

SCHOOL OF SCIENCE AND HUMANITIES

DEPARTMENT OF PHYSICS

UNIT – I – Mechanics

Simple Harmonic Motion

What is Simple Harmonic Motion?

Simple Harmonic Motion or SHM is defined as a motion in which the restoring force is directly proportional to the displacement of the body from its mean position. The direction of this restoring force is always towards the mean position. The acceleration of a particle executing simple harmonic motion is given by, $a(t) = -\omega^2 x(t)$. Here, ω is the angular velocity of the particle.





Simple harmonic motion can be described as an oscillatory motion in which the <u>acceleration of the</u> <u>particle</u> at any position is directly proportional to the displacement from the mean position. It is a special case of oscillatory motion.

All the Simple Harmonic Motions are oscillatory and also periodic but not all <u>oscillatory motions</u> are SHM. Oscillatory motion is also called the harmonic motion of all the oscillatory motions wherein the most important one is **simple harmonic motion (SHM)**.



In this type of oscillatory motion displacement, velocity and acceleration and force vary (w.r.t time) in a way that can be described by either sine (or) the cosine functions collectively called sinusoids.

Difference between **Periodic,** Oscillation and Simple Harmonic Motion

Periodic Motion

- •A motion repeats itself after an equal interval of time. For example, uniform circular motion.
- •There is no equilibrium position.
- •There is no restoring force.
- •There is no stable equilibrium position.

Oscillation Motion

•To and fro motion of a particle about a mean position is called an oscillatory motion in which a particle moves on either side of equilibrium (or) mean position is an oscillatory motion.

•It is a kind of periodic motion bounded between two extreme points. For example, Oscillation of Simple Pendulum, Spring-Mass System.

•The object will keep on moving between two extreme points about a fixed point is called mean position (or) equilibrium position along any path. (the path is not a constraint).

•There will be a restoring force directed towards <u>equilibrium position</u> (or) mean position.

•In an oscillatory motion, the net force on the particle is zero at the mean position.

•The mean position is a stable equilibrium position.

Simple Harmonic Motion or SHM

•It is a special case of oscillation along with straight line between the two extreme points (the path of SHM is a constraint).

•Path of the object needs to be a straight line.

•There will be a restoring force directed towards equilibrium position (or) mean position.

•Mean position in Simple harmonic motion is a stable equilibrium.

Conditions for SHM:

 $F \propto -x$ $a \propto -x$

Types of Simple Harmonic Motion

SHM or Simple Harmonic Motion can be classified into two types,

•Linear SHM

•Angular SHM

Linear Simple Harmonic Motion

When a particle moves to and fro about a fixed point (called equilibrium position) along with a straight line then its motion is called linear Simple Harmonic Motion.

For Example: spring-mass system

Conditions for Linear SHM:

The restoring force or acceleration acting on the particle should always be proportional to the displacement of the particle and directed towards the equilibrium position.

F∝–x

•x – displacement of particle from equilibrium position. *•F* – Restoring force

Angular Simple Harmonic Motion

When a system oscillates angular long with respect to a fixed axis then its motion is called angular simple harmonic motion.

Conditions to Execute Angular SHM:

The restoring force (or) <u>Angular acceleration</u> acting on the particle should always be proportional to the angular displacement of the particle and directed towards the equilibrium position.

F = -kx



Simple Harmonic Motion Equation and its Solution

Consider a particle of mass (m) executing Simple Harmonic Motion along a path x o x; the mean position at O. Let the <u>speed of the particle</u> be v_0 when it is at position p (at a distance no from O)

At t = 0 the particle at P(moving towards the right)

At t = t the particle is at Q(at a distance x from O)

With a velocity (v)

Angular Simple Harmonic Motion

A body free to rotate about an axis can make angular oscillations. For example, a photo frame or a calendar suspended from a nail on the wall. If it is slightly pushed from its mean position and released, it makes angulations.

Conditions for an Angular Oscillation to be Angular SHM

The body must experience a net Torque that is restoring in nature. If the angle of oscillation is small, this restoring torque will be directly proportional to the angular displacement.

- $T \propto \, \theta$
- T = kθ
- T = Ια
- α = kθ

$$I\frac{d^2\theta}{dt^2} = -K\theta \ \frac{d^2\theta}{dt^2} = -\left(\frac{K}{I}\right)\theta = -\omega_0^2\theta \ \frac{d^2\theta}{dt^2} = -\omega_0^2\theta = 0$$

This is the **differential equation of an angular Simple Harmonic Motion**. Solution of this equation is angular position of the particle with respect to time.

 $\theta = \theta_0 \sin(\omega_0 t + \phi)$

Then angular velocity,

 $\omega = \theta_0 . \omega_0 \cos\left(\omega_0 t + \phi\right)$

θ_0 – amplitude of the angular SHM

Example:

- Simple pendulum
- Seconds pendulum
- The physical pendulum

extreme point extreme point mean position O A' A

Let us consider a particle executing Simple Harmonic Motion between A and A_1 about passing through the mean position (or) equilibrium position (O). Its analysis is as follows

SHM about Position O



Torsional pendulum

Equation of Position of a Particle as a Function of Time



$$rac{v^2}{2} = rac{-\omega^2 A^2}{2} + c v = 0$$

$$0 = \frac{-\omega^2 A^2}{2} + c$$

Let us consider a particle, which is executing SHM at time t = 0, the particle is at a distance from the equilibrium $c = \frac{\omega^2 A^2}{2}$ position.

Necessary conditions for Simple Harmonic Motion

$$\overrightarrow{F} \propto -\overrightarrow{x}$$

$$\overrightarrow{v} = -\overrightarrow{w}$$

$$\overrightarrow{d} \propto -\overrightarrow{x}$$

$$\overrightarrow{d} = -\omega^{2}x$$

$$\overrightarrow{d} = \frac{dv}{dx}\frac{dx}{dt} = v\frac{dv}{dx}$$

$$v = \sqrt{\omega^{2}(A)}$$

•
$$\overrightarrow{a} = v \frac{dv}{dx} = -\omega^2 a$$

• $\int_{0}^{v} v dv = \int_{0}^{x} -\omega^{2} x dx$ • $\frac{v^{2}}{2} = \frac{-\omega^{2} x^{2}}{2} + c \dots (1)$

Sub the value of C in equation (1)

$$\frac{v^2}{2} = \frac{-\omega^2 x^2}{2} + \frac{\omega^2 A^2}{2}$$

$$\Rightarrow v^2 = -\omega^2 x^2 + \omega^2 A^2$$

$$\Rightarrow v^2 = \omega^2 \left(A^2 - x^2\right)$$

v =
$$\sqrt{\omega^2 \left(A^2 - x^2\right)}$$

v =
$$\omega\sqrt{A^2-x^2}$$
 ... (2)

where, v is the velocity of the particle executing simple harmonic motion from definition instantaneous v

$$v = \frac{dx}{dt} = \omega \sqrt{A^2 - x^2}$$
$$\Rightarrow \int \frac{dx}{\sqrt{A^2 - x^2}} = \int_0^t \omega dt$$



$$O (composition of Oscillations in Atomight line
x_1 = n, Sin(wet + a_1)
x_2 = n_2 Sin(wet + a_2)
z = n_2 Sin(wet + a_2)
Sin(A+B) = Sinn (cost + a_2)
Sin(A+B) = Sinn (cost + cost sing)
= n_{(sinwet cost, + cost + cost + cost + a_2)}
= Sinwet (n_{(cost, + tost + tost + sing)) + tost + tos$$

To Find R From egn (1) # Ticoski + To cosky = Rcos d rising + masing = Rsing Squaring and Adding the above an RECOSA + Resina = a costor = (miles x, +3 ces x) + (msinx,+2 sing) = 57 cos 2, + 5 cos 2, + 27 2 cos 4, cos 4, cos 42 + mising, + 2 singer + 2 Titz Sind, Sinds = ri² (sin²a', + cos²a') + r²₂ (sin²d2+cos²a') = 2xix2 (cos dicesda + sind, sinda) (hyteda)= r12 + r22 + 2 r1 r2 (os (21-22) Los (A-B) CusAcesB SINASINA R- 72+ 22+ 201 22 cos (2, -22)

Page No. Expt. No. Date Expt. Name. $R = \sqrt{r_1^2 + r_2^2 + 2r_1r_2 \cos(\alpha_1 - \alpha_2)}$ 3) Angle: -RSina = a, sina, +a2sina2 Q1005x1+92 (08 d2 RLOSA





Undamped Oscillations

The oscillations whose amplitude remains constant with time are called undamped oscillations.

Such oscillations can occur if frictional forces are absent.

For example, if the bob of a pendulum is displaced in vacuum and then released, the bob will continue to execute SHM of constant amplitude.

Damped Oscillations

The oscillations whose amplitude goes on decreasing with time are called damped oscillations.

In real oscillating systems, forces like friction are always present that dissipate the oscillating energy.

Unless energy is somehow added, dissipation eventually brings the system to rest at equilibrium.

Figure 15-16 An idealized damped simple harmonic oscillator. A vane immersed in a liquid exerts a damping force on the block as the block oscillates parallel to the x axis.

 $m\frac{\mathrm{d}^2 \mathbf{x}}{\mathrm{d} \mathbf{t}^2} = -\mathbf{'}$ $b \frac{\mathrm{dx}}{\mathrm{dt}}$ kx

The tendency of one object to **force** another adjoining or interconnected object into vibrational motion is referred to as a **forced vibration (Oscillation)**.

CENTRE OF GRAVITY - DEFINITION

The centre of gravity (C.G.) of a body is the point about which the algebraic sum of moments of weights of all the particles constituting the body is zero. The entire weight of the body can be considered to act at this point howsoever the body is placed.

•Center of Buoyancy is the center of gravity for the volume of water which a hull displaces

According to the definition "Metacenter is the point, about which a body starts oscillating when it is given a small angular displacement. If the body undergoes angular displacement then the point of intersection of the below mentioned two straight lines is called metacentre.

Let us consider a lamina with definite area. Its plane consists of a number of particles with masses m_1 , m_2 , m_3 and hence, weights m_1g , m_2g , m_3g with co-ordinates (x_1, y_1) , (x_2, y_2) , (x_3, y_3)

Let 'G' be the centre of gravity with co-ordinates (\tilde{x}, \tilde{y}) where resultant weight 'Mg' acts.

Since the sum of the moments of a system of coplanar forces equals the moment of resultant:

Taking moments about 0, with the reference axis OX,

 $m_1gx_1 + m_2gx_2 + m_3gx_3 + \cdots \dots \dots = Mg\tilde{x}$

Hence,
$$\tilde{x} = \frac{m_1 x_1 + m_2 x_2 + m_3 x_3 + \dots + m_1}{m_1 + m_2 + m_3 + \dots + m_2}$$

$$\tilde{x} = \frac{\sum_{i=1}^{n} m_i x_i}{\sum_{i=1}^{n} m_i}$$

Similarly, taking moments about 0, with the reference axis OY,

$$\tilde{y} = \frac{m_1 y_1 + m_2 y_2 + m_3 y_3 + \dots \dots}{m_1 + m_2 + m_3 + \dots \dots}$$

$$\tilde{y} = \frac{\sum_{i=1}^{n} m_i y_i}{\sum_{i=1}^{n} m_i}$$

Let, \tilde{x} and \tilde{y} be the co-ordinates of the centroid w.r.t. some axis of reference.

Consider an elemental are 'dA' of the lamina at a distance 'x' from the axis OY. The weight of the elemental path is ρ . dA. g. The moment of this force about the axis OY = ρ . dA. g. x

Total moment of the weight of lamina = ρ . *A*. *g*. \tilde{x}

Now, ρ . A. g. $\tilde{x} = \sum \rho$. dA. g. \tilde{x}

Hence,
$$\tilde{x} = \frac{\Sigma dA. x}{A}$$
, $\tilde{y} = \frac{\Sigma dA. y}{A}$

(For Discrete Areas)

$$\tilde{x} = \frac{\int dA.x}{\int dA}, \tilde{y} = \frac{\int dA.y}{\int dA}$$

(For Continuous Areas)

Moment of this co	= Weight of each strip	× Distance between these two weights
	$= \rho g x \ \theta L \ dx \ [x+x]$	
	$= \rho g x \ \theta L \ dx \times 2x = 2\rho$	$gx^2 \theta L dx$
Moment of th	e couple for the whole wedge	
	$=\int 2\rho g x^2 \theta L dx$	and the second bought D.M. a seen by Baganana
Moment of couple	e due to shifting of centre of buoya	ncy from B to B_1
	$= F_B \times BB_1$	
	$= F_B \times BM \times \Theta$	$\{ :: BB_1 = BM \times \theta \text{ if } \theta \text{ is very small} \}$
	$= W \times BM \times \Theta$	$\{ \because F_B = W \} \dots 2$
But these two cou	ples are the same. Hence equating	equations 1 and 2 we get
	$W \times BM \times \theta = \int 2\rho g x^2 \theta L dx$	
1	$W \times BM \times \theta = 2\rho g \theta \int x^2 L dx$	and the second state of the second
	$W \times BM = 2\rho g \int x^2 L dx$	Second March 199
Now $Ldx = = dA$		
	$W \times BM = 2\rho g \int x^2 dA.$	Charles and the band of the states.
$2\int x^2 dA$ is the seco	and moment of area of the plan of the	e body
at water surface about	ut the axis y-y. Therefore	(mbar 1 - 2 [- 2 / 4
a destruction of the	$W \times BM = \rho g I$	$\{\text{where } I = 2\} x aA$
ж.,	$BM = \frac{\rho g I}{W}$	
But	W = Weight of the body	
	= Weight of the fluid	displaced by the body
	$= \rho g \times Volume of the$	fluid displaced by the body
	$= \rho g \times \text{Volume of the}$	body sub-merged in water
	$= \rho g \times \forall$	
:	$BM = \frac{\rho g \times I}{\rho g \times \forall} = \frac{I}{\forall}$	a testib lata testible Helphi, GM
	$GM = BM - BG = \frac{1}{\forall} - BG$	g and the second s
:. Meta-centric	height $= GM = \frac{I}{\Omega} - BG.$	A state of the sta

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$$\overline{X} = \frac{\int_{0}^{R} \widehat{x} dv}{\int dv}$$

$$dv = \pi v^{2} dx.$$

$$\widehat{\chi} = \frac{\int_{0}^{R} x \cdot \pi v^{2} dx}{2\sqrt{3} \pi R^{3}}$$

$$R^{2} = \frac{\int_{0}^{R} x \cdot \pi v^{2} dx}{2\sqrt{3} \pi R^{3}}$$

$$\overline{X} = \frac{\int_{0}^{R} x \cdot \pi (R^{2} - x^{2}) dx}{2\sqrt{3} \pi R^{3}}$$

$$\overline{X} = \frac{\int_{0}^{R} x R^{2} dx - \int R^{3} dx}{2\sqrt{3} \pi R^{3}}$$

$$\frac{R^{2}(\frac{x^{2}}{2})_{0}^{R} - [\frac{x^{4}}{4}]_{0}^{R}}{\frac{2}{2}_{3}R^{3}} = \frac{R^{2}(\frac{R^{2}}{2}) - (\frac{R^{4}}{4})}{\frac{2}{2}_{3}R^{3}} = \frac{\frac{R^{4}}{4}}{\frac{2}{2}_{3}R^{3}} = \frac{\frac{R^{4}}{4}}{\frac{2}{2}_{3}R^{3}} = \frac{\frac{R^{4}}{4}}{\frac{2}{2}_{3}R^{3}} = \frac{\frac{R^{4}}{4}}{\frac{2}{2}_{3}R^{3}} = \frac{\frac{R^{4}}{4}}{\frac{2}{2}R^{3}} = \frac{\frac{R^{4}}{4}}{\frac{2}{2}} = \frac{\frac{R^{4}}{4}}{\frac{2}{2}} = \frac{\frac{R^{4}}{4}}{\frac{2}{2}} = \frac{\frac{R^{4}}{4}}{\frac{2}{2}} = \frac{\frac{R^{4}}{4}}{\frac{2}{2}} = \frac{\frac{R^{4}}{4}} = \frac{\frac{R^{4}}{4}}{\frac{2}{2}} = \frac{\frac{R^{4}}{4}}{\frac{2}{2}} = \frac{\frac{R^{4}}{4}} = \frac{\frac{R^{4}}{4}}{\frac{2}{2}} = \frac{\frac{R^{4}}{4}}{\frac{2}} = \frac{\frac{R^{4}}{4}} = \frac{\frac{R^{4}}{4}}{\frac{2}{2}} = \frac{\frac{R^{4}}{4}} = \frac{\frac{R^{$$

X=0 Y= JYdv _ O Jdv _ Jdv Volume of elemental sving r. dv= T922 dy To find or interms of R $\frac{g_2}{R} = \frac{f_1 - Y}{f_1} \Rightarrow g_2 = R\left(1 - \frac{Y}{f_1}\right)$: $dv = \pi R^2 (1 - \frac{\gamma}{L})^2 dy$

1) To find the center of mass from 3 kg mass:

The origin is shifted to 3 kg mass along X-axis. The position of 3 kg point mass is zero (x1 = 0) and the position of 5 kg point mass is 4 m from the shifted origin (x2 = 4 m).

2)To find center of mass from the origin:

The point masses are at positions, x1 = 4 m, x2 = 8 m from the origin along X axis.

$$x_{CM} = \frac{m_1 x_1 + m_2 x_2}{m_1 + m_2}$$
$$x_{CM} = \frac{(3 \times 4) + (5 \times 8)}{3 + 5}$$
$$x_{CM} = \frac{12 + 40}{8} = \frac{52}{8} = 6.5 \,\mathrm{m}$$

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DEPARTMENT OF PHYSICS

UNIT – II– SOUND

$\mathbf{UNIT} - \mathbf{V}$

ACOUSTICS OF BUILDINGS

Introduction - musical sound and noise, characteristics of musical sound - pitch, loudness, quality -Weber-Fechner law, decibel scale, sound intensity level and sound pressure level. Sound absorption-OWU, sound absorption coefficient and its measurements - Reverberation - Reverberation time -Standard Reverberation time -Sabine's formula to determine the Reverberation time (Jaegar method), Factors affecting the acoustics of a building and the remedies, Principles to be followed in the acoustical design of a good auditorium.

5.1 Introduction

Acoustics is the science of sound that deals with the origin, propagation and auditory sensation of sound. The acoustic properties of buildings were not studied on a scientific basis till about 1900. Buildings designed to screen movies, to stage dramas or for music concerts often lacked the proper acoustic quality and were found to be unfit for the activity. The Fogg Art Museum hall in Harvard University, U.S.A was highly defective when it was built. The lectures given in it were not intelligible to audience. Prof. Wallace C. Sabine, Professor of Physics in Harvard University was entrusted with the responsibility of eliminating the acoustical defects of the hall. Sabine undertook a systematic study of the problem and evolved conditions for the satisfactory acoustic quality of a hall. He found that quite often reverberation was the main cause for a defective quality of sound in the halls. Other precautions to be taken are about the shapes of walls, ceiling and the hall in total so that acoustic defects do not rise. Thus Prof. Sabine laid foundations for acoustic engineering.

5.2 Sound

Sound is always produced by some vibrating body. The vibrating body excites mechanical waves in the surrounding medium. The mechanical waves propagate in the form of a series of compressions and rarefactions in the air and set the ear drum vibrating. It causes a sensation of hearing. The propagation of sound requires the presence of an elastic medium. Sound cannot travel in a vacuum. Sound waves are longitudinal waves, as illustrated in Fig. 5.1. The compressions and rarefactions due to a sound modulate the normal atmospheric pressure with small pressure changes occurring regularly above and below it. Thus, a sound wave is one complete cycle of pressure variation.

1

Fig. 5.1 Schematic representation of a sound wave

The waves that produce a sense of sound on a human ear are called sound waves or audible waves. The waves with frequencies below 16 Hz are called infrasonic waves and above 20 kHz are ultrasonic waves. The velocity of sound depends on the nature and temperature of the medium through which it travels. In general, the velocity of sound in a gaseous medium is governed by the relation,

where β is the bulk modulus and ρ is the density of the medium.

Medium	Speed m/s	Medium	Speed m/s
Hydrogen	1305	Brick	4300
Air	344	Mild Steel	5050
Pure water	1480	Aluminum	5150
Plexi glass	1800	Glass	5200
Soft wood	3350	Granite	6400
Concrete	3400	Gypsum board	6800

Table 5.1: Speed of sound in some media at 20 °C

The speed of sound in air is commonly taken as 344 m/s for normal conditions. This is very less compared to the velocity of light. Table 1 lists the speed of sound in different media. Sound travels faster in liquid media than in gaseous media and much faster in solid media. Speed of sound in different media is shown in Table 5.1.

As in case of light waves, the velocity of sound waves is given by the product of its frequency f and wavelength λ .

 $v = f\lambda$

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It follows that the wavelength will be larger in a medium having a higher velocity. When the medium is air,

$$\lambda = v/f = 344/f$$

Further all the audible sounds can be classified as musical sound and noise.

5.3 Musical Sound

Sound waves which produce a pleasing effect to our ears, while receiving them are known as musical sound waves. Musical sound waves are produced when a series of similar impulses follow each other at regular intervals without any sudden change in their amplitude.

Examples of musical sound are sounds produced by a tuning fork, sitar, violin, piano etc. The important characteristic properties of a musical sound are as follows:

- i) It has a regular waveform
- ii) It has a definite periodicity
- iii) There is no sudden change in amplitude

Fig. 5.2 Musical - Sound Waveform

The typical waveform of the musical sound waves produced by musical instrument is shown in Fig. 5.2.

5.4 Noise

Sound waves which produce an unpleasant effect or jarring effect to our ears are known as noise. Noise sounds of high intensity may produce permanent or temporary deafness. Examples of noise are sounds produced by road traffic, moving furniture, explosion of bombs etc.

A noise sound is characterized by the following properties:

- i) It has an irregular shaped waveform
- ii) It lacks periodicity
- iii) There are sudden changes in amplitude & frequency.

Fig. 5.3 Noise Waveform

A typical waveform for noise is shown in Fig. 5.3.

Sound waves are longitudinal in type, because the particles of the medium carrying the wave vibrate in the direction of the wave. Other terms related to sound waves are as follows.

Sound power (P)

It is defined as the rate at which sound energy is produced at the source. It is measured in watts.

Sound Intensity (I)

It is defined as the sound power distributed over unit area or it is defined as the amount of sound energy flowing per second through unit area in a direction perpendicular to the direction of propagation of sound. It is measured in Watt/m². i.e. $I = p_{max}^2 / 2\rho v$

Sound Pressure (P)

It is the average variation in atmospheric pressure caused by the sound. It is measured in Pascal.

5.5 Human Audiogram

Fig. 5.4 Audiogram of an average human being

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An audiogram for the normal human ear is shown in Fig. 5.4. The human ear exhibits basically a nonlinear response. The lower curve represents the faintest sounds that can be heard without pain. Further the sensitivity of the ear varies with frequency. For a person with normal hearing, the threshold of audibility at 1 kHz is 0 dB; at 200 Hz and 15 kHz it is about 20 dB and at 50 Hz and 18 kHz it is about 500 dB.

Thresholds of the Ear

i) Threshold of Hearing or Threshold of Audibility.

It is the weakest sound, the average human ear can detect.

ii) Threshold of feeling

It is the strongest sound that the average human ear can tolerate. As the intensity of the incident acoustic waves is increased, the resulting sound grows louder and produces a tickling sensation and has a value of approximately 120 dB. Sounds having intensity lesser than the threshold of audibility cannot be heard and sounds having intensity greater than the threshold of feeling produce painful sensation. When the intensity is further increased, the tickling sensation becomes one of pain at about 140 dB (Threshold of pain). Prolonged stimulation at an appreciably higher intensity levels will cause permanent damage to the hearing mechanism. Finally, immediate damage will result when the hearing mechanism is exposed to intensity levels greater than 160dB.

5.6 Characteristics of sound

Pitch: The pitch of a musical sound is determined by its frequency but it is also a function of its intensity and waveform, Greater is the frequency of a musical note, higher is the pitch and vice versa. The frequency and pitch are two different things. The frequency is a physical quantity and can be measured accurately, while the pitch of a note is a physiological quantity.

S.No.	Frequency	Pitch		
1.	It is the number of vibrations /sec.	It is merely the mental sensation		
		experienced by the observer.		
2.	Its unit is hertz.	Its units are mel.		
3.	It is a physical quantity and can	It is a physiological quantity and it		
	be measured accurately	depends on the number of overtones		
		present with the fundamental.		

Table 5.2: Distinction between Frequency & Pitch

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The change in pitch with loudness is most pronounced at a frequency of about 100 Hz. Pitch enables us to classify a note as high or low and to distinguish a shrill sound from a flat sound of the same intensity sounded on the same musical instrument. It also helps us to distinguish a male voice from a female voice even though the two sounds have the same intensity and loudness. The frequency and pitch can be differentiated as shown in Table 5.2.

Timbre:

The timbre of a musical sound is the objective characteristics that make it possible for us to distinguish between two tones having the same intensity level and fundamental frequency but different waveforms. i.e., it helps us to recognize the sound of a violin and that of a trumpet, even when the two instruments are sounding the same note with same equal loudness. By timbre, one can identify the individual person's voice. Various objectives such as mellow, brilliant, reedy, brassy etc., have been used by musicians to describe timbre. Therefore, memory of timbre helps us identify different sounds such as the instrument being played or the person who is speaking or singing.

Loudness:

Loudness measures the amount of sensation produced in the ear and hence depends upon the listener. Loudness is not purely a physical quantity but is subjective in nature. Loudness signifies how far and to what extent, sound is audible. Loudness 'L' is directly related to intensity 'I' and is proportional to log I. According to Weber and Fechner law, the magnitude of any sensation is proportional to the logarithm of the physical stimulus that produces it.

Hence, L $\propto \log I$

where L - Loudness (sensation)

I - Intensity of sound (Physical stimulus)

Intensity and hence loudness are found to depend upon the following factors.

- i) Amplitude of vibration of the sound waves
- ii) Distance between the source and the listener
- iii) Density of the medium.
- iv) Motion of the medium
- v) Presence of other sound producing bodies
- vi) Surface area of the sonorous body

A comparison of intensity and loudness is shown in Table 5.3.
S.No.	Loudness	Intensity
1.	It is defined as the degree of	It is defined as the amount of sound
	sensation received by the ear.	energy that crosses per second through unit area.
2.	Its units are Bel, decibel, phon	Its unit is W /m ²
3.	It is not measurable but can	It is measurable using any physical
	only be compared	apparatus.
4.	It is subjective in nature	It is objective in nature
5.	It is a physiological quantity	It is a physical quantity

Table 5.3: Distinction between Intensity and Loudness

5.7 Measurement of Loudness

The range of variation of intensity is very large. The loudness of a sound as judged by the ear is proportional to the logarithm of intensity. If I and I_0 represent the intensities of two sounds of a particular frequency and L_1 and L_0 are their corresponding measures of loudness, then

$$L_{1 \propto} \log I$$

 $L_{2 \propto} \log I_0$

The difference in the loudness of the two sounds is technically called Intensity level (L) and is given by

$$L \propto log \frac{I}{I_o}$$

Taking the proportionality constant as unity, the above relation may be expressed in equation form, as

$$L = log \frac{I}{I_o}$$
 bels

he intensity level L is expressed in bels, a unit named after Alexander Graham Bell, the inventor of telephone. The unit of bel is large and in practice a smaller unit decibel abbreviated to dB is used.

$$1 \, decibel = \frac{1}{10} bel$$

Accordingly, the intensity level of a sound wave is defined as

$$L = 10 \log \frac{I}{I_o} \, dB$$

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The sound intensity corresponding to the threshold of hearing is chosen as the reference. 10^{-12} W/m² is taken as the reference intensity.

Decibel Scale :

In order to consider the decibel scale which extends from 0dB to 120 dB, let us first take 0dB. **0 dB** :

Let the experimental sound be with intensity I and standard sound with intensity I₀. Using Weber - Fechner law, we can write

$$L = 10 \log \frac{I}{I_o} \, dB$$

Where $I_o = 10^{-12}$ W/m²

For the intensity I to be heard by our ear, the minimum intensity that sound should possess is 10^{-12} W/m^2 Hence I = I = 10^{-12} W/m^2

 $L = 10 \log 1 dB \qquad [\therefore I/I_o = 1]$

120 dB :

Let us consider here $I = 1 W/m^2$ which is the threshold of pain

Hence $L = 10 \log I/I_o$ becomes

L=
$$10 \log 1 / 10^{-12} dB$$

L= $10 \log 10^{12} dB$
L= $10x12 \log 10 dB$
L= $120 dB$

L= 1 dB

We get

 $1 = 10 \log I_1/I_0$

where I, is the experimental sound intensity

$$1/10 = \log I_1/I_0$$

 $I_1/I_0 = Antilog (0.1)$

 $I_1/I_0 = 1.26$

Comparing $I_1/I_0 = 1$ (when L= 0 dB), we can see that the increase of loudness by 1dB means an increase in intensity by 26%. This is practically the smallest change in intensity level that the ear can ordinarily detect.

In order to understand the decibel scale still better consider,

8

$$L = 10 \log \frac{I_1}{I_0}$$

$$L = 10 \log \frac{1000 I_0}{I_0}$$

$$L = 10 \log 10^3$$

$$L/10 = \log 10^3$$

$$L/10 = 3\log_{10} 10$$

$$L = 3.0 \times 10 = 30 \text{ dB}$$

.

ie., Increase in loudness by 30 dB means, the louder sound is 1000 times more intense than the other.

Similarly if

$$I_{1} = \frac{100}{I_{0}}$$

$$L = 10 \log \frac{100 I_{0}}{I_{0}}$$

$$L = 20 \log \frac{I_{0}}{I_{0}}$$

$$L = 20 \text{ dB}$$

ie., increase in loudness by 20 dB means the louder sound is 100 times more intense than the other.

5.8 Other units of loudness.

When we express the loudness in decibels we have taken the zero intensity level (I_0) to be the same for sounds of all frequencies. But the sensitivity of the ear and the limits of audibility vary over wide ranges of intensity and frequency. Hence, the sound energy of same intensity at different frequencies seems to differ in loudness; therefore different units for measuring loudness are used.

Phon

The measure of loudness in phons of any sound is equal to the loudness in decibels of an equally loud pure tone of frequency 1000 Hz.

Sone

Loudness in sones gives an idea of the subjective loudness of sound. One sone is defined as the loudness experienced by a typical listener when listening binaurally to a tone of 1000 cycles at a level of 40 dB above the threshold (10^{-12} W/m^2) .

The relation between sone and phon can be written as

5.9 Sound intensity level and sound pressure level

Difference in loudness of two different sounds is known as sound intensity level, measured in decibels. Let L_1 and L_2 be the loudness of the given two sound notes. Then,

$$L_1 - L_2 = 10 \log \frac{l_1}{l_o} - 10 \log \frac{l_2}{l_o}$$

where $I_0=10^{-12}$ W/m² at 1kHz

Sound Intensity Level (SIL) = $L_1 - L_2$

$$SIL = L_1 - L_2 = 10 \log \frac{l_1}{l_2}$$

Since,

$$I = \frac{P_{max}^2}{2\rho v}$$
$$I_1 = \frac{P_{1max}^2}{2\rho v}$$
$$I_2 = \frac{P_{2max}^2}{2\rho v}$$

since I_1 and I_2 are in the same medium, the impedance will be the same. Hence,

SIL = 10
$$log \frac{I_1}{I_2} = 10 log \frac{P_1^2}{P_2^2}$$

SPL = 10 × 2log $\frac{P_1}{P_2}$

$$SPL = 20 \log \frac{P_1}{P_2}$$

where SPL = Sound Pressure Level

$$SPL = 20 \log \frac{P_1}{P_0} - 20 \log \frac{P_2}{P_0}$$

SPL = change in sound pressure level.

Hence, SIL = SPL

5.10 Reverberation

Reverberation is an important factor to be considered in the design of a hall (or) theatre (or) music hall with good acoustical properties. The persistence (or) prolongation of sound in the hall (or) room even though the source of sound is turned off is called Reverberation.

Reverberation time

The time required for the intensity of sound pulse (or) wave to fall below the audible limit is known as the Reverberation time of the hall, when the sound source is cut off.

Standard Reverberation time

Sabine found that the sound waves produced by an organ pipe of frequency 512 Hz becomes inaudible, when its intensity is reduced to one millionth of its original intensity just before stopping the organ pipe. Therefore, standard reverberation time is defined as the time taken by the sound to reduce its intensity to one - millionth of its original intensity, when the sound source is cut-off.

5.11 Sabine's formula to determine the reverberation time (Jaegar Method)

According to Sabine's law, "The standard reverberation time is the time taken by the intensity of sound to fall one - millionth (10^{-6}) of its original intensity, after the sound source is cut off".

i.e. $I_{\tau} = I_0 (10^{-6})$

where I_T = Intensity of sound after 'T' seconds

 I_0 = Original intensity of sound

T = Reverberation time in seconds

Using this, one can derive the Sabine's formula as

$$T = \frac{0.167V}{A} = \frac{0.167V}{\overline{a}.S}$$

where, $V = Volume of the hall in m^3$

a = Average sound absorption co-efficient

- A = Total sound absorption in the hall
- S = Sum of the surface area of all the reflecting surface

In order to derive the formulae, the following assumptions are to be considered.

- (i) The energy density of the sound is uniform throughout the room (or) hall.
- (ii) Energy is transmitted equally in all directions.
- (iii) The rate of emission of sound from the source is constant.
- (iv) The co-efficient of sound absorption is independent of the frequency of sound.

Derivation:

Let 'n' be the number of reflecting surfaces in a room (or) hall. Let a_1 , a_2 a_n be the absorption coefficient of various reflecting surfaces. let s_1 , s_2 s_n be the corresponding surface area of the reflecting surfaces.



Fig. 5.5 Reflecting surfaces in the room or hall

Let \overline{a} be the average sound absorption coefficient and is given by

$$\bar{a} = \frac{a_1 s_1 + a_2 s_2 + \dots + a_n s_n}{s_1 + s_2 + \dots + s_n}$$
$$= \frac{\sum_{i=1}^n a_i s_i}{s_i}$$

where S= s1 +s2 +....sn

(or) $\overline{a}.S = \sum_{i=1}^{n} a_i S_i = A$ = Total sound absorption in the room or hall.

According to Jaegar, the mean free path between the two successive reflections of sound = $\frac{4V}{c}$

Let v be the velocity of sound

At each reflection, the fraction of sound that is absorbed = \overline{a}

Then the time taken between 2 successive reflection of sound = $\frac{4V}{Sv}$ Number of reflection in one second = $\frac{1}{Time} = \frac{Sv}{4V}$

Then the average number of reflection in 't' seconds $=\frac{Svt}{4V}$

From the figure 5.5, at first reflection, sound absorbed = \bar{a}

: Sound reflected at the 1st surface = $(1 - \bar{a})$

At the second surface, sound absorbed = \bar{a} (1 - \bar{a})

... Sound reflected from the 2nd surface = Incident sound - Absorbed sound

$$=(1-\bar{a})-\bar{a}(1-\bar{a})=(1-\bar{a})[1-\bar{a}]$$
$$=(1-\bar{a})^{2}$$

Similarly after 'n' no. of reflections, sound reflected = $(1 - \bar{a})^n$

From the definition of standard reverberation time,

$$I_{t} = I_{0} (10^{-6})$$
(2)

At t=T, Equation (1) can be written as

$$V_{\tau} = V_0 (1 - \bar{a}) \frac{SvT}{4V}$$
(3)

From Equation (2),

$$I_{\rm T} / I_0 = (10^{-6})$$

∴ Equation (3) becomes

$$(10^{-6}) = (1 - \bar{a}) \frac{S_{VT}}{4V}$$
(4)

Taking log on both sides of Equation (4), we have

Mathematically, we know that $\log_e(1-\bar{a}) = -\bar{a}$

: Equation (5) can be written as

$$-6\log_e 10 = SvT/4V \times \log_e(1 - \bar{a}) = SvT/4V \times - \bar{a}$$

(or)
$$T = \frac{4 \times 6 \times 2.303V}{S \times 330 \times \bar{a}} = \frac{0.167V}{S \cdot \bar{a}}$$
(6) [since v=330m/s]
(or) $T = \frac{0.167V}{A}$ (7) [S \cdot \bar{a} = A]

Limitation of Sabine's formula

The Sabine formula is applicable only to a live room.

Live Room

It is the one, where there is less sound absorption, gradual growth and decay of sound and large reverberation time.

Dead room

It is the one, where there is large sound absorption, rapid or sudden growth and decay of sound and less reverberation time.

5.12 Sound Absorption

Sound absorption is defined as the dissipation of sound energy into other forms of energy and finally into heat.

Unit : Sabine (or) open window unit (OWU) Absorption of sound is mainly due to

- (i) Porosity and
- (ii) Flexural vibration

(i) Porosity

Many sound absorbing materials such as wool, pads and blankets have many pores. When sound waves fall on these pores, they readily propagate themselves into these pores, where a portion of sound energy is converted into heat by frictional and viscous resistance within the material. Absorption by porous materials is large at high frequencies and small at low frequencies.

(ii) Flexural Vibration

When sound waves strike a panel of flexible material like cardboard, it is set into vibration and damping forces called into play, which will dissipate the incident sound energy into heat. Absorption by panel vibration is small at high frequencies and large at low frequencies.

5.13 Sound Absorption co-efficient

The sound absorption co-efficient (a) is defined as the ratio between the sound energy absorbed by the surface to the total sound energy incident on the surface. It is expressed in terms of open window unit (OWU) or Sabine. It is also given by

```
a = sound energy absorbed by 1 m^2 of the surface / sound energy absorbed
by 1 m^2 of open window
```

An open window is an ideal or perfect sound absorber. It is so because whole of the sound energy falling on an open window passes out and none is reflected. Table 5.4 gives the values of absorption co-efficient of some commonly used surfaces.

S.No	Material	Soundabsorption	
		coefficient (a) in OWU	
1.	Marble	0.01	
2.	Glass	0.02	
3.	Wooden Floor	0.06	
4.	Carpets	0.15	
5.	Open window	1	

Table 5.4 : Absorption co-efficient

5.14 Measurement of sound absorption co-efficient

Method - I

In this method, Sabine used a source of sound as an organ pipe of frequency 512 Hz. The reverberation time of a room with cushions (or) other absorbent materials placed in the hall are first measured. The cushions (or) the absorbent materials are then removed and the extent of the open window is gradually adjusted until the reverberation time is the same as before. In this case, the absorption of sound by the substance is equal to the absorption of sound by the open window.

The ratio of the area of window opened to the total area of cushions (or) other materials is then determined. The result is a fraction and measures the absorption co-efficient of the substance.

Method - II

The absorption co-efficient of the absorbing material can be determined in terms of the reverberation time.

Let us consider a hall or room of volume V and the surface area S. First the reverberation time T_1 is measured, when the absorbing material is not fixed in the room as shown in (Fig. 5.6 (a)) and is given by



Fig. 5.6 (a) Reverberation time (T₁) without absorbing material



Sound absorbing material

Fig. 5.6 (b) Reverberation time (T_2) with absorbing material.

Next, the absorbing material is fixed inside the room and then the reverberation time T_2 is measured (Fig. 5.6 (b)) and is given by

$$T_2 = \frac{0.167V}{\sum as + a1s1}$$
(3)

(or)
$$\frac{1}{T2} = \frac{\sum as + a1s1}{0.167V}$$
(4)

where a1 - Absorption co-efficient of the absorbing material

s1 - its surface area

on subtracting Equation (4) from Equation (2), we have

from Equation (5), the value of a_1 is given by

$$a1 = \frac{0.167V}{s1} \left[\frac{1}{T2} - \frac{1}{T1}\right]$$

(or)
$$a1 = \frac{0.167V}{s1} \left[\frac{T1 - T2}{T1T2} \right]$$
(6)

By knowing the value of S_1 and V, a_1 can be determined.

5.15 Factors affecting acoustics of buildings and their remedies

Acoustics of building

The branch of physics which deals with the production of best sound effects in various public buildings such as cinema theatre, Auditoriums etc. is called Acoustics of buildings. It is also known as Architectural acoustics. The pioneering work in architectural acoustics was done by Prof. W.C. Sabine.

A hall or room is said to be acoustically correct, only if the following conditions are satisfied;

- (a) The sound heard by the observer or listener must be sufficiently louder.
- (b) The tonal quality of the speech and music must be unchanged.

(c) In order to achieve clarity, the successive sounds in the speech and music should be uniformly distributed and there should not be any overlapping in the hall.

Factors affecting the acoustics of buildings

In order to achieve good acoustic property, the hall or room should have the following factors. These factors must be considered carefully while designing a building,

- (i) Optimum reverberation time
- (ii) Loudness
- (iii) Focusing
- (iv) Echo
- (v) Echelon effect
- (vi) Resonance and
- (vii) Noise

(i) Optimum reverberation time

The reverberation time in a hall or a room should not be too large or too short because if it is too large, echoes will be present which leads to unintelligible speech. Similarly if it is too short, the sound may not be sufficiently heard in all portions of the hall or room.

The optimum value of the reverberation time of a hall for speech, music and theatres are

For speeches	-	0.5 Seconds
For Music	-	1 to 2 seconds
For Theatres	-	1.1 to 1.5 seconds

Remedies

By adjusting the reverberation time to optimum value, a good acoustical effect in a room or hall can be achieved. The reverberation time can be controlled by the following ways.

- i. Providing windows or ventilators
- ii. Decorating the wall with pictures, maps etc
- iii. Covering the ceiling, parts of the walls with sound absorbent materials
- iv. Covering the floor with carpets
- v. Having a packed audience
- vi. Using heavy curtains with folds

(ii) Loudness

For a satisfactory hearing, sufficient loudness is needed in every portion of the room or hall. Loudness is the degree of sensation produced on the ear.

Remedies

The loudness of sound can be increased in order to reach the listener or observer in the hall or room by the following ways.

- i. Using large sounding boards behind the speaker which faces the audience.
- ii. By providing the height of the ceiling of the hall or room to be low, which helps in reflecting the sound waves towards the listener.
- iii. By providing a parabolic shape in the wall surface at the speaker's end as shown in Fig. 5.7 in order to achieve an uniform sound intensity in every part of the room or hall.



Fig. 5.7 Uniform distribution of sound in a hall

(iii) Focusing

As shown in the Fig. 5.8, that if there are any focusing surfaces like concave, spherical, cylindrical or parabolic on the walls or ceiling or the floor of the hall or room, this will cause the sound waves to be concentrated at that particular region so that no sound waves will be reached to all other regions.

Here the observer or listener at O receives sound waves from the source S along the direct path 'SO' and also receives the sound waves after reflection from the ceiling. Thus the intensity of sound at O is comparatively higher than other positions in the auditorium or hall.



Fig. 5.8 Focusing

Remedies

The uniform distribution of sound in the hall or room can be achieved by the following ways;

- (i) The ceiling of the hall or room should be low
- (ii) By avoiding any curved surfaces in the hall or room. If there is any such surface, then it should be covered with suitable sound absorbing materials.

(iv) Echoes

Echo is a sound wave which can be reflected or otherwise returned by a distant extended surface like building, hill etc. with sufficient magnitude and time delay. The reflected sound is distinct from the directly transmitted sound wave.

The person will hear echo if he is standing at a distance more than 17 m away from the wall. Further, he will not hear echo if the distance of the separation between the sound source and the wall is less than 17 m.

An echo is heard, when the direct and reflected sound waves coming from the sound source reaches the listener within a time interval of 1/10 th of a second.

Remedies

Echoes may be avoided by covering the long distant walls and high ceiling with sound absorbent material.

(v) Echelon effect

A set of railings or any regular spacing of reflected surfaces may produce a musical note due to the regular succession of echoes of the original sound to the listener. This effect is known as Echelon effect (Fig. 5.9). This makes the original sound confusing or unintelligible.



Fig. 5.9 Echelon effect - Regular spacing of reflected surfaces

Remedies

By avoiding this type of surface or covered the surface with proper sound absorbing materials.

(vi) Resonance

Sometimes walls, sections of the wooden portions and the window - panes, which are lacking in rigidity are thrown into forced vibrations and create sound.

Due to the interference between the original sound and created sound, the original sound gets distorted. Thus the intensity of the note is entirely different from the original one.

Remedies

The resonant vibrations should be suitably damped.

(vii) Noise

The noise is an unwanted sound reaching the ears and it should not be permitted to reach into a room or hall from outside.

Generally the noise is of two types

- (1) Indoor noises
- (2) Outdoor noises

(1) Indoor noises

The noises that are produced inside the building in the same room or in the adjacent room is called Indoor noises.

(2) Outdoor noises

The noises that are produced outside the building by road traffic, aero planes, loud speakers etc., is called outdoor noises.

Remedies

This can be reduced by closing the doors and windows.

5.16 Principles to be followed in the acoustical design of a good auditorium

- (a) Volume
- (b) Shape and
- (c) Sound absorption

(a) Volume

- (i) The requirement of a hall or auditorium is based on its purpose or use.
- (ii) A music hall requires a large volume than a speech /theatre hall.

(iii) The height of a hall will play a dominant role in deciding the volume of the hall than the width or breadth of the hall.

- (iv) The thumb rule for the ratio of ceiling height and width of a hall is 2:3
- (v) The volume required per person for construction is shown in table 5.5.

Table 5.5 : Required volume per person

S.No.	Requirement	Required volume per person (m ³)
1.	Cinema Theatre	3.74 - 4.2
2.	Public hall	2.8 - 3.7
3.	Concert hall	4.2 - 5.6

(b) Shape

(i) Similar to the volume of a hall, the shape of the wall and ceiling will also play an important role in optimizing the distribution of sound waves.

(ii) The shape of the walls and ceiling of a hall will controls the echo and reflections of the sound waves.

(iii) The concave surface focused more amount of sound on a particular place, whereas the plain surface will distribute the sound to the entire hall.

(iv) The multiple reflections from a concave ceiling can be reduced by keeping the radius of curvature of a concave surface as twice the height of a hall.

(v) The reflections of sound waves from the side wall of fan-shaped (a) and dome - shaped wall ceiling (b) are shown in Fig. 2.10.



(a) Fan-shaped wall ceiling

(b) Dome-shaped wall ceiling

Fig. 2.10 Reflection of Sound ways

(c) Sound absorption

(i) The sound absorbing materials should be introduced into the hall at proper places, which helps to obtain the required reverberation time.

(ii) When sound - absorbing materials are placed at the right place in a hall, they absorb sound energy.

(iii) The important factors to be considered for optimizing reverberation time are

- a. Sound absorption co-efficient of the audience
- b. Arrangement of seats in a hall.
- c. Using of various sound absorbing materials.

(iv) The seats are arranged in such a way that the passage of direct sound is not affected by the heights of head of the audience in the other row.

(v) A typical arrangement of seats is shown in Fig. 5.11.



Fig. 5.11 Typical arrangement of seats

Solved Problems

1. Calculate the intensity level of a turbine whose sound intensity is 100 Wm^{-2} under operation. Given that the standard intensity level is 10^{-12} Wm^{-2} .

Given Data

The Intensity of sound of the turbine $I_{1=}100 \text{ Wm}^{-2}$

The standard intensity $I_0 = 10^{-12}$ Wm⁻².

Sound intensity level $\beta = 10 \log_{10} \left(\frac{I}{I_0} \right)$

$$\beta = 10 \log_{10} \left(\frac{100}{10^{-12}} \right)$$
$$\beta = 10 \log_{10} 10^{14}$$
$$= 140 \text{ dB}$$

The intensity level of a turbine = 140 dB.

2. Calculate the actual pressure of a sound which has a SPL of 72 dB

SPL (Sound Pressure Level) =
$$72 = 20 \log_{10} \left(\frac{P}{20 \times 10^{-6}} \right)$$

 $\frac{72}{20} = \log_{10} \left(\frac{P}{20 \times 10^{-6}} \right)$

 $\frac{P}{20 \times 10^{-6}} = \text{Antilog}\left(\frac{72}{20}\right)$ $P = 20 \times 10^{-6} \times 3.981 \times 10^{3}$ P = 0.0796 Pascals

3. Calculate the reverberation time of a hall with volume 1500m³ and total absorption is 100m² Sabine.

Solution:

Given data :

Volume of the hall, $V = 1500m^3$ Total absorption $\sum as = 100m^2$ SabineThe reverberation time of the hall, $T = \frac{0.167V}{\sum as}$

$$T = \frac{0.167 \times 1500}{100}$$

T = 2.505 seconds .

4. The volume of an auditorium is 12000 m³, its reverberation time is 1.5 seconds. If the average absorption coefficient of interior surface is 0.4 Sabine m⁻². Calculate the area of interior surfaces. Solution:

Given data :

Volume of the auditorium, $V = 12000 \text{m}^3$

Reverberation Time, T = 1.5 sec.

Average absorption coefficient of interior surface, $\bar{a} = 0.4$ Sabine m⁻²

$$T = \frac{0.167V}{\overline{a}.S}$$
$$S = \frac{0.167V}{T.\overline{a}}$$
$$S = \frac{0.167 \times 12000}{1.5 \times 0.4}$$
$$S=3340m^{2}$$

5. The volume of a room is 1500m³. The wall area of the room is 260m², the floor area is 140m² and the ceiling area is 140m². The sound -absorption coefficient for the wall is 0.03, for the ceiling is 0.8 and for the floor is 0.06. Calculate average absorption co-efficient and the reverberation time.

Solution:

Given data:

Volume of the hall, $V = 1500 \text{m}^3$

Surface	Area(m ²)	Absorption Co-efficient
Ceiling	140	0.8
Wall	260	0.03
Floor	140	0.06

$$T = \frac{0.167V}{\sum as}$$

$$\sum as = a1s1 + a2 s2 + a3s3$$

$$= (0.03 \times 260) + (0.8 \times 140) + (0.06 \times 140)$$

$$\sum as = 128.2$$

T = $\frac{0.167 \times 1500}{128.2}$
T = 1.9539 seconds.

Exercise Problems

1. The intensity of sound produced by thunder is 0.1 Wm⁻². Calculate the intensity level in decibels. [Ans: 110 dB]

2. A loud speaker limits energy in all directions at the rate of 1.5 Js^{-1} . What is the intensity level at a distance of 20m. Given standard intensity level of sound is 10^{-12} W m⁻². [Ans: 84.7 dB]

3. Calculate the intensity level of a jet plane just leaving the runaway having a sound intensity of about 100 Wm⁻². [Ans:140 dB]

4. A window whose area is $2.5m^2$ opens on a street where the street noises result in a intensity level at the window of 60 dB. How much acoustic power enters the window through the sound waves? [Ans: (Power = 1 × Area); 2.5×10^{-6} watts]

5. A hall with a volume of 1000m³ has a sound absorbing surface of area 400m². If the average absorption coefficient of the hall in 0.2 Sabine. Calculate the reverberation time of the hall. [Ans: 2.0875 seconds]

6. The volume of an auditorium is 6000m³. Its reverberation time is 1.5 seconds, if the average absorption coefficient at interior surface is 0.5 Sabine m⁻². Calculate the area of the interior surface. [Ans: 1336 m²]

Part - B Questions

1. Derive the Sabine's formula to determine the reverberation time of a room (or) hall using Jaegar's method.

- 2. Discuss the various factors affecting the acoustics of buildings. Mention their remedies.
- 3. Explain the various principles to be followed in the acoustical design of a good auditorium.
- 4. Discuss in detail the characteristics of musical sound.

5. State Weber - Fechner law. Obtain an expression for the relation between sound intensity level and sound pressure level.



SCHOOL OF SCIENCE AND HUMANITIES

DEPARTMENT OF PHYSICS

UNIT – III – PROPERTIES OF MATTER

PROPERTIES OF MATTER

ELASTICITY:

Elasticity is the property of materials to regain its original condition (of length, volume and shape) on the removal of deforming forces.

On the removal of deforming forces, some materials completely recover their original condition called **perfectly elastic materials** and some materials do not show any tendency to recover their original condition called **plastic materials**.

Deforming force (Load) is a combination of all external forces acting on the material changing the dimension.

Stress (σ):

It is the deforming force applied per unit area of the material or is the restoring force per unit area set up inside the deformed material.

$$\sigma = (F/A)$$

Unit is Nm⁻² or Pascal.

Strain (ε):

It is the ratio of change in dimension to original dimension of a body when it is deformed. It is a dimensionless quantity and no unit.

HOOKE'S LAW:

Hooke's law gives a relationship between the stress and strain.

According to Hooke's law, within the elastic limit, strain produced in a body is directly proportional to the stress produced.

i.e. Stress α Strain

(or) (Stress/Strain) = constant, known as Modulus of Elasticity. Its unit is Nm⁻².



Types of modulus of elasticity:

Depending upon the three types of strains (linear, volume and shear), modulus of elasticity is classified into 3 categories. They are as follows:

- 1. Young's Modulus (E or y)
- 2. Bulk Modulus (k) and
- 3. Rigidity Modulus or Shear Modulus (n)

ELASTIC CONSTANTS:

Young's modulus, Bulk modulus, and Rigidity modulus of an elastic material are together called as Elastic constants.

Young's Modulus (E or y):

It is a measure of stiffness of an isotropic elastic material. Within the elastic limit, it is defined as the ratio of the longitudinal stress to longitudinal strain.

E = y = (longitudinal stress/ longitudinal strain) = (F/A)/(dL/L) = (FL)/(A dL)

If A=1, L=1 and dL=1 then y=F. So Young's Modulus of a material is equal to the force required to extend a material of unit length and unit area of cross section through unity. Unit is Pascal (Nm^{-2})



Bulk Modulus (k):

It is a measure of resistance of the substance to uniform compression. It is defined as the ratio of the normal stress to volumetric strain.

k = (normal stress/ volumetric strain) = (F/A)/(dV/V) = (FV)/(A dV)

It is also referred to incompressibility and hence its reciprocal is compressibility (1/k).



Rigidity Modulus or Shear Modulus (n):

It is concerned with the deformation of a solid when it experiences a force parallel to one of its surface while its opposite faces experience an opposing force (friction). Within the elastic limit, it is defined as the ratio of the tangential stress to shear strain.

n = (tangential stress/ shear strain) = $(F/A)/(\theta) = (F)/(A\theta)$

When A=1 and θ =1 then n=F,

Rigidity Modulus of a material is defined as the shearing stress per unit shear.



Poisson's ratio (γ):

It is the ratio of the relative contractive strain or transverse strain (normal to applied load) to the relative extension strain or axial strain (in the direction of the applied load). When a material is stretched in one direction, it tends to contract in the other directions and vice versa.

Consider a wire of length L and diameter D is stretched by a force, so that the length increased by dL while diameter decreased by dD.

 $\gamma =$ (relative contractive strain / relative extension strain)

```
= (transverse strain / axial strain)
```

= (Lateral strain / Longitudinal strain) = (dD/D)/(dL/L)



BENDING OF BEAM:

Beam is defined as a rod or bar made of homogeneous and isotropic elastic material with uniform cross section.

The length of a beam is very large compared to its breath and thickness.

Thus the shearing stress at any point of the beam is very small and negligible.

Assumptions:

- 1. The weight of the beam is negligible in comparison to the load.
- 2. The beam should have small curvature.
- 3. There are no shearing forces.
- 4. The minimum deflection of the beam is small compared to its length

5. The cross section of the beam remains unaltered during bending. So moment of inertia of the beam remains constant.

Consider one end of the beam is fixed while a load is applied at the other end. So longitudinal filament is extended at the convex side while a contraction is obtained at the concave side. There is no change in the filament at the centre. The central filament is in the neutral stage called neutral filament and corresponding central axis is known as **neutral axis**.

BENDING MOMENT OF A BEAM:

The beam ABCD is fixed at one end AD, while a load W is applied at the other end BC. Let EF be the neutral axis of the beam.

A	<	P
E		r 7 x 8
D	1	TRT - TE
	Nontral axis	atte
		R 'd'
		15 riodalin)
		4 10

Consider PBCQ is a small portion of the beam in the bending, RF is its neutral axis, Φ is the angle substantial by it at the centre of curvature O and R is the distance between neutral axis RF and centre of curvature O (radius of curvature of the beam).

When the beam is at equilibrium,

Bending moment = Restoring couple = Moment of couple

Couple: Two equal and opposite forces will constitute a couple.

Consider a thin filament XY in the upper half portion of the beam (above the neutral axis) situated at a distance r from the neutral axis RF.

Length of filament (XY) without bending = length of neutral axis (RF)

Original length of the filament = $R\Phi$

Length of filament (XY) with bending = $(R+r)\Phi$

Change in length of the filament = $[(R+r)\Phi] - [R\Phi] = r$

Therefore, Strain produced at the filament (XY) = (Change in length/Original length) = (r/R)

WKT, Young's modulus = Y = (Stress/Strain) = (F/a)/(r/R) = (FR/ar)

Where a is the area of cross section of the filament

Force on the area (a) = F = (Yar / R)

Therefore,

Moment of this force about neutral axis RF = (Force) x (Distance) = (Yar / R) x (r) = (Yar^2/R)

WKT, the moment of inertia of the force acting on the upper and lower halves of the beam is same.

Hence, the Total moment of inertia = $\sum (Yar^2/R) = (Y/R) \sum (ar^2) = (Y/R) I_g$

Where, I_g is the geometrical moment of inertia of the beam (= AK^2)

A is the area of cross section of the beam

K is the radius of gyration of the beam

In equilibrium, bending moment of the beam is equal and opposite to the moment of bending couple.

Therefore, Bending moment of the beam = $(Y/R) I_g$

The quantity (YI_g) is called **flexural rigidity** of the beam.

Flexural rigidity is defined as the bending moment required to produced a unit radius of curvature.

CANTILEVER:

A cantilever is a beam which is fixed horizontally at one end and a load is applied at other end.

DEPRESSION AT THE LOADED END OF A CANTILEVER:

Consider a cantilever of length L and PQ is the neutral axis of the cantilever.

When a load W is applied at the free end Q of the cantilever. Then the end Q is deflected to Q'.

Thus neutral axis takes a new position PQ'.

Consider a point U in the cantilever which is at a distance x from the fixed end P.



Moment of couple at U due to load W = Force x Distance = (W)(UQ) = W(L-x)

WKT, under equilibrium condition,

Moment of couple = Bending moment = Restoring couple

 $W(L-x) = (Y/R) I_g$ ------(1)

Y is the young's modulus of the rod of the cantilever

Ig is the geometric moment of inertia

R is the radius of curvature of the neutral axis

Consider a point V at a distance dx from U. the radius of curvature at V is same as that of at U, since the point V is very close to the point U.

Hence, $UV = dx = R d\theta$

(or) $R = (dx/d\theta)$

On substituting this in eqn (1) we get,

 $W(L-x) = (YI_g d\theta / dx)$

(or)

$$d\theta = W(L-x) dx / YI_g$$

Draw tangents at U and V, which meet the vertical line QQ' at S and T respectively. So observed depression dy of V below U is

 $dy = (L-x) d\theta = W(L-x)^2 dx / YI_g$

Total depression of the beam QQ' is obtained by integrating the above equation with limit 0 to L.

Total depression = $\int dy = y = {}_0 \int^L W(L-x)^2 dx / YI_g$

Therefore, Total depression (y) = $(W/YI_g)_0 \int^L (L^2 - 2Lx + x^2) dx$

(or)
$$y = (W/YI_g) [L^2x - 2Lx^2/2 + x^3/3]_0^L$$

(or)
$$y = (W/YI_g) [L^3 - L^3 + L^3/3]$$

(or)
$$y = (W L^3 / 3YI_g)$$

(or)
$$y = (mg L^3 / 3YI_g) (W = mg)$$

Where, m is the mass and g is the acceleration due to gravity

For a circular cross section, $I_g = (\Pi r^4/4)$

For a rectangular cross section, $I_g = (bd^3/12)$

Where, r is the radius of circular cross section

b and d are the breath and thickness of rectangular cross section

The Young's modulus of the cantilever with rectangular

cross section is determined by

 $Y = (mg L^3) / 3y (bd^3/12)$

The breath (b) and thickness (d) of the can be determined using Vernier caliper and Screw gauge respectively.

Uniform bending:

Consider a beam is placed above the two knife edges C and D. Consider that, an equal load W is applied at the two ends. The bending of the beam is uniform and forms an arc of a circle. This bending is known as **uniform bending**.



Non-uniform bending:

Consider a beam AB is supported symmetrically on two knife edges C and D. The load W is applied at the centre of the beam. This bending is known as **non-uniform bending** since the bending of the beam does not describe an arc of a circle. A depression is produced at the centre depending on the applied load.



DETERMINATION OF YOUNG'S MODULUS (Y):

(a) By Non-uniform bending method:

Due to the application of load at the centre, the beam appears as two separate inverted cantilevers. It appears that, the cantilevers are fixed at the centre E and loaded at the ends each with a load (W/2). The length of the cantilever is (L/2).

Young's modulus of the beam under non uniform bending by W = (W/2) and L = (L/2)

WKT, the depression (y) = $(W L^3 / 3YI_g)$

(or) Young's modulus $(Y) = (W L^3 / 3yI_g)$

In this case, W = (W/2) and L = (L/2)

Hence, the above equation can be written as

$$Y = (W/2) (L/2)^3 / 3yI_g$$

(or) $Y = (W L^3 / 48yI_g)$

(or) $Y = (mg L^3 / 48yI_g)$

Where, m is the mass and g is the acceleration due to gravity

For a circular cross section, $I_g = (\Pi r^4/4)$

For a rectangular cross section, $I_g = (bd^3/12)$

Where, r is the radius of circular cross section

b and d are the breath and thickness of rectangular cross section

(b) By Uniform bending method:

Young's modulus $(\mathbf{Y}) = (\mathbf{W} \times \mathbf{L}^2 / 8\mathbf{y}\mathbf{I}_g)$

(or) $Y = (mg x L^2 / 8yI_g)$

Where, m is the mass and g is the acceleration due to gravity

For a circular cross section, $I_g = (\Pi r^4/4)$

For a rectangular cross section, $I_g = (bd^3/12)$

Where, r is the radius of circular cross section

b and d are the breath and thickness of rectangular cross section

TORSION:

It is the application of a twisting or turning force to an object. This twisting force most often involves movement in one direction at one end of an object and stability or movement in the opposite direction at the other end.

TORSION COUPLE (OR) TWISITNG COUPLE PER UNIT TWIST (C) :

Torsional rigidity is also known as the twisting couple per unit twist. It is the amount of twisting couple or torque required to twist the object by one unit angle, i.e., one radian.





Let us consider a cylindrical wire of length, L and radius, r. The wire is fixed at its upper end and twisted through an angle, θ by applying a torque at the lower end. The wire can be assumed to be made up of hollow cylindrical tubes whose radii vary from 0 to r.

The twisting couple on the wire, $C = \Pi n \theta r^4 / 2L$

If $\theta = 1$ radian. Then

The twisting couple per unit twist on the wire,

 $C = \Pi nr^4/2L$

POTENTIAL ENERGY IN A TWISTED WIRE:

The potential energy (restoring couple) in a twisted wire through an angle $(\theta) = {}_0 \int^{\theta} M \theta$ Moment of couple x d θ

 $P.E = {}_{0} \int^{\theta} C\theta \ d\theta$ $P.E = 1/2 \ C\theta^{2}$

WKT, $C = \Pi nr^4/2L$

Therefore, P.E = $1/2 \Pi nr^4/2L \theta^2$

(or) P.E = $\Pi nr^4 \theta^2/4L$

TORSIONAL PENDULUM:

Consider a disc suspended from a torsion wire (thin rod) attached to its center. This setup is known as a **torsion pendulum (or) torsional pendulum**. A torsion wire is essentially inextensible, but is free to twist about its axis. As the wire twists it also causes the disc attached to it to rotate in the horizontal plane. Therefore, the disc is said to be executing **simple harmonic motion (SHM)**. The rigidity modulus of the given wire can be determined using torsional pendulum.



Principle:

When a disc (torsion pendulum) is rotated in a horizontal plane, the disc will execute a Simple Harmonic Oscillation (or) Motion due to the restoring couple produced in the wire.

Determination of Time period of oscillation (T) and Rigidity modulus (n):

From the Law of conservation of energy,

Total energy (TE) = Kinetic energy (KE) + Potential energy (PE)

WKT, KE (Deflecting couple) = $1/2 \text{ I}\omega^2$

PE (Restoring couple) = $1/2 \ C\theta^2$

Therefore, TE = KE + PE

(or) TE = $1/2 I\omega^2 + 1/2 C\theta^2$ (1)

On Differentiating Eq. (1) w.r.t. 't', we have

 $[1/2 . 2 I\omega d\omega/dt] + [1/2 . 2C\theta d\theta/dt] = 0$

(or) $C\theta d\theta/dt + I\omega d\omega/dt = 0$ (2)

WKT, angular velocity, $\omega = d\theta/dt$

And angular acceleration, $d\omega/dt = d^2\theta/dt^2$

On substituting the value of ω and $d\omega/dt$ in Eq. (2), we have

 $C\theta \ d\theta/dt + I \ d\theta/dt \ d^2\theta/dt^2 = 0$

(or) $d\theta/dt [C\theta + I \cdot d^2\theta/dt^2] = 0$

Here, $d\theta/dt \neq 0$. Therefore, $C\theta + I \cdot d^2\theta/dt^2 = 0$

(or) $d^2\theta/dt^2 = -C\theta/I$ (3)

WKT, the time period of oscillation (T) is given by

 $T = 2\Pi \sqrt{\text{Displacement/Acceleration}}$ (4)

On substituting Eq. (3) in Eq. (4), we have

 $T = 2\Pi \sqrt{\theta} / C\theta / I$

(or) $T = 2\Pi \sqrt{I} / C$ (5)

Hence, Frequency, $f = 1/T = 1/2\Pi \sqrt{C/I}$

If 'L' be the length of the wire and 'r' be the radius of the wire. Then

WKT, The twisting couple per unit twist on the wire,

 $C = \Pi nr^4 / 2L_{(6)}$

On substituting Eq. (6) in Eq. (5), we have

$$T = 2\Pi \sqrt{2LI} / \Pi nr^{4}$$
(or) $T^{2} = 4\Pi^{2} . (2LI / \Pi nr4)$
(or) $\mathbf{n} = (8\Pi I / r^{4}) . (L/T^{2}) N/m^{2}$

VISCOUS FORCE AND VISCOSITY OF A LIQUID:

The frictional force offered by the adjacent liquid layers during its flow is called as **Viscous force** and the phenomenon is known as **Viscosity**.

Definition: The property of the fluid by virtue of which it opposes the relative motion between its different layers is called as **Viscosity**.

Both liquids and gases exhibit viscosity, but liquids are much more viscous than gases.

CO-EFFICIENT OF VISCOSITY OF A LIQUID (η) :

Consider a liquid flowing over a horizontal surface. The layer in contact with the surface is at rest. The velocities of other layers increase uniformly from layer to layer. The velocity is maximum for the top layer (Fig. 2.17).



Consider two layers of liquid separated by a distance dz (Fig. 2.18). Let v and v + dv be the velocities of two layers. So the velocity gradient is dv/dz. Let A be surface area of the layer. The viscous force is directly proportional to the surface area A and velocity gradient dv/dz.

$$F \propto A \frac{dv}{dz}$$
 or $F = \eta A \frac{dv}{dz}$.

Here, η is a constant for the liquid. It is called coefficient of viscosity. If A = 1 and dv/dz = 1, we have $F = \eta$.

Definition : *The coefficient of viscosity is defined as the tangential force per unit area required to maintain a unit velocity gradient.*

Unit of η is N s m⁻². It is called the Pascal second.

Dimensions of
$$[\eta] = \frac{[F]}{[A][(dv/dz)]} = \frac{MLT^{-2}}{L^2(LT^{-1}/L)} = [ML^{-1}T^{-1}]$$

COMPARISON OF VISCOSITIES OF TWO LIQUIDS BY GRADUATED BURETTE METHOD:

Apparatus : A graduated burette is clamped vertically. The nozzle is connected to a horizontal capillary tube AB by means of rubber tube (Fig. 2.22.)



The rubber tube is provided with a pinch clip. A beaker is placed below the free end B of the capillary tube.

Experiment : (*i*) The burette is filled with the first liquid whose viscosity is η_1 . The pinch clip is opened completely. The liquid is allowed to flow out. The time taken for the liquid level to fall from 10 cc to 20 cc graduation is determined using stop watch. This is repeated and average time (t_1 sec.) is found. Similarly, the time of flow of the liquid for the ranges 20–30, 30–40cc are also found out.

(*ii*) The burette and the capillary tube are washed, cleaned and arranged again. The pressure head is kept the same as before. The burette is then filled with the second liquid whose viscosity is η_2 . The times of flow for the same ranges 10–20, 20–30, 30–40cc graduations are determined.

The ratio $\frac{t_1}{t_2}$ for each range is calculated. The mean value of $\frac{t_1}{t_2}$ is determined. The readings are tabulated as follows :

	Time for liquid I		Time for liquid II				
Range	1	2	Mean t ₁	1	2	Mean t ₂	$\frac{t_1}{t_2}$
10-20							
20-30							
30-40							

Mean (t_1/t_2) =

Let ρ_1 and ρ_2 be the densities of the two liquids respectively.

Using a U-tube or Hares' apparatus, the ratio of the densities $\frac{\rho_1}{\rho_2}$ is determined.

 $\frac{\eta_l}{\eta_2}$ is calculated using the formula,

$$\frac{\eta_1}{\eta_2} = \left(\frac{t_1}{t_2}\right) \times \left(\frac{\rho_1}{\rho_2}\right).$$

Theory : Let l and a be the length and radius of the capillary tube respectively. Let the volume of liquid flowing in t seconds be Q. Volume of liquid flowing per second

$$= V = \frac{Q}{t} = \frac{\pi p a^4}{8\eta l}$$
 (Poiseuille's formula)
Pressure difference between the ends of the capillary tube is
 $p = h \rho g.$
 $Q = \frac{\pi h \rho g a^4 t}{8\eta l}$

...

For the first liquid,
$$\eta_1 = \frac{\pi h \rho_1 g a^4 t_1}{8 I Q}$$
 ...(1)

For the second liquid,
$$\eta_2 = \frac{\pi h \rho_2 g a^2 t_2}{8lO}$$
 ...(2)

Dividing (1) by (2), we get

$$\frac{\eta_1}{\eta_2} = \left(\frac{t_1}{t_2}\right) \times \left(\frac{\rho_1}{\rho_2}\right).$$

πhpga1

SURFACE TENSION:

Surface tension is that property of liquids owing to which they tend to acquire minimum surface area.

Small liquid drops acquire spherical shape due to surface tension. Big liquid drops flatten out due to weight.

The following experiment illustrates the tendency of a liquid to decrease its surface area.

When a camel hair brush is dipped into water, the bristles spread out [Fig. 2.24 (*a*)]. When the brush is taken out, the bristles cling together on account of the films of water between them contracting [Fig. 2.24 (*b*)]. This experiment clearly shows that the surface of a liquid behaves like an elastic membrane under tension with a tendency to contract. This tension or pull in the surface of a liquid is called its *surface tension*.





Definition : Surface tension is defined as the force per unit length of a line drawn in the liquid surface, acting perpendicular to it at every point and tending to pull the surface apart along the line.

Unit of Surface Tension : Surface tension is force per unit length. So its SI unit is newton per metre (Nm^{-1}) .

Dimensions of Surface Tension : Surface tension is the ratio of a force to a length.

Surface tension = force/length

Dimensions of force
$$= MLT^2$$
.

Dimensions of length = L

 \therefore Dimensions of surface tension = $\frac{MLT^{-2}}{L} = MT^{-2}$. The dimensional formula for surface tension is $[MT^{-2}]$.

INTERFACIAL SURFACE TENSION:

In general, surface tension is the property of the liquid in contact with gas phase (usually air). Interfacial surface tension, on the other hand, is the property between any two substances. It could be liquid-liquid, liquid-solid or solid-air.

Surface tension can also be defined as the amount of energy required to increase the surface area between a liquid and a gas (e.g. air and water).

$$\sigma = \frac{mg}{3.8r}$$

 $\sigma =$ Surface tension of the given liquid

- m = Mass of a single drop
- g = Acceleration due to gravity
- r = External radius of the cube

Interfacial tension is defined as the amount of energy required to increase the interfacial area between two immiscible liquids (e.g. oil and water).

$$\sigma = \frac{mg\left(1 - \frac{\rho_2}{\rho_1}\right)}{3.8 r}$$

 σ = Interfacial tension between water and kerosene

m = Mass of a single drop

- ρ_1 = Density of the heavier liquid
- ρ_2 = Density of the lighter liquid
- r = External radius of the tube.

DETERMINATION OF SURFACE TENSION AND INTERFACIAL SURFACE TENSION BY THE METHOD OF DROPS (OR) DROP WEIGHT METHOD:

(I) DETERMINATION OF SURFACE TENSION:



Procedure : (*i*) **S.T. of a liquid :** A short glass tube is connected to the lower end of a burette (or funnel), clamped vertically, by means of a rubber tube (Fig. 4.1). The funnel is filled with the liquid whose surface tension is to be determined. A beaker is arranged under the glass tube to collect the liquid dropping from the funnel. The stopcock is adjusted so that the liquid drops are formed slowly.

An empty beaker is taken and weighed in a balance. Now 50 drops of liquid are collected in the beaker. The beaker is again weighed. The difference between this weight and the weight of the empty beaker gives the weight of 50 drops of the liquid. From this the mass m of each drop is calculated. The external radius (r) of the tube is determined using a screw gauge or microscope.

Liquid	Mass of empty beaker W ₁ kg	$Mass of \\ beaker + 50 \\ drops \\ W_2 kg$	Mass of each $\frac{drop}{m = \frac{W_2 - W_1}{50}}$ kg	$\sigma = \frac{mg}{3.8 r}$ Nm ⁻¹
Water				
Kerosene				

Observations :

Mass of empty beaker	$= \dots W_1 \text{kg}$
Mass of beaker + 50 drops of liquid	$= \dots W_2 \text{kg}$
Mass of 50 drops	= kg
\therefore Average of mass of one drop (<i>m</i>)	= kg.

Radius of the tube :

Lea	ast count of the vernier	= 1	m.
Dia	ameter (along any one direction)	=1	n.
Dia	ameter (in a perpendicular direction)	=1	m.
	Mean radius (r)	= 1	n.
÷.	Surface tension = $\frac{mg}{3.8 r}$	=]	Nm^{-1}

(II) DETERMINATION OF INTERFACIAL SURFACE TENSION:




(ii) Interfacial Tension between water and kerosene

Sufficient amount of the lighter liquid (kerosene) is taken in a beaker. The weight w_1 of the beaker with kerosene is determined. The heavier liquid (water) is taken in the burette (Fig. 4.2). The glass tube is fixed vertically with its end under the surface of kerosene. The flow of water is regulated so that drops of water detach themselves into kerosene one by one. After collecting 50 drops, the beaker is again weighed. Let this weight be w_2 . Then $w_2 - w_1$ gives mass of 50 drops. From this the average mass *m* of each drop is calculated.

The external radius (r) of the tube is determined using a screw gauge or microscope.

The value of ρ_2/ρ_1 is determined using a Hare's apparatus (Fig. 4.3).

One limb of the apparatus is dipped into a beaker of water and the other into a beaker containing

the liquid. Air is sucked out of the apparatus through the rubber tube attached to the side tube. When the liquids have risen to suitable heights in the limbs, the pinch clip is closed. The height of water column (h_1) and the height of liquid column (h_2) from the respective levels in the beaker are measured.

Then $\frac{h_1}{h_2} = \frac{\rho_2}{\rho_1}$.

The experiment is repeated by drawing in liquids to different heights.

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003	ci valions.				
_		- T.			

No.	Mass of beaker + lighter liquid		Mean w_1 kg	Mass of + lighte + 50	Mass of beaker + lighter liquid + 50 drops		Mass of each drop m $=\frac{w_2 - w_1}{v_2 - w_1} \text{kg}$
	Trial I	Trial II		Trial I	Trial II		50
		· · ·					

Mass of beaker + kerosene $= \dots w_1 \text{ kg}$ Mass of beaker + kerosene + 50 drops $= \dots w_2 \text{ kg}$ of water collected inside kerosene $= \dots w_2 \text{ kg}$ Mass of 1 drop of water collected $= \dots m \text{ kg}$ Acceleration due to gravity (g) $= 9.8 \text{ ms}^{-2}$ Mean radius of the tube (r) $= \dots m$

Hare's apparatus : Ratio of densities of the two liquids

	Heig	ght of	k o
Trial No.	Water column (h ₁)	Liquid column (h ₂)	$\frac{h_1}{h_2} = \frac{\rho_2}{\rho_1}$
1.			
2.			
3.			
4.			

Mean =

Calculation:

Interfacial surface tension =
$$\frac{mg}{3.8 r} \left(1 - \frac{\rho_2}{\rho_1}\right) \text{Nm}^{-1}$$

Osmosis

Spontaneous movement of solvent particles from a dilute solution or from a pure solvent towards the concentrated solution through a semipermeable membrane is known as **osmosis** (Greek word : 'Osmos' = to push).

Fig. depicts Osmosis in a simple way. The flow of the solvent from its side (a) to solution side (b) separated by semipermeable membrane

(c) can be stopped if some definite extra pressure is applied on the solution risen to height (h). This pressure that just stops the flow of solvent is called **osmotic pressure** of the solution. This pressure (p) has been found to depend on the concentration of the solution.

Characteristics of Osmostic Pressure (Pi)

It is the minimum external pressure which must be applied on solution side in order to prevent osmosis if separated by a solvent through a semi permeable membrane.

A solution having lower or higher osmotic pressure than the other is said to be hypotonic or hypertonic respectively in respect to other solution.

Two solutions of different substances having same osmotic pressure at same temperature are said to be isotonic to each other. They are known as isotonic solutions.

Fick's first law

Fick's first law relates the diffusive <u>flux</u> to the gradient of the concentration. It postulates that the flux goes from regions of high concentration to regions of low concentration, with a magnitude that is proportional to the concentration gradient (spatial derivative), or in simplistic terms the concept that a solute will move from a region of high concentration to a region of low concentration across a concentration gradient. In one (spatial) dimension, the law can be written in various forms, where

the most common form is in a molar basis:

where

 J is the diffusion flux, of which the <u>dimension</u> is <u>amount of</u> <u>substance</u> per unit <u>area</u> per unit <u>time</u>. J measures the amount of substance that will flow through a unit area during a unit time interval.

- *D* is the diffusion coefficient or <u>diffusivity</u>. Its dimension is area per unit time.
- φ (for ideal mixtures) is the concentration, of which the dimension is amount of substance per unit volume.
- *x* is position, the dimension of which is length.

D is proportional to the squared velocity of the diffusing particles, which depends on the temperature, <u>viscosity</u> of the fluid and the size of the particles according to the <u>Stokes–Einstein relation</u>. In dilute aqueous solutions the diffusion coefficients of most ions are similar and have values that at room temperature are in the range of $(0.6-2)\times10^{-9}$ m²/s. For biological molecules the diffusion coefficients normally range from 10^{-11} to 10^{-10} m²/s.

In two or more dimensions we must use ∇ , the <u>del</u> or <u>gradient</u> operator, which generalises the first derivative, obtaining

where ${\bf J}$ denotes the diffusion flux vector.

The driving force for the one-dimensional diffusion is the quantity $-\partial \varphi / \partial x$, which for ideal mixtures is the concentration gradient.

Osmotic pressure and concerned laws

Vant Hoff noted the striking resemblance between the behaviour of dilute solutions and gases. He concluded that, a substance in solution behaves exactly like gas and the osmotic pressure of a dilute solution is equal to the pressure which the solute would exert if it is a gas at the same temperature occupying the same volume as the solution. Thus it is proposed that solutions also obey laws similar to gas laws.

1.Boyle's - Vant Hoff law

The osmotic pressure (Pi) of the solution at temperature is directly propositional to the concentration (C) of the solution.

Pi Dir. Props to C at constant T

C = Molar concentration

2. Charle's - Vant Hoff law

At constant concentration the osmotic pressure(Pi) is directly proportional to the temperature (T).

Pi dirc.Prop.to T at constnt C.

Combining these two laws,

Pi = CRT

Where R is the gas constant.

Determination of molecular weight by osmotic pressure measurement

The osmotic pressure is a colligative property as it depends, on the number of solute molecules and not on their identity.

Solution of known concentration is prepared by dissolving a known weight (W_2) of solute, in a known volume $(V \text{ dm}^3)$ of the solvent and its osmotic pressure is measured at room temperature(T).

Since Pi = CRT

C = n2/V = number of moles of solute / Volume of the solution in dm³

 $C^{=}\,W2\;/\;M_{2}V$

We get

 $Pi = W_2 R T / M_2 V$

 $M_2 = W_2 R T / Pi V$

Thus M₂, molecular weight of the solute can be calculated by measuring osmotic pressure value.

Determination of osmotic pressure by Berkley-Hartley method

The osmotic pressure of a solution can be conveniently measured by Berkley - Hartley method. The apparatus (Fig.) consists of two concentric tubes. The inner tube (a) is made of semipermeable membrane



Fig. Berkley - Hartley apparatus

(c) with two side tubes. The outer tube (b) is made of gun metal which contains the solution. The solvent is taken in the inner tube. As a result of osmosis, there is fall of level in the capillary indicator (d) attached to the inner tube. The external pressure is applied by means of a piston (e) attached to the outer tube so that the level in the capillary indicator remains stationary at (d). This pressure is equal to the osmotic pressure (p) and the solvent flow from inner to outer tube is also stopped.

Advantages of this Method

The osmotic pressure is recorded directly and the method is quick.

There is no change in the concentration of the solution during the measurement of osmotic pressure.

The osmotic pressure is balanced by the external pressure and there is minimum strain on the semipermeable membrane.

Elevation of Boiling point and depression of Freezing point

People who live in colder climates have seen the trucks put salt on the roads when snow or ice is forecast. Why do they do that? As a result of the information you will explore in this section you will understand why these events occur. You will also learn to calculate exactly how much of an effect a specific solute can have on the boiling point or freezing point of a solution.

The example given in the introduction is an example of a colligative property. **Colligative properties** are properties that differ based on the concentration of solute in a solvent, but not on the type of solute. What this means for the example above is that people in colder climates don't necessarily need salt to get the same effect on the roads - any solute will work. However, the higher the concentration of solute, the more these properties will change.

Boiling Point Elevation

Water boils at 100oC100oC at 1atm1atm of pressure, but a solution of salt water does not . When table salt is added to water the resulting solution has a higher boiling point than the water did by itself. The ions form an attraction with the solvent particles that then prevent the water molecules from going into the gas phase. Therefore, the salt-water solution will not boil at 100oC100oC. In order to cause the salt-water solution to boil, the temperature must be raised about 100oC100oC. This is true for any solute added to a solvent; the boiling point will be higher than the boiling point of the pure solvent (without the solute). In other words, when anything is dissolved in water the solution will boil at a higher temperature than pure water would.

The boiling point elevation due to the presence of a solute is also a colligative property. That is, the amount of change in the boiling point is related to the number of particles of solute in a solution and is not related to chemical composition of the solute. A 0.20m0.20m solution of table salt and a 0.20m0.20m solution of hydrochloric acid would have the same effect on the boiling point.

Freezing Point Depression

The effect of adding a solute to a solvent has the opposite effect on the freezing point of a solution as it does on the boiling point. A solution will have a lower freezing point than a pure solvent. The **freezing point** is the temperature at which the liquid changes to a solid. At a given temperature, if a substance is added to a solvent (such as water), the solute-solvent interactions prevent the solvent from going into the solid phase. The solute-solvent interactions require the temperature to decrease further in order to solidify the solution. A common example is found when salt is used on icy roadways. Here the salt is put on the roads so that the water on the roads will not freeze at the normal 0oC0oC but at a lower temperature, as low as -9oC-9oC. The de-icing of planes is another common example of freezing point depression in action. A number of solutions are used but commonly a solution such as ethylene glycol, or a less toxic monopropylene glycol, is used to de-ice an aircraft. The aircrafts are sprayed with the solution when the temperature is predicted to drop below the freezing point. The **freezing point** depression is the difference in the freezing points of the solution from the pure solvent. This is true for any solute added to a solvent; the freezing point of the solution will be lower than the freezing point of the pure solvent (without the solute).

Applications

The concept of simple diffusion is applied in various fields like the food, medicine, and environment

- 1. In beverages like tea and soda, the diffusion of gases and chemicals from tea leaves plays a vital role in the development of the particular taste.
- The process of simple diffusion is applied in the action of medicines in the body. Once a medicine is ingested, the molecules are released into the respective sites of action through the process of simple diffusion.
- 3. Air pollution is another phenomenon that is a result of diffusion. The diffusion of various gases released from agricultural, industrial, and mechanical processes results in air pollution.
- 4. The formation of alloys is also a result of diffusion. Under long-term exposure of one metal to another, the atoms diffuse from one metal to another to fill the spaces. This results in the formation of different alloys.



SCHOOL OF SCIENCE AND HUMANITIES

DEPARTMENT OF PHYSICS

UNIT - IV - THERMAL PHYSICS

Newton's Law of Cooling

Newton's law of cooling describes the rate at which an exposed body changes temperature through radiation which is approximately proportional to the difference between the object's temperature and its surroundings, provided the difference is small.

Definition: According to Newton's law of cooling, the rate of loss of heat from a body is directly proportional to the difference in the temperature of the body and its surroundings.

Newton's law of cooling is given by, $dT/dt = k(T_t - T_s)$

Where,

- T_t = temperature at time t and
- $T_s =$ temperature of the surrounding,
- k = Positive constant that depends on the area and nature of the surface of the body under consideration.

Newton's Law of Cooling Formula

Greater the difference in temperature between the system and surrounding, more rapidly the heat is transferred i.e. more rapidly the body temperature of body changes. Newton's law of cooling formula is expressed by,

 $T(t) = T_s + (T_o - T_s) e^{-kt}$

Where,

- t = time,
- T(t) = temperature of the given body at time t,
- T_s = surrounding temperature,
- $T_o = initial$ temperature of the body,
- k = constant.

This **Law of Cooling** is named after the famous English Physicist Sir Isaac Newton, who conducted the first experiments on the nature of cooling.

Statement of the Law :

According to Newton's Law of Cooling, the rate of cooling of a body is directly proportional to the difference in temperatures of the body (T) and the surrounding (T_0), provided difference in temperature should not exceed by 30^oC.

From the above statement,

$$\frac{\mathrm{d}Q}{\mathrm{d}t}\alpha(T - T_0)$$

For a body of mass m, specific heat s, and temperature T kept in surrounding of temperature T_0 ;

$$Q = msT$$

Now, the rate of cooling,

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = ms\frac{\mathrm{d}T}{\mathrm{d}t}$$

Hence,

$$ms\frac{\mathrm{d}T}{\mathrm{d}t}\alpha\left(T-T_0\right)$$

Since the mass and the specific heat of the body are taken as constants, the rate of change of temperature with time can be written as,

$$\frac{\mathrm{d}T}{\mathrm{d}t}\alpha\left(T-T_0\right)$$

The above equation explains that, as the time increases, the difference in temperatures of the body and surroundings decreases and hence, the rate of fall of temperature also decreases.

It can be graphically represented as,



Learning Outcomes

- Students understand the different modes of transfer of heat.
- Students identify the variables which affect the cooling rate of a substance.
- Students verify Newton's Law of Cooling.
- Students understand the relationship between temperature and time of cooling of objects.

Heat and temperature

Heat is a form of <u>energy</u>, The flow of heat from one position to another depends on the difference in temperature between them, The atoms or molecules of substances are in a continuous motion (vibration), but they differ in their speed in the same substance, Temperature is a measurement of the average kinetic energy of matter molecules and it is an indication of hotness and coldness of an object.

When <u>the system</u> absorbs the heat energy, the average speed of its molecules increases, This expresses the kinetic energy of the molecules and leads to the rise of temperature of <u>the system</u> and vice versa (direct relationship), Kinetic energy is expressed by the average speed of molecules not by speed of molecules because of the difference in speed of molecules in one substance.

There are two measuring units of quantity of heat lost or gained by the system :

Calorie is the quantity of heat needed to raise the temperature of 1 g of water by 1 ° C (15° C : 16° C), Joule is the quantity of heat needed to raise the temperature of 1 g of water by (1/4.184) ° C.

The Calorie is used when calculating quantity of heat gained from the food, The level of your Calorie consumption depends on the level of your activity.

For example, if you spend a day working in the library, You consume approximately 800 Calories, while a marathon runner consumes approximately 1800 Calories to complete the race.

1 Calorie = 1 kilocalorie = 1000 calorie.

Specific Heat (Cs)

Specific heat: The quantity of heat required to raise the temperature of one gram of the substance by one degree Celsius (1 $^{\circ}$ C), The unit used in measuring specific heat is J/g. $^{\circ}$ C.

The specific heat of <u>water</u> is higher than the specific heat of any other substance. The substance that has a large specific heat needs a long time to decrease or increase its temperature - like <u>water</u> – in contrary of the substance that has lower specific heat .

Example: The of heat required to raise the temperature of 1 g of iron by 1° C equals 0.448 J, While the quantity of heat requires to raise the temperature of 1 g of water by 1° C equals 4.18 J.

Specific heat differs according to the type of substance and its physical state, when the specific heat of copper is $0.385 \text{ J/g.}^{\circ}\text{C}$, this means that the quantity of heat required to raise temperature of 1 g of copper by 1°C equals 0.385 J.

Specific heat is a characteristic property for the substance because specific heat is a constant value for the substance, but it differs from one substance to another and also it depends on the physical state of the substance.

Specific heat of <u>water</u> is higher than that of the other substances because the quantity of heat required to raise the temperature of 1 g of water by 1° C is higher than that of other substance.

<u>Water</u> causes a moderate climate in coastal areas in both winter and summer because the specific heat of <u>water</u> is higher than that of the other substances, So, <u>Water</u> can absorb a high quantity of heat in summer and release a high quantity of heat in winter.

In very cold countries, farmers sprinkle <u>water</u> over fruit trees because of the high specific heat of <u>water</u>, thus it protects fruits from freezing.

When two equal masses of copper and aluminum gain the same amount of heat , the temperature of copper (specific heat = $0.385 \text{ J/g.}^{\circ}\text{C}$) rises much greater than the temperature of aluminum (specific heat = $0.9 \text{ J/g.}^{\circ}\text{C}$) because specific heat of copper is less than specific heat of aluminum .

Calculation of the quantity of heat

The quantity of heat (absorbed or released) is directly proportional with the difference in the temperature , The quantity of heat needed to raise or decrease the temperature of a <u>system</u> can be calculated by the following relation :

$$q = m \times c \times \Delta T$$

q is the quantity of heat measured at constant pressure , m is the mass , c is the specific heat , ΔT is the change in temperature ($\Delta T = T2 - T1$).



Combustion (bomb) Calorimeter

The Calorimeter

It is an isolated system used to determine the change in the temperature of chemical reactions Δ T by knowing each of the initial temperature T1 and the final temperature T2, It prevents losing or gaining of any quantity of heat or substance with its surrounding.

The Calorimeter is consisted of Isolated container, Stirrer, The reactants (represent an isolated system) and Thermometer, There are types of Calorimeters, such as the combustion Calorimeter.

The combustion (bomb) Calorimeter

It is used to measure the heat of combustion of some substances, A known amount of substance is burned in an excess amount of <u>oxygen</u> under constant atmospheric pressure, It occurs in an isolated steel container called the steel bomb which is surrounded by an identified amount of the heat exchange liquid (almost water).

The substance is ignited by using an electric wire, The combustion temperature is determined by measuring the change in temperature of the exchange liquid (water), Water is used in the calorimeter as a heat exchange liquid due to its high specific heat which allows it to absorb or lose a large amount of heat energy.

Solar constant

Solar constant, the total radiation energy received from the Sun per unit of time per unit of area on a theoretical surface perpendicular to the Sun's rays and at Earth's mean distance from the Sun. It is most accurately measured from satellites where atmospheric effects are absent. The value of the constant is approximately 1.366 kilowatts per square metre. The "constant" is fairly constant, increasing by only 0.2 percent at the peak of each 11-year solar

cycle. Sunspots block out the light and reduce the emission by a few tenths of a percent, but bright spots, called plages, that are associated with solar activity are more extensive and longer lived, so their brightness compensates for the darkness of the sunspots. Moreover, as the Sun burns up its hydrogen, the solar constant increases by about 10 percent every billion years.

Angstrom pyrheliometer

Pyrheliometer is an instrument used to measure the quantity of heat radiation and solar constant.

Pyrheliometer designed by Angstrom is the simplest and most accurate.

Angstrom's pyrheliometer consists of two identical strips S_1 and S_2 of area A. One junction of a thermocouple is connected to S_1 and the other junction is connected to S_2 . A sensitive galvanometer is connected to the thermo couple.



Strip S2 is connected to an external electrical circuit as shown in Fig.. When both the strips S1 and S2 are shielded from the solar radiation, galvanometer shows no deflection as both the junctions are at the same temperature. Now strip S1 is exposed to the solar radiation and S2 is shielded with a cover M. As strip S1 receives heat radiations from the sun, its temperature rises and hence the galvanometer shows deflection. Now current is allowed to pass through the strip S₂ and it is adjusted so that galvanometer shows no deflection. Now, the strips S₁ and S₂ are again at the same temperature.

If the quantity of heat radiation that is incident on unit area in unit time on strip S_1 is Q and *a* its absorption co-efficient, then the amount of heat radiations absorbed by the strip S_1 in unit time is QA*a*.

Also, heat produced in unit time in the strip S_2 is given by *VI*, where *V* is the potential difference and I is the current flowing through it.

As heat absorbed = heat produced

QAa = VI (or)

Q=VI/Aa

Knowing the values of *V*, *I*, *A* and *a*, *Q* can be calculated.

Temperature of the Sun

At the core of the sun, gravitational attraction produces immense pressure and temperature, which can reach more than **27 million** degrees Fahrenheit (**15 million** degrees Celsius). Hydrogen atoms get compressed and fuse together, creating helium. This process is called nuclear fusion.

Outline

11.1 Conduction11.2 Convection11.3 Radiation11.4 Global warming

11. Heat Transfer

By Liew Sau Poh

Objectives

- a) explain the mechanism of heat conduction through solids, and hence, distinguish between conduction through metals and non-metals
- b) define thermal conductivity
- c) use the equation $\frac{Q}{t} = kA \frac{\theta_2 \theta_1}{x}$

for heat conduction in one dimension

Objectives

- h) describe heat transfer by radiation
- i) use Stefan-Boltzmann equation $dQ/dt = e\sigma AT^4$
- j) define a black body
- k) explain the greenhouse effect and thermal pollution
- 1) suggest ways to reduce global warming

11.1 Conduction

Objectives

- d) describe and calculate heat conduction through a cross-sectional area of layers of different materials
- e) compare heat conduction through insulated and non-insulated rods
- f) describe heat transfer by convection
- g) distinguish between natural and forced convection

11 Heat Transfer

- Internal energy may be transferred from one body to another.
- These occur in 3 modes:



(http://docushare.barford.edu/dsweb/Get/Document-239986/Physical%20Science%20105%20Chapter%2007.pp

11.1 Conduction

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- The type of energy transfer that is due to atoms transferring vibrations to neighboring atoms is called thermal conduction.
- The **rate of thermal conduction** depends on the substance.

11.1 Conduction



- A metal rod heated at one end will transfer thermal energy to the other end by conduction.
- In this method, some of the electrons in the metal (called conduction electrons) are free to roam and collide with other electrons.
- Metals like copper are good conductors.
- Water is not a good conductor, rather it is considered to be an insulator, a poor conductor.

11.1 Conduction

- Copper Cookware
 - Copper has a high thermal conductivity. When you heat from below, the flame or element concentrates heat. A good copper bottom will conduct heat evenly across the bottom for better heat distribution in the pot.

Silver	1.01		
Copper	0.99		
Aluminum	0.50		
Ice	0.005		
Water	0.0014		
Snow	0.00026		
Fiberglass	0.00015		
Cork	0.00011		
Wool	0.0001		
Wood	0.0001		
Air	0.00057 3		

Relative Thermal Conductivities

11.1 Conduction

- *Thermal conductors* are materials that are good conductors of heat.
- Metals (a type of solid) are thermal conductors. *Why*?
 - •A metal has a large number of electrons that are free to move around (*conduction electrons*), and are not permanently bound to any particular atom or molecule. The free electrons are believed to be primarily responsible for the heat conduction of metals.

11.1 Conduction



- Ions in the lattice structure of a solid can also vibrate, causing their neighbors to vibrate.
- The neighbors then cause their neighbors to shake, and the process spreads until the solid approaches thermal equilibrium.
- This spreads more slowly then electron collisions so that materials that do not have many free electrons are not good thermal conductors.

11.1 Conduction

- Good insulators are poor conductors
- Double Pane Windows with Air Insulation
 - The superior insulating properties of air (poor thermal conductivity) provide insulation for windows. The air is sandwiched between two panes of glass and sealed.
- Down is a good insulator.

11.1 Conduction

- The process of *heat conduction* is visualized as resulting from molecular interactions (interactions/collisions between electrons and molecules):
 - Molecules in one part of a body at higher temperature vibrate faster. They collide with and transfer some of their energy to less energetic molecules located toward the cooler part of the body. In this way energy is conductively transferred from a higher-temperature region to a lowertemperature region - transfer as a result of a temperature difference.

11.1 Conduction

• *Thermal insulators* are materials that are poor conductors of heat.

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• *Non*-metals such as wood or cloth are thermal insulators. *Why*?

11.1 Conduction

- In general, *the* ability of a substance to conduct heat depends on its phase.
 - Gases are poor thermal conductors because their molecules are relatively far apart, and collisions are therefore infrequent.
 - Liquids are better thermal conductors than gases because their molecules are closer together and can interact more readily.
 - Non-metals have relatively few free electrons.

11.1 Conduction

• Heat flow through a uniform slab of material is directly proportional to its surface area, , and inversely proportional to its thickness, (Fourier's law of conduction): $Q = kA \frac{\Delta T}{L}$,

where $\frac{\Delta T}{d}$ is called the *thermal gradient* (the change in temperature per unit length), and the constant, k is called the *thermal conductivity*

11.1 Conduction

• Thermal Resistance to Conduction: *R*-Value: If you are interested in insulating your house or in keeping coke cans cold on a picnic, you are more concerned with poor heat conductors than with good ones. For this reason, the concept of thermal resistance has been introduced into engineering practice. The value of a slab of thickness is defined as $R = \frac{d}{k}.$

11.1 Conduction

- Heat: Q = C Δ T (internal energy transferred)
 - Q = amount of heat that must be supplied to raise the temperature by an amount Δ T.
 - [Q] = Joules or calories. (1 Cal = 4.186 J, 1 kcal = 1 Cal = 4186 J)
 - Energy to raise 1 g of water from 14.5 to 15.5 °C
 - (James Prescott Joule found the mechanical equivalent of heat.)
 - $C \equiv$ Heat capacity (in J/K)

11.1 Conduction

- Can we describe heat conduction quantitatively?
- *Heat* conduction is the time rate of heat flow $(Q/\Delta t)$ in a material for a given temperature difference (Δt) .
- Experiments have established that the rate of heat flow through a substance depends on the temperature difference between its boundaries.
- Heat conduction also depends on the size and shape of the object.

11.1 Conduction

- The thermal conductivity characterizes the heat-conducting ability of a material: the greater the value of *k* for a material, the more rapidly it will conduct heat.
- The SI units of thermal conductivity *k* are: J/(m s K).
- The thermal conductivity varies slightly over different temperature ranges, but can be considered constant over the usual temperature ranges and differences

11.1 Conduction

• Thus, the lower the thermal conductivity of the material of which a slab is made, the higher the *R*-value of the slab. Note that is a property attributed to a slab of a specified thickness, not to a material.

11.1 Conduction

• $Q = c m \Delta T$

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- c: specific heat (heat capacity per units of mass)
- amount of heat to raise T of 1 kg by 1 °C
- $[c] = J/(kg \circ C)$
- Sign convention: +Q : heat gained, -Q : heat lost

<mark>Latent Heat</mark>



Latent Heat

- e.g. : solid ⇔ liquid or liquid ⇔ gas (heat goes to breaking chemical bonds)
- L = Q / m
- Heat per unit mass
- [L] = J/kg
- $Q = \pm m L$
- + if heat needed (boiling)
- - if heat given up (freezing)
- Lf : Latent heat of fusion: solid \Leftrightarrow liquid
- Lv : Latent heat of vaporization: liquid \Leftrightarrow gas

Energy transfer mechanisms

- Rate of energy transfer (J / s or W)
 - Through a slab of area A and thickness Dx, with opposite faces at different temperatures, Tc and Th



• P = Q / $\Delta t = k A$ (Th - Tc) / $\Delta x k$:Thermal conductivity (J/s m °C)

11.1 Conduction

• Two identically shaped bars (one blue and one green) are placed between two different thermal reservoirs . The thermal conductivity coefficient k is twice as large for the blue as the green.



Latent Heat

- Latent heat: amount of internal energy needed to add or to remove from a substance to change the state of that substance.
- Phase change: T remains constant but internal energy changes
- Heat does not result in change in T (latent = "hidden")

Energy transfer mechanisms

- Thermal conduction (or conduction):
 - Energy transferred by direct contact.
 - e.g.: energy enters the water through the bottom of the pan by thermal conduction.



• Important: home insulation, etc.

Thermal Conductivity

Matter	J/s	Matter	J/s	Matter	J/s
	$m \circ C$		m° C		m° C
Aluminum	238	Air	0.0234	Asbestos	0.25
Copper	397	Helium	0.138	Concrete	1.3
Gold	314	Hydrogen	0.172	Glass	0.84
Iron	79.5	Nitrogen	0.0234	Ice	1.6
Lead	34.7	Oxygen	0.0238	Water	0.60
Silver	427	Rubber	0.2	Wood	0.10

11.1 Conduction

- P = Q / $\Delta t = k A (T_h T_c) / \Delta x$
- Top: $P_{green} = P_{blue} = Q / \Delta t = 2 k A (T_{high} T_j) / \Delta x = k A (T_j T_{low}) / \Delta x$
- $\bullet 2 (T_{high} T_{j}) = (T_{j} T_{low})$
- \rightarrow 3 T_{j(top)} = 2 T_{high} + T_{low}(eq.1)
- By analogy for the bottom (comparing eq.1): $3 T_{j(bottom)} = 2 T_{low} + T_{high} \dots (eq.2)$

11.1 Conduction

- 3 $T_{j(top)}$ = 2 T_{high} + T_{low} (eq.1)
- 3 $T_{j(bottom)} = 2 T_{low} + T_{high} \dots (eq.2)$
- Eq.1 Eq.2:
- 3 ($T_{j(top)}$ $T_{j(bottom)}$) = T_{high} T_{low} = 300-100 > 0 (positive) T_{joint} 300 c → The joint at upper

bar has highier Temp then lower bar.



11.1 Conduction



Temperature Distribution for a Rod

Insulated rod

- No heat escapes from the sides of the rod.
- Same quantity of heat flux flows passed a crosssection in every second.
- Since dQ/dt is constant where dQ/dt = kAdθ/dx, then the temperature gradient dθ/dx must be also constant, (same at any point along the length of the rod). Hence the line in the temperature distribution graph is a straight line that slants downwards.

Temperature Distribution for a Rod

Non-insulated rod

- Heat escapes from the sides of the rod.
- Heat flux passing through one cross-section nearer at the cold end of the rod is less then passing through another cross-section slightly further apart from the cold end.
- The quantity of heat flowing from the hot wnd through a cross-section per second gets lesser and lesser as moving along the rod towards the cold end.

11.1 Conduction

- Conduction through a composite slab
 - The energy transferred through one material in a certain time must be equal to that transferred through the other material in the same time. i.e. $P_{1,cond} = P_{2,cond}$

11.1 Conduction



-examples: "dry wall + insulation +outside wall" for your house, and "shirt + sweater + coat" for your body in the winter.

Temperature Distribution for a Rod

• Insulated rod



Temperature Distribution for a Rod

Non-insulated rod

- dQ/dt become smaller and smaller as the heat moving towards the cold end, as same as the dθ/dt.
- A curve is observed in the temperature distribution graph whose gradient decreases towards the cold end.

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Temperature Distribution for a Rod



Temperature Distribution for Composite Rod

• Insulated composite rod



Temperature Distribution for Composite Rod

• Non-insulated composite rods

Temperature







Temperature Distribution for Composite <mark>Rod</mark>

Insulated composite rod

- No heat escapes from the sides of the rods.
- Therefore $dQ/dt = -k_1A(d\theta/dx)_1 = -k_2A(d\theta/dx)_2 = = constant$
- If $k_1 > k_2$, then $(d\theta/dx)_1 < (d\theta/dx)_2$ and get line (i) in the temperature distribution graph shown in figure (a). If $k_1 > k_2$, then we get line (ii).

Temperature Distribution for Composite <mark>Rod</mark>

Non-insulated composite rods

• If the rods are not insulated, the graph of temperature distribution gives a curve as shown in figure (b).

Determination of thermal conductivity

- Thermal conductivity, k = dQ/dt, where $A = 1 \text{ m}^2$, $\theta_2 \theta_1 = 1 \text{ K}$ and x = 1 m.
- The unit of k is W m⁻¹ K⁻¹.
- Thermal conductivity of a solid is defined as the rate at which heat flows perpendicularly through unit cross-sectional area of a solid under steady condition, per unit temperature gradient along the direction of heat flow.

Determination of Thermal Conductivity of Good Conductors (Searle's Method)

- Figure above shows the apparatus used in Searle's method which is used to determine the thermal conductivity of a good conductor, such as a metal.
- The special feature of the apparatus is that the sample is in the form of a thick, long insulated rod.
- Although the rod is insulated, a little heat is lost from the sides of the rod. The rod is of large cross-sectional area, so that the rate of heat lost from the sides is negligible compared to the rate of heat flow along the rod.

Determination of Thermal Conductivity of Good Conductors (Searle's Method)

- A long rod is used, so that the larger temperature dropped across the long length of the rod can be measured accurately. A bigger temperature differences reduces the percentage error in the measurement of the temperature difference.
- Since the rod is insulated, the rate of heat flow and the temperature gradient are constant along the rod. Hence, the temperature gradient can be measured along one section of the rod, and the rate of heat flow along another section.

Determination of Thermal Conductivity of Good Conductors (Searle's Method)

- The temperature gradient, $\frac{d\theta}{dx} = \frac{(\theta_2 \theta_1)}{l}$ where l = distance between the thermometers T₁, and T₂.
- If m = mass of water collected in time
 - interval *l*, then rate of heat flow $\frac{dQ}{dt} = mc(\theta \theta)$

 $\frac{mc(\theta_2 - \theta_1)}{t}$, where c = specific heat capacity of water

Determination of Thermal Conductivity of a Poor Conductor (Lees' Method)



Determination of Thermal Conductivity of a Poor Conductor (Lees' Method)

- Since the sample is a poor conductor, for the steady state to be achieved in a short time, the sample must be thin. Heat will require a very long time to flow through a thick sample.
- On top of the sample is placed a steam chest which has a thick brass base with a hole holding a thermometer T1.

Determination of Thermal Conductivity of Good Conductors (Searle's Method)

- The end M of the rod is heated in a steam chest. Water from a constant pressure apparatus flows in a coil around the end N of the rod.
- When the steady state is attained, the readings θ1, θ1, θ1 and θ4 of the thermometers T1, T1, T1 and T4 resolutively are nolec.

Determination of Thermal Conductivity of Good Conductors (Searle's Method)

• Using is
$$\frac{dQ}{dt} = -kA\frac{d\theta}{dx}$$
,
where $A = \frac{\pi d^2}{4}$, $d = \text{diameter of rod}$
measured using a venire calipers
 $\frac{mc(\theta_4 - \theta_3)}{t} = -k\left(\frac{\pi d^2}{4}\right)\left(\frac{\theta_2 - \theta_1}{t}\right)$
• Thermal conductivity

$$k = \frac{4mc(\theta_4 - \theta_3)l}{\pi d^2 t(\theta_2 - \theta_1)}$$

Determination of Thermal Conductivity of a Poor Conductor (Lees' Method)

- A thick brass disc B with a hole holding a thermometer Z, is hung using thin suspension wires.
- The sample, in the form of a thin circular disc with the same diameter as the disc B, is placed on B.
- No lagging is required because the rate of heat loss from the sides of the thin sample is negligible. The surface area of the sides of the sample is small compared to the large crosssectional area of the sample.

Determination of Thermal Conductivity of a Poor Conductor (Lees' Method)

- Steam is allowed into the steam chest. When the readings of the thermometers T1 and T2 do not increase further but stay constant, steady state has been achieved.
- Heat flows from the steam in the steam chest through the brass base C the sample, the thick brass disc B and out from the base of disc B.

Determination of Thermal Conductivity of a Poor Conductor (Lees' Method)

- Brass is a good conductor of heat. Hence, the temperature o, at the upper surface of the circular sample is recorded by the thermometer T1. Thermometer T, records the temperature o, of the lower surface of the sample.
- The thickness, x of the sample is measured using a micrometer screw gauge. Hence, temperature gradient across the sample $\frac{d\theta}{dx} = \frac{(\theta_2 - \theta_1)}{x}$

Determination of Thermal Conductivity of a Poor Conductor (Lees' Method)



(b)

Determination of Thermal Conductivity of a Poor Conductor (Lees' Method)

- The sample is placed on top of disc B and the reading θ of the thermometer T2 recorded every 20 seconds until the reading is a few degrees below θ2.
- A graph of temperature θ against time t is plotted.
- The gradient of the graph when $\theta = \theta_{2'} \left(\frac{d\theta}{dt}\right)_{\theta_2}$ is calculated

Determination of Thermal Conductivity of a Poor Conductor (Lees' Method)

$$mc\left(\frac{dQ}{dt}\right)_{\theta_2} = -k\left(\frac{\pi D^2}{4}\right)\left(\frac{\theta_2 - \theta_1}{x}\right)$$

Thermal conductivity,

$$k = \frac{mc\left(\frac{dQ}{dt}\right)_{\theta_2}}{\left(\frac{\pi D^2}{4}\right)\left(\frac{\theta_2 - \theta_1}{x}\right)}$$

Determination of Thermal Conductivity of a Poor Conductor (Lees' Method)



Determination of Thermal Conductivity of a Poor Conductor (Lees' Method)

- The second part of the experiment is to measure the rate of heat flow achieved
- The steam chest and sample are removed.
- The brass disc B is slowly heated using a Bunsen burner until its temperature is a few degrees above θ₂ in the first part of the experiment.

Determination of Thermal Conductivity of a Poor Conductor (Lees' Method)

- Using the equation Q = mcQ• $\frac{dQ}{dt} = mc\frac{d\theta}{dt}$
- When the lower surface of the temperature is or, the rate of heat flow through the sample is $\frac{dQ}{dt} = -kA\frac{d\theta}{dx}$ where $A = \frac{\pi D^2}{4}$ D = diameter of sample

11.2 Convection

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SCHOOL OF SCIENCE AND HUMANITIES

DEPARTMENT OF PHYSICS

UNIT – V– OPTICS

Electromagnetic spectrum, the entire distribution of electromagnetic radiation according to frequency or wavelength. Although all electromagnetic waves travel at the speed of light in a vacuum, they do so at a wide range of frequencies, wavelengths, and photon energies. The electromagnetic spectrum comprises the span of all electromagnetic radiation and consists of many subranges, commonly referred to as portions, such as visible light or ultraviolet radiation. The various portions bear different names based on differences in behaviour in the emission, transmission, and absorption of the corresponding waves and also based on their different practical applications. There are no precise accepted boundaries between any of these contiguous portions, so the ranges tend to overlap.



Spectral sensitivity of the human eye

The sensitivity of the human eye to light of a certain intensity varies strongly over the wavelength range between 380 and 800 nm. Under daylight conditions, the average normal sighted human eye is most sensitive at a wavelength of 555 nm, resulting in the fact that green light at this wavelength produces the impression of highest "brightness" when compared to light at other wavelengths. The spectral sensitivity function of the average human eye under daylight conditions (photopic vision) is defined by the **CIE spectral luminous efficiency function V**(λ). Only in very rare cases, the spectral sensitivity of the human eye under dark adapted conditions (scotopic vision), defined by the spectral luminous efficiency function V'(ë), becomes technically relevant. By convention, these sensitivity functions are normalized to a value of 1 in their maximum.

As an example, the photopic sensitivity of the human eye to monochromatic light at 490 nm amounts to 20% of its sensitivity at 555 nm. As a consequence, when a source of monochromatic light at 490 nm emits five times as much power (expressed in watts) than an otherwise identical source of monochromatic light at 555 nm, both sources produce the impression of same "brightness" to the human eye. $V(\lambda), V'(\lambda)$



Fig. II.13. Spectral luminous efficiency functions $V(\lambda)$ for photopic vision and $V'(\lambda)$ for scotopic vision, as defined by the CIE.

UV Spectroscopy

- 1. Basically, spectroscopy is related to the interaction of light with matter.
- 2. As light is absorbed by matter, the result is an increase in the energy content of the atoms or molecules.
- 3. When ultraviolet radiations are absorbed, this results in the excitation of the electrons from the ground state towards a higher energy state.
- 4. Molecules containing π -electrons or non-bonding electrons (n-electrons) can absorb energy in the form of ultraviolet light to excite these electrons to higher anti-bonding molecular orbitals.
- 5. The more easily excited the electrons, the longer the wavelength of light it can absorb. There are four possible types of transitions (π - π *, n- π *, σ - σ *, and n- σ *), and they can be ordered as follows: σ - σ * > n- σ * > π - π * > n- π *
- 6. The absorption of ultraviolet light by a chemical compound will produce a distinct spectrum which aids in the identification of the compound.

Infrared (IR) Spectroscopy

- 1. Infrared Spectroscopy is the analysis of infrared light interacting with a molecule.
- 2. The portion of the infrared region most useful for analysis of organic compounds have a wavelength range from 2,500 to 16,000 nm, with a corresponding frequency range from 1.9*1013 to 1.2*1014 Hz.
- Photon energies associated with this part of the infrared (from 1 to 15 kcal/mole) are not large enough to excite electrons, but may induce vibrational excitation of covalently bonded atoms and groups.
- 4. It is known that in addition to the facile rotation of groups about single bonds, molecules experience a wide variety of vibrational motions, characteristic of their component atoms.
- 5. Consequently, virtually all organic compounds will absorb infrared radiation that corresponds in energy to these vibrations.
- 6. Infrared spectrometers, similar in principle to other spectrometer, permit chemists to obtain absorption spectra of compounds that are a unique reflection of their molecular structure.
- 7. The fundamental measurement obtained in infrared spectroscopy is an infrared spectrum, which is a plot of measured infrared intensity versus wavelength (or frequency) of light.
- IR Spectroscopy measures the vibrations of atoms, and based on this it is possible to determine the functional groups.
- Generally, stronger bonds and light atoms will vibrate at a high stretching frequency (wavenumber).

Raman Spectroscopy

Raman spectroscopy is often considered to be complementary to IR spectroscopy. For symmetrical molecules with a center of inversion, Raman and IR are mutually exclusive. In other words, bonds that are IR-active will not be Raman-active and vice versa. Other molecules may have bonds that are either Raman-active, IR-active, neither or both. Raman spectroscopy measures the scattering of light by matter. The light source used in Raman spectroscopy is a laser. The laser light is used because it is a very intense beam of nearly monochromatic light that can interact with sample molecules. When matter absorbs light, the internal energy of the matter is changed in some way. Since this site is focused on the complementary nature of IR and Raman, the infrared region will be discussed. Infrared radiation causes molecules to undergo changes in their vibrational and rotational motion. When the radiation is absorbed, a molecule jumps to a higher vibrational or rotational energy level. When the molecule relaxes back to a lower energy level, radiation is emitted. Most often the emitted radiation is of the same frequency as the incident light. Since the radiation was absorbed and then emitted, it will likely travel in a different direction from which it came. This is called Rayleigh scattering. Sometimes, however, the scattered (emitted) light is of a slightly different frequency than the incident light. This effect was first noted by Chandrasekhara Venkata Raman who won the Nobel Prize for this discovery. (6) The effect, named for its discoverer, is called the Raman effect, or Raman scattering.

Raman scattering occurs in two ways. If the emitted radiation is of lower frequency than the incident radiation, then it is called Stokes scattering. If it is of higher frequency, then it is called anti-Stokes scattering.



original ground state. The anti-Stokes scattered light has a higher frequency than the original because it started in an excited energy level but relaxed back to the ground state.

Though any Raman scattering is very low in intensity, the Stokes scattered radiation is more intense than the anti-Stokes scattered radiation. The reason for this is that very few molecules would exist in the excited level as compared to the ground state before the absorption of radiation. The diagram shown represents electronic energy levels as shown by the labels "n=". The same phenomenon, however, applies to radiation in any of the regions.

In the infrared region, methods have been developed to enhance the intensity of the scattered light in order to make Raman instruments more sensitive. One of these methods involves placing the sample on roughened gold or silver surfaces, then focusing the light on the sample. The laser light is chosen



such that it will interact with the surface particles in order to resonate, therefore increasing the intensity of the scattered light. This greatly enhances the ability to detect the scattered radiation. (7) This is called Surface Enhanced Raman Scattering or SERS. SERS has made it much more practical to detect the scattered light, making Raman a more available technique.

Introduction

An optical fiber is a flexible, transparent fiber made of high quality extruded glass or plastic, slightly thicker than a human hair. It can function as a waveguide, or light pipe to transmit light between the two ends of the fiber. The field of applied science and engineering concerned with the design and application of optical fibers is known as fiber optics. Optical fibers are widely used in fiber-optic communications, which permits transmission over longer distances and at higher bandwidths than other forms of communication. Fibers are used instead of metal wires because signals travel along them with less loss and are also immune to electromagnetic interference. Fibers are also used for illumination, and are wrapped in bundles so that they may be used to carry images, thus allowing viewing in confined spaces. Specially designed fibers are used for a variety of other applications, including sensors and fiber lasers. Optical fiber can be used as a medium for telecommunication and computer networking because it is flexible and can be bundled as cables. It is especially advantageous for long-distance communications, because light propagates through the fiber with little attenuation compared to electrical cables. This allows long distances to be spanned with few repeaters.

They are used as light guides in medical and other applications where bright light needs to be shown on a target without a clear line-of-sight path. In some buildings, optical fibers route sunlight from the roof to other parts of the building. Optical fiber is also used in imaging optics. A coherent bundle of fibers is used, sometimes along with lenses, for a long, thin imaging device called an endoscope, which is used to view objects through a small hole. Medical endoscopes are used for minimally invasive exploratory or surgical procedures. Industrial endoscopes (see fiberscope or borescope) are used for inspecting anything hard to reach, such as jet engine interiors. Many microscopes use fiber-optic light sources to provide intense illumination of samples being studied.

Principle of Optical fiber Transmission

An optical fiber is a cylindrical dielectric waveguide that transmits light along its axis, by the process of total internal reflection. The fiber consists of a core surrounded by a cladding layer, both of which are made of dielectric materials. To confine the optical signal in the core, the refractive index of the core must be greater than that of the cladding. The boundary between the core and cladding may either be abrupt, in step-index fiber, or gradual, in gradedindex fiber.

Total internal reflection

Total internal reflection is a phenomenon that happens when a propagating wave strikes a medium boundary at an angle larger than a particular critical angle with respect to the normal to the surface. If the refractive index is lower on the other side of the boundary and the incident angle is greater than the critical angle, the wave cannot pass through and is entirely reflected.

The critical angle is the angle of incidence above which the total internal reflectance occurs. This is particularly common as an optical phenomenon, where light waves are involved, but it occurs with many types of waves, such as electromagnetic waves in general or sound waves.



Fig.1.1 Diagram for the total internal reflection

The critical angle is the angle of incidence above which total internal reflection occurs. The angle of incidence is measured with respect to the normal at the refractive boundary (Fig.1.1) Consider a light ray passing from glass into air. The light emanating from the interface is bent towards the glass. When the incident angle is increased sufficiently, the transmitted angle (in air) reaches 90 degrees. It is at this point no light is transmitted into air. The critical angle θ_c is given by Snell's law,

$$n_1 \sin \theta_i = n_2 \sin \theta_t$$

Rearranging Snell's Law, we get incidence

$$\sin \theta_i = \frac{n_2}{n_1} \sin \theta_t$$

To find the critical angle, we find the value for when $\theta_t = 90^\circ$ and thus Sin $\theta_t = 1$. The resulting value of θ_i is equal to the critical angle θ_c .



Combines both Refraction and Reflection

An effect that combines both refraction and reflection is total internal reflection. Consider light coming from a dense medium like water into a less dense medium like air. When the light coming from the water strikes the surface, part will be reflected and part will be refracted. Measured with respect to the normal line perpendicular to the surface, the reflected light comes off at an angle equal to that at which it entered at, while that for the refracted light is larger than the incident angle. In fact the greater the incident angle, the more the refracted light bends away from the normal. Thus, increasing the angle of incidence from path ``1" to ``2" will eventually reach a point where the refracted angle is 90°, at which point the light appears to emerge along the surface between the water and air. If the angle of incidence is increased further, the refracted light cannot leave the water. It gets completely reflected. The interesting thing about total internal reflection is that it really is total. That is 100% of the light gets reflected back into the denser medium, as long as the angle at which it is incident to the surface is large enough.

Acceptance cone and Numerical Aperture







Acceptance angle and acceptance cone of fiber

When light traveling in an optically dense medium hits a boundary at a steep angle (larger than the critical angle for the boundary), the light is completely reflected. This is called total internal reflection. This effect is used in optical fibers to confine light in the core. Light travels through the fiber core, bouncing back and forth off the boundary between the core and cladding. Because the light must strike the boundary with an angle greater than the critical angle, only light that enters the fiber within a certain range of angles can travel down the fiber without leaking out. This range of angles is called the acceptance cone of the fiber. The size of this acceptance cone is a function of the refractive index difference between the fiber's core and cladding. In simpler terms, there is a maximum angle from the fiber axis at which light may enter the fiber so that it will propagate, or travel, in the core of the fiber. The sine of this maximum angle is the numerical aperture (NA) of the fiber. Fiber with a larger NA requires less precision to splice and work with than fiber with a smaller NA. Single-mode fiber has a small NA.

A multi-mode optical fiber will only propagate light that enters the fiber within a certain cone, known as the acceptance cone of the fiber. The half-angle of this cone is called the acceptance angle, θ_{max} . For step-index multimode fiber, the acceptance angle is determined only by the indices of refraction of the core and the cladding:

$$n\sin\theta_{\rm max} = \sqrt{n_{\rm core}^2 - n_{\rm clad}^2},$$

where n_{core} is the refractive index of the fiber core, and n_{clad} is the refractive index of the cladding. While the core will accept light at higher numerical apertures (higher angles), those rays will not totally reflect off the core–cladding interface, and so will not be transmitted to the other end of the fiber. When a light ray is incident from a medium of refractive index n to the

core of index *n*_{core} at the maximum acceptance angle, Snell's law at the medium–core interface gives

$$n\sin\theta_{\rm max} = n_{\rm core}\sin\theta_r.$$

From the geometry of the above figure we have:

$$\sin \theta_r = \sin \left(90^\circ - \theta_c\right) = \cos \theta_c$$
$$\theta_c = \sin^{-1} \frac{n_{\text{clad}}}{n_{\text{core}}}$$

Where $\theta_{c is}$ the critical angle for total internal reflection Substituting $\cos \theta_c$ for $\sin \theta_r$ in Snell's law we get:

$$\frac{n}{n_{\rm core}}\sin\theta_{\rm max} = \cos\theta_c.$$

By squaring both sides

$$\frac{n^2}{n_{\text{core}}^2} \sin^2 \theta_{\text{max}} = \cos^2 \theta_c = 1 - \sin^2 \theta_c = 1 - \frac{n_{\text{clad}}^2}{n_{\text{core}}^2}.$$

Solving, we find the formula stated above:

$$n\sin\theta_{\rm max} = \sqrt{n_{\rm core}^2 - n_{\rm clad}^2},$$

This has the same form as the numerical aperture in other optical systems, so it has become common to *define* the NA of any type of fiber to be

$$\mathrm{NA} = \sqrt{n_{\mathrm{core}}^2 - n_{\mathrm{clad}}^2},$$

Where n_{core} is the refractive index along the central axis of the fiber. Note that when this definition is used, the connection between the NA and the acceptance angle of the fiber becomes only an approximation. In particular, manufacturers often quote "NA" for single-mode fiber based on this formula, even though the acceptance angle for single-mode fiber is quite different and cannot be determined from the indices of refraction alone.

Fiber optic cable

Fiber optics uses this property of light to keep light beams focused without significant loss. The light enters the glass cable, and as long as the bending is not too sudden, will be totally internally reflected when it hits the sides, and thus is guided along the cable. This is used in telephone and cable TV cables to carry the signals. Light as an information carrier is much faster and more efficient than electrons in an electric current. Also, since light rays don't

interact with each other (whereas electrons interact via their electric charge), it is possible to pack a large number of different light signals into the same fibre optics cable without distortion. You are probably most familiar with fibre optics cables in novelty items consisting of thin, multi-coloured strands of glass which carry light beams.



Propagation of light ray through Optical fiber

Fibre Geometry

This cylinder is known as the core of the fiber. The core is surrounded by a solid dielectric called cladding which has a refractive index n_2 that is less than n_1 . Although, in principle, a cladding is not necessary for light to propagate along the core of the fiber, it serves several purposes. (a)The cladding reduces scattering loss that results from dielectric discontinuities at the core surface, (b) it adds mechanical strength to the fiber, and (c) it protects the core from absorbing surface contaminants with which it could come in contact.



Geometry of Optical Fiber

The fiber must be cabled - enclosed within a protective structure. This usually includes strength members and an outer jacket. The most common strength member is Kevlar aramid yarn, which adds mechanical strength. During and after installation, strength members provide crush resistance and handle the tensile stresses applied to the cable so that the fiber is not damaged. Steel and fiberglass rods are also used as strength members in multifiber bundles. It
consists of a dielectric core (usually doped silica) of high refractive index surrounded by a lower refractive index cladding (fig.1.5).

Types of Rays

Two types of rays can propagate along an optical fiber. The first type is called meridional rays. Meridional rays are rays that pass through the axis of the optical fiber. Meridional rays are used to illustrate the basic transmission properties of optical fibers. The second type is called skew rays. Skew rays are rays that travel through an optical fiber without passing through its axis. Meridional rays can be classified as bound or unbound rays. Bound rays remain in the core and propagate along the axis of the fiber. Bound rays propagate through the fiber by total internal reflection. Unbound rays are refracted out of the fiber core. Fig.1.6 shows a possible path taken by bound and unbound rays in a step-index. Skew rays are not confined to a single plane, but instead tend to follow a helical-type path along the fiber as shown in Fig.1.6. These rays are more difficult to track as they travel along the fiber, since they do not lie in a single plane.

Light injected into the core and striking the core-to-cladding interface at an angle greater than the critical angle will be reflected back into the core. Since angles of incidence and reflection are equal, the light ray continues to zig-zag down the length of the fiber shown in fig 1.6. The light is trapped within the core. Light striking the interface at less than the critical angle passes into the cladding and is lost.



Types of rays

Rays of light do not travel randomly. They are channeled into modes, which are possible paths for a light ray traveling down the fiber. A fiber can support as few as one mode and as many as tens of thousands of modes. While we are normally not interested in modes per se, the number of modes in a fiber is significant because it helps determine the fiber's bandwidth. More modes typically mean lower bandwidth. The reason is dispersion.

As a pulse of light travels through the fiber, it spreads out in time. While there are several reasons for such dispersion, two are of principal concern. The first is modal dispersion,

which is caused by different path lengths followed by light rays as they bounce down the fiber. Some rays follow a more direct route than others. The second type of dispersion is material dispersion: different wavelengths of light travel at different speeds. By limiting the number of wavelengths of light, you limit the material dispersion. Dispersion limits the bandwidth of the fiber. At high data rates, dispersion will allow pulses to overlap so that the receiver can no longer distinguish where one pulse begins and another ends.

Classification of fibers on the basis of materials

Generally, optical fibers are made up of materials like silica and plastic. Therefore, there are two different types of fibers namely glass and plastic fibers. The most important properties required for the selection of optical fibers are that the materials should be an efficient guide for light waves: it should have low scattering cross section and low loss of optical energy due to the absorption, attenuation and dispersion during the propagation of waves.

Glass fiber

Glass optical fibers are almost always made from silica, Silica and fluoride glasses usually have refractive indices of about 1.5, but some materials such as the chalcogenides can have indices as high as 3. Typically the index difference between core and cladding is less than one percent.

Plastic Fiber

Plastic fiber optic differs from single-mode and multi-mode fiber optic because the cables are made of plastic instead of glass. Therefore, plastic fiber optic is generally not used to transmit data because it does not have the capability to offer reliable data transmission. Instead plastic fiber optic is used to create impressive light displays and other ornamental purposes. Technology specialists have experimented with plastic fiber optic for data transmission because it is easier to install and work with, however the results so far have been inconclusive as to whether it can be a possible alternative to traditional fiber optic cable connections.

Classification of fibers based on number of modes

Understanding the characteristics of different fiber types aides in understanding the applications for which they are used. Operating a fiber optic system properly relies on knowing what type of fiber is being used and why. There are two basic types of fiber: multimode fiber optic cable and single-mode fiber optic cable. Multimode fiber is best designed for short

transmission distances, and is suited for use in LAN systems and video surveillance. Singlemode fiber is best designed for longer transmission distances, making it suitable for longdistance telephony and multichannel television broadcast systems



Single and multimode fiber

Single-Mode Fiber

A single-mode fiber optic connection is used for longer cable runs due to the fact that it only allows for a single stream of data flow. The single stream of data is transmitted through a single light pulse which carries a significant amount of bandwidth providing for a faster transmission of data. Single-mode fiber optic is used for Ethernet connections that require long distances for data transmission.

Multi-Mode Fiber

In a multimode fibre, the core diameter is much bigger than the wavelength of the transmitted light. A number of modes can be simultaneously transmitted. Fibre modes are related to the possible ways the light travels inside the fibre. The primary mode travels parallel to the axis of the fibre and therefore takes the minimum time to reach the end of the fibre. When the incoming beam enters with an angle respect to the fibre axis, the light will follow a longer path and therefore will take longer to reach the end. The number of modes that can be transmitted along the fibre increases with the core diameter.

Multimode fibres may be divided in step and gradient index. In step index fibres the refraction index of the core is constant and the light travels in straight paths. In gradient index fibres the refraction index decreases gradually (parabolic) from the core out through the cladding and therefore the light travels along smooth curves.



Step and Graded Index Fiber with diameter

Classification of fibers based on refractive index profile

Step index fiber

For an optical fiber, a step-index profile is a refractive index profile characterized by a uniform refractive index within the core and a sharp decrease in refractive index at the corecladding interface so that the cladding is of a lower refractive index. The step-index profile corresponds to a power-law index profile with the profile parameter approaching infinity. The step-index profile is used in most single-mode fibers and some multimode fibers.

Step index fibres are the most used fibres in fields other than telecommunications. They are relatively cheap and they have the widest range of core diameters: basically from 50 µm up to 2mm. The material may be plastic, liquid or glass. Plastic fibres are not wide used nowadays; their optical transmission is poor and the core relatively big (0.5 to 2 mm). The most efficient fibres are made in acrylic and they are mainly used for short length telecommunication networks. In spite of their limited performances, new developments in plastic fibres might open applications in the field of high speed home networks (Gigabit/s). New polymers are being proposed with attenuations approaching the silica fibres. Most common step index fibres are made in silica glass (core and cladding) because of its high optical transmission in a very broad spectral range.

Graded index fiber

In fiber optics, a graded-index or gradient-index fiber is an optical fiber whose core has a refractive index that decreases with increasing radial distance from the optical axis of the fiber. Because parts of the core closer to the fiber axis have a higher refractive index than the parts near the cladding, light rays follow sinusoidal paths down the fiber. The most common refractive index profile for a graded-index fiber is very nearly parabolic. The parabolic profile results in continual refocusing of the rays in the core, and minimizes modal dispersion. Multi-mode optical fiber can be built with either graded index or step index. The advantage of the graded index compared to step index is the considerable decrease in modal dispersion. In the simplest optical fiber, the relatively large core has uniform optical properties. Termed a step-index multimode fiber, this fiber supports thousands of modes and offers the highest dispersion - and hence the lowest bandwidth.



Multimode fiber

By varying the optical properties of the core, the graded-index multimode fiber reduces dispersion and increases bandwidth. Grading makes light following longer paths travel slightly faster than light following a shorter path. Put another way, light traveling straight down the core without reflecting travels slowest. The net result is that the light does not spread out nearly as much. Nearly all multimode fibers used in networking and data communications have a graded index.



Step and Graded Index Fiber with loss

But the ultimate in high-bandwidth, low-loss performance is single mode fiber. Here the core is so small that only a single mode of light is supported. The bandwidth of a single mode fiber far surpasses the capabilities of today's network electronics. Indeed, the information-carrying capacity of the fiber is essentially infinite. Not only can the fiber support speeds of tens of gigabits per second, it can carry many gigabit channels simultaneously. This is done by having each channel carried by a different wavelength of light. The wavelengths do not interfere with one another. Singlemode fiber is the preferred medium for long distance telecommunications. It finds use in networks for interbuilding runs and will eventually become popular for high-speed backbones. Applications for singlemode fiber to the desk are not anticipated.

Fiber Properties

Numerical aperture (NA)

Numerical aperture (NA) of the fiber defines which light will be propagated and which will not NA defines the light-gathering ability of the fiber. Imagine a cone coming from the core. Light entering the core from within this cone will be propagated by total internal reflection. Light entering from outside the cone will not be propagated.



Low and High NA and bandwidth in Optical fiber

A high NA gathers more light, but lowers the bandwidth. A lower NA increases bandwidth. NA has an important consequence. A large NA makes it easier to inject more light into a fiber, while a small NA tends to give the fiber a higher bandwidth. A large NA allows greater modal dispersion by allowing more modes in which light can travel. A smaller NA reduces dispersion by limiting the number of modes

Advantages of single mode and multimode fiber

Although single-mode fiber hasadvantages for longer distances (> 550 meters at 10 Gb/s), multimodefiber easily supports most distances required for enterprise networks and data centers. In fact, multimode fibercan support 100 Gb/s transmission to150 meters, supporting the vastmajority of data center links. Furthermore, the optoelectronics commonly used with multimode fiber areless expensive than those required for single-mode system. And multimode fiber is easier to install andterminate in the field - important considerations in enterprise environments with frequent moves, adds, and changes.

Fiber optical communication system

An optical fiber communication system uses light as a carrier. It is used to transfer a message from a source to distant recipient.

Principle of optical fiber communication

The basic principle of optic fiber communication is the transmission of information over the required distance by the propagation of optical signal through optical fiber. It involves deriving an optical signal from electrical signal at the transmitting end and converting the optical signal back to the electrical signal at the receiving end.

Description

The main parts of a fiber optic communication system are,

- (i) Information signal source
- (ii) Transmitter and Light source
- (iii) Propagation medium
- (iv) Photo detector
- (v) Receiver



Block Diagram of fiber optic communication

(i) Information Signal Source

The information signal source may be voice, music, digital data or analog voltage and video signal. Here it is analog information.

(ii) Transmitter and light source

The transmitter consists of a drive circuit and a light source. The drive circuit transfers the electric input signal into digital pulses and the light source converts that input optical pulses. The light source is usually LED/LASER. Here the electric pulses moderate the intensity if the light source and are focused on to the optical fiber.

(iii) Propagation medium

Optical fiber acts as a waveguide and transmits the optical pulses towards the receiver by the principle of total internal reflection.

(iv) Photo detector

It detects optical energy and converts it into an electrical signal.

(v) Receiver

It consists of a photo detector, an amplifier and a signal restoring circuit. It converts an optical signal back into an electrical signal.

Working

Initially telephone user produces a signal in analog form. This analog signal converted into digital signal, which is in the form of electrical pulse. These electrical pulses are transformed into an optical signal with the help of optical transmitter. In the optical transmitter electrical signal is modulated and carried by an optical source this optical signal is fed into the fiber. At the receiving end, the optical signal travelling through the fiber is fed into a photo detector. The photo detector detects the optical signal and converts it into pulses of electric current. The digital signal is once again converted into analog signal. This analog signal contains the same information which is transferred from the transmitter end.

Features

- (i) It is light in weight
- (ii) It is easy to manage
- (iii) It is non conducting and non radiating
- (iv) There is no short circuiting
- (v) It can withstand to any range of temperature and moisture condition.

Advantageous Of Optical Fibers Communication:

- 1. Information bandwidth is more.
- 2. Optical fibers are small in size and light weighted.
- 3. Optical fibers are more immune to ambient electrical noise, electromagnetic interference.
- 4. Cross talk and internal noise are eliminated in optical fibers.
- 5. There is no risk of short circuit in optical fibers.
- 6. Optical fibers can be used for wide range of temperature.
- 7. Optical fibers are cheaper than copper cables.

8. Optical fibers are having less transmission loss and hence less number of repeaters are used.

9. Optical fibers are more reliable and easy to maintain.

Disadvantageous Of Optical Fibers Communication:

- 1. Attenuation offered by the optical fibers depends upon the material by which it is made.
- 2. Complex electronic circuitry is required at transmitter and receiver.
- 3. The coupling of optical fibers is difficult.
- 4. Skilled labors are required to maintain the optical fiber communication.
- 5. Separated power supply is required for electronic repeaters at different stages.

Problems

1. Estimate the critical angle when the core refractive index is 1.5 and the refractive index is 1.8%.

Given

 Δ =1.8% and μ_1 =1.5; θ_c =?

Solution:

To find θ_c : $\Delta = (\mu_2 - \mu_1)/\mu_1$ $\mu_2/\mu_1 = 0.982$ $\theta_c = \sin^{-1}(\mu_2/\mu_1)$ $= 79^\circ 06'$

A fibre has a diameter of 5 μm and its core refractive index is 1.5 and for cladding is
 1.45. How many modes can propagate into the step index fiber if the wave length of the source is 2 μm.

Given

d = $5x10^{-6}$ m ; λ = $2x10^{-6}$ m; μ_1 = 1.5 and μ_2 = 1.45

Solution:

To find number of modes (N):

N_{Step}=4.9 [d*NA/ λ]² [N_{Grad} = N_{Step}/2] NA= (μ_1^{2} - μ_2^{2})^{1/2} NA= 0.3841 N ≈ 5 modes

3. A signal of 80 mW is injected into a fiber of length 1m. The outcoming signal from the other end is 60 m. Find the loss in dB.

Given

L=1m; P_i=80 mW; P_o=60 mW; Loss (α)=?

Solution:

To find Loss:

 α = (-) 10/L log (P_i/ P_o)

4. Calculate the refractive indices of core and cladding of an optical fiber if its numerical aperture is 0.22 and relative refractive index difference is 0.012.

```
Given
NA=0.22; \Delta= 0.012 and \mu_1(\mu_2) =?
Solution:
To find \mu_1 and \mu_2:
\mu_1 = NA / (2\Delta)^{1/2}
= 1.4201
\mu_2 = \mu_1 (1- \Delta)
= 1.4031.
```

Part B

- 1. Explain the propagation of light through optical fiber and the application of optical fiber as waveguide and sensor.
- 2. Classify the optical fiber on the basis of material, modes of propagation and refractive index difference.
- Define numerical aperture and derive an expression for numerical aperture and angle of acceptance of fiber in terms of refractive index of core and fiber. Mention six advantages of optical fibre for communication as a wave guide.
- 4. Describe crucible-crucible technique for manufacturing an optical fiber.
- 5. Describe vapour phase deposition technique for manufacturing an optical fiber
- 6. Describe the losses that occur in fiber optic communication and give the remedies for it.
- 7. Explain with neat block diagram, the basic instrumentation technique adopted to explain the fiber optic communication link.

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