Course Material
ESME-401
Elements of Mechanical Engineering

For UG Programme

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DEPARTMENT OF MECHANICAL ENGINEERING
SANT LONGOWAL INSTITUTE OF ENGINEERING & TECHNOLOGY, LONGOWAL
(*Deemed to-be University*)

Syllabus

L	T	P	Credits	Weekly Load
2	1	0	3	3

COURSE OUTCOMES:

After successful completion of course, the students should be able to

CO1: Learn about the basic concepts and laws of thermodynamics.

CO2: Apply laws of thermodynamics on various engineering devices.

CO3: Learn various mechanical properties of engineering materials under different types of loads.

CO4: Learn about different mechanisms, inversions and their engineering applications.

CO5: Develop problem solving abilities related to mechanical engineering fundamentals.

CO/PO Mapping: (Strong(3) / Medium(2) / Weak(1) indicates strength of correlation):

COs	Programme Outcomes (POs)												Programme Specific Outcomes		
	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PSO1	PSO2	PSO3
CO1	3	1	1	-	1	1	1	1	1	1	-	1	1	-	2
CO2	3	3	2	1	1	2	2	1	2	1	-	1	2	2	2
CO3	3	3	2	2	2	2	2	1	1	1	-	1	2	2	2
CO4	3	3	2	2	2	1	1	1	1	1	-	1	2	2	2
CO5	3	3	3	2	2	2	1	1	3	2	1	2	2	2	2
Avg.	3	2.6	2	1.75	1.6	1.6	1.4	1	1.6	1.2	1	1.2	1.8	2	2

Sant Longowal Institute of Engineering and Technology, Longowal

Department of Mechanical Engineering

ESME-401: Elements of Mechanical Engineering

Syllabus

L	T	P	Credits	Weekly Load
2	1	0	3	3

Unit	Main Topics	Course outlines	Lecture(s)
Unit-1	Basic Concept of Thermodynamics	Definition, Thermodynamic system, boundary and surroundings, Thermodynamic property, Thermodynamic processes, Thermodynamic cycle and its concept, Energy and its forms, Ideal gas and characteristic gas equation, Zeroth law of thermodynamics.	06
	First Law of Thermodynamics and its Applications	Definition, Essence and corollaries of the first law, expressions for first law applicable to a process and cycle, concept of internal energy, enthalpy, total energy, specific heats, Closed and open systems, analysis of non-flow and flow processes for an ideal gas under constant volume, constant pressure, constant temperature, adiabatic and polytropic conditions, Analysis of free expansion and throttling processes, analysis of first law to steady flow energy equation and its applications to various engineering devices.	09
	Second Law of Thermodynamics	Limitations of first law, statements of second law and their equivalence, heat engine, heat pump and refrigerator. Philosophy of Carnot cycle and its consequences, Carnot theorem for Heat engine, refrigerator and heat pump, Clausius inequality, philosophy and concept of entropy, Third law of Thermodynamics.	09
Unit-2	Mechanics of Solids	Introduction, stress and strain, Hook's Law, longitudinal and lateral strain, Poisson's ratio, Stress strain diagram for ductile and brittle materials, Factor of safety, strain energy and resilience, Sudden and impact load, Stresses in bars, Thermal stresses, Elastic constants and their significance, relations between Elastic constants.	18
	Mechanism and Simple Machines	Introduction, Mechanisms and their concept, Definition of element, link, kinematic chain, mechanism, machine, Examples of mechanisms and their applications, Concept of Basic machines, Law of Lifting Machine, Different systems of pulleys and wheels.	08
	Engineering Materials	Materials and Engineering, Classification of Engineering Materials, Mechanical Properties of Engineering Materials, Various properties and Industrial applications of metals (ferrous: cast iron, tool steels, stainless steels and non-ferrous: Aluminum, brass, bronze), polymers, ceramics, composites, smart materials, Conductors, Semiconductors and insulators.	08

Recommended Books:

1. Nag P.K. Engineering Thermodynamics, Mc. Graw Hill.
2. Yadav R., Thermodynamics and Heat Engines, Central Publishing House, Allahabad
3. Singh V.P., Theory of Machines, Dhanpat Rai and Company, New Delhi.
4. Jindal U.C., Engineering Mechanics, Part-I, Galgotia Publications Pvt.Ltd. , New Delhi.

Thermodynamics

It is the branch of science that deals with energy interactions and its effects on the system and surroundings

Energy

It can measured as the ability to effect changes in the system

System

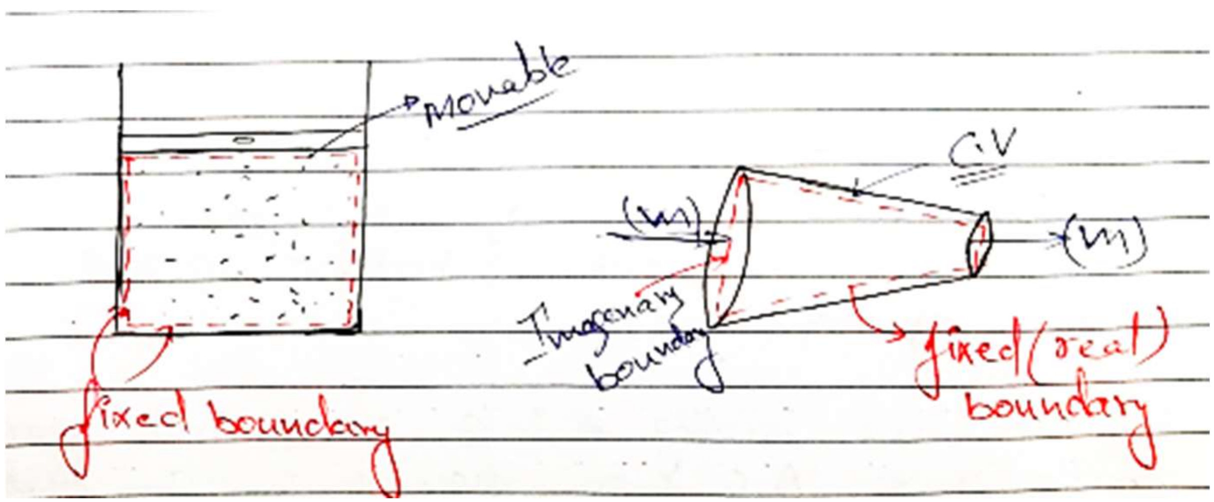
It is fixed mass or a fixed region in space where our study is focussed

Surroundings

Everything except the system is called surroundings.

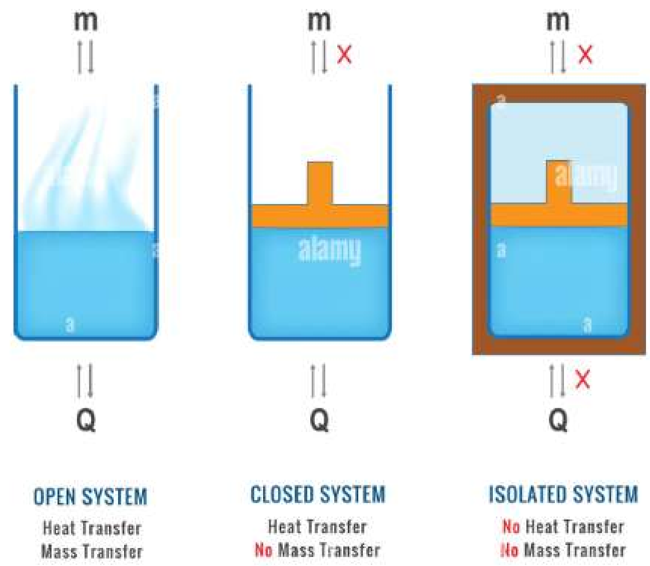
Boundary

A real or imaginary surface that separates the system from the surroundings. Boundary can be fixed or moveable.



Types of Systems:

1. Closed system: Exchange energy not mass with surroundings
2. Open system : Exchange energy and mass with surroundings
3. Isolated system: Does not exchange energy as well mass



Property

Any characteristics of the system is called property of the system.

Intensive properties: Independent of mass of the system under study such as density, temperature and all specific properties.

Extensive properties: Dependent on mass of the system under consideration such as volume, energy, enthalpy etc.

Salient features of Property

- Point function
- Exact differential
- Independent of past history

State, Process and Path

The condition of the system is called **state** of the system. State depends on properties and change in even one property changes the state of the system.

The change in the state of the system is called **process**.

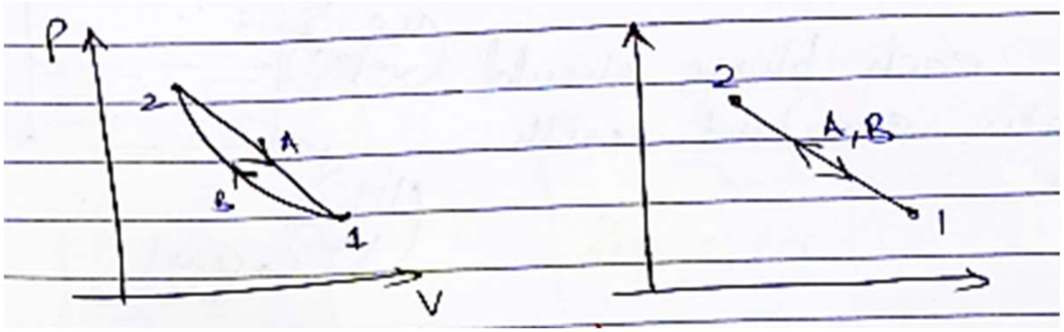
The infinite states of the system through which the system passes to reach the final state is called process **path**.

Every system has certain characteristics by which its physical condition may be described, e.g., volume, temperature, pressure, etc. Such characteristics are called properties of the system. These are all macroscopic in nature. When all the properties of a system have definite values, the system is said to exist at a definite state. Properties are the coordinates to describe the state of a system. They are the state variables of the system. Any operation in which one or more of the properties of a system changes is called a change of state. The succession of states passed through during a change of state is called the path of the change of state. When the path is completely specified, the change of state is called a process, e.g., a constant pressure process.

A thermodynamic cycle is defined as a series of state changes such that the final state is identical with the initial state.

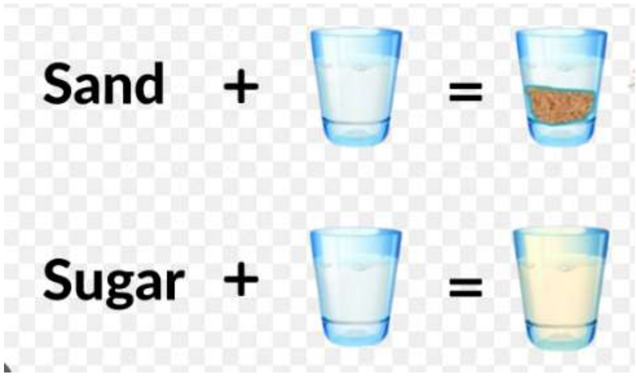
Process:

- Quasistatic (very slow—represented by solid line)
- Non-quasistatic (Not slow- dashed line)
- Reversible (can be reversed through the same path without leaving any effect on system and surroundings). A quasistatic process is always reversible however vice versa is not true.
- Irreversible process



HOMOGENEOUS AND HETEROGENEOUS SYSTEMS

A quantity of matter homogeneous throughout in chemical composition and physical structure is called a phase. Every substance can exist in any one of the three phases, viz., solid, liquid and gas. A system consisting of a single phase is called a homogeneous system, while a system consisting of more than one phase is known as a heterogeneous system.



Unit -1
Basic Concepts of Thermodynamics

THERMODYNAMIC EQUILIBRIUM

A system is said to exist in a state of thermodynamic euilibrium when no change in any macroscopic property is registered, if the system is isolated from its surroundings. An isolated system always reaches in course of time a state of thermodynamic equilibrium and can never depart from it spontaneously. Therefore, there can be no spontaneous change in any macroscopic property if the system exists in an equilibrium state. Thermodynamics studies mainly the properties of physical systems that are found in equilibrium states. A system will be in a state of thermodynamic equilibrium, if the conditions for the following three types of equilibrium are satisfied:

(a) Mechanical equilibrium

(b) Chemical equilibrium

(c) Thermal equilibrium

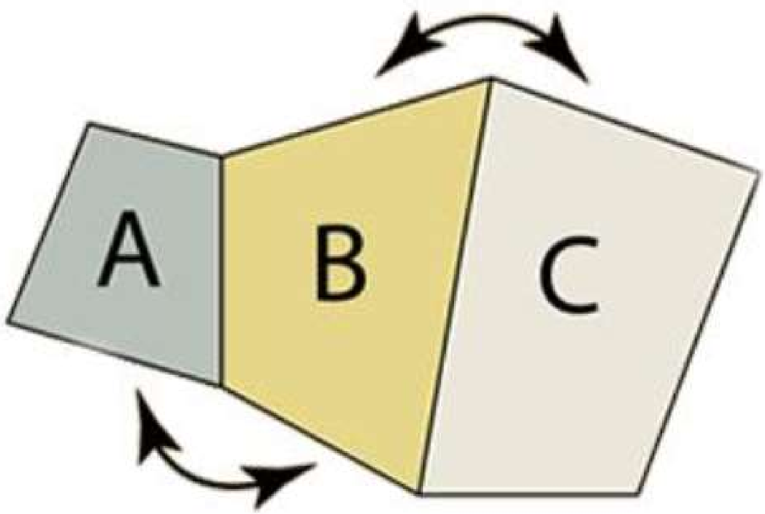
(d) Phase Equilibrium

In the absence of any unbalanced force within the system itself and also between the system and the surroundings, the system is said to be in a state of mechanical equilibrium. If an unbalanced force exists, either the system alone or both the system and the surroundings will undergo a change of state till mechanical equilibrium is attained.

If there is no chemical reaction or transfer of matter from one part of the system to another, such as diffusion or solution, the system is said to exist in a state of chemical equilibrium. When a system existing in mechanical and chemical equilibrium is separated from its surroundings by a diathermic wall (diathermic means which allows heat to flow') and if there is no spontaneous change in any property of the system, the system is said to exist in a state of thermal equilibrium. When this is not satisfied, the system will undergo a change of state till thermal equilibrium is restored.

ZEROTH LAW OF THERMODYNAMICS

When a body A is in thermal equilibrium with a body B, and also separately with a body C, then B and C will be in thermal equilibrium with each other. It is the basis of temperature measurement.

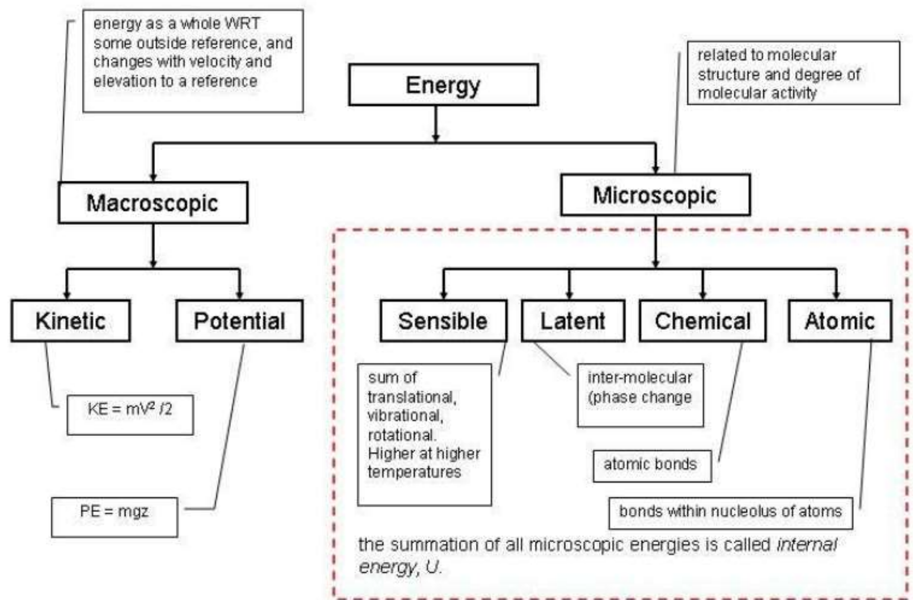


DIFFERENT FORMS OF STORED ENERGY

The symbol E refers to the total energy stored in a system. Basically there are two modes in which energy
may be stored in a system:
(a) Macroscopic energy mode
(b) Microscopic energy mode

The macroscopic energy mode includes the macroscopic kinetic energy and potential energy of a system.

The microscopic energy mode refers to the energy stored in the molecular and atomic structure of the system, which is called the molecular internal energy or simply internal energy, customarily denoted by the symbol U.



$$E = U + KE + PE \qquad (kJ)$$

- The sum of translational, vibrational, and rotational energies of molecules is the kinetic energy of molecules, and it is also called the ***sensible energy.*** At higher temperatures, system will have higher sensible energy.
- Internal energy associated with the phase of a system is called ***latent heat*.** The intermolecular forces are strongest in solids and weakest in gases.
- The internal energy associated with the atomic bonds in a molecule is called ***chemical* or *bond energy*.**
- The tremendous amount of energy associated with the bonds within the nucleolus of atom itself is called ***atomic energy***

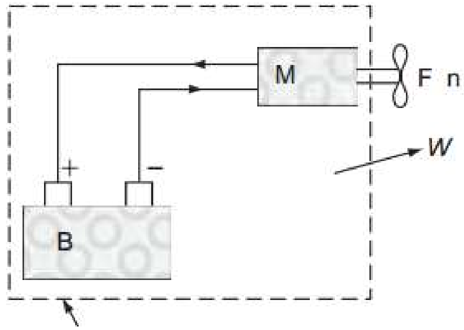
Energy interactions

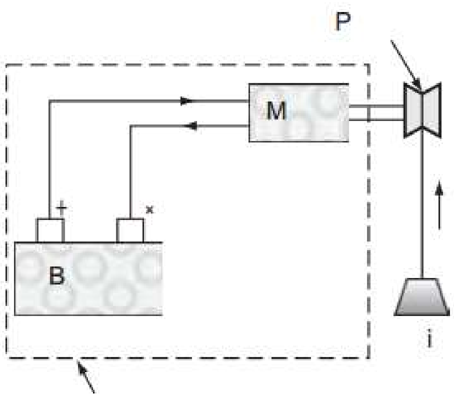
A closed system and its surroundings can interact in two ways:

(a) by work transfer
(b) by heat transfer.

The work is done by a force as it acts upon a body moving in the direction of the force.

In thermodynamics, work transfer is considered as occurring between the system and the surroundings. Work is said to be done by a system if the sole effect on things external to the system can be reduced to the raising of a weight. The weight may not actually be raised, but the net effect external to the system would be the raising of a weight.



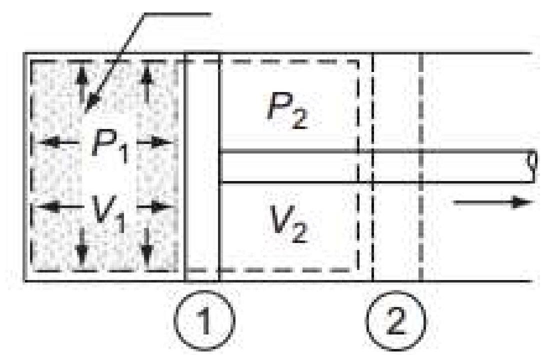


Work

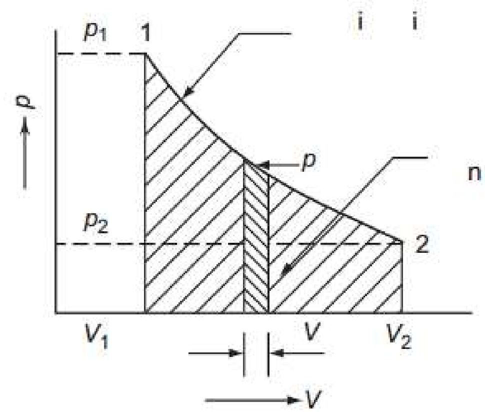
When work is done by a system, it is arbitrarily taken to be positive, and when work is done on a system, it is taken to be negative. The symbol W is used for work transfer.

pdV–WORK OR DISPLACEMENT WORK

Let the gas in the cylinder be a system having initially the pressure p1 and volume V1. The system is in thermodynamic equilibrium, the state of which is described by the coordinates p1, V1. The piston is the only boundary which moves due to gas pressure. Let the piston move out to a new final position 2, which is also a thermodynamic equilibrium state specified by pressure p2 and volume V2. At any intermediate point in the travel of the piston, let the pressure be p and the volume V. This must also be an equilibrium state, since macroscopic properties p and V are significant only for equilibrium states. When the piston moves an infinitesimal distance dl, and if a' be the area of the piston, the force F acting on the piston F = p.a. and the infinitesimal amount of work done by the gas on the piston



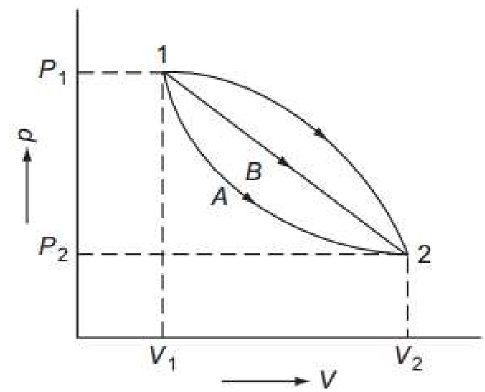
$$\text{đ}W = F \cdot dl = padl = pdV \qquad W_{1-2} = \int_{V_1}^{V_2} pdV$$



where *dV* = *adl* = infinitesimal displacement volume. The differential sign in *dW* with the line drawn at the top of it will be explained later. When the piston moves out from position 1 to position 2 with the volume changing from V_1 to V_2, the amount of work *W* done by the system will be

The magnitude of the work done is given by the area under the curve 1–2, as shown in Fig. Since p is at all times a thermodynamic coordinate, all the states passed through by the system as the volume changes from V_1 to V_2 must be equilibrium states, and the path 1–2 must be quasi static. The piston moves infinitely slowly so that every state passed through is an equilibrium state. The integration ∫ pdV can be performed only on a quasi static path.

Path Function and Point Function



With reference to Fig. 3.6, it is possible to take a system from state 1 to state 2 along many quasi-static paths, such as A, B or C. Since the area under each curve represents the work for each process, the amount of work involved in each case is not a function of the end states of the process, and it depends on the path the system follows in going from state 1 to state 2. For this reason, work is called a path function, and d W is an inexact or imperfect differential. Thermodynamic properties are point functions, since for a given state, there is a definite value for each property. The change in a thermodynamic property of a system in a change of state is independent of the path the system follows during the change of state, and depends only on the initial and final states of the system. The differentials of point functions are exact or perfect differentials, and the integration is simply

$$\int_{V_1}^{V_2} dV = V_2 - V_1$$

The change in volume thus depends only on the end states of the system irrespective of the path the system follows. On the other hand, work done in a quasi-static process between two given states depends on the path followed.

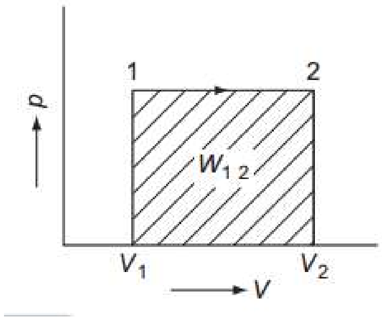
$$\int_1^2 dW \neq W_2 - W_1$$

$$\int_1^2 dW = W_{1-2} \text{ or } {}_1W_2$$

pdV-Work in Various Quasi-Static Processes

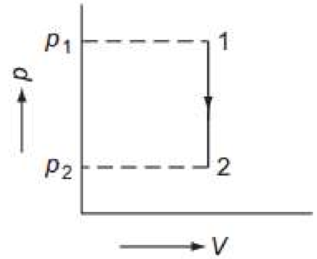
1. Constant Pressure process (Isobaric)

$$W_{1-2} = \int_{V_1}^{V_2} p\mathrm{d}V = p(V_2 - V_1)$$



2. Constant Volume process (Isochoric)

$$W_{1-2} = \int p\mathrm{d}V = 0$$



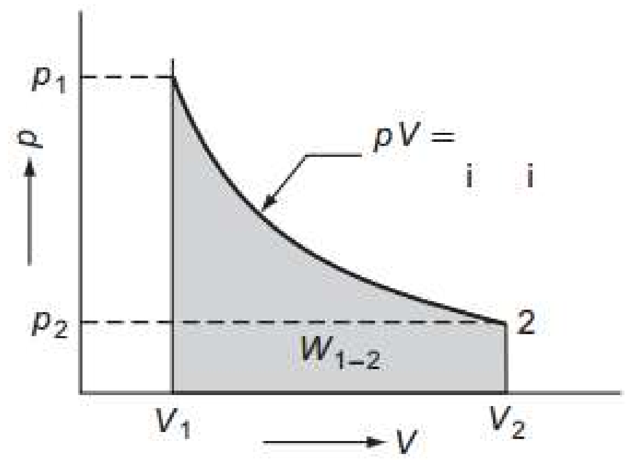
3. Process in which *pV = C*

$$W_{1-2} = \int_{V_1}^{V_2} p\mathrm{d}V, \quad pV = p_1 V_1 = C$$

$$p = \frac{(p_1 V_1)}{V}$$

$$W_{1-2} = p_1 V_1 \int_{V_1}^{V_2} \frac{\mathrm{d}V}{V} = p_1 V_1 \ln \frac{V_2}{V_1}$$

$$= p_1 V_1 \ln \frac{p_1}{p_2}$$



4. Process in which $pV^n = C$, where n is a constant

$$pV^n = p_1 V_1^n = p_2 V_2^n = C$$

$$p = \frac{(p_1 V_1^n)}{V^n}$$

$$W_{1-2} = \int_{V_1}^{V_2} p\,dV$$

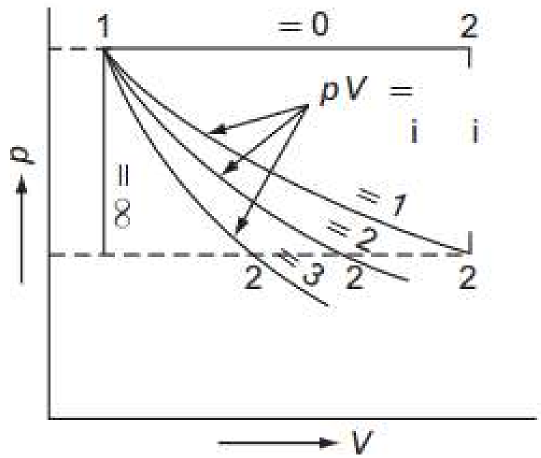
$$= \int_{V_1}^{V_2} \frac{p_1 V_1^n}{V^n} . dV$$

$$= (p_1 V_1^n) \left[\frac{V^{-n+1}}{-n+1} \right]_{V_1}^{V_2}$$

$$= \frac{p_1 V_1^n}{1-n} (V_2^{1-n} - V_1^{1-n})$$

$$= \frac{p_2 V_2^n \times V_2^{1-n} - p_1 V_1^n \times V_1^{1-n}}{1-n}$$

$$= \frac{p_1 V_1 - p_2 V_2}{n-1} = \frac{p_1 V_1}{n-1} \left[1 - \left(\frac{p_2}{p_1} \right)^{n-1/n} \right]$$

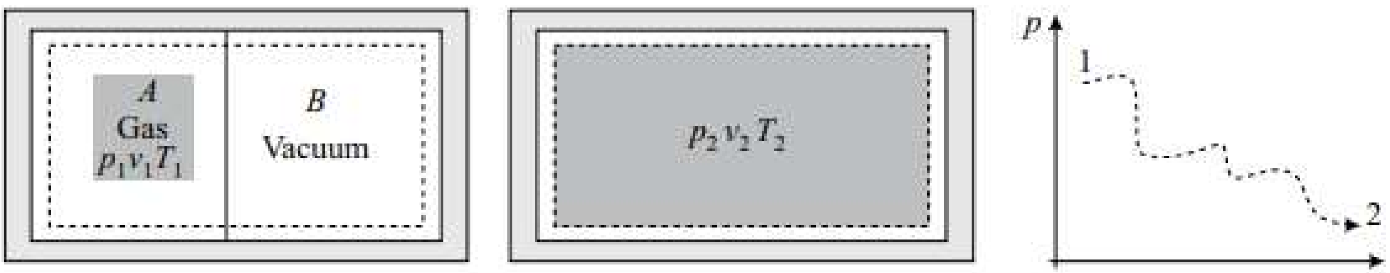


Realizations of different processes

1. Isochoric: Container boundaries are fixed
2. Isobaric: Piston is free to move and external force remains constant
3. Isothermal Process : Infinitely slow process (Phase change)
4. Adiabatic Process: Very fast or insulated container at slow pace
5. Polytropic Process: All practical processes .

Free expansion Process

Free expansion process is unrestricted expansion of a gas without any work output. As the gas cannot be compressed back to its initial state without the use of external work, the process of free expansion is highly irreversible process. The process is also called constant internal energy process as there is no exchange of heat and work between the system and the surrounding. The process can be explained by a simple example.



(a) Before expansion (b) After expansion p-v diagram

Free expansion Process

There are two chambers A and B completely insulated and separated by a membrane. Chamber A has gas at parameters $p_1 v_1 T_1$ and chamber B is completely evacuated. The state is plotted as point 1 on p-v diagram. The partition is removed and the gas occupies the total volume of chambers A and B. The final conditions of the system are $p_2 v_2 T_2$ are shown by point 2 on the p-v diagram. The free expansion is shown by a dotted line as the process is uncontrolled, irreversible and unspecified.

1. The work done is zero as there is no expansion of boundary

$$W_{1-2} = 0$$

2. The system is insulated and there is no exchange of heat with the surrounding.

$$Q_{1-2} = 0$$

3. Applying the first law of thermodynamics to the closed system,

$$Q_{1-2} - W_{1-2} = U_2 - U_1$$

$$0 - 0 = U_2 - U_1$$

$$\therefore \quad U_2 = U_1$$

The internal energy of the system during free expansion remains constant.

4. $$U_2 - U_1 = m\,Cv\,(T_2 - T_1) = 0$$

$$\therefore \quad T_2 = T_1.$$

Free expansion Process

The process of free expansion is isothermal process.

5. $$H_2 - H_1 = m\,Cp\,(T_2 - T_1) = 0$$

The enthalpy of the system remains constant.

Heat Transfer

Heat is defined as the form of energy that is transferred across a boundary by virtue of a temperature difference. The temperature difference is the potential or force.

The transfer of heat between two bodies in direct contact is called conduction. Heat may be transferred between two bodies separated by empty space or gases by the mechanism of radiation through electromagnetic waves. A third method of heat transfer is convection which refers to the transfer of heat between a wall and a fluid system in motion. The direction of heat transfer is taken from the high temperature system to the low temperature system. Heat flow into a system is taken to be positive, and heat flow out of a system is taken as negative

Heat is a form of energy in transit (like work transfer). It is a boundary phenomenon, since it occurs only at the boundary of a system. Energy transfer by virtue of temperature difference only is called heat transfer. All other energy interactions may be termed as work transfer. Heat is not that which inevitably causes a temperature rise. When heat is transferred to an ice-and-water mixture, the temperature does not rise until all the ice has melted. When a temperature rise in a system occurs, it may not be due to heat transfer, since a temperature rise may be caused by work transfer also. Heat, like work, is not a conserved quantity, and is not a property of a system. A process in which no heat crosses the boundary of the system is called an adiabatic process. Thus, an adiabatic process is one in which there is only work interaction between the system and its surroundings.

$Q \propto m$

$Q \propto \Delta T \rightarrow \quad Q = mc\Delta T \quad where\ c\ is\ specific\ heat.$

Hence specific heat is the heat required to raise the temperature of body of 1kg substance by 1 unit (degree C or K)

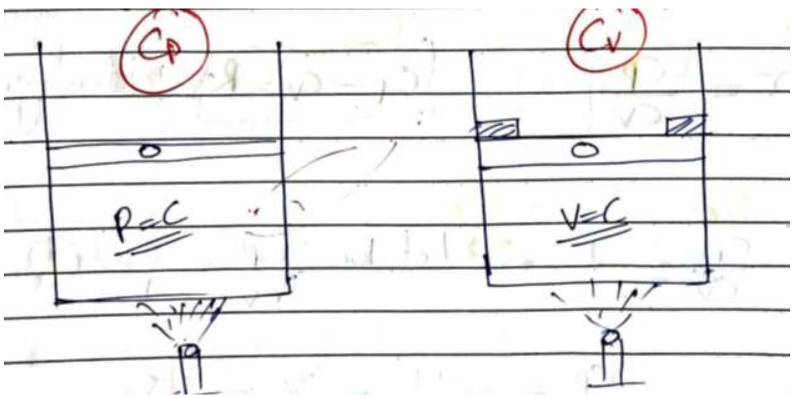
There are two types of specific heats

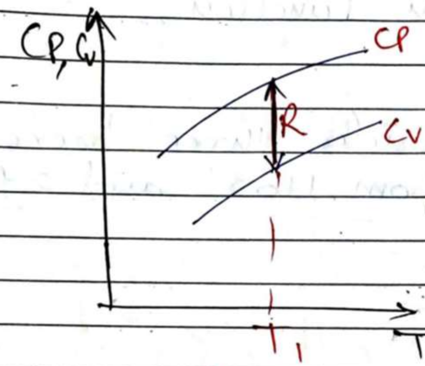
Cv = specific heat at constant volume and Cp= specific heat at constant pressure

Cp is greater than Cv because Cp is consumed in raising the internal energy as well as doing some work whereas Cv is used only to raise the internal energy.

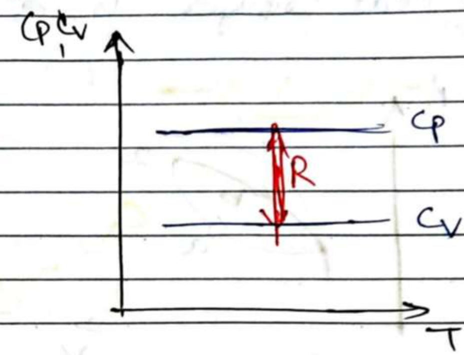
$\gamma = \frac{Cp}{Cv}$ also

$Cp - Cv = R$----- Meyer's Equation





Diatomic



Monoatomic

→ $\frac{C_P}{C_V} > 1 \Rightarrow$ Let be $\frac{C_P}{C_V} = \frac{2}{1} = ②$

$$\frac{C_P}{C_V} = \frac{2+1}{1+1} = \frac{3}{2} = 1.5$$

$$\frac{C_P}{C_V} = \frac{3+1}{2+1} = \frac{4}{3} = \underline{\underline{1.33}}$$

Ideal Gas

A hypothetical gas which obeys the law $P\bar{V} = \bar{R}\,T$ at all pressures and temperatures is called an ideal gas.

Real gases do not conform to this equation of state with complete accuracy.

Assumptions:

1. Intermolecular forces are negligible
2. Volume occupied by the gas molecules is very small as compared to the container volume

Low Pressure: At low pressure molecules are less in specific volume.

High Temperature: At high temp. the particles have high energy and they are able to overcome the effect of inter molecules attractive forces

Ideal Gas

Note:

All the gases that are gases under normal conditions will be considered as ideal gases. Water vapours in air will always be considered as ideal gas unless mentioned. Steam should never be considered as an ideal gas unless mentioned because of high pressure.

From Avogadro's law, when $p = 760$ mm Hg $= 1.013 \times 10^5$ N/m^2, $T = 273.15$ K, and $\bar{v} = 22.4$ m^3/kg mol

$$\bar{R} = \frac{1.013 \cdot 10^5 \cdot 22.4}{273.15}$$

$$= 8314.3 \text{ Nm/kg mol K}$$

$$= 8.3143 \text{ kJ/kg mol K}$$

$\bar{R}$ is the universal gas constant.

Since $\bar{V} = V/n$, where V is the total volume and n the number of moles of the gas, the equation of state for an ideal gas may be written as

$$pV = n\bar{R}T$$

Also $$n = \frac{m}{\mu}$$

where μ is the molecular weight

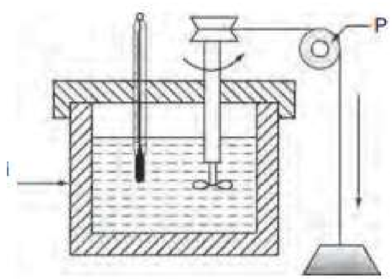
$\therefore$ $$pV = m \cdot \frac{\bar{R}}{\mu} \cdot T$$

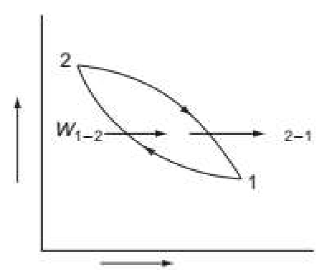
or $$pV = mRT$$

where $$R = \text{characteristic gas constant} = \frac{\bar{R}}{\mu}$$

First law of Thermodynamics

The transfer of heat and the performance of work may both cause the same effect in a system. Heat and work are different forms of the same entity, called energy, which is conserved. Energy which enters a system as heat may leave the system as work, or energy which enters the system as work may leave as heat.





$$(\Sigma W)_{\text{cycle}} = J\,(\Sigma Q)_{\text{cycle}}$$

where J is the Joule's equivalent. This is also expressed in the form $\oint dW = J \oint dQ$

Let there be change in the state of the system during which heat and work both are transferred. The net energy transfer is stored in the system. If

Q= Heat transferred

W= work transferred

Therefore $$Q - W = \Delta E$$

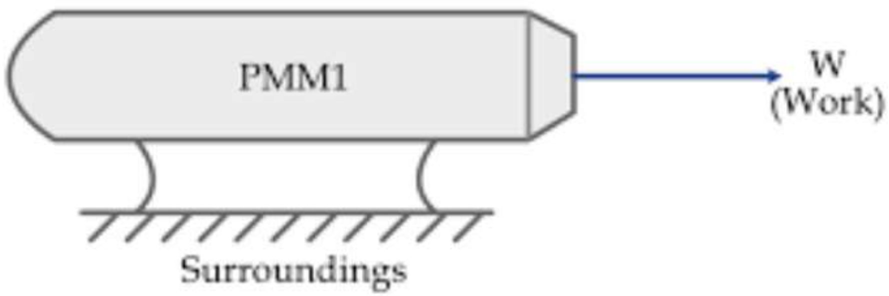
where ΔE is the increase in the energy of the system

Here *Q, W, and ΔE* are all expressed in the same units as Joules

The first law of thermodynamics states that heat is a form of energy, and thermodynamic processes are, therefore, subject to the principle of conservation of energy. This means that heat energy cannot be created or destroyed. It can, however, be transferred from one location to another and converted to and from other forms of energy.

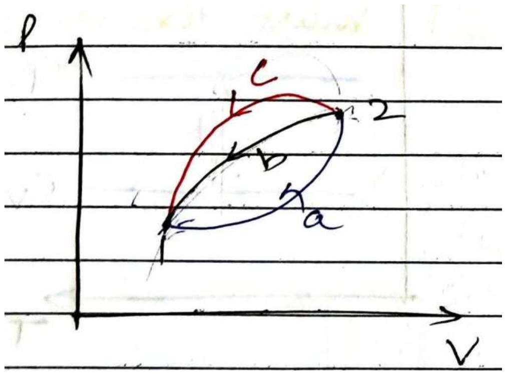
Perpetual Motion Machine of First Kind (PMM1)

It is impossible to construct a machine that can continuously supply mechanical work without consuming any energy simultaneously. Such a hypothetical machine is known as the perpetual motion machine of the first kind. These types of machines violate the 1st law of thermodynamics and do not exist in reality.



Consequences of 1st Law Thermodynamics

1. Heat transfer – path function



There are two cyclic processes
1-a-2-b-1 and 1-a-2-c-1
according to first law of thermodynamics
For a cyclic process total heat transfer is equal to total work transfer
Hence

$\Delta Q_{1a2} + \Delta Q_{2b1} = \Delta W_{1a2} + \Delta W_{2b1}$

$\Delta Q_{1a2} + \Delta Q_{2c1} = \Delta W_{1a2} + \Delta W_{2c1}$

Subtracting the two equations
$\Delta Q_{2c1} - \Delta Q_{2b1} = \Delta W_{2c1} - \Delta W_{2b1}$

Since work is path function hence $\Delta W_{2c1} - \Delta W_{2b1}$=x

Therefore $\Delta Q_{2c1} - \Delta Q_{2b1}$=x which proves that heat transfer is a also a path function

2. Energy is a property

Also

$$\Delta Q_{2c1} - \Delta Q_{2b1} = \Delta W_{2c1} - \Delta W_{2b1}$$

After rearrangement we get

$$\Delta Q_{2c1} - \Delta W_{2c1} = \Delta Q_{2b1} - \Delta W_{2b1}$$

Which proves that net energy stored is same irrespective of path.

It can be deduced that

$$\Delta \mathrm{Q} = \mathrm{dE} + \Delta W$$

$$\Delta \mathrm{Q} = \mathrm{dE} + \Delta W$$

$$\mathrm{dE} = dU + \Delta KE + \Delta PE$$

If the system is stationary and grounded
Then

$$\mathrm{dE} = dU$$

$$\Delta \mathrm{Q} = d\mathrm{U} + \Delta W_b + \Delta W_{other}$$

If $\Delta W_{other} = 0$

$$\Delta \mathrm{Q} = d\mathrm{U} + pdV$$

3. Energy of an Isolated system

For isolated system

$\Delta Q = 0; \Delta W = 0;$

Therefore $dE = 0 \rightarrow$ *Energy of isolated system is constant*

4. Enthalpy

$$h = u + pv$$

Constant pressure process

$$dQ = du + pdv$$
$$pdv = d(pv)$$
$$(dQ)_p = du + d(pv)$$
$$(dQ)_p = d(u + pv)$$
$$(dQ)_p = dh$$

Heat Interactions during different processes

$$\Delta \mathrm{Q} = d\mathrm{U} + \Delta W_b + \Delta W_{other}$$

Constant Volume ΔW_b=0

Therefore $\Delta \mathrm{Q} - \Delta W_{other} = d\mathrm{U}$

$\Delta \mathrm{Q} - \Delta W_{other}$= energy supplied at constant volume= $\Delta \mathrm{m} C_v \mathrm{dT}$

$$d\mathrm{U} = \Delta \mathrm{m} C_v \mathrm{dT}$$

Process

$1 \to 2 = 1-2' + 2'-2$

$du_{2'-2} = 0$ Being Isothermal

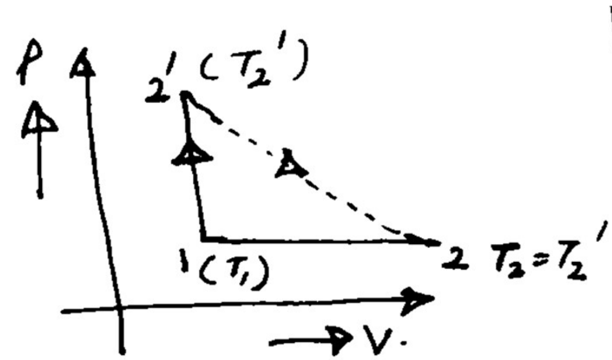
Process $1-2'$ is Isochoric Process.

$du_{1-2'} = m c_v (T_2' - T_1)$

$U_{2'} - U_1 = U_2 - U_1$

$du_{1-2} = m c_v (T_2' - T_1)$

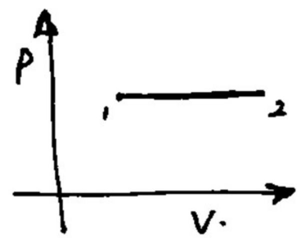
$= m c_v (T_2 - T_1)$



② <u>Isobasic System</u>

$$\Delta Q = du + \Delta W_0 + \Delta W_b$$

$$\Delta Q - \Delta W_0 = du + \Delta W_b$$
$$= du + PdV$$
$$= d(U + PV)$$



$$\Delta Q - \Delta W_0 = dH$$
$$= m C_p dT$$

$$dH = m C_p dT$$

If $\Delta W_0 = 0$

Then $\Delta Q = dH$

Heal suppied (Transfered) is used in raising its enthalpy.

Meyer's Eqn

$$dH = du + PdV$$

$$dH = mC_p\,dT$$

$$du = mC_v\,dT$$

$$PdV = mR\,dT \rightarrow \text{from Gas Eq}^n$$

$$mC_p\,dT = mC_v\,dT + mR\,dT$$

$$C_p = C_v + R$$

$$C_p - C_v = R$$

Now $\dfrac{C_p}{C_v} = \gamma$

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

For air

$C_p = 1.005$ kJ/kgK

$C_v = 0.718$ kJ/kgK

$R = 0.287$ kJ/kgK

$\gamma = 1.4$, $M = 29$ kg/kmol

③ **Isothermal Process**

$\Delta Q = du + \Delta W$ [- closed system, - stationary system]

$dT = 0$ being isothermal (ideal gas).

$\Delta Q = m c_v dT + \Delta W$ ($dT \to 0$)

$\Delta Q = \Delta W$

④ **Adiabatic Process** ($\Delta Q = 0$) [- closed & stationary system]

$\Delta Q = du + \Delta W$ ($\Delta Q \to 0$)

$du = -\Delta W$

No heat transfer, but work transfer is possible

(5) Polytropic Process

$$\Delta Q = dE + \Delta W_D + \Delta W_\delta$$ for closed system

let $\Delta W_D = 0$
* stationary System

$$\Delta Q = du + PdV$$

$$\Delta Q = mC_v(T_2 - T_1) + \frac{P_1V_1 - P_2V_2}{n-1}$$

$$\Delta Q = \frac{m \cdot R}{\gamma - 1}(T_2 - T_1) + \frac{P_1V_1 - P_2V_2}{n-1}$$

$$= \frac{P_2V_2 - P_1V_1}{\gamma - 1} + \frac{P_1V_1 - P_2V_2}{n-1}$$

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

$$= W_p\left[1 - \frac{n-1}{\gamma-1}\right]$$

$$\Delta Q = W_P\left[\frac{\gamma - n}{\gamma - 1}\right]$$

Polytropic specific heat

$$\Delta Q = m C_v (T_2 - T_1) + \frac{P_1V_1 - P_2V_2}{n-1}$$

$$= \frac{mR}{\gamma-1}(T_2 - T_1) + \frac{mR(T_1 - T_2)}{n-1}$$

$$= \frac{mR(T_2 - T_1)}{\gamma - 1}\left[1 - \frac{\gamma-1}{n-1}\right]$$

$$= m(T_2 - T_1)\left(\frac{R}{\gamma-1}\right)\left[\frac{n-\gamma}{n-1}\right]$$

$$\Delta Q = m(T_2 - T_1)\, C_v \left[\frac{n-\gamma}{n-1}\right]$$

$$= m(T_2 - T_1)\left[-C_v\right]\left[\frac{\gamma-n}{n-1}\right] \quad \because 1 < n < \gamma$$

$\left[-C_v\right]\left[\frac{\gamma-n}{n-1}\right] \rightarrow C_{Poly}$

$$\Delta Q = m\, C_{Poly}\left[T_2 - T_1\right]$$

C_{Poly} is -ve.

Hence during Polytropic heat transfer temperature will decrease as work transfer is more than heat transfer.

Energy is of Two types:

High grade energy: Organized form of energy called available energy

Low grade energy : Energy in Random order called unavailable energy

Entropy $\propto$ Unavailable energy

Available energy keeps on decreasing with time and unavailable energy increases with time . This implies entropy of the universe increases with time.

Thermal Energy Reservoir

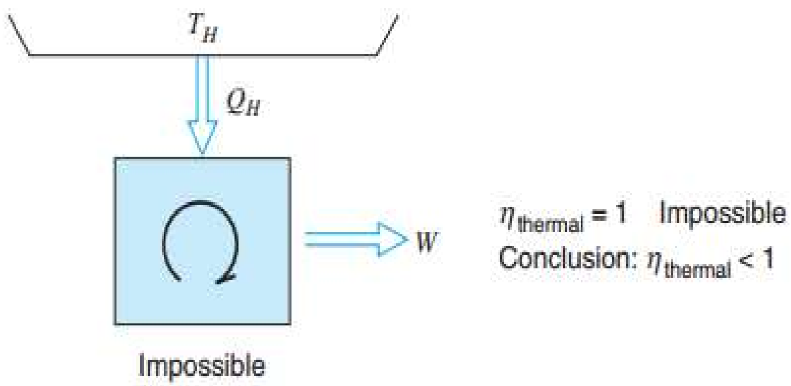
Source: Source is a TER that can supply infinite amount of energy without any change in its temperature

Sink: Sink is a TER that can absorb infinite amount of energy without any change in its temperature

According to 2nd law of Thermodynamics :

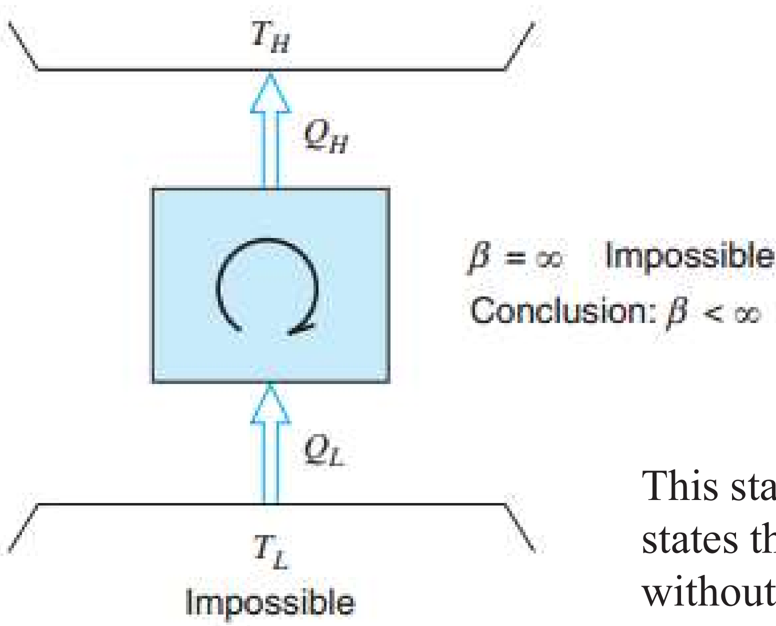
Complete conversion of low grade energy into high grade energy in a cycle is impossible

The Kelvin–Planck statement: It is impossible to construct a device that will operate in a cycle and produce no effect other than the raising of a weight and the exchange of heat with a single reservoir.



In effect, it states that it is impossible to construct a heat engine that operates in a cycle, receives a given amount of heat from a high-temperature body, and does an equal amount of work. The only alternative is that some heat must be transferred from the working fluid at a high- temperature to a low-temperature body. Thus, work can be done by the transfer of heat only if there are two temperature levels, and heat is transferred from the high-temperature body to the heat engine and also from the heat engine to the low-temperature body. This implies that it is impossible to build a heat engine that has a thermal efficiency of 100%.

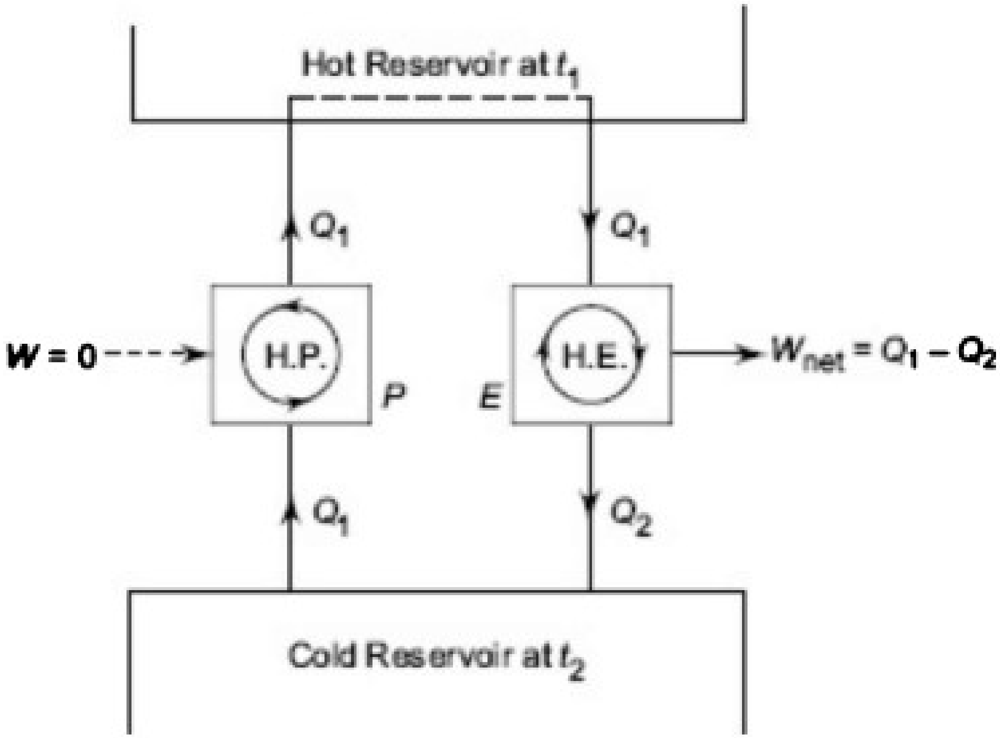
***The Clausius statement*:** It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a cooler body to a warmer body.



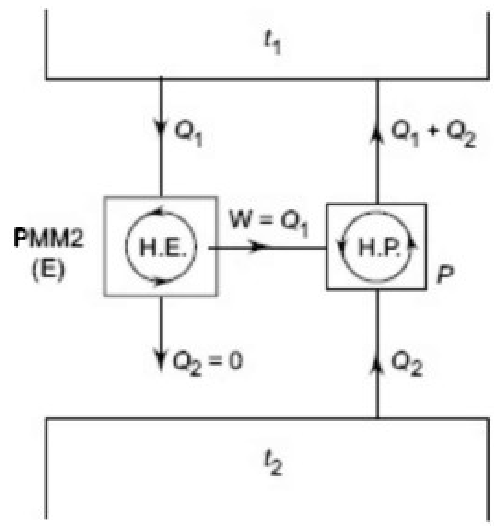
This statement is related to the refrigerator or heat pump. In effect, it states that it is impossible to construct a refrigerator that operates without an input of work. This also implies that the COP is always less than infinity.

Two statements are equivalent if the truth of either statement implies the truth of the other or if the violation of either statement implies the violation of the other.

That a violation of the Clausius statement implies a violation of the Kelvin–Planck statement may be shown. The device shown in Fig. is a refrigerator that requires no work and thus violates the Clausius statement. Let an amount of heat Q_1 be transferred from the low-temperature reservoir to this refrigerator, and let the same amount of heat Q_1 be transferred to the high temperature reservoir. Let an amount of heat Q_1 be transferred from the high-temperature reservoir to the heat engine, and let the engine reject the amount of heat Q_2 as it does an amount of work, W, that equals
$Q_1 - Q_2$. Because there is no net heat transfer to the high-temperature reservoir, the low temperature reservoir, along with the heat engine and the refrigerator, can be considered together as a device that operates in a cycle


Hot Reservoir at t_1
Q_1
Q_1
$W = 0$
H.P.
H.E.
$W_{net} = Q_1 - Q_2$
P
E
Q_1
Q_2
Cold Reservoir at t_2

The complete equivalence of these two statements is established when it is also shown that a violation of the Kelvin–Planck statement implies a violation of the Clausius statement.



Let us assume a cyclic heat pump (P) extracting heat Q_2 from a low temperature reservoir at t_2 and discharging heat to the high temperature reservoir at t_1 with the expenditure of work W equal to what the PMM2 delivers in a complete cycle. So E and P together constitute a heat pump working in cycles and producing the sole effect of transferring heat from a lower to a higher temperature body, thus violating the Clausius statement.

Carnot Cycle

Figure shows a power plant that is similar in many respects to a simple steam power plant and, we assume, operates on the Carnot cycle. Consider the working fluid to be a pure substance, such as steam. Heat is transferred from the high-temperature reservoir to the water (steam) in the boiler. For this process to be a reversible heat transfer, the temperature of the water (steam) must be only infinitesimally lower than the temperature of the reservoir. This result also implies, since the temperature of the reservoir remains constant, that the temperature of the water must remain constant.

Therefore, the first process in the Carnot cycle is a reversible isothermal process in which heat is transferred from the high-temperature reservoir to the working fluid. A change of phase from liquid to vapor at constant pressure is, of course, an isothermal process for a pure substance.

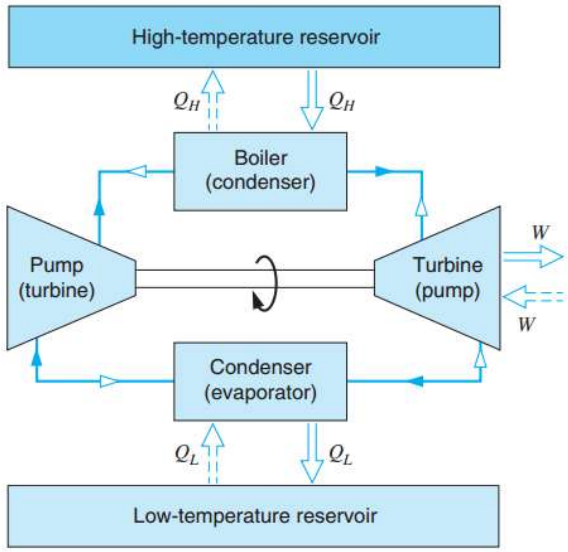
The next process occurs in the turbine without heat transfer and is therefore adiabatic. Since all processes in the Carnot cycle are reversible, this must be a reversible adiabatic process, during which the temperature of the working fluid decreases from the temperature of the high-temperature reservoir to the temperature of the low-temperature reservoir.

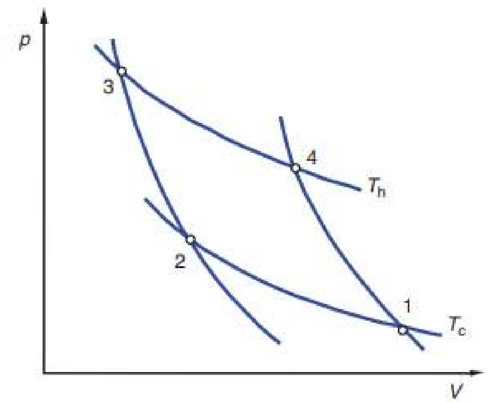
In the next process, heat is rejected from the working fluid to the low-temperature reservoir. This must be a reversible isothermal process in which the temperature of the working fluid is infinitesimally higher than that of the low-temperature reservoir. During this isothermal process some of the steam is condensed.

The final process, which completes the cycle, is a reversible adiabatic process in which the temperature of the working fluid increases from the low temperature to the high temperature. If this were to be done with water (steam) as the working fluid, a mixture of liquid and vapor would have to be taken from the condenser and compressed. (This would be very inconvenient in practice, and therefore in all power plants the working fluid is completely condensed in the condenser. The pump handles only the liquid phase.) .

Carnot Cycle

Since the Carnot heat engine cycle is reversible, every process could be reversed, in which case it would become a refrigerator. The refrigerator is shown by the dotted arrows and text in parentheses in Fig.





1–2--- Isothermal compression, while interacting with the cold reservoir at $T_c = T_1 = T_2$ ($W_{12} < 0$)

2–3--- Adiabatic compression up to T_h ($W_{23} < 0$)

3–4--- Isothermal expansion, while interacting with the hot reservoir at $T_h = T_3 = T_4$ ($W_{34} > 0$)

4–1----Adiabatic expansion to T_c ($W_{41} > 0$).

Carnot Cycle

The important point to be made here is that the Carnot cycle, regardless of what the working substance may be, always has the same four basic processes. These processes are:

1. A reversible isothermal process in which heat is transferred to or from the high temperature reservoir.

2. A reversible adiabatic process in which the temperature of the working fluid decreases from the high temperature to the low temperature.

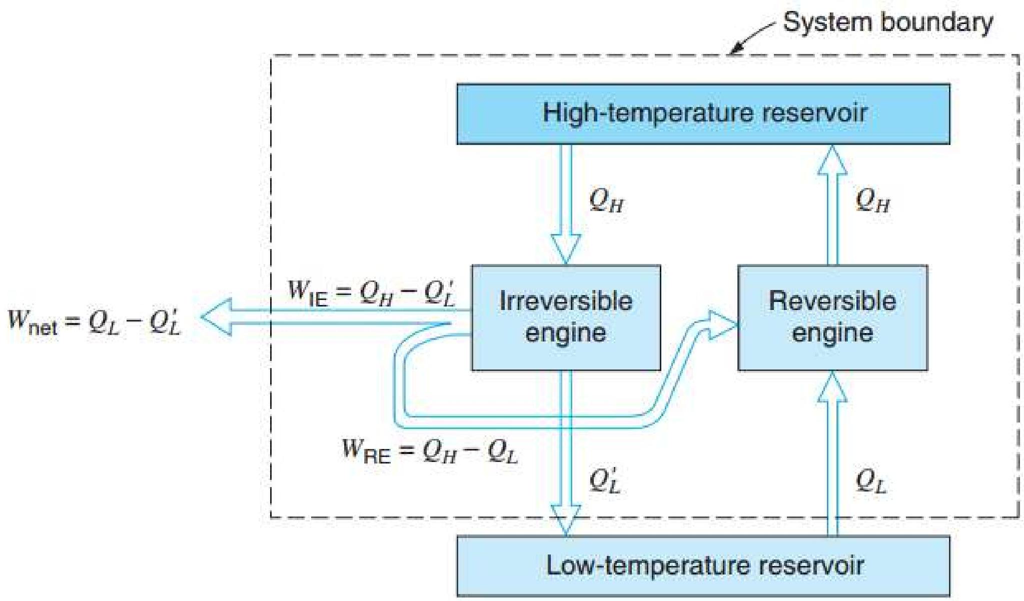
3. A reversible isothermal process in which heat is transferred to or from the low temperature reservoir.

4. A reversible adiabatic process in which the temperature of the working fluid increases from the low temperature to the high temperature.

Carnot Theorem

It is impossible to construct an engine that operates between two given reservoirs and is more efficient than a reversible engine operating between the same two reservoirs.

Proposition I: $\eta_{any} \leq \eta_{rev}$



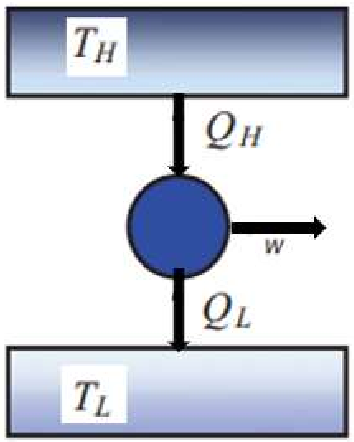
Let us assume that there is an irreversible engine operating between two given reservoirs that has a greater efficiency than a reversible engine operating between the same two reservoirs. Let the heat transfer to the irreversible engine be Q_H, the heat rejected be $Q_{L'}$, and the work be W_{IE} (which equals $Q_H - Q_{L'}$), as shown in Fig. Let the reversible engine operate as a refrigerator (this is possible since it is reversible). Finally, let the heat transfer with the low-temperature reservoir be Q_L, the heat transfer with the high-temperature reservoir be Q_H, and the work required be W_{RE} (which equals $Q_H - Q_L$). Since the initial assumption was that the irreversible engine is more efficient, it follows (because Q_H is the same for both engines) that $Q_{L'} < Q_L$ and $W_{IE} > W_{RE}$. Now the irreversible engine can drive the reversible engine and still deliver the net work W_{net}, which equals $W_{IE} - W_{RE} = Q_L - Q_{L'}$. If we consider the two engines and the high-temperature reservoir as a system, as indicated in Fig., we have a system that operates in a cycle, exchanges heat with a single reservoir, and does a certain amount of work. However, this would constitute a violation of the second law, and we conclude that our initial assumption (that an irreversible engine is more efficient than a reversible engine) is incorrect. Therefore, we cannot have an irreversible engine that is more efficient than a reversible engine operating between the same two reservoirs.

Corollary-1

All engines that operate on the Carnot cycle between two given constant-temperature reservoirs have the same efficiency.

Proposition II: $\eta_{rev\ 1} = \eta_{rev\ 2}$

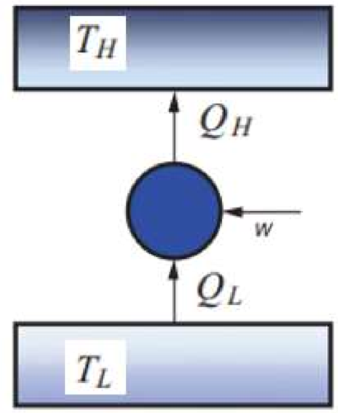
IDEAL VERSUS REAL MACHINES



$$\eta_{engine} = 1 - \frac{Q_L}{Q_H} \le 1 - \frac{T_L}{T_H}$$

$$\eta_{heat\ pump} = \frac{Q_L}{Q_H - Q_L} \le \frac{T_L}{T_H - T_L}$$

$$\eta_{ref} = \frac{Q_H}{Q_H - Q_L} \le \frac{T_H}{T_H - T_L}$$



First equality sign is the definition with the use of the energy equation and thus is always true. The second equality sign is valid only if the cycle is reversible, that is, a Carnot cycle. Any real heat engine, refrigerator, or heat pump will be less efficient

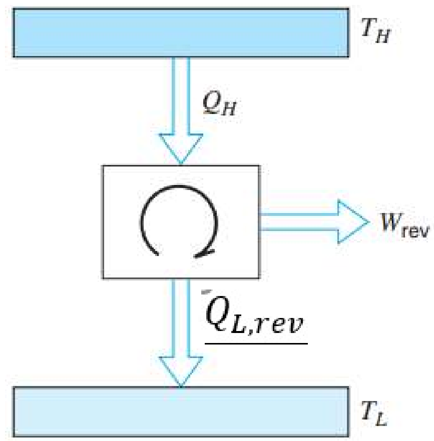
THE INEQUALITY OF CLAUSIUS

Consider first a reversible (Carnot) heat engine cycle operating between reservoirs at temperatures T_H and T_L

For this cycle, the cyclic integral of the heat transfer, $\oint \delta Q$, is greater than zero and

For any closed system undergoing a cycle, the integral of $\oint \frac{\delta Q}{T}$ *can never be positive.*

$$\oint\left(\frac{\delta Q}{T}\right) \leq 0$$



Case 1: For reversible,

$$\oint \frac{\delta Q}{T} = \frac{Q_H}{T_H} - \frac{Q_{L,rev}}{T_L} = 0$$

$$\frac{Q_H}{T_H} = \frac{Q_{L,rev}}{T_L}$$

Case 1: For irreversible,

$$\oint \frac{\delta Q}{T} = \frac{Q_H}{T_H} - \frac{Q_{L,irr}}{T_L}$$

$$\frac{Q_H}{T_H} = \frac{Q_{L,rev}}{T_L}$$

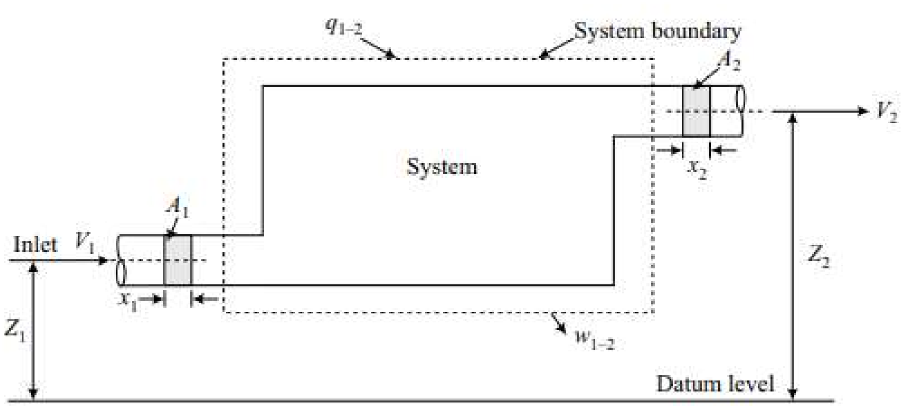
$$\oint \frac{\delta Q}{T} = \frac{Q_{L,rev}}{T_L} - \frac{Q_{L,irr}}{T_L}$$

$$Q_{L,irr} > Q_{L,rev}$$

$$\oint \frac{\delta Q}{T} = \frac{Q_{L,rev}}{T_L} - \frac{Q_{L,irr}}{T_L} < 0$$

Steady Flow Energy Equation

According to the first law of thermodynamics, the total energy entering a system must be equal to total energy leaving the system. For unit mass,



$$e_1 = e_2$$

$$u_1 + p_1 v_1 + \frac{V_1^2}{2} + gz_1 + q_{1-2} = u_2 + p_2 v_2 + \frac{V_2^2}{2} + gz_2 + w_{1-2}$$

where, suffix 1 is for inlet and 2 for outlet.

u = Specific internal energy
pv = Flow work
V = Fluid velocity
Z = Height
q_{1-2} = Heat exchange
w_{1-2} = Work exchange

Now, $h = u + pv$

$$h_1 + \frac{V_1^2}{2} + qz_1 + q_{1-2} = h_2 + \frac{V_2^2}{2} + qz_2 + w_{1-2}$$

This is called steady flow energy equation. This equation may also be written as follows:

$$q_{1-2} - w_{1-2} = (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + q(z_2 - z_1)$$

Case I. If the effect of gravity can be neglected, i.e., $z_2 \approx z_1$

$$q_{1-2} - w_{1-2} = (h_2 - h_1) + \left(\frac{V_2^2 - V_1^2}{2}\right)$$

Case II. If gravity can be neglected and the change in velocity is negligible, i.e., $V_2 \approx V_1$

$$q_{1-2} - w_{1-2} = (h_2 - h_1).$$

Case III. Applying the steady flow energy equation to a closed system (non-flow process)

$p_1 v_1 = 0$ (Flow energy or displacement energy at inlet and outlet is zero)

$$p_2 v_2 = 0$$
$$h_1 = u_1$$
$$h_2 = u_2$$
$$q_{1-2} - w_{1-2} = u_2 - u_1$$

This is called energy equation for a non-flow process.

Equation of Continuity

The mass flow rate ($\dot{m}$) of the working substance entering the system is same as leaving the system. The steady flow energy equation will be:

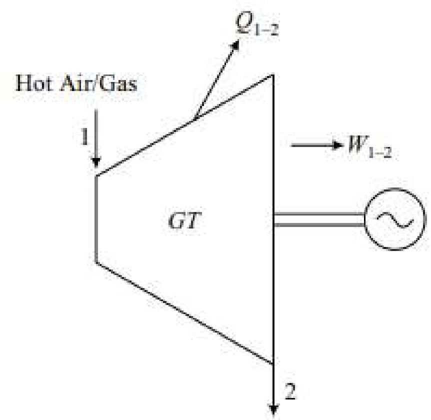
$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + qZ_1 + q_{1-2}\right) = \dot{m}\left(h_2 + \frac{V_2^2}{2} + qZ_2 + W_{1-2}\right)$$

or

$$\dot{Q}_{1-2} - \dot{W}_{1-2} = \dot{m}(h_2 - h_1) + \frac{\dot{m}}{2}(V_1^2 - V_1^2) + \dot{m}g(z_2 - z_1)$$

Gas Turbine

A gas turbine converts the heat energy of hot gases into mechanical work. A compressor driven by the gas turbine compresses air or gas to a higher pressure. The high pressure air or gas is heated by combustion of fuel. The high pressure and high temperature air or gas is admitted to a gas turbine. Power is produced in the turbine at the expense of enthalpy drop of the gas. The main characteristics of the system are:



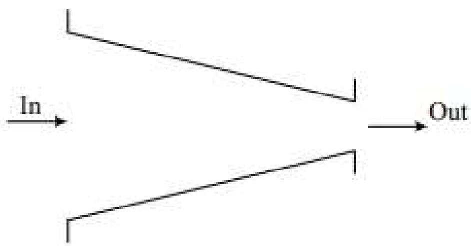
$$V_2 \approx V_1$$

$$Z_2 = Z_1$$

$$\dot{W}_{1-2} = Q_{1-2} + \dot{m}(h_1 - h_2)$$

Nozzle

The nozzle converts the pressure energy of a stream into its kinetic energy and as a result the velocity of the stream increases. The enthalpy drop of the fluid is used to accelerate the flow. Nozzles are used in steam turbines, gas turbines, pumps, etc. The operating characteristics of a nozzle are:



1. There is no work output,

$$W_{1-2} = 0$$

2. The heat loss is normally absent,

$$Q_{1-2} = 0$$

3. The change of potential energy is negligible,

$$Z_2 = Z_1$$

4. The steady flow energy equation,

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

$$V_2 = \sqrt{2(h_1 - h_2) + V_1^2}$$

If $V_2 >> V_1$ and V_1 can be neglected,

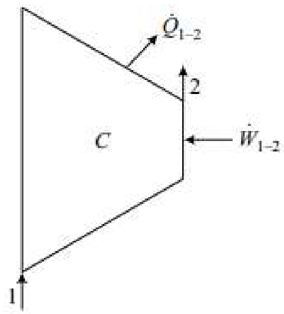
$$V_2 = \sqrt{2(h_1 - h_2)}$$

The mass flow rate,

$$\dot{m} = \frac{A_1 V_1}{v_1} = \frac{A_2 V_2}{v_2}$$

The area of nozzle at the inlet and outlet can be estimated.

Compressor



1. Work is done on the system and, hence, it is negative.

   $\dot{W}_{1-2}$ is –ve.
2. Potential energy and kinetic energy can normally be neglected.

$$Z_2 \approx Z_1$$
$$V_2 \approx V_1$$

3. Heat is lost from the compressor either by radiation or through a coolant (air or water).

   The heat exchange is –ve.

   $\dot{Q}_{1-2}$ is –ve or zero.

$$-\dot{Q}_{1-2} - (-\dot{W}_{1-2}) = \dot{m}(h_2 - h_1)$$

$$\therefore \quad \dot{W}_{1-2} = \dot{Q}_{1-2} + \dot{m}(h_2 - h_1)$$

Therefore, work is done on the system to increase the enthalpy of the fluid.

Throttling Device

The expansion of gas through an obstruction in the form of a partly opened valve or orifice is called throttling.

There is reduction in pressure and increase in the volume of the fluid. The process is adiabatic as there is no exchange of heat but it is irreversible. No work output occurs during throttling. It is not possible to compress the fluid back to initial pressure without the aid of external work. Therefore, the process is irreversible.

$$V_1 \approx V_2$$

$$KE_1 = KE_2$$

Applying steady flow energy equation to unit mass flow

$$h_1 + \frac{v_1^2}{2} + gz_1 + q_{1-2} = h_2 + \frac{v_2^2}{2} + gz_2 + w_{1-2}$$

$$h_1 = h_2$$

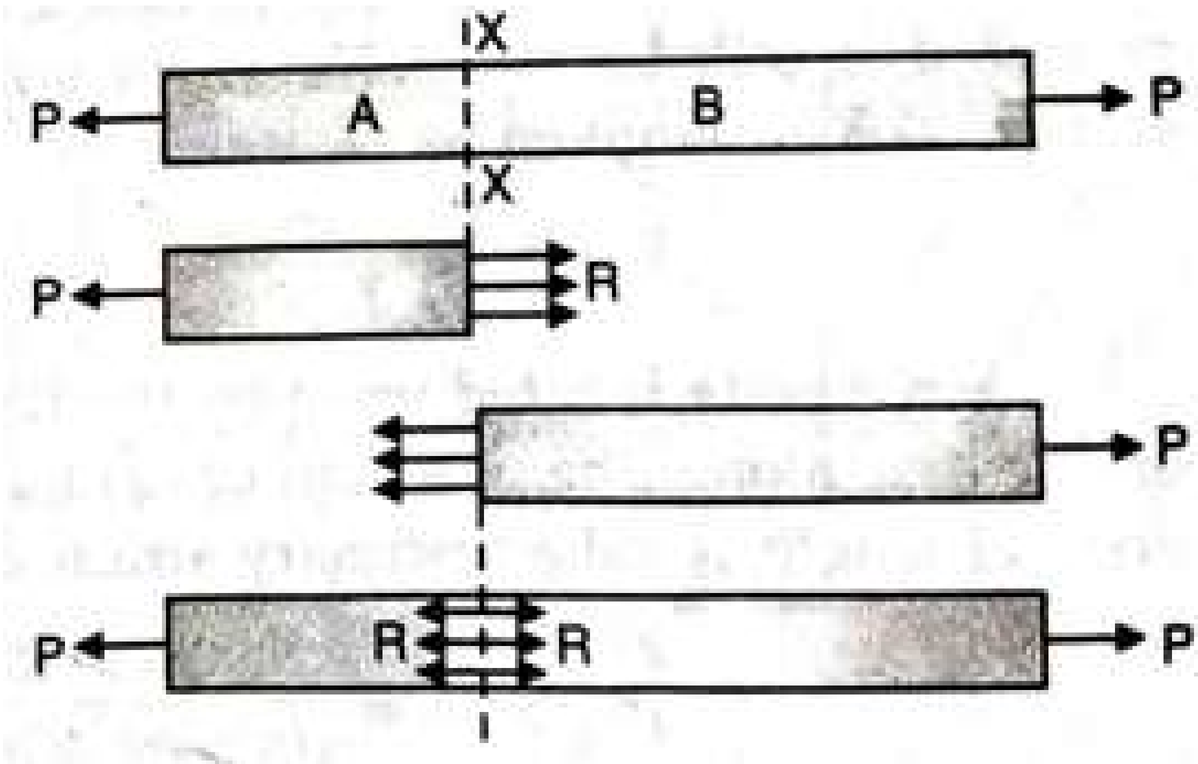
Therefore, throttling process is a constant enthalpy process

Strength of Materials

- Behaviour of materials under various types of loads and moments
- The action of forces and their effects on structural and machine elements such as angle, circular bars and beams etc.
- Homogeneous and isotropic
- No internal stresses present in the material before application of loads

- Load
- Stress
- Intensity of stress

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



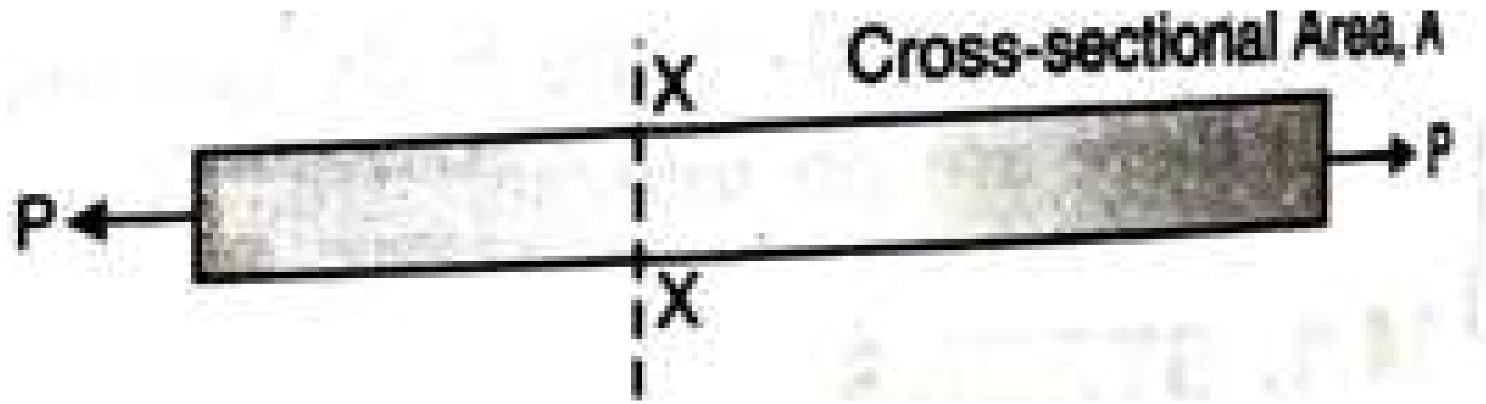
Stress:

It is encountered in solids and its magnitude depends upon direction of applied load w.r.t. plane passing through the point under consideration.

Pressure:

It is associated with fluids and it represents the force extended per unit area due to impact of fluids molecules on the walls of the container or on the body immersed in a fluid and its value is same at a point in a fluid.

Tension, Compression and Strain



Elastic Limit, Hook's Law and Modulus of Elasticity

Experimental evidences are there that shows that upon removal of external loads, the forces of internal resistance vanish and the body regains its original shape and size. However, such a situation exists only if the external loading is within a certain limit.

Hook's law states that when a material is loaded within elastic limit, stress is directly proportional to strain, mathematically

Stress ∝ strain ; $\sigma \propto \varepsilon$

Stress = constant of proportionality × strain

or $\sigma = E\ \varepsilon$; $E = \dfrac{\sigma}{\varepsilon} = \dfrac{\text{stress}}{\text{strain}}$

Recalling that $\varepsilon = \dfrac{\delta l}{l}$ and $\sigma = \dfrac{P}{A}$, we get

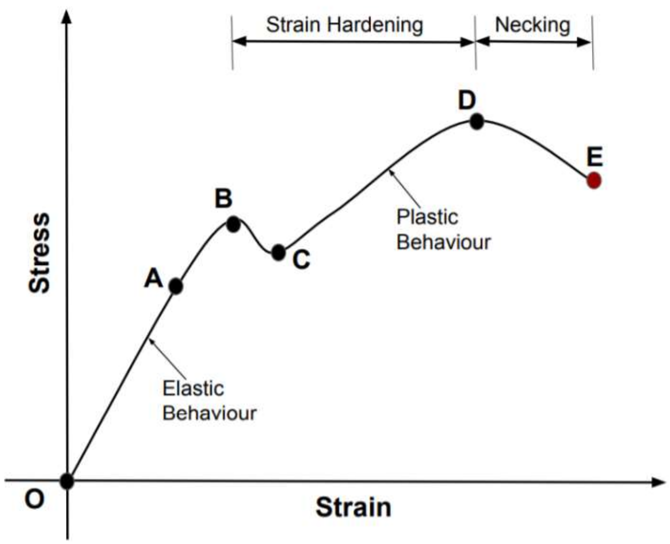
$$\frac{P}{A} = E\,\varepsilon = E\,\frac{\delta l}{l}$$

Change in length $\delta l = \dfrac{\sigma l}{E} = \dfrac{Pl}{AE}$

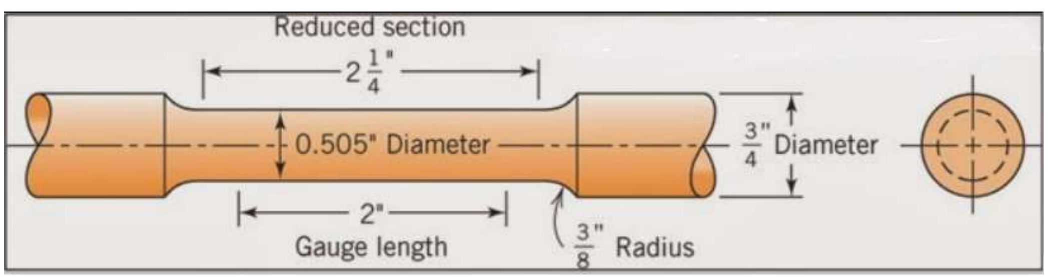
E is called Young's modulus of elasticity (N/sqm. kPa , Mpa)

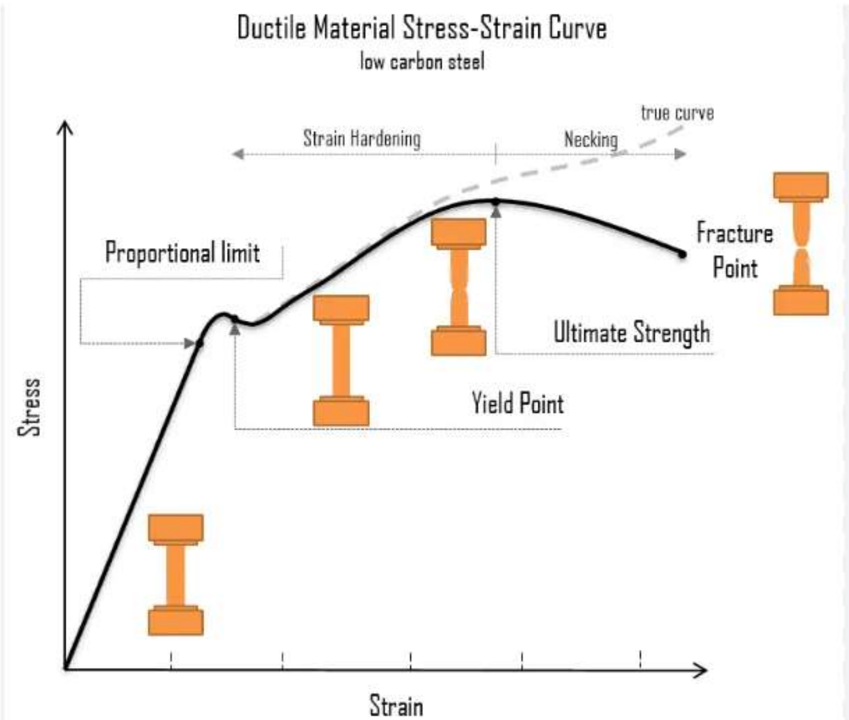
1. A hollow right circular cylinder is made of cast iron and has an outside diameter of 75 mm and an inside diameter of 60mm. The cylinder measures 600 mm in length and is subjected to axial compressive load of 50 kN. Neglecting any possibility of lateral buckling of the cylinder, determine the normal stress and shortening in length of the cylinder under this load. Take the modulus of elasticity of cast iron to be 100 Gpa.
2. A steel bar of 1.5 m long, 50 mm wide and 20 mm thick is subjected to an axial tensile load of 120 kN. If the extension in the length of the bar is 0.9 mm, make calculations for the intensity of stress, strain and modulus of elasticity of the bar material
3. A wire working on a railway signal is 6 mm in diameter and 250 m long. If the movement at the signal end is to be 15 cm, make calculations for the movement which must be given to the end of the wire at the signal box. Assume a pull of 1500 N on the wire and take E = 200000 N/sqmm

Stress-Strain Diagram



OA : Proportional Limit
B : Upper Yield Stress Point
C : Lower Yield Stress Point
D : Ultimate Stress Point
E : Fracture





- **Proportional limit :** Stress is a linear function of strain and the material obeys Hook's law. This proportionality extends upto point A and this point is called ***proportional limit*** or ***limit of proportionality***. 0-A is a straight line portion of the curve and its slope represents the value of modulus of elasticity.
- **Elastic limit :** Beyond proportional limit, stress and strain depart from straight line relationship. The material however, remains elastic upto state point B. The word elastic implies that the stress developed in the material is such that there is no residual or permanent deformation when the load is removed. Upto to this point, the deformation is reversible or recoverable. Stress at B is called the ***elastic limit stress;*** this represents the maximum unit stress to which a material can be subjected and is still able to return to its original form upon removal of load.

- **Yield point :** Beyond elastic limit, the material shows consideral strain even though there is no increase in load or stress. This strain is not fully recoverable, *i.e.*, there is no tendency of the atoms to return to their original positions. The behaviour of the material is inelastic and the onset of plastic deformation is called yielding of the material. Yielding pertains to the region C-D and there is drop in load at the point D. The point C is called the ***upper yield point*** and point D is the ***lower yield point***. The difference between the upper and lower yield point is small and the quoted yield stress is usually the lower value.
- **Ultimate strength or tensile strength :** After yielding has taken place, the material becomes strain hardened (strength of the specimen increases) and an increase in load is required to take the material to its maximum stress at point E. Strain in this portion is about 100 times than that of the portion from 0 to D. Point E represents the maximum ordinate of the curve and the stress at this point is known either as ***ultimate stress*** or the **tensile stress** of the material.
- **Breaking strength :** In the portion EF, there is falling off the load (stress) from the maximum until fracture takes place at F. The point F is referred to as the fracture or breaking point and the corresponding stress is called the ***breaking stress***.

The percentage elongation of gage length after fracture

$$\text{Elongation \%age} = \frac{l_f - l_o}{l_o} \times 100$$

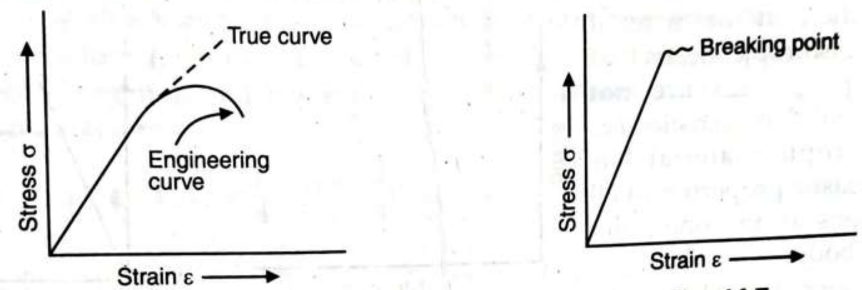
L_o is the original specimen length and
L_f is the specimen length at fractured.

The percentage reduction of cross-sectional area

$$\text{\% reduction in area} = \frac{A_o - A_f}{A_o} x100$$

A_o is the original cross-sectional area and
A_f is the area of the fractured section.

The apparent fall in stress from E to F may be attributed to the fact that stress calculations are made on the basis of original cross-sectional area. In fact elongation of the specimen is accompanied by reduction in cross-sectional area and this reduction becomes significant near the ultimate stress. In case stress calculations are based on actual area, the curve would be seen to rise until fracture occurs. For mild steel, the test piece breaks making a cup and cone type fracture; the two pieces can be joined together to find out the diameter (actual area) at the neck under the specimen breaks.



Proof stress: Normally at strain = 0.2% of gauge length ---stress level

Working stress and factor of safety: Design stress level. FoS required to take care of –

- Internal flaws in the material
- Stress concentration points
- Uncertainties

Magnitude of FoS is decided by –

- Loading type
- Reliability of material
- Extent of damage caused by the sudden failure

Material Classification:

1. Homogeneous and isotropic
2. Rigid and linearly elastic
3. Plastic and rigid-plastic material
4. Ductile and Brittle material

A homogeneous material is a material for which the physical properties are identical at each point within the sample.
An isotropic material is a material for which the physical properties are identical in all directions.
A sample of mild steel or aluminum can usually be assumed to be both homogeneous and isotropic.

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

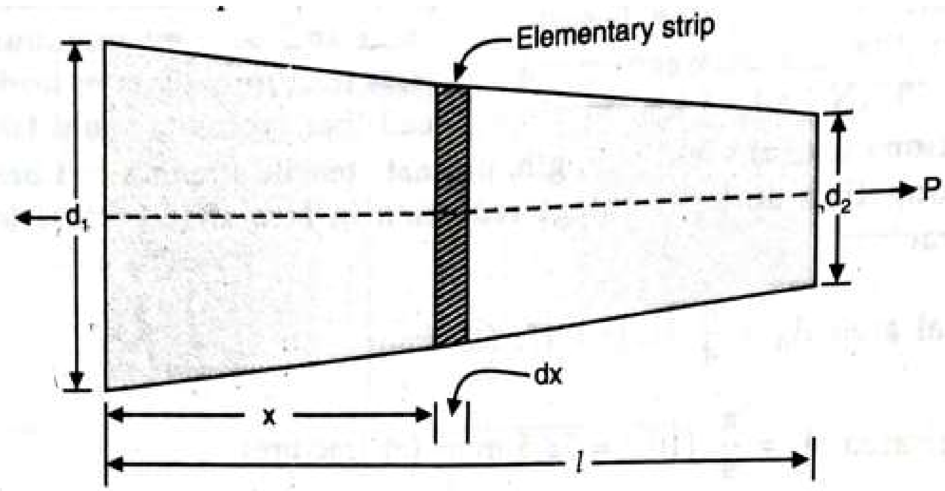
A plastic material can be transformed to any shape and size and can change shape permanently when subjected to stresses of intermediate magnitude

A rigid-plastic material is defined as a material exhibiting no elastic deformation and perfect plastic deformation.

Ductile materials are easily stretched into wires and clearly show deformation under pressure.
Brittle materials break rather than stretch and often fracture cleanly

Extension of a tapered bar

Diameter of elementary strip:



$$d_x = d_1 - (d_1 - d_2)\frac{x}{l}$$
$$= d_1 - kx \text{ where } k = (d_1 - d_2)/l$$

Cross-sectional area of the strip,

$$A_x = \frac{\pi}{4} d_x^2 = \frac{\pi}{4} (d_1 - k x)^2$$

Stress in the strip, $\sigma_x = \dfrac{P}{A_x} = \dfrac{P}{\frac{\pi}{4}(d_1 - k x)^2} = \dfrac{4P}{\pi (d_1 - k x)^2}$

Strain in the strip $\varepsilon_x = \dfrac{\sigma_x}{E} = \dfrac{4P}{\pi (d_1 - k x)^2 E}$

Elongation of the strip $\delta l_x = \varepsilon_x \, dx = \dfrac{4P\,dx}{\pi (d_1 - k x)^2 E}$

...(14.7)

The total elongation of this tapering bar can be worked out by integrating the above expression between the limits $x = 0$ to $x = l$

$$\delta l = \int_0^l \frac{4P\,dx}{\pi(d_1 - kx)^2 E} = \frac{4P}{\pi E}\int_0^l \frac{dx}{(d_1 - kx)^2}$$

$$= \frac{4P}{\pi E}\left[\frac{(d_1 - kx)^{-1}}{(-1)\times(-k)}\right]_0^l = \frac{4P}{\pi E k}\left[\frac{1}{d_1 - kx}\right]_0^l$$

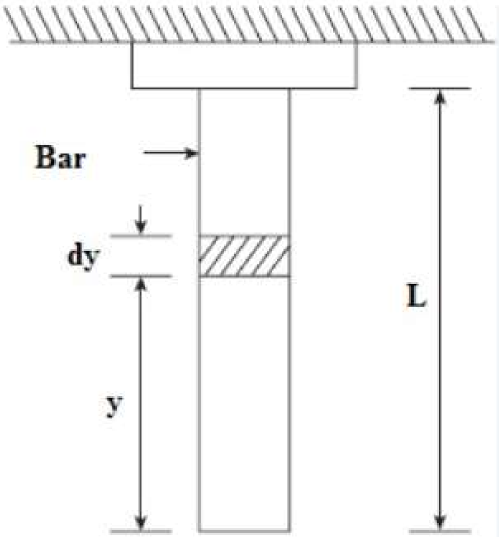
Putting the value of $k = \frac{(d_1 - d_2)}{l}$ in the above expression, we obtain

$$\delta l = \frac{4Pl}{\pi E(d_1 - d_2)}\left[\frac{1}{d_1 - \frac{(d_1 - d_2)l}{l}} - \frac{1}{d_1}\right] = \frac{4Pl}{\pi E(d_1 - d_2)}\left[\frac{1}{d_2} - \frac{1}{d_1}\right]$$

$$= \frac{4Pl}{\pi E(d_1 - d_2)} \times \frac{d_1 - d_2}{d_1 d_2} = \frac{4Pl}{\pi E d_1 d_2}$$

A conical bar tapers uniformly from a diameter of 4 cm to 15 cm in a length of 40 cm. If an axial force of 80 kN is applied at each end, determine the elongation of the bar. Take E = 200 GPa.

Extension of bar due to self weight: Uniform Section



Area = A, Length = L,

w= specific weight (weight per unit volume)

The total tension at se tion m-n equals weight of the bar for length

y and is given by:-

P= w.A.y. As a result of this load, the elemental length dy

elongates by a small amount Δy, and

Δy = Pdy/AE = wAy.dy/AE = w.y.dy/E

The total change in length of the bar due to self weight is worked out by integrating the above expression between the limits y= 0 and y =l.

$$\delta l = \int_0^l \frac{w}{E} y \, dy = \frac{w}{E}\left[\frac{y^2}{2}\right]_0^l = \frac{w}{E}\frac{l^2}{2}$$

If W is the total weight of the bar ($W = w.A\ l$), then $w = W/Al$. In that case, total extension of the bar

$$\delta l = \left(\frac{W}{Al}\right)\frac{l^2}{2E} = \frac{Wl}{2\,AE}$$

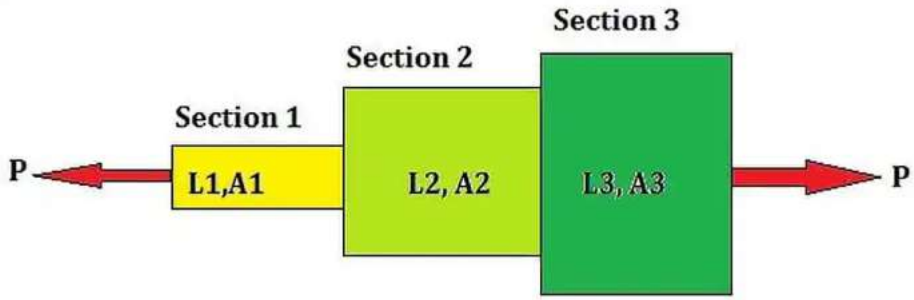
Principle of Superposition:

Quite often a machine member is subjected to a number of forces acting on its outer edges (ends) as well as at some intermediate sections along its length. The forces are then split up and their effects are considered on individual sections. The resulting deformation is then given by the algebraic sum of the deformation of the individual sections. This is the ***principle of superposition*** which may be stated as

"The resultant elongation due to several loads acting on a body is the algebraic sum of the elongations caused by individual loads"

Mathematically $\delta l = \sum_{i=1}^{i=n} \delta l_i$

Stresses in bars of varying cross-sections:



For such a bar, the following conditions apply :
(*i*) Each section is subjected to the same external pull or push
(*ii*) Total change in length is equal to the sum of changes of individual lengths

That is : $P_1 = P_2 = P_3 = P$ and

$$\delta l = \delta l_1 + \delta l_2 + \delta l_3$$

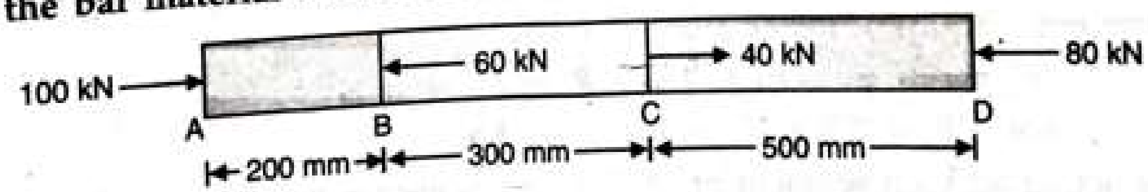
$$= \frac{\sigma_1 l_1}{E_1} + \frac{\sigma_2 l_2}{E_2} + \frac{\sigma_3 l_3}{E_3}$$

$$= \frac{P_1 l_1}{A_1 E_1} + \frac{P_2 l_2}{A_2 E_2} + \frac{P_2}{A_3 E_3}$$

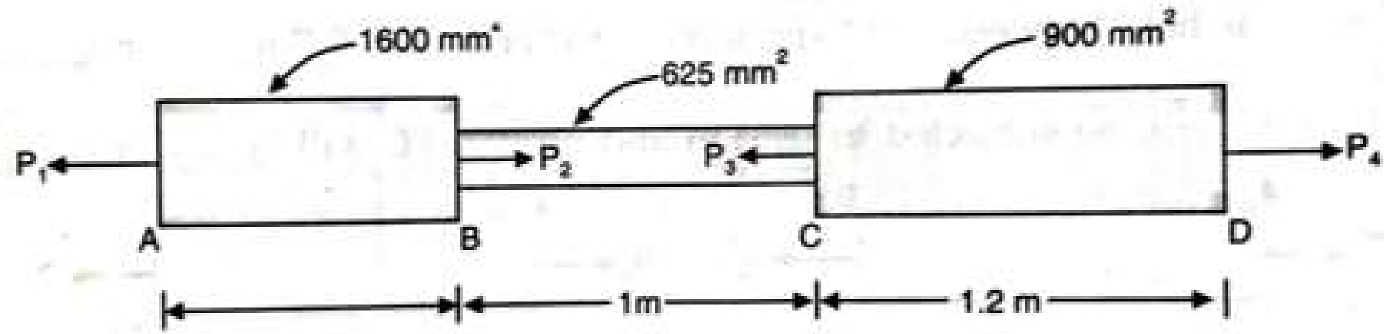
If the bar segments are made of same material, then $E_1 = E_2 = E_3 = E$.
In that case

$$\delta l = \frac{P}{E}\left[\frac{l_1}{A_1} + \frac{l_2}{A_2} + \frac{l_3}{A_3}\right]$$

A member *ABCD* of uniform diameter 200 mm has been subjected to point loads as shown in the figure given below. Determine the net change in the length of the bar. Take modulus of elasticity of the bar material as $E = 200\ GN/m^2$.



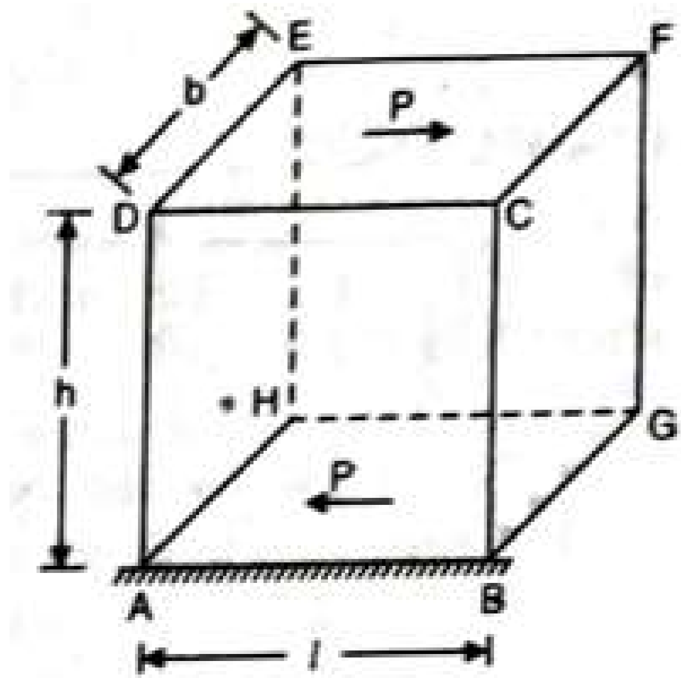
A member ABCD is subjected to point loads P_1, P_2, P_3 and P_4 as shown in the figure given below :



Calculate the force P_3 necessary for equilibrium if P_1 = 120 kN, P_2 = 220 kN and P_4 = 160 kN. Determine also the net change in length of the member. Take modulus of elasticity E = 200 GN/m^2.

Shear Stress. Shear Strain and Modulus of rigidity

Stress and strain produced by a force tangential to the surface of a body are known as shear stress and shear strain. Normal stress acts perpendicular to the plane while shear stress acts along the plane. Eg. Riveted, welded joint, punching operation etc.



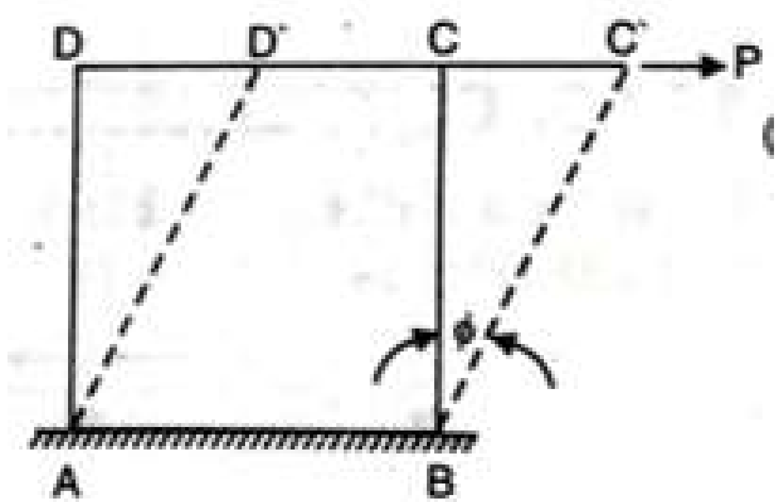
$$\text{shear stress } \tau = \frac{\text{tangential force}}{\text{area of face } DCFE} = \frac{P}{bl}$$

The angular deformation in radians is called shear strain.

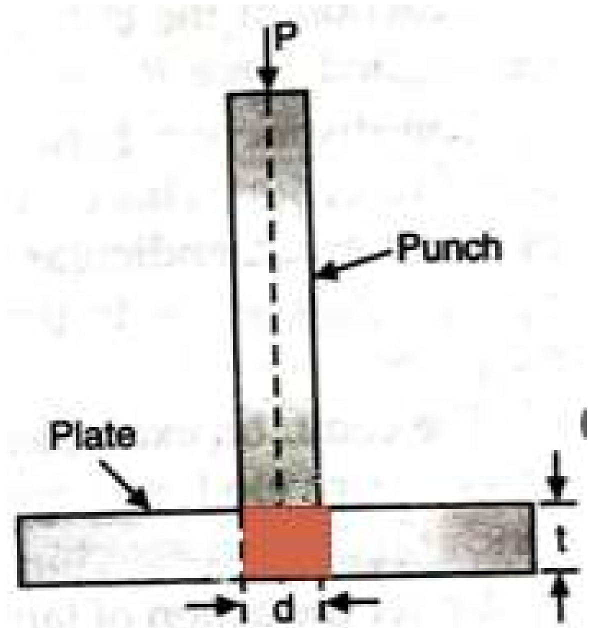
$$\phi = \tan\phi = \frac{CC'}{BC}$$

$$\tau \propto \phi$$

$$\tau = C\phi \quad ; \quad C = \frac{\tau}{\phi}$$

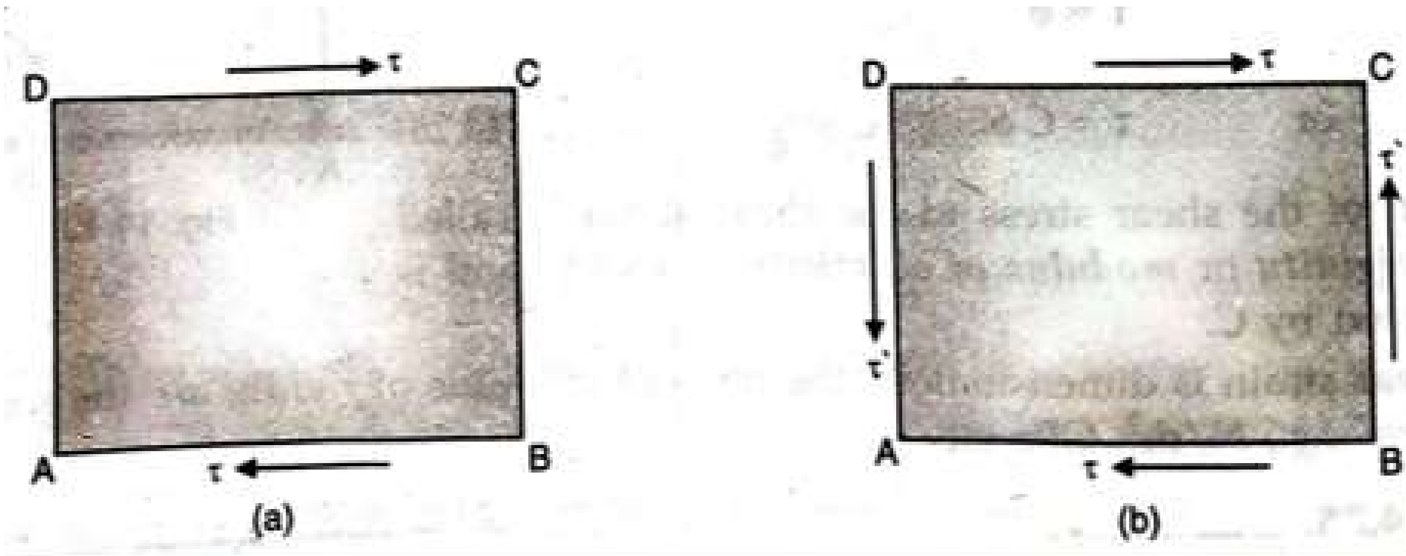


A steel punch can be worked to a compressive stress of 800 N/mm^2. Find the least diameter of hole which can be punched through a steel plate 10 mm thick if its ultimate shear strength is 350 N/mm^2



Complimentary shear stress:

Block ABCD with unit thickness perpendicular to the plane of paper.

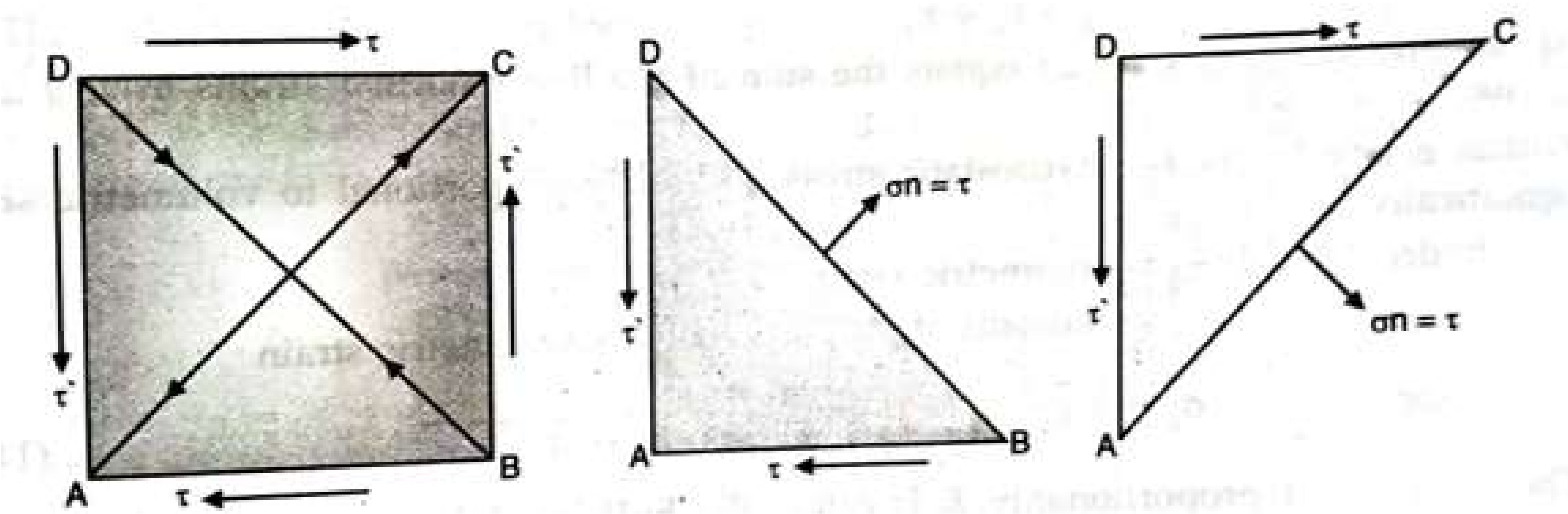


$\tau \times AB$ or $\tau \times DC$.

$(\tau \times AB) \times BC$ or $(\tau \times DC) \times BC$

This couple will tend to rotate the block in clockwise direction. To keep the block in equilibrium, shear stress must act on the other two faces of the block to provide a counter couple. The stress is called complimentary shear stress.

$$(\tau \times AB) \times BC = (\tau' \times BC) \times AB \quad ; \quad \tau' = \tau$$



Considering equilibrium of the free body diagram of the triangular portion ABD,

Shear forces on face $DA = \tau' \times (l \times l) = \tau l^2$ $\quad (\because \tau' = \tau)$

Shear force on face $AB = \tau \times (l \times l) = \tau l^2$

Resultant of these forces is $\sqrt{2}\,\tau l$, and this is balanced by force σ_n acting normal to diagonal BD.

Sectional area of face $BD = \sqrt{l^2 + l^2} = \sqrt{2}\,l$

$\therefore$ Normal stress on diagonal BD,

$$\sigma_n = \frac{\sqrt{2}\,\tau l}{\sqrt{2}\,l} = \tau$$

Likewise, equilibrium of free body diagram of triangular portion DCA would give normal stress on diagonal AC

$$\sigma_n = \tau$$

The above analysis shows that when a element is in a state of simple shear, tensile (along diagonal AC) and compressive (along diagonal BD) stresses equal in magnitude to the shear stress act on planes inclined at 45° to the planes of simple shear.

Hydrostatic Stress. Volumetric Strain and Bulk modulus

When a body is immersed in a fluid to a large depth, the body gets subjected to equal external pressure at all points on the body. This external pressure is compressive in nature and is called hydrostatic stress

The hydrostatic stress causes change in volume of the body, and this change of volume per unit volume is called volumetric strain, ε_v.

$$\varepsilon_v = \frac{\Delta V}{V}$$

Consider a cuboid of sides x, y and z subjected to hydrostatic stress and let its sides change by dx, dy and dz respectively. Then change in volume,

$$\Delta V = (x + dx)(y + dy)(z + dz) - xyz$$

Neglecting product of small changes,

$$\Delta V = (x\,y\,z + x\,y\,dz + y\,z\,dx + x\,z\,dy) - x\,y\,z$$

$$= y\,z\,dx + x\,z\,dy + x\,y\,dz$$

$\therefore$ Volumetric strain,

$$\varepsilon_v = \frac{\Delta V}{V} = \frac{yz\,dx + xz\,dy + xy\,dz}{xyz}$$

∴ Volumetric strain,

$$\varepsilon_v = \frac{\Delta V}{V} = \frac{yz\,dx + xz\,dy + xy\,dz}{xyz}$$

$$= \frac{dx}{x} + \frac{dy}{y} + \frac{dz}{z}$$

$$= \varepsilon_x + \varepsilon_y + \varepsilon_z$$

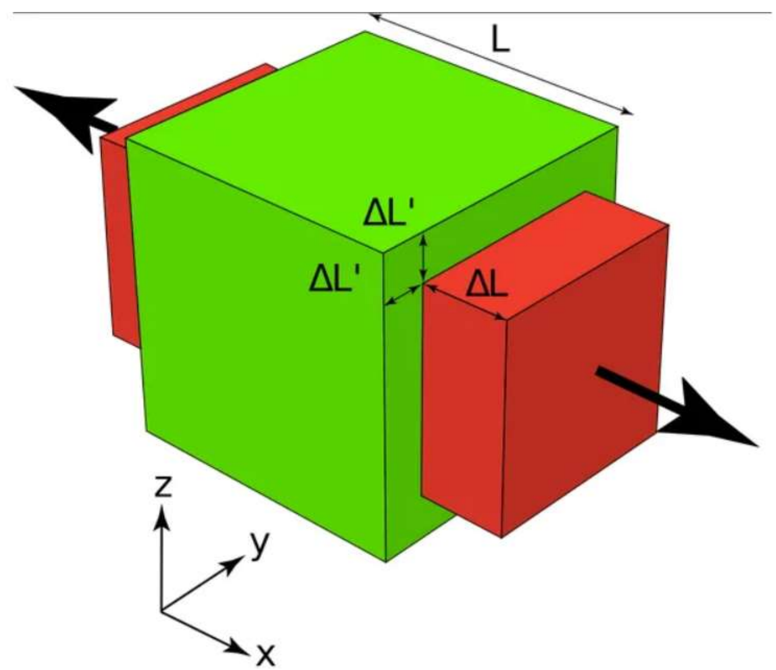
Apparently volumetric strain equals the sum of the linear normal strains in x, y and z directions.

$$\sigma_v = K\,\varepsilon_v \quad ; \quad K = \frac{\sigma_v}{\varepsilon_v}$$

Poisson's Ratio

- Longitudinal strain or primary strain
- Lateral or secondary strain

Both are of opposite nature. **Within elastic limit ratio of lateral strain to the longitudinal strain is called Poisson's ratio. It is denoted by μ (0.25 – 0.33)**



Relation between Elastic constants E, K and C

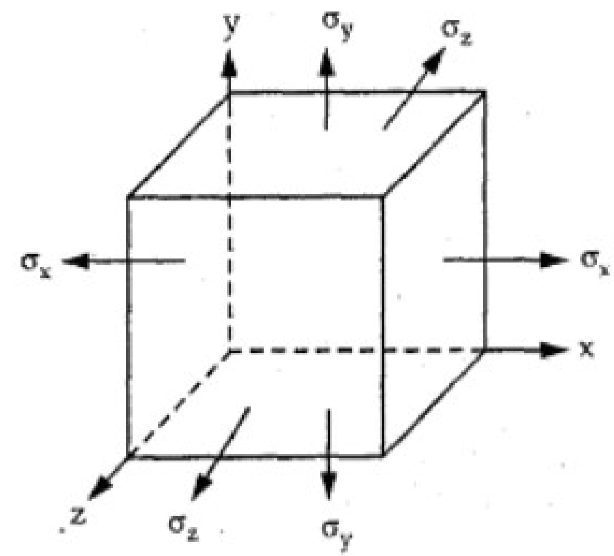
- Relation between E, K and **μ**

Strain in the x-direction,

ε_x = strain in x-direction due to σ_x − strain in x-direction due to σ_y − strain in x-direction due to σ_z

$$= \frac{\sigma_x}{E} - \mu \frac{\sigma_y}{E} - \mu \frac{\sigma_z}{E}$$

But $\sigma_x = \sigma_y = \sigma_z = \sigma$



$$\therefore \quad \varepsilon_x = \frac{\sigma}{E} - \mu \frac{\sigma}{E} - \mu \frac{\sigma}{E} = \frac{\sigma}{E}(1 - 2\mu)$$

Likewise $\varepsilon_y = \frac{\sigma}{E}(1 - 2\mu)$ and $\varepsilon_z = \frac{\sigma}{E}(1 - 2\mu)$

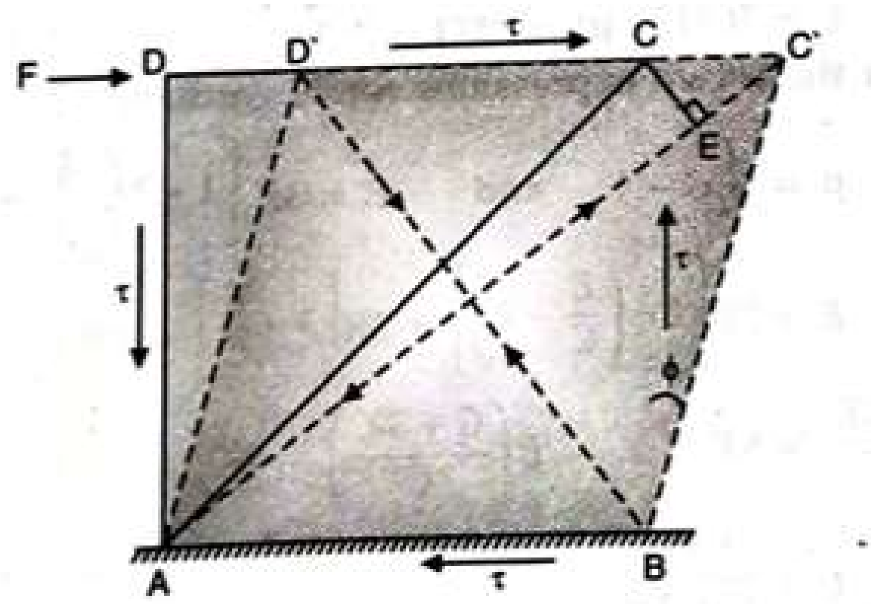
Volumetric strain $\varepsilon_v = \varepsilon_x + \varepsilon_y + \varepsilon_z = \frac{3\sigma}{E}(1 - 2\mu)$

Now, bulk modulus $K = \frac{\text{volumetric stress}}{\text{volumetric strain}} = \frac{\sigma}{\frac{3\sigma}{E}(1-2\mu)} = \frac{E}{3(1-2\mu)}$

$$\therefore \quad E = 3K(1 - 2\mu)$$

Relation between E, C and μ

- Shear stress along DC and AB
- Complimentary shear stress on faces AD and BC .
- Block distorts to a new configuration ABC'D'
- The diagonal AC elongates and BD shortens



Longitudinal strain in diagonal AC

$$= \frac{AC' - AC}{AC} = \frac{AC' - AE}{AC} = \frac{EC'}{AC}$$

where CE is perpendicular from C onto AC'

Since extension CC' is small, $\angle AC'B$ can be assumed to be equal to $\angle ACB$ which is 45°. Therefore

$$EC' = CC' \cos 45° = \frac{CC'}{\sqrt{2}}$$

$$\text{Longitudinal strain} = \frac{CC'}{\sqrt{2}\, AC} = \frac{CC'}{\sqrt{2} \times \sqrt{2}\, BC} = \frac{CC'}{2\, BC}$$

From triangle BCC' : $\dfrac{CC'}{BC} = \tan \phi$

$\therefore$ Longitudinal strain $= \dfrac{\tan\phi}{2} = \dfrac{\phi}{2}$

where $\phi = \dfrac{CC'}{BC}$ represents the shear strain.

In terms of shear stress τ and modulus of rigidity C, shear strain $= \tau/C$

$\therefore$ longitudinal strain of diagonal $AC = \dfrac{\tau}{2C}$

The strain in diagonal AC is also given by

= strain due to tensile stress in AC − strain due to compressive stress in BD

$$= \frac{\tau}{E} - \left(-\mu\frac{\tau}{E}\right) = \frac{\tau}{E}(1+\mu)$$

From expressions 14.36 and 14.37

$$\frac{\tau}{2C} = \frac{\tau}{E}(1+\mu)$$

or $\quad E = 2C(1+\mu)$

Relation between E, C and K

$$E = 2C(1 + \mu) = 3K(1 - 2\mu)$$

To eliminate μ from these two expressions for E, we have

$$\mu = \frac{E}{2C} - 1 \quad \text{and} \quad E = 3K\left[1 - 2\left(\frac{E}{2C} - 1\right)\right]$$

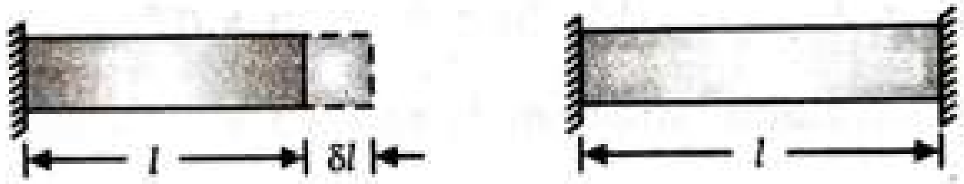
or $$E = 3K\left[1 - \left(\frac{E}{C} - 2\right)\right] = 3K\left[3 - \frac{E}{C}\right] = 9K - \frac{3KE}{C}$$

or $$E + \frac{3KE}{C} = 9K \quad ; \quad E\left(\frac{C + 3K}{C}\right) = 9K$$

or $$E = \frac{9KC}{C + 3K}$$

Accordingly : $$E = 2C\,(1 + \mu) = 3K\,(1 - 2\mu) = \frac{9KC}{C + 3K}$$

Temperature Stresses



$$\text{thermal strain} = \frac{l\,\alpha\,\Delta t}{l} = \alpha\,\Delta t$$

$$\delta l = l\,\alpha\,\Delta t$$

If expansion is allowed , only thermal strain and no stresses are developed. However, If the ends are fixed to rigid supports, stresses are developed called thermal or temperature stresses. The temperature strains and stresses due to temperature rise are compressive in nature , and due to fall in temperature are tensile.

$$\text{thermal stress} = \text{modulus of elasticity} \times \text{thermal strain}$$
$$= E\,\alpha\,\Delta t$$

$$\text{thermal strain} = \frac{l\,\alpha\,\Delta t - \delta}{l}$$

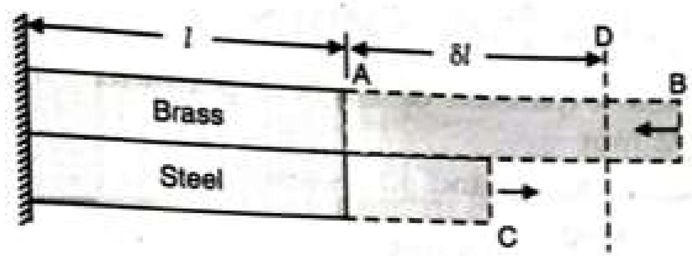
$$\text{normal thermal stress} = E\left(\frac{l\,\alpha\,\Delta t - \delta}{l}\right)$$

Effect of temperature change in a composite bar

Consider temperature rise of a composite bar consisting of two members; one of steel and other of brass rigidly fastened to each other. If allowed to expand freely;

expansion of brass bar : $AB = l\,\alpha_b\,\Delta t$

expansion of steel bar : $AC = l\,\alpha_s\,\Delta t$



Since the coeff. Of expansion of brass is greater than steel, expansion of brass will be more. But the bars are fastened together and accordingly both will expand to the same final position represented by DD with net expansion of composite system AD equal to δl. Brass bar is pushed back (compressive stress) and steel bar is pulled (tensile stress). At equilibrium:

compressive force in brass = tensile force is steel

$$\sigma_c A_c = \sigma_s A_s$$

Corresponding to brass rod :

Reduction in elongation, $DB = AB - AD = l\,\alpha_b\,\Delta t - \delta l$

$$\text{Strain, } \varepsilon_b = \frac{l\,\alpha_b\,\Delta t - \delta l}{l} = \alpha_b\,\Delta t - \varepsilon$$

where $\varepsilon = \delta l / l$ is the actual strain of the composite system.

Corresponding to steel rod :

extra elongation, $CD = AD - AC$

$$= \delta l - l\,\alpha_s\,\Delta t$$

$$\text{strain, } \varepsilon_s = \frac{\delta l - l\,\alpha_s\,\Delta t}{l} = \varepsilon - \alpha_s\,\Delta t$$

Adding ε_b and ε_s, we get

$$\varepsilon_b + \varepsilon_s = (\alpha_b - \alpha_s)\,\Delta t$$

It may be pointed out that the nature of the stresses in the bars will get reversed if there is reduction in the temperature of the composite system.

Strain Energy and Resilience

Internal resistance offered by material on application of external forces, does some work which is stored within the material as energy and this strain energy is known as **Resilience**. During unloading phase same energy is released and material springs back to its original dimension. Machine members like helical , spiral and leaf springs possess this property of resilience.

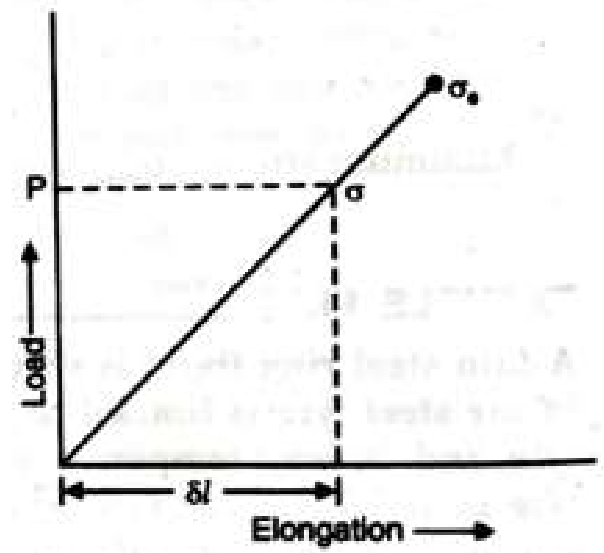
- Strain energy due to axial loads: Gradually applied load

Work done = average load × deformation

$$= \frac{1}{2} P\,\delta l = \frac{1}{2}(\sigma A) \times \frac{\sigma l}{E}$$

$$= \frac{1}{2}\frac{\sigma^2}{E}(Al) = \frac{\sigma^2}{2E} \times \text{volume}$$

$$U = \frac{\sigma^2}{2E} \times \text{volume}$$

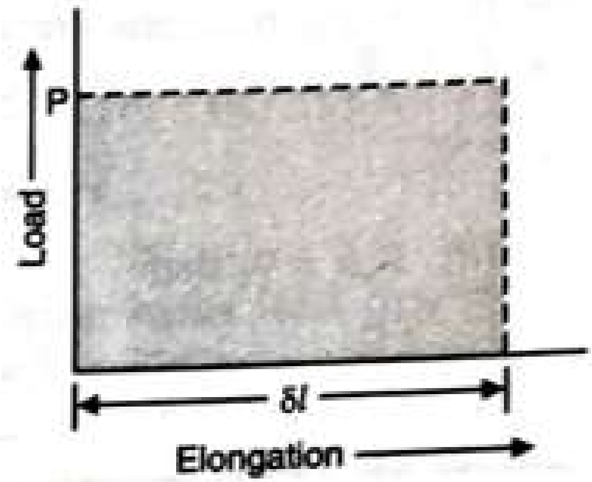


$$\text{Proof resilience} = \frac{\sigma_e^2}{2E} \times \text{volume}$$

where σ_e is the stress at elastic limit.

$$\text{Modulus of resilience} = \frac{\sigma_e^2}{2E}$$

Strain energy due to axial loads: Suddenly applied load



Work done = area of shaded portion

$$= P\,\delta l = P\,\frac{\sigma_{su}\,l}{E}$$

The subscript *su* refers to suddenly applied load.

The work done equals the strain energy given by $\frac{\sigma_{su}^2}{2E} \times Al$

$$\therefore \quad \frac{\sigma_{su}^2}{2E}\,Al = P\,\frac{\sigma_{su}\,l}{E}$$

or $$\sigma_{su} = 2\,\frac{P}{A} = 2 \times \text{stress due to gradually applied load}$$

Strain energy due to axial loads: Impact loading

Impact loading occurs when a weight is dropped on a member from some height . The KE of the falling weight is utilized in deforming the member.

$$W(h + \delta l_i) = \frac{\sigma_i^2}{2E} \times \text{volume} = \frac{\sigma_i^2}{2E} Al$$

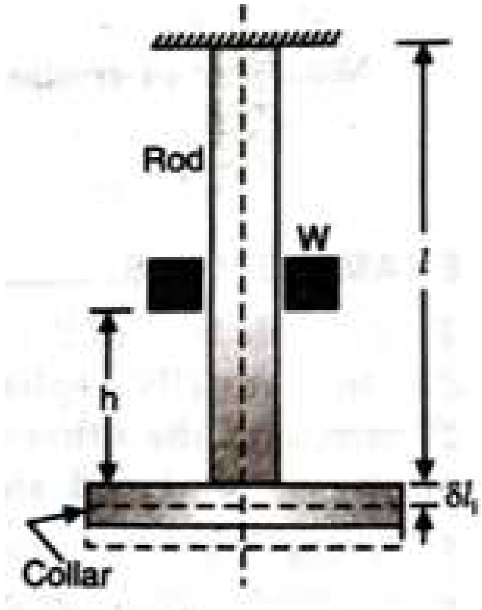
or

$$W\left(h + \frac{\sigma_i l}{E}\right) = \frac{\sigma_i^2}{2E} Al$$

or $\frac{Al}{2E}\sigma_i^2 - \frac{Wl}{E}\sigma_i - Wh = 0$

Solution of this quadratic equation gives

$$\sigma_i = \frac{\frac{Wl}{E} \pm \sqrt{\left(\frac{Wl}{E}\right)^2 - 4 \times \left(\frac{Al}{2E}\right) \times (-Wh)}}{2 \times \frac{Al}{2E}}$$



$$= \frac{W}{A} \pm \sqrt{\frac{W^2}{A^2} + \frac{2WhE}{Al}}$$

Negative sign is inadmissible as the stress cannot be compressive when the bar gets elongated.

$$\therefore \quad \sigma_i = \frac{W}{A} + \frac{W}{A}\sqrt{1 + \frac{2hAE}{Wl}} = \frac{W}{A}\left[1 + \sqrt{1 + \frac{2hAE}{Wl}}\right]$$

Following relations are worth noting :

(*i*) If δl_i is neglected as compared to h, then

$$Wh = \frac{\sigma_i}{2E} Al \quad \text{and} \quad \sigma_i = \sqrt{\frac{2WhE}{Al}}$$

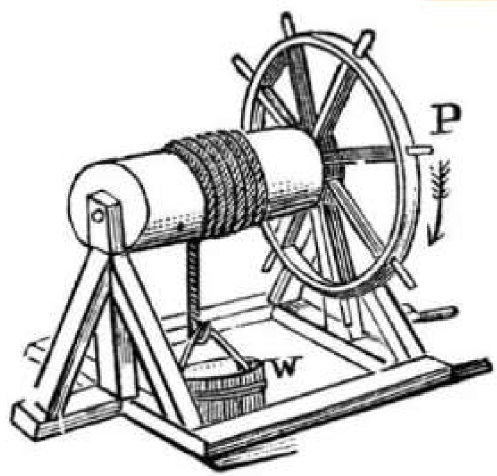
(*ii*) If $h = 0$, then

$$W = \frac{\sigma_i l}{E} = \frac{\sigma_i^2}{2E} Al \quad \text{and} \quad \sigma_i = \frac{2W}{A}$$

Machine

A machine is the assembly of resistant bodies or links whose relative motions are successfully constrained so that available energy can be converted into useful work.

- Both motion and force



Kinematics of machines: relative motion of various machine elements without consideration of forces.
Dynamics of machines: Study of forces acting on various machine elements

- **Kinetics**: inertial forces as a result of mass and motion of machine elements
- **Statics**: External forces and their equilibrium in the rest mode.

Resistant body

A body is said to be resistant if it can transmit the required force with negligible deformation. These bodies are the parts of the machine which are employed for transmitting motion and forces

Kinematic Link or Element

It is a resistant body or an assembly of resistant bodies which go to make a part or parts of a machine connecting other parts which have motion relative to it.

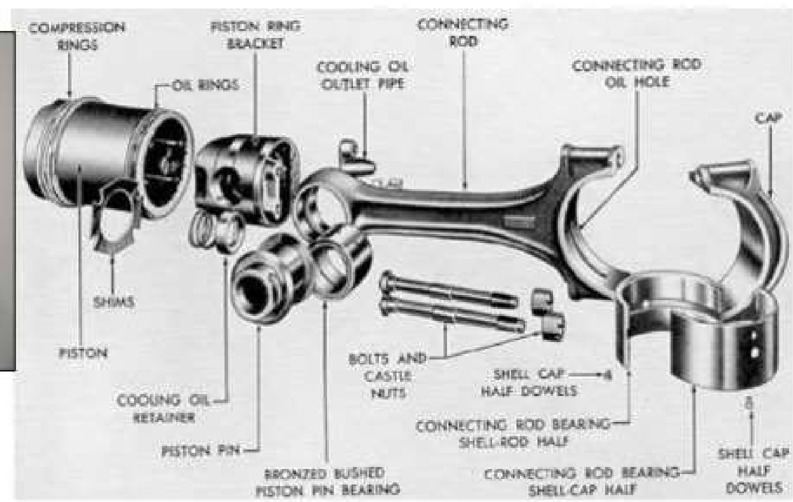
TYPES OF LINKS :

a) Rigid Link
b) Flexible Link
c) Fluid Link

a) Rigid link :

A link which <u>does not undergo any deformation</u> while transmitting motion.

eg. Connecting rod, crank, piston etc.



b) Flexible Link :

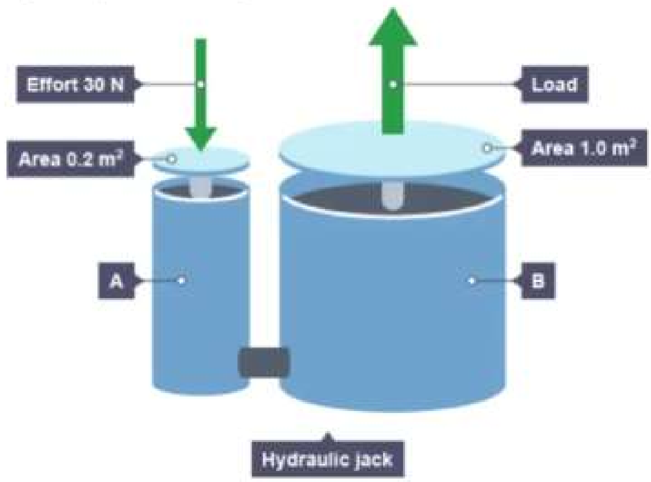
A link which partly deforms but does not affect the transmission of motion.

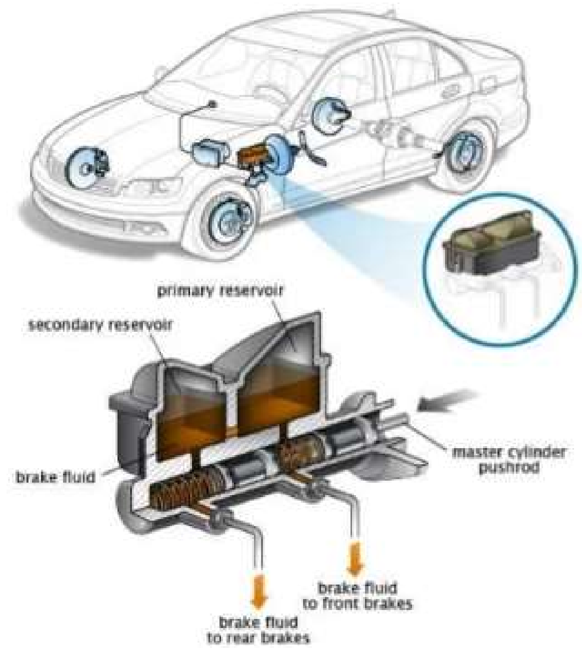
Eg. Belts, ropes, chains, wires

c) Fluid Link :

A link which transmits motion through fluid by pressure or compression only.

eg. Hydraulic presses, brakes, etc.





Structure:

Structure is an assembly of a number of resistant bodies having no relative motion between them and meant for carrying load having straining actions. A railway bridge , a roof truss , machine frames etc.

Sr. No.	Machine	Structure
1	Relative motion exist between its parts	No relative motion exists between its members.
2	Links are meant to transmit motion and forces which are dynamic (both static and kinetic)	Members are meant for carrying loads or subjected to forces having straining actions
3	Machines serve to modify and transmit mechanical work.	Structure serves to modify and transmit forces only.
4	Example: shaper, lathe , screw jack etc	Examples: roof trusses, bridges, buildings, machine frames etc.

MECHANISM

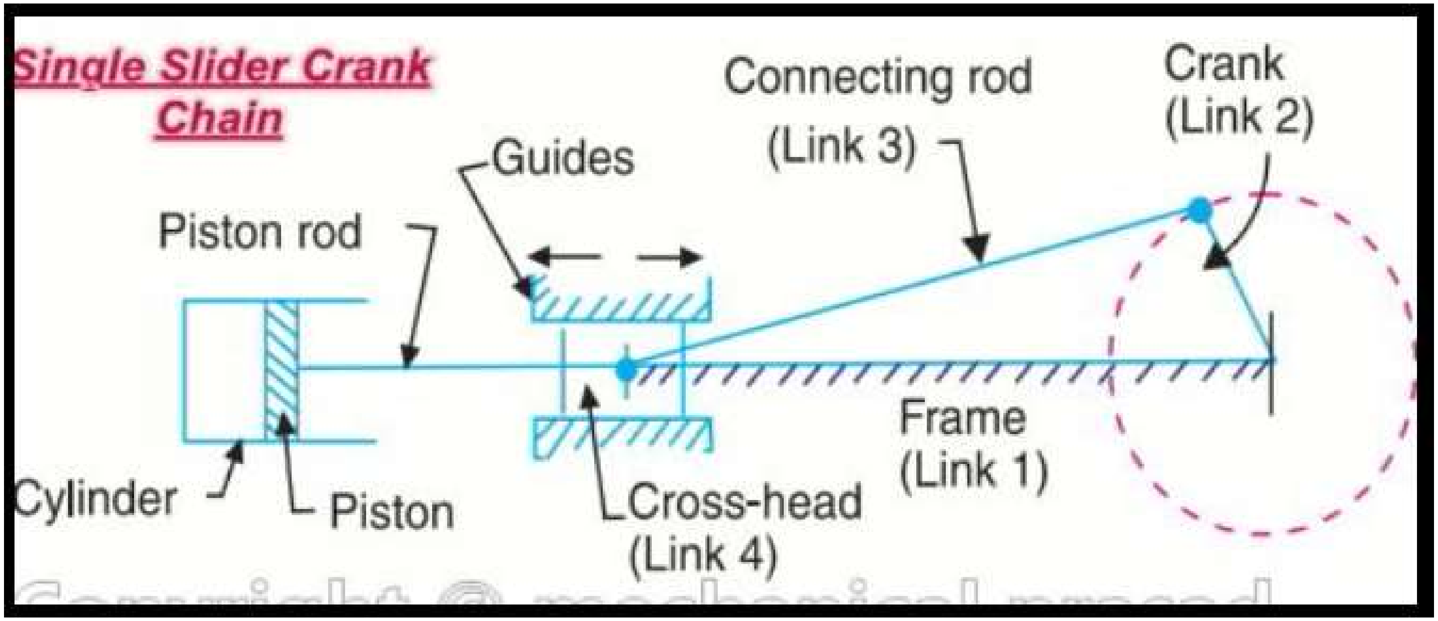
When one of the link of a kinematic chain is fixed and is used to transmits motion then the chain is known as mechanism.

Simple & Compound Mechanism:

A mechanism with four links is known as simple mechanism and a mechanism with more than four links is known as compound mechanism.

When the mechanism is required to transmit power or to do some particular type of work , then it becomes machine.

Sr. No.	Mechanism	Machine
01	Primary function is used to transmit or modify the motion.	Primary function is to obtain the mechanical advantage.
02	It is not used to transmit the force.	It is used transmit the force.
03	A mechanism is a single system to transfer the motion	A machine has one or more mechanism to perform the desired function.
04	eg. In watch, energy stored on winding the spring is used to move hands An indicator is used to draw P-V diagram of engine	eg. Shaper receives mechanical power which is used to suitably convert to do work of cutting the metal A hoist is machine to lift the loads.


Single Slider Crank Chain
Connecting rod
(Link 3)
Crank
(Link 2)
Guides
Piston rod
Frame
(Link 1)
Cylinder
Piston
Cross-head
(Link 4)

KINEMATIC PAIR

If two links or elements of a machine are in contact with each other, then it is known as pair.

And If the relative motion between them is completely or successfully constrained (i.e. in definite direction), the pair is known as kinematic pair.

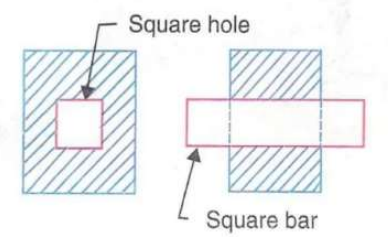
Constrained Motion → Motion in Definite Direction

Types of Constrained motion:

1. Completely constrained motion
2. Incompletely constrained motion
3. Successfully constrained motion

a) Completely Constrained Motion :

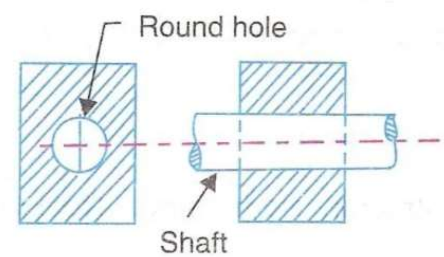
When a motion between a pair is limited to a definite direction then the motion is known as completely constrained motion.



b) Incompletely Constrained Motion :

When the motion between a pair can take place in more than one direction, then the motion is called incompletely constrained motion.

eg: A circular bar in circular hole

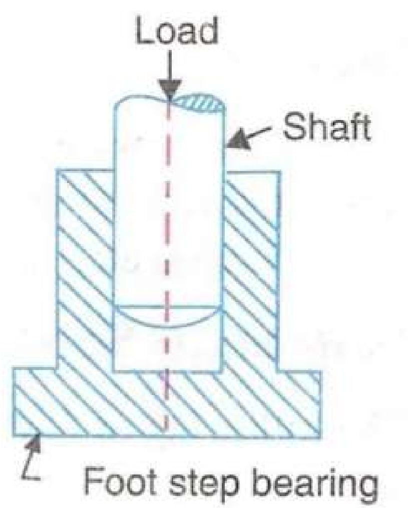


C) Successfully constrained motion :

When the motion between the pairs is not completely constrained by itself, but by some other means , then the motion is said to be successfully constrained motion.

eg: Motion of I.C. Engine valves

Shaft in footstep bearing



Classification of Kinematic Pair:

I] Classification according the type of Relative motion between the elements

a) Sliding pair
b) Turning pair
c) Rolling pair
d) Screw pair
e) Spherical pair

II] Classification according to the type of contact between the elements

a) Lower pair
b) Higher pair

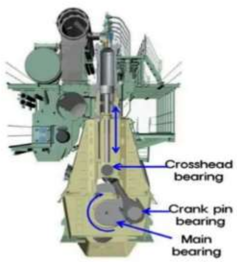
III] Classification according to the type of Closure

a) Self closed pair
b) Force closed pair

a) Sliding Pair

In a pair, if one element can only slide relative to other element, the pair is known as sliding pair.

eg: Piston & cylinder, crosshead & guides, tail stock on lathe bed



b) Turning Pair

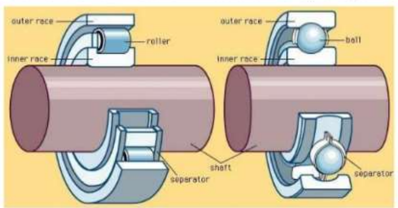
In a pair, if one element can turn or revolve about the fixed center of other, the pair is known as turning pair.

eg: Shaft in bearing, Lathe spindle on Headstock, Cycle wheel on axle

C) Rolling Pair:

In a pair, if one element rolls over another fixed element, the pair is known as rolling pair.

Eg: Ball & Roller Bearing



d) Screw Pair:

In a pair, if one element can turn about the other by screw threads, the pair is known as screw pair.

Eg: Nut & bolt, lead screw of lathe with nut

e) Spherical Pair:

In a pair, if one element turns or swivels about the other fixed element, the pair is known as spherical pair.

Eg: Ball & socket joint, Attachment of vehicle mirrors, Pen stand, etc.

II] a) Lower Pair:

When the two elements of a pair have a surface contact during their relative motion and the motion between them is sliding, the pair is known as lower pair.

Eg: sliding pairs, turning pairs, screw pairs

b) Higher Pairs:

When two elements of a pair have a line or point contact during their relative motion & the motion between them is partly sliding & partly turning, the pair is known as higher pairs.

Eg.: cam & follower, toothed gearing, ball & roller bearing.

III] a) Self Closed Pairs:

When two element in a pairs are in contact mechanically itself, it is known as self closed pairs.

Eg: Lower Pairs

b) Force Closed Pairs :

When two elements in a pair are in contact by applying external forces, a pair is known as force closed pair.

Eg: cam & follower, I.C. engine valve, etc

KINEMATIC CHAIN:

When the kinematic pairs are coupled together to transmit definite motion (i.e. completely or successfully constrained) then it is called a kinematic chain.

In a kinematic chain

Relation between number of pairs (p) & number of links (l) is given by

$$l = 2p - 4 \quad (1)$$

Relation between number of joints (j) & number of links (l) is given by

$$J = 3/2l - 2 \quad (2)$$

In above eqn 1 & 2

If LHS > RHS ⟹ Locked chain \ structure

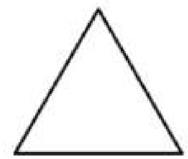
IF LHS = RHS ⟹ Kinematic chain

IF LHS < RHS ⟹ Unconstrained chain

1) l=3, p=3,j=3

l=2p-4	j=3/2l-2
3=2(3)-4	3=3/2*3-2
3>2	3>2.5
LHS>RHS	LHS>RHS

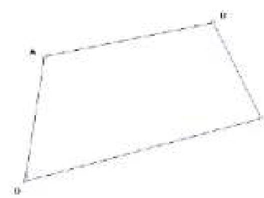
Above chain is locked chain/ Structure



2) l=4, p=4, j=4

L=2p-4	j=3/2l-2
4=2*4-4	4=3/2*4-4
4=4 4=4	
LHS=RHS	LHS=RHS

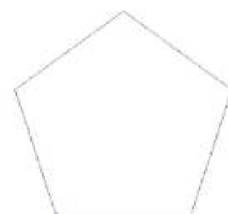
Hence above chain is a Kinematic Chain of ONE DEGREE OF FREEDOM.



3) l=5, p=5, j=5

L=2P-4	J=3/2*L-2
5=2*5-4	5=3/2*5-2
5<6	5<5.5
LHS<RHS	LHS<RHS

Hence above chain is a Unconstrained chain.



Types of Joints in a Kinematic Chain

a) Binary joint
b) Ternary joint
c) Quaternary joint

a) Binary Joint :

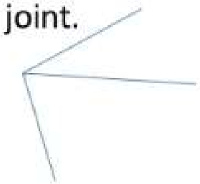
When the two links are joined at the same connection, the joint is known as binary joint.

b) Ternary joint:

When the three links are joined at the same connection the joint is known as ternary joint.

c) Quaternary joint:

When the four links are joined at the same connection the joint is known as quaternary joint.


Types of Kinematic Chain

1) Four bar chain
2) Single slider crank chain
3) Double slider crank chain

Inversion of the Mechanism

The method of obtaining different mechanisms by fixing different links in a kinematic chain is known as inversion of the mechanism.

Types and Inversion of the Mechanisms:

Types of Mechanisms/ Kinematic Chain:

1. Four bar chain
2. Single slider crank chain
3. Double slider crank chain

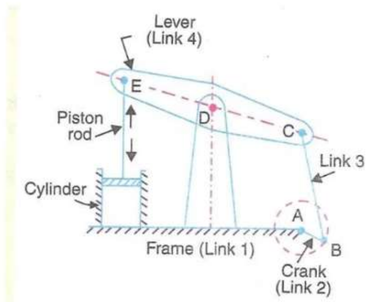
Four bar chain or Quadric cycle chain

It consist of four links, each of them forms a turning pair with each other.

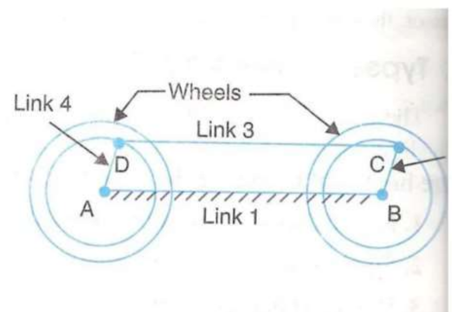
- In four bar chain a link which makes complete revolution relative to other three links is known as **crank/driver.**
- A link which makes partial rotation or oscillates is known as **Lever/follower/**
- A link which connects crank & lever is known as **connecting rod.**
- A link which is fixed is known as **frame.**

Inversions of Four Bar Chain

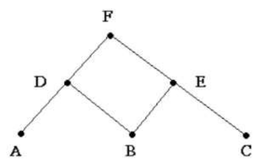
1. Beam Engine (Crank & Lever Mechanism)

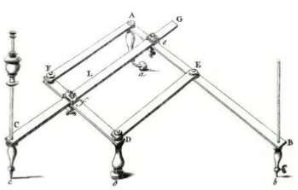


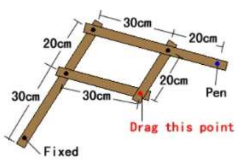
2. Coupling Rod of Locomotive (Double Lever Mechanism)



3. Pantograph (Double Lever Mechanism)

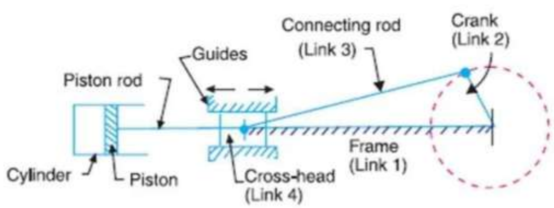






SINGLE SLIDER CRANK CHAIN

It is the modification of four bar chain.
It consist of one sliding pair & three turning pairs.
This type of mechanism converts rotary motion into reciprocating or viceversa.

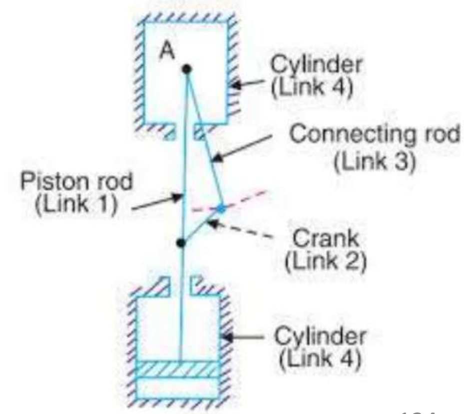


In fig. link 1&2, 2&3, 3&4 forms turning pairs.
Link 1&4 forms sliding pair.

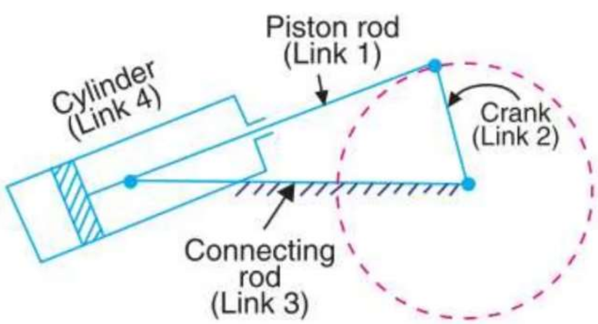
INVERSIONS OF SINGLE SLIDER CRANK CHAIN

1. Pendulum pump
2. Oscillating Cylinder Engine
3. Rotary Internal Combustion Engine (Gnome Engine)
4. With worth Quick Return Mechanism
5. Crank and Slotted Lever Mechanism

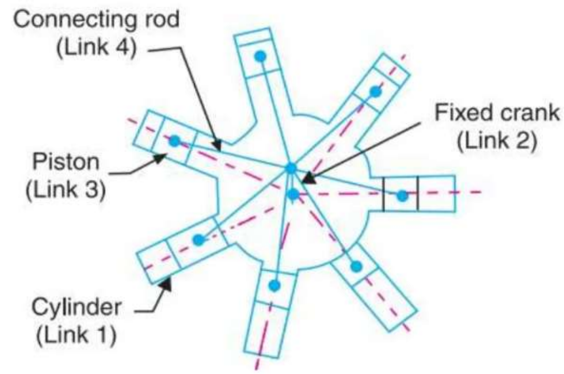
1. Pendulum pump



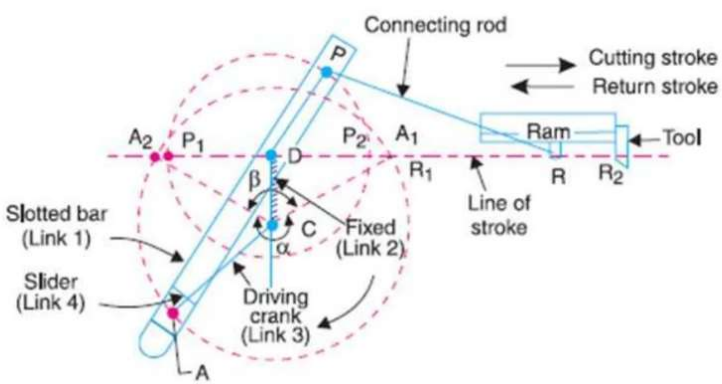
2. Oscillating Cylinder Engine



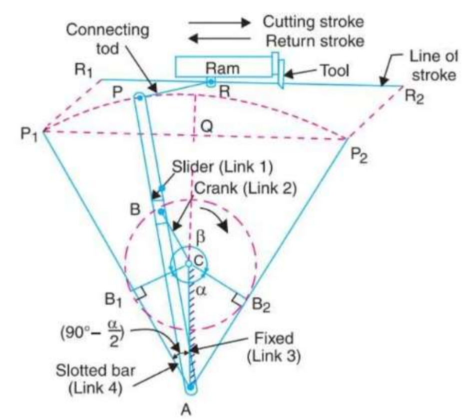
c) Rotary Internal Combustion Engine (Gnome Engine)



d) With worth Quick Return Mechanism



e) Crank and Slotted Lever Mechanism

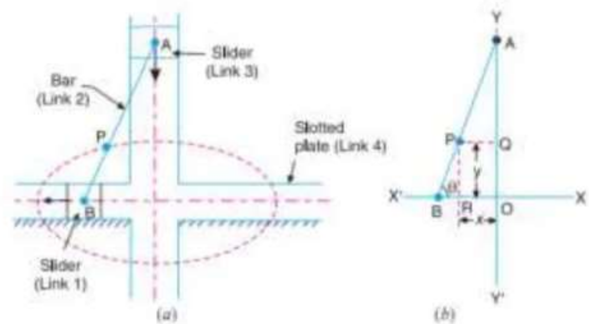


DOUBLE SLIDER CRANK CHAIN

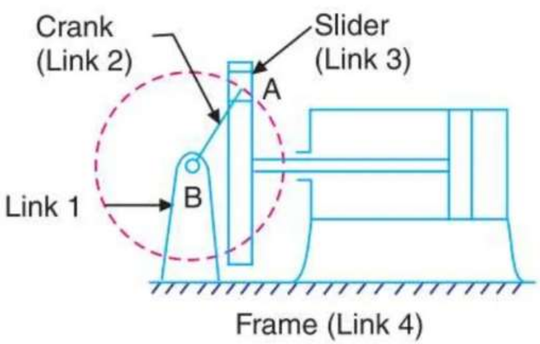
- The inversion of the double slider crank mechanism consists of two sliding pair and two turning pairs.

INVERSIONS OF DOUBLE SLIDER CRANK CHAIN

a) Elliptical Trammel

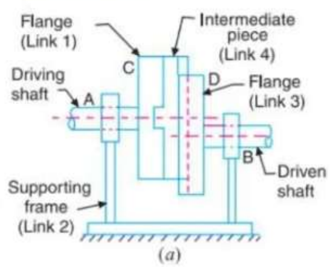


b) Scotch Yoke Mechanism

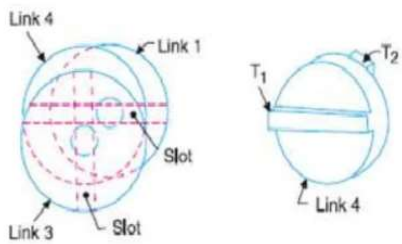


c) Oldham's Coupling

i) Assembly



ii) Working



Simple Machine

A machine is a device which receives energy in some available form and uses it for doing a particular useful work.
A lifting machine may be defined as device to overcome a force or load (W) applied at one point by means of another force called effort (P) applied at another point. In most of the cases, P is smaller than W.

- The point of application of effort
- Mechanism
- Point where load is lifted.

1. **Simple machine**: one point of application for load and one point for load. Lever, screw jack
2. **Compound machine**: More than one point. Lathe machine

Mechanical advantage (M.A.)

It is ratio of the weight lifted to the effort applied. Unit less quantity.

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

Velocity Ratio (V.R.)

It is ratio of the distance (y) moved by the effort to the distance (x) moved by the load. Unit less quantity.

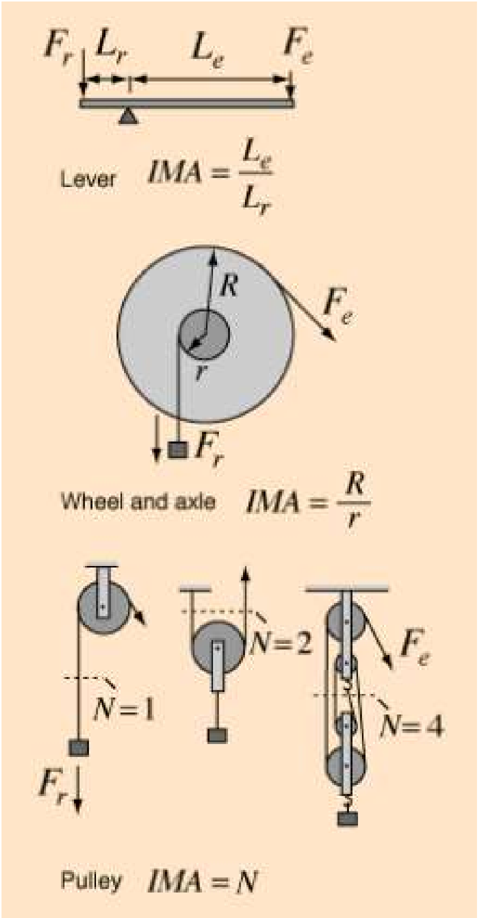
$$\text{V.R.} = \frac{y}{x}$$

Input of a machine.

It is the work done on the machine . In a lifting machine, it is measured by the product of effort and the distance through which it has moved (P . y).

Output of a machine.

It is the actual work done by the machine . In a lifting machine, it is measured by the product of weight lifted and the distance through which it has been lifted (W . x).


F_r L_r L_e F_e
Lever $IMA = \frac{L_e}{L_r}$
R
F_e
r
F_r
Wheel and axle $IMA = \frac{R}{r}$
$N=1$
$N=2$
F_e
$N=4$
F_r
Pulley $IMA = N$

Efficiency of a machine

It is ratio of output to the input of a machine. It is generally expressed as percentage

$$\eta = \frac{Output}{Input}$$

An ideal machine has its efficiency 100%. Output is equal to input.

Relation between efficiency , M.A. and V.R. of machine

Let

$$W = Load\ lifted$$
$$P = effort\ required\ to\ lift\ the\ load$$
$$y = distance\ moved\ by\ the\ effort\ in\ lifting\ the\ load$$
$$x = distance\ moved\ by\ the\ load$$
$$\eta = efficiency\ of\ the\ machine$$

Then the M.A. of the machine is given by

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

And the V.R. of the machine is given by

$$\text{V.R.} = \frac{y}{x}$$

$$\eta = \frac{Output}{Input} = \frac{W.x}{P.y} = \frac{W/p}{y/x} = \frac{M.A.}{V.R.}$$

Law of a machine

The law of a machine gives the relationship between the effort applied and the load lifted.

For any machine if a graph is plotted between effort P and load lifted W , it will be found that it follows a straight line relation.

$$P = mW + C$$

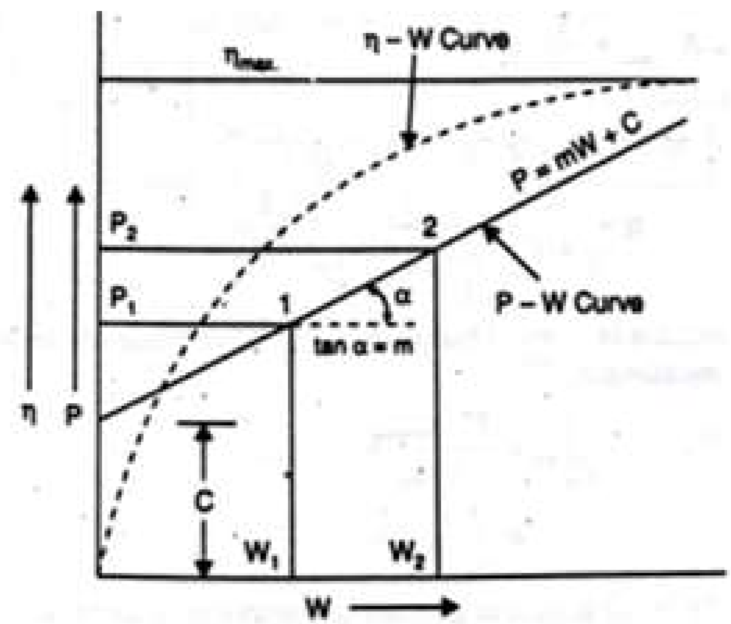
$$P_1 = mW_1 + C$$
$$P_2 = mW_2 + C$$

$$P_1 - P_2 = m(W_1 - W_2)$$

$$m = \frac{P_1 - P_2}{W_1 - W_2}$$

$$P_1 = \left(\frac{P_1 - P_2}{W_1 - W_2}\right) W_1 + C$$

$$C = P_1 - \left(\frac{P_1 - P_2}{W_1 - W_2}\right) W_1$$



$$\text{M.A.} = W/P$$
$$= \frac{W}{mW + C}$$
$$= \frac{1}{m + \frac{C}{W}}$$

$$\text{M.A.}_{max} = \frac{1}{m}$$

$$\text{M.A.} = \eta \times \text{V.R.}$$
$$\eta = \frac{\text{M.A}}{\text{V.R}} = \frac{1}{\left(m + \frac{C}{W}\right)} \times \frac{1}{\text{V.R}}$$

V.R. of any machine is fixed. So efficiency is proportional to M.A.

$$\eta_{max} = \frac{\text{M.A.}_{max}}{\text{V.R.}}$$
$$= \frac{1}{m} \times \frac{1}{\text{V.R.}}$$

Conclusions:

1. M.A. increases with load
2. Efficiency also increases with load
3. M.A. will be maximum at a very high value of load.
4. Efficiency will also be maximum at a very high value of load.

Pulleys:

A simple pulley is a wheel of metal having a groove on its circumference to receive a rope or chain, capable of rotation about an axle passing through its centre and perpendicular to its plane. The axle is supported in a frame work of metal or wood known as the block. The pulley is known as fixed pulley if the frame work supporting the axle of pulley is fixed. If the frame work or the block is movable the pulley is termed as movable pulley.

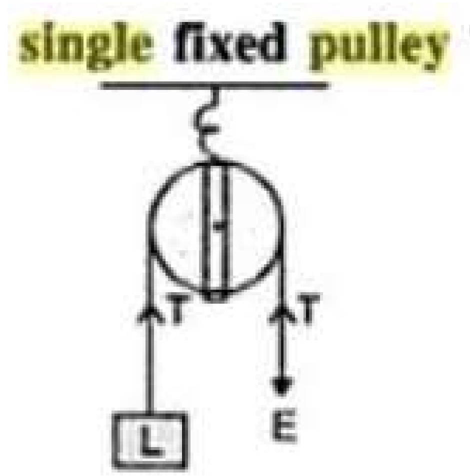
Assumptions:

1. The weight of pulley block is small as compared to the weight lifted and, thus may be neglected in calculations
2. The friction between pulley surface and string is negligible, and thus the tension in the two sides of the rope may be taken to be equal.

A single fixed pulley:

M.A. = V.R. =1

M.A. = m where m = number of chords supporting moveable pulleys.



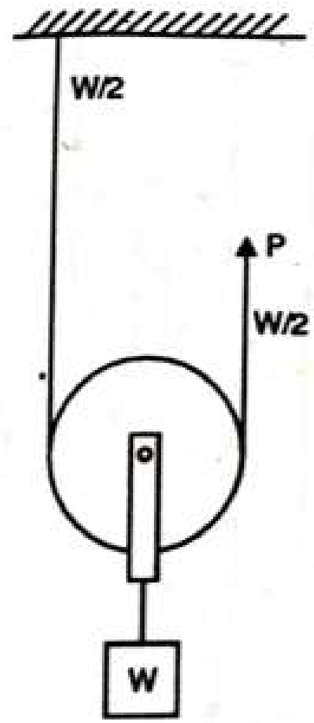
A single moveable pulley:

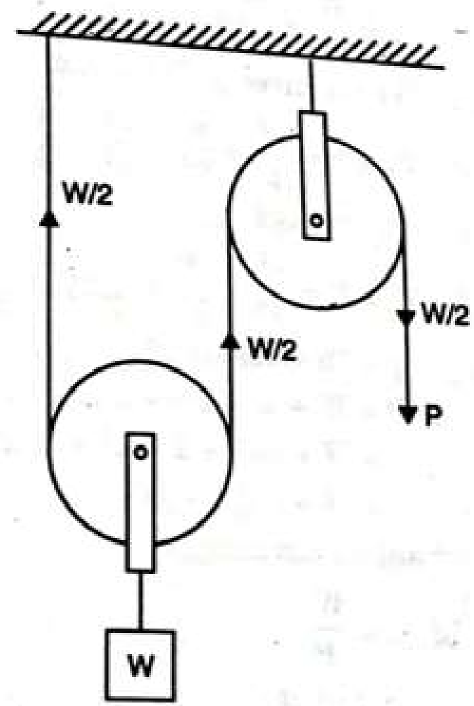
Thus, $P = W/2$ or $W/P = 2$

If weight of the pulley is w then

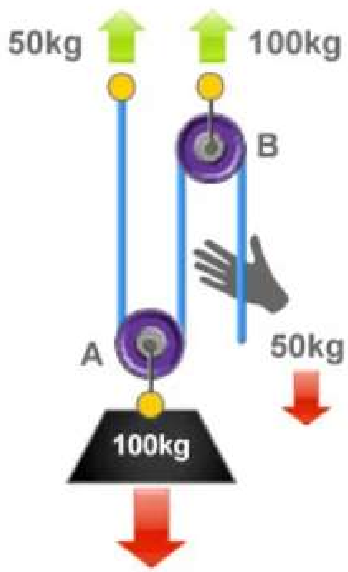
$$P = \frac{1}{2}(W + w)$$

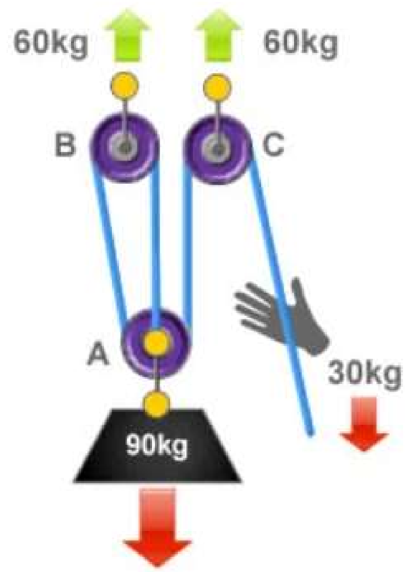
$$\frac{W}{P} + \frac{w}{P} = 2 \qquad \frac{W}{P} = 2 - \frac{w}{P}$$

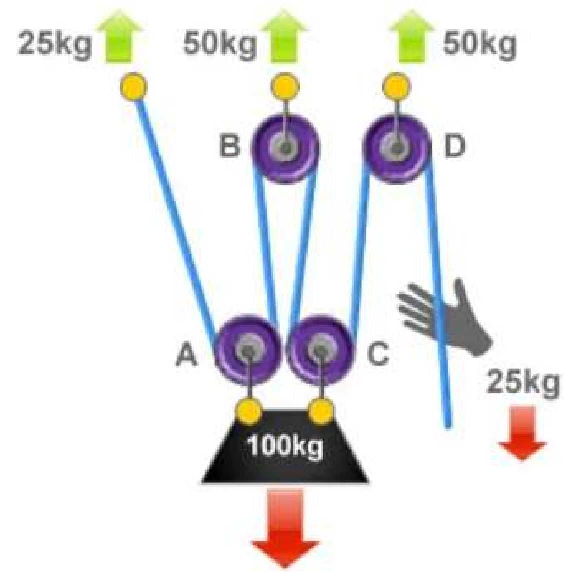


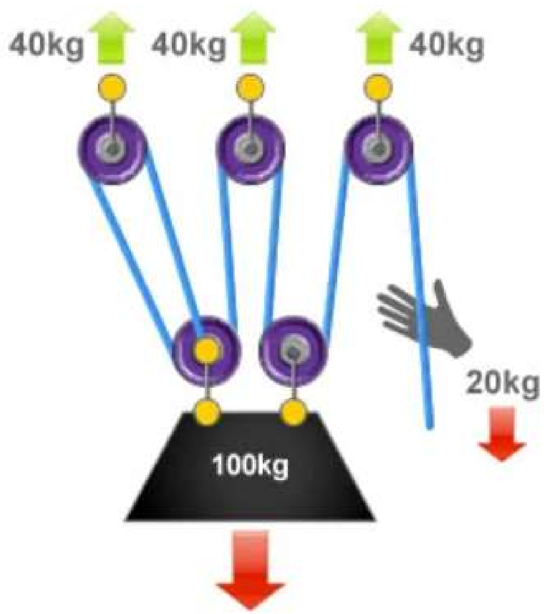


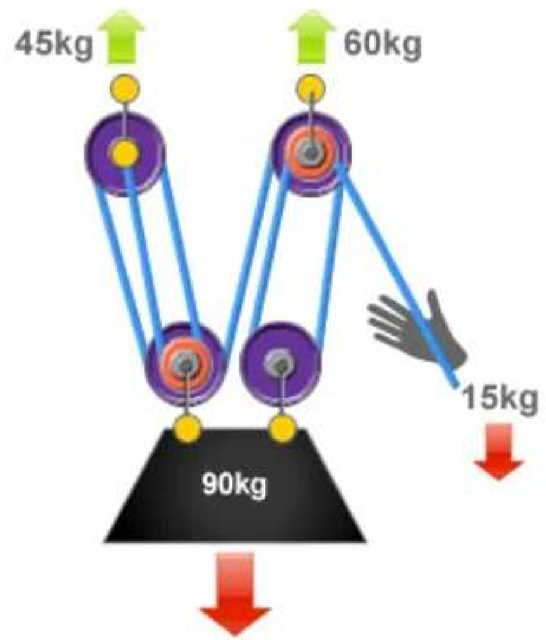
The M.A. in case of moveable pulley is greater than one but application of force is not easy. A fixed pulley can be introduced to remove this issue.


50kg
100kg
B
A
50kg
100kg


60kg
60kg
B
C
A
30kg
90kg


25kg
50kg
50kg
B
D
A
C
25kg
100kg


40kg
40kg
40kg
20kg
100kg


45kg
60kg
15kg
90kg

Classification of engineering Materials

The engineering materials are mainly classified as :

1. Metals and their alloys, such as iron, steel, copper, aluminium, etc.
2. Non-metals, such as glass, rubber, plastic, etc.

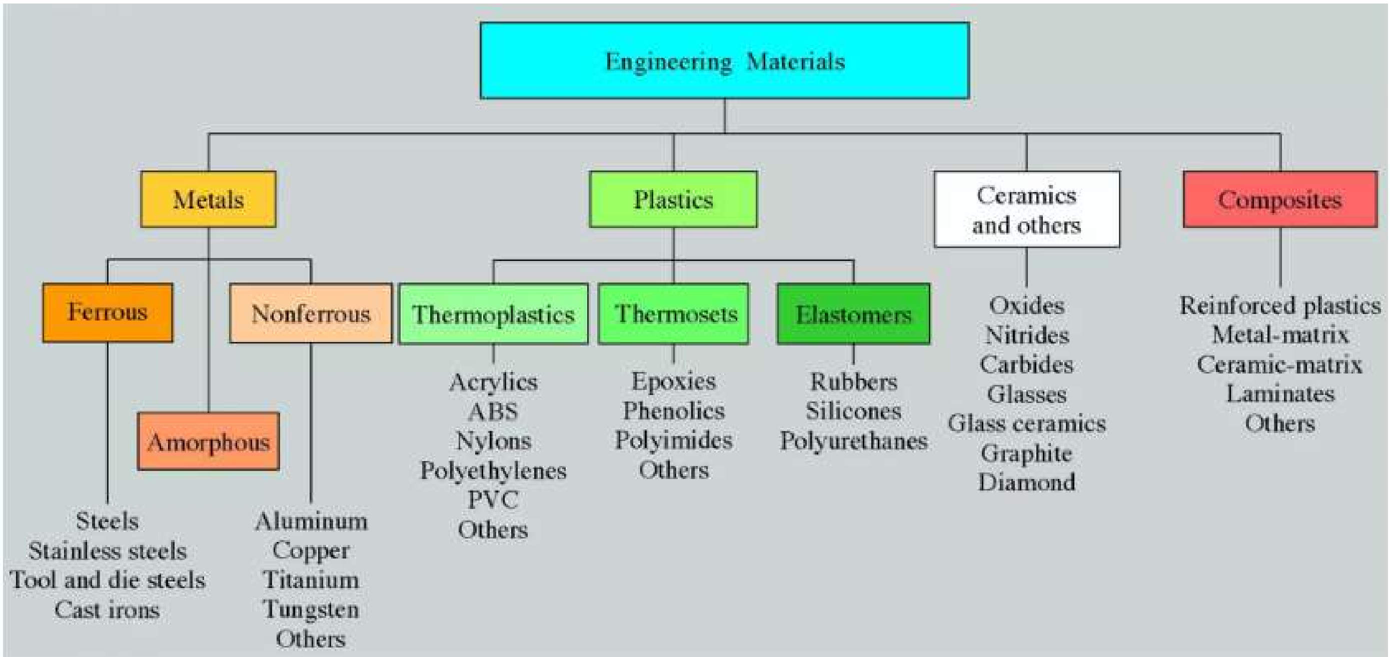
The metals may be further classified as :

(*a*) Ferrous metals, and (*b*) Non-ferrous metals.

The ******ferrous metals*** are those which have the iron as their main constituent, such as cast iron, wrought iron and steel.

The ***non-ferrous*** metals are those which have a metal other than iron as their main constituent, such as copper, aluminium, brass, tin, zinc, etc.

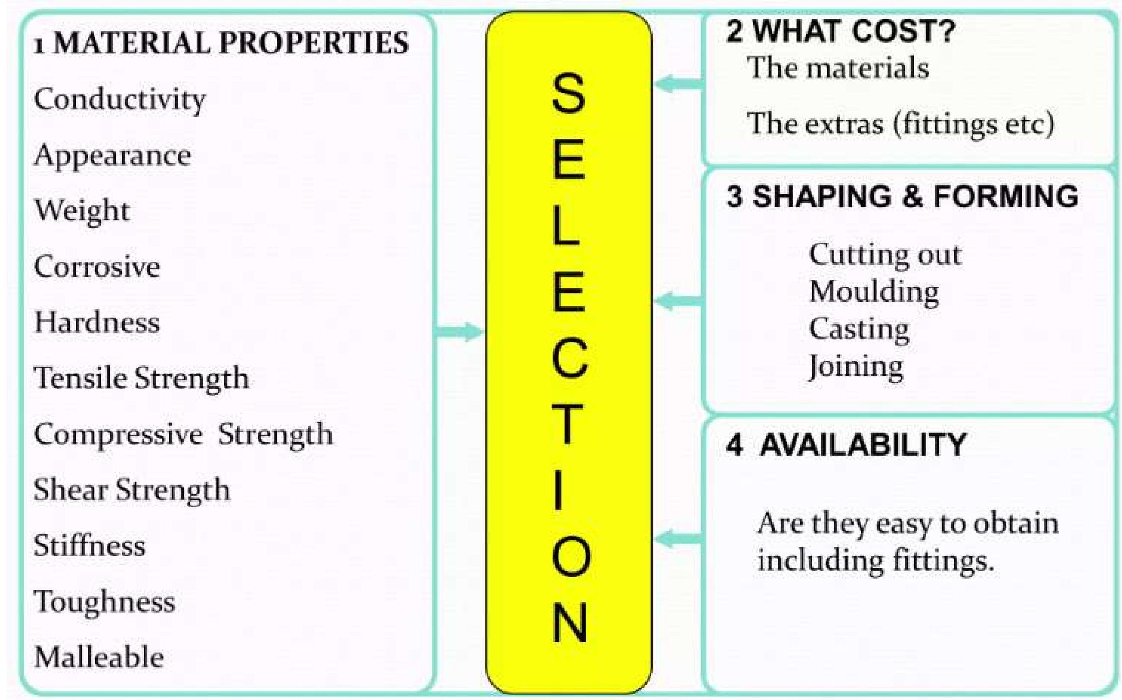
Classification of engineering Materials



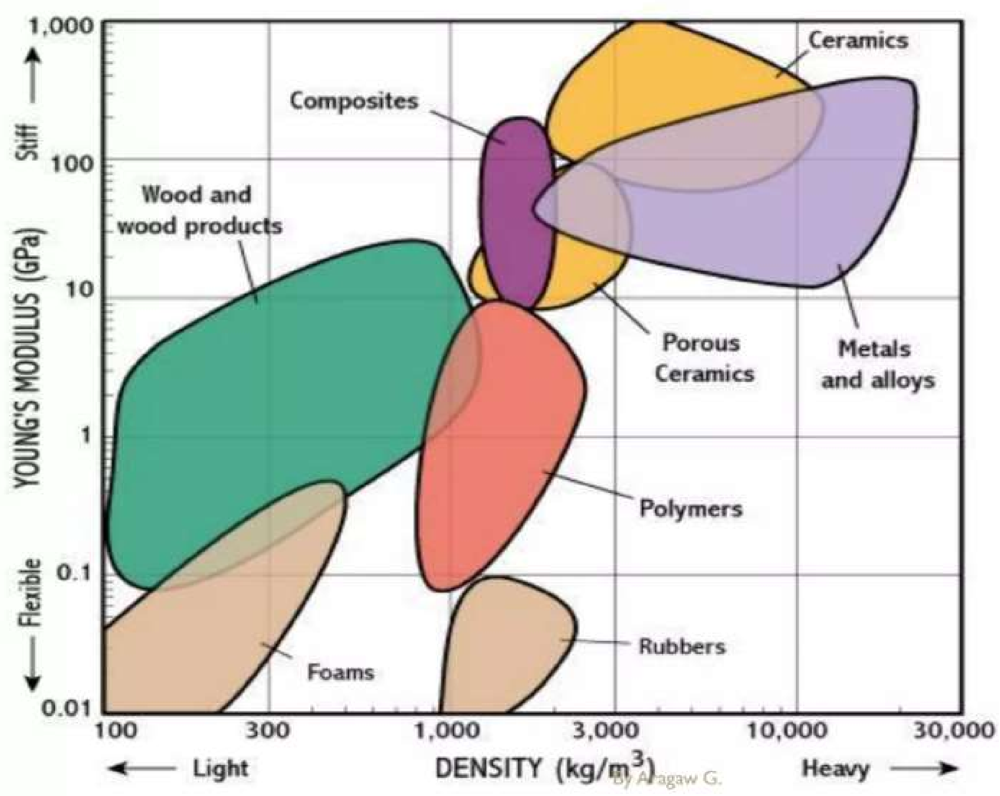
Selection of engineering Materials

The selection of a proper material, for engineering purposes, is one of the most difficult problem for the designer. The best material is one which serve the desired objective at the minimum cost. The following factors should be considered while selecting the material :

1. Availability of the materials,
2. Suitability of the materials for the working conditions in service, and
3. The cost of the materials.



Using Material Selection Charts



Physical Properties of Metals

The physical properties of the metals include luster, colour, size and shape, density, electric and thermal conductivity, and melting point. The following table shows the important physical properties of some pure metal

Table 2.1. Physical properties of metals.

Metal	*Density (kg/m³)*	*Melting point (°C)*	*Thermal conductivity (W/m°C)*	*Coefficient of linear expansion at 20°C (μm/m/°C)*
Aluminium	2700	660	220	23.0
Brass	8450	950	130	16.7
Bronze	8730	1040	67	17.3
Cast iron	7250	1300	54.5	9.0
Copper	8900	1083	393.5	16.7
Lead	11 400	327	33.5	29.1
Monel metal	8600	1350	25.2	14.0
Nickel	8900	1453	63.2	12.8
Silver	10 500	960	420	18.9
Steel	7850	1510	50.2	11.1
Tin	7400	232	67	21.4
Tungsten	19 300	3410	201	4.5
Zinc	7200	419	113	33.0
Cobalt	8850	1490	69.2	12.4
Molybdenum	10 200	2650	13	4.8
Vanadium	6000	1750	—	7.75

Materials Class	Definition	Examples	Properties	Applications
Metals	Metals are combinations of one or more "metallic elements," such as iron, gold, or lead. Alloys are metals like steel or bronze that combine more than one element, and may include non-metallic elements e.g. carbon.	Steel, aluminium, titanium iron, gold, lead, copper, platinum, brass, bronze, pewter, solder	Strong, dense, ductile, electrical and heat conductors, opaque	Electrical wiring, structures (buildings, bridges), automobiles (body, springs), airplanes, trains (rails, engine components, body, wheels), shape memory materials, magnets
Ceramics	Ceramic materials are inorganic materials with non-metallic properties usually processed at high temperature at some time during their manufacture	Structural ceramics, refractories, porcelain, glass	Lower density than metals, strong, low ductility (brittle), low thermal conductivity, corrosion resistant	Dinnerware, figurines, vases, art, bathtubs, sinks, electrical and thermal insulation, sewage pipes, floor and wall tile, dental fillings, abrasives, glass windows
Polymers	A polymer contains many chemically bonded parts or units that are bonded together to form a solid.	Plastics (synthetic, nylon, liquid crystals, adhesives, elastomers (rubber)	Low density, poor conductors of electricity and heat, different optical properties	Fabrics, car parts, packaging materials, bags, packing materials (Styrofoam*), fasteners (Velcro*), glue, containers, telephone headsets, rubber bands
Composites	Composites are two or more distinct substances that are combined to produce a new material with properties not present in either individual material.	Fibreglass (glass and a polymer), plywood (layers of wood and glue), concrete (cement and pebbles)	Properties depend on amount and distribution of each type of material. Collective set of properties are more desirable and possible than with any individual material.	Golf clubs, tennis rackets, bicycle frames, tires, cars, aerospace materials, paint

By Aragaw G. 33

Mechanical Properties of Metals

The mechanical properties of the metals are those which are associated with the ability of the material to resist mechanical forces and load. These mechanical properties of the metal include strength, stiffness, elasticity, plasticity, ductility, brittleness, malleability, toughness, resilience, creep and hardness. We shall now discuss these properties as follows:

1. ***Strength.*** It is the ability of a material to resist the externally applied forces without breaking or yielding. The internal resistance offered by a part to an externally applied force is called *stress.

2. ***Stiffness.*** It is the ability of a material to resist deformation under stress. The modulus of elasticity is the measure of stiffness.

3. ***Elasticity.*** It is the property of a material to regain its original shape after deformation when the external forces are removed. This property is desirable for materials used in tools and machines. It may be noted that steel is more elastic than rubber.

4. ***Plasticity.*** 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 images on coins and in ornamental work.

5. ***Ductility.*** It is the property of a material enabling it to be drawn into wire with the application of a tensile force. A ductile material must be both strong and plastic. The ductility is usually measured by the terms, percentage elongation and percentage reduction in area. The ductile material commonly used in engineering practice (in order of diminishing ductility) are mild steel, copper, aluminium, nickel, zinc, tin and lead.

6. ***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 materials when subjected to tensile loads, snap off without giving any sensible elongation. Cast iron is a brittle material.

7. ***Malleability.*** It is a special case of ductility which permits materials to be rolled or hammered into thin sheets. A malleable material should be plastic but it is not essential to be so strong. The malleable materials commonly used in engineering practice (in order of diminishing malleability) are lead, soft steel, wrought iron, copper and aluminium.

8. ***Toughness.*** It is the property of a material to resist fracture due to high impact loads like hammer blows. The toughness of the material decreases when it is heated. It is measured by the

Amount of energy that a unit volume of the material has absorbed after being stressed upto the point of fracture. This property is desirable in parts subjected to shock and impact loads

9. ***Machinability.*** It is the property of a material which refers to a relative case with which a material can be cut. The machinability of a material can be measured in a number of ways such as comparing the tool life for cutting different materials or thrust required to remove the material at some given rate or the energy required to remove a unit volume of the material. It may be noted that brass can be easily machined than steel.

10. ***Resilience.*** It is the property of a material to absorb energy and to resist shock and impact loads. It is measured by the amount of energy absorbed per unit volume within elastic limit. This property is essential for spring materials.

11. ***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.

12. ***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***. The failure is caused by means of a progressive crack formation which are usually fine and of microscopic size. This property is Considered in designing shafts, connecting rods, springs, gears etc.

13. ***Hardness.*** It is a very important property of the metals and has a wide variety of meanings. It embraces many different properties such as resistance to wear, scratching, deformation and machinability etc. It also means the ability of a metal to cut another metal. The hardness is usually expressed in numbers which are dependent on the method of making the test. The hardness of a metal may be determined by the following tests :

(*a*) Brinell hardness test,

(*b*) Rockwell hardness test,

(*c*) Vickers hardness (also called Diamond Pyramid) test, and

(*d*) Shore scleroscope.

Ferrous Metals

We have already discussed in Art. 2.2 that the ferrous metals are those which have iron as their main constituent. The ferrous metals commonly used in engineering practice are cast iron, wrought iron, steels and alloy steels. The principal raw material for all ferrous metals is pig iron which is obtained by smelting iron ore with coke and limestone, in the blast furnace. The principal iron ores with their metallic contents are shown in the following table :

Table 2.2. Principal iron ores.

Iron ore	*Chemical formula*	*Colour*	*Iron content (%)*
Magnetite	Fe_2O_3	Black	72
Haemetite	Fe_3O_4	Red	70
Limonite	$FeCO_3$	Brown	60–65
Siderite	$Fe_2O_3\ (H_2O)$	Brown	48

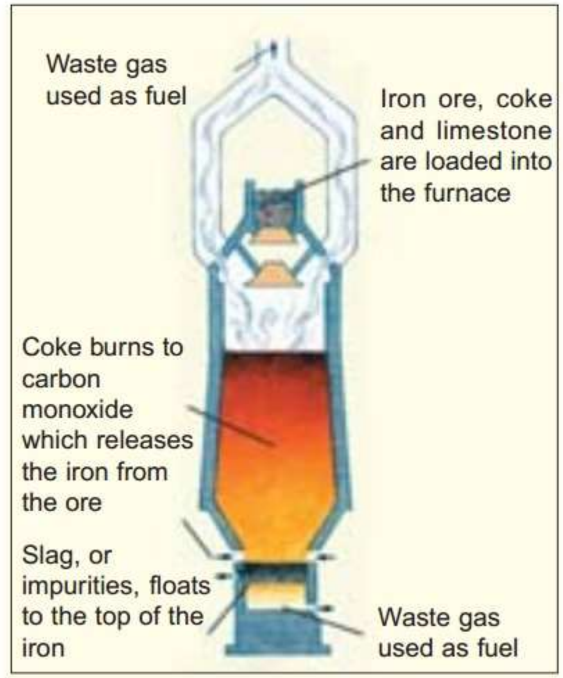
Cast Iron

The cast iron is obtained by re-melting pig iron with coke and limestone in a furnace known as cupola. It is primarily an alloy of iron and carbon. The carbon contents in cast iron varies from 1.7 per cent to 4.5 per cent. It also contains small amounts of silicon, manganese, phosphorous and sulphur. The carbon in a cast iron is present in either of the following two forms:

1. Free carbon or graphite, and **2.** Combined carbon or cementite.

Since the cast iron is a brittle material, therefore, it cannot be used in those parts of machines which are subjected to shocks. The properties of cast iron which make it a valuable material for engineering purposes are its low cost, good casting characteristics, high compressive strength, wear resistance and excellent machinability. The compressive strength of cast iron is much greater than the tensile strength. Following are the values of ultimate strength of cast iron :

Tensile strength	=	100 to 200 MPa*
Compressive strength	=	400 to 1000 MPa
Shear strength	=	120 MPa



Smelting : Ores consist of non-metallic elements like oxygen or sulphur combined with the wanted metal. Iron is separated from the oxygen in its ore heating it with carbon monoxide derived from coke (a form of carbon made from coal). Limestone is added to keep impurities liquid so that the iron can separate from them.

Effect of Impurities on Cast Iron

We have discussed in the previous articles that the cast iron contains small percentages of silicon, sulphur, manganese and phosphorous. The effect of these impurities on the cast iron are as follows:

1. *Silicon.* It may be present in cast iron upto 4%. It provides the formation of free graphite which makes the iron soft and easily machinable. It also produces sound castings free from blow-holes, because of its high affinity for oxygen.

2. *Sulphur.* It makes the cast iron hard and brittle. Since too much sulphur gives unsound casting, therefore, it should be kept well below 0.1% for most foundry purposes.

3. *Manganese.* It makes the cast iron white and hard. It is often kept below 0.75%. It helps to exert a controlling influence over the harmful effect of sulphur.

4. *Phosphorus.* It aids fusibility and fluidity in cast iron, but induces brittleness. It is rarely allowed to exceed 1%. Phosphoric irons are useful for casting of intricate design and for many light engineering castings when cheapness is essential.

Wrought Iron

It is the purest iron which contains at least 99.5% iron but may contain upto 99.9% iron. The typical composition of a wrought iron is

Carbon = 0.020%, Silicon = 0.120%, Sulphur = 0.018%, Phosphorus = 0.020%, Slag = 0.070%, and the remaining is iron.

Steel

It is an alloy of iron and carbon, with carbon content up to a maximum of 1.5%. The carbon occurs in the form of iron carbide, because of its ability to increase the hardness and strength of the steel. Other elements *e.g.* silicon, sulphur, phosphorus and manganese are also present to greater or lesser amount to impart certain desired properties to it. Most of the steel produced now-a-days is ***plain carbon steel*** or simply ***carbon steel.*** A carbon steel is defined as a steel which has its properties mainly due to its carbon content and does not contain more than 0.5% of silicon and 1.5% of manganese. The plain carbon steels varying from 0.06% carbon to 1.5% carbon are divided into the following types depending upon the carbon content.

1. Dead mild steel — up to 0.15% carbon
2. Low carbon or mild steel — 0.15% to 0.45% carbon
3. Medium carbon steel — 0.45% to 0.8% carbon
4. High carbon steel — 0.8% to 1.5% carbon

According to Indian standard *[IS : 1762 (Part-I)–1974], a new system of designating the steel is recommended. According to this standard, steels are designated on the following two basis :

(*a*) On the basis of mechanical properties, and (*b*) On the basis of chemical composition.

Effect of Impurities on Steel

The following are the effects of impurities like silicon, sulphur, manganese and phosphorus on steel.

1. *Silicon.* The amount of silicon in the finished steel usually ranges from 0.05 to 0.30%. Silicon is added in low carbon steels to prevent them from becoming porous. It removes the gases and oxides, prevent blow holes and thereby makes the steel tougher and harder.

2. *Sulphur.* It occurs in steel either as iron sulphide or manganese sulphide. Iron sulphide because of its low melting point produces red shortness, whereas manganese sulphide does not effect so much. Therefore, manganese sulphide is less objectionable in steel than iron sulphide.

3. *Manganese.* It serves as a valuable deoxidising and purifying agent in steel. Manganese also combines with sulphur and thereby decreases the harmful effect of this element remaining in the steel. When used in ordinary low carbon steels, manganese makes the metal ductile and of good bending qualities. In high speed steels, it is used to toughen the metal and to increase its critical temperature.

4. *Phosphorus.* It makes the steel brittle. It also produces cold shortness in steel. In low carbon steels, it raises the yield point and improves the resistance to atmospheric corrosion. The sum of carbon and phosphorus usually does not exceed 0.25%.

Free Cutting Steels

The free cutting steels contain sulphur and phosphorus. These steels have higher sulphur content than other carbon steels. In general, the carbon content of such steels vary from 0.1 to 0.45 per cent and sulphur from 0.08 to 0.3 per cent. These steels are used where rapid machining is the prime requirement. It may be noted that the presence of sulphur and phosphorus causes long chips in machining to be easily broken and thus prevent clogging of machines. Now a days, lead is used from 0.05 to 0.2 per cent instead of sulphur, because lead also greatly improves the machinability of steel without the loss of toughness.

According to Indian standard, IS : 1570 (Part III)-1979 (Reaffirmed 1993), carbon and carbon manganese free cutting steels are designated in the following order :

1. Figure indicating 100 times the average percentage of carbon,
2. Letter 'C',
3. Figure indicating 10 times the average percentage of manganese, and
4. Symbol 'S' followed by the figure indicating the 100 times the average content of sulphur. If instead of sulphur, lead (Pb) is added to make the steel free cutting, then symbol 'Pb' may be used.

Table 2.7 shows the composition and uses of carbon and carbon-manganese free cutting steels, as per IS : 1570 (Part III)-1979 (Reaffirmed 1993).

Alloy Steel

An alloy steel may be defined as a steel to which elements other than carbon are added in sufficient amount to produce an improvement in properties. The alloying is done for specific purposes to increase wearing resistance, corrosion resistance and to improve electrical and magnetic properties, which cannot be obtained in plain carbon steels. The chief alloying elements used in steel are nickel, chromium, molybdenum, cobalt, vanadium, manganese, silicon and tungsten. Each of these elements confer certain qualities upon the steel to which it is added. These elements may be used separately or in combination to produce the desired characteristic in steel. Following are the effects of alloying elements on steel:

1. ***Nickel***. It increases the strength and toughness of the steel. These steels contain 2 to 5% nickel and from 0.1 to 0.5% carbon. In this range, nickel contributes great strength and hardness with high elastic limit, good ductility and good resistance to corrosion. An alloy containing 25% nickel possesses maximum toughness and offers the greatest resistance to rusting, corrosion and burning at high temperature. It has proved to be of advantage in the manufacture of boiler tubes, valves for use with superheated steam, valves for I.C. engines and spark plugs for petrol engines. A nickel steel alloy containing 36% of nickel is known as ***invar***. It has nearly zero coefficient of expansion. So it is in great demand for measuring instruments and standards of lengths for everyday use.

2. ***Chromium***. It is used in steels as an alloying element to combine hardness with high strength and high elastic limit. It also imparts corrosion-resisting properties to steel. The most common chrome steels contains from 0.5 to 2% chromium and 0.1 to 1.5% carbon. The chrome steel is used for balls, rollers and races for bearings. A ***nickel chrome steel*** containing 3.25% nickel, 1.5% chromium and 0.25% carbon is much used for armour plates. Chrome nickel steel is extensively used for motor car crankshafts, axles and gears requiring great strength and hardness.

3. ***Tungsten.*** It prohibits grain growth, increases the depth of hardening of quenched steel and confers the property of remaining hard even when heated to red colour. It is usually used in conjuction with other elements. Steel containing 3 to 18% tungsten and 0.2 to 1.5% carbon is used for cutting tools. The principal uses of tungsten steels are for cutting tools, dies, valves, taps and permanent magnets.

4. ***Vanadium.*** It aids in obtaining a fine grain structure in tool steel. The addition of a very small amount of vanadium (less than 0.2%) produces a marked increase in tensile strength and elastic limit in low and medium carbon steels without a loss of ductility. The ***chrome-vanadium steel*** containing about 0.5 to 1.5% chromium, 0.15 to 0.3% vanadium and 0.13 to 1.1% carbon have extremely good tensile strength, elastic limit, endurance limit and ductility. These steels are frequently used for parts such as springs, shafts, gears, pins and many drop forged parts.

5. *Manganese.* It improves the strength of the steel in both the hot rolled and heat treated condition. The manganese alloy steels containing over 1.5% manganese with a carbon range of 0.40 to 0.55% are used extensively in gears, axles, shafts and other parts where high strength combined with fair ductility is required. The principal uses of manganese steel is in machinery parts subjected to severe wear. These steels are all cast and ground to finish.

6. *Silicon.* The silicon steels behave like nickel steels. These steels have a high elastic limit as compared to ordinary carbon steel. Silicon steels containing from 1 to 2% silicon and 0.1 to 0.4% carbon and other alloying elements are used for electrical machinery, valves in I.C. engines, springs and corrosion resisting materials.

7. *Cobalt.* It gives red hardness by retention of hard carbides at high temperatures. It tends to decarburise steel during heat-treatment. It increases hardness and strength and also residual magnetism and coercive magnetic force in steel for magnets.

8. *Molybdenum.* A very small quantity (0.15 to 0.30%) of molybdenum is generally used with chromium and manganese (0.5 to 0.8%) to make molybdenum steel. These steels possess extra tensile strength and are used for air-plane fuselage and automobile parts. It can replace tungsten in high speed steels.

Non-ferrous Metals

We have already discussed that the non-ferrous metals are those which contain a metal other than iron as their chief constituent. The non-ferrous metals are usually employed in industry due to the following characteristics :

1. Ease of fabrication (casting, rolling, forging, welding and machining),
2. Resistance to corrosion,
3. Electrical and thermal conductivity, and
4. Weight.

The various non-ferrous metals used in engineering practice are aluminium, copper, lead, tin, zinc, nickel, etc. and their alloys. We shall now discuss these non-ferrous metals and their alloys in detail, in the following pages.

Aluminium

It is white metal produced by electrical processes from its oxide (alumina), which is prepared from a clayey mineral called ***bauxite.*** It is a light metal having specific gravity 2.7 and melting point 658°C. The tensile strength of the metal varies from 90 MPa to 150 MPa.

In its pure state, the metal would be weak and soft for most purposes, but when mixed with small amounts of other alloys, it becomes hard and rigid. So, it may be blanked, formed, drawn, turned, cast, forged and die cast. Its good electrical conductivity is an important property and is widely used for overhead cables. The high resistance to corrosion and its non-toxicity makes it a useful metal for cooking utensils under ordinary condition and thin foils are used for wrapping food items. It is extensively used in aircraft and automobile components where saving of weight is an advantage.

Aluminium Alloys

The aluminium may be alloyed with one or more other elements like copper, magnesium, manganese, silicon and nickel. The addition of small quantities of alloying elements converts the soft and weak metal into hard and strong metal, while still retaining its light weight. The main aluminium alloys are discussed below:

1. ***Duralumin.*** It is an important and interesting wrought alloy. Its composition is as follows:

Copper = 3.5 – 4.5%; Manganese = 0.4 – 0.7%; Magnesium = 0.4 – 0.7%, and the remainder is aluminium.

This alloy possesses maximum tensile strength (upto 400 MPa) after heat treatment and age hardening. After working, if the metal is allowed to age for 3 or 4 days, it will be hardened. This phenomenon is known as ***age hardening.***

It is widely used in wrought conditions for forging, stamping, bars, sheets, tubes and rivets. It can be worked in hot condition at a temperature of 500°C. However, after forging and annealing, it can also be cold worked. Due to its high strength and light weight, this alloy may be used in automobile and aircraft components. It is also used in manufacturing connecting rods, bars, rivets, pulleys, etc.

2. ***Y-alloy.*** It is also called copper-aluminium alloy. The addition of copper to pure aluminium increases its strength and machinability. The composition of this alloy is as follows :

Copper = 3.5 – 4.5%; Manganese = 1.2 – 1.7%; Nickel = 1.8 – 2.3%; Silicon, Magnesium, Iron = 0.6% each; and the remainder is aluminium.

This alloy is heat treated and age hardened like duralumin. The ageing process is carried out at room temperature for about five days.

It is mainly used for cast purposes, but it can also be used for forged components like duralumin. Since *Y*-alloy has better strength (than duralumin) at high temperature, therefore, it is much used in aircraft engines for cylinder heads and pistons.

3. ***Magnalium.*** It is made by melting the aluminium with 2 to 10% magnesium in a vacuum and then cooling it in a vacuum or under a pressure of 100 to 200 atmospheres. It also contains about 1.75% copper. Due to its light weight and good mechanical properties, it is mainly used for aircraft and automobile components.

4. ***Hindalium.*** It is an alloy of aluminium and magnesium with a small quantity of chromium. It is the trade name of aluminium alloy produced by Hindustan Aluminium Corporation Ltd, Renukoot (U.P.). It is produced as a rolled product in 16 gauge, mainly for anodized utensil manufacture.

Copper

It is one of the most widely used non-ferrous metals in industry. It is a soft, malleable and ductile material with a reddish-brown appearance. Its specific gravity is 8.9 and melting point is 1083°C. The tensile strength varies from 150 MPa to 400 MPa under different conditions. It is a good conductor of electricity. It is largely used in making electric cables and wires for electric machinery and appliances, in electrotyping and electroplating, in making coins and household utensils.

It may be cast, forged, rolled and drawn into wires. It is non-corrosive under ordinary conditions and resists weather very effectively. Copper in the form of tubes is used widely in mechanical engineering. It is also used for making ammunitions. It is used for making useful alloys with tin, zinc, nickel and aluminium.

Copper Alloys

The copper alloys are broadly classified into the following two groups :

1. *Copper-zinc alloys (Brass).* The most widely used copper-zinc alloy is brass. There are various types of brasses, depending upon the proportions of copper and zinc. This is fundamentally a binary alloy of copper with zinc each 50%. By adding small quantities of other elements, the properties of brass may be greatly changed. For example, the addition of lead (1 to 2%) improves the machining quality of brass. It has a greater strength than that of copper, but have a lower thermal and electrical conductivity. Brasses are very resistant to atmospheric corrosion and can be easily soldered. They can be easily fabricated by processes like spinning and can also be electroplated with metals like nickel and chromium. The following table shows the composition of various types of brasses according to Indian standards.

2. *Copper-tin alloys (Bronze).* The alloys of copper and tin are usually termed as bronzes. The useful range of composition is 75 to 95% copper and 5 to 25% tin. The metal is comparatively hard, resists surface wear and can be shaped or rolled into wires, rods and sheets very easily. In corrosion resistant properties, bronzes are superior to brasses. Some of the common types of bronzes are as follows:

(a) ***Phosphor bronze.*** When bronze contains phosphorus, it is called phosphor bronze. Phosphorus increases the strength, ductility and soundness of castings. The tensile strength of this alloy when cast varies from 215 MPa to 280 MPa but increases upto 2300 MPa when rolled or drawn. This alloy possesses good wearing qualities and high elasticity. The metal is resistant to salt water corrosion. The composition of the metal varies according to whether it is to be forged, wrought or made into castings. A common type of phosphor bronze has the following composition according to Indian standards :

Copper = 87–90%, Tin = 9–10%, and Phosphorus = 0.1–3%.

It is used for bearings, worm wheels, gears, nuts for machine lead screws, pump parts, linings and for many other purposes. It is also suitable for making springs.

(b) ***Silicon bronze.*** It contains 96% copper, 3% silicon and 1% manganese or zinc. It has good general corrosion resistance of copper combined with higher strength. It can be cast, rolled, stamped, forged and pressed either hot or cold and it can be welded by all the usual methods.

It is widely used for boilers, tanks, stoves or where high strength and good corrosion resistance is required.

(c) ***Beryllium bronze.*** It is a copper base alloy containing about 97.75% copper and 2.25% beryllium. It has high yield point, high fatigue limit and excellent cold and hot corrosion resistance. It is particularly suitable material for springs, heavy duty electrical switches, cams and bushings. Since the wear resistance of beryllium copper is five times that of phosphor bronze, therefore, it may be used as a bearing metal in place of phosphor bronze.

It has a film forming and a soft lubricating property, which makes it more suitable as a bearing metal.

(*d*) ***Manganese bronze.*** It is an alloy of copper, zinc and little percentage of manganese. The usual composition of this bronze is as follows:

Copper = 60%, Zinc = 35%, and Manganese = 5%

This metal is highly resistant to corrosion. It is harder and stronger than phosphor bronze. It is generally used for bushes, plungers, feed pumps, rods etc. Worm gears are frequently made from this bronze.

(*e*) ***Aluminium bronze.*** It is an alloy of copper and aluminium. The aluminium bronze with 6–8% aluminium has valuable cold working properties. The maximum tensile strength of this alloy is 450 MPa with 11% of aluminium. They are most suitable for making components exposed to severe corrosion conditions. When iron is added to these bronzes, the mechanical properties are improved by refining the grain size and improving the ductility.

Aluminium bronzes are widely used for making gears, propellers, condenser bolts, pump components, tubes, air pumps, slide valves and bushings, etc. Cams and rollers are also made from this alloy. The 6% aluminium alloy has a fine gold colour which is used for imitation jewellery and decorative purposes.

Gun Metal

It is an alloy of copper, tin and zinc. It usually contains 88% copper, 10% tin and 2% zinc. This metal is also known as ***Admiralty gun metal.*** The zinc is added to clean the metal and to increase its fluidity.

It is not suitable for being worked in the cold state but may be forged when at about 600°C. The metal is very strong and resistant to corrosion by water and atmosphere. Originally, it was made for casting guns. It is extensively used for casting boiler fittings, bushes, bearings, glands, etc.

Lead

It is a bluish grey metal having specific gravity 11.36 and melting point 326°C. It is so soft that it can be cut with a knife. It has no tenacity. It is extensively used for making solders, as a lining for acid tanks, cisterns, water pipes, and as coating for electrical cables.

The lead base alloys are employed where a cheap and corrosion resistant material is required. An alloy containing 83% lead, 15% antimony, 1.5% tin and 0.5% copper is used for large bearings subjected to light service.

Tin

It is brightly shining white metal. It is soft, malleable and ductile. It can be rolled into very thin sheets. It is used for making important alloys, fine solder, as a protective coating for iron and steel sheets and for making tin foil used as moisture proof packing.

A tin base alloy containing 88% tin, 8% antimony and 4% copper is called ***babbit metal.*** It is a soft material with a low coefficient of friction and has little strength. It is the most common bearing metal used with cast iron boxes where the bearings are subjected to high pressure and load.

Note : Those alloys in which lead and tin are predominating are designated as ***white metal bearing alloys.*** This alloy is used for lining bearings subjected to high speeds like the bearings of aero-engines.

Non-metallic Materials

The non-metallic materials are used in engineering practice due to their low density, low cost, flexibility, resistant to heat and electricity. Though there are many non-metallic materials, yet the following are important from the subject point of view.

1. *Plastics*. The plastics are synthetic materials which are moulded into shape under pressure with or without the application of heat. These can also be cast, rolled, extruded, laminated and machined. Following are the two types of plastics :

(*a*) Thermosetting plastics, and

(*b*) Thermoplastic.

The ***thermosetting plastics*** are those which are formed into shape under heat and pressure and results in a permanently hard product. The heat first softens the material, but as additional heat and pressure is applied, it becomes hard by a chemical change known as phenol-formaldehyde (Bakelite), phenol-furfural (Durite), urea-formaldehyde (Plaskon), etc.

The ***thermoplastic*** materials do not become hard with the application of heat and pressure and no chemical change occurs. They remain soft at elevated temperatures until they are hardened by cooling. These can be remelted repeatedly by successive application of heat. Some of the common thermoplastics are cellulose nitrate (Celluloid), polythene, polyvinyl acetate, polyvinyl chloride (P.V.C.), etc.

The plastics are extremely resistant to corrosion and have a high dimensional stability. They are mostly used in the manufacture of aeroplane and automobile parts. They are also used for making safety glasses, laminated gears, pulleys, self-lubricating bearing, etc. due to their resilience and strength.

2. ***Rubber.*** It is one of the most important natural plastics. It resists abrasion, heat, strong alkalis and fairly strong acids. Soft rubber is used for electrical insulations. It is also used for power transmission belting, being applied to woven cotton or cotton cords as a base. The hard rubber is used for piping and as lining for pickling tanks.

3. ***Leather.*** It is very flexible and can withstand considerable wear under suitable conditions. It is extensively used for power transmission belting and as a packing or as washers.

4. ***Ferrodo.*** It is a trade name given to asbestos lined with lead oxide. It is generally used as a friction lining for clutches and brakes.