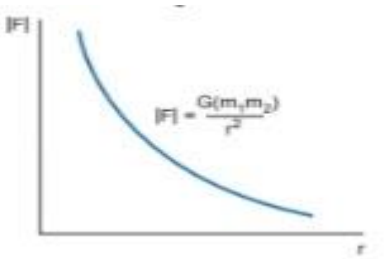
UNIT - 6

1. Discuss the important features of the law of gravitation.

1. As the distance between two masses increases , the strength of the force tends to decreases. Because of *inverse dependence on* r^2 .

- **Planet Uranus experiences less gravitational force from the Sun than the Earth.**
- **Uranus is at large distance from the sun compared to the Earth.**



2. The gravitational forces between two particles constitute an *action - reaction pair.*

- **Gravitational force exerted by the Sun on the Earth is always towards the sun.**
- **The reaction force is exerted by the Earth on the sun.**
- **The direction of this reaction force is towards Earth.**

3. The torque experienced by the Earth due to the gravitational force of the sun is ,

$$\vec{\tau} = \vec{r} \times \vec{F} = \vec{r} \times \left(- \frac{G\, M_S\, M_E}{r^2} \hat{r} \right) = 0$$

$$\vec{\tau} = \frac{d\vec{L}}{dt} = 0 \qquad \text{since } \vec{r} = r\,\hat{r} \;,\; \hat{r} \times \hat{r} = 0$$

- **Angular momentum L is a constant vector.**
- **Angular momentum of the Earth about the sun is constant throughout the motion.**

4. Earth orbits around the sun due to sun's gravitational force , we assumed Earth and sun to be point masses.

$$\vec{F} = - \frac{G\, M_1\, M_2}{r^2} \hat{r}$$

- **Both M_1 and M_2 are treated as point masses.**
- **The distance between two bodies is very much larger than their diameter.**

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5. To calculate force of attraction between a hollow sphere of mass M with uniform density and point mass m kept outside the hollow sphere , we can replace the hollow sphere of mass M as equivalent to a point mass M located at the centre of the hollow sphere. If another object of mass m inside this hollow sphere the force experienced by this mass m will be zero.

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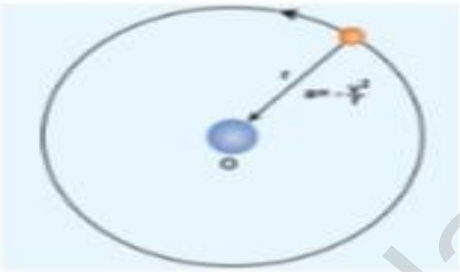
2. Explain how Newton arrived at his law of gravitation from Kepler's law.

Newton's inverse square law :

- **Newton considered the orbits of the planets as circular .**
- **For circular orbit of radius r , centripetal acceleration acts towards the centre.**

Diagram :



Derivation :

1. **Centripetal Acceleration** : $a = \frac{v^2}{r}$ ---------- (1)

2. **Velocity in terms of r and T** : $v = \frac{2\pi r}{T}$ ---------- (2)

3. **Sub eqn (2) in (1)** : $a = -\frac{\left(\frac{2\pi r}{T}\right)^2}{r} = \frac{-4\pi^2 r}{T^2}$

4. **From Newton's second law** : $F = -\frac{4\pi^2 m r}{T^2}$

5. **From Kepler's third law** : $\frac{r^3}{T^2} = \frac{k}{r^2}$

$$\frac{r}{T^2} = \frac{k}{r^2} \quad \text{---------- (3)}$$

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6. Sub eqn (3) in (2) : $F = -\frac{4\pi^2 m k}{r^2}$

7. Negative sign implies that force is attractive and it acts towards the centre.

8. If Earth is attracted by the sun , then the sun must also be attracted by the Earth with the same magnitude of force .

9. Newton equated the constant $4\pi^2 k$ to G M which is the law of gravitation.

$$F = -\frac{G M m}{r^2}$$

10. Negative sign in the above equation implies that the gravitational force is attractive.

---

3. Explain how Newton verified his law of gravitation.

1. Newton verified his law of universal gravitation by comparing the acceleration of a terrestrial object to the acceleration of the moon.

2. He knew that the distance from the centre of earth to the centre of two spheres of known mass at either end of a light rod suspended by a then fibre from the centre of the rod.

3. He had earlier found the small force that was needed to twist the fibre.

4. By bringing a third sphere close to one of the suspended spheres.

5. He was able to measure the force of gravity between the spheres and gravitation.

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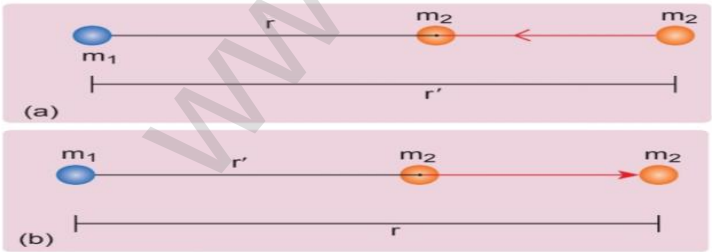
4. Derive the expression for gravitational potential energy.

Diagram :



Formula :

$$U(r) = -\frac{G m_1 m_2}{r}$$

Theory :

- Two masses m_1 and m_2 are initially separated by a distance r.

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- Assuming m_1 to be fixed in its position , work must be done on m_2.
- To move mass m_2 from the distance r' to r.
- To move the mass m_2 through an infinitesimal displacement $\vec{dr}$ from r to $\vec{r} + \vec{dr}$ work has to be done externally.

Derivation :

1. Infinitesimal Work is given by,

$$dW = \vec{F}_{ext} \cdot \vec{dr} \qquad \text{------- (1)}$$

2. Work is done against the gravitational force

$$|\vec{F}_{ext}| = |\vec{F}_G| = \frac{G\, m_1\, m_2}{r^2} \qquad \text{------- (2)}$$

3. Sub eqn (2) in (1)

$$dW = \frac{G\, m_1\, m_2}{r^2} \hat{r} \cdot \vec{dr}$$

$$\vec{dr} = \hat{r}\, dr \quad \text{and} \quad \hat{r} \cdot \hat{r} = 1$$

$$dW = \frac{G\, m_1\, m_2}{r^2} \hat{r} \cdot \hat{r}\, dr$$

$$dW = \frac{G\, m_1\, m_2}{r^2} dr \qquad \text{---------- (3)}$$

4. Total work done for displacing the particle r' to r is ,

$$W = \int_{r'}^{r} dW \quad \int_{r'}^{r} \frac{G\, m_1\, m_2}{r^2} dr$$

$$W = -\left[\frac{G\, m_1\, m_2}{r^2}\right]_{r'}^{r}$$

$$W = -\frac{G\, m_1\, m_2}{r} + \frac{G\, m_1\, m_2}{r'}$$

$$W = U(r) - U(r')$$

5. Work done gives the gravitational potential energy difference of the system of masses m_1 and m_2 when separation between them are r and r' respectively.

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5. Gravitational potential energy :

$$U(r) = -\frac{G m_1 m_2}{r}$$

S.NO	Case 1 : If $r < r'$	Case 2 : If $r > r'$
1.	Object move from r to r' .	Object move from r' to r
2.	Work done is to be negative.	Work done is to be positive.
3.	Work done by the body spend internal energy.	Work is done on the body by external force.

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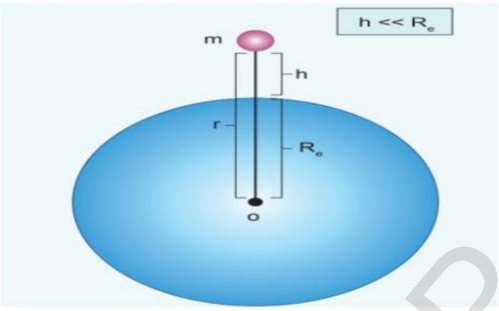
5. Prove that at points near the surface of the Earth , the gravitational potential energy of the object is $U = m g h$

Diagram :



Formula :

$$U = m g h$$

Theory :

- Consider the Earth and mass system with r the distance between the mass m and Earth's centre.
  - Mass of the earth → M_e
  - Radius of the earth → R_e
  - Mass of the object → m
  - Height above Earth's surface → h

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Potential Energy :

1. $U = -\frac{G M_e m}{r}$

2. $r = R_e + h$

3. $U = -\frac{G M_e m}{R_e + h}$

4. If $h << R_e$ then ,

$$U = -\frac{G M_e m}{R_e\left(\frac{R_e + h}{R_e}\right)}$$

5. $U = -\frac{G M_e m}{R_e\left(1 + \frac{h}{R_e}\right)}$

6. $U = -\frac{G M_e m}{R_e}\left(1 + \frac{h}{R_e}\right)^{-1}$

7. By using Binomial expansion and neglecting the higher order terms we get

$$U = -\frac{G M_e m}{R_e}\left(1 - \frac{h}{R_e}\right)$$

$$U = -\frac{G M_e m}{R_e} - \frac{G M_e m h}{R_e^2} \quad \text{----------} \quad (1)$$

8. Acceleration due to gravity

$$g = \frac{G M_e}{R_e^2}$$

$$m g R_e = G M \quad \text{----------} \quad (2)$$

9. Sub eqn (2) in (1)

$$U = -m g R_e + m g h \quad \text{----------} \quad (3)$$

10. If the object is taken from height h_1 to h_2 .

Potential energy at h_1 : $U(h_1) = -m g R_e + m g h_1$

Potential energy at h_2 : $U(h_2) = -m g R_e + m g h_2$

11. Potential energy difference between h_1 and h_2

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$$U(h_2) - U(h_1) = -mgR_e + mgh_2 - (-mgR_e + mgh_1)$$

$$U(h_2) - U(h_1) = -\cancel{mgR_e} + mgh_2 + \cancel{mgR_e} - mgh_1$$

$$U(h_2) - U(h_1) = mgh_2 - mgh_1$$

$$U(h_2) - U(h_1) = mg(h_2 - h_1)$$

12. The gravitational potential energy stored in the particle of the mass m at a height h from the surface of the Earth is $U = mgh$

13. On the surface of the Earth , $U = 0$ since h is zero.

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6. Explain in detail the idea of weightlessness using lift as an example.

Weightlessness :

1. When the lift falls with downward acceleration $a = g$, the person inside the elevator is in the state of weightlessness or free fall.
2. Freely falling objects experience only gravitational force.
3. As they fall freely , they are not in contact with any surface.
4. Normal force acting on the object is zero.
5. Downward acceleration is equal to acceleration due to gravity of the earth.

$$\boxed{a = g \text{ then } N = m(g - g) = 0}$$

6. This is called the state of " weightlessness ".

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7. Derive an expression for escape speed.

Escape Speed :

The escape speed is defined as , the minimum speed required by an object to escape from Earth's gravitational field .

$$\boxed{V_e = \sqrt{2gR_E}}$$

Theory :

1. Consider an object of mass M on the surface of the Earth.
2. When it is thrown up with an initial speed v_i .
3. Initial total energy of the object is,

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$$E_i = \frac{1}{2} M v_i^2 - \frac{G M M_E}{R_E}$$

M_E → Mass of the earth .

R_E → Radius of the earth .

4. Potential energy of the mass M : $U(r) = -\frac{G M M_E}{R_E}$

5. When the object reaches a height far away from Earth and approach infinity.

6. Potential energy becomes zero and kinetic energy becomes zero.

7. Therefore final total energy of the object becomes zero. $E_f = 0$

Derivation :

1. According to the law of energy conservation , $E_i = E_f$

2. $$\frac{1}{2} M v_i^2 - \frac{G M M_E}{R_E} = 0$$

3. $$\frac{1}{2} \cancel{M} v_i^2 = \frac{G \cancel{M} M_E}{R_E}$$

4. $$\frac{1}{2} v_i^2 = \frac{G M_E}{R_E}$$

5. $$v_i^2 = \frac{2 G M_E}{R_E}$$

6. Hence replace v_i by v_e

$$v_e^2 = \frac{2 G M_E}{R_E}$$

7. Acceleration due to gravity : $g = \frac{G M_E}{R_E^2}$

8. $v_e^2 = 2 g R_E$

9. Escape Speed : $v_e = \sqrt{2 g R_E} = 11.2 \text{ km s}^{-1}$

10. Escape Speed depends on two factors :

i) Acceleration due to gravity

ii) Radius of the earth R_E = 6400 km

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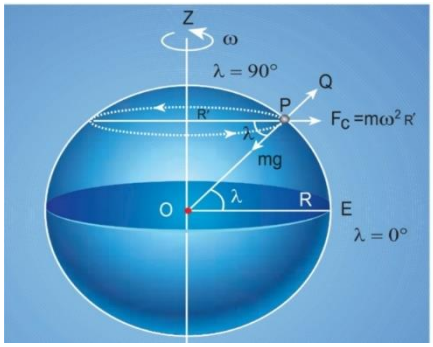
8. Explain the variation of g with latitude.

Diagram :



Formula :

$$g' = g - \omega^2 R \cos^2 \lambda$$

Theory :

1. The motion of objects in *rotating frame* must consider *centrifugal force*.
2. We treat Earth as an *inertial frame* , it is not exactly correct.
3. Because the Earth spins about its own axis.
4. When an object is on the earth surface , it experiences centrifugal force.
5. It depends on the *latitude* of the object on Earth.
6. If the Earth were not spinning , the force on the object is mg.
7. Object experiences an additional centrifugal force due to spinning of the Earth.

Derivation :

1. Centrifugal force $= m\,\omega^2 R'$
2. Centrifugal acceleration $= \omega^2 R'$
3. Component of centrifugal acceleration experienced by the object in the direction opposite to g.

$$a_{PQ} = \omega^2 R' \cos \lambda \quad \text{------} \quad (1)$$

4. From figure : $\cos \lambda = \dfrac{R'}{R}$

$$R' = R \cos \lambda \quad \text{----------} \quad (2)$$

5. Sub eqn (2) in (1)

$$a_{PQ} = \omega^2 R \cos \lambda \cos \lambda = \omega^2 R \cos^2 \lambda$$

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6. Variation of g with latitude : $g' = g - \omega^2 R \cos^2 \lambda$

Case i :	At equator	$\lambda = 0$	$g' = g - \omega^2 R$	Gravity is minimum
Case ii :	At poles	$\lambda = 90^0$	$g' = 0$	Gravity is maximum

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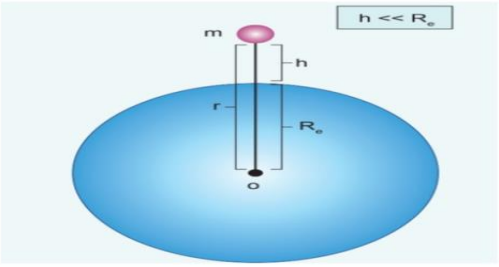
9. Explain the variation of g with altitude.

Diagram :



Formula :

$$g' = g\left(1 - \frac{2h}{R_E}\right)$$

Theory :

Consider an object of mass m at a height h from the Earth.

- Mass of the Earth → M
- Radius of the Earth → R_E
- Mass of the object → m

Derivation :

1. Acceleration due to gravity : $g = \frac{GM}{R_E^2}$

2. Gravity with altitude : $g' = \frac{GM}{(R_E + h)^2}$

3. Taking R_E outside : $g' = \frac{GM}{R_E^2\left(1 + \frac{h}{R_E}\right)^2} = \frac{GM}{R_E^2}\left(1 + \frac{h}{R_E}\right)^{-2}$

4. By using Binomial expansion : $g' = \frac{GM}{R_E^2}\left(1 - \frac{2h}{R_E}\right)$

5. Variation of g with altitude : $g' = g\left(1 - \frac{2h}{R_E}\right)$

6. $g' < g$, " Altitude h increases then acceleration due to gravity g decreases "

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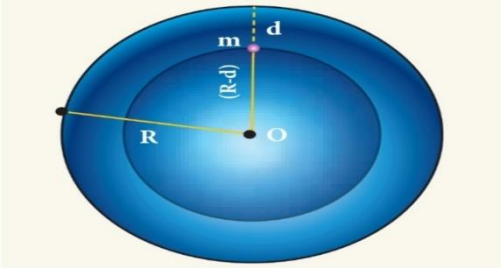
10 . Explain the variation of g with depth from the Earth's surface.

Diagram :



Formula :

$$g' = g\left(1 - \frac{d}{R_E}\right)$$

Theory :

1. Consider a particle of mass m which is in a deep mine on the Earth.

   Ex : Coal mines in Neyveli

2. Acceleration due to gravity is g .

3. Assume the depth of the mine as d .

4. The part of Earth which is above radius (R_E - d) do not contribute to acceleration.

5. Assuming the density of Earth ρ to be constant .

6. Mass of the Earth → M

7. Volume of the Earth → V

Derivation :

1. $$g = \frac{G M}{R_E^2} \quad \text{-------} \quad (1)$$

2. $$g' = \frac{G M'}{(R_E - d)^2} \quad \text{-------} \quad (2)$$

3. $$\rho = \frac{M}{V} = \frac{M'}{V'} \quad \text{--------} \quad (3)$$

4. $$M' = \frac{M}{V} V'$$

5. $$M' = \frac{M}{\left(\frac{4}{3}\pi R_E^3\right)}\left(\frac{4}{3}\pi (R_E - d)^3\right)$$

6. $$M' = \frac{M}{R_E^3}(R_E - d)^3 \quad \text{-------} \quad (4)$$

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7. Sub eqn (4) in (2)

8. $$g' = \frac{G M (R_E - d)^3}{R_E^3 (R_E - d)^2}$$

9. $$g' = \frac{G M}{R_E^3} (R_E - d)$$

10. $$g' = \frac{G M}{R_E^2} \frac{(R_E - d)}{R_E}$$

11. $$g' = \frac{G M}{R_E^2} \left(1 - \frac{d}{R_E}\right)$$

12. Variation of g with depth : $$\boxed{g' = g \left(1 - \frac{d}{R_E}\right)}$$

13. $g' < g$; " As depth increases , g' decreases "

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11. Derive the time period of satellite orbiting the Earth.

Time Period :

The distance covered by the satellite during one rotation in its orbit is equal to $2\pi (R_E + h)$ and time taken for it , is the time period.

$$\text{Time Period} = \frac{\text{Distance Travelled}}{\text{Time Taken}}$$

Derivation :

1. $$v = \frac{2\pi (R_E + h)}{T}$$

2. Orbital speed :

$$v = \sqrt{\frac{G M_E}{(R_E + h)}}$$

3. $$\sqrt{\frac{G M_E}{(R_E + h)}} = \frac{2\pi (R_E + h)}{T}$$

4. $$T = \frac{2\pi}{\sqrt{G M_E}} \frac{(R_E + h)}{(R_E + h)^{1/2}}$$

5. $$T = \frac{2\pi}{\sqrt{G M_E}} (R_E + h)^{3/2}$$

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6. Squaring on both sides

$$T^2 = \frac{4\pi^2}{G M_E} (R_E + h)^3$$

7. $$c = \frac{4\pi^2}{G M_E}$$

8. $$T^2 = c (R_E + h)^3$$

9. A satellite orbiting the Earth has same relation between time and distance as that of " *Kepler's law of planetary motion* ".

10. For a satellite orbiting near the surface of the Earth , h is negligible compared to the radius of the Earth.

11. $$T^2 = \frac{4\pi^2}{G M_E} (R_E + h)^3$$

12. $$T^2 = \frac{4\pi^2}{G M_E} R_E^3 \quad (h = 0)$$

13. $$T^2 = \frac{4\pi^2}{\frac{G M_E}{R_E^2}} R_E^3$$

14. $$T^2 = \frac{4\pi^2}{g} R_E$$

15. $$T = 2\pi \sqrt{\frac{R_E}{g}}$$

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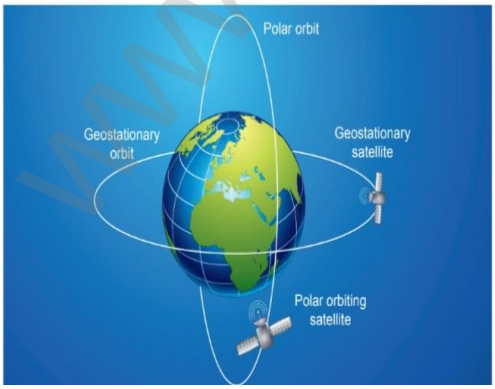
13. Explain in detail the geostationary and polar satellite.

Diagram :



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Geostationary Satellite :

1. Geostationary satellites appear to be stationary , when seen from Earth.
2. Distance h turns out be 36,000 km.
3. India uses the INSAT group of satellites that are basically geostationary satellite.
4. They are used for purpose of telecommunication.
5. The satellite orbiting the Earth have different time periods corresponding to different orbital radii.
6. Orbital radius of satellite if its time period is 24 hours calculated by Kepler's 3rd law

$$T^2 = \frac{4\pi^2}{G M_E} (R_E + h)^3$$

$$(R_E + h)^3 = \frac{G M_E T^2}{4\pi^2}$$

$$R_E + h = \left(\frac{G M_E T^2}{4\pi^2}\right)^{1/3}$$

7. The time period 24 hrs = 86400 sec , mass and radius of the Earth , h turns out to be 36,000 km . Such satellites are called " Geo - stationary satellite ".

Polar Satellite :

1. Another type satellite which is placed at a distance of 500 to 800 km.
2. This type satellite that orbits Earth from pole to south pole .
3. The time period of polar satellite is nearly 100 minutes.
4. The satellites completes many revolution in a day.
5. A polar satellite covers small strip of area from pole to pole during one revolution.
6. In the next revolution , it covers a different strip of area since the Earth would have moved by a small angle.
7. In this way polar satellite cover the entire surface area of the Earth.

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14. Explain how geocentric theory is replaced by heliocentric theory using the idea of retrograde motion of planets.

Retrograde Motion :

1. When the motion of the planets are observed in the night sky by naked eyes .

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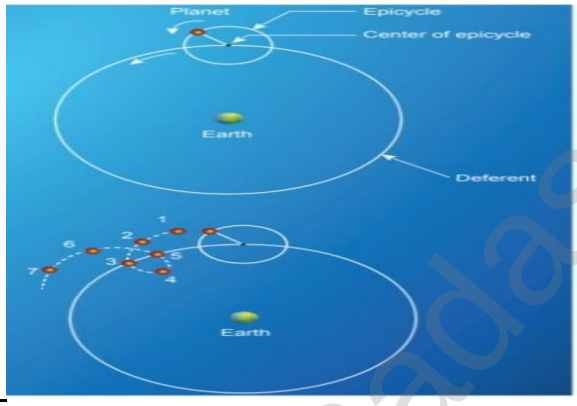
2. The planets move eastwards and reverse their motion for a while and return to eastward motion again.

3. This is called " *retrograde motion* " of the planets.

Examples :

- The retrograde motion of the planet Mars.
- Initially moves eastwards (Feb to June)
- Reverse its path & moves backwards (July, Aug , Sep)
- It changes its direction of motion once again and continue its forward motion (October onwards)

Diagram :



Ptolemy Concept :

1. To explain this retrograde motion , Ptolemy introduced the concept of " *epicycle* " in geocentric model.
2. According to this theory , while the planet orbited the Earth it also underwent another circular motion termed as " *epicycle* "
3. A combination of epicycle and circular motion around the Earth gave rise to retrograde motion of the planets with respect to Earth.
4. But Ptolemy's model became more and more complex as every planet was found to undergo retrograde motion.

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5. In the 15th century , the Polish astronomer Copernicus proposed.

6. The heliocentric model to explain this problem in a simple manner .

7. According to this model , the sun is at the centre of the solar system and all planets orbited the sun.

8. The retrograde motion of planets with respect to Earth is because of the planet of the relative motion of the planet with respect to Earth.

9. The Earth orbits around the Sun faster than Mars.

10. Because of the relative motion between Mars and Earth appears to move backwards from July to October.

11. The retrograde motion of all other planets was explained successfully by the Copernicus model.

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15. Explain in detail the Eratosthenes method of finding the radius of Earth.

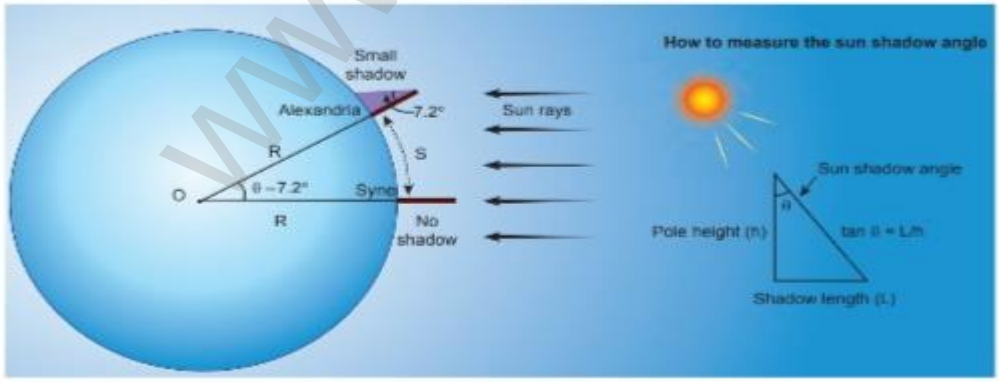
1. During noon time of summer solstice the Sun's rays cast no shadow in the city Syne which was located 500 miles away from Alexandria.

2. At the same day and same time he found that in Alexandria the Sun's rays made 7.2 degree with local vertical .

3. He realized that this differences of 7.2 degree was degree was due to the curvature of the Earth.

6. The angle 7.2 degree is equivalent to 1 / 8 radian . So θ = 1 / 8 rad .

Diagram :



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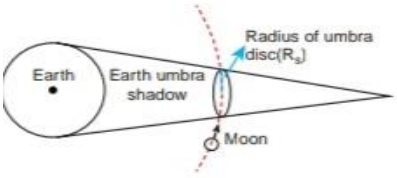
Derivation :

If S is the length of the length of the arc between the cities of Syne and Alexandria , and if R is radius of Earth.



1. $S = R\theta$

2. $R = \frac{S}{\theta}$

3. $S = 500$ miles and $\theta = 1/8$

4. $R = \frac{500}{(1/8)}$

5. $R = 4000$ miles

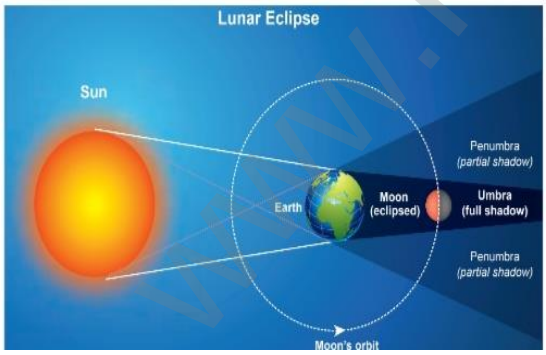
6. $R = 4000 \times 1.609$ km (1 mile = 1.609 km)

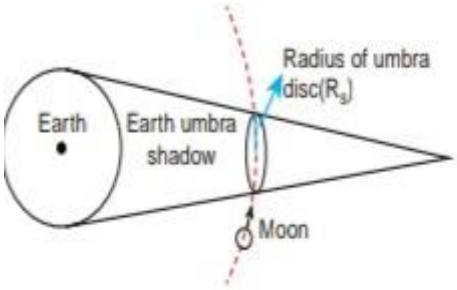
7. $R = 6436$ km (which is close to correct value 6378 km)

---

16. Describe the measurement of Earth's shadow (umbra) radius during total lunar eclipse.

Diagram:





1. **It is possible to measure the radius of shadow of the Earth at the point where the Moon crosses.**

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2. When the Moon is inside the umbra shadow , it appears red in colour.

3. As soon as the Moon exits from the umbra shadow , it appears in crescent shape.

4. By finding the apparent radii of the Earth's umbra shadow and the Moon , the ratio of the these radii can be calculated.

Derivation :

1. The apparent radius of Earth's umbra shadow = R_s = 13.2 cm

2. The apparent radius of the Moon = R_m = 5.15 cm

3. The ratio $\frac{R_s}{R_m}$ = 2.56

4. The radius of the Earth's umbra shadow is = R_s = 2.56 X R_m

5. The radius of the moon R_m = 1737 km

6. The radius of the Earth's umbra shadow is R_s = 2.56 X 1737 km = 4446 km

7. The correct radius is 4610 km.

8. The percentage of error in the calculation

$$\frac{4610 - 4446}{4610} \times 100 = 3.5\ \%$$

9. The error will reduce if the pictures taken using a high quality telescope is used.

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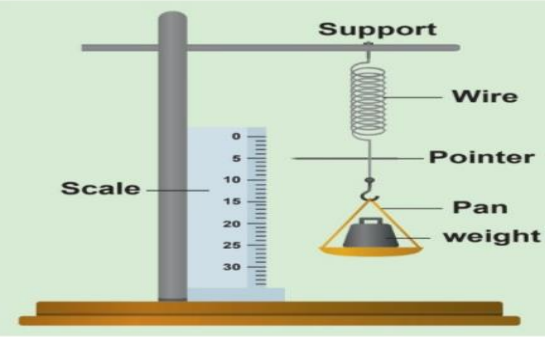
7. Properties of Matter

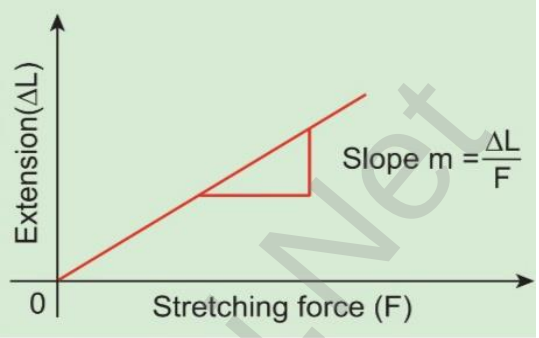
1. State Hooke's law and verify it with the help of an experiment.

Hooke's Law :

"Within the elastic limit , the stress is directly proportional to the strain ".

Diagram :





Theory :

1. **Let us consider stretching thin straight wire of length L.**
2. **And uniform cross – sectional area A suspended from a fixed point O.**
3. **A pan and a pointer are attached at the free end of the wire.**
4. **Extension produced on the wire is measured using a vernier scale arrangement.**
5. **For a given load , the corresponding stretching force is F and elongation is Δ L.**
6. **It is directly proportional to the original length L and inversely proportional to the area of cross section A.**
7. **A graph is plotted using F on the X – axis and Δ L on the Y – axis.**
8. **This graph is a straight line passing through the origin.**

Derivation :

1. **Slope** $= \frac{\Delta L}{F}$

2. $\Delta L = (\text{slope})\ F$

3. **Multiplying and dividing by volume** $V = A\ L$

4. $F\ (\text{slope}) = \frac{A\ L}{A\ L}\ \Delta L$

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5. Rearranging , we get

$$\frac{F}{A} = \left(\frac{L}{A\,(\text{slope})}\right)\frac{\Delta L}{L}$$

6. $\frac{F}{A} \;\alpha\; \frac{\Delta L}{L}$

7. $\sigma \;\alpha\; \varepsilon$

8. Stress is proportional to the strain with in the elastic limit.

---

2. Explain the different types of modulus of elasticity .

Modulus of elasticity :

From Hooke's law , stress α strain

$$\frac{\text{Stress}}{\text{Strain}} = \text{constant}$$

SI unit : $N\,m^{-2}$ or pascal

Dimension : $M\,L^{-1}\,T^{-2}$

Types of modulus :

1. Young's modulus 2. Rigidity modulus or shear modulus 3. Bulk modulus

1. Young's modulus :

"Ratio between tensile stress and tensile strain is defined as " Young's modulus "

$$\text{Young modulus} = \frac{\text{Tensile stress or compressive stress}}{\text{Tensile strain or compressive strain}}$$

$$Y = \frac{\sigma_t}{\varepsilon_t} \text{ or } \frac{\sigma_c}{\varepsilon_c}$$

2. Bulk modulus :

"Ratio between volume stress and volume strain is defined as " Bulk modulus "

$$\text{Bulk modulus} = \frac{\text{Normal (perpendicular) stress}}{\text{Volume strain}}$$

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- **Normal stress or pressure :** $\sigma_n = \frac{F_n}{\Delta A} = \Delta p$

- **Volume strain :** $\varepsilon_v = \frac{\Delta V}{V}$

- $K = \frac{\sigma_n}{\varepsilon_v} = \frac{-\Delta p}{\frac{\Delta V}{V}}$

- **Negative sign implies that when the pressure is applied , its volume decreases.**

2. Rigidity or Shear modulus :

"Ratio between shearing stress and shearing strain is called as Rigidity modulus "

Rigidity modulus $= \frac{\text{Shearing stress}}{\text{Shearing strain}}$

- **Shearing stress :** $\frac{\text{Tangential force}}{\text{Area over which it is applied}}$

- $\sigma_s = \frac{F_t}{\Delta A}$

- **Angle of strain :** $\varepsilon_s = \frac{x}{h} = \theta$

- $\eta_R = \frac{\sigma_s}{\varepsilon_v} = \frac{F_t}{\frac{\Delta A}{x/h}} = \frac{F_t}{\Delta A\,\theta}$

- **Rigidity modulus is inversely proportional to angle of shear.**

---

3. Derive an expression for the elastic energy stored per unit volume a wire.

Elastic Energy :

When a body is stretched , work is done against the restoring force. This work done is stored in the body in the form of " Elastic energy "

Explanation :

Let us consider a unstretched wire.

- **Length of the wire** ⟶ **L**

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- Force on the wire ⟶ F
- Area of cross section ⟶ A
- Extension in length ⟶ l

Derivation :

Work done by the force F is equal to the energy gained by the wire.

1. Work done : $W = \int_0^{l} F\,dl$

2. Young's Modulus : $Y = \frac{F}{A} \times \frac{L}{l}$

3. Force : $F = \frac{Y A l}{L}$

4. Work done : $W = \int_0^{l} \frac{Y A l}{L}\,dl$

5. $W = \frac{Y A}{L} \int_0^{l} l\,dl$

6. $W = \frac{Y A}{L} \left(\frac{l}{2}\right)^2$

7. $W = \frac{1}{2} \frac{Y A l}{L} l$

8. $W = \frac{1}{2} F l$

9. Work done = Elastic potential energy

10. Energy Density : Energy per unit volume

Energy Density = $\frac{\text{Elastic potential energy}}{\text{Volume}}$

$u = \frac{1}{2} \frac{F}{A} \frac{l}{L}$

$u = \frac{1}{2}$ x Stress x Strain

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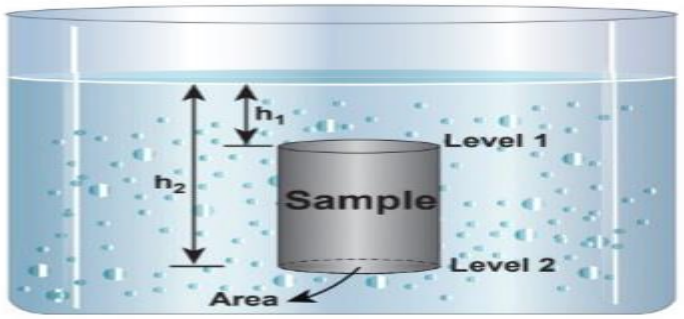
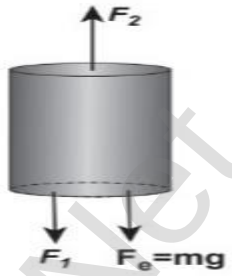
4. Derive an equation for the total pressure at a depth " h " below the liquid surface.

Consider a water sample of cross sectional area in the form of cylinder.

Diagram :





Theory :

1. Cross sectional Area → A
2. Depth at Level 1 → h_1
3. Depth at Level 2 → h_2
4. Force acts downward → $F_1 = P_1 A$
5. Force acts upward → $F_2 = P_2 A$
6. Gravitational Force → F_G

Derivation :

1. Under equilibrium condition ,

Total upward force (F_2) balanced by total downward force (F_1)

$$F_2 = F_1 + F_G \longrightarrow (1)$$

2. Gravitational force :

$$F_G = m\,g$$

$$F_G = V\,\rho\,g$$

$$F_G = A\,(h_2 - h_1)\,\rho\,g \longrightarrow (2)$$

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3. Sub eqn (2) in (1)

$$F_2 = F_1 + F_G$$

$$P_2 A = P_1 A + A (h_2 - h_1) \rho g$$

$$P_2 \cancel{A} = [P_1 - (h_2 - h_1) \rho g] \cancel{A}$$

$$P_2 = [P_1 - (h_2 - h_1) \rho g]$$

4. If we choose the level 1 at the surface of the liquid and level 2 at a depth h below the surface.

h_1 becomes zero then $P_1 = P_a$

h_2 becomes h then $P_2 = P$

$$P = P_a + h \rho g$$

5. If the atmospheric pressure is ignored then $P = h \rho g$

---

5. State and prove Pascal's law in fluids.

Pascal's Law :

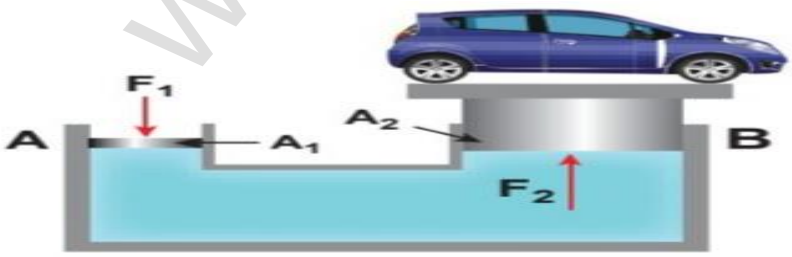
" If the pressure in a liquid is changed at a particular point , the change is transmitted to the entire liquid without being diminished in magnitude".

Application of Pascal's Law :

1. A practical application of Pascal's law is *Hydraulic lift* .

2. It is used to lift heavy load with small force. 3. It is a Force multiplier.

Diagram :



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Construction :

1. Consists of two cylinders A and B.

2. They are connected to each other.

3. Horizontal pipe is filled with liquid.

4. They are fitted with frictionless piston.

5. Cross sectional areas are A_1 and A_2 . ($A_2 > A_1$)

Working :

1. Downward force F_1 is applied on the smaller piston.

2. Pressure of the liquid under this piston increases to P . ($P = F_1 / A_1$)

3. Increased pressure is exerted on piston B is F_2 .

According to Pascal's Law :

$$F_2 = P \times A_2$$

$$F_2 = \frac{F_1}{A_1} \times A_2$$

$$\boxed{F_2 = \frac{A_2}{A_1} \times F_1}$$

Mechanical advantage of lift :

1. The factor A_2 / A_1 is called mechanical advantage of lift.

2. Changing force on smaller piston A , force on the piston B increased by the factor A_2 / A_1.

6. State and prove Archimedes principle.

Archimedes principle :

It states that when a body is partially or wholly immersed in a fluid , it experiences an upward thrust equal to weight of the fluid displaced by it and its upthrust acts through the centre of gravity of the liquid displaced.

Upthrust or Buoyant force = Weight of liquid displaced

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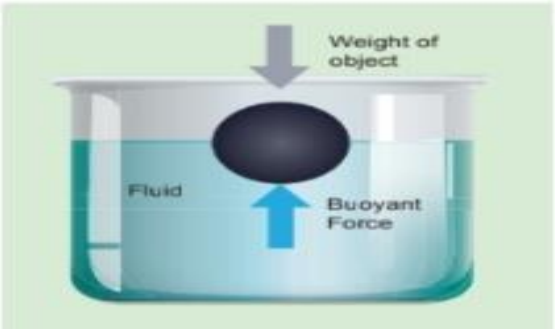
Diagram :



Buoyancy :

The upward force exerted by a fluid that opposes the weight of an immersed object in a fluid is called upthrust or buoyant force and the phenomenon is called " buoyancy "

Law of flotation :

A body will float in a liquid if the weight of the liquid displaced by the immersed part of the body equals the weight of the body.

Example :

A wooden object 300 kg (about 3000 N) floats in water displaces 300 kg of water.

7.Derive the expression for the terminal velocity of a sphere moving in a high viscous fluid using stokes force.

Consider a sphere which falls freely through highly viscous liquid.

1. **Radius of the sphere** $\longrightarrow$ **r**
2. **Density of the sphere** $\longrightarrow$ **ρ**
3. **Density of the liquid** $\longrightarrow$ **σ**
4. **Coefficient of viscosity** $\longrightarrow$ **η**

Derivation :

Downward Force = Upward force [F_G = U + F]

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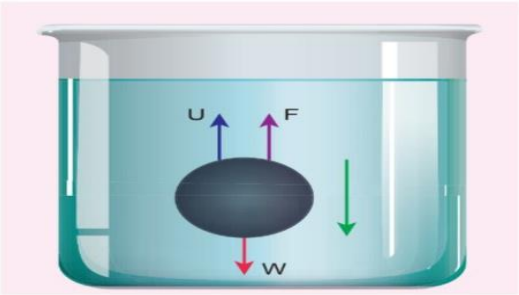
Diagram :



1. Gravitational Force :

$$F_G = m\,g = V\,\rho\,g$$

$$F_G = \frac{4}{3}\pi r^3 \rho g$$

2. Upthrust :

$$U = \frac{4}{3}\pi r^3 \sigma g$$

3. Viscous Force :

$$F = 6\pi\eta r v_t$$

4. $F_G = U + F$

$$\frac{4}{3}\pi r^3 \rho g = \frac{4}{3}\pi r^3 \sigma g + 6\pi\eta r v_t$$

$$6\pi\eta r v_t = \frac{4}{3}\pi r^3 \rho g - \frac{4}{3}\pi r^3 \sigma g$$

$$6\pi\eta r v_t = \frac{4}{3}\pi r^3 (\rho - \sigma) g$$

$$3\eta v_t = \frac{2}{3} r^2 (\rho - \sigma) g$$

$$\boxed{v_t = \frac{2}{9}\frac{r^2(\rho - \sigma) g}{\eta}}$$

Terminal speed of the sphere is directly proportional to the square of its radius $v_t \alpha r^2$

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8. Derive Poiseuille's formula for the volume of a liquid flowing per second through a pipe under streamlined floor.

- **Consider a liquid flowing steadily through horizontal capillary tube.**
- **Let volume of the liquid flowing out per second (v = V / t) through a capillary tube.**

Quantity and Dimension :

S.NO	Quantity	Dimension
1.	$v = V / t$	$L^3 T^{-1}$
2.	H	$M L^{-1} T^{-1}$
3.	P / l	$M L^{-2} T^{-2}$
4.	R	L

It depends on ,

1. **Coefficient of viscosity (η)**
2. **Radius of the tube (r)**
3. **Pressure Gradient (P / ℓ)**
4. $v \alpha \eta^a r^b \left(\frac{P}{\ell}\right)^c$
5. $v = k \eta^a r^b \left(\frac{P}{\ell}\right)^c \longrightarrow (1)$
6. $\left(L^3 T^{-1}\right) = K \left(M L^{-1} T^{-1}\right)^a \left(L\right)^b \left(M L^{-2} T^{-2}\right)^c$

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7. $M^0 L^3 T^{-1} = K M^a L^{-a} T^{-a} L^b M^c L^{-2c} T^{-2c}$

8. $M^0 L^3 T^{-1} = K M^{a+c} L^{-a+b-2c} T^{-a-2c}$

Power of M : $a + c = 0$

Power of L : $-a + b - 2c = 3$

Power of T : $a - 2c = -1$

After solving these equations we get $a = -1$, $b = 4$, $c = 1$ sub in eqn (1)

$$v = k \eta^a r^b \left(\frac{P}{l}\right)^c$$

$$v = k \eta^{-1} r^4 \left(\frac{P}{l}\right)^1$$

Experimentally the value of $k = \pi / 8$ then

$$\boxed{v = \frac{\pi r^4 P}{8 \eta l}}$$

---

9. Obtain an expression for the excess of pressure inside i) liquid drop ii) soap bubble iii) air bubble.

i . Liquid drop :

- Consider a liquid drop of radius R having surface tension T.
- Let P_1 and P_2 be the pressures outside and inside the bubble.

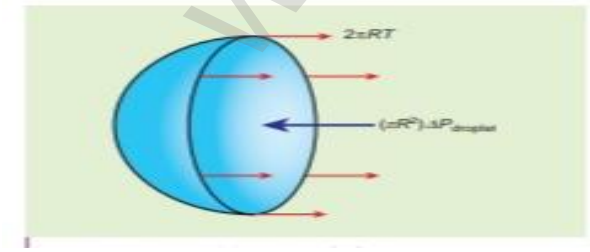
The various forces acting on the liquid drop are ,

i) Force due to surface tension $F_T = 2 \pi R T$

ii) Force due to outside pressure $F_{P1} = P_1 \pi R^2$

iii) Force due to outside pressure $F_{P2} = P_2 \pi R^2$

Diagram :



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As the drop is in equilibrium ,

$$F_{P2} = F_T + F_{P1}$$

$$P_2 \pi R^2 = 2 \pi R T + P_1 \pi R^2$$

$$P_2 \pi R^2 - P_1 \pi R^2 = 2 \pi R T$$

$$(P_2 - P_1) \pi R^2 = 2 \pi R T$$

$$P_2 - P_1 = \frac{2T}{R}$$

$$\boxed{\text{Excess Pressure} = \Delta P = \frac{2T}{R}}$$

ii Soap Bubble :

- Consider a soap bubble of radius R having surface tension T.
- Let P_1 and P_2 be the pressures outside and inside the bubble.

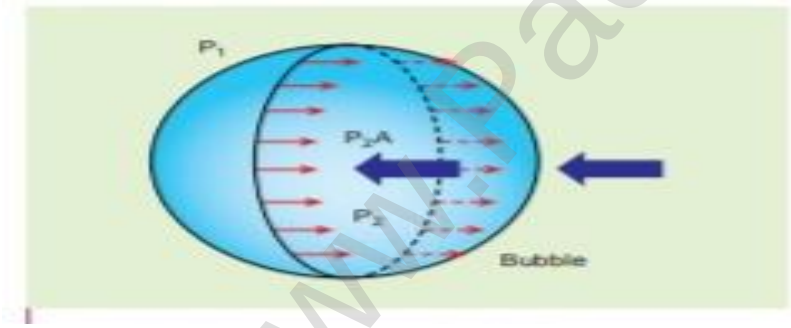
The various forces acting on the liquid drop are ,

i) Force due to surface tension $F_T = 4 \pi R T$

ii) Force due to outside pressure $F_{P1} = P_1 \pi R^2$

iii) Force due to outside pressure $F_{P2} = P_2 \pi R^2$

Diagram :



As the drop is in equilibrium ,

$$F_{P2} = F_T + F_{P1}$$

$$P_2 \pi R^2 = 4 \pi R T + P_1 \pi R^2$$

$$P_2 \pi R^2 - P_1 \pi R^2 = 4 \pi R T$$

$$(P_2 - P_1) \pi R^2 = 4 \pi R T$$

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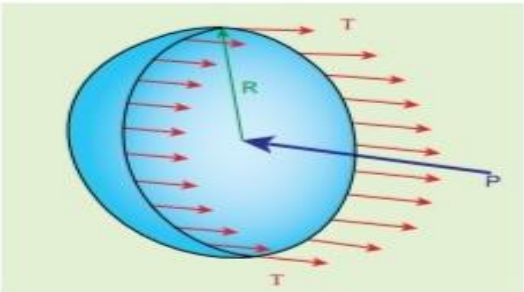
$$P_2 - P_1 = \frac{4T}{R}$$

$$\boxed{\text{Excess Pressure} = \Delta P = \frac{4T}{R}}$$

iii . Air Bubble :

- Consider a air bubble of radius R having surface tension T.
- Let P_1 and P_2 be the pressures outside and inside the bubble.

Diagram :



The various forces acting on the liquid drop are ,

i) Force due to surface tension $F_T = 2\pi R T$

ii) Force due to outside pressure $F_{P1} = P_1 \pi R^2$

iii) Force due to outside pressure $F_{P2} = P_2 \pi R^2$

As the drop is in equilibrium ,

$$F_{P2} = F_T + F_{P1}$$

$$P_2 \pi R^2 = 2\pi R T + P_1 \pi R^2$$

$$P_2 \pi R^2 - P_1 \pi R^2 = 2\pi R T$$

$$(P_2 - P_1)\pi R^2 = 2\pi R T$$

$$P_2 - P_1 = \frac{2T}{R}$$

$$\boxed{\text{Excess Pressure} = \Delta P = \frac{2T}{R}}$$

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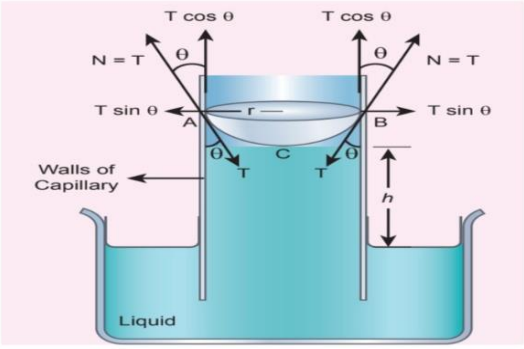
10. What is capillarity ? Obtain an expression for the surface tension of a liquid by capillary rise method .

Diagram :



Theory :

Consider a capillary tube which is held vertically in a beaker containing water.

- **Capillary rise → h**
- **Angle of contact → θ**
- **Surface Tension → T**
- **Horizontal component → T sin θ**
- **Vertical component → T cos θ**

Derivation :

1. **Total upward force = Downward weight liquid**
2. $2 \pi r T \cos \theta = m g$
3. $2 \pi r T \cos \theta = V \rho g \longrightarrow (1)$
4. **Volume of liquid = (Volume of liquid column of radius r height h) + (Volume of liquid radius r & height r - Volume of hemisphere of radius r)**
5. $V = \pi r^2 h + \left(\pi r^2 \times r - \frac{2}{3} \pi r^3 \right)$
6. $V = \pi r^2 h + \frac{\pi r^3}{3}$
7. **If the capillary is very fine tube of radius is very small then r / 3 can be neglected.**

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8. $V = \pi r^2 h \longrightarrow (2)$

9. Sub eqn (2) in (1)

$$2 \pi r T \cos \theta = \pi r^2 h \rho g$$

$$2 T \cos \theta = r h \rho g$$

$$\boxed{T = \frac{r h \rho g}{2}}$$

10. Smaller radius have greater capillarity. h is inversely proportional to r^2.

---

11. Obtain an equation of continuity for a flow of liquid on the basis of conservation of mass.

Assumption :

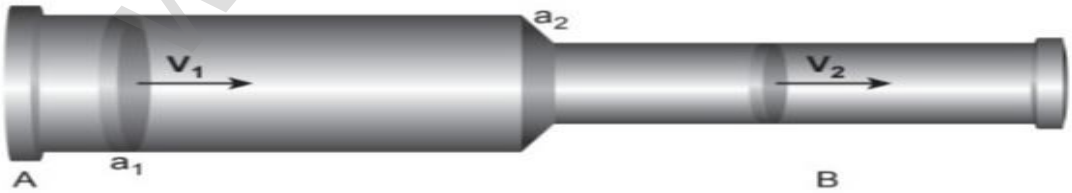
Mass flow rate through a pipe depends on following ,

1. Flow of fluid is *steady* .
2. Velocity of fluid particle remains *constant* wrt time.
3. Path taken by the fluid particle is a *streamline.*

Construction :

1. Consider a pipe AB of varying cross sectional area a_1 & a_2 . ($a_1 > a_2$)
2. A non - viscous and incompressible liquid flows through the pipe.
3. Let v_1 and v_2 velocities of the liquid flows through the pipe.
4. Let m_1 and m_2 mass of fluid through the pipe.

Diagram :



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Derivation :

1. Mass of fluid flowing through section A in time Δt

$$m_1 = (a_1 v_1 \Delta t)\rho$$

2. Mass of fluid flowing through section B in time Δt

$$m_2 = (a_2 v_2 \Delta t)\rho$$

3. For an incompressible liquid , mass is conserved

$$a_1 v_1 \Delta t \rho = a_2 v_2 \Delta t \rho$$

$$a_1 v_1 = a_2 v_2$$

$$\boxed{a v = \text{constant}}$$

- It is called the equation of continuity.
- It is conservation of mass in the flow of fluid.

---

12. State and prove Bernoulli's theorem for a flow of incompressible , non – viscous and streamlined flow of fluid.

Bernoulli's theorem :

The sum of pressure energy , kinetic energy and potential energy , kinetic energy and potential energy per unit mass of an incompressible non – viscous fluid in a streamlined flow remains a constant.

$$\boxed{\frac{P}{\rho} + \frac{1}{2} v^2 + g h = \text{constant}}$$

Flow of liquid through a pipe AB

1. Let us consider a flow of liquid through a pipe AB.
2. Let V be the volume of the liquid , when it enters A in a time t which is equal to liquid leaving from B.

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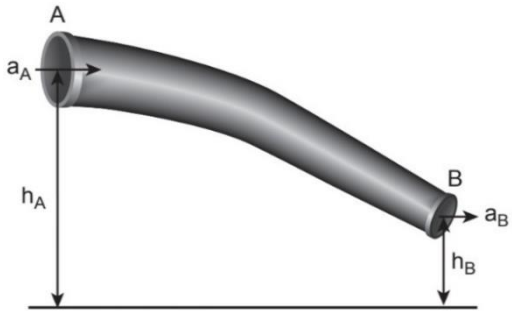
Diagram :



S.NO	Quantity	Section A	Section B
1.	Velocity	V_A	V_B
2.	Height	h_A	h_B
3.	Area of cross section	a_A	a_B

Pressure Energy :

Pressure Energy = Work done

$$E_P = W = F\ d$$

$$E_P = P\ A\ d$$

$$E_P = P\ V$$

$$E_P = \frac{P}{\rho}\ m$$

Kinetic Energy :

$$K.E = \frac{1}{2}\ m\ v^2$$

Potential Energy :

$$P.E = m\ g\ h$$

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S.NO	Energy	Section A	Section B
1.	Pressure Energy	$\frac{P_A}{\rho} m$	$\frac{P_B}{\rho} m$
2.	Kinetic Energy	$\frac{1}{2} m V_A^2$	$\frac{1}{2} m V_B^2$
3.	Potential Energy	$m g h_A$	$m g h_B$

Total Energy at A

$$E_A = \frac{P_A}{\rho} m + \frac{1}{2} m V_A^2 + m g h_A$$

Total Energy at B

$$E_A = \frac{P_B}{\rho} m + \frac{1}{2} m V_B^2 + m g h_B$$

Law of conservation of energy $E_A = E_B$

$$\frac{P_A}{\rho} m + \frac{1}{2} m V_A^2 + m g h_A = \frac{P_B}{\rho} m + \frac{1}{2} m V_B^2 + m g h_B$$

Divide both sides by m

$$\frac{P_A}{\rho} + \frac{1}{2} V_A^2 + g h_A = \frac{P_B}{\rho} + \frac{1}{2} V_B^2 + m g h_B$$

Bernouli's Equation

$$\boxed{\frac{P}{\rho} + \frac{1}{2} v^2 + g h = \text{constant}}$$

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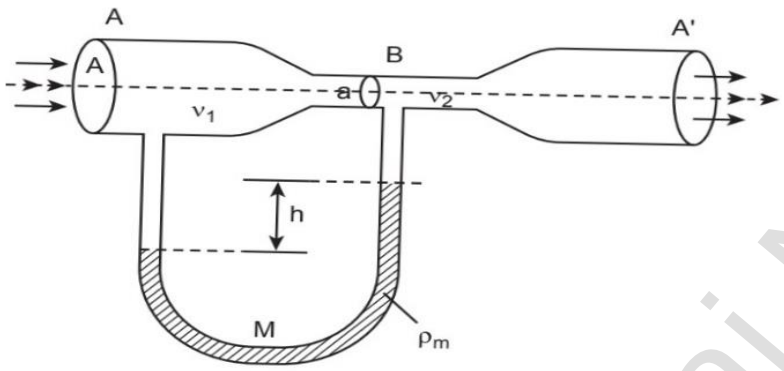
13. Describe the construction and working of venturi meter and obtain an equation for the volume of liquid flowing per second through a wider entry of the tube.

Venturi meter

A device is used to measure the rate of flow of incompressible fluid flow through a pipe. It works on the principle of " Bernoulli's theorem ".



Construction :

1. It consists of two wider tubes A and A′ and connected by narrow tube B.

2. A manometer in the form of U – tube is attached between wide and narrow tube.

3. Let us assume the fluid of density ρ flows from the pipe .

4. According to Bernoulli's equation , increase in speed is by decrease in pressure.

5. By measuring the height difference between surfaces of the manometer liquid.

S.NO	Quantity	Section A	Section B
1.	Pressure	P_1	P_2
2.	Velocity	V_1	V_2
3.	Area	A	a

From Equation of continuity

$$a_1 v_1 = a_2 v_2$$

$$A v_1 = a v_2$$

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$$V_2 = \frac{A}{a} v_1 \longrightarrow (1)$$

Using Bernoulli's equation

$$\frac{P}{\rho} + \frac{1}{2} v^2 = \text{constant}$$

Multiply by ρ

$$P + \frac{1}{2} \rho v^2 = \text{constant}$$

$$P_1 + \frac{1}{2} \rho v_1^2 = P_2 + \frac{1}{2} \rho v_2^2 \longrightarrow (2)$$

Sub eqn (1) in (2)

$$P_1 + \frac{1}{2} \rho v_1^2 = P_2 + \frac{1}{2} \rho \left(\frac{A}{a}\right) v_1^2$$

$$P_1 + \rho \frac{v_1^2}{2} = P_2 + \rho \frac{A}{a^2} \frac{v_1^2}{2}$$

$$P_1 - P_2 = \rho \frac{A}{a^2} \frac{v_1^2}{2} - \rho \frac{v_1^2}{2}$$

$$\Delta P = \rho \frac{v_1^2}{2} \left(\frac{A^2}{a^2} - 1\right)$$

$$\Delta P = \rho \frac{v_1^2}{2} \left(\frac{A^2 - a^2}{a^2}\right)$$

$$V_1^2 = \frac{2 (\Delta P) a^2}{\rho (A^2 - a^2)}$$

$$\boxed{V_1 = a \sqrt{\frac{2 (\Delta P)}{\rho (A^2 - a^2)}}}$$

Volume of liquid flow per sec

$$V = \frac{v}{t} = A v_1$$

$$\boxed{V = a A \sqrt{\frac{2 (\Delta P)}{\rho (A^2 - a^2)}}}$$

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UNIT -8

1.Explain the working of heat and work with suitable examples.

1. When hands are rubbed against each other the temperature of the hands increases. Some work is done on hands by rubbing.

2. The temperature of the hands increases due to this work. Now if the hands are placed on the chin , the temperature of the chin increases. This is because the hands are at higher temperature than the chin.

3. The temperature of hands is increased due to work and temperature of the chin is increased due heat transfer from the hands to the chin.

4. By doing work on the system , the temperature in the system will increase and sometimes may not. Like heat , work is also not a quantity and through the work energy is transferred to the system.

5. Either the system can transfer energy to the surrounding or the surrounding may transfer energy to the system by doing work on the system.

6. For the transfer of energy from one body to another body through the process of work , they need not be at different temperatures.

---

2. Discuss the ideal gas laws.

1. Boyle's Law :

When the gas is kept at constant temperature , the pressure of the gas is inversely proportional to the volume.

$$P \alpha \frac{1}{V}$$

2. Charle's Law :

When the gas is kept at constant pressure , the volume of the gas is directly proportional to the absolute temperature.

$$V \alpha T$$

3. By combining these two equations : $PV = CT$

- **The constant C as k times the number of particles N.**

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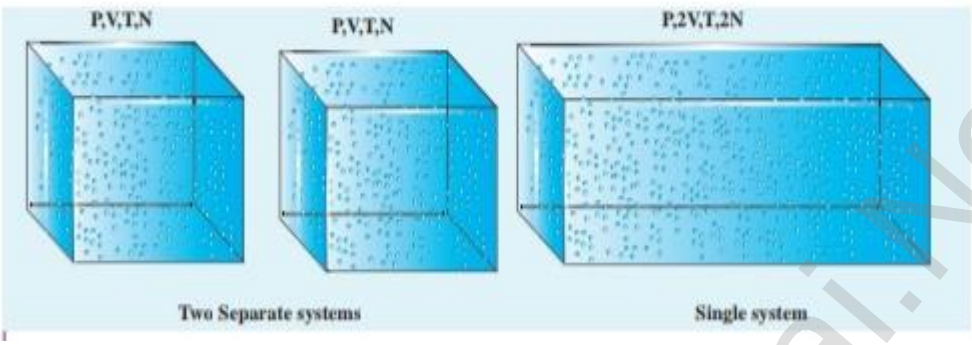
4. If we take containers of same type of gas with same volume V , same pressure P same temperature T then the gas in each container obeys the equation P V = C T.

5. If two containers of gas is considered as a single system , then the pressure and temperature of this combined system will be same but volume will be twice and the number of particles will also double.



6. For this combined system , V becomes 2 V so C should also double to match with the ideal gas equation

$$\frac{P\,(2\,V)}{T} = 2\,C$$

7. It implies that C must depend on the number of particles in the gas and also should have the dimension

$$\left(\frac{P\,V}{T}\right) = J\,K^{-1}$$

8. We can write the constant C and k times the number of particles N.

- K is the Boltzmann constant $1.381 \times 10^{-23}\ J\ K^{-1}$.
- Ideal Gas Law : $P\,V = N\,k\,T$

---

3. Explain in detail the thermal expansion.

1. The tendency of matter to change in shape , area and volume due to a change in temperature.
2. All three states of matter (solid , liquid and gas) expand when heated.
3. When solid is heated , its atoms vibrate with higher amplitude about their fixed points.

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4. The relative change in the size of solids is small.

5. Railway tracks are given small gaps so that in the summer , the tracks expand and do not buckle . Railroad tracks and bridges have expansion joints to allow them to expand and contracts freely with temperature changes.

6. Liquids have less intermolecular forces than solids and hence they expand more than solids. This is the principle behind the mercury thermometers.

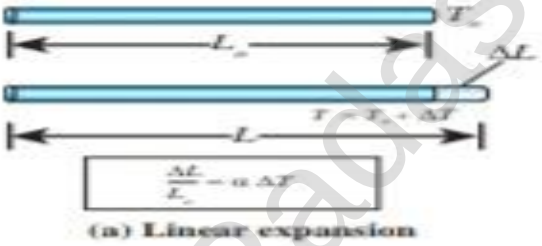
7. In the case of gas molecules , the intermolecular forces are almost negligible and hence they expand much more than solids.

8. The increase in dimension of a body due to the increase in its temperature is called *" thermal expansion "*.

9. Unit of coefficient of linear , area and volumetric expansion of solid is ^{o}C or K^{-1}.

Linear Expansion :

In solids ,small fractional change in length ($\Delta L / L_0$) is directly proportional to ΔT



$$\frac{\Delta L}{L_0} = \alpha_L \Delta T$$

$$\alpha_L = \frac{\Delta L}{L_0 \Delta T}$$

Coefficient of linear expansion → α_L

Change in length → ΔL

Original length → L_0

Change in temperature → ΔT

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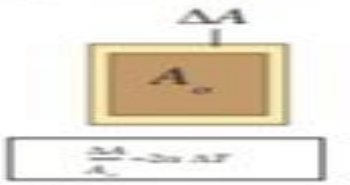
Area Expansion :

In solids , small fractional change in area ($\Delta A / A_0$) is directly proportional to ΔT



(b) Area expansion

$$\frac{\Delta A}{A_0} = \alpha_A \Delta T$$

$$\alpha_A = \frac{\Delta A}{A_0 \Delta T}$$

Coefficient of area expansion → α_A

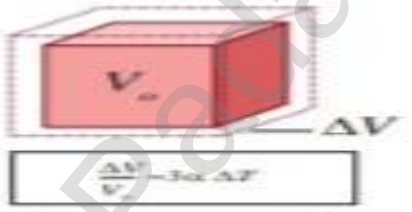
Change in area → ΔA

Original area → A_0

Change in temperature → ΔT

Volume Expansion :

In solids , small fractional change in volume ($\Delta V / V_0$) is directly proportional to ΔT



(c) Volume expansion

$$\frac{\Delta V}{V_0} = \alpha_V \Delta T$$

$$\alpha_V = \frac{\Delta V}{V_0 \Delta T}$$

Coefficient of volume expansion → α_V

Change in volume → ΔV

Original volume → V_0

Change in temperature → ΔT

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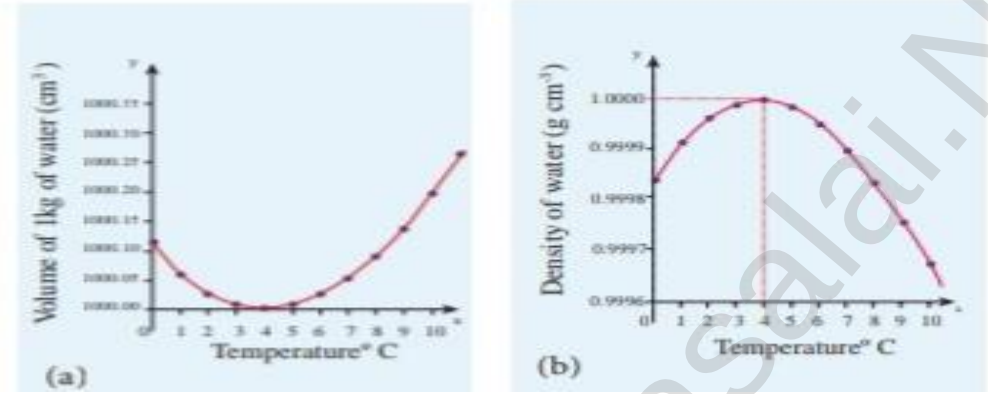
4. Describe the anomalous expansion of water . How is it helpful in our lives ?

1. Liquids expand on heating and contract on cooling moderate temperatures . But water exhibits an anomalous behaviour. It contracts on heating between 0^0C & 4^0 C.

2. The volume of the given amount of water decreases as it is cooled from room temperature , until it reach 4^0 C.

3. Below 4^0 C the volume increases and so the density decreases. This means that the water has a maximum density at 4^0 C . This behaviour of water is called anomalous expansion of water.



4. In cold countries during the winter season , the surface of the lakes will be at lower temperature than the bottom.

5. Since the solid water (ice) has lower density than its liquid form ,below 4^0 C , the frozen water will be on the top surface above the liquid water.

6. This is due to the anomalous expansion of water. As the water in lakes and ponds freeze only at the top the species living in the lakes will be safe at the bottom.

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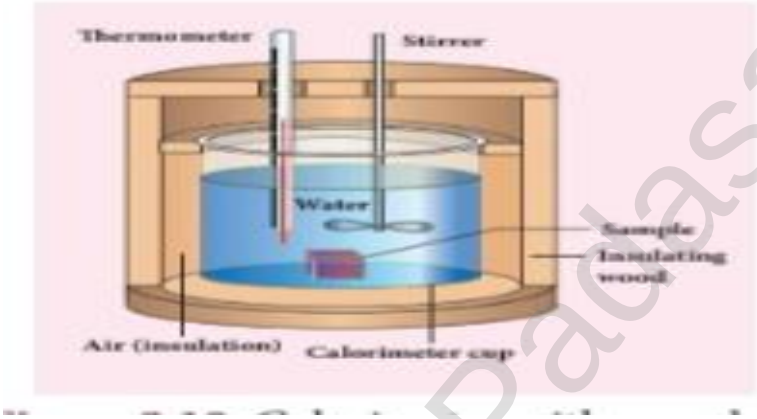
6. Explain Calorimetry and derive an expression for final temperature when two thermodynamics systems are mixed.

Calorimetry :

- **Calorimetry means the measurement of the amount of heat released or absorbed by thermodynamic system during the heating process.**
- **When a body at higher temperature is brought in contact with another body at lower temperature , the heat lost by the cold body.**
- **No heat is allowed to escape to the surroundings .**
- **Heat gained or lost is measured with a calorimeter.**
- **Usually the calorimeter is an insulated container of water .**

Diagram :



$$Q_{gain} = -Q_{lost}$$

$$Q_{gain} + Q_{lost} = 0$$

Experiment :

- **A sample is heated at high temperature (T_1) and immersed into water at room temperature (T_2) in calorimeter .**
- **After some time both sample & water reach a final equilibrium temperature T_f**
- **Since the calorimeter is insulated , heat given by the hot sample is equal to heat gained by water.**
- **The heat lost is denoted by negative sign and heat gained is denoted as positive.**

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Working :

1. $Q_{gain} = m_2 s_2 (T_f - T_2)$
2. $Q_{lost} = m_1 s_1 (T_f - T_1)$
3. $m_2 s_2 (T_f - T_2) = - m_1 s_1 (T_f - T_1)$
4. $m_2 s_2 T_f - m_2 s_2 T_2 = - m_1 s_1 T_f + m_1 s_1 T_1$
5. $m_2 s_2 T_f + m_1 s_1 T_f = m_1 s_1 T_1 + m_2 s_2 T_2$
6. $(m_2 s_2 + m_1 s_1) T_f = m_1 s_1 T_1 + m_2 s_2 T_2$

Final Temperature :

$$T_f = \frac{m_1 s_1 T_1 + m_2 s_2 T_2}{m_1 s_1 + m_2 s_2}$$

---

6. Discuss various modes of heat transfer .

1. Conduction :

The process of direct transfer of heat through matter due to temperature difference. When two objects are in direct contact with one another , heat will be transferred from the hotter object to the colder one.

2. Convection :

The process in which heat transfer is by actual movement of molecules in fluids such as liquids and gases. In convection , molecules move freely from one place to another.

3.Radiation :

It is a form of energy transfer from one body to another by electromagnetic waves. Radiation does not require medium to transfer energy from one object to another.

Examples :

1. **Solar energy from the sun**
2. **Radiation from room heater.**

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7. Explain in detail Newton's law of cooling .

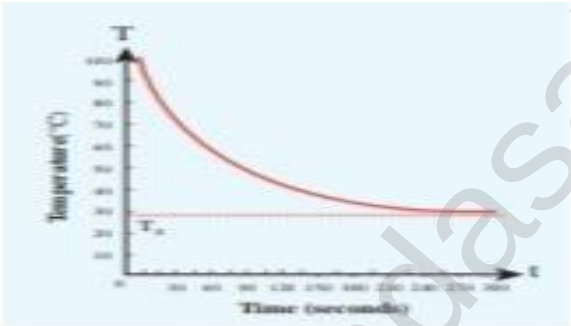
1. Newton's law of cooling states that the rate of loss of heat of a body is directly proportional to the difference in the temperature between that body & its surroundings .

$$\frac{dQ}{dt} \alpha -(T - T_S)$$

2. The negative sign indicates that the quantity of heat lost by liquid goes on decreasing with time .

- **Temperature of the object → T**
- **Temperature of the surrounding → T_S**

3. From the graph , the rate of cooling is high initially and decreases with falling temperature.



4. Let us consider an object of mass m and specific heat capacity at temperature T. Let T_S be the temperature of the surroundings . If the temperature falls by a small amount d T in time d t , then the amount of heat lost is calculated.

<u>Derivation :</u>

1. $dQ = m s dT$
2. **Dividing both sides by d t**

$$\frac{dQ}{dt} = \frac{m s dT}{dt} \quad \text{-------} (1)$$

3. **From Newton's law of cooling**

$$\frac{dQ}{dt} \alpha -(T - T_S)$$

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4. $\frac{dQ}{dt} = -a(T - T_S)$ ----- (2)

5. Sub eqn (1) in (2)

$$\frac{m\,s\,dT}{dt} = -a(T - T_S)$$

$$\frac{dT}{T - T_S} = -\frac{a}{m\,s}\,dt$$

6. Integrating above eqn

$$\int \frac{dT}{T - T_S} = -\frac{a}{m\,s}\int dt$$

7. $\ln(T - T_S) = \frac{a}{m\,s}t + b_1$

8. Taking exponential on both sides

$$T - T_S = b_2\, e^{a/ms\,t}$$

9. $b_2 = e^{b_1} = \text{constant}$

10. $T = T_S + b_2\, e^{a/ms\,t}$

---

8. Explain Wien's law and why our eyes sensitive only to visible rays ?

1. Wien's law states that wavelength of maximum intensity of emission of a black body radiation is inversely proportional to the absolute temperature of the body.

$$\lambda_m \;\alpha\; \frac{1}{T}$$

$$\lambda_m = \frac{b}{T}$$

b is known as Wien's constant .

$b = 2.898 \times 10^{-3}$ m K .

2. The sun is approximately taken as a black body. Since any object above 0 K will emit radiation , sun also emits radiation . Its surface temperature is about 5700 K.

$$\lambda_m = \frac{b}{T} = \frac{2.898 \times 10^{-3}}{5700} = 508\ \text{nm}$$

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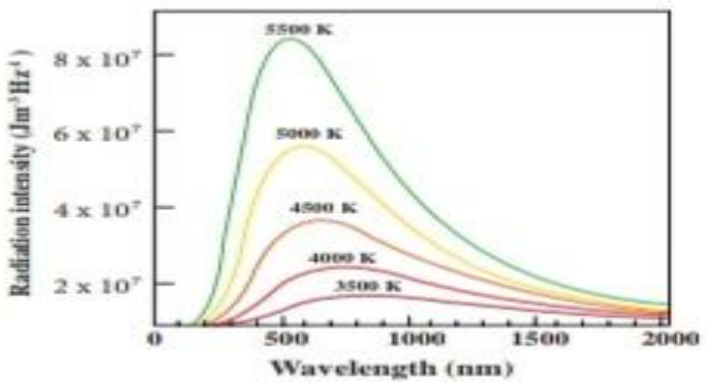

3. It is the wavelength at which maximum intensity is 5 0 8 n m . Since the sun's temperature is around 5700 k , the spectrum of radiations emitted by sun lie between 400 n m and 700 nm which is the visible part of the spectrum.

4. The humans evolved under sun by receiving its radiations . The human eye is sensitive only in the visible not in infrared or X - ray ranges in the spectrum.

5. Suppose if humans had evolved in a planet near the star Sirius (9940 K) , then they would have had the ability to see the ultraviolet rays.

---

9. Discuss the following a) Thermal equilibrium b) Mechanical equilibrium c) Chemical equilibrium d) Thermodynamic equilibrium

<u>a) Thermal Equilibrium :</u>

Two systems are said to be in thermal equilibrium with each other if they are at the same temperature , which will not change with time.

<u>b) Mechanical equilibrium :</u>

- **Consider a gas container with piston . When some mass is placed on the piston , it will move downward due to downward gravitational force and after certain humps and jumps the piston will come to rest at a new position.**
- **When the downward gravitational force given by the piston is balanced by the piston is balanced by the upward force exerted by the gas , the system is said be in mechanical equilibrium .**

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- **A system is said to be in mechanical equilibrium if no unbalanced force acts on the thermodynamics system or on the surrounding by thermodynamic system.**

c) Chemical Equilibrium :

If there is no net chemical reaction between two thermodynamics systems in contact with each other then it is said to be in chemical equilibrium.

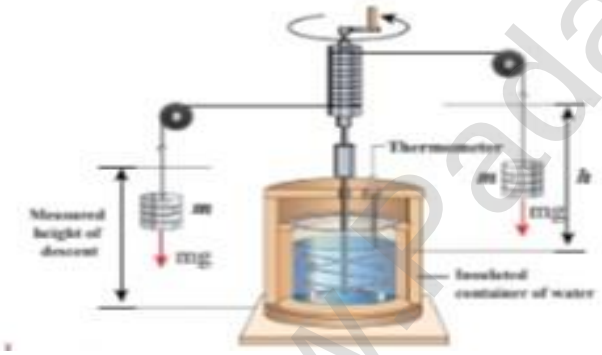
d) Thermodynamic Equilibrium :

- **If two systems are said to be in thermodynamic equilibrium , then the systems are at thermal , mechanical and chemical equilibrium with each other.**
- **In a state of thermodynamic equilibrium the macroscopic variables such as pressure , volume and temperature will have fixed values and do not change with time.**

---

10. Explain Joule's experiment of the mechanical equivalent of heat.

Diagram :



- **Joule showed that mechanical energy can be converted into internal energy . In his experiment , two masses were attached with a rope and a paddle wheel.**
- **When these masses fall through a distance h due to gravity , both the masses lose potential energy equal to 2 m g h.**
- **When the masses fall , the paddle wheel turns . Due to the turning of wheel inside water , frictional force comes in between the water and paddle wheel.**

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- This cause a rise in temperature of the water. This implies that gravitational potential energy is converted to internal energy of water.
- The temperature of water increases due to the work done by the masses. Joule was able to show that the mechanical work has the same effect as giving heat.
- He found that to raise 1 g of an object by 1^0 C , 4.186 J of energy is required. In earlier days the heat was measured in calorie.

1 Cal = 4.186 J

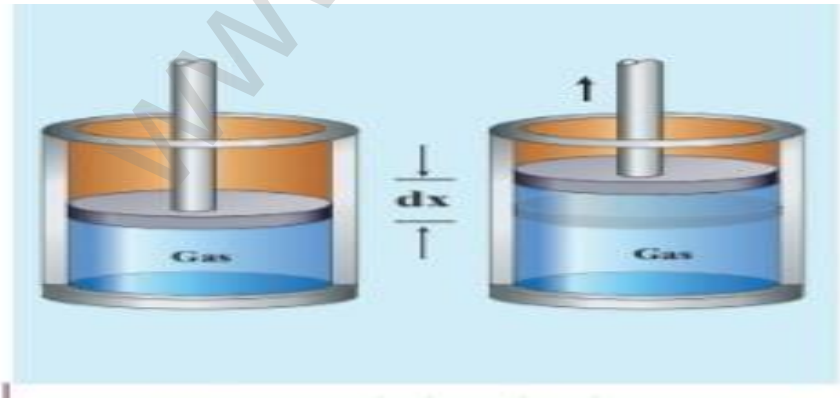
- This is called Joule's mechanical equivalent of heat.

---

11. Derive the expression for the work done in a volume change in a thermodynamics system.

1. Consider a gas contained in the cylinder fitted with a movable piston.
2. Suppose the gas is expanded quasi statically by pushing the piston by a small distance dx.
3. Since the expansion occurs quasi - statically the pressure , temperature and internal energy will have unique values at every instant. The small work done by the gas on the piston $dW = F\,dx$
4. The force exerted by the gas on the piston $F = P\,A$. Here A is area of the piston and P is pressure exerted by the gas on the piston.

Diagram :



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Derivation :

1 $dW = F\,dx$

2. $F = P\,A$

3. $dW = P\,A\,dx$

4. $\int dW = \int_{V_i}^{V_f} P\,dV$

5. $W = \int_{V_i}^{V_f} P\,dV$

6. Work is done by the system then $V_i < V_f$ then W is positive.

7. Work is done on the system then $V_i > V_f$ then W is negative.

---

12. Derive Mayer's relation for an ideal gas.

1. Consider μ mole of an ideal gas in a container with volume V , pressure P and temperature T.

2. When the gas is heated at constant volume the temperature increases by d T.

3. As no work is done by the gas , the heat that flows into the system will increase only the internal energy . Let the change in internal energy by d U.

4. If C_V is the molar specific heat capacity at constant volume.

$$dU = \mu C_V\,dT \text{ ---------- } (1)$$

5. The gas is heated at constant pressure so that the temperature increases by d T . If ' Q ' is the heat supplied in this process and 'd V ' the change in volume of the gas.

$$Q = \mu C_P\,dT \text{ ---------- } (2)$$

6. If W is the work done by the gas $W = P\,dV$ ---------- (3)

7. First law of thermodynamics $Q = dU + W$ ---------- (4)

8. Sub eqn (1) , (2) , (3) in (4)

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$$\mu C_P \, dT = \mu C_V \, dT + P \, dV \quad \text{----------} \quad (5)$$

9. For mole of ideal gas equation , $PV = \mu RT$

10. Diff the above eqn $P\,dV + V\,dP = \mu R\,dT$

11. Since the pressure is constant , $dP = 0$ then $P\,dV = \mu R\,dT$ ----- (6)

12. Sub eqn (6) in (5) ➔ $\mu C_P \, dT = \mu C_V \, dT + \mu R \, dT$

13. $\mu C_P \, dT - \mu C_V \, dT = \mu R \, dT$

14. $\mu (C_P - C_V) \, dT = \mu R \, dT$

15. $C_P - C_V = R$ " Mayer's Relation "

---

13. Explain in detail the isothermal process.

1. It is a process in which the temperature remains constant.

2. But the pressure and volume of thermodynamic system will change.

3. Equation of state for isothermal process : PV = constant

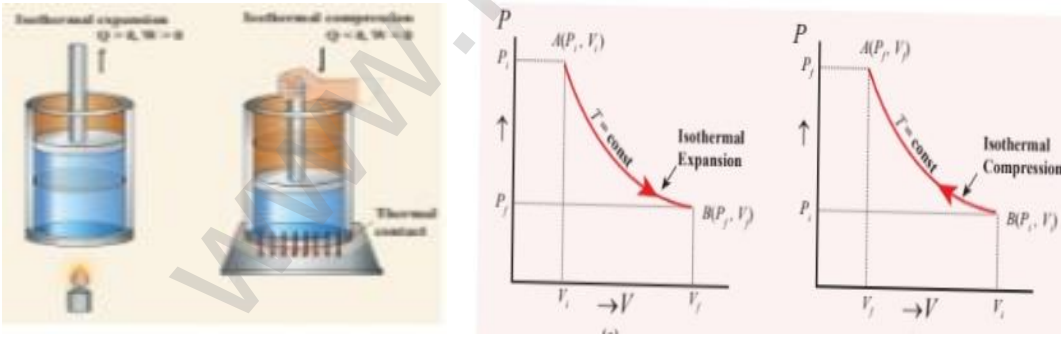
4. If the gas goes from one equilibrium state (P_1 , V_1) to another equilibrium state (P_2 , V_2) then $P_1 V_1 = P_2 V_2$

5. P V graph is *hyperbola* . P V diagram is also called *isotherm.*

6. Temperature is constant , internal energy is also constant . $\Delta U = 0$

7. First law of thermodynamics , $Q = W$

8. Isothermal expansion and compression takes place.



9. The isothermal compression takes place when the piston of the cylinder is pushed.

10. This will increase the internal energy which will flow out of the system through thermal contact.

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14. Derive the work done in an isothermal process.

1. Consider an ideal gas which is allowed to expand quasi - statically at constant temperature from initial state (P_i , V_i) to the final state (P_f , V_f) .

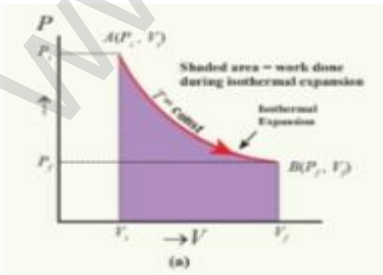
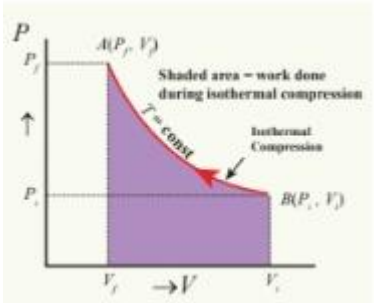
2. Work done by the gas , $W = \int_{V_i}^{V_f} P\,dV$ ➔ (1)

3. Ideal gas equation $PV = \mu RT$ then $P = \frac{\mu RT}{V}$ ➔ (2)

4. Sub eqn (2) in (1) $W = \int_{V_i}^{V_f} \frac{\mu RT}{V}\,dV$

5. $W = \mu RT \int_{V_i}^{V_f} \frac{dV}{V}$

6. $W = \mu RT \ln\left(\frac{V_f}{V_i}\right)$

S.NO	Isothermal Expansion	Isothermal Compression
1.	$\frac{V_f}{V_i} > 1$	$\frac{V_f}{V_i} < 1$
2.	$\ln\left(\frac{V_f}{V_i}\right) > 0$	$\ln\left(\frac{V_f}{V_i}\right) < 0$
3.	Work done by the gas is positive	Work done by the gas is negative
4.		

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15 . Explain in detail an adiabatic process.

1. This is a process in which no heat flows into or out of the system (Q = 0)

2. The pressure , volume and temperature of the system may change .

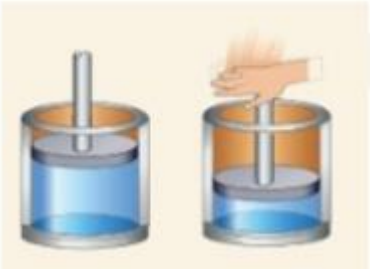
3. Equation of state for adiabatic process : $P V^{\gamma}$ = constant --------- (1)

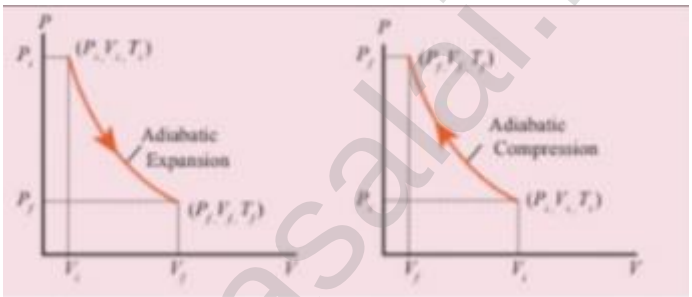
4. Adiabatic exponent $\gamma = C_P / C_V$

5. If the gas goes from one equilibrium state (P_i , V_i) to another equilibrium state (P_f , V_f) then $P_i V_i^{\gamma} = P_f V_f^{\gamma}$

6. P V diagram is also called *adiabat.*

7. First law of thermodynamics : $\Delta U = Q - P \Delta V$





8. Ideal gas equation $P V = \mu R T$ then $P = \frac{\mu R T}{V}$ ----- (2)

9. Sub eqn (2) in (1)

$$\frac{\mu R T}{V} V^{\gamma} = \text{Constant}$$

10. $$T V^{\gamma - 1} = \text{Constant}$$

11. $$T^{\gamma} P^{1-\gamma} = \text{Constant}$$

---

16. Derive the work done in an adiabatic process.

1. Consider μ moles of an ideal gas enclosed in a cylinder having perfectly non – conducting walls and base.

2. A frictionless and insulating piston of cross - sectional area A is fitted in the cylinder.

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3. Let W be the work done when the system goes from the initial state (P_i , V_i , T_i) to the final state (P_f , V_f , T_f) adiabatically.

4. Work done by the gas , $W = \int_{V_i}^{V_f} P\,dV$ ➔ (1)

5. Adiabatic equation $P V^{\gamma} = \text{Constant}$ then $P = \frac{\text{Constant}}{V^{\gamma}}$ ➔ (2)

6. Sub eqn (2) in (1)

$$W_{adia} = \int_{V_i}^{V_f} \frac{Constant}{V^{\gamma}}\, dV$$

$$W_{adia} = \text{Constant} \int_{V_i}^{V_f} V^{-\gamma}\, dV$$

$$W_{adia} = \text{Constant} \left(\frac{V^{-\gamma+1}}{-\gamma+1} \right)_{V_i}^{V_f}$$

$$W_{adia} = \frac{\text{Constant}}{1-\gamma} \left(\frac{1}{V_f^{\gamma-1}} - \frac{1}{V_i^{\gamma-1}} \right)$$

$$W_{adia} = \frac{1}{1-\gamma} \left(\frac{\text{Constant}}{V_f^{\gamma-1}} - \frac{\text{Constant}}{V_i^{\gamma-1}} \right) \rightarrow (3)$$

7. $P_i V_i^{\gamma} = P_f V_f^{\gamma} = \text{Constant}$ ➔ (4)

8. Sub eqn (4) in (3)

$$W_{adia} = \frac{1}{1-\gamma} \left(\frac{P_f V_f^{\gamma}}{V_f^{\gamma-1}} - \frac{P_i V_i^{\gamma}}{V_i^{\gamma-1}} \right)$$

9. $W_{adia} = \frac{1}{1-\gamma} \left(P_f V_f - P_i V_i \right)$

10. From ideal gas eqn , $P_f V_f = \mu R T_f$ and $P_i V_i = \mu R T_i$

11. $W_{adia} = \frac{\mu R}{1-\gamma} (T_f - T_i)$ $\boxed{W_{adia} = \frac{\mu R}{\gamma - 1} (T_i - T_f)}$

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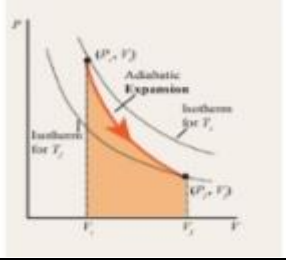
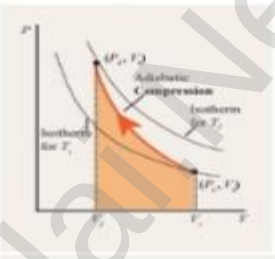
S.NO	Adiabatic Expansion	Adiabatic Compression
1.	$T_i > T_f$	$T_i < T_f$
2.	W_{adia} is positive .	W_{adia} is negative .
3.	Work done by the gas is positive	Work done by the gas is negative
4.		

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17. Explain the isobaric process and derive the work done in this process.

Diagram :

Isobaric Process :

1. This is a process that occurs at constant pressure .
2. The temperature , volume and internal energy are not constant.
3. Equation of state for isobaric process : $V \alpha T$; $\frac{V}{T}$ = Constant
4. V - T graph is a straight line .
5. If the gas goes from one equilibrium state (V_i , T_i) to another equilibrium state (V_f , T_f) then $\frac{T_f}{V_f} = \frac{T_i}{V_i}$

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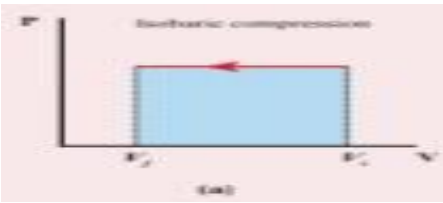
S.NO	Isobaric Expansion	Isobaric Compression
1.	ΔV is positive	ΔV is negative
2.	W_{adia} is positive	W_{adia} is negative
3.	Work done by the gas is positive	Work done by the gas is negative
4.		

Work done in a isobaric process :

1. Work done by the gas , $W = \int_{V_i}^{V_f} P\,dV$ ➔ (1)

2. $W = P \int_{V_i}^{V_f} dV$

3. $W = P (V_f - V_i) = P \Delta V$ ➔ (2)

4. From ideal gas eqn $P V = \mu R T$ and $V = \frac{\mu R T}{P}$

5. $V_f = \frac{\mu R T_f}{P}$ and $V_i = \frac{\mu R T_i}{P}$ ➔ (3)

6. Sub eqn (3) in (2)

$$W = P \left(\frac{\mu R T_f}{P} - \frac{\mu R T_i}{P} \right)$$

$$W = \mu R \left(T_f - T_i \right)$$

$$W = \mu R T_f \left(1 - \frac{T_i}{T_f} \right)$$

7. First law of thermodynamics : $\Delta U = Q - P \Delta V$

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18. Explain in detail the isochoric process.

1. This is a thermodynamics process in which volume of the system is kept constant.

2. But pressure , temperature and internal energy are variables.

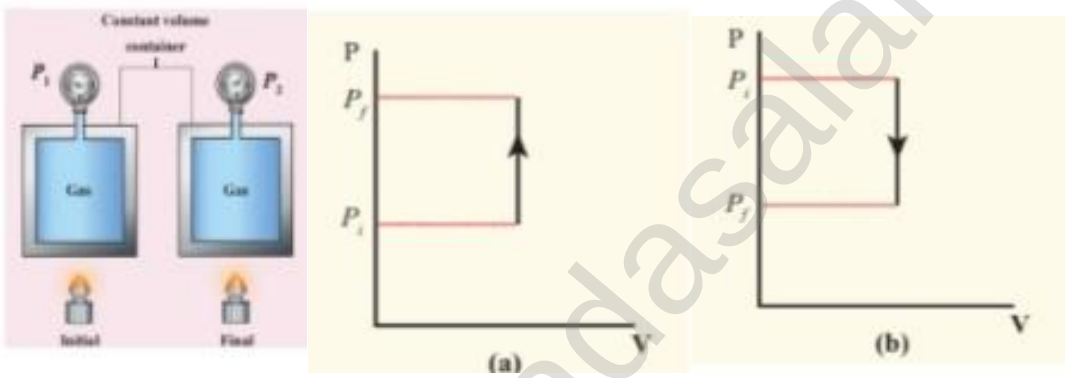
3. Equation of state for isochoric process : $P \alpha T$; $\frac{P}{T}$ = Constant

4. V - T graph is a straight line .

5. If the gas goes from one equilibrium state (P_i , T_i) to another equilibrium state (P_f , T_f) then $\frac{P_i}{T_i} = \frac{P_f}{T_f}$

6. For an isochoric process $\Delta V = 0$ and $W = 0$

7. First law of thermodynamics : $\Delta U = Q$



8. Heat supplied is used to increase only the internal energy . As a result the temperature increases and pressure also increases.

9. Suppose a system loses heat to the surroundings through conducting walls by keeping the volume constant , then its internal decreases. As a result the temperature decreases , the pressure also decreases.

---

19. What are the limitations of the first law of thermodynamics ?

<u>Limitations of the first law of thermodynamics :</u>

The first law of thermodynamics explains the inter convertibility of heat and work . But it does not indicate the direction of change.

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Example :

1. When a hot object is in contact with a cold object , heat always flows from the hot object to cold object but not in the reverse direction.
2. According to first law , it is possible for the energy to flow from hot object to cold object or from cold object to hot object.
3. But in nature the direction of heat flow is always from higher to lower temperature.
4. When brakes are applied , a car stops due to friction and the work done against friction is converted into heat.
5. But this heat is not reconverted to the kinetic energy of the car. So the first law is not sufficient to explain many of natural phenomena.

---

20. Explain the heat engine and obtains its efficiency.

Heat Engine :

Heat engine is a device which takes heat as input and converts this haet into work by undergoing a cyclic process.

Parts of Heat Engine :

1. Hot Reservoir 2. Working Substance 3. Cold Reservoir

1. Hot Reservoir (or) Source :

- It supplies heat to the engine.
- It is always maintained at a high temperature T_H.

2. Working Substance :

- It is a substance like gas or water .
- It converts the heat supplied into work.

3. Cold Reservoir (or) Sink :

- Heat engine ejects some amount of heat Q_L into cold reservoir after it doing work.
- It is always maintained at a low temperature T_L.

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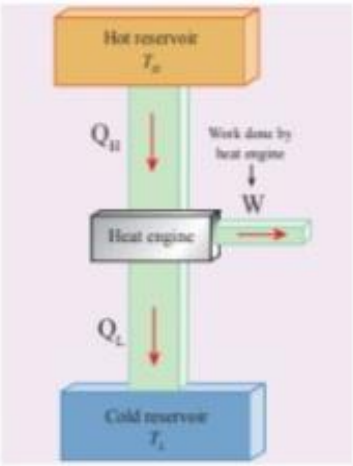
Diagram :



Working :

1. The heat engine works in a cyclic process .
2. After a cyclic process it returns to the same state .
3. Since the heat engine returns to the same state after it ejects heat , the change in the internal energy of the heat engine is zero.

Efficiency :

The efficiency of the heat engine is defined as the ratio of the work done (output) to the heat absorbed (input) in one cyclic process.

- Working substance absorb heat ➔ Q_H
- Working substance reject heat ➔ Q_L
- Input heat = Work done + Ejected heat
- $Q_H = W + Q_L$
- $\eta = \frac{\text{Output}}{\text{Input}}$
- $\eta = \frac{W}{Q_H} = \frac{Q_H - Q_L}{Q_H}$
- $Q_L < Q_H$, η less than 1.
- This implies that heat absorbed is not completely converted into work.

$$\boxed{\eta = 1 - \frac{Q_H}{Q_L}}$$

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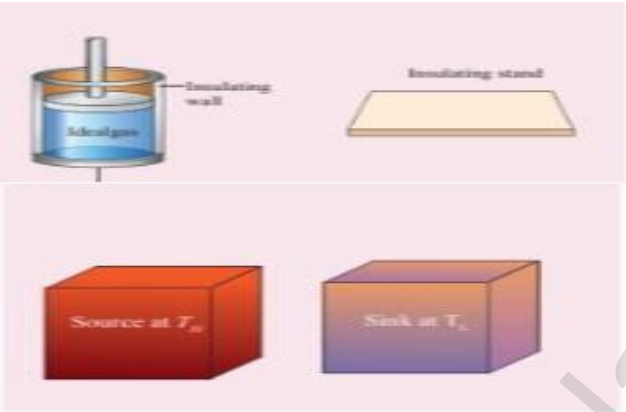
21. Explain in detail Carnot heat engine.

Carnot Engine :

A reversible heat engine operating in a cycle between two temperatures in a particular way is called a Carnot engine.

Parts of Carnot engine :



1.Source :

- **It is the source of heat maintained at constant high temperature T_H .**
- **Any amount of heat can be extracted from it , without changing its temperature.**

2. Sink :

- **It is a cold body maintained at a constant low temperature T_L .**
- **It can absorb any amount of heat .**

3. Insulating Stand :

- **It is made of perfectly non - conducting material .**
- **Heat is not conducted through this stand.**

4. Working Substance :

- **It is an ideal gas enclosed in a cylinder with perfectly non - conducting walls and perfectly conducting bottom.**
- **A non - conducting and frictionless piston is fitted in it.**

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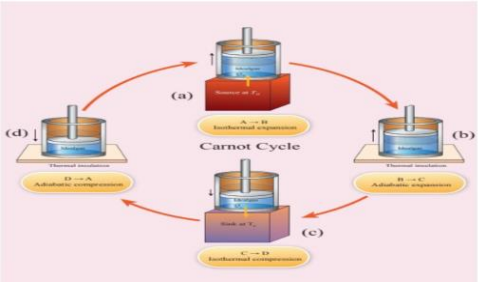
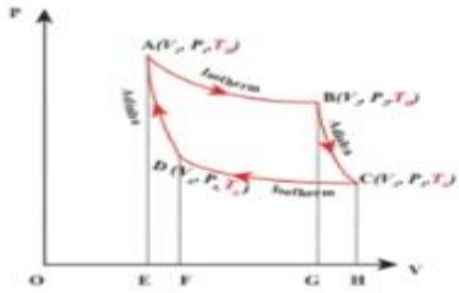
Carnot Cycle :





1. Step A to B :

1. Quasi – static isothermal expansion from (P_1 , V_1 , T_H) to (P_2 , V_2 , T_H)
2. Cylinder is placed on the source .
3. Heat (Q_H) flows from source to the working substance.
4. Volume of gas expands from V_1 to V_2 .
5. Pressure decrease from P_1 to P_2.
6. P - V diagram along the path AB.

$$W_{A\to B} = \int_{V_1}^{V_2} P\,dV = \mu R T_H \ln\left(\frac{V_2}{V_1}\right) = \text{Area under the curve AB}$$

2. Step A to B :

1. Quasi – static adiabatic expansion from (P_2 , V_2 , T_H) to (P_3 , V_3 , T_L)
2. Cylinder is placed on the insulating stand .
3. Temperature falls to T_L.
4. Volume of gas expands from V_2 to V_3 .
5. Pressure decrease from P_2 to P_3.
6. P - V diagram along the path BC.

$$W_{B\to C} = \int_{V_2}^{V_3} P\,dV = \left(\frac{\mu R}{\gamma - 1}\right)[T_H - T_L] = \text{Area under the curve BC}$$

3. Step C to D :

1. Quasi – static isothermal compression from (P_3 , V_3 , T_L) to (P_4 , V_4 , T_L)
2. Cylinder is placed on the sink .

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3. Heat (Q_H) flows from source to the working substance.

4. Volume of gas become V_4 .

5. Pressure of gas P_4.

6. P - V diagram along the path CD.

$$W_{C\to D} = \int_{V_3}^{V_4} P\,dV = \mu R T_L \ln\left(\frac{V_4}{V_3}\right) = \text{- Area under the curve CD}$$

4. Step D to A :

1. Quasi – static adiabatic compression from (P_4 , V_4, T_L) to (P_1 , V_1 , T_H)

2. Cylinder is placed on the insulating stand .

3. Temperature rise to T_H.

4. Volume of gas attains V_1.

5. Pressure of gas attains P_1.

6. P - V diagram along the path DA.

$$W_{D\to A} = \int_{V_4}^{V_1} P\,dV = \left(\frac{\mu R}{\gamma - 1}\right)[T_L - T_H] = \text{Area under the curve DA}$$

---

22. Derive the expression for Carnot engine efficiency .

Efficiency :

The ratio of work done by the working substance in one cycle to the amount of heat extracted from the source.

$$\eta = \frac{\text{Work done}}{\text{Heat Extracted}} = \frac{W}{Q_H}$$

1. From the first law of thermodynamics $W = Q_H - Q_L$

2. Efficiency : $\eta = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$ -------- (1)

3. Applying isothermal conditions

$$Q_H = \mu R T_H \ln\left(V_2 / V_1\right)$$

$$Q_L = \mu R T_L \ln\left(V_3 / V_4\right)$$

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4. $$\frac{Q_L}{Q_H} = \frac{\mu R T_L \ln (V_3 / V_4)}{\mu R T_H \ln (V_2 / V_1)}$$

5. $$\frac{Q_L}{Q_H} = \frac{T_L \ln (V_3 / V_4)}{T_H \ln (V_2 / V_1)} \quad \text{-------- (2)}$$

6. Applying adiabatic conditions

$$T_H V_2^{\gamma - 1} = T_L V_3^{\gamma - 1}$$

$$T_H V_1^{\gamma - 1} = T_L V_4^{\gamma - 1}$$

7. $$\frac{T_H V_2^{\gamma - 1}}{T_H V_1^{\gamma - 1}} = \frac{T_L V_3^{\gamma - 1}}{T_L V_4^{\gamma - 1}}$$

8. $$\left(\frac{V_2}{V_1}\right)^{\gamma - 1} = \left(\frac{V_3}{V_4}\right)^{\gamma - 1}$$

9. $$\frac{V_2}{V_1} = \frac{V_3}{V_4} \quad \text{-------- (3)}$$

10. Sub eqn (3) in (2)

$$\frac{Q_L}{Q_H} = \frac{T_L \ln (V_3 / V_4)}{T_H \ln (V_3 / V_4)}$$

11. $$\frac{Q_L}{Q_H} = \frac{T_L}{T_H} \quad \text{-------- (4)}$$

12. Sub eqn (4) in (1)

$$\boxed{\eta = 1 - \frac{T_L}{T_H}}$$

---

23. Explain the second law of thermodynamics in terms of entropy.

1. Quantity Q / T is called entropy.

2. It is a very important thermodynamic property.

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3. It is also a state variable.

4. Q_H / T_H is the entropy received by the Carnot engine from hot reservoir.

5. Q_L / T_L is the entropy given out by the Carnot engine to cold reservoir.

6. For reversible engines both entropies should be same.

7. The change in entropy of the Carnot engine in one cycle is zero.

8. For all practical engines like diesel and petrol engines which are not reversible engines , they satisfy the relation $Q_L / T_L > Q_H / T_H$.

9. " For all the process that occur in nature , the entropy always increases . For reversible process entropy will not change " .

10. Entropy determines the direction in which natural process should occur.

11. Entropy increases when heat flows from hot object to cold object. If heat flow from cold to hot object , entropy decreases leading to violation of second law of thermodynamics.

12. Entropy is also called " measure of disorder " . All natural process occur such that the disorder should always increases.

EX :

A drop of ink diffusing into water . Once the drop of ink spreads , its entropy is increases its entropy is increased. The diffused ink can never become a drop again. So the natural processes occur in such a way that entropy should increase for all irreversible process.

---

24 . Explain in detail the working of a refrigerator.

A refrigerator is a Carnot's engine working in the reverse order.

Working Principle :

1. The working substance (gas) absorb a quantity of heat Q_L from the cold body (sink) at a lower temperature T_L .

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2. A certain amount of work W is done on the working substance by the compressor.

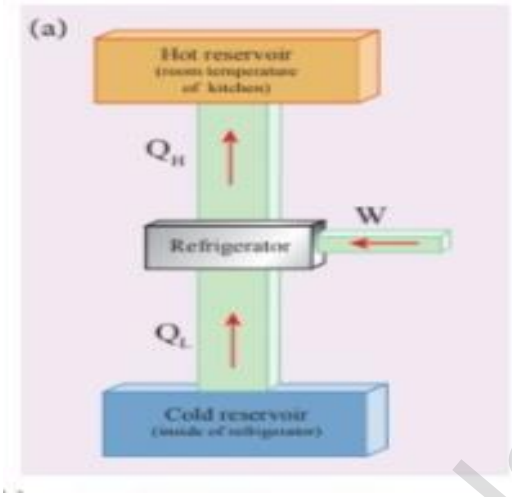
3. A quantity of heat Q_H is rejected to the hot body (source) at T_H .

4. When you stand beneath of refrigerator , you can feel warmth air.

5. From the first law of thermodynamics : $Q_L + W = Q_H$

6. As a result the cold reservoir (refrigerator) further cools down and the surroundings kitchen gets hotter.

Diagram :



Coefficient of performance :

It is defined as the ratio of heat extracted from the cold body to the external from the cold body to the external work done by the compressor .

$$COP = \beta = \frac{Q_L}{W}$$

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9 . Kinetic theory of gases

1. Write down the postulates of kinetic theory of gases

1. All molecules of a gas are identical elastic spheres.

2.The molecules of different gases are different.

3. The molecules of a gas are in a state of continuous random motion.

4. The molecules obey Newton's laws of motion even though they move randomly.

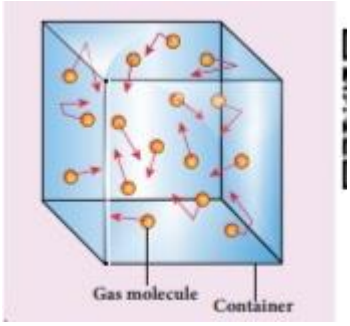
5. The molecules collide with one another and also with the walls of the container.

6. These collision are perfectly elastic there is no loss of kinetic energy during collision.

7. Between two successive collisions , molecule moves with uniform velocity.

2.Derive the expression of pressure exerted by the gas on the walls of the container.

Diagram :



Formula :

$$P = \frac{1}{3} n m \overline{v^2}$$

Theory :

Consider a monoatomic gas inside a cubical container.

- **Mass of the molecule → m**
- **Velocity of the molecule → v**
- **Number of the molecule → N**

Pressure exerted by the gas molecule

1. Molecules of gas are in random motion.

2. They collide with each other and with container walls.

3.There is no loss of kinetic energy.

4. Change in momentum occurs.

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5. Due to momentum , experiences force.

6. Force per unit area determines pressure exerted by the gas molecules.

Derivation :

1. Component of velocity : v_x , v_y , v_z

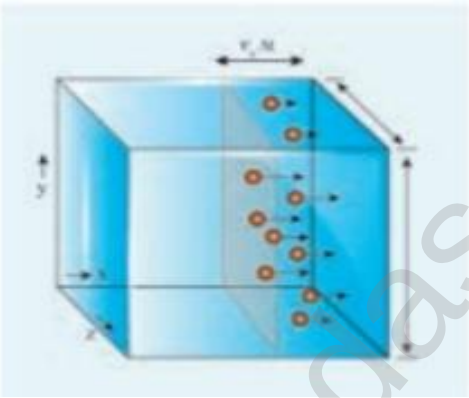
2. Momentum of the molecule :

Before collision = $m\,v_x$

After collision = $-\,m\,v_x$

Change in momentum = $-\,m\,v_x - m\,v_x$ = $-\,2\,m\,v_x$

3. Law of conservation of momentum = $2\,m\,v_x$



4. Number of molecules hit right side wall = $\frac{n}{2}\,A\,v_x\,\Delta t$

5. Total momentum transfer by molecule $\Delta p = \frac{n}{2}\,A\,v_x\,\Delta t \times 2\,m\,v_x = A\,v_x^2\,nm\,\Delta t$

6. Newton's second law : $F = \frac{\Delta p}{\Delta t} = n\,m\,A\,v_x^2$

7. Pressure exerted by gas molecule : $P = \frac{F}{A} = n\,m\,v_x^2$

8.The molecules do not have same speed . so we can replace the term

v_x^2 by the average $\overline{v_x^2}$

$P = n\,m\,\overline{v_x^2}$

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9.The molecules have same average speed.

$$\overline{v_x^2} = \overline{v_y^2} = \overline{v_z^2}$$

$$\overline{v^2} = \overline{v_x^2} + \overline{v_x^2} + \overline{v_x^2} = 3\,\overline{v_x^2}$$

$$\overline{v_x^2} = \frac{1}{3}\overline{v^2}$$

10. $P = \frac{1}{3} n m \overline{v^2} = \frac{1}{3}\frac{N}{V} m v^2 \quad (n = N / V)$

---

3. Explain in detail the kinetic interpretation of temperature.

1. Microscopic Origin of temperature

$$P = \frac{1}{3}\frac{N}{V} m \overline{v^2}$$

$$P V = \frac{1}{3} N m \overline{v^2}$$

2. Ideal gas equation $P V = N K T$

$$N K T = \frac{1}{3} N m \overline{v^2}$$

$$K T = \frac{1}{3} m \overline{v^2}$$

3. Multiply both sides by 3 / 2

$$\frac{3}{2} K T = \frac{3}{2}\frac{1}{3} m \overline{v^2}$$

$$\frac{3}{2} K T = \frac{1}{2} m \overline{v^2}$$

$$\frac{1}{2} m \overline{v^2} = \frac{3}{2} K T$$

4. Average kinetic energy per molecule

$$K.E = \frac{3}{2} K T$$

5. Average K.E directly proportional to temperature.

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6. Average K.E depends only on temperature not on mass of the molecule.

7. Internal energy of ideal gas

$$U = N\left(\frac{1}{2} m \overline{v^2}\right) = \frac{3}{2} NKT$$

---

4. Describe the total degrees of freedom for monoatomic molecule , diatomic molecule and triatomic molecule.

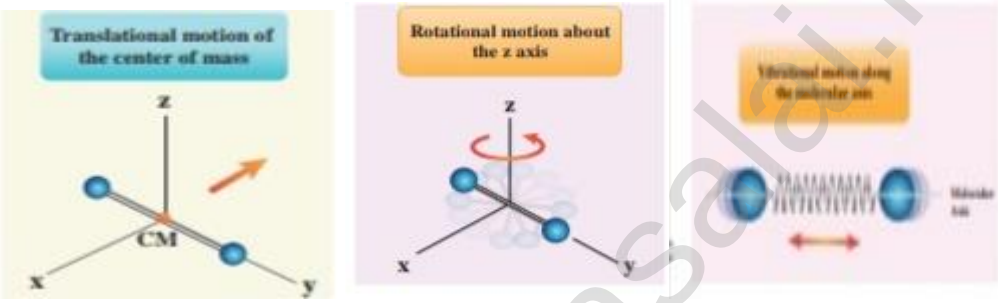
1.<u>Monoatomic Molecule</u>

It has three translational degrees of freedom.

$$\boxed{f = 3}$$

Example : He , Ne , Ar

2.<u>Diatomic Molecule :</u>



At Normal Temperature	At High Temperature
Translational : f = 3	Translational : f = 3
Rotational : f = 2	Rotational : f = 2
Degrees of freedom : f = 5	Vibrational : f = 2
	Degrees of freedom : f = 7

3 .<u>Triatomic Molecule :</u>

i) Linear Triatomic molecule

i i) Non - Linear Triatomic molecule

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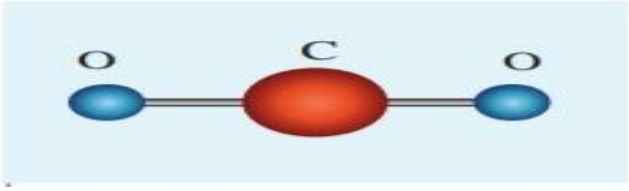
i) Linear Triatomic molecule

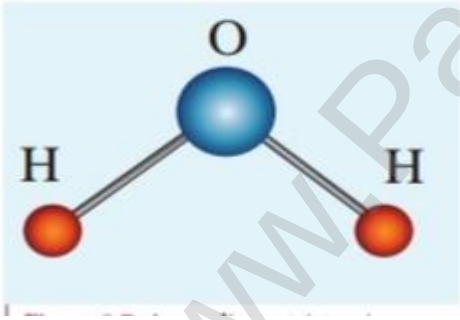
Two atoms lie on either side of central atom. Example : Carbon di oxide



At Normal Temperature	At High Temperature
Translational : f = 3	Translational : f = 3
Rotational : f = 2	Rotational : f = 2
Degrees of freedom : f = 5	Vibrational : f = 2
	Degrees of freedom : f = 5

i i) Non - Linear Triatomic molecule

Three atoms lie at the vertices of triangle. Example : H_2O



Translational : f = 3
Rotational : f = 3
Degrees of freedom : f = 6

---

5. Derive the ratio of two specific heat capacities of monoatomic , diatomic and triatomic molecules.

1. Total energy of a one mole of gas : $U = \frac{3}{2} RT$

2. Mayer's relation of specific heat : $C_p = C_V + R$

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3. Ratio between two specific heats : $\gamma = \frac{C_P}{C_V}$

i . Monoatomic Molecule

1. $C_V = \frac{dU}{dT} = \frac{d}{dT}\left[\frac{3}{2} R T\right] = \frac{3}{2} R$

2. $C_p = C_V + R = \frac{3}{2} R + R = \frac{5}{2} R$

3. $\gamma = \frac{C_P}{C_V} = \frac{5/2\ R}{3/2\ R} = \frac{5}{3} = 1.67$

ii . Diatomic Molecule

1. At Low Temperature

1. $C_V = \frac{dU}{dT} = \frac{d}{dT}\left[\frac{5}{2} R T\right] = \frac{5}{2} R$

2. $C_p = C_V + R = \frac{5}{2} R + R = \frac{7}{2} R$

3. $\gamma = \frac{C_P}{C_V} = \frac{7/2\ R}{5/2\ R} = \frac{7}{5} = 1.4$

2. At High Temperature

1. $C_V = \frac{dU}{dT} = \frac{d}{dT}\left[\frac{7}{2} R T\right] = \frac{7}{2} R$

2. $C_p = C_V + R = \frac{7}{2} R + R = \frac{9}{2} R$

3. $\gamma = \frac{C_P}{C_V} = \frac{9/2\ R}{7/2\ R} = \frac{9}{7} = 1.28$

iii .Triatomic Molecule

1. Linear Molecule :

1. $C_V = \frac{dU}{dT} = \frac{d}{dT}\left[\frac{7}{2} R T\right] = \frac{7}{2} R$

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2. $C_p = C_V + R = \frac{7}{2} R + R = \frac{9}{2} R$

3. $\gamma = \frac{C_P}{C_V} = \frac{9/2\ R}{7/2\ R} = \frac{9}{7} = 1.28$

2. At High Temperature

1. $C_V = \frac{dU}{dT} = \frac{d}{dT} [\frac{6}{2} R T] = 3 R$

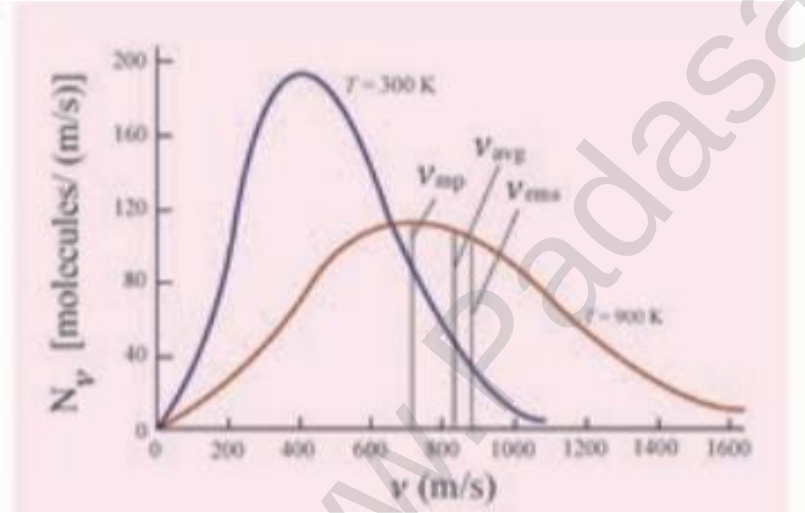
2. $C_p = C_V + R = 3 R + R = 4 R$

3. $\gamma = \frac{C_P}{C_V} = \frac{4 R}{3 R} = \frac{4}{3} = 1.33$

---

6. Explain in detail the Maxwell Boltzmann distribution function.

Maxwell Boltzmann distribution function:



1. **In a class room , the air molecules are moving in random directions.**
2. **The speed of each molecule is not the same.**
3. **Difficult to calculate the speed of each molecule.**
4. **Each molecule collide with every other molecule.**
5. **And the molecules exchanges their speed.**

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6. **We can calculate the RMS speed of each molecule.**

7. **Gas molecules have range of speed from v to v + dv.**

Formula :

$$N_V = 4\pi N \left(\frac{m}{2\pi KT}\right)^{3/2} v^2 e^{-m v^{2/2KT}}$$

- **Number of molecules having lower speed**

  i) Increases parabolically (v^2)

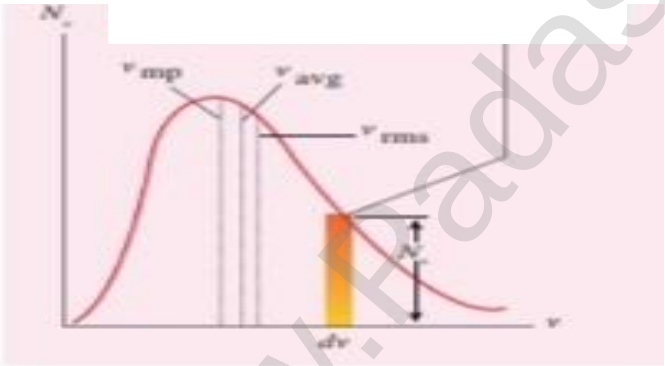
  ii) Decreases exponentially ($e^{-m v^{2/2KT}}$)

- **The rms speed, average speed and most probable speed are calculated.**

- **The rms speed is greater among the three.**

- **Area under each graph is same since it represents total number of gas molecules.**

Graph:



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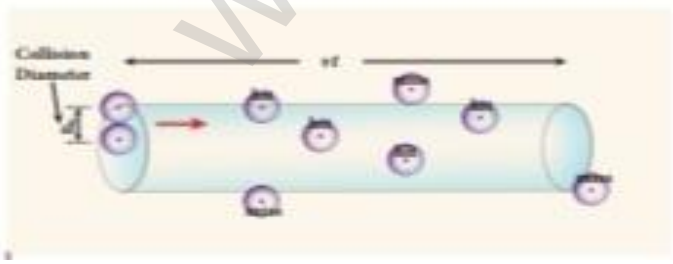
7. Derive the expression for mean free path of the gas.

Diagram :



Formula :

$$\lambda = \frac{1}{\sqrt{2}\, n \pi d^2}$$

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Theory :

- **Consider only one molecule is in motion.**
- **All others are at rest in an imaginary cylinder.**

Explanation :

1. **Number of molecule** → n
2. **Diameter of molecule** → d
3. **Speed of molecule** → v
4. **Time taken by molecule** → t
5. **Distance travel by molecule** → $v\,t$
6. **Area of the cylinder** → πd^2
7. **Volume of the cylinder** → $\pi d^2 v\,t$
8. **Number of collision** → $n \pi d^2 v\,t$

Derivation:

$$\text{Mean free path} = \frac{\text{Distance travelled}}{\text{Number of collisions}}$$

$$\lambda = \frac{v\,t}{n \pi d^2 v\,t} = \frac{1}{n \pi d^2} = \frac{1}{\sqrt{2}\, n \pi d^2}$$

Case I :

1. $\lambda = \dfrac{1}{\sqrt{2}\, n \pi d^2}$

2. $\lambda = \dfrac{1}{\sqrt{2}\, n \pi d^2} \times \dfrac{m}{m}$

3. $\lambda = \dfrac{m}{\sqrt{2}\, \pi d^2 n\, m}$

4. $\lambda = \dfrac{1}{\sqrt{2}\, \pi d^2 \rho}$

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Case ii :

1. $PV = NKT$

2. $P = \frac{N}{V} KT$

3. $P = n K T$

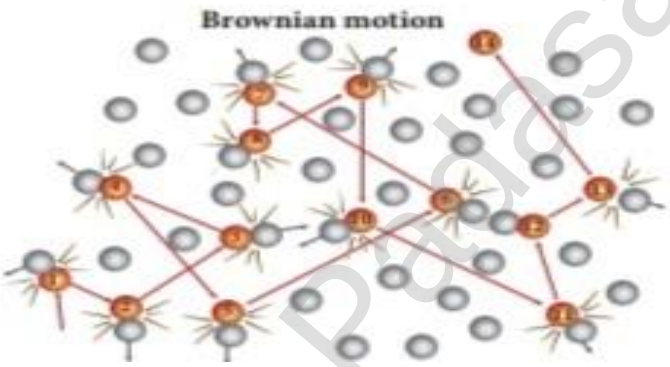
4. $n = \frac{P}{KT}$

5. $\lambda = \frac{KT}{\sqrt{2}\ \pi d^2 P}$

---

8. Describe the Brownian motion.

Diagram:



Robert Brown

- **Grains of pollen in a liquid moves randomly .**
- **Pollen in a liquid moves in Zig – zag path.**
- **It is called as " Brownian Motion "**

Wiener Gouy

- **Brownian motion is due to the bombardment of particles of molecules in fluid.**

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Einstein

- **Brownian motion based on the kinetic theory.**
- **Deduce average size of molecule.**

Reason for Brownian motion:

- **Any particle in a liquid bombarded from all the directions .**
- **Mean free path is almost negligible.**
- **It leads the particle motion in zig – zag.**

Factors affect Brownian motion

- **Brownian motion increases with increasing temperature.**
- **Brownian motion decreases with particle size , high viscosity and density.**

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10. Oscillations

1. What is meant by simple harmonic oscillations ? Give examples and explain SHM is a periodic motion.

S H M :

- **S H M means that Simple Harmonic Motion .**
- **It is a special type of oscillatory motion.**

Acceleration :

- **Acceleration on the particle is directly proportional to its displacement.**

$$a_x \ \alpha \ x \ ; \quad a_x = -b\,x$$

- **x → Displacement**
- **a_x → Acceleration**
- **b → Acceleration per unit displacement**

Force :

From Newton's second law

- **Force on the particle is directly proportional to its displacement.**
- $F_x \ \alpha \ x \ ; \quad F_x = -k\,x$
- **k → Force Constant = Force per unit displacement**

Displacement :

- **Force towards left of equilibrium position x takes positive value.**
- **Force towards right of equilibrium position x takes negative value.**

Restoring force :

Particle execute SHM to restore its original position or equilibrium position.

In vector notation :

$$F = = K\vec{r}$$

- **r → Displacement of the particle from the origin**
- **Force and displacement have linear relationship.**

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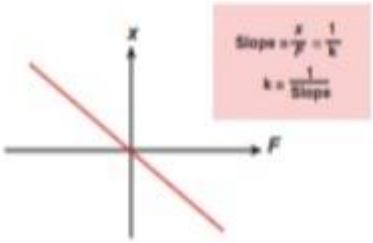
Graph :

Graph between force and displacement is straight line.



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3. What is meant by angular harmonic oscillation ? Compute the time period of angular harmonic oscillation ?

1. Angular Oscillation :

When a body is allowed to rotate freely about a given axis , it is angular oscillation.

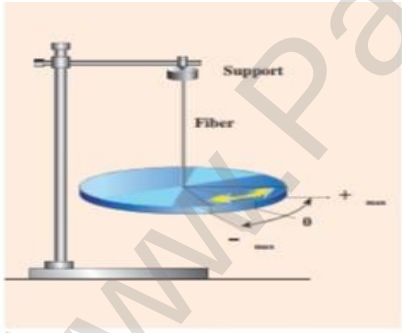
2. Mean Position :

The point at which the resultant torque acting on the body is taken to be zero.

3.Torque :

- **Torque is directly proportional to the angular displacement.**
- **Torque has a tendency to bring the body towards mean position.**

Diagram :



Derivation :

1. $\tau \ \alpha \ \Theta$
2. $\tau = - k \Theta$
3. $\tau = I \alpha$
4. $I \alpha = - k \Theta$

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5. $\alpha = -\frac{k}{I}\Theta$

6. $\frac{d^2\Theta}{dt^2} = -\frac{k}{I}\Theta$

7. $-\omega^2\Theta = -\frac{k}{I}\Theta$

8. $\omega^2 = \frac{k}{I}$

9. $\omega = \sqrt{\frac{k}{I}}$

10. $2\pi f = \sqrt{\frac{k}{I}}$

11. $f = \frac{1}{2\pi}\sqrt{\frac{k}{I}}$

12. $T = 2\pi\sqrt{\frac{I}{k}}$

---

4. Difference between simple harmonic motion and angular simple harmonic motion.

S.NO	Simple Harmonic Motion	Angular Harmonic Motion
1.	Linear displacement of the particle $\vec{r}$	Angular displacement of the particle $\vec{\Theta}$
2.	Acceleration of the particle $\vec{a} = -\omega^2\vec{r}$	Acceleration of the particle $\vec{\alpha} = -\omega^2\vec{\Theta}$
3.	Force : $\vec{F} = m\vec{a}$	Torque : $\vec{\tau} = I\vec{\alpha}$
4.	Restoring Force : $\vec{F} = -k\vec{r}$	Restoring Torque : $\vec{\tau} = -k\vec{\Theta}$
5.	Angular Frequency : $\omega = \sqrt{\frac{k}{m}}$	Angular Frequency : $\omega = \sqrt{\frac{k}{I}}$

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5. Describe about simple pendulum in detail.

1. **It exhibits periodic motion.**
2. **It has a bob with mass m.**
3. **It is suspended by a long string.**
4. **Length of the pendulum is l.**
5. **At equilibrium , The pendulum not oscillate.**
6. **The bob of pendulum displaced from mean position , it executes to and fro motion.**
7. **Force acts on the bob is classified as two types.**

   i) Gravitational Force $\vec{F}$

   ii) Tensional Force $\vec{T}$

8. Component of gravitational force :

i) Normal Component : $F_{as} = m g \cos \Theta$

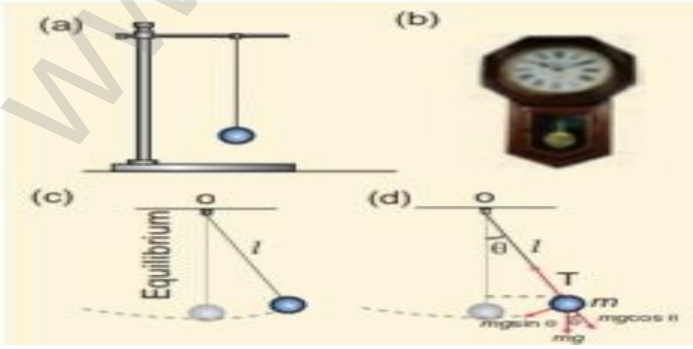
ii) Tangential Component : $F_{ps} = m g \sin \Theta$

9. $$T - F_{as} = m a$$

$$T - m g \cos \Theta = m \frac{v^2}{l}$$

10. $$m \frac{d^2 s}{d t^2} + F_{ps} = 0$$

<u>Diagram :</u>



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Derivation :

1. $m \frac{d^2 s}{d t^2} = - F_{ps}$

2. $m \frac{d^2 s}{d t^2} = - m g \sin \Theta$

3. $\frac{d^2 s}{d t^2} = - g \sin \Theta$

4. $l \frac{d^2 \Theta}{d t^2} = - g \sin \Theta$

5. $\frac{d^2 \Theta}{d t^2} = - \frac{g}{l} \sin \Theta$

6. $- \omega^2 \Theta = - \frac{g}{l} \Theta$

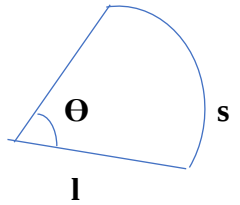
7. $\omega^2 = \frac{g}{l}$

8. $\omega = \sqrt{\frac{g}{l}}$

9. $2 \pi f = \sqrt{\frac{g}{l}}$

10. $f = \frac{1}{2 \pi} \sqrt{\frac{g}{l}}$

11. $T = 2 \pi \sqrt{\frac{l}{g}}$



$s = l \Theta \qquad \frac{d^2 s}{d t^2} = l \frac{d^2 \Theta}{d t^2}$

$\sin \Theta = \Theta$

---

6. Explain the horizontal oscillations of a spring.

Theory :

1. **Consider a block of mass m.**
2. **Equilibrium position or mean position x_0 .**

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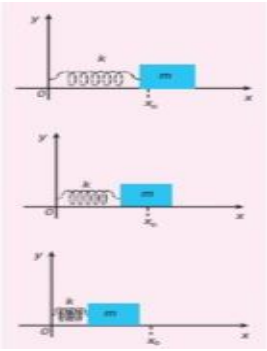
3. **Small displacement of mass is x.**

4. **Restoring force be F.**

5. **Stiffness constant or force constant be k.**

Diagram :



Formula :

$$T = 2\pi\sqrt{\frac{m}{k}}$$

Derivation :

1. $F \alpha x$

2. $F = -kx$

3. $ma = -kx$

4. $m\frac{d^2x}{dt^2} = -kx$

5. $\frac{d^2x}{dt^2} = -\frac{k}{m}x$

6. $-\omega^2 x = -\frac{k}{m}x$

7. $\omega^2 = \frac{k}{m}$

8. $\omega = \sqrt{\frac{k}{m}}$

9. $2\pi f = \sqrt{\frac{k}{M}}$

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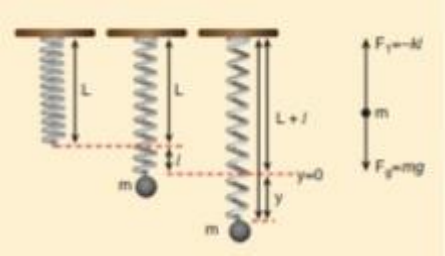
10. $f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$

11. $T = 2\pi\sqrt{\frac{m}{K}}$

---

7. Explain the vertical oscillations of a spring.

Diagram:



Theory :

1. Consider a block of mass m.
2. Length of a spring before loading L.
3. Length of a spring after loading l.
4. Restoring force due to stretched spring F_1.
5. Small external force applied is F_2.

Derivation :

1. $F_1 + mg = 0$
2. $F_1 \alpha l$
3. $F_1 = -Kl$
4. $-Kl + mg = 0$
5. $mg = kl$
6. $F_2 \alpha y + l$
7. $F_2 = -k(y + l)$
8. $F_2 = -ky - kl$
9. $F = F_2 + mg$
10. $F = -ky - kl + kl$

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11. $F = -ky$

12. $m \frac{d^2 y}{dt^2} = -ky$

13. $-\omega^2 y = -ky$

14. $\omega^2 = \frac{k}{m}$

15. $\omega = \sqrt{\frac{k}{m}}$

16. $2\pi f = \sqrt{\frac{k}{m}}$

17. $f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$

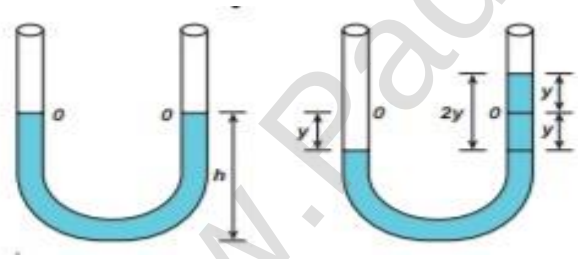
18. $T = 2\pi\sqrt{\frac{m}{k}}$

19. $g = 4\pi^2 \left(\frac{l}{T^2}\right)$

---

8. Oscillations of liquid column in U – tube.

Diagram :



Theory :

1. Consider U-shaped glass tube.
2. Consists of yow open arms.
3. Let us pour non- viscous incompressible liquid.
4. Density of the liquid is P.
5. Length of liquid column l.

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Working :

1. **If the tube is not disturbed, is in Equilibrium position.**
2. **By blowing air at one arm, the liquid gets disturbed.**
3. **Pressure difference cause the liquid to oscillate.**
4. **After short duration of time finally comes to rest.**
5. **Time period of oscillation:**

$$T = 2\pi\sqrt{\frac{l}{2g}} \text{ sec}$$

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9. Energy in simple harmonic motion.

Potential Energy :

1. $F = -\frac{dU}{dx}$

2. $-kx = -\frac{dU}{dx}$

3. $dU = kx\,dx$

4. $\int dU = K \int x\,dx$

5. $U = k\frac{x^2}{2}$

6. $U = \frac{1}{2} m\omega^2 x^2 \quad (k = m\omega^2)$

7. $U = \frac{1}{2} m\omega^2 A^2 \sin^2 \omega t \quad (x = A \sin \omega t)$

Kinetic Energy :

1. $x = A \sin \omega t$

2. $v_x = \frac{dx}{dt} = A\omega \cos \omega t$

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3. $K.E = \frac{1}{2} m v_x^2$

4. $K.E = \frac{1}{2} m \left(\frac{dx}{dt}\right)^2$

5. $K.E = \frac{1}{2} m A^2 \omega^2 \cos^2 \omega t = \frac{1}{2} m A^2 \omega^2 (1 - \sin^2 \omega t)$

6. $K.E = \frac{1}{2} m A^2 \omega^2 \left(1 - \frac{x^2}{A^2}\right)$

7. $K.E = \frac{1}{2} m \omega^2 (A^2 - x^2)$

Total Energy :

1. $E = U + K.E$

2. $E = \frac{1}{2} m \omega^2 x^2 + \frac{1}{2} m \omega^2 (A^2 - x^2)$

3. $E = \frac{1}{2} m \omega^2 A^2$

Another method :

1. $E = \frac{1}{2} m \omega^2 A^2 \sin^2 \omega t + \frac{1}{2} m \omega^2 A^2 \cos^2 \omega t$

2. $E = \frac{1}{2} m \omega^2 A^2$

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10. Explain in detail the four different types of oscillations.

1. **Free Oscillations :**

When oscillator is allowed to oscillate by displacing its position from equilibrium position, its oscillations with frequency equal to natural frequency .

Ex: Vibration of tuning fork.

2. **Damped Oscillations :**

Due to the pressure of function and air drag

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- **Amplitude of oscillation decreases.**
- **Energy of SHM decreases.**
- **Energy lost is absorbed by surrounding.**
- **Damping (resistive) force proportional to velocity of the oscillations.**

  Ex: Electromagnetic oscillations in tank circuit.

3. <u>Maintained Oscillations :</u>

1. **While playing in swing, due to damping oscillation will stop.**
2. **To avoid damping, to supply push to sustain oscillation.**
3. **By supplying energy, amplitude made constant.**

   Ex: Vibration of tuning fork getting energy from battery.

4. <u>Forced Oscillation :</u>

Any oscillation by an external periodic agency to overcome the damping is known as forced oscillation or drawn oscillator.

Ex: Sound boards.

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