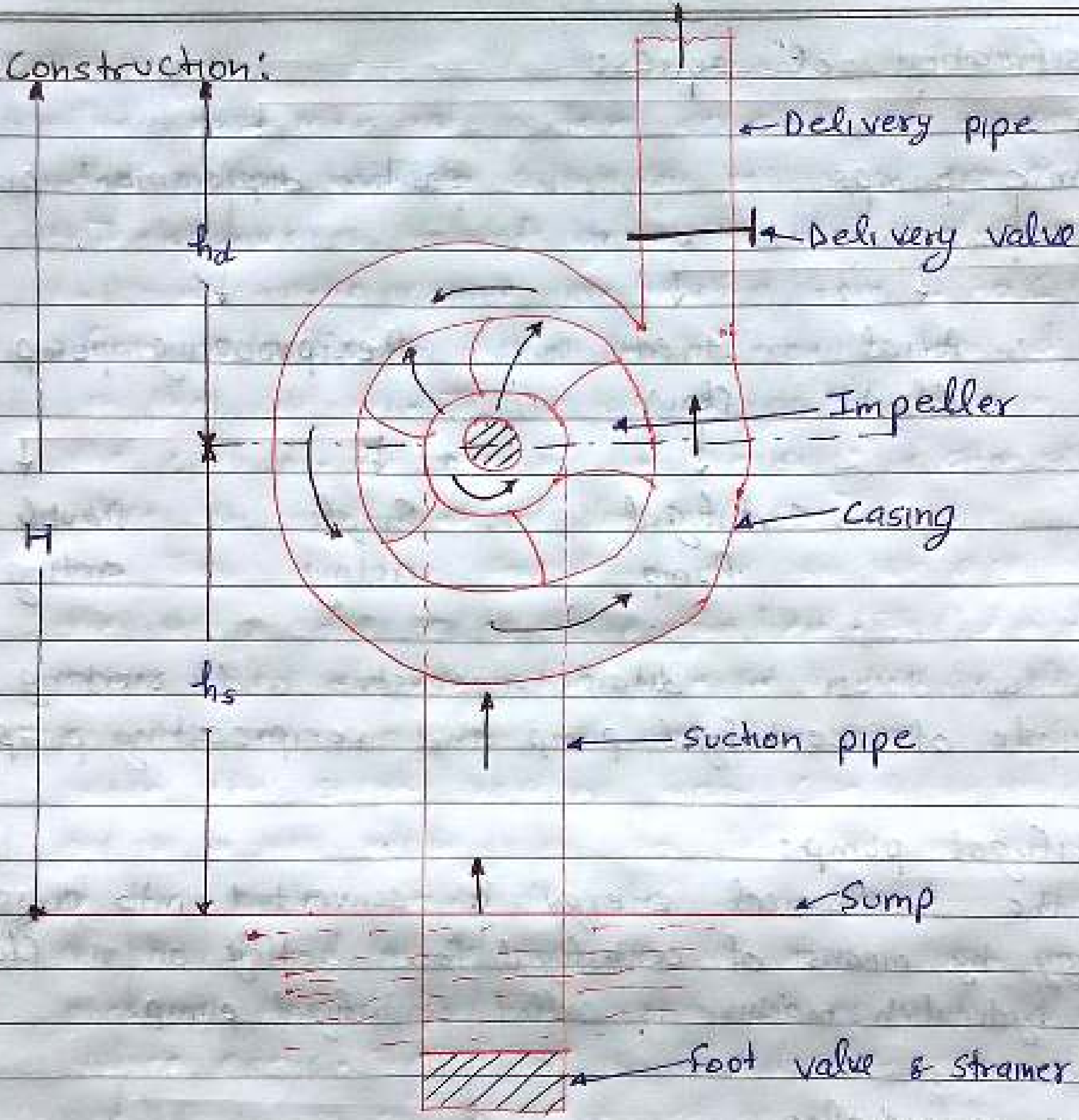
If the mechanical energy is converted into pressure energy by means of centrifugal force acting on the fluid, the hydraulich machine is called centrifugal pump.

Working principle:

Centrifugal pump acts as a reverse of inward flow reaction turbine. The centrifugal pump works on principle of forced vortex flow which means that when a certain mass of liquid is rotated by an external torque, the rise in pressure head of the rotating liquid takes place. The rise in pressure head at any point of the rotating liquid is proportional to the square of tangential velocity of the liquid at that point i.e. rise in pressure head $= \frac{V^2}{2g}$ or $\frac{r^2\omega^2}{2g}$.

Date..........................

Construction:



The main part of a centrifugal pump are:

1- Impeller: It is the rotating part which consists of a series of curved vanes.

2- Casing: It is an air tight passage surrounding the impeller & designed in such a way that kinetic energy is converted into pressure energy.

3- Suction pipe with a foot valve and a strainer: Suction pipe is connect inlet of the pump to water sump. A foot valve opens only in the upward direction (one way valve)

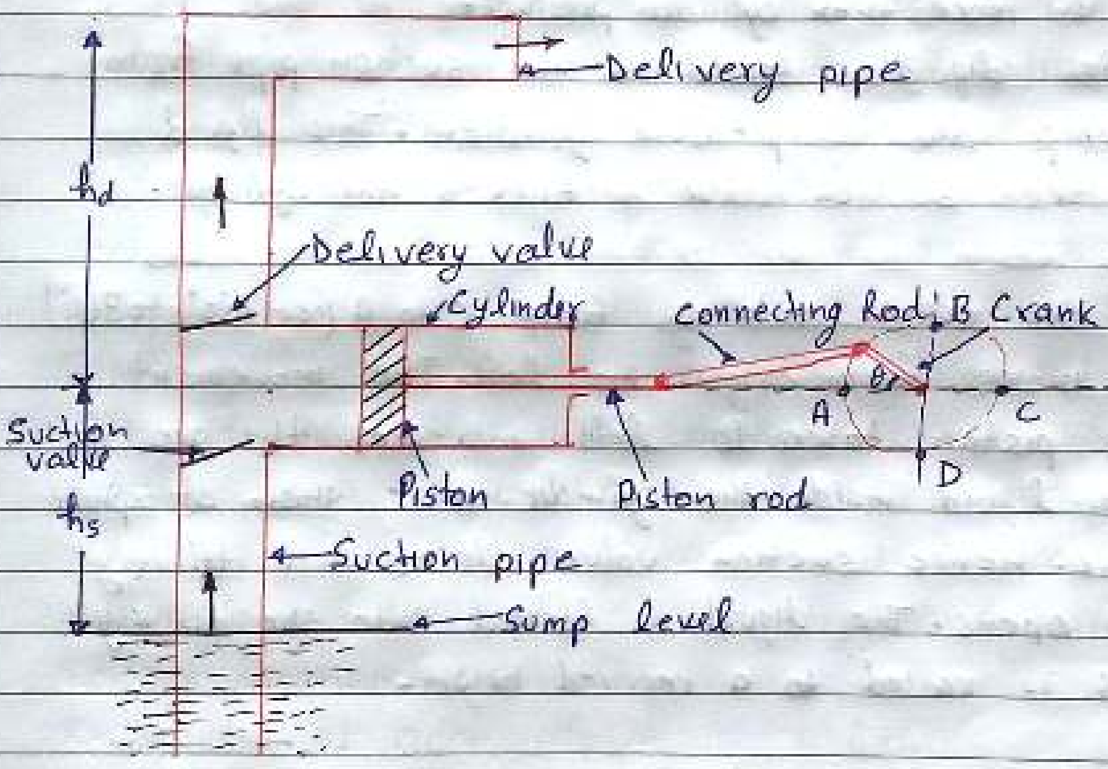
4- Delivery pipe: One end is connected to the outlet of the pump and other end delivers the water at a required height.

Spiral

Reciprocating pump:

If the mechanical energy is converted into hydraulic energy [pressure energy] by sucking the liquid into a cylinder in which a piston is reciprocating, which exerts the thrust on the liquid and increase its hydraulic energy, the pump is known as reciprocating pump.

Constouction and working of Reciprocating pump:



Main parts of the reciprocating pump

1- A cylinder with a piston, piston rod, connecting rod and a crank.
2- Suction pipe: Connected between sump to cylinder.
3- Dieldvery pipe: Conected between cylinder & delivery point.
4- Suction valve: fitted in suction pipe.
5- Delivery valve: fitted in delivery pipe.
valves are one way value which allowed water only upward direction.

Sairal

Working:

The movement of piston is obtained by connecting the piston rod to crank by means of connecting rod. The crank is rotated by means of an electric motor.

When the crank is rotating from A to C (ie from 0 to 180°), the piston is moving toward right in the cylinder. This creates a partial vacuum in the cylinder. But pressure in the sump is atmospheric which is more than cylinder pressure.

Thus liquid is forced in the suction pipe from the sump due to pressure gradient. This liquid opens the suction valve & enters the cylinder.

When the crank rotating from C to A (ie 180° to 360°) piston moves from right to left. The movement of the piston towards left increases the pressure of the liquid inside the cylinder more than atmospheric pressure. Hence suction valve closes and delivery valve opens. The liquid is forced into the delivery pipe & is raised to a required height.

Weight of the water delivered per second

$$W = \rho g Q = \frac{\rho g A L N}{60}$$

Work done per second $= \dfrac{\rho g A L N}{60} \times (h_s + h_d)$

Power required to drive the pump in kW

$$\boxed{P = \frac{\rho g A L N (h_s + h_d)}{60 \times 1000} \text{ kW}}$$

Seeral

Fluid System:

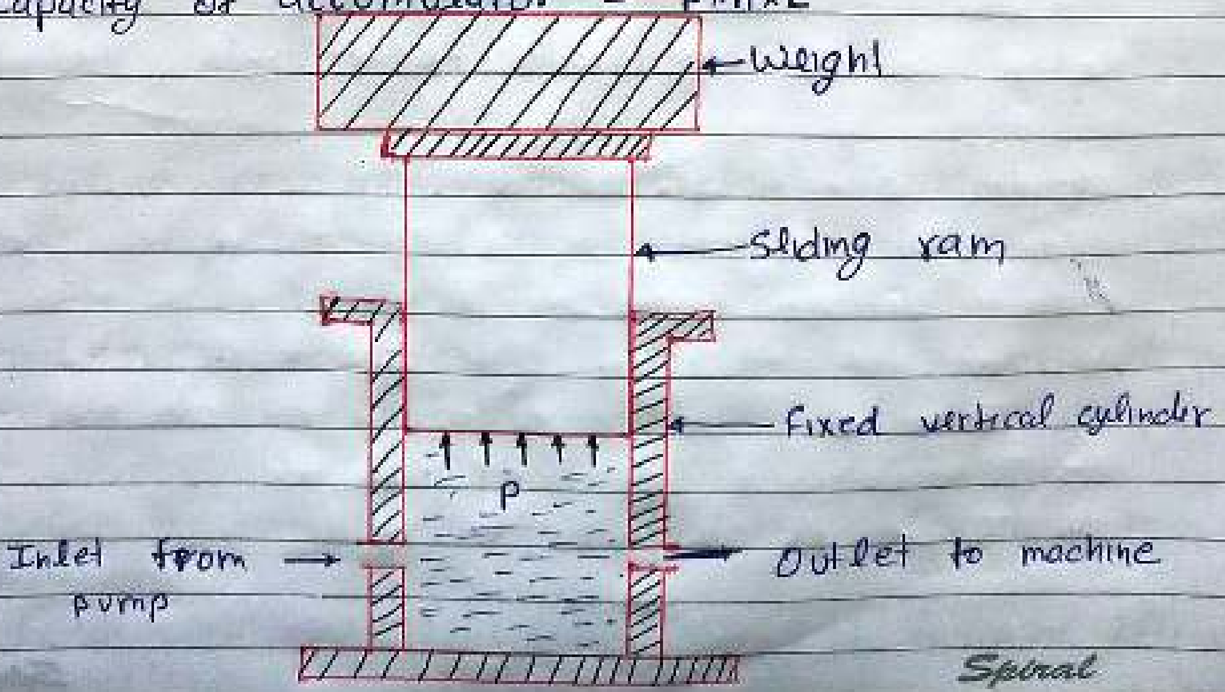
Fluid system is defined as the device in which power is transmitted with the help of a fluid [liquid or gas] under pressure. These devices are based on the principles of fluid statics and fluid kinematics.

Hydraulic accumulator: It is a device used for storing the energy of a liquid in the form of pressure energy which may be supplied for any sudden or intermittent requirement. Ex for hydraulic lift and hydraulic crane.

It consists of a fixed vertical cylinder containing a sliding ram. A heavy weigh is placed on the ram. The inlet of the cylinder is connected to the pump, which continuously supply fluid under pressure to the cylinder. The outlet of the cylinder is connected to the machine (lift or crane).

If the fluid under pressure is not required by the machine, the energy will be stored in the cylinder. When the machine required a large amount of energy, the hydraulic accumulator will supply this energy and ram will move in the downward direction.

Capacity of accumulator = $p \times A \times L$



Spiral

Date..................

Hydraulic lift: It is a device used for carrying passenger or goods from one floor to another in multistoreyed building.

Hydraulic lifts are of two types:

1- Direct acting hydraulic lift

2- Suspended hydraulic lift.

Direct acting hydraulic lift consists of a ram, sliding in fixed cylinder. At the top of the sliding ram, a cage [on which the persons may stand or goods may be placed] is fitted. The liquid under pressure flows into the fixed cylinder. This liquid exerts force on the sliding ram, which moves vertically up & thus raises the cage to the required height.

The cage is moved downward direction, by removing the liquid from the fixed cylinder.

Date.................

Q.1 Define the following fluid properties:
Density, weight density & specific gravity of a fluid

Q.2 Explain the terms: Dynamic viscosity and kinematic viscosity. Give their dimension.

Q.3 Define Newtonian and non-Newtonian fluid.

Q.4 Define pressure. State the pascal's law.

Q.5 Define the equation of continuity. Also derive its expression.

Q.6 What is Euler's equation of motion? How will you obtain Bernoulli's equation from it?

Q.7 Define the terms: Hydraulic machines, turbines and pumps.

Q.8 How will you classify the turbines.

Q.9 Explain construction and working of turbine (Pelton turbine)

Q.10 Explain classification of pumps.

Q.11 Define a centrifugal pump. Explain the working of a single acting centrifugal pump with sketch.

Q.12 What is a reciprocating pump? Describe the principle and working of a reciprocating pump with a neat sketch.

Q.13 Define the term hydraulic accumulator. Explain its working.

Q.14 Explain with neat sketch, the working of hydraulic lift.

Contents of UNIT 4

Measurements and Control System: Concept of Measurement, Error in measurements, Calibration, measurements of pressure, temperature, mass flow rate, strain, force and torques; Concept of accuracy, precision and resolution, Basic Numerical problems. System of Geometric Limit, Fit, Tolerance and gauges, Basic Numerical problems.
Control System Concepts: Introduction to Control Systems, Elements of control system, Basic of open and closed loop control with example.

Measurements System

Measurement:

- Measurement is the process of systematically assigning numbers to objects and their properties, to facilitate the use of mathematics in studying and describing objects and their relationships. Some types of measurement are fairly concrete: for instance, measuring a person's weight in pounds or kilograms, or their height in feet and inches or in meters. Note that the particular system of measurement used is not as important as a consistent set of rules: we can easily convert measurement in kilograms to pounds, for instance. Although any system of units may seem arbitrary (try defending feet and inches to someone who grew up with the metric system!), as long as the system has a consistent relationship with the property being measured, we can use the results in calculations.

Basic Concepts of Measurement:

- The process or the act of measurement consists of obtaining a quantitative comparison between a predefined Standard and a Measurand.
- The measurand or measured quantity is the physical quantity in metrology that is subject to measurement.
- A measurand in the general sense refers to a physical quantity that was or will be subject to measurement. The word Measurand is used to designate the particular physical parameter being observed and quantified; that is, the input quantity to the measuring process.
- A Measurement is an act of assigning a specific value to a physical variable. That physical variable becomes the Measured Variable.
- The standard of comparison must be of the same character as the measurand, and usually is prescribed and defined by a legal or recognized agency or organization.
  Few Examples of Standard Organisation:
  ISO: The International Organization for Standardization
  IS: Indian Standard
  ANSI: The American National Standards Institute.
  NIST: The National Institute of Standards and Technology.
- An engineer is not only interested in the measurement of physical variables but is also concerned with their control. The two functions are closely related, however because one must be able to measure a variable such as temperature or flow in order to control it. The accuracy of control is absolutely dependent on the accuracy of measurement.

- Measurement is also a fundamental element in any control process. Statistical techniques are available for analysing data to determine expected errors and deviations from the actual measurements. An engineer must be therefore be familiar with these techniques in order to analyse the data effectively.

1.1 NEED OF MEASUREMENT

- The word measurement is used to tell us the length, the weight, the temperature, the colour or a change in one of these physical entities of a material.
- Measurement provides us with means for describing the various physical and chemical parameters of materials in quantitative terms.
- Measurement is the result of an opinion formed by one or more observers about the relative size or intensity of some physical quantity. The opinion is formed by the observer after comparing the object with a quantity of same kind chosen as a unit, called standard.
- The result of measurement is expressed by a number representing the ratio of the unknown quantity to the adopted standard. This number gives the value of the measured quantity. For example, 10 cm length of and object implies that the object is 10 times as large as 1 cm; the unit employed in expressing length.

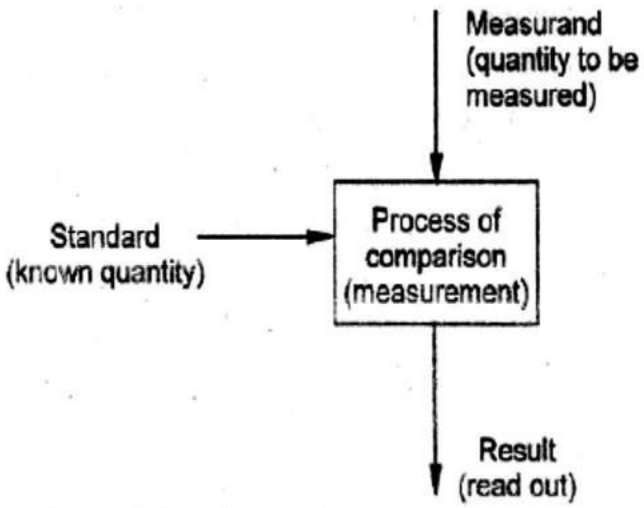


Figure 1.1 Fundamental measuring process

INSTRUMENT:

- Scientific instruments allow the human to observe and measure aspects of the physical universe beyond the range and precision of the unaided human senses. Instruments are the essential extensions of human sensing and perception without which scientific exploration of nature would be impossible.

- The instrument would sense a physical parameter (pressure, temperature, velocity etc.), process and translate it into a format and range which can be interpreted. By the observer.
- The instrument must also provide the controls by which the operator can obtain, manipulate and respond to the information. Apparently, the instrument designer aims to produce a scientific instrument that not only works efficiently but does so taking due account of the comfort, safety, limitation and frailties of the human operator when setting up, using and maintaining the instrument.
- The man-made instruments are not only accurate and sensitive in their response but also retain their characteristic for extended periods of time. Instruments may be quite simple, such as liquid-in-glass thermometer or extremely complex such as the device to sense the physiological reactions of a man during space flight.

GENERALIZED MEASUREMENT SYSTEM AND ITS FUNCTIONAL ELEMENTS:

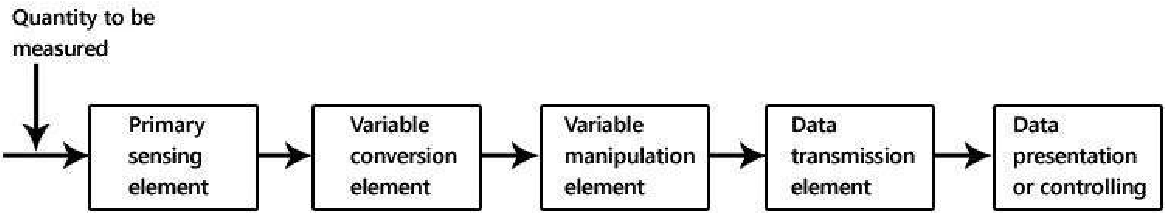


Fig: **Generalized Measurement System**

- The principal function of an instrument is the acquisition of information by sensing and perception, the processing of that information and its final presentation to a human observer. For the purpose of analysis and synthesis, the instruments are considered as systems, i.e. assemblies of interconnected components organized to perform a specified function.
- The different components are called elements and they perform certain definite and required steps in the act of measurement. The following basic components can be identified in a **generalized measurement system (as shown in fig above)** the scope of the different elements is determined by their functioning rather than by their construction.

Primary sensing element

- An element that is sensitive to the measured variable. The sensing elements sense the condition, state or value of the process variable by extracting a small part of energy from the measurand, and then produce an output which reflects this condition, state or value of the measurand.
- Because of this energy extraction or utilization, the measured quantity is always disturbed by the act of measurement and that makes a perfect measurement theoretically impossible. Good instruments are designed to minimise this loading effect.

Variable conversion or transducer element

- An element that converts the signal from one physical form into another without changing the information content of the signal. The signal after transduction is more suitable for purpose of measurement and control. The transduction may be from mechanical, electrical or optical to any other related form.
- Some examples of transducers and the conversions associated with them are: -

1. bourdon tube and bellows which transform pressure into displacement
2. proving ring and other elastic members which convert force to displacement
3. rack and pinion which convert the linear to rotary motion and vice versa
4. obstruction flow meters which transform flow to pressure
5. thermocouples which convert information about temperature difference to information in the form of emf.

Manipulation element

- An element that operates on the signal according to some mathematical rule without changing the physical nature of the variable.

[Input] x constant= output

- For the odometer of an automobile, the above mathematical operation takes the form:

$$[\text{revolution}] \times \frac{\text{kilometer}}{\text{revolution}} = \text{kilometer}$$

Data transmission element

- An element that transmits the signal form one location to another without changing its information content.
- Data may be transmitted over long distances (from one location to another) or short distances (from a test centre to a nearby computer).
- Further, the transmission element may be as simple as a shaft and gearing assembly or as complicated as a telemetry system for transmitting signals from missiles to, ground equipment direct transmission via cables, called land-line telemetry, generally employs either current, voltage, frequency, position or impulses to convey the information.

Data processing element

- An element that modifies the data before it is displayed or finally recorded. Data processing may be used for such purposes as:

1. Corrections to the measured physical variables to compensate for scaling, non-linearity, zero offset, temperature error etc.
2. perform repeated calculations that involve addition, subtraction, multiplication or division of two or more physical variables and their associated constants
3. collect information regarding average, statistical and logarithmic values
4. convert the data into useful form, e.g., calculation of engine efficiency from speed, power input and torque developed
5. separate out signals burried in noise, generate information for displays, and a variety of other goals

Data presentation element

- An element that provides a record or indication of the output from the data processing element. In a measuring system using electrical instrumentation, an exciter and an amplifier are also incorporated into the circuit.
- The exciter is a source of electrical energy for the transducer. The amplifier serves to amplify the voltage from the transducer if this voltage is small.
- The display unit may be required to serve the following functions:

1. Transmitting: to convey the information concerning the measured quantity Over some distance to a remote point
2. Signalling: to give a signal that the desired value has been reached.
3. Registering: to indicate by numbers or by some other symbol the value of some quantity
4. Indicating: to indicate the specific value with an indicating hand over a suitably calibrated scale
5. Recording: to produce a written continuous record of the measurand against

1.3 Measurement methods

- Measurement is a process of comparison of the physical quantity with a reference standard. Depending upon the requirement and based upon the standards employed, there are two basic methods of measurement.

1. Direct measurements

- The value of the physical parameter (measurand) is determined by comparing it directly with reference standards. The physical quantities like mass, length and time are measured by direct comparison.
- Direct measurements are not to be preferred because they involve human factors, are less accurate and also less sensitive. Further, the direct methods may not always be possible, feasible and practicable.

2. Indirect measurements

- The value of the physical parameter (measurand) is more generally determined by indirect comparison with secondary standards through calibration.
- The measurand is converted into an analogous signal which is subsequently processed and fed to the end ·device that presents the result of measurement. The indirect technique saves the primary or secondary standards from a frequent and direct handling.
- The accuracy of each approach is apparently traceable to the primary standard via secondary standard and the calibration.

1.3.1 Primary, secondary and tertiary measurements

- The complexity of an instrument system depends upon the measurement being made and upon the accuracy level to which the measurement is needed.
- Based upon complexity of the measurement system, the measurements are generally grouped into three categories namely the primary, secondary and tertiary measurements.

- In the primary mode, the sought value of a physical parameter is determined by comparing it directly with reference standards. The requisite information is obtainable through senses of sight and touch. Examples are:
  1. matching of two lengths when determining the length of an object with a ruler
  2. matching of two colours when judging the temperature of red hot steel
  3. Estimating the temperature difference between the contents of containers by inserting fingers.
  4. use of beam balance to measure (actually compare) masses
  5. measurement of time by counting the number of strokes of a clock
- The primary measurements provide subjective information only. That is, the observer can indicate only that the contents of one container are hotter than the contents of the other, one rod is longer than the other rod; one object contains more or less mass than the other.
- The indirect methods make comparison with a standard through use of a calibrated system, i.e. an empirical relation is established between the measurement actually made and the results that are desired.
- For example, an indirect method may consist of developing an electrical voltage proportional to a physical variable to be measured, measuring that voltage and then converting the measured voltage back to the corresponding value of the original measurand.
- Electrical methods are preferred in the indirect methods due to their high speed of operation and simple processing of the measured variable.
- The indirect measurements involving one translation are called secondary measurements and those involving two conversions are called tertiary measurements.
- The measurement of the speed of a rotating shaft by means of an electric tachometer (Fig.1.4) is another typical example of tertiary measurement.
- The angular speed of the rotating shaft is first translated in to an electrical voltage which is transmitted by a pair of wires to a voltmeter. In the voltmeter, the voltage moves a pointer on a scale, i.e. voltage is translated into a length change. The tertiary signal of length change is a measure of the speed of the shaft and is transmitted to the observer.

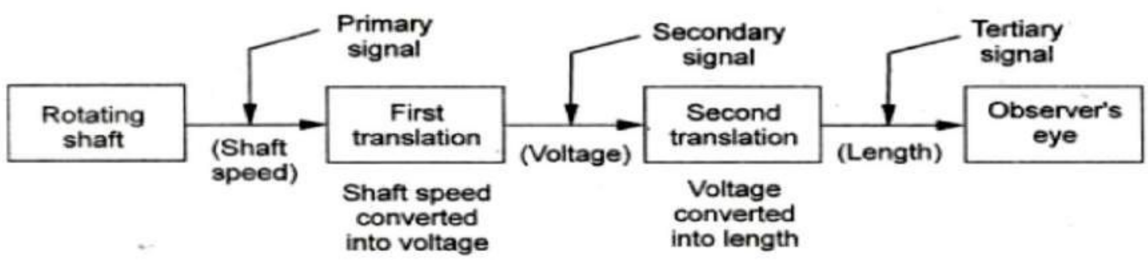


Figure 1.4 Tertiary measurement: measurement of angular speed by an electric tachometer

1.3.2 Contact and non-contact type measurements

- Measurements may also by described as (i) contact type where the sensing element of the measuring device has a contact with the medium whose characteristics are being measured and (ii) non-contact type where the sensor does not communicate physically with the medium. The optical, radioactive and some of the electrical/electronic measurements belong to this category.

1.5 STATIC TERMS AND CHARACTERISTICS

1.5.1 Range and span

- The region between the limits within which an instrument is designed to operate for measuring, indicating or recording a physical quantity is called the range of the instrument. The range is expressed by stating the lower and upper values. Span represents the algebraic differences between the upper and lower range values of the instrument.
- For example, Range - 10°C to 80 °C; Span 90 °C
  Range 5 bar to 100 bar; Span 95 bar
  Range 0 volt to 75 volts; Span 75 volt

1.5.2 Accuracy, error and correction

- No instrument gives an exact value of what is being measured. There is always some uncertainty in the measured value. This uncertainty is expressed in terms of accuracy and error. Accuracy of an indicated (measured) value may be defined as conformity with or closeness to an accepted Standard value (true value).
  1. Accuracy of the measured signal depends upon:
  2. Intrinsic accuracy of the instrument itself,
  3. Variation of the signal being measured,
  4. Accuracy of the observer and
  5. Whether or not the quantity is being truly impressed upon the instrument.
- For example, the accuracy of a micrometer depends upon factors like error in screw, anvil shape, temperature difference, and the applied torque variations etc.
- In general, the result of any measurement differs somewhat from the true value of the quantity being measured. The difference between the measured value (V_m) and the true value (V_t) of the quantity represents static error or absolute error of measurement (E_s), i.e.

$$E_s = V_m - V_t$$

- The error may be either positive or negative. For positive static errors the instrument reads high and for negative static errors the instrument reads low.
- From experimentalist's view point, static correction or simple correction is more important than the static error. The static correction is defined as the difference between the true value and the measured value of a quantity.
- The correction of the instrument reading is of the same magnitude as the error, but opposite in sign, i.e.

$$C_s = -E_s$$

Error specification or representation:

$$\text{error} = \frac{\text{measured value - true value}}{\text{true value}} \times 100 \text{ precent}$$

$$= \left\{\frac{V_m - V_t}{V_t}\right\} \times 100 \text{ precent}$$

The percentage error stated in this way is the maximum for any point in the range of the instrument. The size of the error, however, diminishes with a drop in the true value.

s

BASIS FOR COMPARISON	ACCURACY	PRECISION
Meaning	Accuracy refers to the level of agreement between the actual measurement and the absolute measurement.	Precision implies the level of variation that lies in the values of several measurements of the same factor.
Represents	How closely result agree with the standard value?	How closely the results agree with one another?
Degree	Degree of conformity	Degree of reproducibility
Factor	Single factor	Multiple factors
Measure of	Statistical bias	Statistical variability
Concerned with	Systematic Error	Random Error

1.5.3 Calibration

- The magnitude of the error and consequently the correction to be applied is determined by making a periodic comparison of the instrument with Standards which are known to be constant.
- The entire procedure laid down for making, adjusting or checking a scale so that readings of an instrument or measurement System conform to an accepted Standard is called the calibration.
- For example, we may calibrate a flowmeter by comparing it with a Standard flow measurement facility at the National Bureau of Standards; by comparing it with another Flow meter (a secondary Standard) which has already been compared with a primary standard; or by standard or by direct comparison with a primary measurement such as weighing a certain amount of water in a tank and recording the time elapsed for this quantity to flow through the meter.
- The calibration Standards, along with their typical accuracies, for certain physical parameters have been given in Table 1.1. The calibration Standard should be at least an order more accurate than the instrument being calibrated.

Table 1.1 Calibration Standards for certain physical parameters

Parameter	Primary standard	Secondary and working standard
Displacement, velocity and acceleration	i.Length Standard with krypton 86 lamp (1×10^{8}) ii.Motion measurement with Standard gauges; Vibration and rotating table Simulation; laser interferometer (1×10^{-5})	i.Precision micrometer and other gauges (1×10^{-5}) ii.Standard accelerometers (2×10^{-4})
Force and torque	Standard dead weights $(1\times10^{-7}$ to $1\times10^{-8})$	i.Standard load cells ii.Universal testing machines iii.Precision torque meter $(1\times10^{-4}$ to $1\times10^{-5})$
Time and frequency	Cesium beam Standards (Time $\rightarrow$ 0.20 μs per day Frequency $\rightarrow 1\times10^{-12}$ per day)	Quartz crystal oscillators (Time $\rightarrow$ 20 μs per day Frequency $\rightarrow 1\times10^{-10}$ per day)
Pressure	i.Air dead weight testers ii.Precision manometers $(1\times10^{-5}$ to $1\times10^{-6})$	i.Oil dead weight testers ii.Quartz bourdon tub iii.Force balance transducer Mercury and water manometer
Flow	Volume, mass and time measurements (1×10^{-5})	i.Pitot tubes ii.Rotameters iii.Turbine flow meters $(1\times10^{-4}$ to $1\times10^{-3})$
Temperature	i. Boiling and melting point of metals ii. Precision Potentiometers and bridges (2×10^{-3})	i.Standard thermocouples` ii.Platinum resistance iii.Thermometers iv.Radiation pyrometers 0×10^{-3}

❖ Consideration While Calibrating An Instrument:

The following points and observations need consideration while calibrating an instrument:-

- Calibration of the instrument is carried out with the instrument in the same position (upright, horizontal etc.) and subjected to the same temperature and other environmental conditions under which it is to operate while in service.
- The instrument is calibrated with values of the measure and impressed both in the increasing and in the decreasing Order. The results are then expressed graphically; typically, the output is plotted as the Ordinate and the input or measurand as the abscissa.
- Output readings for a series of impressed values going up the scale may not agree with the output readings for the same input values when going down.
- Line or curves plotted in the graphs may not close to form a loop. In a typical calibration curve **(Fig 1.6)** ABC represents the readings obtained while ascending the scale; DEF represents the readings during descent; KLM represents the median and is commonly accepted as the calibration curve.
- The term median refers to the mean of a series of up and down readings. Quite often, the indicated values are plotted as abscissa and the Ordinate represents the Variation of the median from the true values. **(Fig.1.7)**
- Faired curve through the experimental points then represents the correction curve. This type of deviation presentation facilitates a rapid visual assessment of the accuracy of the instrument. The user looks along the abscissa for the value Indicated by the instrument and then reads the correction to be applied.
- A properly prepared calibration correction curve gives information about the absolute static errors of the measuring device, the extent of the instrument's Linearity or conformity, and the hysteresis and repeatability of the instrument.

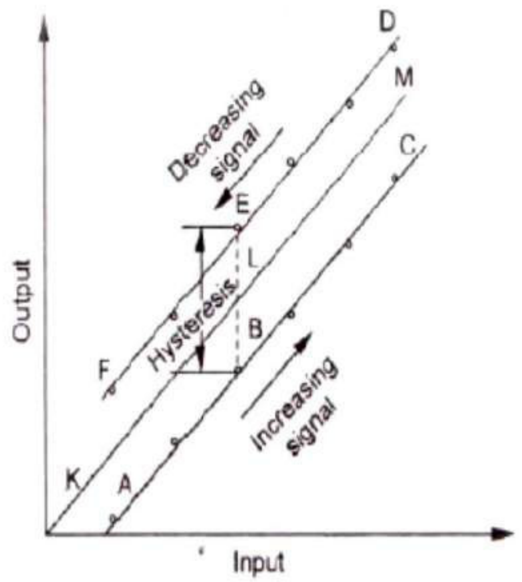


Figure 1.6 Calibration curve

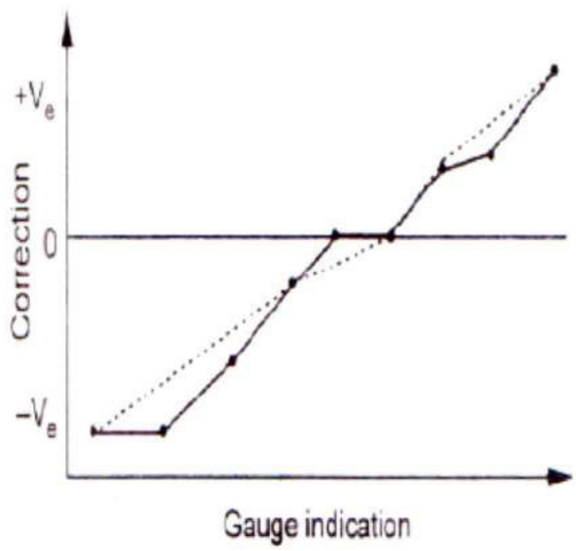


Figure 1.7 Correction curve

1.5.4 Hysteresis, dead zone

- From the instrument calibration curve, it would be noted that the magnitude of output for a given input depends upon the direction of the change of input. This dependence upon previous inputs in called hysteresis.
- Hysteresis is the maximum difference for the same measured quantity (input signal) between the upscale and down scale readings during a full range traverse in each direction.
- Maximum difference is frequently specified as a percentage of full scale. Hysteresis results from the presence of irreversible phenomenon such as mechanical friction, slack motion in bearings and gears, elastic deformation, magnetic and thermal effects.
- Hysteresis may also occur in electronic Systems due to heating and cooling effects which occur differentially under conditions of rising and falling input.
- Dead zone is the largest range through which an input signal can be varied without initiating any response from the indicating instrument. Friction or play is the direct cause of dead zone or band.

1.5.5 Drift

- It is an undesired gradual departure of the instrument output over a period of time that is unrelated to changes in input, operating conditions or load. An instrument is said to have no drift if it reproduces same readings at different times for same Variation in measured variables.
- The following factors may lead to drift in an instrument:
    1. Wear and tear at the mating parts
    2. Mechanical vibrations
    3. Contamination of primary sensing elements
    4. Development of high mechanical stresses in some parts
    5. Temperature changes, stray electric and magnetic fields.

Examples:

1. Drift occurs in thermocouples and resistance thermometers due to contamination of the metal and a change in its metallurgical structure.
2. Drift may occur in obstruction flow meters because of wear and erosion of the orifice plate, nozzle or venturimeter.
3. Drift occurs very slowly and can be checked only by periodic inspection and maintenance of the instrument.

1.5.6 Sensitivity

- Sensitivity of an instrument or an instrumentation System is the ratio of the magnitude of the response (output signal) to the magnitude of the quantity being measured (input signal), i.e.

$$\text{Static sensitivity}, k = \frac{\text{change of output signal}}{\text{change of input signal}}$$

- Sensitivity is represented by the slope of the calibration curve if the ordinates are expressed in the actual units. With a linear calibration curve, the sensitivity is constant. However,
- If the calibration curve is non-linear the static sensitivity is not constant and must be specified in terms of the input value as illustrated in Fig.1.11

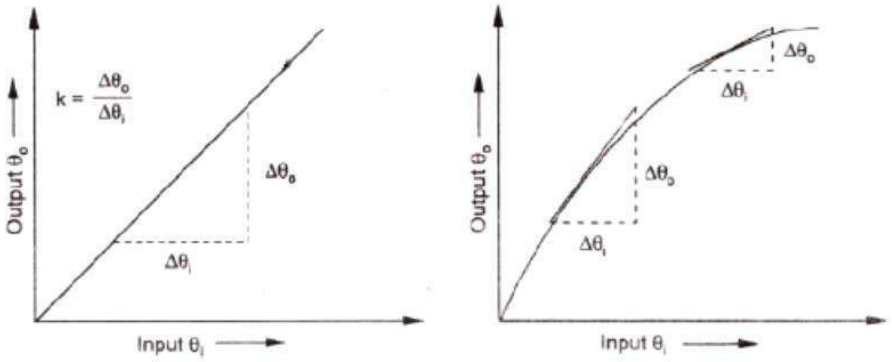


Figure 1.11 Static sensitivity for linear and non-linear instruments

1.5.7 Threshold and resolution

- The smallest increment of quantity being measured which can be detected with certainty by an instrument represents the threshold and resolution of the instrument.
- When the input signal to an instrument is gradually increased from zero, there will be some minimum value input before which the instrument will not detect any output change. This minimum value is called the threshold of the instrument. Thus, threshold defines the minimum value of input which is necessary to cause detectable change from zero output.
- In a digital System, it is the input signal necessary to cause one least significant digit of the output reading to change. Threshold may be cause by backlash or internal noise.
- When the input signal is increased from non-zero value, one observes that the instrument output does not change until a certain input increment is exceeded. This increment is termed resolution or discrimination.
- Thus, resolution defines the smallest change of input for which there will be a change of output. With analog instruments, the resolution is determined by the ability of the observer to judge the position of a pointer on a scale, e.g., the level of mercury in a glass tube.
- Resolution is usually reckoned to be no better than about ± 0.2 of the scale division. With digital instruments, resolution is determined by the number of neon tubes taken to show the measured value.
- For example, if there are four neon tubes to represent voltage measurement on a 1-volt range, one tube will be taken by the decimal point and the others by digits to show readings up to a maximum of .999 volts. Thus the third digit shows or resolves millivolts, and consequently the resolution is 1 mV.
- Threshold and resolution may be expressed as an actual value or as a fraction or percentage of full scale value.

1.5.8 Precision and repeatability

- These terms refer to the closeness or agreement among several measurements of the same true value with the same instrument, by the same operator over a short time span.
- Proper checking and maintenance of instrument should be carried out to ensure its repeatability.
- Accuracy refers to the closeness or conformity to the true value of the quantity under measurement.
- Precision refers to the degree of agreement within a group of measurements, i.e., it prescribes the ability of the instrument to reproduce its readings over and over again for a constant input signal.
- This distinction can be elaborated by considering the following two examples:

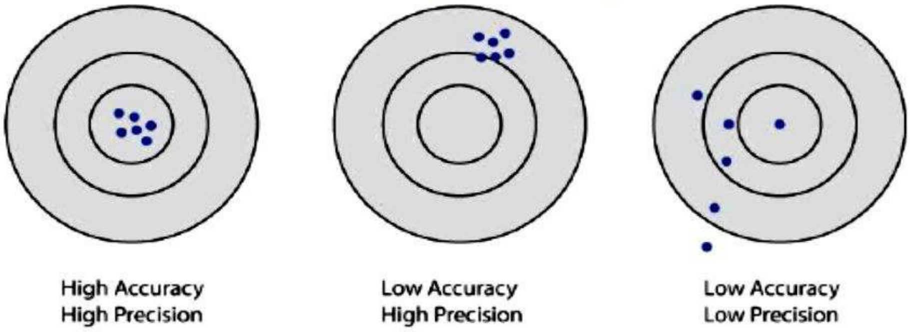


Figure 1.12 Difference between accuracy and precision

1. Consider a micrometer normal in every respect but with its anvil displaced from its true position. The readings taken with this micrometer would be clearly defined and consistent, i.e., a negligible scatter amongst different readings for the same dimension. We would say that the micrometer is as precise as ever. The readings, however, do not conform to truth as the anvil is not placed at its correct position. The readings of the dimension with this micrometer are thus not accurate.
2. Consider two Voltmeters of the same model, make and range. Further, let both have knife-edge pointers, carefully ruled and mirror backed scales to help avoid parallax errors. Both the Voltmeters can be read to the same precision. In case the series resistance of one of the Voltmeters is defective, its readings would be subjected to an error. The accuracy of the two instruments would then be different.

1.5.9 Linearity

- The working range of most of the instruments provides a linear relationship between the output (reading taken from the scale of the instrument) and input (measurand, Signal presented to the measuring System). This aspect tends to facilitate a more accurate data reduction. Linearity is defined as the ability to reproduce the input characteristics symmetrically, and this can be expressed by the straight line equation.

$$y = mx + c$$

Where y is the output, x the input, m the slope and c the intercept. Apparently, the closeness of the calibration curve to a specified straight line is the linearity of the instrument.

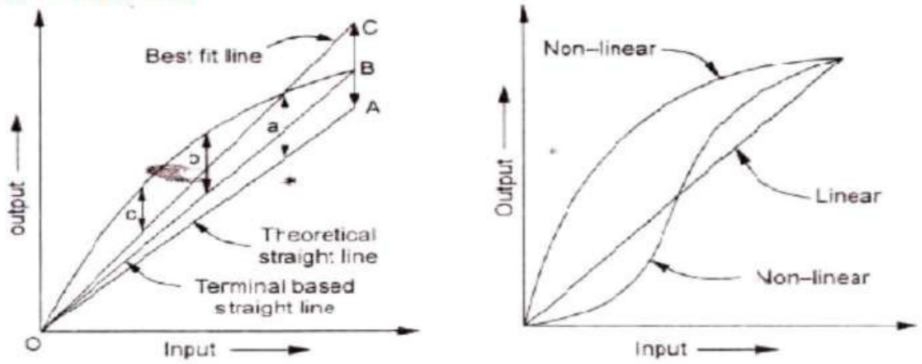


Figure 1.13 Theoretical, end point and least square linearity

1.6 CLASSIFICATION OF ERRORS

Errors may originate in a variety of ways and the following sources need examination:

1.6.1 Instrument errors

- There are many factors in the design and construction of instruments that limit the accuracy attainable. Instruments and standards possess inherent inaccuracies and certain additional inaccuracies develop with use and time. Examples are:
  1. Improper selection and poor maintenance of the instrument.
  2. Faults of construction resulting from finite width of knife edges; lost motion due to necessary clearance in gear teeth and bearings; excessive friction at the mating parts etc.
  3. Mechanical friction and wear, backlash, yielding of supports, pen or pointer drag, and hysteresis of elastic members due to aging.
  4. Unavoidable physical phenomenon due to friction, capillary attraction and imperfection.
  5. Assembly errors resulting from incorrect fitting of the scale zero with respect to the actual zero position of the pointer, non-uniform division of the scale, and bent or distorted pointers.
- The assembly errors do not alter with time, and can be easily discovered and corrected.
- An uncertainty in measurement due to friction at the mating parts, and the pen and pointer Drag is frequently reduced by gentle tapping of the instruments; a vigorous tapping would however lead to delicate bearings being injured and thus increasing friction all the more.

1.6.2 Environmental errors

- The instrument ·location and the environment errors Are introducing by using an instrument in conditions different for which it has, been designed, Assembled and calibrated.
- The different conditions of use may be temperature, pressure, Humidity and altitude etc.; the effect of temperature being more predominant.
- A change in the temperature may alter the elastic constant of a spring, may change the dimensions of a Measuring element or linkage in the system, may alter the resistance values and flux densities of magnetic elements.
- Consider a mercury-in-glass thermometer being used for the measurement of air temperature. The instrument will be located wrongly if during measurements the sun happens to be shining on the thermometer bulb.
- Similarly, the bulb would indicate an effect of heat radiation if the thermometer is placed too close to a window.
- Likewise, a high air pressure would tend to compress the walls of the bulb and force the mercury to rise within the capillary and thus give a spurious temperature reading.
- Environmental errors alter with time in an unpredictable manner. The following methods have been suggested to eliminate or at least reduce the environmental errors:
  1. Use the instrument under the conditions for which it was originally assembled and calibrated. This may involve control of temperature, pressure and humidity conditions.
  2. Measure deviations in the local conditions from the calibrated ones and then apply suitable corrections to the instrument readings.
  3. Automatic compensation for the departures from the calibrated conditions by using sophisticated devices.
  4. Make a complete new calibration under the local conditions.
- The method chosen would depend on the local assessment of the problem.

1.6.3 Translation and signal transmission errors

- The instrument may not sense or translate the measured effect with complete fidelity. The error also includes the non-Capability of the instrument to follow rapid changes in the measured quantity due to inertia and hysteresis effects.
- The transmission errors creep in when the transmitted signal is Rendered faulty due to its distortion by resonance, attenuation, loss leakage, or on being absorbed or otherwise consumed within the communication channel.
- The error may also result from unwanted disturbances such as noise, line pick-up, hum, ripple etc. The errors are remedied by calibration and by monitoring the signal at one or more points along its transmission path.

1.6.4 Observation errors

- There goes a saying that 'instruments are better than the people who use them'. Even when an instrument has been properly selected, carefully installed and faithfully calibrated, short comings in the measurement occur due to certain failings on the part of the observer. The observation errors may be due to:
  1. Parallax, i.e., apparent displacement when the line of vision is not normal to the scale.
  2. Inaccurate estimates of average reading, lack of ability to interpolate properly between graduations.
  3. Incorrect conversion of units in between consecutive readings, and non-simultaneous observation of interdependent quantities.
  4. Personal bias, i.e., a tendency to read high or low, or anticipate a signal and read too soon. Wrong scale reading, and wrong recording of data.
- The poor mistakes resulting from the inexperience and carelessness of the observer are obviously remedied with careful training, and by taking independent readings of each item by two or more observers.

1.6.5 Operational errors

- A pre-requisite to precise and meticulous measurements is that the instruments should be properly used. Quite often, errors are caused by poor operational techniques. Examples are:
  1. A differential type of flowmeter will read inaccurately if it is placed immediately after a valve or a bend.
  2. A thermometer will not read accurately if the sensitive portion is insufficiently immersed or is radiating heat to a colder portion of the installation.
  3. A pressure gauge will correctly indicate pressure only when it is exposed only to pressure which is to be measured.
  4. A steam calorimeter will not give true indication of the dryness fraction of steam unless the sample drawn correctly represents the condition of steam.

1.6.6 System interaction errors

- The act of measurement may affect the condition of the measurand and thus lead to uncertainties in measurements. Example are:

1. Introduction of a thermometer alters the thermal capacity of the system and provides an extra path for heat leakage.
2. A ruler pressed against a body results in a differential deformation of ihe body relative to ruler.
3. An obstruction type flowmeter may partially block or disturb the flow conditions. Consequently, the flow rate shown by the meter may not be same as before the meter installation.
4. Reading shown by a hand tachometer would vary with the pressure with which it is pressed against the shaft.
5. A milliammeter would introduce additional resistance in the circuit and thereby alter the flow current by a significant amount.

- The job of an instrument designer is to see that the alteration due to system interference is minimal. Many of the most precise, expensive and elaborate measuring instruments cost and complexity solely to the means adopted to eliminate, or at least reduce interaction between the instrument and the physical state being measured.
- The errors discussed above may be grouped into random errors as distinguished from systematic errors.
- Random errors are accidental, small and independent, and are mainly due to inconstant factors such as spring hysteresis, stickiness, friction, noise and threshold limitations.
- The magnitude and direction of these errors cannot be predicted from a knowledge of the measurement system; however, these errors are assumed to follow the law of probabilities.
- Systematic errors are repeated consistently with the repetition of the experiment and are caused by such effects as sensitivity shifts, zero off-set and known non-linearity.
- Systematic errors cannot be determined by direct and repetitive observations of the measurand made each time with same technique. The only way to locate these errors is to have repeated measurements under different conditions or with different equipment and where possible by an entirely different method.

Comparison between Systematic Errors and Random Errors

Systematic Errors	**Random Errors**
These errors are repetitive in nature and are of constant and similar form	These are non-consistent. The sources giving rise to such errors are random.
These errors result from improper conditions or procedures that are consistent in action.	Such errors are inherent in the measuring system or measuring instruments.
Except personal errors, all other systematic errors can be controlled in magnitude and sense.	Specific causes, magnitudes and sense of these errors cannot be determined from the knowledge of measuring system or condition.
If properly analyzed these can be determined and reduced or eliminated.	These errors cannot be eliminated, but the results obtained can be corrected.
These include calibration errors, variation in contact pressure, variation in atmospheric conditions, parallax errors, misalignment errors etc.	These include errors caused due to variation in position of setting standard and work-piece, errors due to displacement of lever joints of instruments, errors resulting from backlash, friction etc.

2.5 Measurement of Pressure

Various devices used to measure fluid pressure can be classified into,

1. Manometers 2. Mechanical gauges

2.5.1 Manometers

– Manometers are the pressure measuring devices which are based on the principal of balancing the column of the liquids whose pressure is to be measured by the same liquid or another liquid.

Classification of Manometers

Manometers are broadly classified into:

A. Simple Manometers
B. Differential Manometers

2.5.2 Mechanical Gauges

– Mechanical gauges consist of an elastic element which deflects under the action of applied pressure and this movement will operate a pointer on a graduated scale.

The mechanical pressure gauges are:

1. Diaphragm pressure gauge
2. Bourdon tube pressure gauge
3. Dead weight pressure gauge
4. Below pressure gauge

2.6. Simple Manometers

Simple monometers consists of glass tube having one of its end connected to a point where pressure is to be measured and other end is open to atmosphere.

Types of Simple manometers are:

1. Piezometer
2. U-tube manometer
3. Single column manometer
4. Inclined column manometer

2.6.1 Piezometer

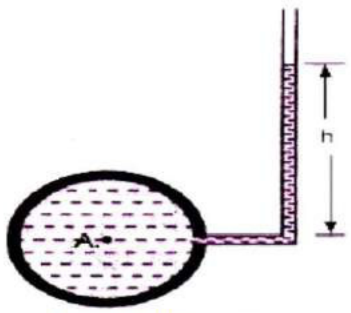


Fig. 2.5 Piezometer

– It consists of a glass tube inserted in the wall of the vessel or pipe at the level of point at which the intensity of pressure is to be measured as shown in Fig. 2.5. The other end of the piezometer is exposed to air. The height of the liquid in the piezometer gives the pressure head from which the intensity of pressure can be calculated.

– If at a point A, the height of liquid say water h in piezometer tube, then pressure at point A is given by ρgh according to the Hydrostatic law. So, In equilibrium condition, $p_A = \rho gh$

– To minimize capillary rise effects the diameters of the tube is kept more than 12mm.

Merits

1. Simple in construction
2. Economical

Demerits

1. Not suitable for high pressure intensity.
2. Pressure of gases cannot be measured.

2.6.2 U-tube Manometer

- A U-tube manometer consists of a glass tube bent in U-Shape, one end of which is connected to the point at which pressure is to be measured and the other end is exposed to atmosphere. U-tube consists of a liquid of specific of gravity is greater than the specific gravity of the liquid whose pressure intensity is to be measured.

(A) For Gauge Pressure

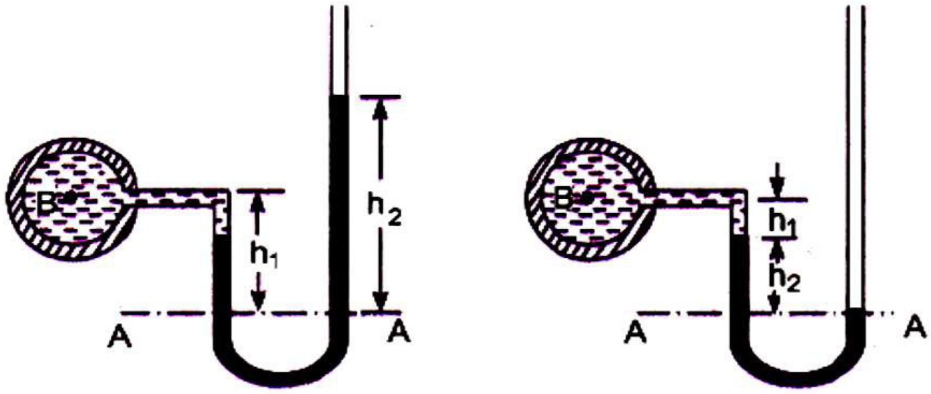
- Let B is the point at which pressure is to be measured, whose value is p . The datum line is $A-A$ as shown in Fig. 2.6 (a).

Let h_1 = Height of the light liquid above the datum line

h_2 = Height of the heavy liquid above the datum line

S_1 = Specific gravity of light liquid and ρ_1 is density of light liquid

S_2 = Specific gravity of heavy liquid and ρ_2 is density of heavy liquid



(a) For gauge pressure (b) For vacuum pressure

Fig. 2.6 U-tube manometer

- As the pressure is the same for the horizontal surface. Hence pressure above the horizontal datum line $A-A$ in the left column and in the right column of U-tube manometer should be same.

Pressure above datum line above $A-A$ in the left column $= p+\rho_1 g h_1$

Pressure above datum line above $A-A$ in the right column $= \rho_2 g h_2$

Hence equating the two pressures $p+\rho_1 g h_1 = \rho_2 g h_2$

$$p = \rho_2 g h_2 - \rho_1 g h_1$$

(B) For Vacuum Pressure

- For measuring vacuum pressure, the level of the heavy liquid in the manometer will be as shown in Fig. 2.6 (b).

Pressure above datum line above $A-A$ in the left column $= \rho_2 g h_2 + \rho_1 g h_1 + p$

Pressure above datum line above $A-A$ in the right column $= 0$

Hence equating the two pressures $\rho_2 g h_2 + \rho_1 g h_1 + p = 0$

$$p = -(\rho_2 g h_2 + \rho_1 g h_1)$$

2.6.3. Single Column Manometer

- A single column manometer is a modified form of U-tube manometer in which reservoir having large cross sectional area (100 times) as compared to cross sectional area of U – tube connected to it as shown in Fig. 2.7.
- For any change in pressure, change in the level of manometeric liquid in the reservoir is small and change in level of manometric liquid in the U- tube is large. The other limb may be vertical or inclined. Thus there are two type of single column manometer as:
  1. Vertical single column manometer
  2. Inclined single column manometer

1. Vertical Single Column Manometer

- Fig. 2.7 shows the vertical single column manometer. Let $X-X$ be the datum line in the reservoir and in the right limb of the manometer, when it is not connected to the pipe. When the manometer is connected to the pipe, due to high pressure at A, the heavy liquid in the reservoir will be pushed downwards and will rise in the right limb.

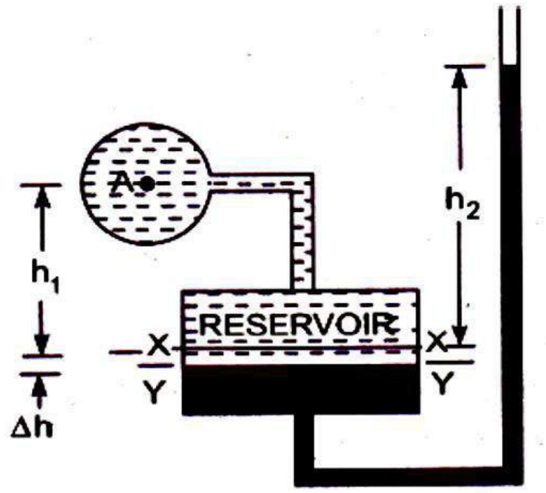


Fig. 2.7 Vertical single column manometer

Let $\Delta h =$ Fall of the heavy liquid in reservoir

$h_2 =$ Rise of heavy liquid in right limb

$h_1 =$ Height of centre of pipe above $X-X$

$p_A =$ Pressure at A, which is to be measured

$A =$ Cross section area of the reservoir

$a =$ Cross section area of the right limb

$S_1 =$ Specific gravity of liquid in pipe and ρ_1 is density of liquid in pipe

$S_2 =$ Specific gravity of heavy liquid in reservoir and right limb and ρ_2 is density of liquid in reservoir

Fall of heavy liquid in reservoir will cause a rise of heavy liquid level in the right limb.

$$A \times \Delta h = a \times h_2$$

$$\Delta h = \frac{a \times h_2}{A} \quad \text{...(2.5)}$$

Now consider the datum line $Y - Y$. Then pressure in the right limb above $Y - Y$

$$= \rho_2 \times g \times (\Delta h + h_2)$$

Then pressure in the left limb above $Y - Y$

$$= \rho_1 \times g \times (\Delta h + h_1) + p_A$$

Equating the pressures we have,

$$\rho_2 g \times (\Delta h + h_2) = \rho_1 g \times (\Delta h + h_1) + p_A$$

$$p_A = \Delta h[\rho_2 g - \rho_1 g] + \rho_2 g h_2 - \rho_1 g h_1$$

Substituting the $\Delta h = \frac{a \times h_2}{A}$ in above equation, we get

$$p_A = \frac{a \times h_2}{A}[\rho_2 g - \rho_1 g] + \rho_2 g h_2 - \rho_1 g h_1$$

As the area A is very large compared to a, hence $\frac{a}{A}$ becomes very small and can be neglected. Then

$$p_A = \rho_2 g h_2 - \rho_1 g h_1 \quad \text{...(2.6)}$$

2. Inclined Single Column Manometer

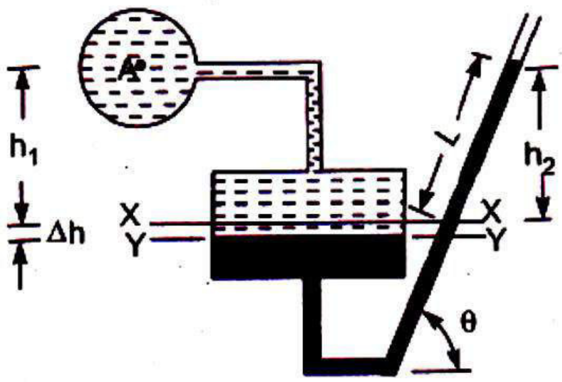


Fig. 2.8 Inclined single column manometer

– Fig. 2.8 shows the inclined single column manometer. This manometer is more sensitive. Due to inclination the distance moved by the heavy liquid in the right limb will be more.

Let L = length of heavy liquid moved in right limb form $X - X$

θ = Inclination of right limb with horizontal

h_2 = Vertical rise of heavy liquid in right limb from $X - X = L \times \sin\theta$

From equation (2.6), the pressure at A is,

$$p_A = \rho_2 g h_2 - \rho_1 g h_1$$

$$p_A = \sin\theta \rho_2 g - \rho_1 g h_1$$

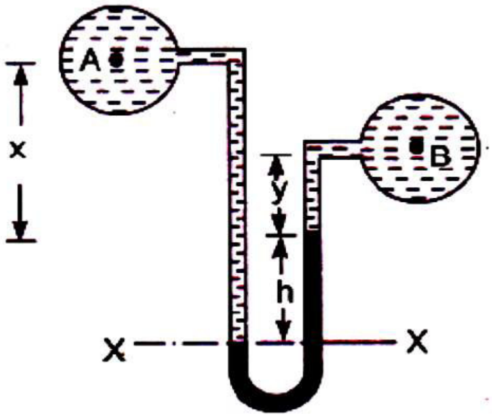
2.7 Differential Manometers

- Differential manometers are used to measure the pressure difference between two points. It is consists of a U-tube, containing heavy liquid, whose two ends are connected to the two points, whose difference of pressure is to be measured.

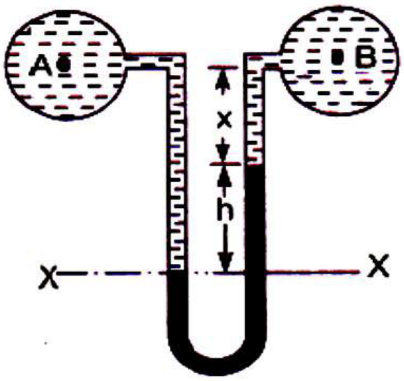
Types of differential manometers are:

1. U-tube Differential manometers
2. Inverted U-tube differential manometers

2.7.1 U-Tube Differential Manometers



(a)Two pipes at different levels



(b) A and B are at the same level

Fig. 2.9 U-tube differential manometer

- In Fig. 2.9 (a), the two points A and B are at different level and also contained liquids of different specific gravity. These points are connected to the U-tube manometer. Let the pressure at A and B are P_A and p_B.

Let $h =$ Difference of mercury level

$y =$ Distance of the centre of B, from the mercury level in the right limb

$x =$ Distance of the centre of A, from the mercury level in the right limb

$\rho_1 =$ Density of liquid at A

$\rho_2 =$ Density of liquid at B

$\rho_g =$ Density of heavy liquid

Taking at datum line at $X-X$.

Pressure above $X-X$ in the left limb $= \rho_1 g(h+x)+p_A$

Pressure above $X-X$ in the right limb $= \rho_g gh+\rho_2 gy+p_B$

Equating the two pressures, we have

$$\rho_1 g(h+x)+p_A = \rho_g gh+\rho_2 gy+p_B$$

$$p_A - p_B = \rho_g gh+\rho_2 gy-\rho_1 g(h+x)$$

In Fig. 2.9 (b), the two points A and B are at same level and contained liquids of density.

Pressure above $X-X$ in the right limb $= \rho_g gh+\rho_1 gx+p_B$

Pressure above $X-X$ in the left limb $= \rho_1 g(h+x)+p_A$

Equating the two pressures, we have

$$\rho_g gh+\rho_1 gx+p_B=\rho_1 g(h+x)+p_A$$

$$p_A-p_B=\rho_g gh+\rho_1 gx-\rho_1 g(h+x)$$

2.7.2 Inverted U-Tube Differential Manometers

– It consists of an inverted U-tube having two ends are connected to the pipes at points A and B whose difference of pressure is to be measured as shown in Fig. 2.10. It is used for measuring the difference of low pressures. Let the pressure at A is more than the pressure at B.

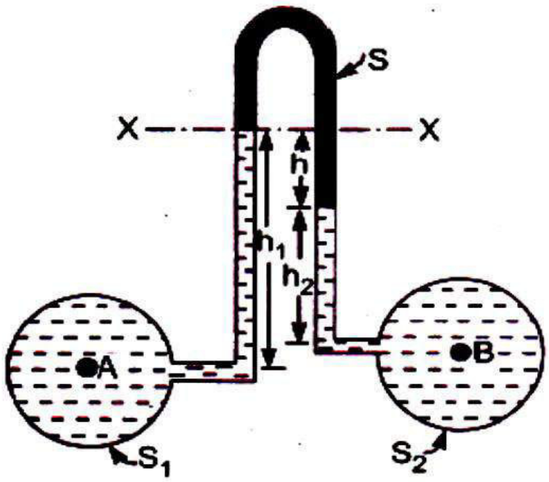


Fig. 2.10 Inverted U-tube differential manometer

Let $h_1 =$ Height of liquid in left limb below the datum line $X-X$

$h_2 =$ Height of liquid in right limb

$h =$ Difference of light liquid

$\rho_1 =$ Density of liquid at A

$\rho_2 =$ Density of liquid at B

$\rho_s =$ Density of light liquid

$p_A =$ Pressure at A

$p_B =$ Pressure at B

Pressure below datum line $X-X$ in the left limb is

$$= p_A-\rho_1\times g\times h_1$$

Pressure below datum line $X-X$ in the right limb is

$$= p_B-\rho_2\times g\times h_2-\rho_s\times g\times h$$

Equating the two pressures, we have

$$p_A-\rho_1 gh_1=p_B-\rho_2 gh_2-\rho_s gh$$

$$p_A-p_B=\rho_1 gh_1-\rho_2 gh_2-\rho_s gh$$

– **Dis-advantages**: Lack of shock and vibration, limited to relatively small pressure, repairing is much difficult.

❖ Mechanical Pressure Measurement Techniques:

➢ Construction and Working of C-type Bourdon tube

Principle:

- When an elastic transducer (bourdon tube in this case) is subjected to a pressure, it deflects. This deflection is proportional to the applied pressure when calibrated.

Construction:

- A C-type Bourdon tube consists of a long thin-walled cylinder of non-circular cross-section, sealed at one end, made from materials such as phosphor bronze, steel and beryllium copper, and attached by a light line work to the mechanism which operates the pointer. The other end of the tube is fixed and is open for the application of the pressure which is to be measured. The tube is soldered or welded to a socket at the base, through which pressure connection is made.

Working:

- As the fluid under pressure enters the Bourdon tube, it tries to change the section of the tube from oval to circular, and this tends to straighten out the tube. The resulting movement of the free end of the tube causes the pointer to move over the scale. The tip of the Bourdon tube is connected to a segmental lever through an adjustable length link. The segmental lever end on the segment side is provided with a rack which meshes to a suitable pinion mounted on a spindle. The segmental lever is suitably pivoted and the spindle holds the pointer.
- Bourdon tubes are made of a number of materials, depending upon the fluid and the pressure for which they are used, such as phosphor bronze, alloy steel, stainless steel, "Monel" metal, and beryllium copper.
- Bourdon tubes are generally made in three shapes: C-type, Helical type and Spiral type.

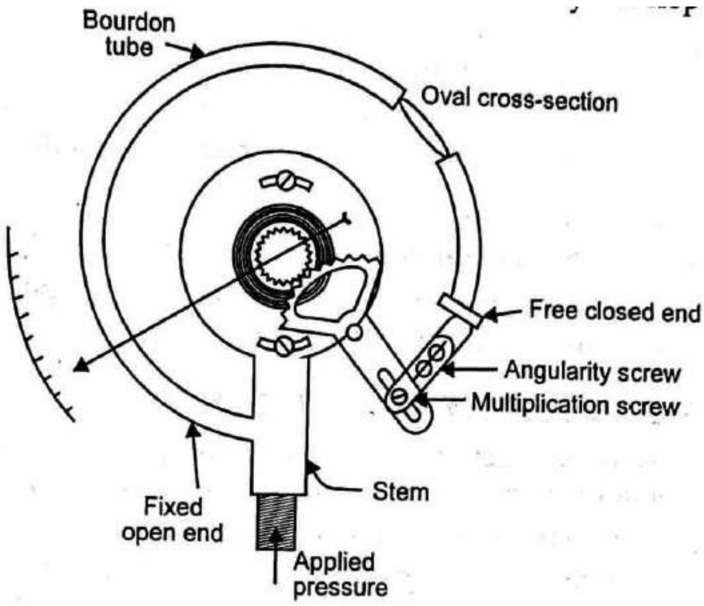


Fig: **C-type Bourdon tube**

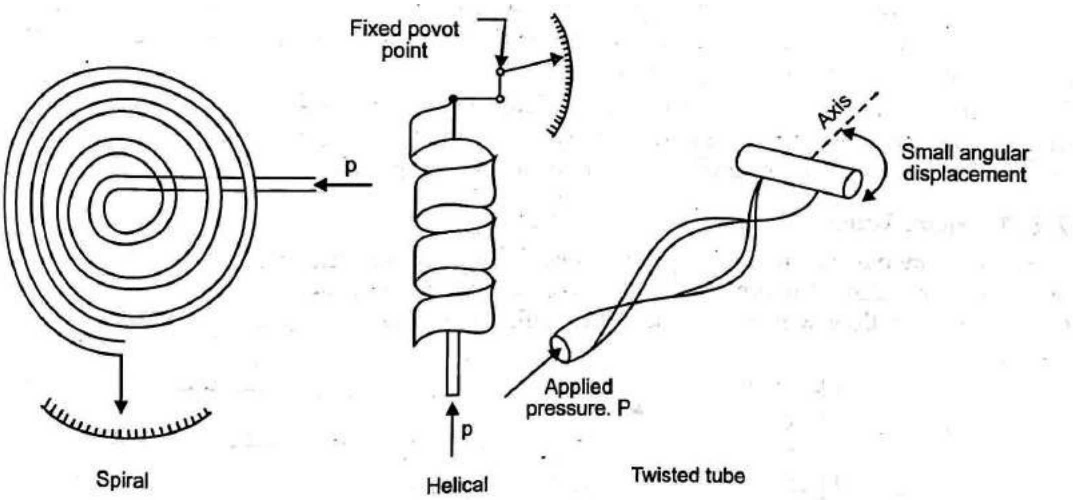


Fig: **Types of Bourdon Tubes**

❖ **Adjustments Need To Perform On Bourdon Tube**

- **Multiplication adjustment:**
  Because of the compound stresses developed in the Bordon tube, actual travel is nonlinear in nature. However, for a small travel of the tip, this can be considered to be linear and parallel to the axis of link. Small linear tip movement is matched with a rotational pointer movement. This is known as multiplication and can be adjusted by adjusting the length of the lever. Shorter lever gives larger rotation for same amount of the tip travel.
- **Angularity:**
  When the approximately linear motion of the tip is converted to a circular motion with the link lever and pinion attachment, a one to one correspondence between them may not occur and a distortion results. This is known as angularity. This can be minimized by adjusting the length of the link.

❖ **Advantages And Disadvantages Of Bourdon Tube**

- **Advantages:**

  1. These Bourdon tube pressure gauges give accurate results.
  2. Bourdon tube cost low.
  3. Bourdon tube are simple in construction.
  4. They can be modified to give electrical outputs.
  5. They are safe even for high pressure measurement.
  6. Accuracy is high especially at high pressures.

- **Disadvantages:**

  1. They respond slowly to changes in pressure
  2. They are subjected to hysteresis.
  3. They are sensitive to shocks and vibrations.
  4. Amplification is a must as the displacement of the free end of the bourdon tube is low.
  5. It cannot be used for precision measurement.

Flow Measurement:

❖ Venturimeter:

- It is a device used for measuring the rate of a flow of a fluid flowing through a pipe. It consist of three parts
  1. A short converging part
  2. Throat
  3. Diverging part.
- The working principle of venture meter is based on Bernoulli's equation.
- Consider a venture meter is fitted in a horizontal pipe through which a fluid is flowing as shown fig 5.4.
- Considering two sections along a pipe line the Bernoulli's equation can be written as

$$\frac{p_1}{\rho g}+\frac{V_1^1}{2g}+Z_1=\frac{p_2}{\rho g}+\frac{V_2^2}{2g}+Z_2$$

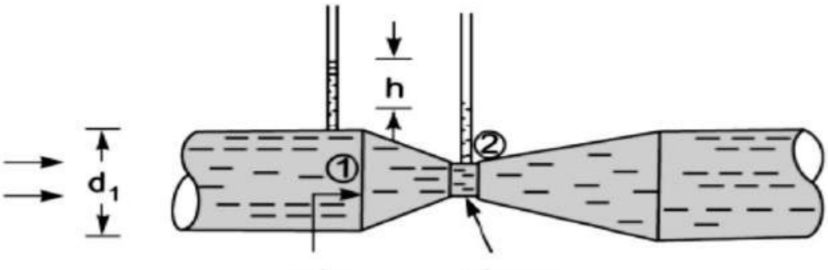


Fig. 5.4 Venturimeter

Let, d_1= diameter at inlet or at section 1,
p_1= pressure at section 1,
V_1= velocity of fluid section 1,
A_1= Area at section 1,

And d_2, p_2, V_2, A_2 are the corresponding values at section 2.

- Applying Bernoulli's equation at section 1 and 2, we get

$$\frac{p_1}{\rho g}+\frac{V_1^2}{2g}+z_1=\frac{p_2}{\rho g}+\frac{V_2^2}{2g}+z_2$$

- Since the pipe is horizontal, $z_1 = z_2$

$$\therefore \frac{p_1}{\rho g}+\frac{V_1^2}{2g}=\frac{p_2}{\rho g}+\frac{V_2^2}{2g}$$

$$\therefore \frac{p_1}{\rho g}-\frac{p_2}{\rho g}=\frac{V_2^2}{2g}-\frac{V_1^2}{2g}$$

$$\therefore h=\frac{V_2^2}{2g}-\frac{V_1^2}{2g} \qquad \cdots\cdots\cdots(1)$$

Where, $\frac{p_1}{\rho g}-\frac{p_2}{\rho g}=h$ = Difference of pressure heads at sections (1) and (2).

- Applying continuity equation at section (1) and (2), we have,

$$A_1V_1=A_2V_2 \text{ OR } V_1=\frac{A_2V_2}{A_1} \qquad \cdots\cdots\cdots(2)$$

From equation (1) and (2),

$$\therefore h=\frac{V_2^2}{2g}-\frac{\left(\frac{A_2V_2}{A_1}\right)^2}{2g}$$

$$\therefore h=\frac{V_2^2}{2g}\left(1-\left(\frac{A_2}{A_1}\right)^2\right)$$

$$\therefore V_2=\frac{A_1\sqrt{2gh}}{\sqrt{A_1^2-A_2^2}} \qquad \text{.........(3)}$$

Discharge, $Q=A_2V_2=\frac{A_1A_2\sqrt{2gh}}{\sqrt{A_1^2-A_2^2}}$ (Using equation. 3)

– Above equation gives the theoretical discharge under ideal condition.

Actual discharge, $\boxed{Q_{act}=C_d\frac{A_1A_2\sqrt{2gh}}{\sqrt{A_1^2-A_2^2}}}$

Where, $C_d=$ Coefficient of discharge for venturimeter and its value taken generally 0.98.

$h=$ Head of fluid in meter of fluid

Value of *h* given by differential U-tube manometer

Case I: Let the differential manometer contains a liquid which is heavier than the liquid flowing through the pipe.(Horizontal Venturimeter)

$$h=x\left[\frac{S_h}{S_o}-1\right]$$

Where S_h = Specific gravity of heavier liquid

S_o = Specific gravity of liquid flowing through pipe

X = Difference of heavier liquid in column in U-tube

Case II: Let the differential manometer contains a liquid which is lighter than the liquid flowing through the pipe. .(Horizontal Venturimeter)

$$h=x\left[1-\frac{S_l}{S_o}\right]$$

Where S_l = Specific gravity of lighter liquid

S_o = Specific gravity of liquid flowing through pipe

X = Difference of heavier liquid in column in U-tube

Case III: Let the differential manometer contains a liquid which is heavier than the liquid flowing through the pipe.(Inclined Venturimeter)

$$h=\left(\frac{p_1}{\rho g}-\frac{p_2}{\rho g}\right)+(z_1-z_2)=x\left[\frac{S_h}{S_o}-1\right]$$

Case IV: Let the differential manometer contains a liquid which is lighter than the liquid flowing through the pipe.(Inclined Venturimeter)

$$h=\left(\frac{p_1}{\rho g}-\frac{p_2}{\rho g}\right)+(z_1-z_2)=x\left[1-\frac{S_l}{S_o}\right]$$

❖ Applications of venturi meter

- Venturi used in a wide variety of applications that includes gas, liquids, slurries, suspended oils and other processes where permanent pressure loss is not tolerable.
- It is widely used in large diameter pipes such as found in the waste treatment process.
- It allows solid particles flow through it because of their gradually sloping smooth design; so they are suitable for measurement of dirty fluid.
- It also be used to measure fluid velocity.

❖ Advantages of venturi meter

- High-pressure recovery. Low permanent pressure drop.
- High coefficient of discharge.
- Smooth construction and low cone angle help to solid particles flow through it. So it can be used for dirty fluids.
- It can be installed in any direction horizontal, vertical and inclined.
- More accurate than orifice and flow nozzle.

❖ Disadvantages of venturi meter

- Size, as well as cost is high
- Difficult to inspection due to its construction
- Nonlinear
- For satisfactory operation, the venturi must be proceeded by long straight pipes.
- Its maintenance is not easy
- It cannot use in pipe that has small diameter (70mm)

❖ Orifice meter

- Orifice meter is a device used for measuring the rate of flow of fluid through a pipe with the using of orifice plate. The working principle is similar to venturimeter and it is works on Bernoulli's theorem.
- It is cheaper device compare to the Venturimeter.
- It consists of flat circular plate which has a circular sharp edge hole called orifice, which is concentric with the pipe.
- The orifice meter generally kept 0.5 times diameter of the pipe, though it may varies from 0.4 to 0.8 times the pipe diameter.
- Consider an orifice meter is fitted in a horizontal pipe through which a fluid is flowing as shown fig 5.5.

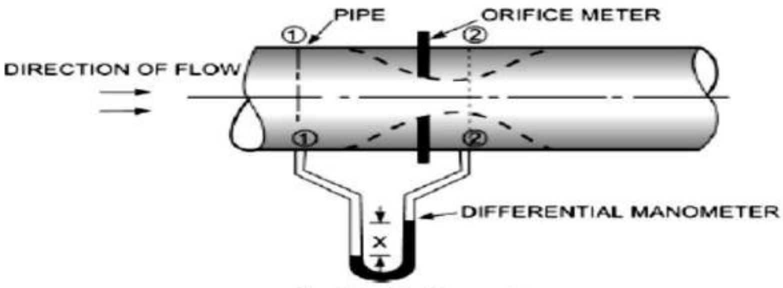


Fig.5.5. Orificemeter

Let, d_1 = diameter at inlet or at section 1,
p_1 = pressure at section 1,
V_1 = velocity of fluid section 1,
A_1 = Area at section 1,

And d_2, p_2, V_2, A_2 are the corresponding values at section 2.

- Applying Bernoulli's equation at section 1 and 2, we get

$$\frac{p_1}{\rho g}+\frac{V_1^2}{2g}+z_1=\frac{p_2}{\rho g}+\frac{V_2^2}{2g}+z_2$$

$$\therefore \left(\frac{p_1}{\rho g}+z_1\right)-\left(\frac{p_2}{\rho g}+z_2\right)=\frac{V_2^2}{2g}-\frac{V_1^2}{2g}$$

$$\text{But}\left(\frac{p_1}{\rho g}+z_1\right)-\left(\frac{p_2}{\rho g}+z_2\right)=\text{Differential head}=h$$

$$\therefore h=\frac{V_2^2}{2g}-\frac{V_1^2}{2g} \qquad \cdots\cdots\cdots(1)$$

- Applying continuity equation at section (1) and (2), we have,

$$A_1V_1=A_2V_2$$

$$\therefore V_1=\frac{A_2V_2}{A_1} \qquad \cdots\cdots\cdots(2)$$

- Consider area of orifice meter is A_o and area at section 2 is A_2, so co-efficient of contraction can be written as below,

$$C_c=\frac{A_2}{A_o}$$

$$\therefore A_2=C_c\times A_o \qquad \cdots\cdots\cdots(3)$$

From equation (2)

$$\therefore V_1=\frac{A_2V_2}{A_1}=\frac{C_cA_oV_2}{A_1}$$

From eq. (1)

$$\therefore h=\frac{V_2^2}{2g}-\frac{V_1^2}{2g}$$

$$\therefore h = \frac{V_2^2}{2g} - \frac{\left(\frac{C_c A_o}{A_1} V_2\right)^2}{2g}$$

$$\therefore h = \frac{V_2^2}{2g}\left(1 - C_c^2\left(\frac{A_o}{A_1}\right)^2\right)$$

$$\therefore V_2 = \frac{\sqrt{2gh}}{\sqrt{1 - \frac{C_c^2 A_o^2}{A_1^2}}} \quad \cdots\cdots\cdots(4)$$

- **Discharge**

$$Q = A_2 V_2$$

$$\boxed{\therefore Q = C_c A_0 \frac{\sqrt{2gh}}{\sqrt{1 - \frac{C_c^2 A_o^2}{A_1^2}}}} \quad \text{(In form of } C_c) \quad \cdots\cdots\cdots(5)$$

- **Equation (4) gives the actual velocity of the fluid flow.**
  According to definition of the co-efficient of contraction (C_c)

$$C_v = \frac{\textit{Actual velocity}}{\textit{Max. velocity}}$$

$$= \frac{\frac{\sqrt{2gh}}{\sqrt{1 - \frac{C_c^2 A_o^2}{A_1^2}}}}{\frac{\sqrt{2gh}}{\sqrt{1 - \frac{A_o^2}{A_1^2}}}} = \frac{\sqrt{1 - \frac{A_o^2}{A_1^2}}}{\sqrt{1 - \frac{C_c^2 A_o^2}{A_1^2}}} \quad \cdots\cdots\cdots(6)$$

- **According to definition of the co-efficient of discharge (C_d)**

$$C_d = \frac{\textit{Actual discharge}}{\textit{Theoritical discharge}} = \frac{A_2 V_2}{A_o V_1} = C_c \times C_v$$

$$C_c = \frac{C_d}{C_v} = C_d \times \frac{\sqrt{1 - \frac{A_o^2}{A_1^2}}}{\sqrt{1 - \frac{C_c^2 A_o^2}{A_1^2}}}$$

- **Putting value of C_c in equation (5)**

$$\boxed{\therefore Q_{act} = C_d \frac{A_0 A_1 \sqrt{2gh}}{\sqrt{A_1^2 - A_o^2}}}$$

❖ Advantages of Orifice meter:

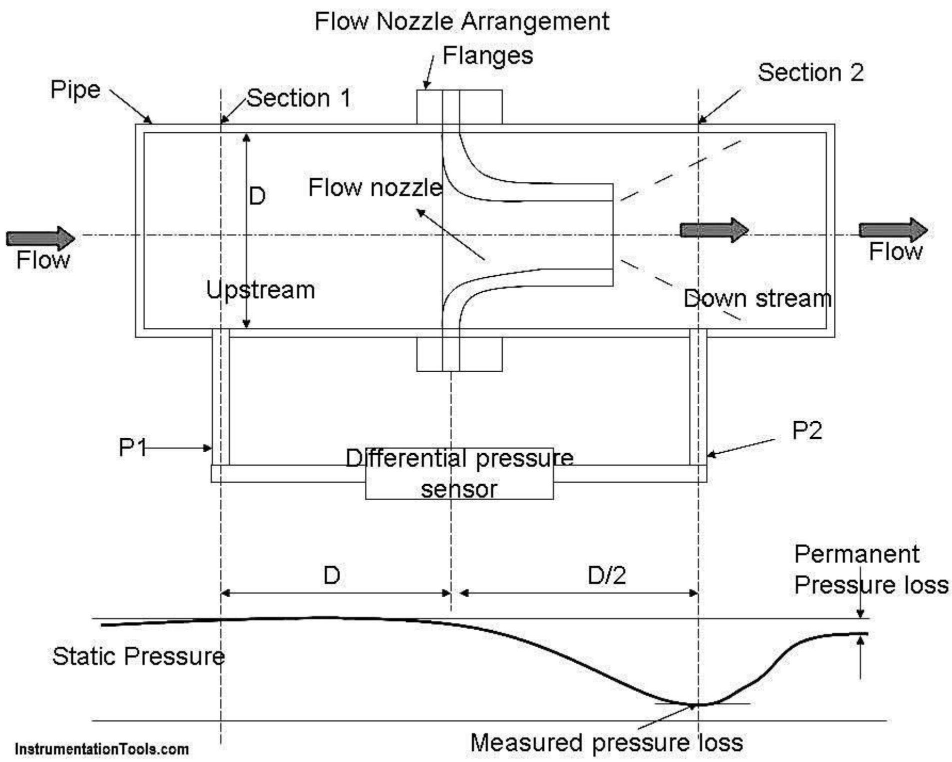
- The Orifice is small plates and easy to install/remove.
- Offer very little pressure drop from which 60% to 65% is recovered.
- The orifice meter can be easily maintained.
- Measures a wide range of flows.
- They have a simple construction.
- They have easily fitted between the flanges.
- They are the most suitable for most gases and liquids.
- They are cheap, the price does not increase dramatically with size.

❖ Disadvantages of orifice meter:

- Requires homogeneous fluid.
- Requires single phase liquid
- It requires the flow of axial velocity vectors.
- It causes a pressure drop in the fluid.
- Its accuracy is affected by the density, pressure and viscosity of the fluid.
- The range of measurement of viscosity limits of fluids.
- It requires straight conduits to ensure accuracy is maintained.
- The pipe must be totally special for the measurement of the flow of liquids.
- They have low range capacity.

❖ Flow Nozzle

- When a flow nozzle is placed in a pipe carrying whose rate of flow is to be measured, the flow nozzle causes a pressure drop which varies with the flow rate. This pressure drop is measured using a differential pressure sensor and when calibrated this pressure becomes a measure of flow rate.



❖ **Description of Flow Nozzle**

The main parts of flow nozzle arrangement used to measure flow rate are as follows:

1. A flow nozzle which is held between flanges of pipe carrying the fluid whose flow rate is being measured. The flow nozzle's area is minimum at its throat.
2. Openings are provided at two places 1 and 2 for attaching a differential pressure sensor (u-tube manometer, differential pressure gauge etc.,) as show in the diagram.

❖ **Operation of flow Nozzle**

1. The fluid whose flow rate is to be measured enters the nozzle smoothly to the section called throat where the area is minimum.
2. Before entering the nozzle, the fluid pressure in the pipe is p1. As the fluid enters the nozzle, the fluid converges and due to this its pressure keeps on reducing until it reaches the minimum cross section area called throat. This minimum pressure p2 at the throat of the nozzle is maintained in the fluid for a small length after being discharged in the downstream also.
3. The differential pressure sensor attached between points 1 and 2 records the pressure difference (p1-p2) between these two points which becomes an indication of the flow rate of the fluid through the pipe when calibrated.

❖ Applications of Flow Nozzle

1. It is used to measure flow rates of the liquid discharged into the atmosphere.
2. It is usually used in situation where suspended solids have the property of settling.
3. Is widely used for high pressure and temperature steam flows.

❖ Advantages of flow Nozzle

1. Installation is easy and is cheaper when compared to venturi meter
2. It is very compact
3. Has high coefficient of discharge.

❖ Disadvantages of flow Nozzle

1. Pressure recovery is low
2. Maintenance is high
3. Installation is difficult when compared to orifice flow meter.

❖ Rotameter

– A rotameter is a discharge measuring device as shown in fig. 5.6. The rotameter is installed in a vertical pipe and measure the discharge directly without any calculation.

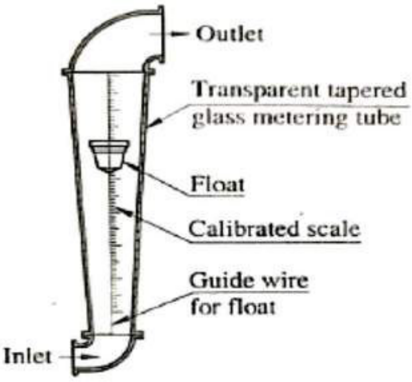


Fig. 5.6 Rotameter

– Rotameter consist different part like, accurately grounded glass tube and a float. One scale is given on the glass tube which is gives the discharge rating.

– If flow is not pass through the rotameter than the float rest at bottom inside the tube. When fluid is enters in the tube, the float moves up and steady at one point and discharge is measured on the calibrated scale.

Note: Generally discharge given by rotameter is in liter per hour.

– The rotameter is used in chemical industries where high degree of accuracy is not required and flow variation is less.

Advantage

a) Good for small flows.
b) Pressure drop is less.
c) Cheaper in cost.
d) It can be handle wide variety of corrosive fluids.

Disadvantage

a) It must be mounted vertically.
b) It is not good for pulsating flows.
c) The glass tube is easily brake.
d) Its accuracy is less.

Measurement of velocity:

❖ Pitot tube

- The Pitot tube is used for measure the velocity of flow at any point in a pipe or a channel.
- It is based on the principle that if the velocity of the flow at a point becomes zero, the pressure head is increase due to velocity head is zero.
- In its simplest form, the Pitot tube consist of a glass tube, bent at right angles as shown in fig. 5.7.

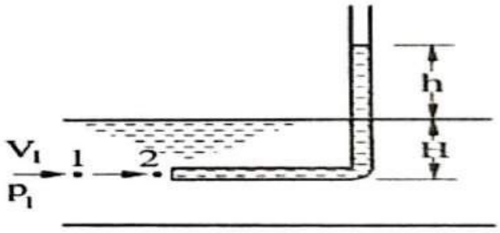


Fig. 5.7 Pitot tube

Consider,

p_1 = Pressure at point 1,
V_1 = Velocity of fluid point 1,
p_2 = Pressure at point 2,
V_2 = Velocity of fluid point 2,
H = Depth of tube in the liquid
h = Rise of the liquid in the tube above the free surface.

- Applying Bernoulli's equation between points 1 and 2, we get

$$\frac{p_1}{\rho g}+\frac{V_1^2}{2g}+z_1=\frac{p_2}{\rho g}+\frac{V_2^2}{2g}+z_2$$

- But $Z_1=Z_2$ and $V_2=0$ (static condition)

From fig $\frac{p_1}{\rho g}=H=$ Pressure head at point 1,

$\frac{p_2}{\rho g}=H+h=$ Pressure head at point 2,

- Substitute this values we get,

$$H+\frac{V_1^2}{2g}=H+h$$

$$\therefore V_1=\sqrt{2gh} \rightarrow \text{Theoretical velocity}$$

- Actual velocity is given by,

$$V=C_v\times V_1$$

$$\boxed{\therefore V=C_v\times\sqrt{2gh}}$$

- Pitot tube with U-tube differential manometer is shown in fig. 5.8.

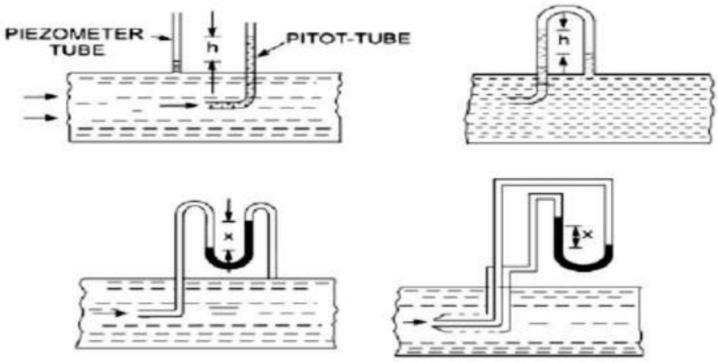


Fig. 5.8 Pitot tube with differential U-tube manometer

- If differential U-tube manometer is used with Pitot tube than value of h can be determine by the equation similar to venturimter. Where, x is the reading of U-tube differential manometer.

  Note: The difference between total pressure (stagnation pressure) and static pressure is called dynamic pressure.

❖ Anemometer

- The anemometer is a mechanical instrument useful to measure the speed or velocity of air or gases. It may be either in a contained flow like airflow in a duct or in the unconfined flows like the atmospheric wind. To determine the air velocity, anemometers are able to detect the change in some physical properties of the fluid. Sometimes to measure the effect of the fluid on a mechanical device inserted into the flow. Actually, the anemometer counts the number of rotations. Further, it is useful to calculate wind speed. Many times these are also important to the work of physicists, who study the way air moves.

- This device is mostly found in the weather stations. Actually, the wind is moving the air in motion and hence it is causing the difference in air pressure. In this case of traditional anemometer has four cups to measure the speed of the wind. Each of these four is attached to the horizontal arm. Obviously, the faster the wind, the faster the cups spin the axis. Its revolutions per minute will give the wind speed in rpm unit. Wind speed measurements help in weather forecasting like hurricanes, storms, and tornadoes.

➢ Types of Anemometers

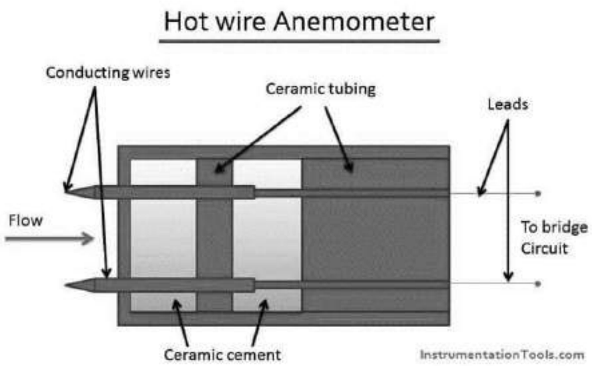
- There are many types of anemometers to measure wind speed. Actually, anemometers can be categorized into two categories such as portable handheld anemometers and those affixed to the ground at weather stations. Portable handheld anemometers are in form of digital anemometers. Further classification of the anemometers gives cup anemometers, hot wire anemometers, ultrasonic anemometers, pressure tube anemometers, and laser Doppler anemometers. Let us have an explanation about each type of anemometer.
  - **Cup anemometer or rotational anemometer:** It is having cups placed onto the vertical axis. Due to the wind pressure against them, cups to rotate around. The wind speed is based on the fact of how faster the cups rotate. These are frequently in use by educational institutions, researchers, and meteorologists.
  - **Hotwire / thermal flow anemometers:** It measures both wind speed and pressure. Mainly, found at businesses for purposes of heating, ventilating and also for air conditioning.
  - **Ultrasonic anemometers:** It is an anemometer which has four sensors arranged in a square pattern.
  - **Pressure tube anemometer or windsock:** It is providing the wind direction and wind speed by who higher the tube rises off the ground. It is mainly found around airports.
  - **Windmill anemometer:** It measures both wind speed as well as direction. The device has the propeller attached on its front side and a large tail at its backside. It does not have any meter for wind speed, but how fast the propeller rotates indicates the speed of the wind.
  - **Laser Doppler:** This anemometer utilizes the concept of Doppler Effect to determine the flow of moving air. In it, a beam of light is used which is further split into two beams. Further speed is determined by calculating the amount of light that has been reflected off by the moving air particles. It is mostly in use in high-tech jet engines and in river hydrology.

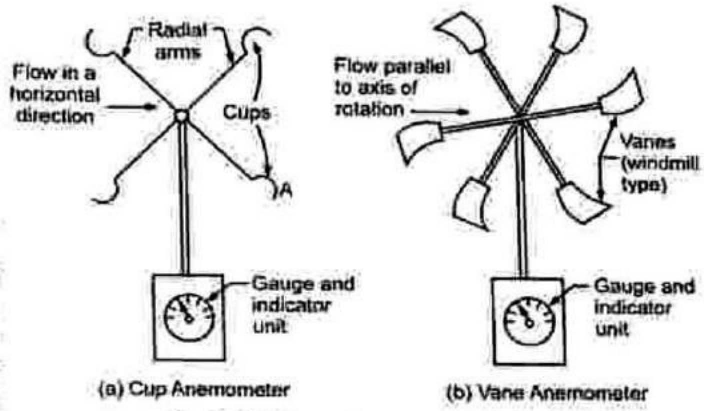
- Mostly handheld anemometers are of waterproof quality. Some can even float and allows the user to access a variety of wind speed measurement units. Whereas digital handheld anemometers have wind meters which further may be connected to the smartphones through Bluetooth.

❖ Applications of Anemometers

Mainly anemometers are useful in the applications areas like weather stations, ship navigation, aviation, weather buoys, and also in wind turbines. Also, monitoring wind turbines usually requires the refresh rate of wind speed measurements of the 3 Hz.

- Other than measuring the speed of the wind by using the anemometer, some others are as follows:
  - For measuring the wind pressure.
  - For measuring the flow of the wind and the direction of the wind.
  - Sometimes the drone users or RC plane users also use it. It is to check the weather conditions before testing their devices
  - Long-range shooters and pilots also use it.
  - Skydivers use it to evaluate wind velocity before they leap into the abyss
  - It is also useful in aerodynamics to measure the airspeed.





Temperature Measurement:

- Temperature is an intensive quantity independent of the size of the system. Temperature measurement depends upon the establishment of the thermodynamic equilibrium between the system and the device used to sense the temperature. The sensor has certain physical characteristics which change with temperature and this effect is taken as a measurement of the temperature. Measurement of temperature potential is involved in thermodynamics, heat transfer and many chemical operations.
- Temperature measuring instruments are :

1. **Liquid-in-glass thermometers**
2. **Bimetallic thermometer**
3. **Thermistors**
4. **Thermocouple**
5. **Resistance thermometers**
6. **Optical pyrometers**

1. Liquid-In-Glass Thermometers

Construction

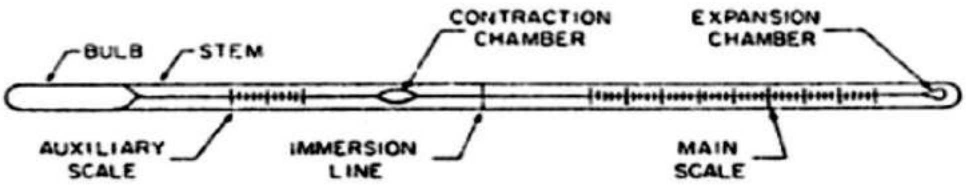


Figure 5.1 Liquid in Glass Thermometer

The components of a typical liquid-in-glass thermometer are shown in Fig. 8.1. These include:

Bulb: The reservoir for containing most of the thermometric liquid.

Stem: The glass tube having a capillary bore along which the liquid moves with changes in temperature.

Auxiliary Scale: A narrow-temperature-range scale for reading a reference temperature (usually the ice point). It should be marked as for the main scale (below). If the main scale range includes the reference temperature no auxiliary scale is supplied.

Contraction Chamber: An enlargement of the capillary bore between the auxiliary and main scales, or between the reservoir and the main scale, to limit the length of the capillary (and hence the thermometer).

Immersion Line: A line marking the depth to which a partial-immersion thermometer should be immersed.

Main Scale: An engraved, etched, or otherwise permanently attached scale with well-defined, narrow graduation lines against which the height of the liquid in the capillary is measured. There may be a colored backing material for better visibility of the lines. The main scale is graduated in fractions or multiples of degrees Celsius. If its range incorporates the reference temperature, it is the only scale.

Expansion Chamber: An enlargement at the top of the capillary into which the liquid can flow if the thermometer temperature exceeds the scale limit. It is undesirable for liquid to enter the expansion chamber, however, so it is much better to ensure that there is no overheating of the thermometer. The expansion chamber also prevents excessive gas pressure when the thermometer is used near the top of its range, especially in high-temperature pressurized thermometers.

The unit consists of a glass envelope, a responsive liquid and an indicating scale. The envelope comprises a thick wailed glass tube with a capillary bore, and a spherical or cylindrical bulb filled with the liquid. The two parts are fused together and the top end of the capillary tube is sealed.

The range of a liquid-in-glass thermometer is limited by the liquid, by the glass, and by the construction. The commonest and best liquid is mercury. The recommended range of use is from near the mercury freezing point (-38 °C) to about 350 °C with soda-lime glasses; higher temperatures require borosilicate or other special glasses. The capillary above the mercury is filled with a dry gas (frequently nitrogen) to prevent separation of the column and to inhibit distillation of the mercury; in the higher-temperature models, substantial gas pressures are required to raise the mercury boiling point above the range of the thermometer. Air is not a good filling gas because it may lead to oxidation of the mercury and consequent sticking of the latter in the capillary.

Working

Changes in the temperature will cause the fluid to expand and rise up the stem. Since the area of the stem is much less than the bulb, the respectively small changes of fluid volume will result in significant fluid rise in the stem. The length of the movement of the free surface of the fluid column serves, by a prior calibration, to indicate the temperature of the bulb. The laboratory work thermometers have a scale engraved directly on the glass stem, while the industry types have separate scale located adjacent to the stem. Quite often the top of the capillary tube is also bulb shaped to provide safety in case the temperature range of the instrument is inadvertently exceeded. The range of application of different liquids is stated in table 8.1

Liquid	*Range (^{0}C)*
Mercury	-35 to 510
Alcohol	-80 to 70
Toluene	-80 to 100
Pentane	-200 to 30
Creosote	-5 to 200

Table 5.1 Liquids used in Glass Thermometers

Salient features / characteristics:

- Simplicity of use and relatively low cost easily pot table
- Ease of checking for physical damage
- Absence of need for auxiliary power
- No need of additional indicating instruments
- Fragile construction; range limited to about 600^{0}C
- Lack of adaptability to remote reading
- Time lag between change of temperature and thermometer response due to relatively high heat capacity of the bulb.

These thermometers arc generally designed and calibrated for one of the following three conditions shown in Fig. 5.2.

A. Total immersion — the bulb and liquid containing part of the capillary is exposed to the temperature being measured.

B. Complete immersion —the entire thermometer is exposed to the temperature being measured.

C. Partial immersion—the liquid in the stem emerging from the liquid bath is subjected to the ambient temperature which may be radically different from the temperature of the liquid bath.

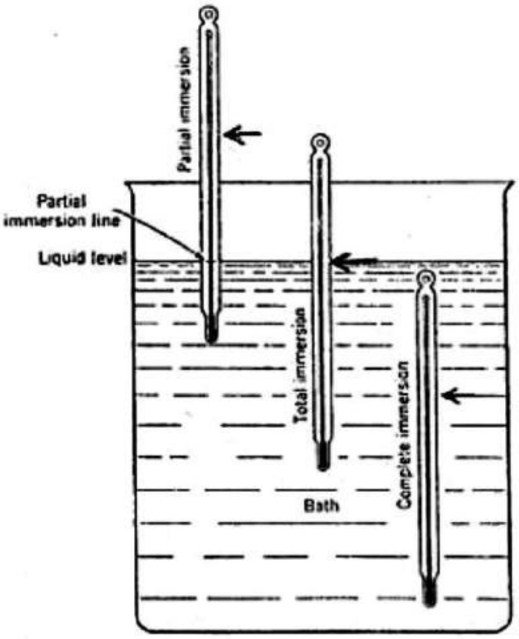


Fig 5.2 immersion techniques for the three types of liquid in glass thermometer

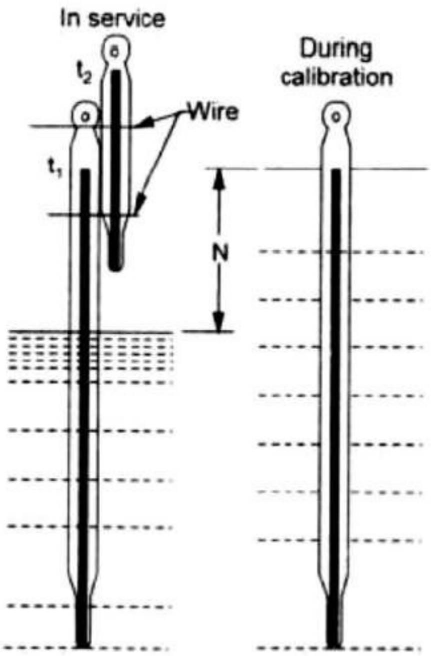


Fig. 5.3 correction technique for stem emergence effects

Generally, the glass stem thermometers are graduated for total immersion of bulb and stem. When the stem of a total-immersion thermometer is only partially immersed, the indicated temperature is corrected for the stem emergence effects. The ASME Power Test Codes recommend that a secondary thermometer be attached to the stem of the primary thermometer (Fig. 5.3) and that a correction to the observed temperature be made in accordance with the emergent-stem error given by:

$$C_s = 0.00016 \cdot N(t_1 - t_2)$$

In this expression C_s is the stem correction in degrees in be added algebraically to the indicated temperature, N is the number of degrees of exposed or emergent stem, t_1 is the reading of the primary thermometer, and t_2 is the average temperature of the exposed stem as determined by the attached (secondary) thermometer.

7.8.2. Solid Expansion or Bimetallic Thermometer

A bimetal strip consists of two pieces of different metals firmly bonded together by welding. For a bi-metal in the form of a straight cantilever beam, temperature changes cause the free end to deflect because of the different expansion rates of the components. This deflection can be correlated quantitatively to the temperature change.

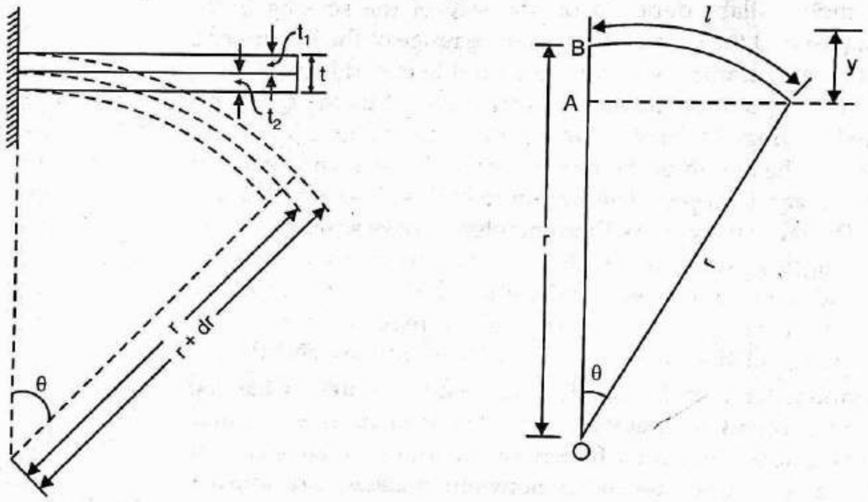


Fig. 7.28. Bimetallic strip

When a bimetal strip in the form of cantilever is assumed to bend through a circular atc, then

$$\frac{r+dr}{r} = \frac{\text{expanded length of strip having higher expansion coefficient}}{\text{expanded length of strip having lower expansion coefficient}}$$

$$= \frac{l[1+\alpha_2(T-T_0)]}{l[1+\alpha_1(T-T_0)]}$$

Simplification gives :

$$r = \frac{dr[1+\alpha_1(T-T_0)]}{(\alpha_2-\alpha_1)(T_1-T_0)}$$

The tip deflection can be increased with choice of materials that give a large value to the difference in their coefficient of expansion. Normally the low expansion material is invar (an iron nickel alloy containing about 36% nickel) and the high expansion metal is brass.

Taking $\alpha_1 \simeq 0$ and $dr = t/2$ (thickness of each metal strip), we get

$$r = \frac{t}{2\alpha_2 (T - T_0)}$$

The movement of free end of the cantilever in a perpendicular direction from the initial horizontal line is worked out as follows :

angular displacement $\theta = l/r$

vertical displacement $y = OB - OA = r - r\cos\theta$

$= r(1 - \cos\theta)$

Apparently when one end of the bimetallic strip is fixed, the position is free and is a direct indication of the temperature of the strip.

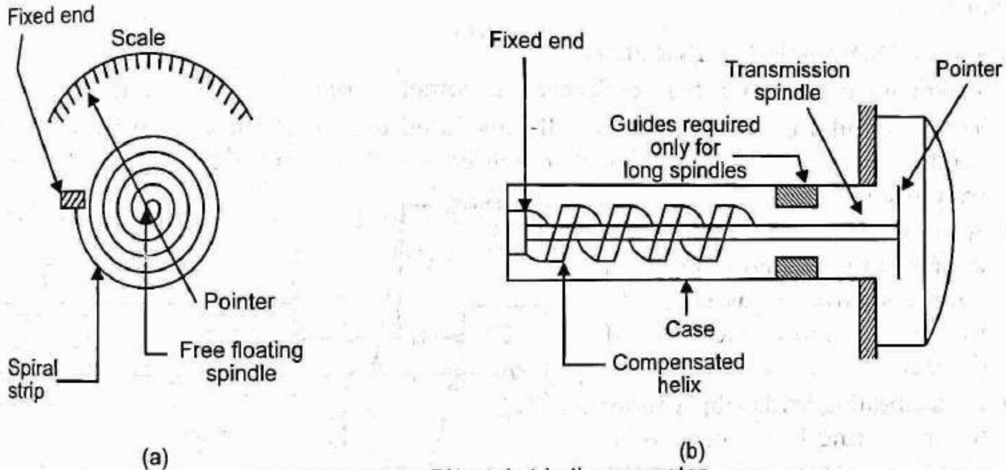


Fig. 7.29. Bimetal strip thermometer

Bimetalic elements can be arranged in the flat, spiral, the single helix, and the multiple helix configuration. Figure 7.29 illustrates the functional principle of the usual industrial form of a bimetal thermometer. One end of the helix is anchored permanently to the casing and the other end is secured to a pointer which sweeps over a circular dial graduated in degree of temperature. In response to temperature change, the bimetal expands and the helical bimetal rotates at its free end, thus turning the stem and pointer to a new position on the dial. Likewise the curvature of bimetal spiral strip (Fig. 7.29 (*b*)) varies with temperature and causes a pointer to deflect. The continuous strip wound into helical or spiral form has the advantages of compactness while providing a long length of strip required for adequate indicator movement.

Bimetallic elements find wide application in simple thermometers in which the deflection of the elements is made to open or close electrical contacts in the electrical heat supply or to control a gas flow. Important applications include the switching devices used in domestic ovens, electric irons, car winker lamps and the refrigerators.

7.8.3. Thermocouples

When two conductors of dissimilar metals M_1 and M_2 are joined together to form a loop (a thermocouple) and two unequal temperatures T_1 and T_2 are imposed at the two interface connections, an electric current flows through the loop.

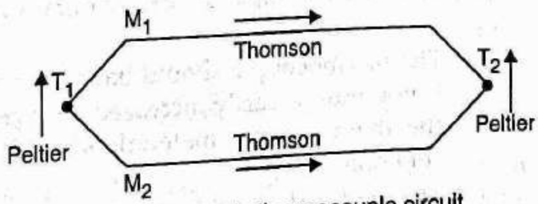


Fig. 7.30. Basic thermocouple circuit

Experimentally it has been found that the magnitude of the current is directly related to the two materials M_1 and M_2 and the temperature difference $(T_1 - T_2)$. In the practical application of the effect, a suitable device is incorporated in the circuit to indicate any electromotive force or flow of current. For convenience of measurement and standardisation, one of the two junctions is usually maintained at some constant known temperature. The output voltage of the circuit then indicates the temperature difference relative to the reference temperature.

Thermo-electric effects arise in two ways:

- a potential difference always exists between two dissimilar metals in contact with each other (*Peltier effect*)
- a potential gradient exists even in a single conductor having a temperature gradient (*Thomson effect*)

In commercial instruments, the thermocouple materials are so chosen that the Peltier and Thomson emf's act in such a manner that the combined value is maximum and that varies directly with temperature.

Elements of a Thermo-electric Pyrometer

The essential elements of a thermo-electrical pyrometer are shown schematically in Fig. 7.31.

- Two dissimilar conductors electrically insulated except at the hot junction, where the conductors may either be soldered or welded together, or may be completely separated from each other.
- A refractory and a metal sheath to protect the thermocouple from injurious furnace gases and to prevent it from mechanical damage.
- Compensating leads which allow the measuring instrument to be placed at a considerable distance from the thermocouple without the necessity of using expensive thermocouple materials as extension leads.
- The cold or the reference junction provided by the instrument used for measuring the emf.

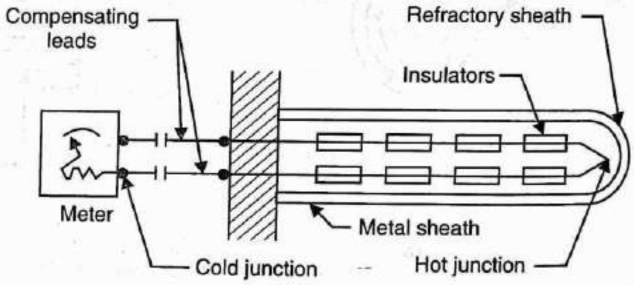


Fig. 7.31. Element of a thermo-electric pyrometer

Thermocouple Materials

The desirable characteristics of thermocouple materials are:

(*i*) The emf produced per degree of temperature change must be sufficient to facilitate detection and measurement.

(*ii*) The temperature–emf relationship should be reasonably linear and reproducible. This will make the scale more easily read and also reduce the problem of reference junction compensation.

(*iii*) The thermocouple should maintain its calibration without drift over a long period of time.

(*iv*) The thermocouple should have a long life so that the cost of temperature measurement is not unnecessarily increased with frequent replacement of the thermocouple. For that, the thermocouple materials should be highly resistant to oxidation, corrosion and contamination.

(*v*) The material should physically be able to withstand high and rapidly fluctuating temperatures. Any phase change or other internal phenomenon will give rise to discontinuity in the temperature–emf relationship.

(vi) The material must be such that successive batches can be produced with the same thermo-electric characteristics. This will allow the replacement of thermocouples without the necessity of recalibrating the temperature scale of the indicating instrument.

Depending upon the composition of metals used, the thermocouples are sometimes grouped into the following broad categories :

(i) *Base metal thermocouples* use combinations of pure metal and alloys of iron, copper and nickel, and are used in lower ranges of temperature upto 1375°C.

(ii) Rare metal *thermocouples* use combinations of pure metals and alloys of
   (a) platinum and rhodium for temperatures upto 1725°C, and
   (b) tungsten, rhodium and molybdenum for temperatures upto 2625°C.

7.8.4. Resistance Thermometers and Thermistors

The resistance R (ohms) of an electrical conductor of resistivity ρ (ohms Ω), length L (cm) and cross sectional area A (cm^2) is given by

$$R = \rho L/A \qquad \text{...(7.19)}$$

As temperature changes, the resistance of the conductor also changes. This is due to two factors : (i) dimensional change due to expansion or contraction and (ii) change in the current opposing properties of the material itself. For an unconstrained conductor, the latter is much more than 99% of the total change for copper. This change in resistance with temperature is used for measuring temperature.

Resistance Thermometers

Most metals become more resistant to the passage of electric current as they become hotter, *i.e.*, their resistance increases with growth in temperature. An adequate approximation of the resistance-temperature relationship is given by :

$$R_t = R_o\,(1 + \alpha t + \beta t^2) \qquad \text{.....(7.20)}$$

where R_t is resistance at any temperature t° C, R_o is resistance at 0°C, α and β are constants depending on the material. The constants R_o, α and β are determined at the ice, steam and sulphur points respectively.

Over a limited temperature range around 0°C, the following linear relationship is equally valid:

$$R = R_o\,(1+\alpha\,\theta)$$

where α is the temperature coefficient of resistance in °C^{-1} and θ is temperature relative to 0°C. Some typical values for temperature coefficient are:

α = 0.0039°C^{-1} for platinum, α = 0.0043°C^{-1} for copper, α = 0.0068°C^{-1} for nickel

If a change in temperature from θ_1 to θ_2 is considered, then

$$R_1 = R_o\,(1 + \alpha\,\theta_1)\ ;\ \ R_2 = R_o\,(1 + \alpha\,\theta_2)$$

Rearrangement gives

$$\theta_2 = \theta_1 + \frac{R_2 - R_1}{\alpha R_o}\ ;\ \ \frac{R_2 - R_1}{\theta_2 - \theta_1} = \alpha\,R_o \qquad \text{...(7.21)}$$

Apparently the linear relationship implies that changes in resistance are directly proportional to changes in temperature.

The thermometer comprises a resistance element or bulb, suitable electrical leads, and an indicating–recording or resistance measuring instrument. The resistance element is usually in the form of a coil of very fine platinum, nickel or copper wound non-conductively onto an insulting ceramic former which is protected externally by a metal sheath. A laboratory type of resistance thermometer is often wound on a crossed mica former and enclosed in a pyrx tube. The tube may be evacuated or filled with an inert gas to protect the metal wire. Care is to be taken to ensure that the resistance wire is free from mechanical stresses. A metal which has been strained will suffer a change in the resistance characteristic; the metal is therefore usually annealed at a temperature higher than that at which it is to operate.

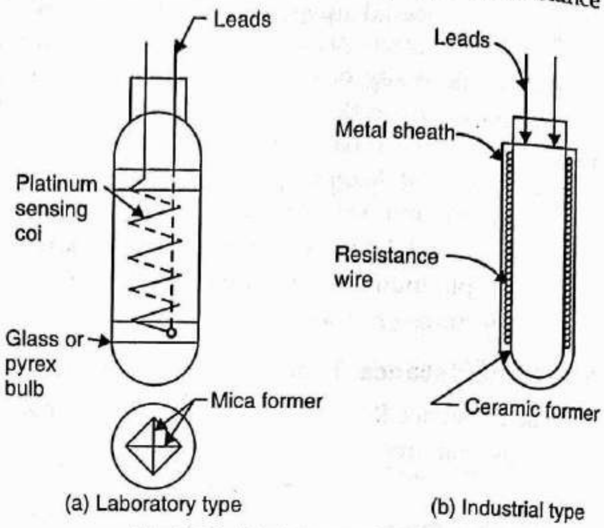


Fig. 7.32. Resistance thermometers

Leads are taken out of the thermometer for the measurement of changes in resistance in order to determine the value of temperature. The change in resistance is usually measured by a wheat stone bridge which may be used either in the null (balanced) condition or in the deflection out of balance condition. For steady state measurement, null conditions suffice wheras transient conditions usually require the use of the deflection mode.

A metal used for the fabrication of sensing elements is required to satisfy the following characteristics :

- Linearity of resistance – temperature relationship for convenience in measurement.
- Relatively large change in resistance with temperature in order to produce a resistance thermometer with good sensitivity.
- No change of phase or state within a reasonable temperature change.
- Resistant to corrosion and absorption under conditions of use.
- Availability in a reproducible condition, *i.e.*, consistent resistance – temperature relationship to provide reliable uniformity.
- High resistivity so that the unit can be fabricated in a compact and convenient size.

Industrial resistance thermometers, often referred to as resistance temperature detectors (RTD) are usually made with elements of platinum (shows little vocalization below 1000°C), nickel (upto 600°C) and copper (upto 250°C). For precise temperature measurements, platinum is preferred because it is physically stable (*i.e.*, relatively indifferent to its environment, resists corrosion and chemical attack and is not readily oxidized) and has high electrical resistance characteristics. It is stated that with careful and in scientific hands, the accuracy attainable with a platinum resistance thermometer is of the order of ± 0.01°C upto 500°C, and with ± 0.1°C upto 1200°C. Because of accuracy, stability and sensitivity, the platinum resistance thermometer has been used to define International Temperature Scale from the boiling point of oxygen (–182.9°C) to the freezing point of antimony (630.5°C).

Thermistors

Thermistor is a contraction of term ***"Thermal Resistor"***. They are essentially semi-conductors which behave as resistors with a high negative temperature coefficient. As the temperature increases, the resistance goes down, and as the temperature decreases, the resistance goes up. This is just opposite to the effect of temperature changes on metals. A high sensitivity to temperature changes (decrease in resistance as much as 6% for each 1°C rise in temperature in some cases) make the thermistors extremely useful for precision temperature measurement, control and compensation in the temperature range of - 100°C to 300°C.

Thermistors are composed of sintered mixture of metallic oxides such as manganese, nickel, cobalt, copper, iron and uranium. These metallic oxides are milled, mixed in appropriate proportione, are pressed into the desired shape with appropriate binders and finally sintered. The electrical terminals are either embedded before sintering or backed afterwards. The electrical characteristics of thermistors are controlled by varying the type of oxide used and physical size and configuration of the thermistor. Thermistors may be shaped in the form of beads, disks, washers, rods and these standard forms are shown in Fig. 7.33. Disks and rods are used more as time delay elements, temperature compensators and for voltage and power control in electrical circuits. Glass and metal probes less than 2 mm diameter are used for temperature measurements metal surface, gases and liquids.

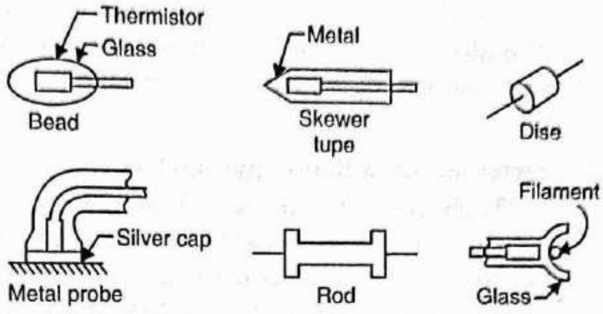


Fig. 7.33. Typical thermistor forms

Thermistors may be used bare but are usually glass coated or positioned under a thin metal cap. The change in resistance is measured by using circuitry similar to that of metal conductors.

7.8.5. Pyrometers

Total Radiation Pyrometers

The total radiation pyrometer is designed to collect the radiations from the radiating object (furnance) and focus it by means of mirrors or lens onto a detector (say hot junction of a thermocouple). The emf developed by the thermocouple circuit is measured by a suitable milli-voltmeter or potentiometer, which after suitable calibration becomes a measure of the temperature of the radiating object. Figure 7.34 is a schematic drawing of typical radiation pyrometers.

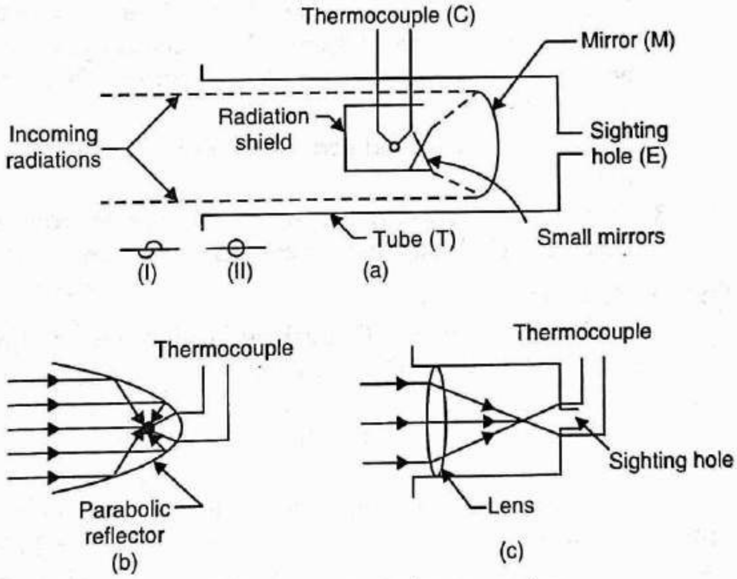


Fig. 7.34. Typical radiation pyrometers

Pyrometer consists of a blackened tube T open at one end to receive radiations from the object whose temperature is desired. The other end of the tube carries the sighting hole E which is essentially an adjustable eye piece. The thermal radiations imping on a concave mirror M whose position can be adjusted by a rack and pinion. The mirror is centrally piecred to allow light to reach the eye piece. The mirror provides maximum reflection of the incoming radiations onto a thermocouple C which is shielded from the incoming radiations and carries a blackened copper target disk. There are two small semicircular flat mirrors which are inclined at a slight angle from the vertical plane. The resulting hole is smaller than the target and this allows radiation from the concave mirror to reach the thermocouple. The eye piece and the concave mirror are adjusted to focus the radiation from the furnace onto the target. Small mirrors help in the focussing process. These mirrors appear as shown at (*i*) when the radiation is not focuseed onto the target and when focusing is achieved they appear as at (*ii*).

The object of directing radiations from the measured surface onto the temperature sensing element can also be achieved by a parabolic reflector [Fig. 7.34(*b*)], or by a lens system [Fig. 7.34(*c*)].

Characteristic of radiation pyrometers

1. High speed of response (0.01 to 0.02 min; fast response is due to small thermal capacitance of the detector. Accuracy ± 2% of scale range.
2. No direct contact is necessary with the object whose temperature is to be measured. This fact allows its use in situations where it is impossible or undesirable to bring the measuring instrument in contact with the object under consideration.
3. Primarily used to measure temperatures in the range 700–2000°C where thermocouple and resistance thermometers cannot be employed.
4. Capable of measures the temperature of an object which may be either stationary or moving, and so adaptable to continuous industrial processing.
5. Suitable for measuring temperatures where the atmospheric or other envirnmental conditions prevent satisfactory operation of other temperature sensing devices.
6. Relatively independent of the distance between the measuring element and the heated body. However, for optimum working the distance from target to receiver should not be greater than 10 or 20 times the maximum useful diameter of the target. Further, with increase in the distance there will be greater opportunity for gases, smoke etc. to intervene and absorb some of the radiant energy. This would tend to reduce the indicated temperature.
7. The effect of dust and dirt on the mirrors or lens is to cause the instrument to read too low.
8. Cooling is required to protect the instrument from overheating where the temperature may be high because of operating conditions.

Optical Pyrometers

A metallic surface is usually dark and dull coloured at room temperature. When the surface is heated, it emits radiations of different wavelengths; these radiations are, however, not visible at low temperatures. As the temperature is progressively increased beyond 540°C, the surface becomes dark red, orange and finally white in colour. A colour variation with temperature growth may thus be taken as an index of the probable temperature.

This principle of temperature measurement by colour or brightness comparison is utilized in optical pyrometers designed to measure temperatures in the range 700–3000°C. These pyrometers compare the energy emitted by a body at a given wavelength with that of a black body calibrated lamp. A sketch of one of the several types of optical pyrometers is shown in Fig. 7.35.

Radiations from the target surface are focused by an objective lens (*L*) upon the plane filament (*F*) of an incandescent electric light bulb. The eye price (*E*) is also adjusted until the filament is in sharp focus and under these conditions the filament is seen supermiposed on the image of the target surface. A red filter (*R*) is placed between the eyepiece and filament, and it allows only a narrowband of wavelength 0.65 μ to pass through it. Matching of brightness of the lamp filament with that of target surface is achieved by adjusting current through the standard lamp by changing the value of circuit resistance. The variable resistance or the magnitude of milliammeter reading (a measure of current through the lamp) may then be calibrated in terms of the target temperature.

When the filament is indistinguishable, in terms of brightness, from the image of the target surface, then it is radiating at the same intensity as the target surface. Three different conditions of the filament as sighted through the eyepiece are also shown in Fig. 7.35. When the filament is colder than the target surface, it appears as a dark wire against a light coloured background. Filament brightness is then increased by causing more current to pass through the filament. A filament hotter than the object would appear brighter than the target surface. The current through the filament is then reduced to provide correct merging of filament and the object.

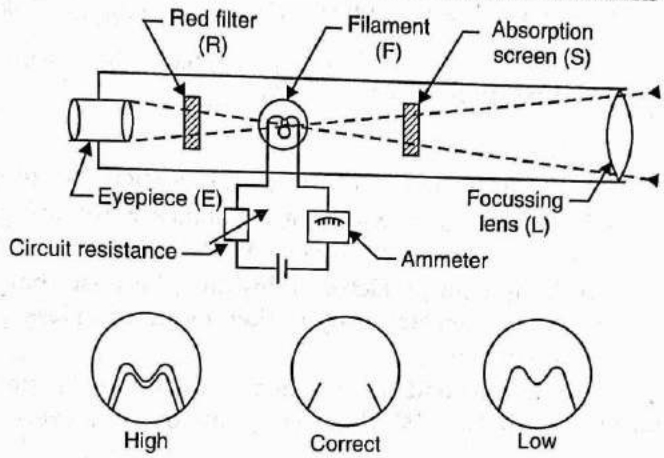


Fig. 7.35. Disappearing—filament optical pyrometer

In an alternative approach, current through the lamp filament is maintained constant. An optical wedge of absorbing material is moved up and down and its variable thickness accentuates the incoming energy to match the filament. The wedge position is then calibrated for temperature. The pyrometer is calibrated by sighting it upon a black body at various known temperatures.

The noteable characteristics of an optical pyrometer are:

(1) No direct contact is necessary with the object whose temperature is to be measured. This aspect allows their use in situations where the measuring target is remote and inaccessible such as molten metals, furnace interiors. etc.

(2) Excellent accuracy; the temperature in the useful operating range (700 – 1000°C) can be determined within ± 5°C.

(3) Measurement is independent of the distance between the target and the measuring instrument. The image of the target, however, should be sufficiently large to make it possible to secure a definite brightness match with the filament of the test spot.

(4) The skill in operating the thermometer can be acquired readily. However, the skill of the operator has more effect upon the resulting temperature measurements when an optical pyrometer is used than when a radiation pyrometer is used.

(5) Because of its manual null-balance operation, this pyrometer is not suitable for continuous recording or automatic control applications.

(6) The lower measuring temperature is limited to 700°C. Below this termperature, the eye is insentive to wavelength characteristics.

7.9 STRAIN MEASUREMENT

A strain gauge is a device for measuring dimensional change on the surface of a structural member under test. Measurement of strain is indispensable in a variety of applications due to utility of strain measurement as a means of determining maximum stress values or in specialized transducers to measure force, pressure, accelerations, torque, etc.

The operation of an electrical resistance strain gauge is based on the fact that when a conductor is subjeted to mechanical deformation, its length and diameter are altered and a change in its resistance occurs. The resistance change is measured by the wheatstone bridge circuit and correlated to strain or the physical effect causing the strain. For many metals used as strain gauge meterial, the following correlation is applicable.

$$F = 1 + 2\mu$$

where μ = Poisson's ratio = $\dfrac{\text{diametral strain}}{\text{longitudinal strain}} = \dfrac{\delta d/d}{\delta l/l}$

and F = Gauge factor = $\dfrac{\text{fractional change in resistance}}{\text{longitudinal strain}} = \dfrac{\delta R/R}{\delta l/l}$

It is to be noted that

(*i*) For most metals μ = 0.3, and as such the guage factor has the value around 1.6

(*ii*) For any given value of resistance R for the gauge element and strain, the change in resistance varies directly with the gauge factor.

(*iii*) A high gauge factor is desirable because that would give a large change in resistance for a given strain input, thereby needing less sensitive circuit for measuring the change in resistance.

Commercial solid strain gauges using doped crystal structures (semi-conductors) have gauge factors from 100 to 5000. These gauges are becoming very popular in modern instrumentation system.

7.10 FORCE MEASUREMENT

A measure of the unknown force may be accomplished by the methods incroporating the following principles :

(*i*) Balancing the force against a known gravitational force on a standard mass (scales end balances).

(*ii*) Translating the force to a fluid pressure and then measuring the resulting pressure (hydraulic and pneumatic load cells).

(*iii*) Applying the force to some elastic member and then measuring the resulting deflection (proving ring).

(*iv*) Applying the force to a known mass and then measuring the resulting acceleration.

(*v*) Balancing the force against a magnetic force developed by interaction of a magnet and a current carrying coil.

Scales and Balances

Force or weight is indicated by making a comparison between the force due to gravity acting on a standard mass and the force due to gravity acting on the unknown mass.

An *equal-arm beam balance* (Fig. 7.36) consists of a beam pivoted on a knife-edge fulcrum at the centre. Attached to the centre of the beam is a pointer which points vertically downwards when the beam is in equilibrium. The equilibrium conditions exist when the clockwise rotating moment equals the anti-clockwise rotating moment, *i.e*,., $m_1l_1 = m_2l_2$. Since the two arms of the beam are equal; the beam would be in equilibrium again when $m_1 = m_2$. Further for a given location, the earth's attraction acts equally on both the masses and therefore at the equilibrium conditions $W_1 = W_2$, *i.e.*, the unknown force or weights equal the known force or weights.

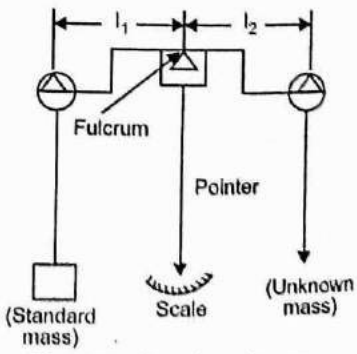


Fig. 7.36. Equal-arm beam balance

The *pendulum scale* (Fig. 7.37) is a self-balancing and direct reading force measuring device of multiple lever tape. The weights are however mounted on bent levers, and the movement of the pendulum levers is magnified and transmitted to the indicator pointer.

When the unknown pull P is applied to the load rod, sectors tend to rotate due to unwinding of the loading tapes and consequently the counter weights W swing out. Equilibrium conditions are attained when the counter weight effective moment balances the load moment. The resulting linear movement of the equalizer bar is converted to indicator movement by a rack and pinion arrangement. An electrical signal proportional to the force can also be obtained by incorporating angular displacement transducer that would measure the angular displacement θ.

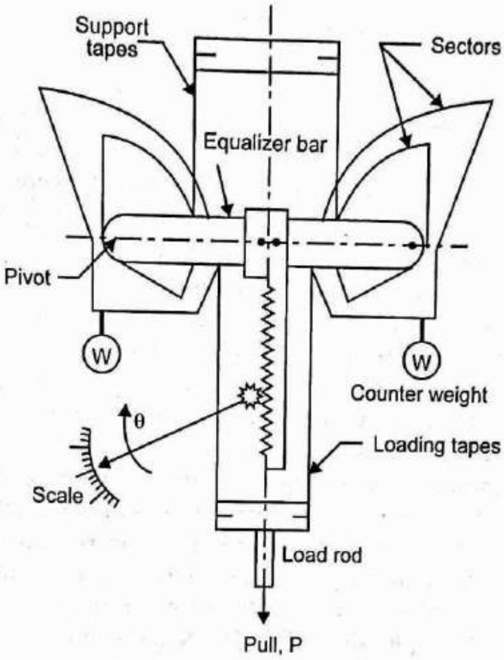


Fig. 7.37. Essentials of a pendulum scale

Elastic Force Meters

These force measuring units measure the force by applying it to an elastic element and then measuring the elastic deformation. Within elastic range of the materials, the deflection of the element is exactly or nearly proportional to the force. Figure 7.38 illustrates the shapes of the more common elastic members used for force estimation.

– *Simple bar* : $x = \dfrac{FL}{AE}$

– *Simply supported beam* : $x = \dfrac{1}{48}\dfrac{FL^3}{EI}$

– *Cantilever* : $x = \dfrac{1}{3}\dfrac{FL^3}{EI}$

– *Spring* : $x = \dfrac{8FD_m^3N}{E_3D_w^4}$

where D_m is mean coil diameter, N is number of turns of the coil, D_w is wire diameter E_s is shear modulus.

The desirable properties of the materials used for constructing the elastic-force meters are (*i*) a large and proportional elastic range and (*ii*) freedom from hysteresis.

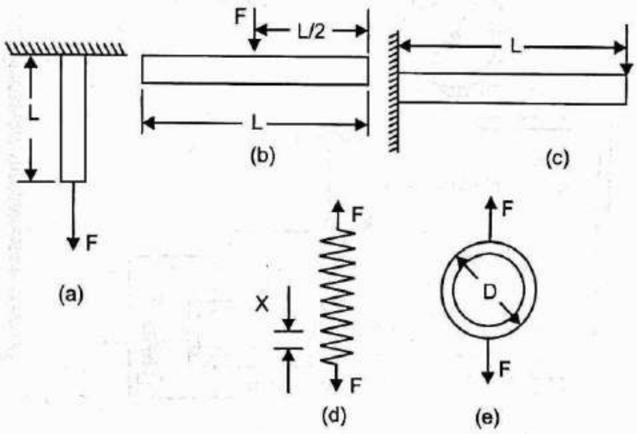


Fig. 7.38. Elastic deflection elements

The *proving* (stress) *ring* is a ring of known physical dimensions and mechanical properties. When an external compressive or tensile load is applied to the lugs or external bosses, the ring changes in its diameter; the change being proportional to the applied force. The amount of ring deflection is measured by means of a micrometer screw and a vibrating reed which are attached to the internal bosses. During use the micrometer tip is advanced and its contact with the reed is indicated by considerable damping of the reed vibration. The difference in the micrometer reading taken before and after the application of load is the measure of the amount of the elongation or compression of the ring. The proving ring deflection can also be picked by LVDT, resulting in a proportional voltage change. The device gives precise results when properly calibrated and corrected for temperature variations.

Instead of deflection, strain in an elastic member may be measured by a strain gauge, and then correlated to the applied force.

Mechanical Load Cells

The term 'load cell' is used to describe a variety of force transducers which may utilize the deflection or strain of elastic member, or the increase in pressure of enclosed fluids. The resulting fluid pressure is transmitted to some form of pressure sensing device such as a manometer or a bourdon tube pressure gauge. The gauge reading is identified and calibrated in units of force.

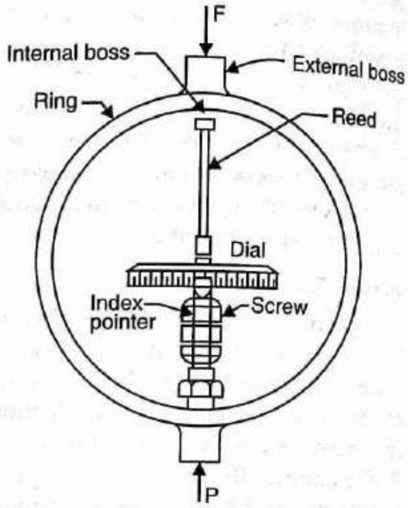


Fig. 7.39. Proving ring

In a ***hydraulic load cell*** (Fig. 7.40) the force variable is impressed upon a diaphragm which deflects and thereby transmits the force to a liquid. The liquid medium, contained in a confined space, has a preload pressure of the order of 2 bar. Application of force increases the liquid pressure; it equals the force magnitude divided by the effective area of the diaphragm. The pressure is transmitted to and read on an accurate pressure gauge calibrated directly in force units. The system has a good dynamic response; the diaphram deflection being less than 0.05 mm under full load. This is because diaphragm has a low modulus and substantially all the force is transmitted to the liquid. These cells have been used to measure loads upto about 25×10^5 N with an accuracy of the order of 0.1 percent of full scale; resolution is about 0.02 percent.

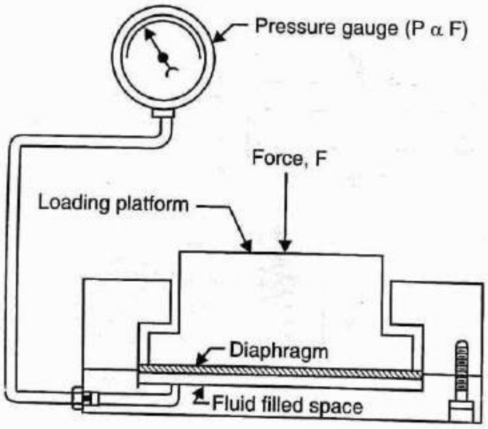


Fig. 7.40. Hydraulic load cell

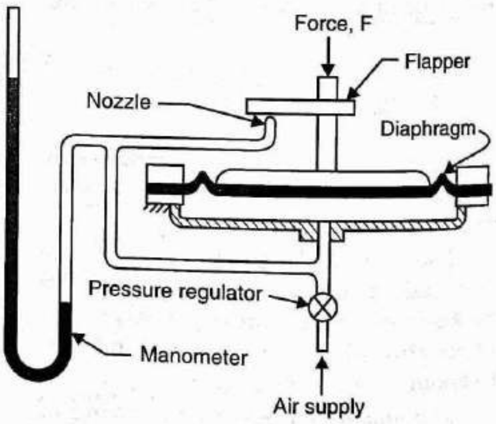


Fig. 7.41. Pneumatic load cell

A ***pneumatic load cell*** (Fig. 7.41), operates on the force-balance principle and employs a nozzle-flapper transducer similar to the conventional relay system. A variable downward force is balanced by an upward force of air pressure against the effective area of a diaphragm. Application of force causes the flapper to come closer to the nozzle, and the diaphragm to deflect downwards. The nozzle opening is nearly shut-off and this results into an increased back pressure in the system. The increased pressure acts on the diaphragm, produces an effective upward force which tends to return the diaphragm to its preload position. For any constant applied force, the system attains equilibrium at a specifie nozzle opening and a corresponding pressure is indicated by the height of mercury column in a manometer. Since the maximum pressure in the system is limited to the air supply pressure, the range of the unit can be extended only by using a larger diameter diaphragm. The commercially available load cells operating on this principle can measure loads upto 25×10^5 N with an accuracy of 0.5 percent of full scale. The air consumption is of the order of 0.17 m^3/hr of free air.

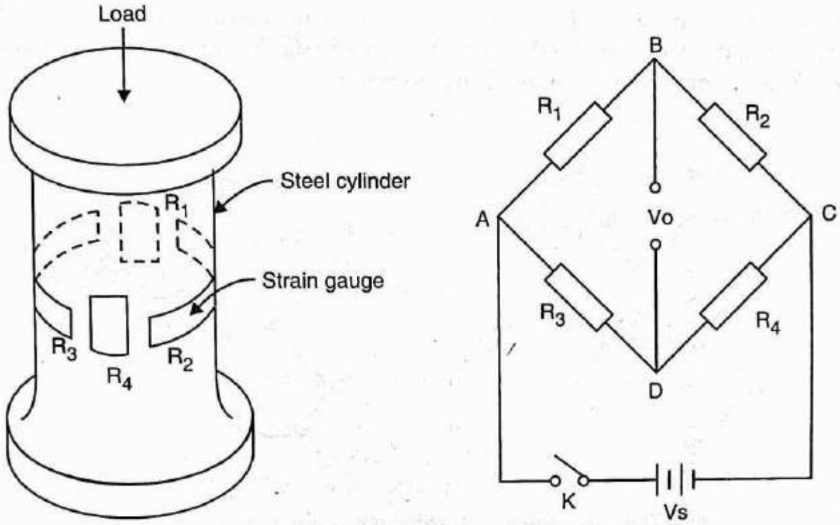


Fig. 7.42. Strain gauge load cell

The ***strain gauge load*** *cells* convert weight or force into electrical outputs which are provided by the strain gauges; these outputs can be connected to various measuring instruments for indicating, recording and controlling the weight or force.

A simple load cell consists of steel cylinder which has four identical strain gauges mounted upon it; the gauges R_1 and R_4 are along the direction of applied load and the gauges R_2 and R_3 are attached cirmumferentially at right angles to gaugesR_1 and R_2. These four gauges are connected electrically to the four limbs of a Wheatstone bridge circuit.

The output voltage or the change in output voltage due to applied load is given by

$$dV_o = 2(1+\mu)\left(\frac{dR}{R} - \frac{V_s}{4}\right)$$

where R is the resistance of each gauge, μ is the Poisson's ratio and V_s is the supply voltage.

Apparently, the output voltage is a measure of applied load.

The strain gauge load cells are excellent force measuring devices, particularly when the force is not steady. They are generally stable, accurate and find extensive use in industrial applications such as drawbar and tool-force dynamometers, crane load monitoring, and road vehicle weighing devices, etc.

7.11. TORQUE MEASUREMENT (TORSION METERS)

Measurement of torque may be necessitated for its own sake or as a part of power measurement for a rotating shaft.

In a ***gravity balance method*** (Fig. 7.43), the known mass (m) is moved along the arm so that the value of torque ($F \times r$) equals the product (T) which is to be measured. Alternatively magnitude of the mass may be varied, keeping the radius constant. For the two arrangements we have:

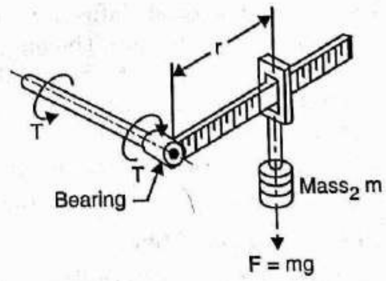


Fig. 7.43. Gravity balance for torque measurement

$r \propto T$ (m and g are constant)

$m \propto T$ (r and g are constant)

Torque transmission through a shaft usually involves a power source, a power transmitter (shaft), and a power sink (also called the power absorber or dissipator). Torque measurement is accomplished by mounting either the source or the sink in bearing and measuring the reaction force F and the arm length L (Fig. 7.44). This concept of bearing mounting is called *cradling* and this forms the basis of most shaft power dynamometers.

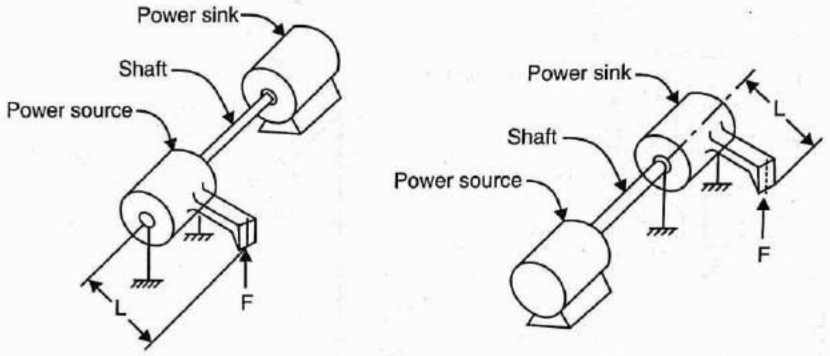


Fig. 7.44. Torque measurement of rotating machines

Further, it may be recalled that the following relation holds good for the angular deflection of a shaft subjected to torque within elastic limits :

$$\frac{T}{I_p} = \frac{f_s}{r} = \frac{C\theta}{l}$$

where T is the torque transmitted by the shaft, I_p is the polar moment of inertia of the shaft section, f_s is the maximum induced shear stress at the outside surface, r is the maximum radius at which the maximum shear stress occurs, C is the modulus of rigidity of the shaft material, θ is the angular twist, and l is the length of the shaft over which the twist is measured.

The shaft-twisting relation gives :

$$T = (I_p/l) \times f_s, \text{ i.e., } T = \text{constant} \times f_s$$

and $$T = (I_p\, C/l) \times \theta, \text{ i.e., } T = \text{constant} \times \theta$$

Thus, torque for any given system can be calculated by measuring either the angle of twist or maximum shear stress.

Figure 7.45 shows the schematics of a mechanical torsion bar wherein angular deflection of a parallel length of shaft is used to measure torque. The angular twist over a fixed length of the bar is observed on a calibrated disk (attached to the rotationg shaft) by using the stroboscopic effect of intermittent viewing and the persistence of vision. The system gives a varying angle of twist between the driving engine and the driven load as the torque changes.

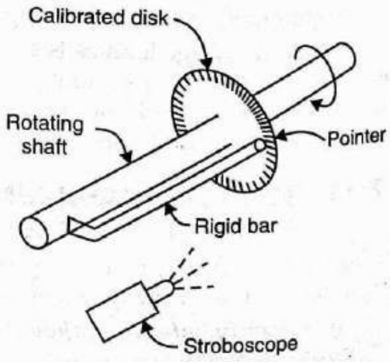


Fig. 7.45. Mechanical torsion meter

Optical Torsion Meter

The meter uses an optical method to detect angular twist of a rotating shaft.

The unit comprises two castings A and B which are fitted to the shaft at a known distance apart. These castings are attached to each other by a tension strip C which transmits torsion but has little resistance to bending. When the shaft is transmitting a torque, there occurs a relative movement between the castings which results in partial inclination between the two mirrors attached to the castings. The mirrors are made to reflect a light beam onto a graduated scale; angular deflection of the light ray is then proportional to the twist of, and hence the torque in the shaft.

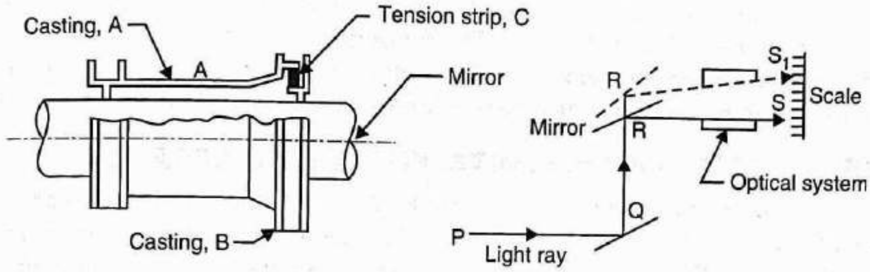


Fig. 7.46. Optical torsion meter

For constant torque measurements from a steam turbine, the two mirrors are arranged back to back and there occurs a reflection from each mirror during every half revolution, A second system of mirrors giving four reflections per revolution is desirable when used with a reciprocating enging whose torque varies during a revolution.

Electrical Torsion Meter

A system using two magnetic or photoelectric transducers, as shown in Fig. 7.47, involves two sets of measurements.

(*i*) A count of the impulse from either slotted wheel. This count gives the frequency or shaft speed.

(*ii*) A measure of the time between pulses from the two wheels. This signal is proportional to the twist θ of, and hence torque T in the shaft.

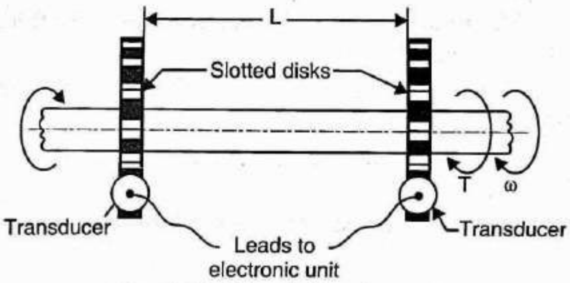


Fig. 7.47. Electrical torsion meter

These two signals, T and ω, can be combined to estimate the power being transmitted by the shaft.

Strain-gauge Torsion Meter

A general configuration of a strain gauge bridge circuit widely employed for torque measurement from a rotating shaft is shown in Fig. 7.48.

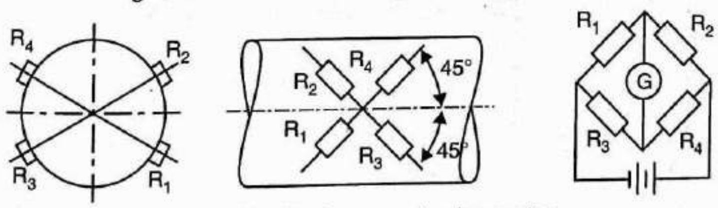


Fig. 7.48. Strain gauge torsion meter

Four bonded-wire strain gauges are mounted on a 45° helix with the axis of the rotation; and are placed in pairs diametrically opposite. If the gauges are accurately placed and have matched characteristics, the system is temperature compensated and insensitive to bending and thrust or pull effects. Any change in the gauge circuit then results only from torsional deflection. When the shaft is under torsion, gauges 1 and 4 will elongate as a result of the tensile component of a pure shear stress on one diagonal axis, while gauges 2 and 3 will contract owing to compressive component on the other diagonal axis. These tensile and compressive principle strains can be measured, and the shaft torque can be calculated.

The main problem of the system is carrying connections from the strain gauges (mounted on the rotating shaft) to a bridge circuit which is stationary. For slow shaft rotations, the connecting wires are simply wrapped around the shaft. For continuous and fast shaft rotations, leads from the four junctions of the gauges are led along the shaft to the slip rings. Contact with the slip rings is made with the brushes through which connections can be made to the measuring instrument.

7.12. INTERCHANGEABILITY: LIMITS, FITS AND TOLERANCES

In the design and manufacture of engineering products, attention is paid to be mating, assembly and fitting of various components. The term ***interchangeability*** implies that the parts which go into the assembly can be selected at random from a large number erf identical parts that have been manufactured within the prescribed limits of dimensions. Apparently then the selective fitting becomes unnecessary except when special allowances are encountered.

The dimension obtained by calculations for strength is known as basic size, basic dimension or nominal dimension. Actual size of actual dimension refers to the dimension as measured of a manufactured part. The algebraic difference between the actual size and the corresponding basic size is known as deviation.

Maximum (high) limit and minimum (low) limit are the dimensions with which the actual size of a part may vary.

(*i*) *upper deviation:* Algebraic difference between the maximum limit of size and the corresponding basic size.

(*ii*) *lower deviation*: Algebraic difference between the minimum limit of size and the corresponding basic size.

The terms 'basic size', 'deviations' and 'tolerances' have been illustrated in Fig. 7.49.

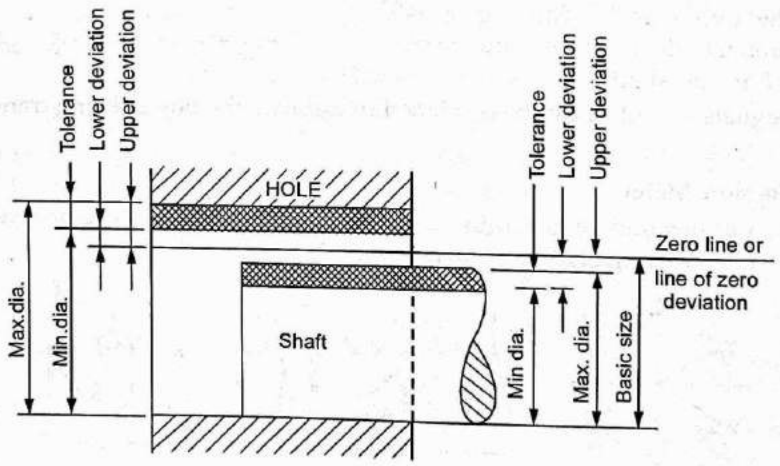


Fig. 7.49.

The degree of tightness or looseness between the two mating parts is known as fit of the system. The two bases of limit size are the shaft basis system and the hole basis system. The term 'shaft' refers to any external dimension of the component, and the term 'hole' defines any internal dimension of the component.

In the shaft basis system, the size of the shaft is kept constant and the different fits are obtained by varying the hole size. The minimum limit of the shaft is the basic size and the upper deviation is zero. Figure 7.50 shows the representation of the basic shaft system.

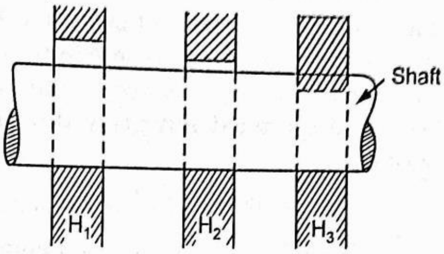


Fig. 7.50.

In the hole basic system, the size of the hole is kept constant and different fits are obtained by varying the shaft size. The minimum limit of the hole size is the basic size and the lower deviation is zero. Figure 7.51 shows the representation of the basic hole system.

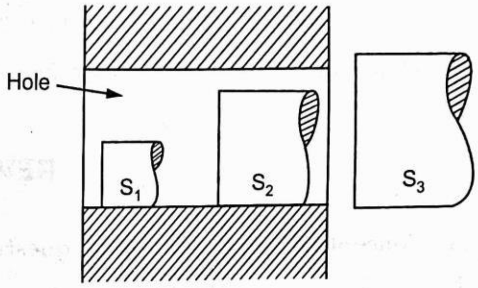


Fig. 7.51.

According to IS specifications, there are 18 grades of fundamental tolerance, *i.e.*, grades of accuracy manufacture and 25 types of fundamental deviations. These deviations for holes are represented by capital letters *A* to *ZC* and for shaft by small letters a to *zc*.

The 18 grades of tolerances are designated by IT 01, IT 0, IT 1 to IT 16.

From the production point of view, the basic hole system is economical and is preferred because a single drill or reamer of fixed size can produce a variety of fits by merely altering the shaft limits. Shafts are comparatively much easier to be accurately produced to size by turning and grinding. The shaft basic system is, however, used in industries where semifinished shafts are used as raw material.

The nature of fit is charácterised by the size of clearance and interference. The term 'clearance', refers to the difference between the sizes of a hole and a shaft which are assembled together when the shaft is smaller than the hole. In situation where the shaft is larger than the hole, the difference between the sizes of a hole and a shaft is called interference.

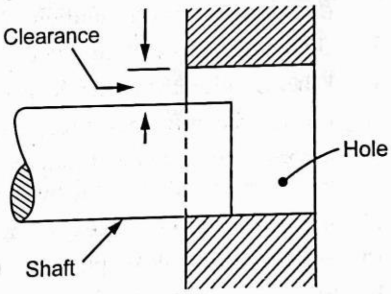


Fig. 7.52.

A clearance fit (Fig. 7.52) is one having limits of size so prescribed that a clearance always results when mating parts are assembled. The shaft is always smaller than the hole into which it fits. Clearance is the positive difference between the size of the hole and the shaft.

Typical applications of clearance fit are on rotating shafts, loose pulleys, bearings, cross-head sliders, etc.

An interference fit (Fig. 7.53) is one having limits of size so prescribed that an interference always results when the mating parts are assembled. The shaft is always bigger than the hole into which it fits. Interference is the negative difference between the sizes of the hole and the shaft. Typical applications of the interference fit are crank pins, shrunk-on-couplings, iron types, railways wheels shrunk onto axles, pressed-in-bushes, etc.

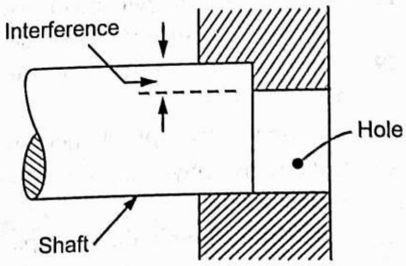


Fig. 7.53.

A transition fit (Fig. 7.54) is one having limits of sizes so prescribed that either a clearance or an interference may result when mating parts are assembled. The shaft may be bigger, smaller or of the same size as the hole into which it fits.

Typical applications of the transition fit are on bushes, spigots, fasteners, pins, keys, etc.

The tolerance or the error permitted in manufacturing a component of specified dimension may be allowed to vary either on one side of the basic size or on either side of the basic size. In the unilateral system, tolerance is applied only in one direction, and it may be written as

$$2.500 + 0.001 - 0.000 \text{ or } 2.500^{+0.001}_{-0.000}$$

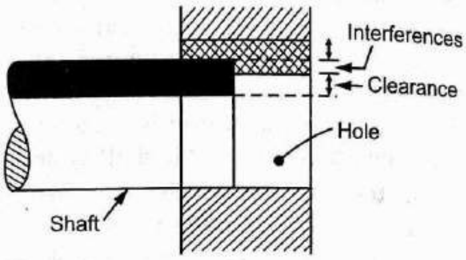


Fig. 7.54.

In the bilateral system, the tolerance is allowed on both sides of the nominal size, and it is written as

$$20.00 + 0.02 - 0.01 \text{ or } 20.00^{+0.02}_{-0.01}$$

Here 0.02 represent the upper limit and –0.01 represents the lower limit.

Control Systems

8.1. CONTROL SYSTEM : WHAT IS IT?

A system is an assemblage of devices and components connected or related by some form of regular interaction or interdependence to form an organized whole and perform specified tasks. The system produces an output corresponding to a given input. The thermometer and the mass-spring damper system can be identified as systems.

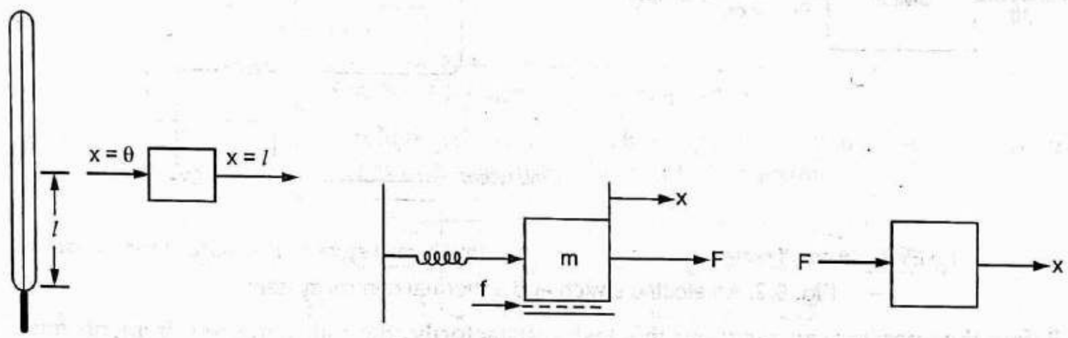


Fig. 8.1. Systems comprising a thermometer and spring-mass

The thermometer has the input $x = \theta$ (temperature) and the output $y = l$ (length of the mercury column in the capillary). In the mass spring arrangement, the force and the position of the mass constitute the input to and output from the system, respectively. In a rotational generator of electricity, the input would be the rotational speed of the prime-mover shaft and the output would either be the induced voltage at the terminals (with no load attached to the generator) or the unit of electrical power (with load attached to the generator).

The term *control* implies to regulate, direct or command. A control system may thus be defined as:

(*i*) *means by which a set of variable quantities is field constant or caused to vary in a prescribed way*

(*ii*) *an assemblage of devices and components connected or related so as to command, direct or regulate itself or another system.*

In a control system, deliberate guidance or manipulation is employed to maintain a system variable at a set point or to change it according to a preset programme.

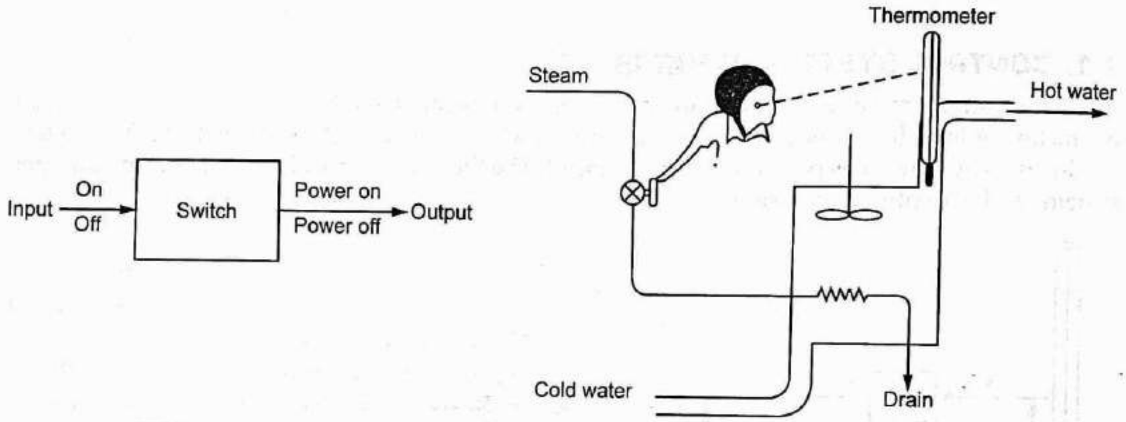
Control systems are intimately related to the concept of automation but have an ancient history. Romans maintained water levels in aqueducts by means of floating balls that opened and closed the valves at appropriate levels. Watt's flyball governor (1769) regulated steam flow to a steam engine to maintain constant engine speed despite a changing load. In world War II, control system theory was applied to anti-aircraft batteries and fire-control systems. The introduction of analog and digital computers has opened the way for much greater complexity in automatic control theory.

8.2. EXAMPLES OF CONTROL SYSTEMS

Illustrated below are some examples of control system :

(*i*) An *electric switch* which serves to control the flow of electricity in a circuit. The input signal (command) is the flipping of the switch on or off, and the corresponding output (controlled) signal is the flow or non-flow of electric current.

(*ii*) A *thermal system* where it is desired to maintain the temperature of hot water at a prescribed value.



(a) Electrical on-off system (b) Thermal system : manual feed back control

Fig. 8.2. An electric switch and a thermal control system

Before the operator can carry out this task satisfactorily, the following requirements must be met:

(*a*) The operator must be told what temperature is required for the water. This temperature called the set point or desired value, constitutes the input to the system.

(*b*) The operator must be provided with some means of observing the temperature (sensing element). For that a thermometer is installed in the hot water pipe and it measures the actual temperature of water. This temperature is output from the system and is called the ***controlled variable.*** The operator watches the thermometer and compares how the measured temperature compares with the desired value. This difference between the desired value and the actual measurement value is error or ***actuating signal.***

$$e = r - c$$

where r refers to the set-point or reference input and c denotes the controlled variable.

(*c*) The operator must be provided with some means of influencing the temperature (***control element***) and must be instructed what to do to change the temperature in a desired direction (***control function***).

The sign of the error signal e indicates whether the controlled temperature is too high or too low, and this determines the direction of the corrective action required : whether to open up the valve or close it down. The size of error signal determines the amount of correction action necessary. When the valve is turned in the correct direction by the correct amount the water will acquire the desired temperature value.

Hence the operator has been able to reduce the error signal to minimum by changing the steam supply to water. The flow of steam constitutes the ***manipulated variable.***

(*iii*) A *driving system* of an automobile (accelerator, carburettor and an engine vehicle where command signal is the force on the acceleration pedal and the automobile is the controlled variable. The desired change in engine speed can be obtained by controlling pressure on the accelerator pedal.

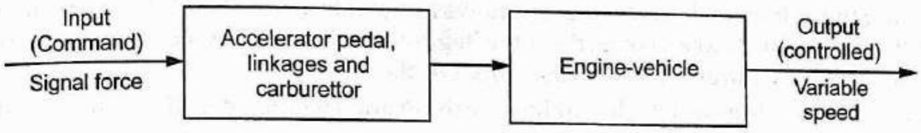


Fig. 8.2. (c) Driving system of an automobile

(*iv*) An *automobile steering system* where the driver is required to keep the automobile in the appropriate lane of the roadways. The eyes measure the output (heading of the automobile), the brain and hands react to any error existing between the input (applied lane) and the output signals, and act to reduce the error to zero.

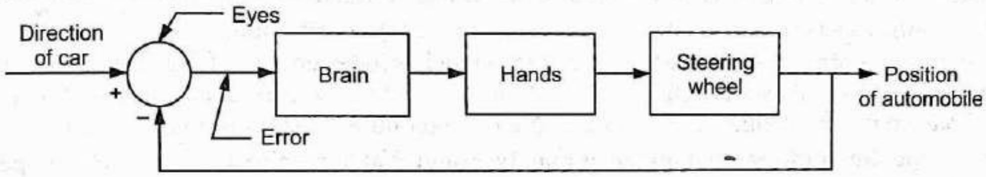


Fig. 8.2. (d) Automobile steering system

(*v*) A *biological control system* where a person moves his finger to point an object. The command signal is the position of the object and the output is the pointed direction.

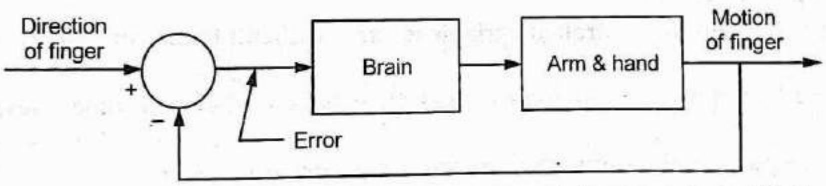


Fig. 8.2. (e) Biological control system : a person pointing towards an object

Other well-known examples of control systems are : electric frying pans, water pressure regulators, toilet-tank water level, electric irons, refrigerators and household furnaces with thermostatic control.

8.3. CLASSIFICATION OF CONTROL SYSTEMS

There are two basic types of control systems, open loop and closed loop systems

8.3.1 Open-loop system (unmonitored control system)

The main features of an open loop system are:

1. There is no comparison between the actual (controlled) and the desired values of a variable.
2. For each reference input, there corresponds a fixed operating condition (output) and this output has no effect on the control action, *i.e.*, the control action is independent of output.
3. For the given set-input, there may be a big variation of the controlled variable depending upon the ambient conditions.

Since there is no comparison between actual output and the desired value, rapid changes can occur in the output if there occurs any change in the external load.

Some examples of open-loop systems are :

(*i*) Trying to guide a car by setting the steering wheel, together with a pattern of subsequent changes of direction, at the beginning of a journey and making no alteration enroute as and when the car deviates from the desired path.

(*ii*) Hitting the golf ball where the player knows his goal to get the ball into a particular hole. To achieve it, the player hits the ball correctly at the beginning of its flight. Once the moment of impact is passed, he loses his control on any further flight of the ball.

(*iii*) A washing machine in which soaking, washing and rinsing operations are carried out on a time basis. The machine does not measure the output signal, viz., the cleanliness of the clothes.

(*iv*) An automatic toaster where the toasting time and temperature are pre-set quantities. The quality of the toast (darkness or lightness) are determined by the user and not by the toaster.

(*v*) The automobile traffic control signals at roadways intersections are the open loop systems. The red and green light time (input to the control action) are predetermined by a calibrated timing mechanism and are in no way influenced by the traffic (output).

The control systems depicted in Figs. 8.2 (*a*) and 8.2 (*c*) are also open loop control system. In the electric switch control system, the flipping of the switch is independent of the flow of electric current through the circuit. Likewise, in the driving of the automobile, no correspondence is shown between the vehicle speed (controlled variable) and the force (command signal) on the pedal.

From the illustrations cited above, it may be noted that any control system which operates on time basis is an open loop system.

An open loop system has the following advantages and limitations :

- simple construction and ease of maintenance
- no stability problems
- convenient when the controlled variable is either difficult to measure or it is economically not feasible
- system affected by internal and external disturbances; the output may deviate from the desired value
- needs frequent and careful calibrations for accurate result

8.3.2. Closed-loop system (monitored control system)

The main features of closed loop system are:

1. There is a comparison between the actual (controlled) and the desired value of the variable. To accomplish it, the output signal is fed back and the loop is completed.

2. The error signal (deviation between the reference input and the feedback) actuates the control element to minimize the error and bring the system output to desired valve

3. The system operation is continually correcting any error that may exist. As the output does not coincide with the desired goal, there is likely to be some kind of the error signal.

Evidently the closed-loop systems correct drift of the output away from the goal, which may be due to external disturbance or due to deterioration of the system.

Common phrases used to describe closed loop are the feedback control or the monitored and automatic control systems. The performance of such a system is evaluated with reference to the following desirable characteristics :

- minimum deviation following a disturbance
- minimum time interval before return to set-point
- minimum off-set due to change in operating conditions

Examples of closed-loop systems are :

(*i*) The control of the thermal system (Fig. 8.2 *b*) is a closed loop. When the operator detects that the output temperature is different from the desired or reference, he initiates an action to reduce the discrepancy by operating a valve that controls the steam supply to water.

(*ii*) The automobile driving system (Fig. 8.2 *c*) would become a closed-loop system when the driver makes a visual observation of the speed indicated by a speedometer and compares this mentally with the desired speed.

Based on the deviation between the actual and the desired speed values, the driver would take the decision either to increase or decrease the speed. The decision is implemented by affecting a change in the pressure of his foot on the accelerator pedal. The driver's eye and the -brain act as the error detectors.

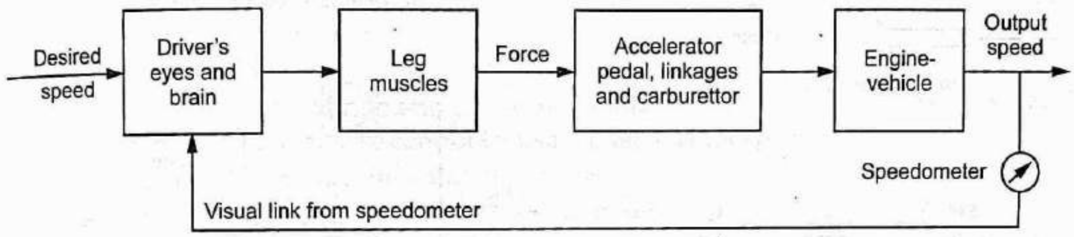


Fig. 8.3. Driving system of an automobile : manually controlled

(*iii*) The traffic control system at a roadway intersection is a closed-loop system when the traffic policeman allows a greater time-interval to cope with a greater traffic volume coming from a particular direction.

The closed loop systems listed above involve a continuous manual control by human operators and are classified as *manual feedback* or *manual closed-loop systems*. In the many complex and fast moving systems, the dull and time consuming manual tasks are accomplished by incorporating in the system some equipment which would perform the desired functions more rapidly and consistently. A close-loop system operating without human is called an *automatic control system*.

Examples of automatic control systems

(*i*) In the automatic feedback control of a thermal system (Fig. 8.4 *a*), the human operator has been replaced by an automatic controller. The actual temperature of the hot water is measured by a thermometer and is fed to the controller for comparison with the reference temperature whose value has been specified by appropriate setting of the thermostat/ regulator. Based on the error signal, the controller generates an output (correcting signal) which is taken to the control valve in order to change the valve opening for steam supply.

(*ii*) The level control system depicted in Fig. 8.4 (*b*) is an automatic control system where inflow of water to the tank is dependent on the water level in the tank. The automatic controller maintains the liquid level by comparing the actual level with a desired level correcting any error by adjusting the opening of the control valve.

(*iii*) A pressure control system where the pressure inside the furnace is automatically tolled by adjusting the opening of the control valve (Fig. 8.4 *d*).

(*iv*) The anti-aircraft radar tracking system (Fig. 8.4 *e*) incorporates a rotating antenna that senses the presence of target plane. The detected signal (velocity and position) of the plane is transmitted to the computer which determines the firing angle. The firing angle then becomes the command signal which is passed on to the firing system through the power amplifiers. The angular position of the gun is fed back to the computer. The gun is triggered when the error between the command signal and the firing angle becomes zero.

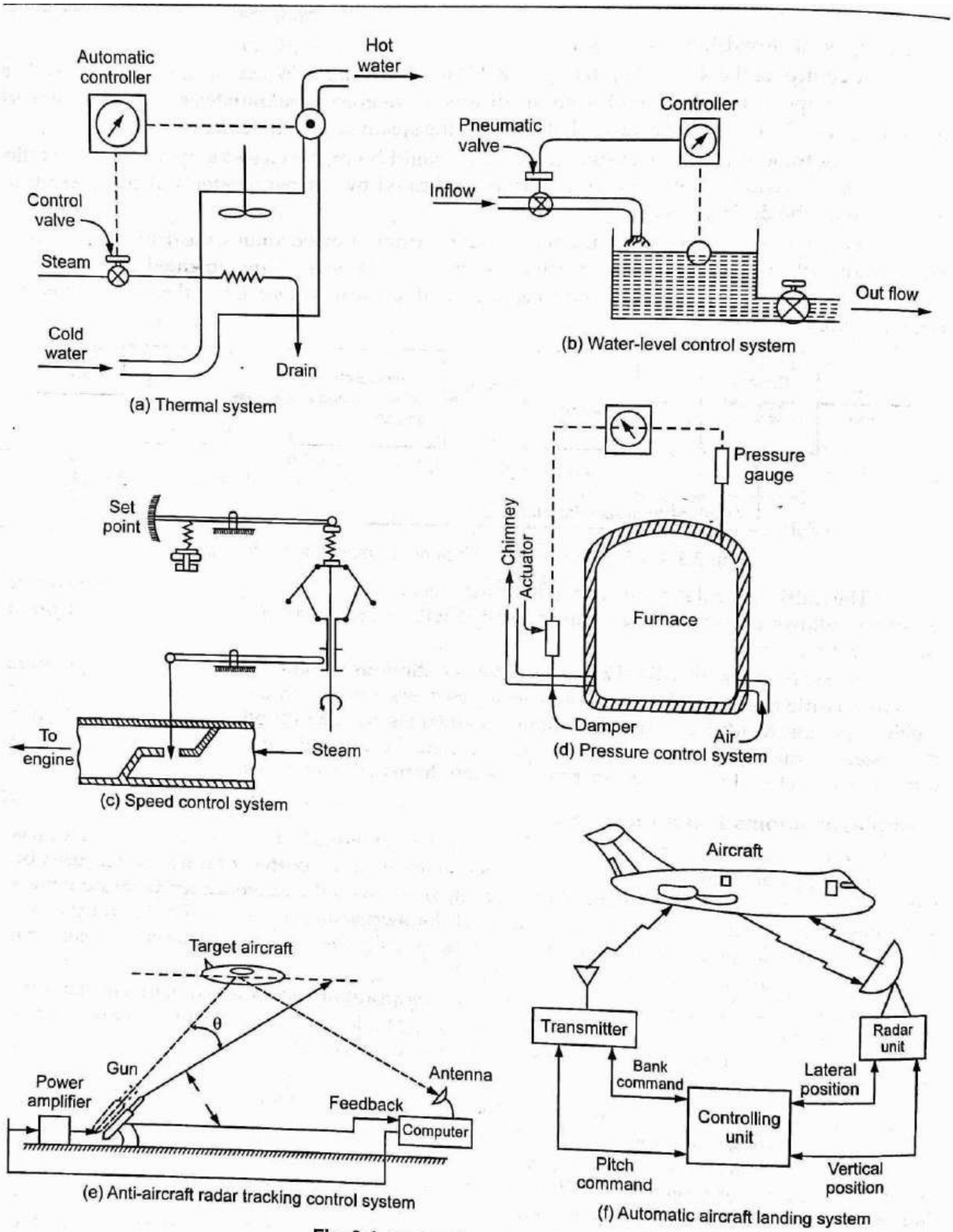


Fig. 8.4. Automatic control systems

(v) The automatic aircraft landing system (Fig. 8.4 *f*) has three basic parts, viz., the aircraft, the radar unit and the controlling unit. The approximate vertical and lateral positions of the aircraft as measured by the radar unit are transmitted to the controlling unit. The controlling unit then determines the appropriate pitch and bank commands. These commands are later transmitted to the aircraft autopilots and that makes the aircraft respond.

(iv) *Advantages and limitations of automatic control systems*

- suitability and desirability in the complex and fast acting systems which are beyond the physical abilities of a man
- relief to human beings from hard physical work, boredom and drudgery which normally result from a continuous repetitive job
- economy in the operating cost due to elimination of the continuous employment of a human operator
- increased output or productivity
- improvement in the quality and quantity of the products
- economy in the plant equipment, power requirement and in the processing material. The feedback permits to initiate precise control by using relatively inexpensive components
- reduced effect of non-linearities and distortions
- satisfactory response over a wide range of input frequencies.

The system has however a tendency to over-correct errors and this may cause oscillations of constant or changing amplitude.

Comparison of open and closed loop control systems

Open loop control system	*Closed loop control system*
1. Less expensive and simple to construct.	1. Costly and complex construction.
2. Easy maintenance..	2. Maintenance is comparatively difficult.
3. Components incorporated in the system to be accurate.	3. Less accurate components can be used for satisfactory operation of the system.
4. Generally stable.	4. Tends to become unstable under certain conditions.
5. No need to measure the output.	5. The output is necessarily to be measured.
6. Slow in operation and there is no possibility of optimization.	6. Faster and optimization is possible.
7. Feedback element and error detector are not needed.	7. Feedback element and error detector are essential components of the system.
8. Highly sensitive to disturbances and environmental changes.	8. Less sensitive to disturbance; the disturbances are taken care of by the feedback present in the system.
9. System needs to be calibrated and recalibrated for accuracy.	9. Calibration is not required ; the error between the reference input and the output is measured through feedback and necessary correction is applied.

8.4. CONTROL SYSTEMS TERMINOLOGY

A closed loop consists essentially of a process, error detector and control elements. Source of the terms related to these basic components are defined below :

Process, plant or controlled system (g_2): a body, process or machine of which a particular quantity or condition is to be controlled, *e.g.*, a furnace, reactor or a spacecraft, etc.

Controlled variable (c) : the quality or condition (temperature, level, flow rate, etc.) characterizing a process whose value is held constant by controller or is changed according to certain law.

Controlled medium : the process material in the controlled system or flowing through it in which the variable is lo be controlled.

Command : an input that is established or varied by some means which are external to and independent of the feedback control system.

Set-point or reference input (r) : a signal established as a standard of comparision for feedback control system by virtue of its relation to command. The set point either remain constant or changes with time according to a preset programme.

Manipulated variable (m) : the quality or condition that is varied as a function of the actuating signal so as to change the plant g_2 by the control element g_1.

Actuating signal (e) : an algebraic sum of the reference input r and the primary feedback b. The actuating signal is also called the error or control action.

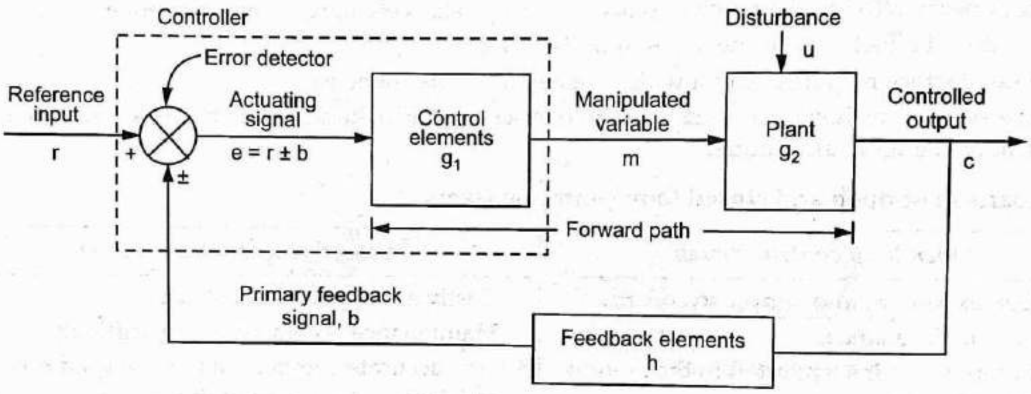


Fig. 8.5. Elements of a control system

Primary feedback signal (b) : a function of the controlled output c, which is compared with the reference input to obtain the actuating signal.

Error-detector : an element that detects the feedback; essentially it is a summing point which gives the algebraic summation of two or more signals. The detection of flow on information is indicated by arrows and the algebraic nature of summation by plus or a minus signs.

Negative feedback occurs when the feedback signal subtracts from the reference signal

$$e = r - b$$

If the feedback signal adds to the reference signal, the feedback is said to be positive

$$e = r + b$$

Negative feed back tries to reduce the error, whereas positive feed back makes the error large.

Disturbance (n) : an undesired variable applied to the system which tends to affect adversely the value of the variable being controlled. The process disturbance may be due to changes in set point, supply, demand, environmental and other associated variables.

Feedback element (h) : an element of the feedback control system that establishes a functional relationship between the controlled variable c and the feedback signal b.

Control element (g_2) : an element that is required to generate the appropriate control signal (manipulated variable) m applied to the plant.

Forward and backward paths : The transmission path from the actuating signal e to the controlled output c constitutes the forward path. The backward path is the transmission path from the controlled output c to the primary feedback signal *b*.

8.5. SERVOMECHANISM, PROCESS CONTROL AND REGULATOR

A servomechanism is an automatic control system in which the controlled variable is mechanical position (displacement), or a time derivative of displacement such as velocity and acceleration. The output is designed to follow a continuously changing input or desired variable (command signal). The servomechanisms are inherently fast acting (small time lag with response time in the order of milliseconds) systems and usually employ electric or hydraulic actuation. These systems are essentially used to control the position or speed of a mechanism which is either too heavy or too remote to be controlled manually. The complete automation of machine tools together with programmed instruction is another notable example of servomechanism.

Servomechanisms find utility in satellite-tracking antennas, automatic navigation systems on boats and planes, and anti-aircraft gun control systems. Other examples are fly-by-wire systems in aircraft which use servers to actuate the aircraft's control surfaces, and radio-controlled models which use RC servers to the same purpose. Many autofocus cameras also use a servomechanism to accurately move the lens and then adjust the focus. A modern hard disk drive has a magnetic servo system with sub-micron positioning accuracy.

A ***process control*** refers to the control of such parameters as level, flow, pressure, temperature and acidity of a process variable, A particular parameter has usually only one optimum desired value (set point) and the control system is required to ensure that the process output is maintained at this level inspite of changes in external conditions (disturbances) which affect the process. The load disturbance could be (*i*) a change in the boiler steam pressure affecting a temperature control system (*ii*) a change in raw materials affecting a mixing process. The process control systems are usually slow acting (large time lags) and usually employ pneumatic actuation.

A ***regulator*** it, a feedback control system in which the output (controlled variable) is maintained at a preset value irrespective of external load on the plant. The reference input or command signal, although adjustable, is held constant for long periods of time. The primary task is then to maintain the output at the desired value in the presence of disturbances (change in load on the system or changes in the environment or changes in the system itself). Examples of an automatic regulator are : regulation of steam supply in steam engines by the fly ball governor ; thermostat control of a home heating system ; control of pressure and of electrical quantities such as voltage, current and frequency.

In general, a control system that regulates a variable in response to a fixed command signal is known as a regulator system whereas a control system that accurately follows changes in the command signal is referred to as follow up system.

8.6. SEQUENCE CONTROL

A sequence control is a special type of open loop system which has the following main features:

(*i*) the finish of one action initiates the start of the next

(*ii*) the acts take place in certain fixed sequence

(*iii*) there is no comparison of desired and actual value

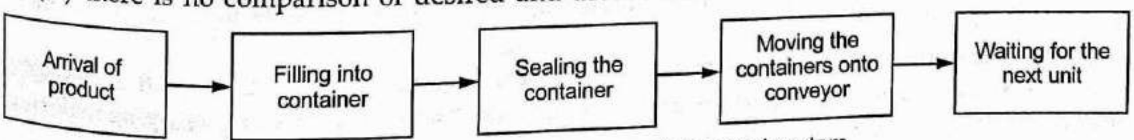


Fig. 8.6. Block diagram of a sequential-control system

Figure 8.6 illustrates the block diagram of one such system involving mechanical handing packaging. The various actions are performed by pneumatic or hydraulic components and the completion of the operation is signalled by mechanical trip valves.

The cloth-washing machine too is a sequence control where the various operations, such as

(*a*) filling of the tub (*b*) washing (*c*) draining the tub
(*d*) rinsing and (*e*) spin drying are controlled by timer switch

Likewise, the sequence of operations on a production machine may be

(*i*) job in position (*ii*) guard in position
(*iii*) tool in position (*iv*) tool motion
(*v*) tool withdrawal and (*vi*) job withdrawl

Logic control devices are used to control each of these operations.

8.7. MANUAL AND AUTOMATIC SYSTEMS

Manual control systems involve a human operator who :

(*i*) takes decision about the required output
(*ii*) ensures that the necessary input (the reference input) is applied to the system
(*iii*) observes the output and compares it with the desired value
(*iv*) readjusts the control elements if the output is not what he wants

In an automatic control system the human operator determines the goal and sets up the system. Subsequently the target output is achieved or maintained automatically. Only the reference input is provided and the necessary corrections are applied by mechanical (non-human) devices and that essentially forms the essence of automatic control.

The automatic control has become obligatory in a wide variety of engineering problems as is evident from the following few examples :

- control of temperature, pressure, humidity, viscosity and flow-rate, etc., in the process industries like synthetic yarn production, oil refining and chemical plants.
- control of heat treatment, tooling, handling and assembling of mechanical parts in the control of manufacture of articles like refrigerators, radio and automobile parts
- control of position, speed and power in machine tools, pumps and compressors, electrical and mechanical power supply units.
- speed regulation of devices like grinding wheel for precision grinding, tape recorders, strip rolling and wire drawing.
- transportation systems such as ship steering and rolling stabilization, aircraft flight control, automatic landing of aircraft, etc. The positioning systems, radar travel systems and other military equipment are necessarily based on feed control systems.

Applications of control system engineering

Some of the common applications that involve the use of control systems are :

1. Range of human activities in the domestic domain such as picking a book from the table, eating meals from the plate, pointing a finger towards an object, walking from a starting point to a destination along a prescribed path.
2. On and off of electric supply to units such as washing machines, toasters, fans, air-conditioners and other electrical appliances.
3. Speed and direction control of transport vehicles.
4. Regulation of temperature and humidity of homes, offices, hospitals and shopping malls for comfort of human beings.

5. Control of temperature, pressure, water level and humidity, etc., in process industry.

6. Quality control of manufactured products, automatic control of machine tools and assembly line in an industry. Operation of computerized numerically controlled (CNC) machines.

7. Regulation of voltage at electric power plants.

8. Space technology, missile launching and guidance.

9. Military operations such as automatic positioning of guns, radar antennas, steering control of ships.

The control system engineering and its applications are not limited to engineering alone ; it is applicable to all fields of knowledge pertaining to biological, biomedical, economic and socio-economic systems.

EXAMPLE 8.1

Name any three electrical devices used at home and which are equipped with suitable controls to achieve the desired purpose. Also mention the control category to which they belong.

Solution: Some common electrical devices used at home are :

(*i*) Radio : one can adjust the volume, the tone, the station.

(*ii*) Television set: one can adjust the volume, the channel, the brightness.

(*iii*) Oven : one can adjust the temperature.

In each of these arrangements, the human operator forms a part of the control loop. He provides the feedback path, makes adjustments with the controls and corrects for the errors so as to get the desired performance from the device. Evidently these electrical devices constitute the manual closed loop control systems.

Electric fires and lights are open arrangements because their outputs cannot be adjusted if they deviate from the desired goal. If the electric fire does not give enough heat or if the lamp is not bright enough, these have to be discarded and replaced with new ones.

EXAMPLE 8.2

Identify the open-loop and closed-loop aspects of cooking.

Solution: Most of the cooking done in an oven by the novice cook is essentially an open loop because :

(*i*) the quantities of the ingredients are specified by the recipe

(*ii*) the mixing of the ingredients is as per instructions

(*iii*) the oven settings and the cooking time are also according to the instructions.

If every act is in accordance with the instructions listed in the cookery book, the meal would emerge as required. Indeed, if the cook tries to add a little feedback to the process by opening the oven to take a look (presumely to make adjustments if things are not going right), he can make things worse.

However, the experienced cooks use their judgement and modify the open-loop instructions with feedback and achieve the required target rather more accurately. Using a frying pan is more of a feedback process. The quantities used, the temperature of the pan, the cooking time, etc., are all adjusted according to how closely the output (cooked meal) approaches the target (the desired quality of the meal).

EXAMPLE 8.3

Is the act of switching a light involves both manual and automatic controls ?

Solution : The process of switching a light involves both manual and automatic controls.

(*i*) The act of switching a light is a normal operation and is obviously a manual control. The person decides that he wants the light and accordingly the switch is turned on. Subsequently, the switch is turned off if the light is not needed.

(*ii*) The bulb gives a predetermined brightness ; this is achieved automatically by exercising careful control in the manufacture of lamp and by keeping constant voltage at the mains. Thus, the lamps either give the intended brightness or fail completely.

The operating system at the power station ensures that mains voltage stays close to 240 volts except during power cuts.

EXAMPLE 8.4

Identify the concept of plant, reference input, controlled output and feedback, etc., in the following control systems:

(*a*) control of temperature in central heating system,

(*b*) control of water level in a cistern,

(*c*) control of the progress of an automobile vehicle,

(*d*) control of water temperature for shower bath.

Solution : (*a*) Refer Fig. 8.7(*a*) for the closed-loop central heating system :

(*i*) The *plant* refers to the room whose temperature is required to be controlled.

(*ii*) The thermostat is set to the specified temperature (*reference input*) and this controls the fuel/oil input to the boiler.

(*iii*) The *controlled output* is the actual room temperature which is fed back to the thermostat.

(*iv*) The *controlled element* is the oil flow valve and the goal is the specified house temperature.

The thermostat switches on the oil flow to the boiler furnace when the room temperature drops below the specified value. This results into heat flow from die radiators in the room and the consequent rise in temperature, The supply of oil to the furnace is automatically shut off when the room temperature rises to the specified reference input.

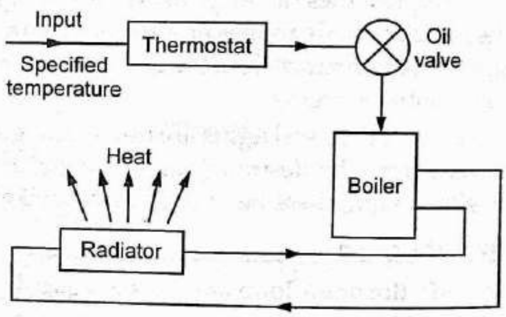


Fig 8.7 (a) A closed-loop central heating system

(*b*) Refer Fig. 8.7 (*b*) for the control of water level in a cistern.

(*i*) The *plant* is the tank (cistern) wherein the level of water is to be controlled.

(*ii*) The *reference input* is prescribed by the initial setting of the ball lever.

(*iii*) The *output* is the constant level of water in the tank.

(*iv*) The *control element* is the pivot-ball arrangement and the feedback is the actual position of the floating ball.

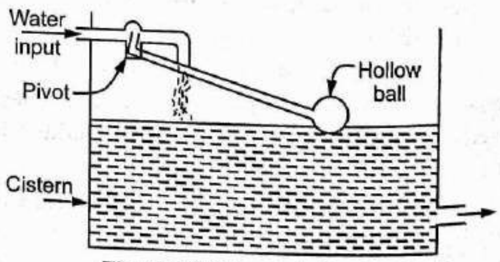


Fig. 8.7 (b) Control of water level in a cistern

When the ball is at a lower position (i.e., the water level is below the desired level), then will be inflow of water into the cistern. With this inflow, the level of water would rise and with that the ball would also rise. Eventually the ball would move up to a position where the arm would cut off the supply of water.

(*c*) Refer Fig. 8.3 for the control of the progress of an automobile vehicle,

(*i*) The *plant* is the automobile vehicle whose progress along a specified track is to controlled.

(ii) The *input* includes turning of the steering wheel and the pressure of foot on the acceleration pedal.

(iii) The engine, transmission links and the steering are the *control elements.*

(iv) The *feedback* loop governing the motion of the vehicle along the road is the driver's observation. This feedback leads to a change in pressure on the accelerator on to an adjustment of the setting of the steering wheel (steering correction).

(d) Refer Fig. 8.7 (c) which depicts a simple arrangement for the control of water temperature for shower bath.

(i) The *inputs* are the temperature and flow rates of hot and cold water.

(ii) The *plant* is the pipe taking the water upto the nozzle.

(iii) The *output* is the temperature of hot water flowing from the nozzle.

(iv) The *control element* is the mixing tap.

(v) The arms of the person taking bath provides *feedback* from the output to the input, and readjusts the setting on the input side. If the water was too hot, he turns the mixer towards cold position. If it was too cold, he would adjust the mixture towards hot. The adjustment is so made that difference between the actual output temperature and the desired output temperature is reduced to minimum.

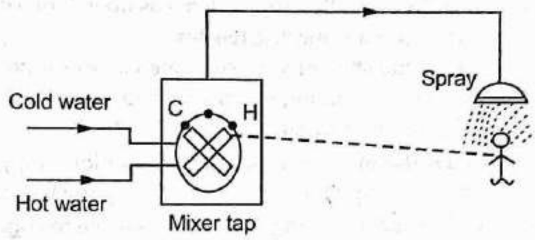


Fig. 8.7 (c) Control of water temperature for shower bath

EXAMPLE 8.5

Draw the schematics and block diagram of a system representing steam-generator set fitted with a speed governor.

Solution : Refer Fig. 8.8 (*a*) for the schematics of a system for speed control of a turbo-governor.

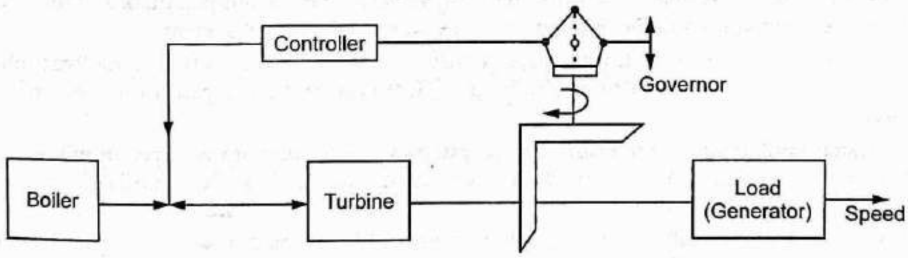


Fig. 8.8 (a)

The system incorporates a centrifugal governor which uses the lift of centrifugal balls as speed monitor, it senses any speed change which may occur due to variation in load. The speed sensed by the governor is compared with the desired speed and an error or deviation signal is generated. A hydraulic amplifier serves as a controller that operates a control valve which moves by an amount proportional to the error. The valve then regulates the steam flow from the boiler to the turbine ; which results into a change in speed until the output speed matches the desired speed.

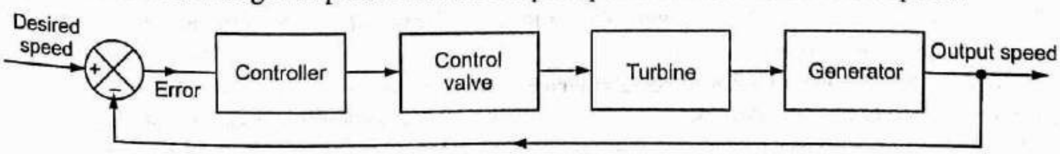


Fig. 8.8 (b)

The system has been represented by a block diagram with various elements as shown in Fig. 8.8 (*b*).

2.11 LIMIT GAUGES

- Gauges are inspection tools which serve to check the dimensions of the manufactured pmts. Limit gauges ensure the size of the component lies within the specified limits. They are non-recording and do not determine the size of the part.
- Gauges are generally classified as:

1. Standard gauges are made to the nominal size of the part to be tested and have the measuring member equal in size to the mean permissible dimension of the part to be checked.
2. Limit Gauges are also called 'GO' and 'NO GO' gauges. These are made to the limit sizes of the work to be measured. One of the sides or ends of the gauge is made to correspond to maximum and the other end to the minimum permissible size. The function of limit gauges is to determine whether the actual dimensions of the work are within outside the specified limits.

- A GO-NO GO gauge is a measuring tool that does not return a size in the conventional sense, but instead returns a state. The state is either acceptable (the part is within tolerance and may be used) or it is unacceptable (and must be rejected).
- They are well suited for use in the production area of the' factory as they require little skill or interpretation to use effectively and have few, if any, moving parts to be damaged in the often hostile production environment

Why limit gauges necessary?

- In the manufacturing firm, the components are manufactured as per the specified tolerance limits, upper limit and lower limit. The dimension of each component should be within this upper and lower limit.
- If the dimensions are outside these limits, the components will be rejected. If we use any measuring instruments to check these dimensions, the process will consume more time.
- Also, in mass production, we are not interested in knowing the amount of en·or in dimensions. It is just enough whether the size of the component is within the prescribed limits or not. For this purpose, limit gauges are used.
- A limit gauge is not a measuring gauge; this gives the information about the products which may be either within the prescribed limit or not. By using limit gauges report, the control charts of P and C charts are drawn to control invariance of the products.
- This procedure is mostly performed by the quality control department of each and every industry. Limit gauge are mainly used for checking for cylindrical holes of identical components with a large numbers in mass production.

Basic concept of Gauge Design (Taylor's Principle):

- According to Taylor, 'GO' and 'NOGO' gauges should be designed to check maximum and minimum material limits.
- The terms minimum metal condition, and maximum metal condition are used to describe the tolerance state of a work piece. The GO gauge is made near the maximum metal condition.
- The GO gauge must be able to slip inside/over the feature without obstruction. For example plug gauge (for checking hole size), as shown in Fig. 2.31 having exactly the GO limit.

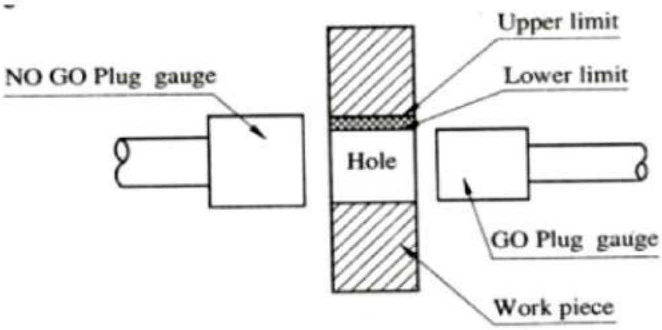


Figure 2.31 Basic concept of gauge design

- Diameter and a length equal to the engagement length of the fit to be made for checking the GO limit of the work piece and this gauge must perfectly assemble with the work piece to be inspected.
- The NO GO gauge is made near the minimum metal condition. NO GO gauge which contacts the work piece surface only in two diametrically opposite points and at those points it should have exactly NO GO limit diameter.
- The NO GO gauge must not be able to slip inside/over the work piece in any consecutive position in various diametric directions on the work piece length.

2.12 TYPES OF LIMIT GAUGES

Plain limit gauges may be classified as follows;

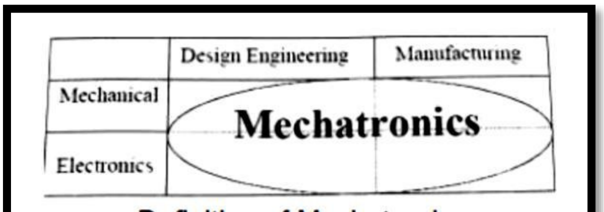
1. According to their purpose:
   a. Work shop gauges: Working gauges are those used at the bench or machine in gauging the work as it being made.
   b. Inspection gauges: These gauges are used by the inspection personnel to inspect manufactured parts when finished.
   c. Reference or Master Gauges: These are used only for checking the size or condition of other gauges.
2. According to form of tested surfaces:
   a. Plug gauges: They check the dimensions of a hole.
   b. Ring gauges: They check the dimensions of a shaft.
   c. Snap gauges: They also check the dimensions of a shaft. Snap gauges can be used for both cylindrical as well as non-cylindrical work as compared toting gauges which are conveniently used only for cylindrical work.
3. According to their design:
   a. Single limit & double limit gauges
   b. Single ended and double ended gauges
   c. Fixed & adjustable gauges

Contents of UNIT 5

Introduction to Mechatronics: Evolution, Scope, Advantages and disadvantages of Mechatronics, Industrial applications of Mechatronics, Introduction to autotronics, bionics, and avionics and their applications. Sensors and Transducers: Types of sensors, types of transducers and their characteristics.
Overview of Mechanical Actuation System – Kinematic Chains, Cam, Train Ratchet Mechanism, Gears and its type, Belt, Bearing,
Hydraulic and Pneumatic Actuation Systems: Overview: Pressure Control Valves, Cylinders, Direction Control Valves, Rotary Actuators, Accumulators, Amplifiers, and Pneumatic Sequencing Problems.

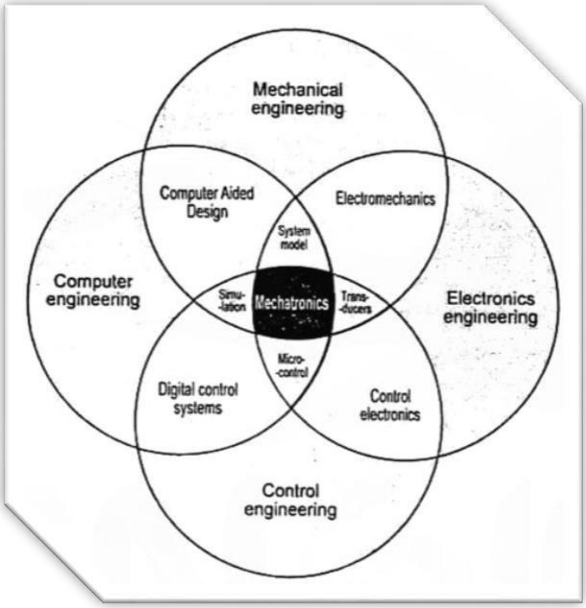
What is "Mechatronics"?

- **Mechatronics can be defined as the application of electronics and computer technology to control the motions of mechanical systems. The term 'mechatronics' was first coined by the Japanese scientist Yoshikaza in 1969. The trademark was accepted in 1972. Mechatronics is a subject which includes mechanics, electronics, and informatics.**



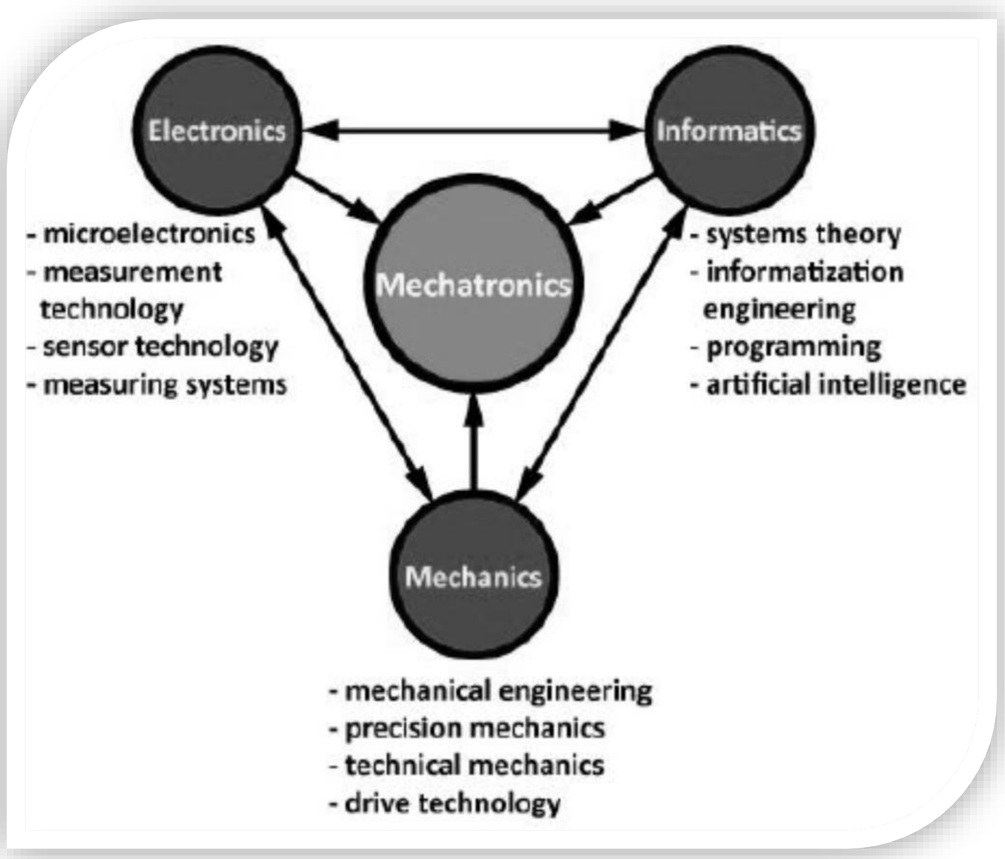
Definition of Mechatronics

- It is a multidisciplinary approach to product and manufacturing system design (Figure). **It involves application of electrical, mechanical, control and computer engineering to develop products, processes and systems with greater flexibility, ease in redesign and ability of reprogramming**. It concurrently includes all these disciplines.

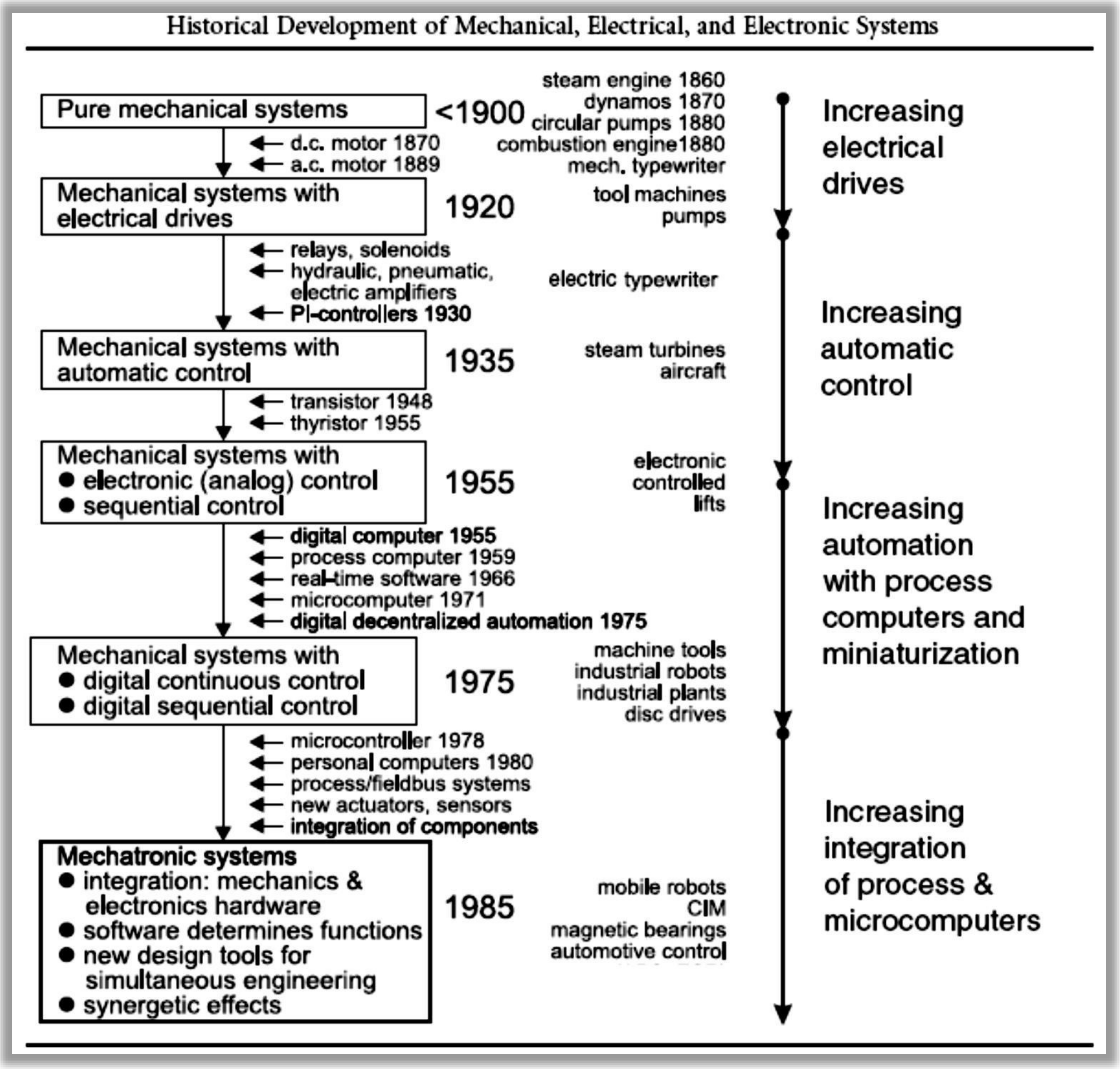


Mechatronics system

- **Mechatronics is a synergistic combination of precision engineering, electronic control and mechanic systems**. It is the science that exists at the interface among the other five disciplines: **• Mechanics • Electronics • Informatics • Automation • Robotics.**



- Mechatronics engineering may be regarded as a modern approach to automation techniques for the broadly defined needs of engineering and education. It can be assumed that mechatronics is an interdisciplinary field of science and technology, dealing with general problems of mechanics, electronics and informatics.
- **Mechatronics can also be termed as replacement of mechanics with electronics or enhance mechanics with electronics.** For example, in modern automobiles, mechanical fuel injection systems are now replaced with electronic fuel injection systems. This replacement made the automobiles more efficient and less pollutant. With the help of microelectronics and sensor technology, mechatronics systems are providing high levels of precision and reliability. It is now possible to move (in x – y plane) the work table of a modern production machine tool in a step of 0.0001 mm. By employment of reprogrammable microcontrollers/microcomputers, it is now easy to add new functions and capabilities to a product or a system. Today's domestic washing machines are "intelligent" and four-wheel passenger automobiles are equipped with safety installations such as air-bags, parking (proximity) sensors, antitheft electronic keys etc.



Scope of the Course:

➢ Mechatronics Engineering is offered with an integrated curriculum to provide a broad-based education in the basic principles of electrical, electronics, mechanical, control, instrumentation and computer engineering. Broad range of topic covered include: Design of machine elements, Analog and Digital system Design, Signal Processing, Measurements, Material Science, Mechanical Vibration, Kinematics of Machinery, PLC Programming, Control Systems, Microcontrollers, Hydraulic and Pneumatic Systems, Industrial Robotics, Embedded Systems, Nanotechnology and Computer Integrated Manufacturing.

Application in Industry Sectors:

- Mechatronics is a multidisciplinary field of engineering with far reaching applications on various sectors of the society. Mechatronics plays a key role in the development of tomorrow's products by being at the forefront of cutting-edge designs. Today, Mechatronics Engineering has gained much recognition and importance in the industrial world and has become an engineering discipline on high demand. Mechatronics may be viewed as a modern mechanical engineering design in the sense that it is the synergistic integration of mechanical engineering with electronics and intelligent computer control in the design and manufacturing that aims at improving and/or optimizing its functionality.
- Mechatronics have following industrial applications:
    - Design and Modelling
    - Software Integration
    - Actuators and Sensors
    - Intelligent Control
    - Robotics
    - Motion control
    - Vibration and Noise Control
    - Microsystems
    - Optics
- The following are further examples of Mechatronics systems:
    1. **Home appliances (e.g. washing machines):** Many of the home appliances that are in use today are Mechatronics systems. They are manufactured in large numbers and typically require small controllers to be "embedded" within them.
    2. **Anti-lock Braking System (ABS),** Engine control unit in Automotive.
    3. **Elevators, Escalators** -They have many sensors to detect the position and speed of the elevator car, as well as any calls registered by the passengers. It has many actuators, the most important of which is the main hoist motor. Safety is also paramount in these systems as they carry human beings.
    4. **Mobile robots and manipulator arms.**
    5. Sorting and packaging systems in production lines.
    6. **Computer Numerically Control (CNC)** production machines.
    7. **Aero planes and helicopters:** These are complex examples of Mechatronics systems.
    8. **Tank fluid level and temperature control systems.**
    9. **Temperature control system** in an industrial oven.
    10. **Heat-seeking missiles**.
    11. **Using robots for painting windows and doors**.
    12. **Coordinate Measuring Machines (CMM)**.

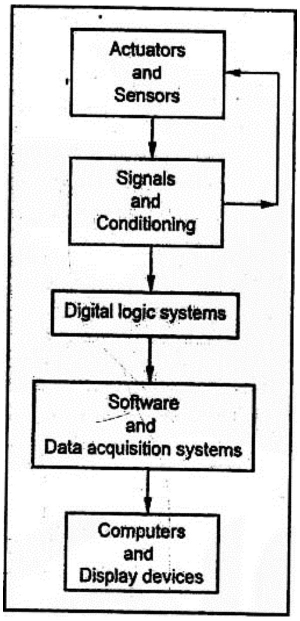
Advantages of Mechatronics system:

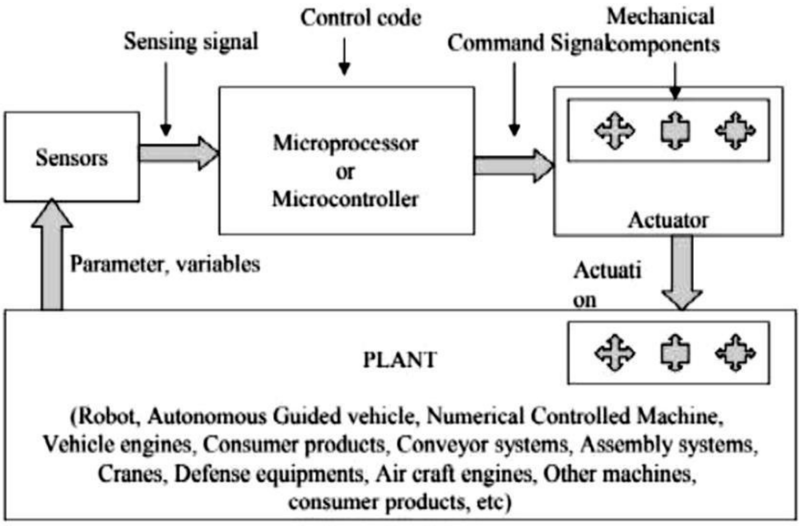
1. It is cost effective and it can produce high quality products.
2. Production of parts and products of international standards gives better reputation and return.
3. It serves effectively for high dimensional accuracy requirements.
4. It provides high degree of flexibility to modify or redesign the systems.
5. It provides excellent performance characteristics.
6. It Results in automation in production, assembly and quality control.
7. Mechatronic systems provide the increased productivity in manufacturing organization.
8. Reconfiguration feature by pre supplied programs facilitate the low volume production.
9. It provides higher level of flexibility required for small product cycles.
10. It provides the possibility of remote controlling as well as centralized monitoring and control. .
11. It has greater extend of machine utilization.
12. Higher life is expected by proper maintenance and timely diagnosis of the fault.

Disadvantages Of Mechatronics System:

1. The initial cost is high.
2. Maintenance and repair may workout costly.
3. Multi-disciplinary engineering background is required to design and implementation.
4. It needs highly trained workers to operate.
5. Techno-economic estimation has to be done carefully in the selection of mechatronic system.
6. It has complexity in identification and correction of problems in the systems.

Basic Elements of Mechatronics System:





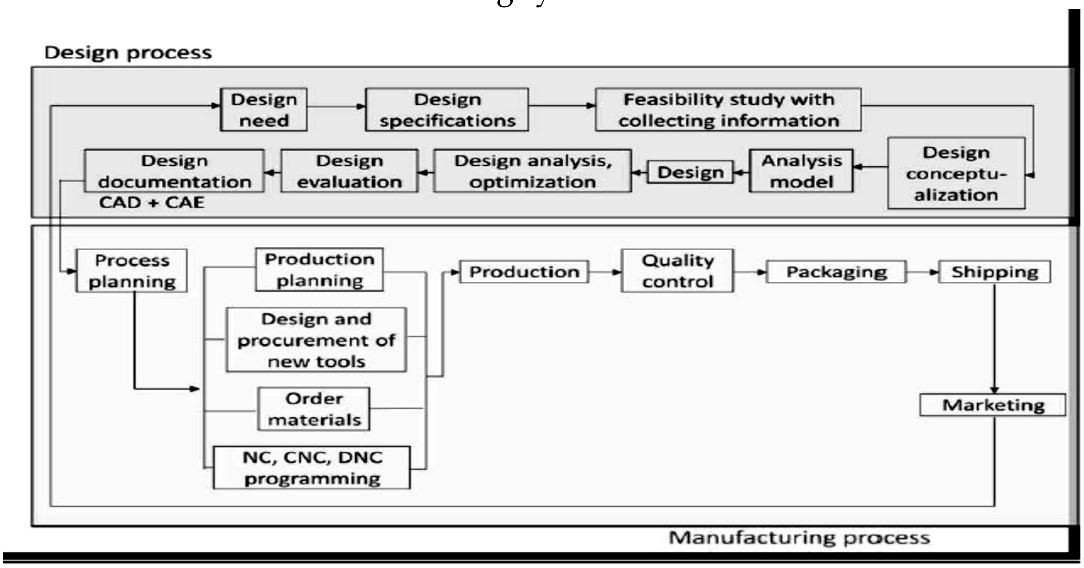
Various elements in typical mechatronic systems are shown in above figures and are described here below.

- **Sensors and actuators**
  Sensors and actuators mostly come under mechanical systems. The actuators produce motion or cause some action. The sensors detect the state of the system parameters, inputs, and outputs. The various actuators .used in the mechatronic system are pneumatic and hydraulic actuators, electro-mechanical actuators, electrical motors such as DC motors, AC motors, stepper motors, servomotors, and piezoelectric actuators. The various types of sensors used in the mechatronic system are linear arid rotational sensors, acceleration sensors, force, torque and pressure sensors, flow sensors, temperature sensors, proximity sensors, light sensors.
- **Signals and conditioning**
  The mechatronic systems deal with two types of signals and conditioning such as – input and output. The input devices receive input signals from the mechatronic systems via interfacing devices and sensors. Then it is sent to the control circuits for conditioning or processing. The various input signal conditioning devices used in the mechatronic system are discrete circuits, amplifiers, Analog-to-Digital (A/D) converters, Digital-to-Digital (DZD) convertors. The output signals from the system are sent to output/display devices through interfacing devices. The various output signal conditioning devices used in the mechatronic system are Digital-to-Analog (D/A) converters, Display Decoders (DD) converters, amplifiers, power transistors, and power op-amps.
- **Digital logic systems**
  Digital logic devices control overall system operation. The various digital logic systems used in the mechatronic system are logic circuits, microcontrollers, programmable logic controllers, sequencing and timing controls, and control algorithms.

- **Software and data acquisition systems**
  The data acquisition system acquires the output signals from sensors in the form of voltage, frequency, resistance etc. and it is inputted into the microprocessor or computer. Software is used to control the acquisition of data through DAC(Digital to Analogue Converter) board. The data acquisition system consists of a multiplexer, amplifier, register, and control circuit, and DAC board. The various data acquisition systems used in the mechatronic system is data loggers, computer with plug-in boards, etc.
- **Computers and display devices**
  Computers are used to store a large number of data and process further through software. Display devices are used to give visual feedback to the user. The various display devices used in the mechatronic system are LEDs, CRT, LCD, digital displays, etc.

Importance of Mechatronics in automation:

- Today's customers are demanding more variety and higher levels of flexibility in the products. Due to these demands and competition in the market, manufacturers are thriving to launch new/modified products to survive. It is reducing the product life as well as lead-time to manufacture a product. It is therefore essential to automate the manufacturing and assembly operations of a product. There are various activities involved in the product manufacturing process. These are shown in figure below these activities can be classified into two groups viz. design and manufacturing activities.
- **Mechatronics based automated systems such as automatic inspection and quality assurance, automatic packaging, record making, and automatic dispatch help to expedite the entire manufacturing operation**. These systems certainly ensure a supply better quality, well packed and reliable products in the market. Automation in the machine tools has reduced the human intervention in the machining operation and improved the process efficiency and product quality. Therefore, it is important to study the principles of mechatronics and to learn how to apply them in the automation of a manufacturing system.



Operations involved in design and manufacturing of a product

Evolution Level of Mechatronics:

- **Primary Level Mechatronics:** This level incorporates I/O devices such as sensors and actuators that integrates electrical signals with mechanical action at the basic control levels. **Examples:** Electrically controlled fluid valves and relays.
- **Secondary Level Mechatronics:** This level integrates microelectronics into electrically controlled devices. **Examples:** Cassette players.
- **Third Level Mechatronics:** This level incorporates advanced feedback functions into control strategy thereby enhancing the quality in terms of sophistication called smart system. The control strategy includes microelectronics, microprocessor and other ' Application Specific Integrated Circuits' (ASIC) **Example:** Control of Electrical motor used to activate industrial robots, hard disk, CD drives and automatic washing machines
- **Fourth Level Mechatronics:** This level incorporates intelligent control in mechatronics system. It introduces intelligence and fault detection and isolation (FDI) capability systems.

Evolution of Mechatronics as a Contemporary Design Paradigm:

- Technological advances in design, manufacturing, and operation of engineered products/devices/processes can be traced through: –
  - **Industrial revolution**-Allowed design of products and processes for energy conversion and transmission thus allowing the use of energy to do useful work.
  - **Semiconductor revolution**-Led to the creation of integrated circuit (IC) technology.
  - **Information revolution**-Development of VLSI technology led to the introduction of microprocessor, microcomputer, and microcontroller

Introduction to autotronics, bionics, and avionics and their applications:

- **AUTOTRONICS: Autotronics can be defined as the combination of automobile and electronics or we can say that the use of electronics science in automobile vehicles is called autotronics**. A lot of research and implementation had been done in this context to make the design of automobiles easier. The use of electronics in the automobile field makes the system safe, improved and efficient. In a vehicle almost all significant parts are featured with electronic items.
- At present, in the new generation automobiles almost 75%-85% of automobile parts are embedded with electronics system. The main areas of automobiles using autotronics are engine controlling system, airbags, antilock braking system, lightening interiors, GPS, music systems etc.

- The application area of autotronics is very vast, brakes, steering system, engine controlling unit, transmission and suspension in the vehicles are the main phases where autotronics are used.
- The use of these technologies has given a phenomenal revolution in the automobile industry from past few decades. The gradual improvements in systems causes the new features in reduced cost.
- In the autotronic systems the use of control units like sensors, motors and digital equipment establishes a communication between the various essential system and components of the vehicle. The various systems are given below:

1. Autotronic braking system/Electronic braking system

- The braking system in such a system is denoted s EBS (electronic braking system). A braking system is defined by its stopping distance. The system with shortest stopping distance is considered the best braking system. So the development phase in the braking system is to minimize the stopping distance of vehicle but without compromising the safety. The ECB solve these purposes with an advance control system. The anti -lock braking system and traction control system are the essential components of ECB. **ABS** is responsible for maneuver control by deciding the braking pressure and wheel rotation control. **Traction** means providing movement or acceleration to a vehicle. So, to control the acceleration the control on traction system should be applied. This system controls the movement of wheel and its steadiness.

2. Control of steering system

- In the vehicle the power steering system is used. Which maintains the communication between pressure applied by steering system on the hydraulic pump and the speed of the automobile. **The EPS (electric power steering) uses sensors and motors, which controls the manoeuvre. Motor controls the steering motions and sensors gives signal to the wheels by analysing the speed and torque.**

3. Suspension system

- Suspension system makes the ride on vehicle shock free, comfortable and safe. There are three types of suspension system 1. Passive, 2. Semi active, and 3. Active suspension system. The important task of the system is to dissipate the heat produced in the system due to friction. The conventional method of suspension is called passive suspension and when we add electronic sensors and hydraulic system then its performance increases and it is called active suspension system.

4. Transmission control

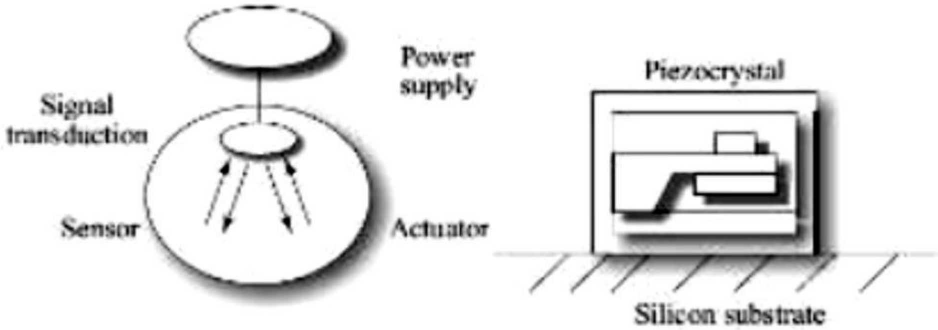
- The transmission of gearing system controls the shifting of gears. Using the electronic gear transmission improves the shifting operation and increases the fuel efficiency by reducing the losses.

5. Electronic control of fuel intake in engine

- The electronic system used to analyse the amount of fuel to supply to the cylinder of engine so that the maximum efficiency can be achieved with minimum loss of energy.

6. Air Bag Deployment System

➢ A sensor and an actuator embedded in a microsystem are used to operate the air bag deployment system in an automobile. The impact of the car in a serious collision is felt by a micro-inertia sensor built on the principle of micro-accelerometer. The sensor generates an appropriate signal to actuate the deployment of an air bag to protect the driver and passengers from serious injuries due to the impact of collision. Figure shows a micro-inertia sensor employed for rapid deployment of an air bag. The sensor contains two micro-accelerometers mounted onto the chassis of the car. The accelerometer on the left measures the deceleration in the horizontal direction and the accelerometer on the right measures the deceleration in the transverse direction. Both these accelerometers are mounted on the same integrated circuit chip along with a signal transducer and processing unit.



7. Antilock or Antiskid Device

➢ A vehicle stops more quickly when the brakes are applied just hard enough to get maximum static friction between the tyres and the road. If the brakes are applied harder than this, the tyres will skid or slide on the road and lesser kinetic friction will result. In this situation, applying brakes is less effective. Several devices have been developed to prevent a vehicle from skidding and thus provide maximum effective braking. Skid control is employed generally for the rear wheel only. As long as the wheels are turning/rotating, the antiskid device permits normal application of the brakes. But if the brakes are applied so hard that wheels stop turning, skid starts to develop. At this point, the antiskid device starts operating and partially releases the brakes so that the wheels continue to turn/rotate. However, intermittent braking continues, but it is held to just below the point where a skid would start. The result is maximum braking effect. The distance in which a vehicle can be brought to rest from a steady speed depends upon the following factors:

- Braking efficiency
- Condition and inflation pressure of tyres
- Nature of road surface
- Air resistance encountered by the vehicle

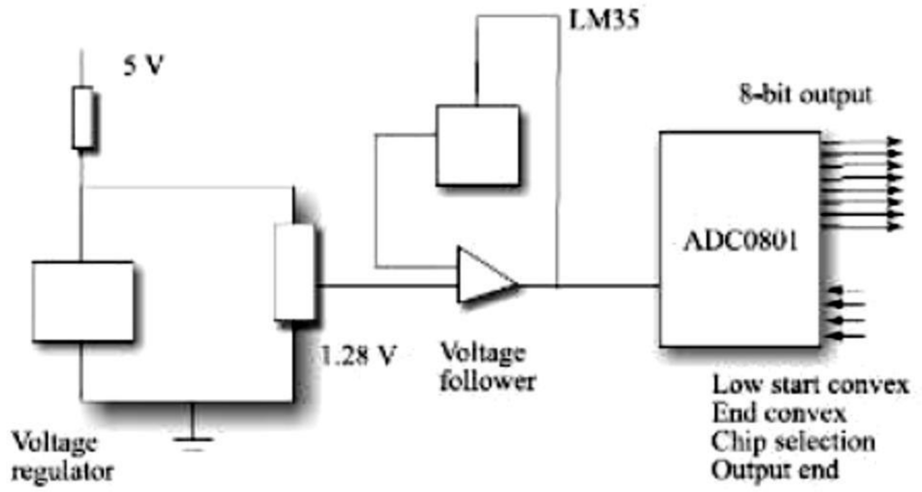
➢ Braking causes a retarding force on the vehicle, which in turn gives rise to deceleration. Braking efficiency is measured in terms of the rate at which it will bring the vehicle to a stationary position from a given speed. It is expressed in terms of the ratio of the deceleration rate to the acceleration rate due to gravity.

9. Car Park Barrier

- Consider the cam-operated barrier for a car park. The barrier opens and allows a car in when the correct money is inserted into the collection box. The barrier opens again to allow the car out on its detection on the park side of the barrier. Figure shows the type of the wall system that can be used to lift and lower the pivoted barrier. When a current flows through the solenoid of valve *A*, the piston in the cylinder moves upwards and causes the barrier to rotate about its pivot and raise to let a car through. When the current through the solenoid of valve *A* ceases, the return spring of the valve results in the valve position changing back to its original position. When the current flows through the solenoid of valve *B*, pressure is applied to the lower barrier. Limit switches are used to detect whether the barrier is in down or up position.

10. Engine Temperature Measurement

- Consider the requirement for a temperature measurement system for measuring temperature in the range 0–100°C, which is the case of the body temperature of the engine of an automobile. The system gives an 8-bit binary output with a change in 1 bit corresponding to the temperature change of 1°C. The output is intended for inputting to a microprocessor as part of a temperature indicating system. Thermistor LM35 can be used since a linear temperature sensor is required. LM35 gives an output of 10 mV/°C when fed with a supply voltage of 5 V. If one supplies from LM35 with an 8-bit **analog to digital converter (ADC)**, then a digital output can be obtained. The resolution of the ADC should be 10 mV so that each strip of 10 mV can generate a change in the output of 1 bit. If one uses a successive approximation ADC, ADC0801, then it requires an input of the response voltage, which when subdivided into 256 bits gives 10 mV per bit. This reference voltage input to the ADC0801 has to be *V*ref /2 and so an accurate input voltage of 1.28 V is required. Such a voltage can be obtained by using a potentiometer circuit across the 5-V supply with a voltage follower to avoid loading problems. Because the voltage has to be steady at 1.25 V even if the 5-V supply voltage fluctuates, a voltage regulator is likely to be used for a 2.54 V supply, ZN458/B. Such a circuit is shown in Fig.



- **BIONICS:** Bionics is a common term for bio-inspired information technology, typically including three types of systems, namely:
  - Bio-morphic (eg: neuromorphic) and bio-inspired electronic/optical devices,
  - Autonomous artificial sensor-processor-activator prostheses and various devices built into the human body, and
  - Living-artificial interactive symbioses, e.g. brain-controlled devices or robot Bionics is poised to have significant stake in mechatronic sensors market in the near future.
  - Biomedical sensors are mainly used for diagnostic analyses. Because of its miniature size, a biomedical sensor requires less amount of sample and can produce results significantly faster. These sensors can be produced in batches, thus resulting low unit cost of the sensor. Another cost cutting factor is that most of these sensors are disposable, thus manual labour involving cleaning and proper treatment for reuse is saved. Biosensors are extensively used in analytical chemistry and biomedical care as well as genetic engineering. These sensors usually involve biological molecules such as antibodies or enzymes, which interact with analytes that are to be detected.
- Major advantages of the use of mechatronic systems in biomedicine are as follows:
  1. Functionality for biomedical operators
  2. Adaptability to existing instruments and equipment
  3. Compatibility with biological systems
  4. Controllability, mobility, and easy navigation facilities for operators
  5. Possibility of the fabrication of mechatronic structures with a high aspect ratio (The ratio of the depth dimension to the surface dimension of the structure)
- **Application of Boinics:**
  1. **Glucose Detection and DNA Sensing:** Detection of glucose levels in human body is a classic case of bio sensing. If the level gets either too high or too low, their condition can be life threatening. Currently such patients must actually draw blood on a daily basis or even more often to monitor the blood glucose level. Sensing the blood glucose level can be done in many ways, using optical, conduction, or molecular recognition methods. The DNA sensing is potentially an enormous area in which the application of Nano science can prove to be path breaking.
  2. **Drug Delivery:** The size of the human body is very large compared to the size of a molecule. It is important for the thermofusion effectiveness that drug molecules find/reach the place in the body where they are needed/effective. Bio-availability refers to the presence of drug molecules where they are needed in the body and where they will do the most good. It is necessary to keep the drug doses to a minimum, otherwise the amount used can adversely affect or even kill a patient. Nanotechnology and Nano science are very useful in developing entirely new ways for increasing bio-availability and improving the drug delivery. Magnetic nanoparticles used for computer memory can be used for drug delivery also.
  3. **Photodynamic Therapy:** In photodynamic therapy, a particle is placed within the patient's body. This particle is illuminated with a light source from outside of the body. The light may come from outside from a laser or light bulb. The

light is absorbed by the particle, after which several things might happen. If the particle is simply a metal nanodot, the energy from the light will heat the dot, which, in turn, will heat any tissue within its neighbourhood. With the same particular molecular dot, light can also be used to produce highly energetic oxygen molecules. Such oxygen molecules are very reactive and will chemically react with (and, therefore, destroy) many organic molecules that are next to them. The photodynamic therapy is attractive for many reasons. One reason is that, unlike the traditional chemotherapy, it is directed at the damaged/diseased cell. The chemically reactive excited oxygen or quantum data is released only where such cells are present and where the light is illuminated. This ensures that, unlike the traditional chemotherapy, the photodynamic therapy does not leave a fixed trail of highly aggressive and reactive molecules throughout the body.

4. **Neuro-electronic Interface:** The neuro-electronic interface involves the idea of constructing nano devices that can permit computers to be joined and linked to the neuro system. The construction of a neuro-electronic interface system requires the building of a molecular structure that will permit control and detection of nerve impulses by an external computer.
5. **Biotechnology:** Mechatronics plays an important role in biotechnology even though it is a small subdomain of biotechnology. Biotechnology includes all techniques that use living organisms or substances obtained from them to make or modify a product. It involves improvement of microbe, plant, and animal species. Genes and gene products are the basic tools in biotechnology. Biotechnology aims at harnessing the genetic diversity in the living organisms for the benefit of the humankind.

- **AVIONICS:** Avionics is a combination of aviation and electronics. Avionics system or Avionics sub-system depends on electronics. Avionics grew in 1950‟s and 1960 as electronic devices which replaces the mechanical or analog equipment in the aircraft. Avionics equipment on a modern military or civil aircraft account for around:
  - 30% of the total cost of the aircraft
  - 40% in the case of a maritime patrol/anti-submarine aircraft or helicopter.
  - Over 75% of the total cost in the case of an airborne early warning aircraft (AWACS).
- **NEED FOR AVIONICS:**
  To enable the flight crew to carry out the aircraft mission safely and efficiently. For civil airliner the mission is carrying passengers to their destination. For military aircraft the mission is intercepting a hostile aircraft, attacking a ground target, reconnaissance or maritime patrol.
- **Advantages**
  - Increased safety
  - Air traffic control requirements
  - All weather operation
  - Reduction in fuel consumption
  - Improved aircraft performance and control and handling and reduction in maintenance costs

➢ APPLICATIONS OF AVIONICS SYSTEMS:

A hierarchical structure comprising layers of specific task and avionics system function for enabling the crew to carry out the aircraft mission. The core avionics system is depicted in figure 1.1. In the core avionics system, the systems which directly interface with pilot are given below:

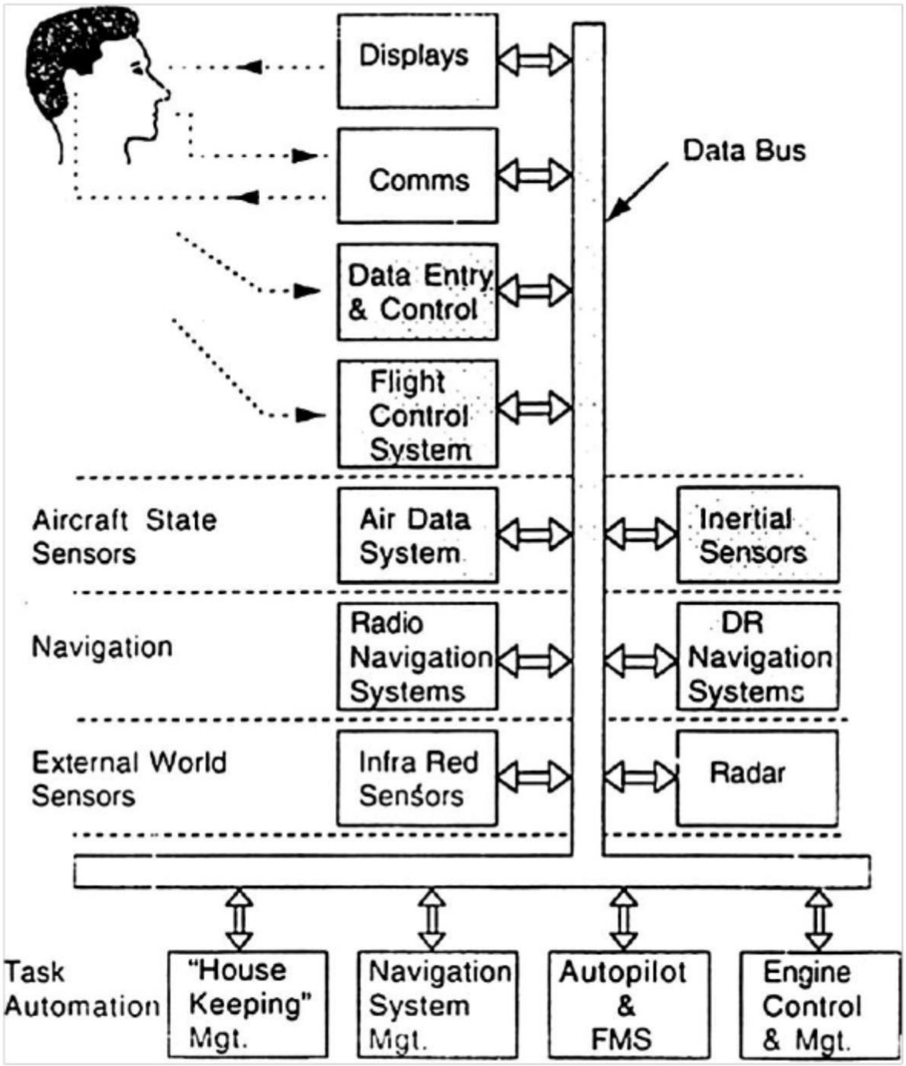


Figure 1.1 Core Avionics System

➢ Display System

It provides the visual interface between the pilot and the aircraft systems.

Types

- HUD - Head Up Displays
- HMD - Helmet Mounted Displays
- HDD – Head Down Displays

➢ **Communication System**

It provides the two way communication between the ground bases and the aircraft or between aircrafts. A Radio Transmitter and Receiver was the first avionics system installed in an aircraft. The different types of frequencies used for several ranges are given below.

Long Range Communication – High Frequency (2 – 30 MHz)

Medium Range Communication – Very High Frequency (30 – 100 MHz)

Military Aircraft – Ultra High Frequency (250 – 400 MHz)

Now a days satellite communication systems are used to provide very reliable communication.

➢ **Data Entry and Control System**

It is essential for the crew to interact with the avionic system. Ex: Keyboards, Touch Panels to use direct voice Input, Voice warning systems and so on.

Flight Control System

It uses the electronic system in two areas.

(i) Auto Stabilization

- **Roll Auto Stabilizer System**
- **Pitch Auto Stabilizer System**

(ii) FBW Flight Control Systems

It provides continuous automatic stabilization of the aircraft by computer control of the control surfaces from appropriate motion sensors.

➢ **Aircraft State Sensor Systems**

For control and navigation of the aircraft the air data quantities are essential.

- Air Data Quantities are,
- Altitude
- Calibrated Airspeed
- Vertical speed
- True Airspeed
- Mach Number
- Airstream Incidence Angle.

The air data computing system computes these quantities from the outputs of sensors which measure the static and total pressure and the outside air temperature.

➢ **Inertial Reference System**

The aircraft attitude and the direction in which it is heading are provided by the inertial sensor systems (Comprise a set of gyros and accelerometers which measures the aircraft's angular and linear motion).

➢ **Navigation System**

The Navigation system provides Navigation Information (Aircraft"s position, Ground speed, Track angle).

- **Dead Reckoning Systems (DR System)**
- **Position Fixing Systems (PF System)**

DR Navigation systems derive the vehicle's present position by estimating the distance travelled from a known position from knowledge of the speed and direction of the vehicle.

Types of DR Navigation systems are,

i) Inertial Navigation systems (Most Accurate)

ii) Doppler / Heading Reference Systems (Used in Helicopters)

iii) Air Data / Heading Reference Systems (Low Accuracy when compared to the above systems)

- **Radio Navigation Systems:** (Position Fixing Systems)

Satellite or ground based transmitter is used to transmit the signal and it was received by the receiver in the aircraft. According to the received signals a supporting computer is used to derive the aircraft's position. The Prime Position Fixing System used in aircraft is GPS.

- **ILS**

Instrument Landing Systems or Microwave Landing System is used for approach guidance to the airfield.

- **Outside World Sensor Systems:**

These systems comprise both radar and infrared sensor which enables all weather and night time operation.

- **Radar Systems**

Weather Radar detects water droplets, cloud turbulence and warning about storms.

- **Fighter Aircrafts Radars**

Multi-Mode Radars for ground attack role and interception role. The Radar must be able to detect aircraft upto 100 miles away and track several aircraft simultaneously (12 aircraft's). The Radar must have a look down capability to track low flying aircraft below it.

- **Infrared Systems**

It is used to provide a video picture of the thermal image scene of the outside world by using fixed Forward Looking Infra-Red (FLIR) sensor or a gimbaled IR imaging sensor. The thermal image picture at night looks similar to the visual picture in day time, but highlights heat sources such as vehicle engines. FLIR can also be installed in civil aircraft to provide enhanced vision in addition with HUD.

- **Task Automation Systems**

These systems reduce the crew workload and enable minimum crew operation.

- **Navigation Management System**

It comprises the operation of all radio navigation aid systems and the combination of data from all navigation sources such as GPS and INS systems, to provide the best estimation of the aircraft position and ground speed.

- **Autopilots and Flight Management Systems**

The autopilot relieves the pilot in long range mission.

FMS came into use in 1980‟s (Civil Aircraft). The FMS tasks are given below.

(i) Flight Planning

(ii) Navigation Management

(iii) Engine control to maintain the planned speed

(iv)Control of Aircraft Flight Path

(v) Minimizing Fuel consumption

(vi)Ensuring the aircraft is at the planned 3D position at the planned time slot (for Air Traffic Control).

- **Engine Control and Management**

Modern jet engines are having the Full Authority Digital Engine Control System (FADEC). This controls flow of fuel. This control system ensures the engine's temperature, speed and acceleration in control.

Engine health monitoring system record a wide range of parameters, so it will give early warning of engine performance deterioration, excessive wear, fatigue damage, high vibrations, excessive temperature etc.,

- **House Keeping Management**

Automation of the background task which are essential for the aircraft's safe and efficient operation.

- **Background tasks include**

  i) Fuel management

  ii) Electrical power supply management

  iii) Hydraulic power supply management

  iv) Cabin / Cockpit pressurization systems

  v) Environmental control systems

  vi) Warning systems

  vii) Maintenance and monitoring systems.

Aircraft Engine Control

The extent and sophistication of engine instrumentation vary widely with the type of the aircraft and intended use. In a small-engine plane, most instruments are simple and a mechanically connected throttle suffices. It is highly desirable to keep fuel and oil under pressure out of the cockpit. Thus most engine parameters are remotely indicated in the cockpit from a transmitter mounted near or on the engine. Instrumentation for a typical jet engine will provide for controlling and monitoring of the following:

1. Low-pressure rotor speed
2. High-compressor rotor speed
3. Fuel flow
4. Exhaust gas temperature
5. Engine pressure
6. Engine inlet air pressure
7. Engine inlet air temperature
8. Fuel pump inlet temperature
9. Fuel decreasing air shut off valve position
10. Fuel pump inlet pressure
11. Fuel filter pressure difference warning
12. Engine oil pressure
13. Engine oil and inlet temperature
14. Engine radial vibration

Lecture 4: Sensors and Transducers: Types of sensors, and their characteristics

Sensor: A sensor is defined as an element which when subjected to some physical change experiences a relative change. A sensor in which the output energy is supplied entirely or almost entirely by its input signals is called a passive element. An active element has an uxiliary source of power that supplies a major part of the output power. There may or may not be a conversion of energy from one form to another.

Sensors are used in mechatronics for the following purposes:

1. To provide position, velocity, and acceleration information of the measuring element in a system which provides feedback information
2. To act as protective mechanism for a system

3. To help eliminate mechanically complex and expensive feeding and sorting devices
4. To provide identification and indication of the presence of different components
5. To provide real time information concerning the nature of the task being performed.

Types of Sensor:

Vision and Imaging Sensors

Vision and Imaging Sensors/Detectors are electronic devices that detect the presence of objects or colors within their fields of view and convert this information into a visual image for display. Key specifications include sensor type and intended application, along with any particular transducer features.

Temperature Sensors

Temperature Sensors/Detectors/Transducers are electronic devices that detect thermal parameters and provide signals to the inputs of control and display devices. A temperature sensor typically relies on an RTD or thermistor to measure temperature and convert it to an output voltage. Key specifications include sensor/detector type, maximum and minimum measurable temperatures, as well as the dimensions of diameter and length. Temperature sensors are used to measure the thermal characteristics of gases, liquids, and solids in many process industries and are configured for both general- and special-purpose uses.

Radiation Sensors

Radiation Sensors/Detectors are electronic devices that sense the presence of alpha, beta, or gamma particles and provide signals to counters and display devices. Key specifications include sensor type and minimum and maximum detectable energies. Radiation detectors are used for surveys and sample counting.

Proximity Sensors

Proximity Sensors are electronic devices used to detect the presence of nearby objects through non-contacting means. A proximity sensor can detect the presence of objects usually within a range of up to several millimeters, and, doing so, produce a usually dc output signal to a controller. Proximity sensors are used in countless manufacturing operations to detect the presence of parts and machine components. Key specifications include sensor type, maximum sensing distance, minimum & maximum operating temperatures, along with dimensions of diameter and length. Proximity sensors are generally short-range devices but are available too in designs that can detect objects up to several inches away. One commonly used type of proximity sensor is known as a capacitive proximity sensor. This device uses the change in capacitance resulting from a reduction in the separation distance between the plates of a capacitor, one plate of which is attached to the object being observed, as a means of determining motion and position of the object from the sensor.

Pressure Sensors

Pressure Sensors/Detectors/Transducers are electro-mechanical devices that detect forces per unit area in gases or liquids and provide signals to the inputs of control and display devices. A pressure sensor/transducer typically uses a diaphragm and strain gage bridge to detect and measure the force exerted against a unit area. Key specifications include sensor function, minimum and maximum working pressures, full-scale accuracy, along with any features particular to the device. Pressure sensors are used wherever information about the pressure of a gas or liquid is needed for control or measurement.

Position Sensors

Position Sensors/Detectors/Transducers are electronic devices used to sense the positions of valves, doors, throttles, etc. and supply signals to the inputs of control or display devices. Key specifications include sensor type, sensor function, measurement range, and features that are specific to the sensor type. Position sensors are used wherever positional information is needed in a myriad of control applications. A common position transducer is a so-called string-pot, or string potentiometer

Photoelectric Sensors

Photoelectric sensors are electrical devices that sense objects passing within their field of detection, although they are also capable of detecting color, cleanliness, and location if needed. These sensors rely on measuring changes in the light they emit using an emitter and a receiver. They are common in manufacturing and material handling automation for purposes such as counting, robotic picking, and automatic doors and gates.

Particle Sensors

Particle Sensors/Detectors are electronic devices used to sense dust and other airborne particulates and supply signals to the inputs of control or display devices. Particle sensors are common in bin and baghouse monitoring. Key specifications include transducer type, minimum detectable particle size, operating temperature range, sample volume, and response time. Particle detectors used in nuclear engineering are referred to as radiation detectors

Motion Sensors

Motion Sensors/Detectors/Transducers are electronic devices that can sense the movement or stoppage of parts, people, etc. and supply signals to the inputs of control or display devices. Typical applications of motion detection are detecting the stalling of conveyors or the seizing of bearings. Key specifications include the intended application, sensor type, sensor function, and minimum and maximum speeds.

Metal Sensors

Metal Detectors are electronic or electro-mechanical devices used to sense the presence of metal in a variety of situations ranging from packages to people. Metal detectors can be permanent or portable and rely on a number of sensor technologies with electromagnetics being popular. Key specifications include the intended application, maximum sensing distance, and certain feature choices like handheld and fixed systems. Metal detectors can be tailored to explicitly detect metal in specific manufacturing operations such as sawmilling or injection molding..

Level Sensors

Level Sensors/Detectors are electronic or electro-mechanical devices used for determining the height of gases, liquids, or solids in tanks or bins and providing signals to the inputs of control or display devices. Typical level sensors use ultrasonic, capacitance, vibratory, or mechanical means to determine product height. Key specifications include sensor type, sensor function, and maximum sensing distance. Level sensors/detectors can be of the contacting or non-contacting type.

Leak Sensors

Leak Sensors/Detectors are electronic devices used for identifying or monitoring the unwanted discharge of liquids or gases. Some leak detectors rely on ultrasonic means to detect air leaks, for example. Other leak detectors rely on simple foaming agents to measure the soundness of pipe joints. Still, other leak detectors are used to measure the effectiveness of the seals in vacuum packages

Humidity Sensors

Humidity Sensors/Detectors/Transducers are electronic devices that measure the amount of water in the air and convert these measurements into signals that can be used as inputs to control or display devices. Key specifications include maximum response time and minimum and maximum operating temperatures.

Gas and Chemical Sensors

Gas and Chemical Sensors/Detectors are fixed or portable electronic devices used to sense the presence and properties of various gases or chemicals and relay signals to the inputs of controllers or visual displays. Key specifications include the intended application, sensor/detector type, measurement range, and features. Gas and chemical sensors/detectors are used for confined space monitoring, leak detection, analytical instrumentation, etc. and are often designed with the capability of detecting multiple gases and chemicals.

Force Sensors

Force Sensors/Transducers are electronic devices that measure various parameters related to forces such as weight, torque, load, etc. and provide signals to the inputs of control or display devices. A force sensor typically relies on a load cell, a piezoelectric device whose resistance changes under deforming loads. Other methods exist for measuring torque and strain. Key specifications include sensor function, number of axes, minimum and maximum loads (or torques), minimum and maximum operating temperature, as well as the dimensions of the sensor itself. Force sensors are used in load measuring applications of all kinds, from truck scales to bolt tensioning devices.

Flow Sensors

Flow Sensors/Detectors are electronic or electro-mechanical devices used to sense the movement of gases, liquids, or solids and provide signals to the inputs of control or display devices. A flow sensor can be all electronic—using ultrasonic detection from outside a pipeline, say—or partially mechanical—a paddlewheel, for instance, that sits and spins directly in the flow stream itself. Key specifications include sensor/detector type, sensor function, maximum flowrate, maximum working pressure, and minimum and maximum operating temperatures. Flow sensors are used extensively in the processing industries. Some designs for panel mounting allow quick indication of flow conditions to process operators

Flaw Sensors

Flaw Sensors/Detectors are electronic devices used in a variety of manufacturing processes to uncover inconsistencies on surfaces or in underlying materials such as welds. Flaw detectors use ultrasonic, acoustic, or other means to identify defects in materials and can be portable or fixed installations. Key specifications include sensor type, detectable defect or thickness range, and intended application.

Flame Sensors

Flame Detectors are optoelectronic devices used to sense the presence and quality of fire and provide signals to the inputs of control devices. A flame detector typically relies on ultraviolet or infrared detection of the presence of flame and finds use in many combustion control applications such as burners. A key specification is detector type. Flame detectors find applications in safety settings too, such as in under-the-hood fire suppression systems

Electrical Sensors

Electrical Sensors/Detectors/Transducers are electronic devices that sense current, voltage, etc. and provide signals to the inputs of control devices or visual displays. Electrical sensors often rely on hall effect detection but other methods are used as well. Key specifications include sensor type, sensor function, minimum and maximum measurement ranges, and operating temperature range.

Electrical sensors are used wherever information on the state of an electrical system is needed and are employed in everything from railway systems to fan, pump, and heater monitoring.

Contact Sensors

Contact sensors refer to any type of sensing device that functions to detect a condition by relying on physical touch or contact between the sensor and the object being observed or monitored. A simple type of contact sensor is used in alarm systems to monitor doors, windows, and other access points. When the door or window is closed, a magnetic switch provides an indication to the alarm control unit so that the status of that entry point is known. Similarly, when a door or window is opened, the contact sensor alerts the alarm controller of the state of that access point and may trigger an action such as engaging an audible siren. There are many uses of contact sensors such as temperature monitoring and as proximity sensors in robotics applications and automated machinery.

Non-Contact Sensors

In contrast to contact sensors, non-contact sensors are devices that do not require a physical touch between the sensor and the object being monitored in order to function. A familiar example of this type of sensor is the motion detector used in security lights. Detection of objects within the range of a motion detector is accomplished using non-mechanical or non-physical means, such as via detection of passive infrared energy, microwave energy, ultrasonic waves, etc. Radar guns used by law enforcement to monitor the speed of vehicles is another example of a form of non-contact sensor. Other types of devices that fall under the category of non-contact sensors include Hall-effect sensors, inductive sensors, LVDTs (linear variable differential transformers), RVDTs (rotary variable differential transformers), and Eddy current sensors, to name a few.

Characteristics of Sensors

To choose an appropriate sensor for a particular need, we have to consider a number of different characteristics.

•These characteristics determine the performance, economy, ease of application, and applicability of the sensor.

•In certain situations, different types of sensors may be available for the same purpose.

•Therefore, the following may be considered before a sensor is chosen:

1. Cost: The cost of a sensor is an important consideration, especially when many sensors are needed for one machine. However, the cost must be balanced with other requirements of the design such as reliability importance of the data they provide accuracy, life, and so on.

2. Size: Depending on the application of the sensor, the size may be of primary importance. For example, the joint displacement sensors have to be adapted into the design of the joints and move with the robot's body elements. The available space around the joint may be limited. Therefore, it is important to ensure that enough room exists for the joint sensors.

3. Weight:

Since robots are dynamic machine, the weight of a sensor is very important. A heavy sensor adds to the inertia of the arm and reduces its overall payload.

4. Type of output (digital or analog):

The output of a sensor may be digital or analog and depending on the application, this output may be used directly or have to be converted.

For example, the output of a potentiometer is analog, whereas that of an encoder is digital.

If an encoder is used in conjunction with a microprocessor, the output may be directly routed to the input port of the processor, while the output of a potentiometer has to be converted to digital signal with an analog-to-digital converter (ADC).

The appropriateness of the type of output must be balanced with other requirements.

5. Interfacing: Sensors must be interfaced with other devices such as microprocessors and controllers. The interfacing between the sensor and the device can become an important issue if they do not match or if other add-on components and circuits become necessary (including resistors, transistor switches, power source, and length of wires involved).

6. Resolution**:** Resolution is the minimum step size within the range of measurement of the sensor

7. Sensitivity: Sensitivity is the ratio of a change in output in response to a change in input. Highly sensitive sensors will show larger fluctuations in output as a result of fluctuations in input, including noise.

8. Linearity. Linearity represents the relationship between input variations and output variations. This means that in a sensor with linear output, the same change in input at any level within the range will produce a similar change in output. Almost all devices in nature are somewhat nonlinear, with varying degrees of nonlinearity.

9. **Range:** Range is the difference between the smallest and the largest outputs the sensor can produce, or the difference between the smallest and largest inputs with which it can operate properly.

10. **Response rime:** Response time is the time that a sensor's output requires to reach a certain percentage of the total change. It is usually expressed in percentage of total change, such as 95%. It is also defined as the time required to observe the change in output as a result of a change in input. For example, the response time of a simple mercury thermometer is long, whereas a digital thermometers response time, which measures temperature based on radiated heat, is short.

11. Frequency response: Suppose you attach a very high-quality radio tuner to a small, cheap speaker. Although the speaker will reproduce the sound, its quality will be very low, whereas a high-quality speaker system with a woofer and tweeter *will reproduce the same signal with much better quality. This is because the frequency response of the two-speaker system is very different from the single, cheap speaker.*

12. Reliability:

Reliability is the ratio of how many times a system operates properly, divided by how many times it is used. For continuous, satisfactory operation it is necessary to choose reliable sensors that last a long time while considering the cost and other requirements.

13. Accuracy:

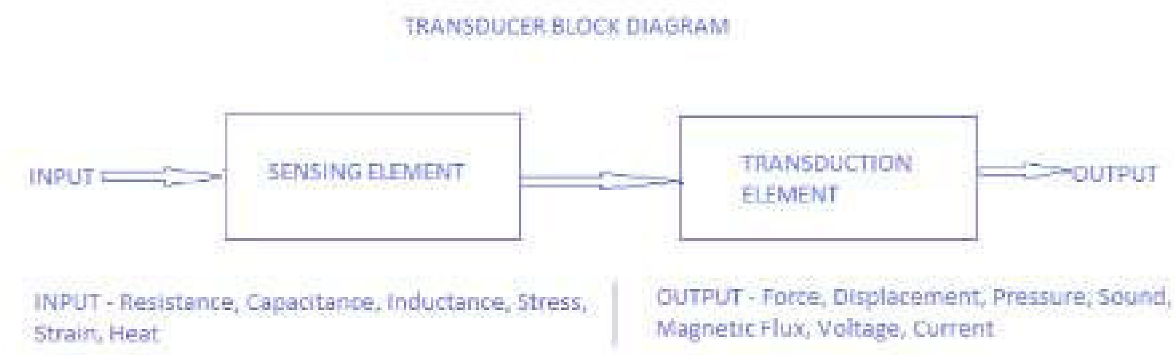
Accuracy is defined as how close the output of the sensor is to the expected value. If for a given input, the output is expected to be a certain value, accuracy is related to how close the sensor's output is to this value.

14. Repeatability:

If the sensor's output is measured a number of times in response to the same input, the output may be different each time. Repeatability is a measure of how varied the different outputs are relative to each other.

Lecture 5: Types of transducers and their characteristics

Transducer: A device that converts variations in a physical quantity, such as pressure or brightness, into an electrical signal, or vice versa. Transducer is a device which converts one form of energy into another form. It is also defined as a device that converts a non electrical quantity into proportional electrical quantity.



For example –

1. An electric generator converts mechanical energy into equivalent electrical energy.
2. A solar cell used in calculators converts light energy into equivalent electrical energy.
3. A pencil cell converts chemical energy into equivalent electrical energy.

Classifications of transducers – broadly the transducers are classified into two main types: Active trans ducers and passive transducers. The active transducer generates its own electrical voltage during conversion. Thus it does not require any battery supply for conversion (e.g. solar cell, thermocouple etc.). In passive transducer, it requires *external*battery supply. It only changes its parameter during conversion like change in resistance or capacitance etc. (e.g. LDR, thermistor etc.)

Active transducers –

Definition – an active transducer is defined as a transducer which generates its own electrical voltage during conversion. It does *not* require any external battery supply for its working.

Examples –

1. **Solar cell –** when it is exposed to strong sunlight or any other light, it converts light energy into proportional *DC voltage*.

2. **Piezo electric crystal –** when it is subjected to *changing pressure* it produces proportional *AC voltage*.

Passive transducers –

Definition – passive transducer is defined as the transducer which requires *external*battery voltage to operate. Also it only changes its parameter like change in resistance or capacitance during conversion.

Examples –

1. **LDR (Light Dependent Resistor) –** when LDR is exposed to light, its resistance decreases *(less than 10W)* proportionally & when it is dark its resistance is very high*(several MW).*

2. **Thermistor –** when thermistor is exposed to heat its resistance decreases and when it is cooled its resistance increases.

According to working principle of transducers they are classified into four main types –

1. **Mechanical transducers –** for example strain gauge, LVDT etc.
2. **Thermal transducers –** for example thermistor, thermocouple etc.
3. **Magnetic transducers –** for example search coil etc.
4. **Radiation transducers –** for example solar cell, photo diode etc.

Characteristics of Transducer

Following factors must be considered while selecting transducer for a particular work or system –

1. Physical quantity to be measured must be considered for –
2. The type of physical quantity whether it is electrical quantity *(AC or DC)* or nonelectrical quantity *(pressure, intensity, displacement, speed, heat etc.)*
3. Range of quantity like pressure *(0–10N)*, intensity *(0–250L)*, temperature *(–10°C to 200° C)* etc.
4. The principle of transducer must be considered for –
5. The system and transducer must be compatible i.e. the output characteristics of transducer and input characteristics of the system and must match.

1. This means that principle of maximum power transfer theorem must be satisfied.
2. The measurement accuracy of the transducer must be considered which depends on
3. Type and range of quantity under measurement.
4. Physical conditions like mechanical and electrical connections, mounting style of transducer.
5. Surrounding conditions like nonlinearity effect and frequency response etc.
6. Environmental conditions like temperature effects, shocks or vibrations etc.
7. Compatibility of some associated equipment’s like zero balancing provision, sensitivity tolerance, impedance matching etc.

Types of transducers

· **Temperature transducers –** this transducer converts heat energy into its equivalent electrical energy. They are of two types –

Active temperature transducers – thermo-couple which converts heat energy into equivalent electrical voltage.

Passive temperature transducers – thermistor or resistance thermometer is a passive transducer. It only changes its resistance due to change in temperature.

Pressure transducers – these are of two types: the stress and strain types. When either stress or strain is applied, they produce a proportional electrical voltage.

Active pressure transducers – piezo electric crystal is a good example of active pressure transducer. It produces proportional electrical voltage when pressure is applied on it.

Passive pressure transducers – strain gauge, capacitive transducer. When either stress or strain is applied, their passive parameter like resistance or capacitance proportionally changes.

Light transducers – it converts light energy into equivalent electrical energy. There are two types of light transducers –

Active light transducers – in this photo–voltaic cell, photo multiplier tubes (made up within vacuum tubes) and solar cells (made up of semiconductor material) are used. They convert light into electrical energy.

Passive light transducer – this contains LDR – light dependent resistor. Its resistance changes as light on it changes.

Sound transducers – it converts sound energy into equivalent electrical energy and vice versa.

Active sound transducer – carbon microphone is good examples of active transducer. It converts sound into proportional AC voltage. This happens because carbon granules in it vibrate and produce proportional voltage across two dissimilar metal plates.

Passive sound transducers – capacitive microphone is passive transducer. Its capacity (C) changes proportionally due to change in sound intensity.

Transducer Applications

The applications of transducers based on the electric parameter used and the principle involved is given below.

1. Passive Type Transducers

a. Resistance Variation Type

Resistance Strain Gauge – The change in value of resistance of metal semi-conductor due to elongation or compression is known by the measurement of torque, displacement or force.

Resistance Thermometer – The change in resistance of metal wire due to the change in temperature known by the measurement of temperature.

Resistance Hygrometer – The change in the resistance of conductive strip due to the change of moisture content is known by the value of its corresponding humidity.

Hot Wire Meter – The change in resistance of a heating element due to convection cooling of a flow of gas is known by its corresponding gas flow or pressure. Displacement transducer

Photoconductive Cell – The change in resistance of a cell due to a corresponding change in light flux is known by its corresponding light intensity.

Thermistor – The change in resistance of a semi-conductor that has a negative co-efficient of resistance is known by its corresponding measure of temperature.

Potentiometer Type – The change in resistance of a potentiometer reading due to the movement of the slider as a part of an external force applied is known by its corresponding pressure or displacement.

b. Capacitance Variation Type

Variable Capacitance Pressure Gauge – The change in capacitance due to the change of distance between two parallel plates caused by an external force is known by its corresponding displacement or pressure.

Dielectric Gauge – The change in capacitance due to a change in the dielectric is known by its corresponding liquid level or thickness.

Capacitor Microphone – The change in capacitance due to the variation in sound pressure on a movable diagram is known by its corresponding sound.

c. Inductance Variation Type

Eddy Current Transducer – The change in inductance of a coil due to the proximity of an eddy current plate is known by its corresponding displacement or thickness.

Variable Reluctance Type – The variation in reluctance of a magnetic circuit that occurs due to the change in position of the iron core or coil is known by its corresponding displacement or pressure.

Proximity Inductance Type – The inductance change of an alternating current excited coil due to the change in the magnetic circuit is known by its corresponding pressure or displacement.

Differential Transformer – The change in differential voltage of 2 secondary windings of a transformer because of the change in position of the magnetic core is known by its corresponding force, pressure or displacement.

Magnetostrictive Transducer – The change in magnetic properties due to change in pressure and stress is known by its corresponding sound value, pressure or force.

d. Voltage and Current Type

Photo-emissive Cell – Electron emission due to light incidence on photo-emissive surface is known by its corresponding light flux value.

Hall Effect – The voltage generated due to magnetic flux across a semi-conductor plate with a movement of current through it is known by its corresponding value of magnetic flux or current.

Ionisation Chamber – The electron flow variation due to the ionisation of gas caused by radio-active radiation is known by its corresponding radiation value.

2. Active Type

Photo-voltaic Cell – The voltage change that occurs across the p-n junction due to light radiation is known by its corresponding solar cell value or light intensity.

Thermopile – The voltage change developed across a junction of two dissimilar metals is known by its corresponding value of temperature, heat or flow.

Piezoelectric Type – When an external force is applied on to a quartz crystal, there will be a change in the voltage generated across the surface. This change is measured by its corresponding value of sound or vibration.

Moving Coil Type – The change in voltage generated in a magnetic field can be measured using its corresponding value of vibration or velocity.

Lecture 6: Overview of Mechanical Actuation System

Kinematic Chains: When the kinematic pairs are coupled in such a way that the last link is joined to the first link to transmit definite motion (i.e. completely or successfully constrained motion), it is called a kinematic chain.

In other words, a kinematic chain may be defined as a combination of kinematic pairs, joined in such a way that each link forms a part of two pairs and the relative motion between the links or elements is completely or successfully constrained. For example, the crank- shaft of an engine forms a kinematic pair with the bearings which are fixed in a pair, the connecting rod with the crank forms a second kinematic pair, the piston with the connecting rod forms a third pair and the piston with the cylinder forms a fourth pair. The total combination of these links is a kinematic chain. If each link is assumed to form two pairs with two adjacent links, then the relation between the number of pairs (p) forming a kinematic chain and the number of links (l) may be expressed in the form of an equation :

$$l = 2p - 4$$

Another relation between the number of links (l) and the number of joints (j) which constitute a kinematic chain is given by the expression

$$j = \frac{3}{2} l - 2$$

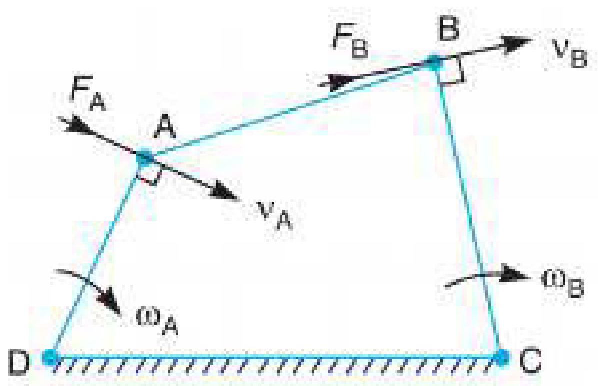
Types of Kinematic Chains: The most important kinematic chains are those which consist of four lower pairs, each pair being a sliding pair or a turning pair. The following three types of kinematic chains with four lower pairs are important from the subject point of view

1. Four bar chain or quadric cyclic chain,

2. Single slider crank chain,

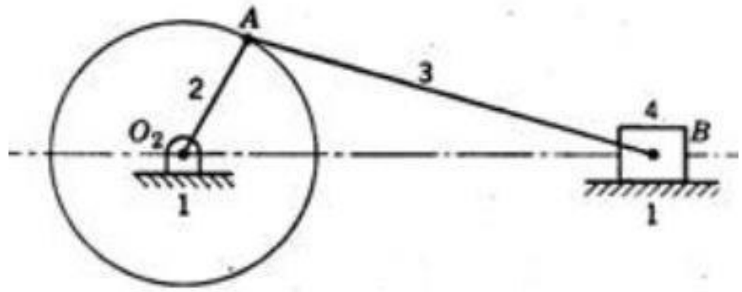
3. Double slider crank chain

Four bar chain or quadric cyclic chain: The kinematic chain is a combination of four or more kinematic pairs, such that the relative motion between the links or elements is completely constrained. The simplest and the basic kinematic chain is a four bar chain or quadric cycle chain. It consists of four links, each of them forms a turning pair at A, B, C and D. The four links may be of different lengths. According to Grashof 's law for a four bar mechanism, the sum of the shortest and longest link lengths should not be greater than the sum of the remaining two link lengths if there is to be continuous relative motion between the two links. A very important consideration in designing a mechanism is to ensure that the input crank makes a complete revolution relative to the other links. The mechanism in which no link makes a complete revolution will not be useful. In a four bar chain, one of the links, in particular the shortest link, will make a complete revolution relative to the other three links, if it satisfies the Grashof 's law. Such a link is known as crank or driver. A D (link 4) is a crank. The link BC (link 2) which makes a partial rotation or oscillates is known as lever or rocker or follower and the link CD (link 3) which connects the crank and lever is called connecting rod or coupler. The fixed link A B (link 1) is known as frame of the mechanism. When the crank (link 4) is the driver, the mechanism is transforming rotary motion into oscillating motion.

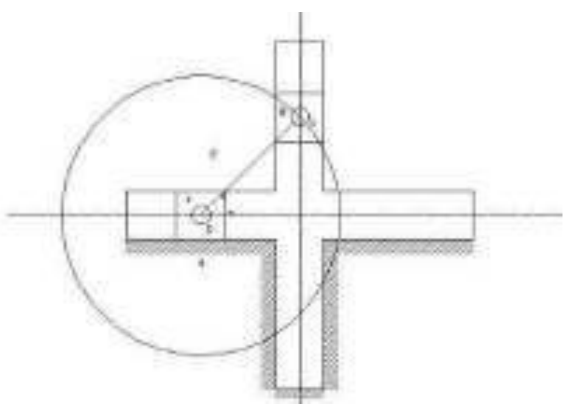


Four bar mechanism.

Single slider crank chain: A single slider crank chain is a modification of the basic four bar chain. It consist of one sliding pair and three turning pairs. It is, usually, found in reciprocating steam engine mechanism. This type of mechanism converts rotary motion into reciprocating motion and vice versa. In a single slider crank chain, as shown the links 1 and 2, links 2 and 3, and links 3 and 4 form three turning pairs while the links 4 and 1 form a sliding pair. The link 1 corresponds to the frame of the engine, which is fixed. The link 2 corresponds to the crank; link 3 corresponds to the connecting rod and link 4 corresponds to cross-head. As the crank rotates, the cross-head reciprocates in the guides and thus the piston reciprocates in the cylinder.

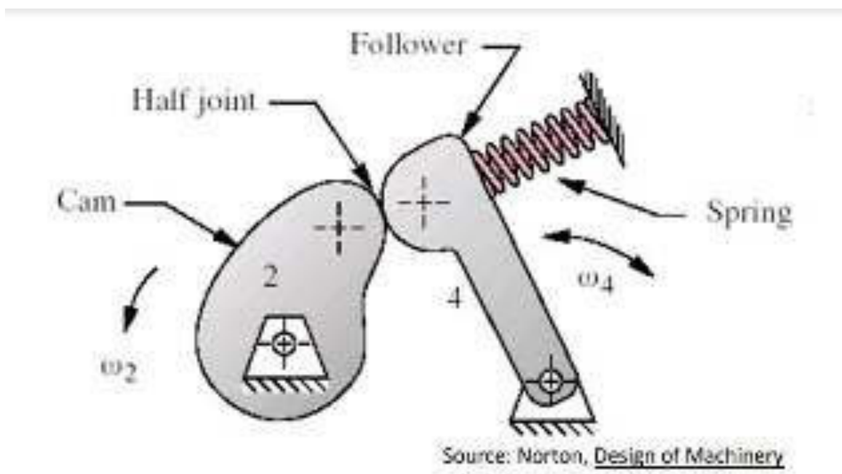


Double Slider Crank Chain: A kinematic chain which consists of two turning pairs and two sliding pairs is known as double slider crank chain. We see that the link 2 and link 1 form one turning pair and link 2 and link 3 form the second turning pair. The link 3 and link 4 form one sliding pair and link 1 and link 4 form the second sliding pair.



CAM: In machines, particularly in typical textile and automatic machines, many parts need to be imparted different types of motion in a particular direction. This is accomplished by conversion of the available motion into the type of motion required. Change of circular motion to translatory (linear) motion of simple harmonic type and vice-versa and can be done by slider-crank mechanism as discussed previously. But now the question arises, what to do when circular or rotary motion is to be changed into linear motion of complex nature or into oscillatory motion. This job is well accomplished by a machine part of a mechanical member, known as cam.

A **cam** may be defined as a rotating, reciprocating or oscillating machine part, designed to impart reciprocating and oscillating motion to another mechanical part, called a follower. A cam and follower have, usually, a line contact between them and as such they constitute a higher pair. The contact between them is maintained by an external force which is generally, provided by a spring or sometimes by the sufficient weight of the follower itself.



Cams are Used For

• Valve actuation in IC engines

• Motion control in machinery

• Force generation

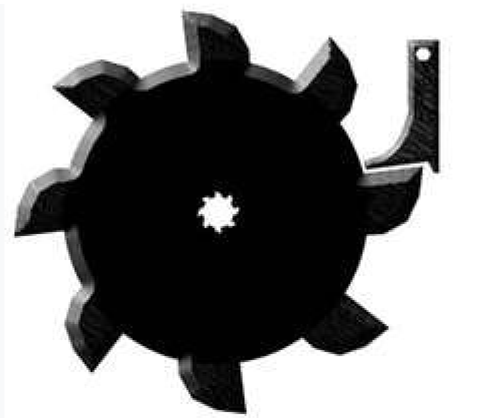
• Precise positioning

• Event timing

Train Ratchet Mechanism

A **ratchet** is a mechanical device that allows continuous linear or rotary motion in only one direction while preventing motion in the opposite direction. Ratchets are widely used in machinery and tools. The word *ratchet* is also used informally to refer to a ratcheting socket wrench.

Theory of operation



A ratchet moving in its "forward" direction

A ratchet consists of a round gear or a linear rack with teeth, and a pivoting, spring-loaded finger called a *pawl* (or *click*, in clocks and watches) that engages the teeth. The teeth are uniform but asymmetrical, with each tooth having a moderate slope on one edge and a much steeper slope on the other edge.

When the teeth are moving in the unrestricted (i.e. forward) direction, the pawl easily slides up and over the gently sloped edges of the teeth, with a spring forcing it (often with an audible 'click') into the depression between the teeth as it passes the tip of each tooth. When the teeth move in the opposite (backward) direction, however, the pawl will catch against the steeply sloped edge of the first tooth it encounters, thereby locking it against the tooth and preventing any further motion in that direction.

Because the ratchet can only stop backward motion at discrete points (i.e., at tooth boundaries), a ratchet does allow a limited amount of backward motion. This backward motion—which is limited to a maximum distance equal to the spacing between the teeth—is called backlash. In cases where backlash must be minimized, a smooth, toothless ratchet with a high friction surface such as rubber is sometimes used. The pawl bears against the surface at an angle so that any backward motion will cause the pawl to jam against the surface and thus prevent any further backward motion. Since the backward travel distance is primarily a function of the compressibility of the high friction surface, this mechanism can result in significantly reduced backlash.

Uses

Ratchet mechanisms are used in a wide variety of applications, including these:

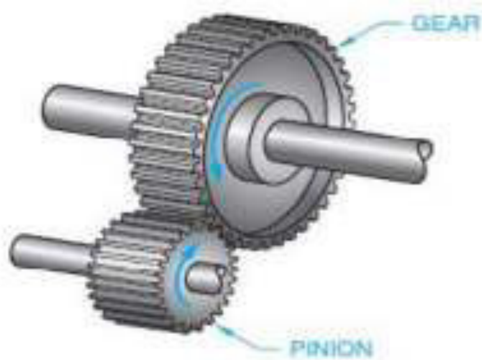
- Cable ties
- Capstans
- Caulking guns
- Clocks
- Freewheel (overrunning clutch)
- Grease guns
- Handcuffs
- Jacks
- Anti-rollback devices used in roller coasters
- Looms
- Slack lines
- Tie down straps
- Turnstiles
- Typewriters

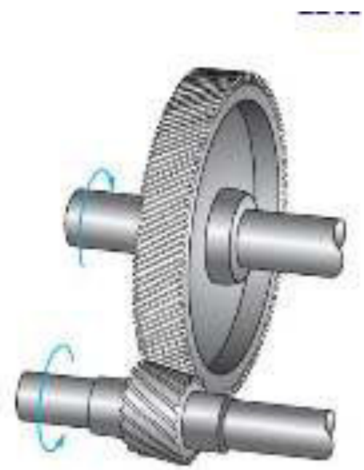
Lecture 7 Gears and its type, Belt, Bearing

Gears: Gears are machine elements that transmit motion by means of successively engaging teeth. The gear teeth act like small levers. Gears are mechanisms that mesh together via teeth and are used to transmit rotary motion from one shaft to another. Gears are defined by two important items:

radius and number of teeth. They are typically mounted, or connected to other parts, via a shaft or base.

Spur gears have teeth parallel to the axis of rotation and are used to transmit motion from one shaft to another, parallel, shaft.





Helical gears have teeth inclined to the axis of rotation. Helical gears are not as noisy, because of the more gradual engagement of the teeth during meshing.

Bevel gears have teeth formed on conical surfaces and are used mostly for transmitting motion between intersecting shafts.

Worms and worm gears The worm resembles a screw. The direction of rotation of the worm gear, also called the worm wheel, depends upon the direction of rotation of the worm and upon whether the worm teeth are cut right-hand or left-hand.

Application:

Gears are devices used throughout industry for a variety of mechanical machines and systems. Several types of gears are available and employed in a wide range of residential, commercial, and industrial applications, including:

- Aircrafts
- Automobiles
- Clocks
- Marine systems
- Material handling equipment
- Measuring instrumentation
- Power plants
- Pumps

Type of Gear	Common Industries and Applications
Spur	• Clocks • Pumps • Watering systems • Household appliances • Clothes washing and drying machines • Power plants • Material handling systems • Aerospace and aircrafts • Railways and trains
Helical	• Same as spur gears but with greater loads and higher speeds (see above) • Automobiles (transmission systems)
Bevel	• Pumps • Power plants • Material handling systems • Aerospace and aircrafts • Railways and trains • Automobiles
Worm	• Instruments • Lifts and elevators • Material handling systems • Automobiles (steering systems)
Rack and Pinion	• Weighing scales • Material handling and transfer systems • Railways and trains • Automobiles (steering systems)

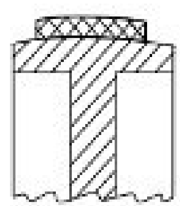
Belt: A **belt** is a loop of flexible material used to link two or more rotating shafts mechanically, most often parallel. Belts may be used as a source of motion, to transmit power efficiently or to track relative movement. Belts are looped over pulleys and may have a twist between the pulleys, and the shafts need not be parallel.

In a two pulley system, the belt can either drive the pulleys normally in one direction (the same if on parallel shafts), or the belt may be crossed, so that the direction of the driven shaft is reversed (the opposite direction to the driver if on parallel shafts). As a source of motion, a conveyor belt is one application where the belt is adapted to carry a load continuously between two points. The belt drive can also be used to change the speed of rotation, either up or down, by using different sized pulleys.

In case of belts, friction between the belt and pulley is used to transmit power. In practice, there is always some amount of slip between belt and pulleys, therefore, exact velocity ratio cannot be obtained. That is why, belt drive is not a positive drive. Therefore, the belt drive is used where exact velocity ratio is not required.

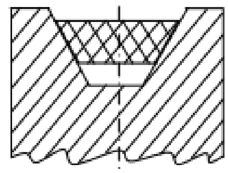
Types of Belt:

Flat belt: The flat belt is rectangular in cross-section as shown in Figure (a). The pulley for this belt is slightly crowned to prevent slip of the belt to one side. It utilizes the friction between the flat surface of the belt and pulley.



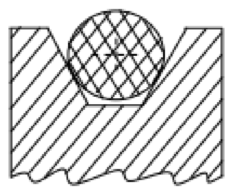
(a) Flat Belt and Pulley

V-belt: The V-belt is trapezoidal in section as shown in Figure (b). It utilizes the force of friction between the inclined sides of the belt and pulley. They are preferred when distance is comparative shorter. Several V-belts can also be used together if power transmitted is more.



(b) V-belt and Pulley

Circular belt or rope: The circular belt or rope is circular in section as shown in Figure (c). Several ropes also can be used together to transmit more power.



(c) Circular Belt or Rope Pulley

Application

1.Drives to beaters on conventional blow rooms. crossed flat-belt transmits drives from cylinder to flat on old cards.

2.Drives in high production cards such as the drive from motor to lickerin and cylinder; drive to cleaner roller at the delivery side; drive from motor to flat-stripper roller and crossed-flat-belt drive from cylinder to a pulley from where further drive proceeds through double stage speed reduction using worm and worm gears and a mechanical clutch to the driving-shaft of flat.

3.Drive to drafting rollers and other rolling elements on a single delivery drawing machine.

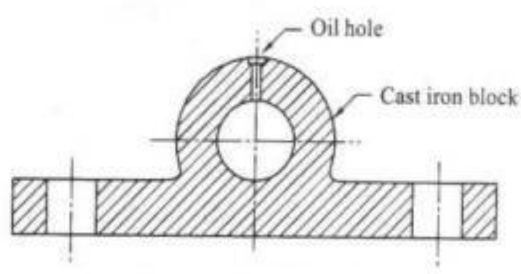
4.Drives to opening rollers, friction drums and take-off rollers on friction spinning machine.

5.Drive to rotor on rotor-spinning machine.

6.Main drive on draw-texturing machine.

7.Drive to creel-rollers of a high speed drawing machine.

Bearings: A bearing is machine part, which support a moving element and confines its motion. The supporting member is usually designated as bearing and the supporting member may be journal. Since there is a relative motion between the bearing and the moving element, a certain amount of power must be absorbed in overcoming friction, and if the surface actually touches, there will be a rapid wear.



Classification: Bearings are classified as follows:

1. Depending upon the nature of contact between the working surfaces:

a) Sliding contact bearings

b) Rolling contact bearings.

a) SLIDING BEARINGS:

• Hydro dynamically lubricated bearings

• Bearings with boundary lubrication

• Bearings with Extreme boundary lubrication.

• Bearings with Hydrostatic lubrication.

b) ROLLING ELEMENT BEARINGS:

♣ Ball bearings

♣ Roller bearings

♣ Needle roller bearings

2. Based on the nature of the load supported:

• Radial bearings - Journal bearings

• Thrust bearings

- Plane thrust bearings

- Thrust bearings with fixed shoes

- Thrust bearings with Pivoted shoes

• Bearings for combined Axial and Radial loads.

Lecture 8: Hydraulic and Pneumatic Actuation Systems: Overview

Actuators: are structures that transmit and support load. A joint is a connection between two or more links at their nodes and allows some motion between the connected links. Levers, cranks, connecting rods, pistons, sliders, pulleys, belts, and shafts are all examples of links. A sequence of joints and links is known as a *kinematics chain*. For a kinematics chain to transmit motion, one link must be fixed. The movement of one link produces predictable relative movement of other links in the chain. For mechatronics system actuation, one can use hydraulic, pneumatic, or electrical drives with kinematic chains.

Hydraulic and Pneumatic Actuators

The hydraulic actuation is powered by fluids. Fluids usually are pressurized oils. The operation of hydraulic actuators is generally similar, except in their ability to contain the pressure of the fluid. Hydraulic systems operate in a pressure range between 60 bars and 200 bars. The main constituents of a hydraulic system are the power supply unit, hydraulic fluid, direction control valve, linear and rotary actuators, and interaction components. The power supply unit is the most important component in a hydraulic pump. The pump drives the hydraulic fluid from a reservoir (tank) and delivers it through a system of lines in the hydraulic installation against the offering resistance.

Pressure should not build up in the flowing liquid which encounters a resistance. An oil filtration unit is also often contained in the power supply section. Impurities are often introduced into a system as a result of mechanical wear. For this reason, filters are installed in the hydraulic circuit to remove impurities in the form of dirt particles from the hydraulic fluids. Water and gases in oil can also act as disrupting factors, so special measures must be taken to remove them. Heaters and coolers are installed for conditioning the hydraulic fluids. The hydraulic fluid is the working medium that transfers the generated energy from the power supply unit to the drive section. Hydraulic fluids have a wide range of characteristics. Therefore, care needs to take to choose a fluid with characteristics that suit the application. Hydraulic fluids on a mineral oil base are generally used. Such fluids are called hydraulic oils.

Valves are the devices for controlling the energy flow. They can control and regulate the direction, pressure, and rate of the hydraulic fluid flow. Four types of valves are commonly used: direction control valves, pressure valves, flow control valves, and non-return valves. Direction control valves control the direction of flow of hydraulic fluid and thus the direction of motion and the positioning of the working components. Direction control valves may be actuated manually, mechanically, electrically pneumatically, or hydraulically. They convert and amplify signals and form an interface between the power control section and the signal control section. When labelling direction control valves, it is necessary to specify the number of ports, followed by the number of switching position. Direction control (DC) valves have at least two switching positions and two ports. Such a valve is designated as a 2/2 way valve. Pressure valves are used to influence the pressure in the complete hydraulic system.

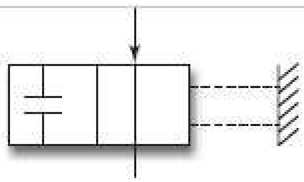
There are three main types of pressure control valves:

(1) Pressure regulating valves used to maintain a constant operating pressure in a circuit.

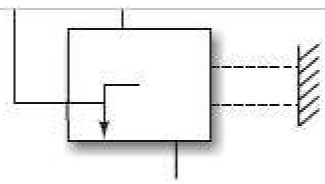
(2) Pressure sequence valves used to sense the pressure of an external line and give a signal when it reaches some preset value.

(3) Pressure limiting valves used as safety devices to limit the pressure in a circuit to below some safe value.

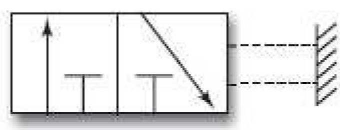
The flow control valve interacts with pressure valves to control the flow rate. They both make it possible to control or regulate the speed of motion of the power components. If the flow rate is constant, the division of flow must take place. This is generally achieved through the interaction of the flow control valve with the pressure valve. Non-return valves block the flow in one direction and permit free flow in the other direction. As there must not be any leakage from the closed direction, these valves always have a poppet design. In the case of a non-return valve, a distinction is made between ordinary non-return valves and piloted non-return valves. In the case of piloted non-return valves, flow in the blocked direction can be released by a signal. Figure shows schematic diagrams of various control valves.



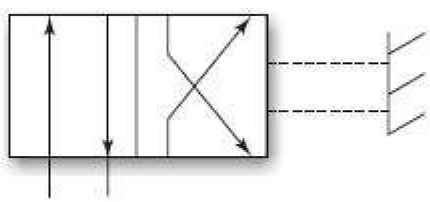
(a) 2/2 way valve



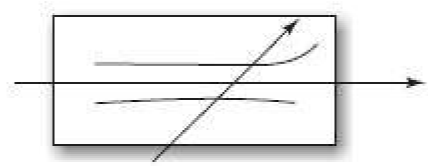
(b) Adjustable pressure valve



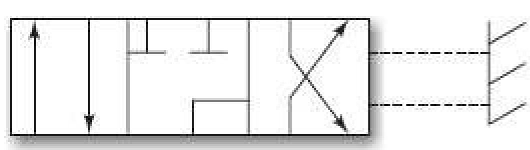
(c) 3/2 way valve



(d) 4/2 way valve



(e) Adjustable flow valves



(f) 4\3 way valve

Some advantages of hydraulic systems are as follows:

1. High load-carrying capacity

2. Low actuator inertia

3. Simple field design of system
4. High flexibility
5. Indefinite stocking capacity
6. High speed at high load
7. Very good strength

Some disadvantages of hydraulic system are as follows:

1. High cost of servo system
2. Need for high resolution feedback
3. Effect of oil temperature on performance
4. Non-availability of small actuators
5. Leakage
6. Low sensitivity
7. Difficulties in maintenance
8. Requirement of skilled workers to connect the system
9. Less natural frequency when actuator is in full value

Pneumatic Actuators: Pneumatic systems have been used for some considerable time for carrying out simplest mechanical tasks. In more recent times, such systems have played an important role in the development of pneumatic technology for automation through mechatronic systems. A pneumatic system can be broken down into a number of levels representing hardware and signal flow. Except the energy supply system, all other levels can be represented as in a hydraulic system. The air supply for a particular pneumatic application should be sufficient and of adequate quality. The air is compressed to 1/7th of its volume with the help of an air compressor and is delivered to an air distribution system in factory. To ensure proper quality of the air, air service equipment is utilized to prepare the air before it is applied to a control system. As a rule, all pneumatic components are designed for a maximum operating pressure of 8–10 bars. But it is recommended to operate the same between 5 and 6 bars for economic use. An air receiver is fitted to reduce pressure fluctuations. In normal operations, a compressor is fitted with the receiver when required, and the receiver is available as a reserve at all the times. This helps reduce the switching cycle of the compressor. If oil is required for a pneumatic system, then there should be a separate oil meter using air service unit. An air service unit is a combination of compressed-air filter, regulator, and lubricator. The compressed-air filter performs the job of filtering all contamination from the compressed air flowing through it as well as water which has already condensed. The purpose of the regulator is to keep the operating pressure virtually constant regardless of any fluctuation in line pressure and air consumption. Different types of sequence operations can be designed using sequence circuits associated with hydraulic systems. Pneumatic actuators are very useful and have the following advantages:

1. Compressed air is readily available in most factories.
2. Compressed air can be stored and conveyed easily to larger distances.
3. Compressed air need not be returned to sump.
4. Compressed air is clean.
5. Operation is fast and offers high load-carrying capacity.
6. Digital and logical switches can be prepared using fluidic circuits.
7. Pneumatic elements are simple and reliable.

Lecture 9: Pressure Control Valves

Pressure-control valves are used in hydraulic systems to control actuator force (force = pressure × area) and to determine and select pressure levels at which certain machine operations must occur. Pressure controls are mainly used to perform the following system functions:

- Limiting maximum system pressure at a safe level.
- Regulating/reducing pressure in certain portions of the circuit.
- Unloading system pressure.
- Assisting sequential operation of actuators in a circuit with pressure control.
- Any other pressure-related function by virtue of pressure control.
- Reducing or stepping down pressure levels from the main circuit to a lower pressure in a sub-circuit.

Pressure-control valves are often difficult to identify mainly because of the many descriptive names given to them. The function of the valve in the circuit usually becomes the basis for its name. The valves used for accomplishing the above-mentioned system functions are therefore given the following names:

- Pressure-relief valve.
- Pressure-reducing valve.
- Unloading valve
- Counterbalance valve.
- Pressure-sequence valve.
- Brake valve

Pressure-Relief Valves: Pressure-relief valves limit the maximum pressure in a hydraulic circuit by providing an alternate path for fluid flow when the pressure reaches a preset level. All fixed-volume pump circuits require a relief valve to protect the system from excess pressure. Fixed-volume pumps must move fluid when they turn. When a pump unloads through an open-center circuit or actuators are in motion, fluid movement is not a problem. A relief valve is essential when the actuators stall with the directional valve still in shifted position.

Unloading Valves: Unloading valves are pressure-control devices that are used to dump excess fluid to the tank at little or no pressure. A common application is in high-low pump circuits where two pumps move an actuator at a high speed and low pressure. The circuit then shifts to a single pump providing a high pressure to perform work. Another application is sending excess flow from the cap end of an oversize-rod cylinder to the tank as the cylinder retracts. This makes it possible to use a smaller, less-expensive directional control valve while keeping pressure drop low.

Directional control valves: Directional control valves are essentially used for distribution of energy in a fluid power system. They establish the path through which a fluid traverses a given circuit. For example they control the direction of motion of a hydraulic cylinder or motor. These valves are used to control the start, stop and change in direction of flow of pressurized fluid.

As the name implies directional control valves are used to control the direction of flow in a hydraulic circuit. They are used to extend, retract, position or reciprocate hydraulic cylinder and other components for linear motion. Valves contains ports that are external openings for fluid to enter and leave via connecting pipelines, The number of ports on a directional control valve (DCV

) is usually identified by the term " way". For example, a valve with four ports is named as four-way valve.

Directional control valves can be classified in a number of ways:

1. According to type of construction :
   - Poppet valves
   - Spool valves
2. According to number of working ports:
   - Two- way valves
   - Three – way valves
   - Four- way valves
3. According to number of Switching position:
   - Two – position
   - Three - position
4. According to Actuating mechanism:
   - Manual actuation
   - Mechanical actuation
   - Solenoid (Electrical) actuation
   - Hydraulic (Pilot) actuation
   - Pneumatic actuation
   - Indirect actuation

Cylinders:

Lecture 10: Rotary Actuators, Accumulators

Rotary Actuators: A rotary actuator is an actuator that produces a rotary motion or torque.

The simplest actuator is purely mechanical, where linear motion in one direction gives rise to rotation. The most common actuators are electrically powered; others may be powered pneumatically or hydraulically, or use energy stored in springs.

The motion produced by an actuator may be either continuous rotation, as for an electric motor, or movement to a fixed angular position as for servomotors and stepper motors. A further form, the torque motor, does not necessarily produce any rotation but merely generates a precise torque which then either causes rotation or is balanced by some opposing torque.

Electric actuators

Stepper motors are a form of electric motor that has the ability to move in discrete steps of a fixed size. This can be used either to produce continuous rotation at a controlled speed or to move by a controlled angular amount. If the stepper is combined with either a position encoder or at least a single datum sensor at the zero position, it is possible to move the motor to any angular position and so to act as a rotary actuator.

Servomotors

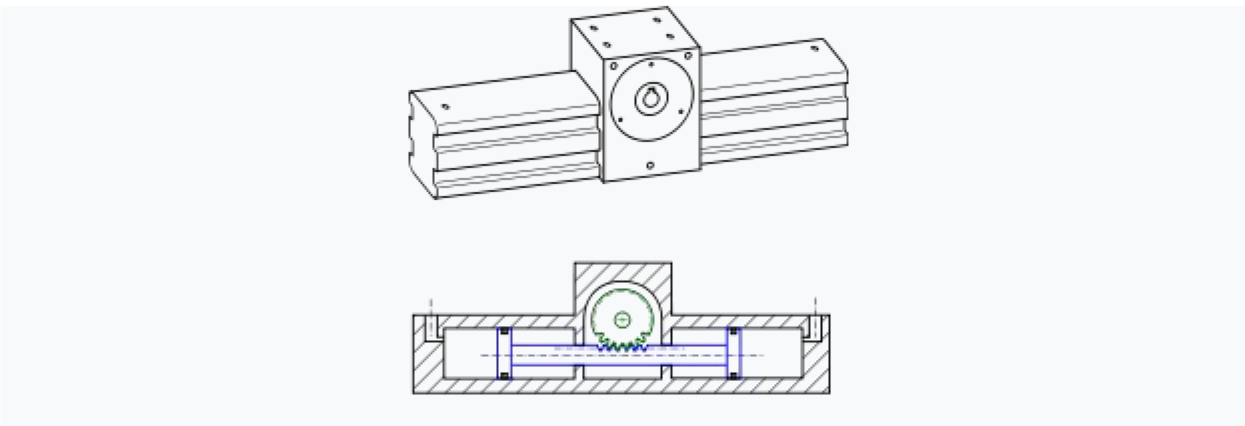
A servomotor is a packaged combination of several components: a motor (usually electric, although fluid power motors may also be used), a gear train to reduce the many rotations of the motor to a higher torque rotation, a position encoder that identifies the position of the output shaft and an inbuilt control system. The input control signal to the servo indicates the desired output position. Any difference between the position commanded and the position of the encoder gives rise to an error signal that causes the motor and geartrain to rotate until the encoder reflects a position matching that commanded.

A simple low-cost servo of this type is widely used for radio-controlled models.

Other types

A recent, and novel, form of ultra-lightweight actuator uses memory wire. As a current is applied, the wire is heated above its transition temperature and so changes shape, applying a torque to the output shaft. When power is removed, the wire cools and returns to its earlier shape.[1]

Fluid power actuator



Both hydraulic and pneumatic power may be used to drive an actuator, usually the larger and more powerful types. As their internal construction is generally similar (in principle, if not in size) they are often considered together as fluid power actuators.[2] Fluid power actuators are of two common forms: those where a linear piston and cylinder mechanism is geared to produce rotation (illustrated), and those where a rotating asymmetrical vane swings through a cylinder of two different radii. The differential pressure between the two sides of the vane gives rise to an unbalanced force and thus a torque on the output shaft.[2] Vane actuators require a number of sliding seals and the joints between these seals have tended to cause more problems with leakage than for the piston and cylinder type.

Vacuum actuators

Where a supply of vacuum is available, but not pneumatic power, rotary actuators have even been made to work from vacuum power. The only common instance of these was for early automatic windscreen wipers on cars up until around 1960. These used the manifold vacuum of a petrol engine to work a quarter-turn oscillating vane actuator. Such windscreen wipers worked adequately when the engine was running under light load, but they were notorious that when working hard at top speed or climbing a hill, the manifold vacuum was reduced and the wipers slowed to a crawl.[3]

Applications

Rotary actuators are used in a vast range of applications. These require actuators of all sizes, power and operating speed. These can range from zero power actuators that are only used as display devices, such as air core gauges. Others include valve actuators that operate pipeline and process valves in the petrochemical industry, through to actuators for large civil engineering projects such as sluice gates and dams. Examples are... Car wiper

Accumulators: Accumulators make it possible to store useable volumes of almost non-compressible hydraulic fluid under pressure. A hydraulic accumulator is a pressure storage reservoir in which an incompressible hydraulic fluid is held under pressure that is applied by an external source of mechanical energy. The external source can be an engine, a spring, a raised weight, or a compressed gas. An accumulator enables a hydraulic system to cope with extremes of demand using a less powerful pump, to respond more quickly to a temporary demand, and to smooth out pulsations. It is a type of energy storage device.

Accumulator types

No separator: Some original accumulators were high-pressure containers with a sight glass to show fluid level. They were filled approximately half with oil and half with nitrogen gas -- with no separation barrier between them. Before stopping the pump, a shut off valve at the accumulator discharge port was closed to prevent fluid and gas from escaping. This type of accumulator is not used on new circuits today, but there still are many in service.

Gas-charged bladder: Many accumulators now use a rubber bladder to separate the gas and liquid. A poppet valve in the discharge port keeps the bladder from extruding when the pump is off. The original design was the bottom-repair style, shown on the left in Figure 16-1. It is still offered by most manufacturers. The top-repair style on the right is now available and makes bladder replacement simple and fast.

Gas-charged piston: The gas-charged piston accumulator has a free-floating piston with seals to separate the liquid and gas. It operates and performs similarly to the bladder type, but has some advantages in certain applications. A gas-charged piston accumulator can cost twice as much as an equal-sized bladder type.

Spring-loaded piston: A spring-loaded piston accumulator is identical to a gas-charged unit, except that a spring forces the piston against the liquid. Its main advantage is that there is no gas to leak. A main disadvantage is that this design is not good for high pressure and large volume.

Weight loaded: All gas-charged accumulators lose pressure as fluid discharges. This is because the nitrogen gas was compressed by incoming fluid from the pump and the gas must expand to push fluid out. The weight-loaded accumulator in Figure 16-1 does not lose pressure until the ram bottoms out. Thus 100% of the fluid is useful at full system pressure. The major drawback to weight-loaded accumulators is their physical size. They take up a lot of space and are very heavy if much volume is required. They work well in central hydraulic systems because there usually is room for them in the power unit area. However, central hydraulic systems are falling out of favor, so only a few facilities use weight-loaded accumulators. (Rolling mills are one application where space to place large items is not a problem.) Note that there is often a long dwell time to fill these monsters.

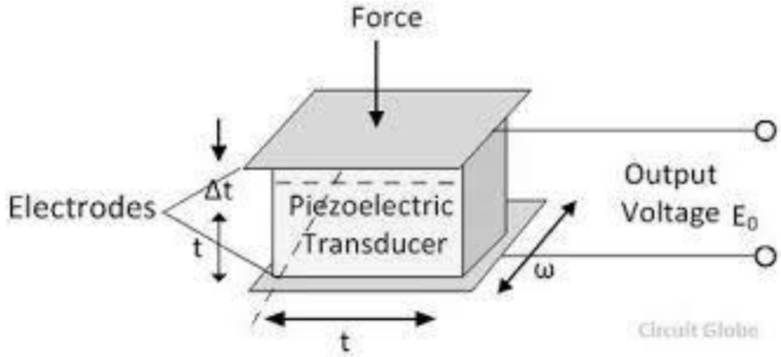
Diaphragm accumulators: There are also diaphragm accumulators with resilient or metal diaphragms. They are used where the stored volume is small.

Why are accumulators used?

To supplement pump flow: The most common use for accumulators is to supplement pump flow. Some circuits require high-volume flow for a short time and then use little or no fluid for an extended period. Generally speaking, when half or more of the machine cycle is not using pump flow, the application is a likely candidate for an accumulator circuit.

DIAGRAMS FOR UNIT 5

1. PIEZOELECTRIC TRANSDUCER:



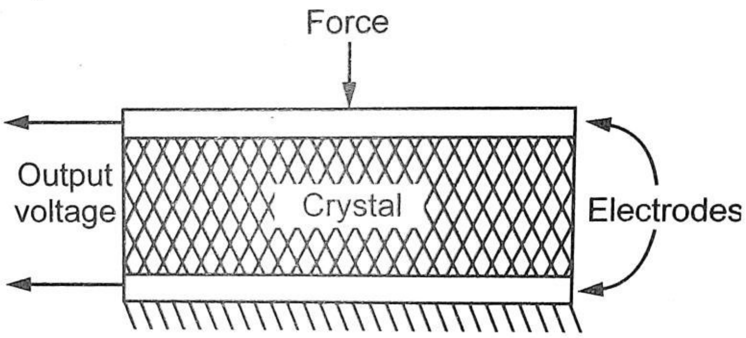


Fig. 9.16. Piezo-electric transducer

2. PHOTO-EMISSIVE TRANSDUCER:

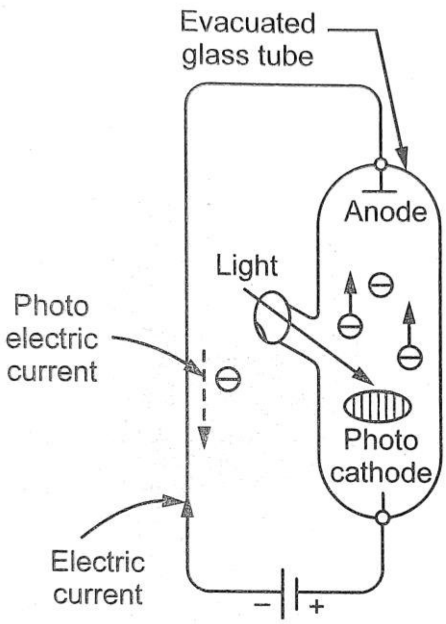


Fig. 9.17. Photo tube

3. PHOTO CONDUCTIVE AND PHOTO VOLTAIC CELLS:

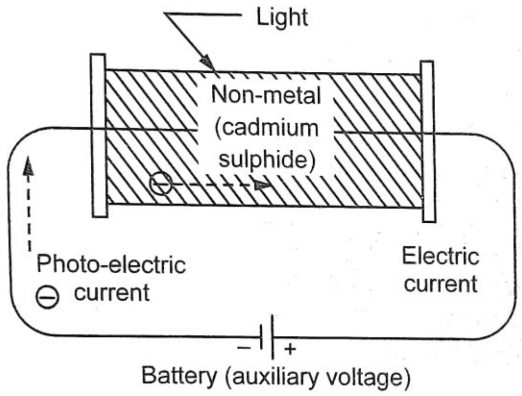


Fig. 9.19. Photo-conductive cell

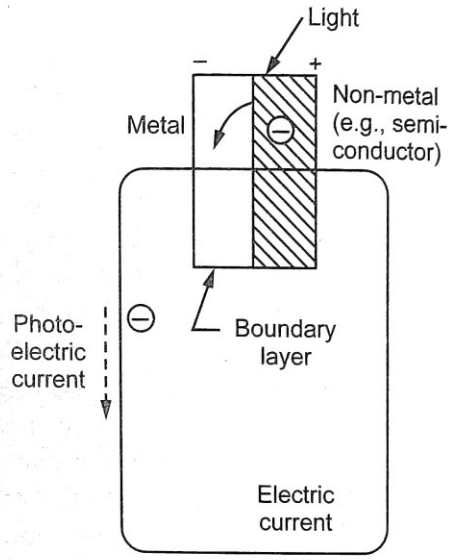


Fig. 9.20. Photo-voltaic cell

4.

5. POTENTIOMETERS:

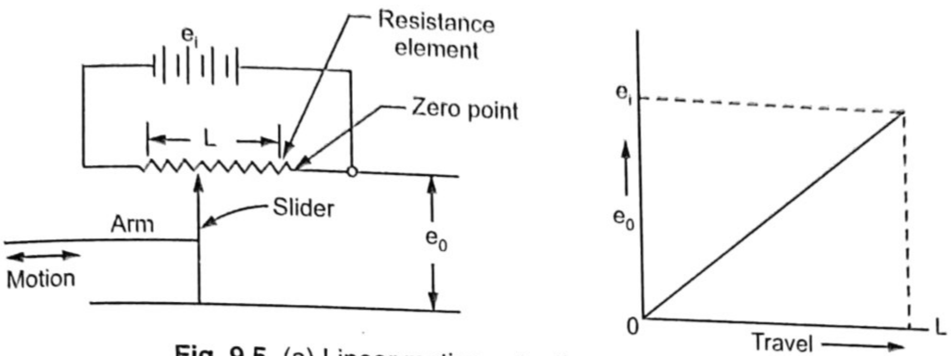


Fig. 9.5. (a) Linear motion potentiometer schematics

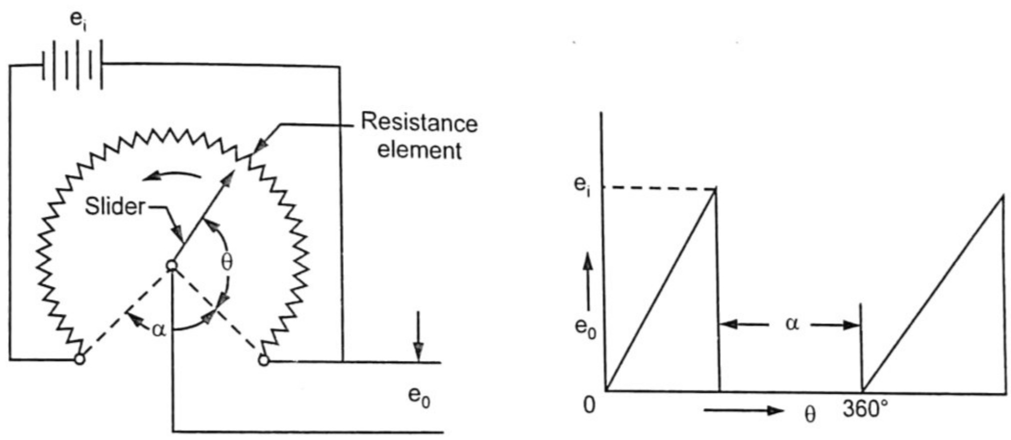


Fig. 9.5. (b) Rotary motion potentiometer schematics

6. LINEAR VARIABLE DIFFERENTIAL TRANSFORMER(LVDT):

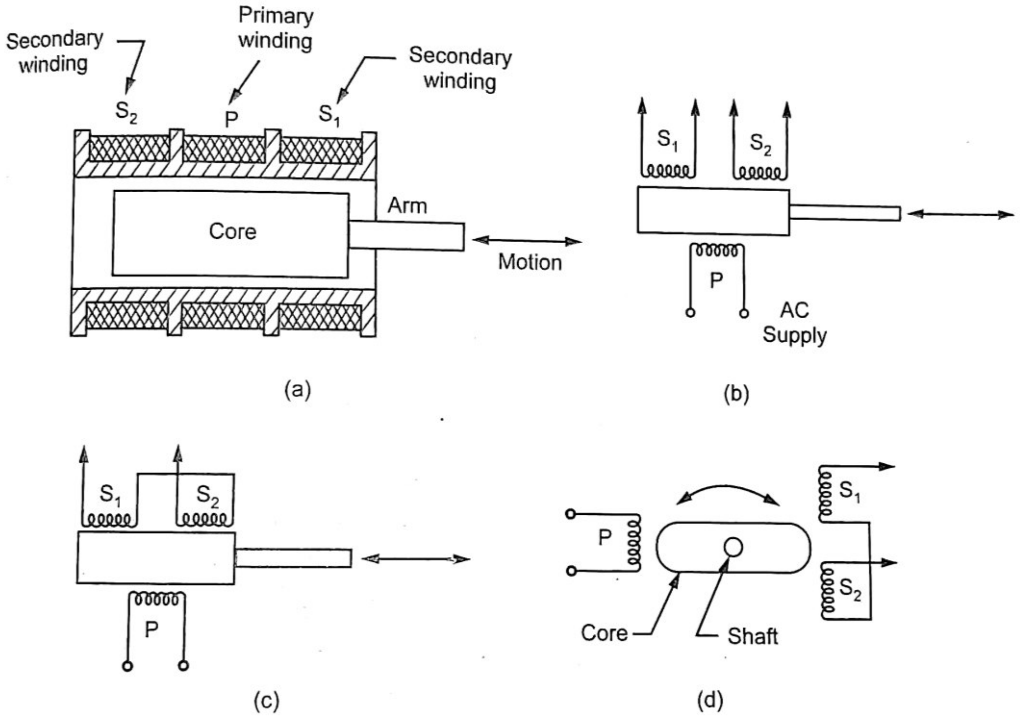


Fig. 9.12. Variable differential transformer

7. INDUCTANCE TYPE TRANSDUCER:

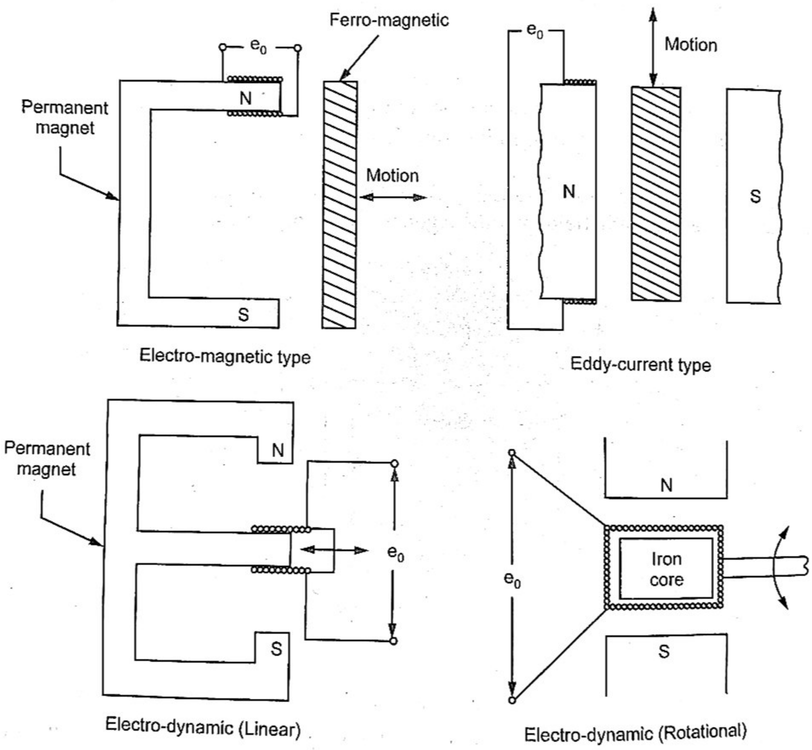


Fig. 9.7. Self-generating variable inductance transducers

8. HALL EFFECT TRANSDUCER:

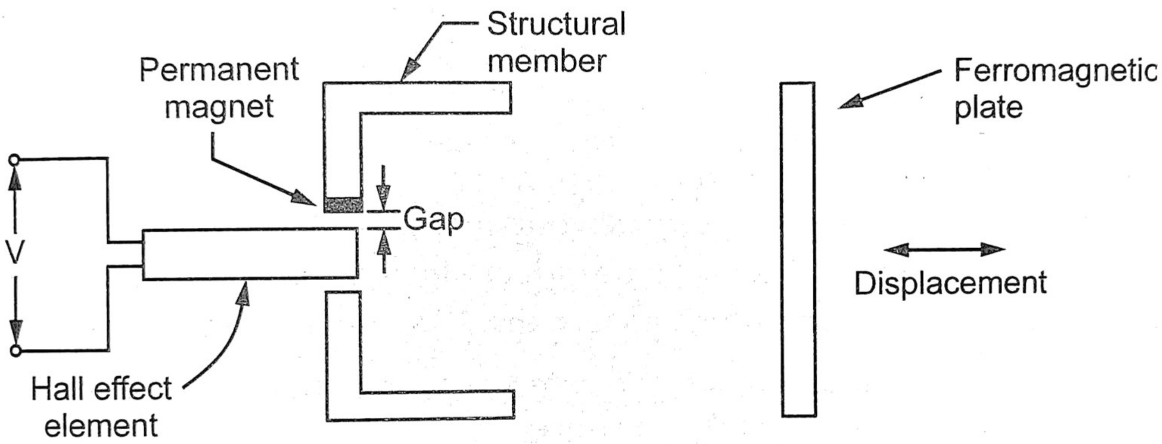


Fig. 9.22. Hall effect displacement transducer

9. 4-WAY DIRECTIONAL VALVE:

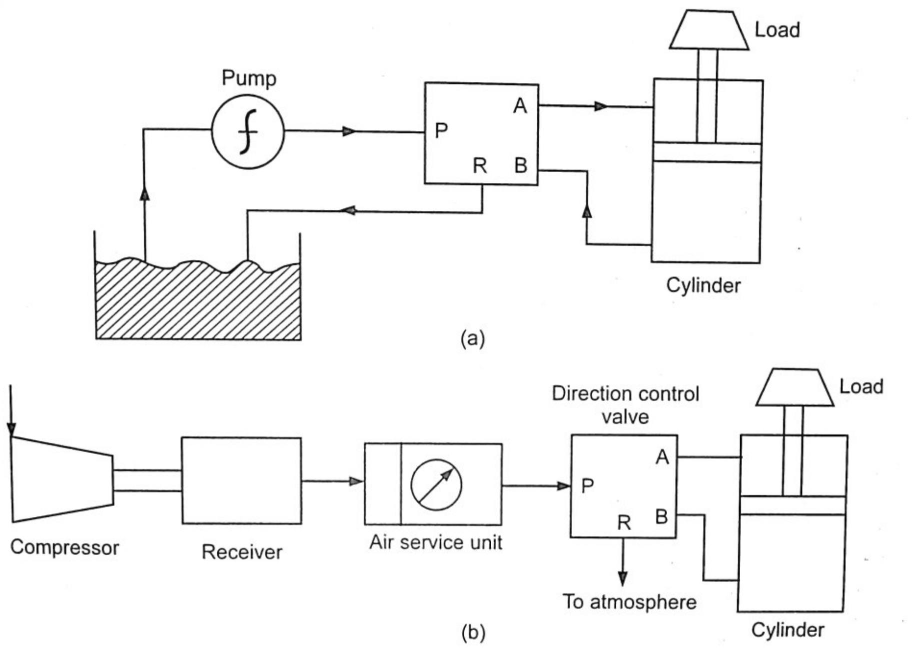
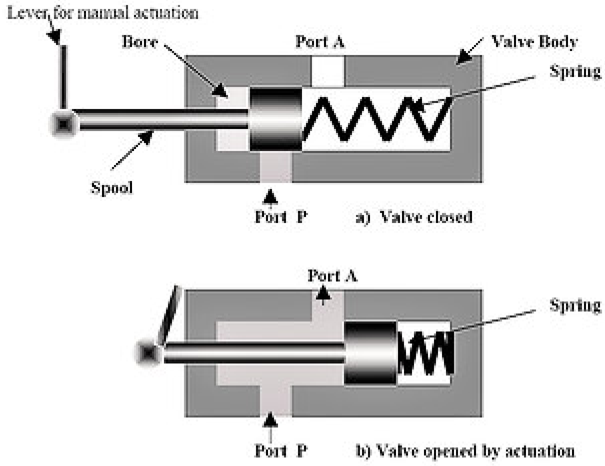


Fig. 10.63. Fig. 4-way directional valve

These valves are generally used to operate cylinders and fluid motors in both directions hydraulically. These valves are available with a choice of actuation, manual, mechanical, solenoid, pilot & pneumatic. Four-way valve comes with two or three positions. One should note that the graphical symbol of the valve shows only one tank port even though the physical design may have two as it is only concerned with the function. Three- position, four-way DCV have different varieties of centre configurations. The common varieties are the open centre, closed centre, tandem centre, floating centre, & regenerative centre with open, closed and tandem are the three basic types

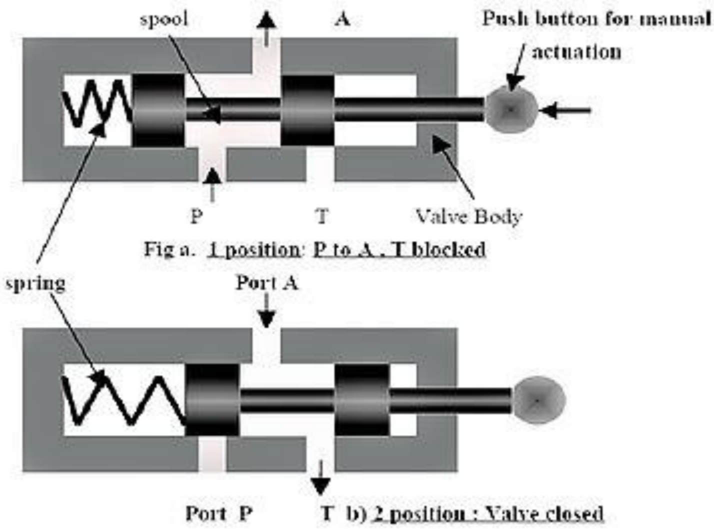
2-WAY Valves:

There is normally closed and normally opened two-way valves, external actuation is needed to do the position change of the valve actuator. A flow path is established or closed when the actuator is moved. These valves are also called as on-off valves.



3-WAY Valves:

A three-way valve has two plug actuators each plug controls the flow in two different ways. The two plug positions are shown in the above figure. When one of the plugs closes a node other one opens the other node. This normally closed valve neutralize the position of the actuator closing both the node to close the valve. Three-way directional valves are available for manual, mechanical, pilot, solenoid actuation.



10. RELIEF VALVE:

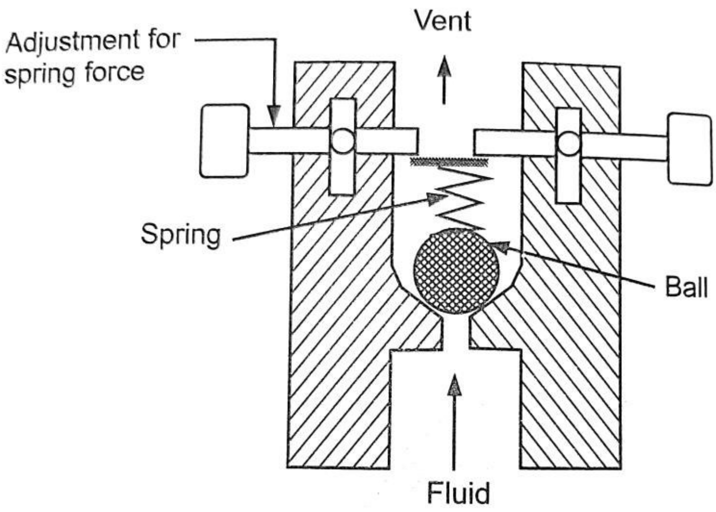


Fig. 10.62. Relief valve

11. HYDRAULIC ACCUMULATOR TYPES:

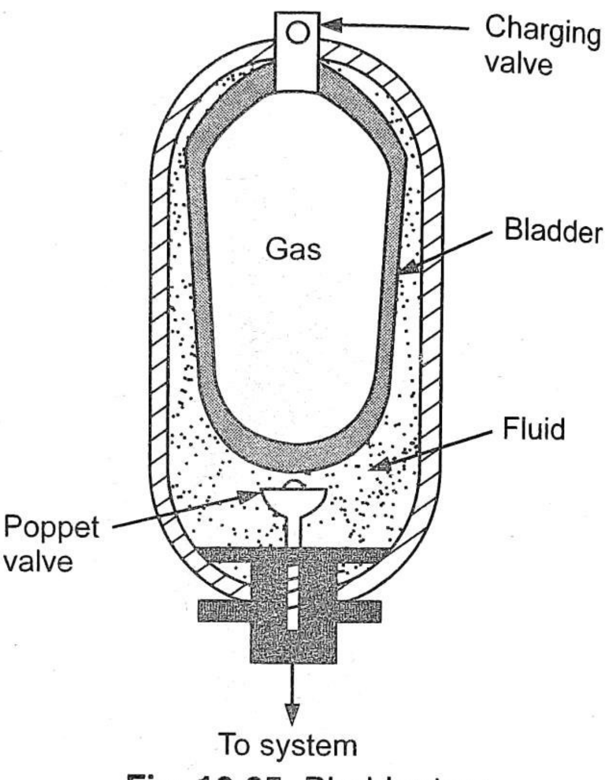


Fig. 10.65. Bladder type accumulator

12. HYDRAULIC ACTUATION SYSTEM:

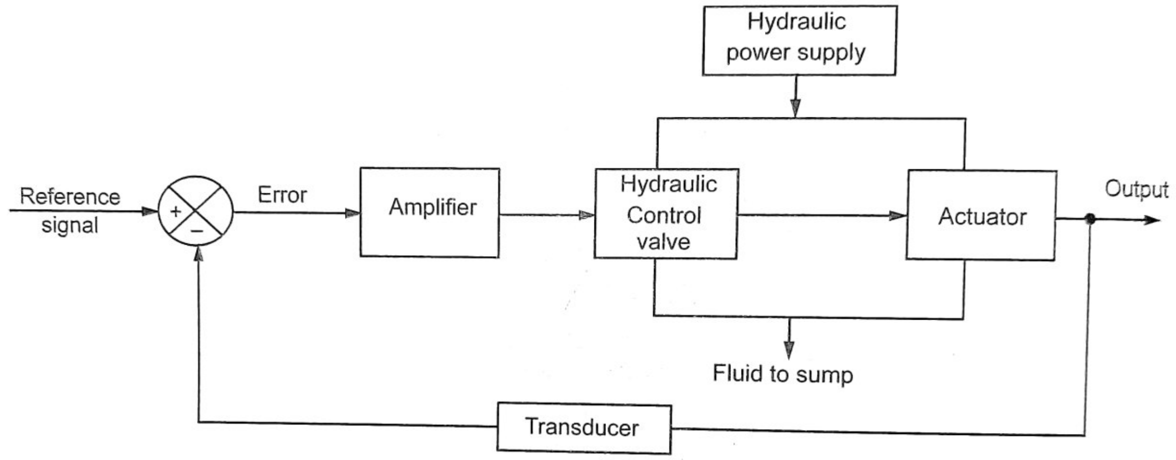


Fig. 10.75. Schematics of a hydraulic actuating system

13. HYDRAULIC ACTUATOR TYPE:

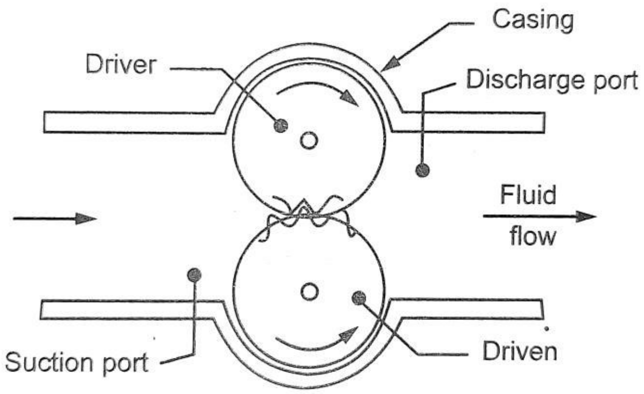


Fig. 10.77. Gear pump

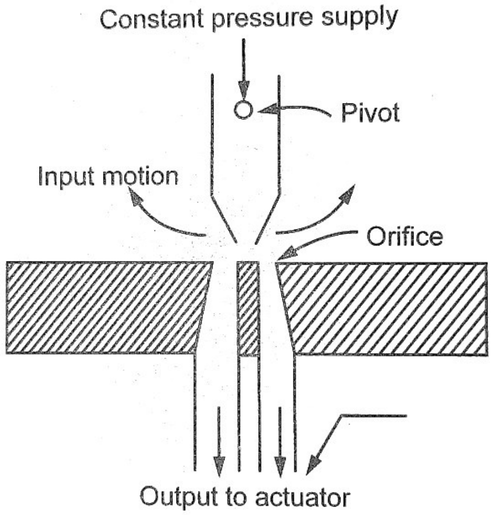


Fig. 10.82. Jet-pipe valve

14. PNEUMATIC ACTUATION SYSTEM:

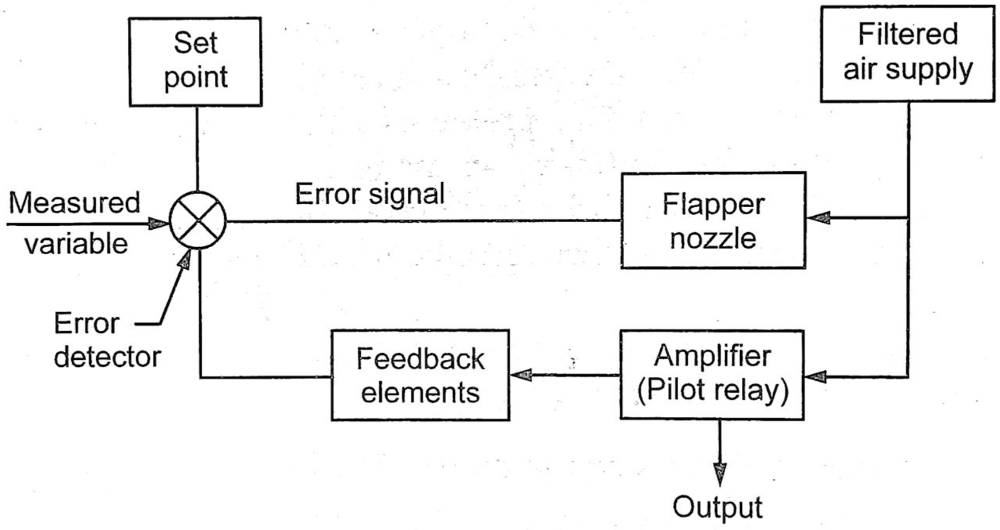


Fig. 10.83. Schematics of a pneumatic actuating system

15. PNEUMATIC ACTUATOR TYPE:

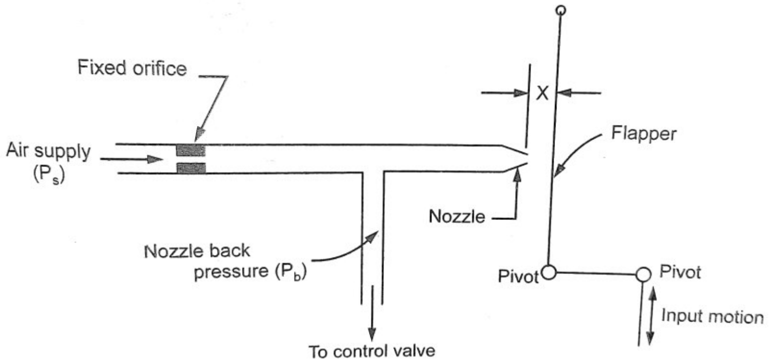


Fig. 10.85. Pneumatic nozzle flapper

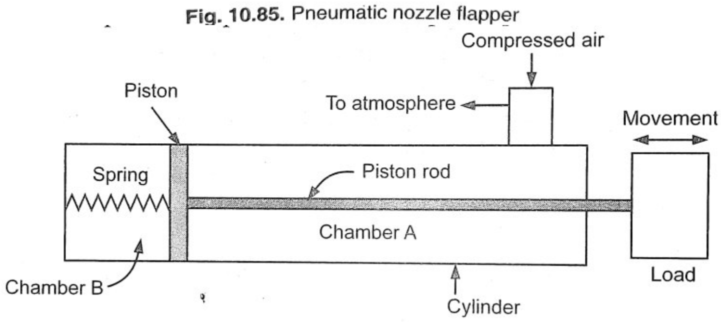


Fig. 10.88. Single acting pneumatic actuator

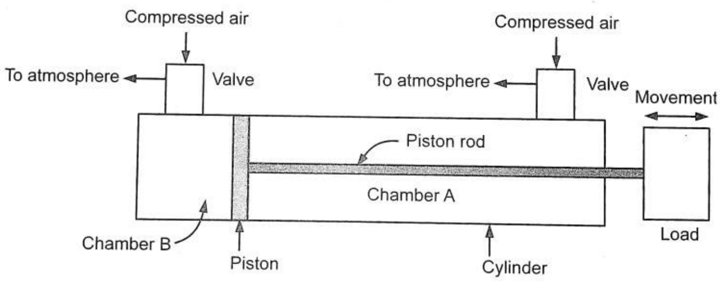


Fig. 10.89. Double acting pneumatic actuator