CHAPTER 5

MAGNETISM AND MATTER

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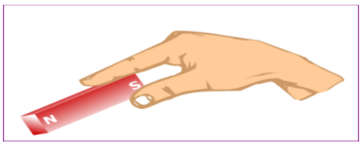
INTRODUCTION

- Chinese sailors employed magnets as navigational compasses approximately 900 years ago.
- Electric generators, simple electric motors, television sets, cathode-ray displays, tape recorders, and computer hard drives all depend on the magnetic effects of electric currents.

The Bar Magnet

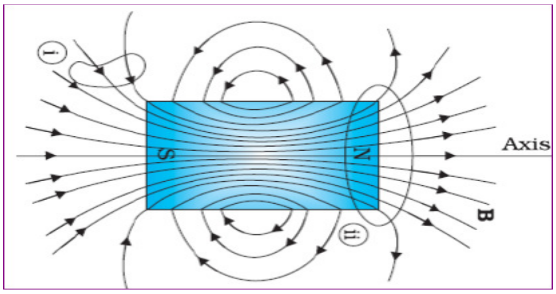


Properties of a Magnet

- When a bar magnet is freely suspended, it points in the north-south direction.
- Like poles of the magnet repels and unlike poles attracts.
- If a bar magnet is broken into two halves, we get two similar bar magnets with somewhat weaker properties.
- *Magnetic monopoles do not exist.*
- It is possible to make magnets out of iron and its alloys.
- Magnetic strength is higher at the poles.
- If a magnet is cut longitudinally into two halves pole strength and magnetic moment become half.
- If a magnet is cut transversely in to two equal halves pole strength does not change but the magnetic moment becomes half.

Magnetic Field Lines

- The magnetic field lines of a bar magnet is as shown in figure



Properties of Magnetic Field Lines

- The magnetic field lines are continuous closed loops.
- Two magnetic field lines never intersect.
- The number density of field lines in a region gives the intensity of magnetic field.
- The tangent drawn to the field line at any point gives the direction of the field at that point.

Difference between electric field lines and magnetic field lines

- Magnetic field lines are continuous closed loops.
- But electric field lines do not form closed loops.

Expression for the magnetic field on the axial line of a bar magnet

$$B = \frac{\mu_0}{4\pi}\frac{2m}{r^3}$$

Where m - magnetic moment , r – distance to the point

Expression for the magnetic field on the equatorial line of a bar magnet

$$B = \frac{\mu_0}{4\pi}\frac{m}{r^3}$$

Magnetic dipole

- Two equal and opposite magnetic poles separated by a distance is called a magnetic dipole

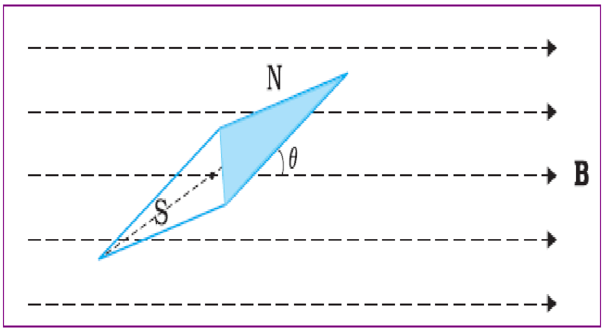
Magnetic Dipole Moment (m)

- Magnetic dipole moment is the product of pole strength and distance between the poles.

m = P × 2l where ,P - the pole strength

- The S.I unit of pole strength is **Am**.
- The SI unit of magnetic dipole moment is **Am^2**
- Magnetic dipole moment is a vector quantity.
- The direction is from South Pole to North Pole.

Magnetic dipole placed in a uniform magnetic field



- The torque on the needle is τ = m × B
- If I is the moment of inertia , then the restoring torque is given by

$$\tau = I\frac{d^2\theta}{dt^2} = -\,mB\sin\theta$$

- For small values of θ in radians, sin θ ≈ θ
- Thus $\tau = I\frac{d^2\theta}{dt^2} = -\,mB\theta$
- Then the magnetic dipole executes simple harmonic motion(SHM)
- The time period is given by

$$\mathbf{T = 2\pi\sqrt{\frac{I}{mB}}}$$

- Frequency,

$$\nu = \frac{1}{2\pi}\sqrt{\frac{mB}{I}}$$

To find the magnetic field at a place

- B can be determined by oscillating a magnetic needle of known magnetic moment (m) and moment of inertia I.

$$T^2 = 4\pi^2\frac{I}{mB}$$

$$\Rightarrow \mathbf{B = \frac{4\pi^2 I}{mT^2}}$$

- Using the above equation, we can calculate the magnitude of the external magnetic field 'B'.

Potential energy of a magnetic dipole in an external uniform magnetic field

- The magnetic potential energy *is given by*

$$U_m = \int \tau(\theta)d\theta$$

$$= \int mB\sin\theta = -mB\cos\theta$$

$$= -\mathbf{m}\cdot\mathbf{B}$$

Special cases:-

- When θ = 0 degree , Um = -mB cos 0 = -mB (PE is minimum) - this is the most stable position
- when θ = 180 degree ,Um = -mB cos 180 = -mB × -1 = mB (maximum) -this is the most unstable position.

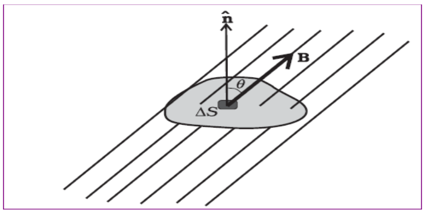
Comparison between Electrostatics and Magnetism

	Electrostatics	Magnetism
	$1/\varepsilon_0$	μ_0
Dipole moment	**p**	**m**
Equatorial Field for a short dipole	$-\mathbf{p}/4\pi\varepsilon_0 r^3$	$-\mu_0\,\mathbf{m}/4\pi r^3$
Axial Field for a short dipole	$2\mathbf{p}/4\pi\varepsilon_0 r^3$	$\mu_0\,2\mathbf{m}/4\pi r^3$
External Field: torque	**p x E**	**m x B**
External Field: Energy	**-p·E**	**-m·B**

Gauss's Law in magnetism

- The law states that "**the net magnetic flux through any closed surface is zero**"

$$\phi_B = \sum_{'all'} \Delta\phi_B = \sum_{'all'} \mathbf{B} \cdot \Delta\mathbf{S} = 0$$



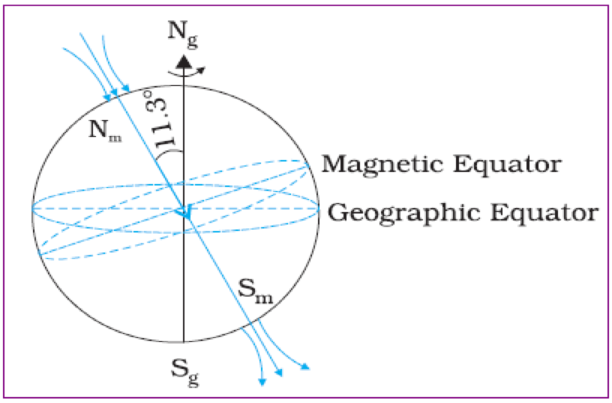
Earth's Magnetism

- Earth has an immense magnetic field surrounding it and is of the order of 10^{-5} T.
- The location of the north magnetic pole is at latitude of 79.74^0 N and a longitude of 71.8^0 W, a place somewhere in north Canada.
- The magnetic South Pole is at 79.74^0 S, 108.22^0 E in the Antarctica.

Source of Earth's Magnetism – Dynamo Effect

- Earth's magnetism is due to the electric currents produced by the convective motion of metallic fluids (consisting mostly of metallic iron and nickel) in the outer core of earth. This is known as **Dynamo Effect**.

Magnetic Meridian



- A vertical plane passing through the magnetic axis of a freely suspended magnet is called the magnetic meridian.

Geographic Meridian

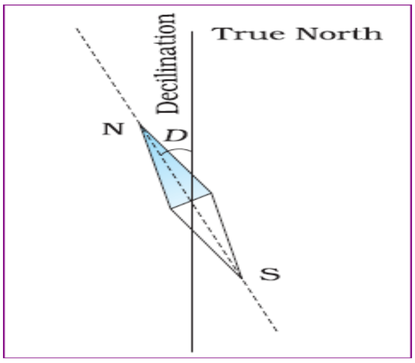
- The vertical plane passing through a place and the geographic north and south poles is called the geographic meridian at that place.

Elements of earth's magnetism

The three elements of earth's magnetic field are

- **Angle of declination (D)**
- **Angle of Dip or inclination (I)**
- **Horizontal component of earth's magnetic field (BH)**

Magnetic Declination

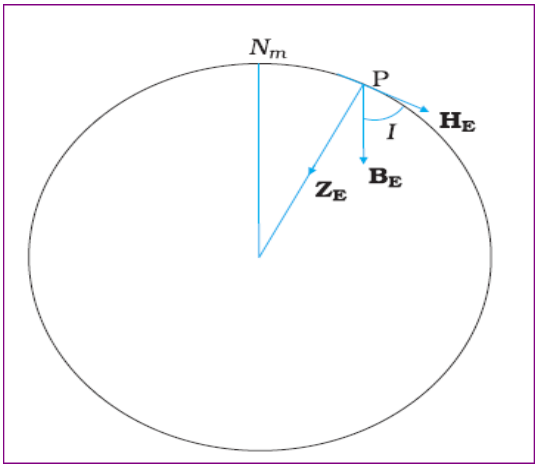


- The angle between the geographic meridian and magnetic meridian is called the angle of declination.
- The magnetic declination is different at different places on the surface of earth.
- The declination is greater at higher latitudes and smaller near the equator.
- The declination in India is small, it being $0^0 41'$ E at Delhi and $0^0 58'$ W at Mumbai.

Dip or Inclination

- Dip is the angle that the total magnetic field B_E of the earth makes with the surface of the earth.

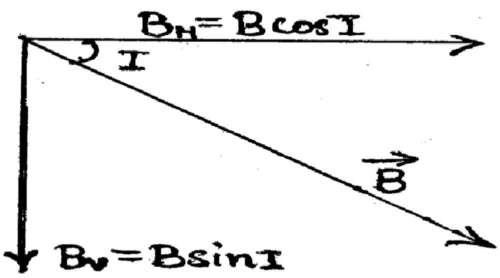
- The angle of dip is maximum (90 degree) at the magnetic poles and minimum (0 degree) at the magnetic equator.
- At other places its value lies between 0 degree and 90 degree.



- In most of the northern hemisphere, the north pole of the dip needle tilts downwards.
- In most of the southern hemisphere, the south pole of the dip needle tilts downwards

<u>Horizontal Component of earth's magnetic field</u>

- The total magnetic field at P can be resolved into *a horizontal component* B_H and a vertical component B_V.



<u>Relation Connecting Horizontal component and vertical component</u>

- We have $B_H = B\cos I$ and $B_V = B\sin I$
- Thus $\tan I = B_V / B_H$
- Also

$$B = \sqrt{B_H^2 + B_V^2}$$

<u>Some Important Terms</u>

<u>Magnetistion or Intensity of Magnetisation (M)</u>

- *Magnetisation M* of a sample is the net magnetic moment per unit volume, when the sample is subjected to magnetizing field.

$$\mathbf{M} = \frac{\mathbf{m}_{net}}{V}$$

- M is a vector with dimensions $L^{-1}A$ and is measured in a units of $A\ m^{-1}$.

<u>Magnetic Intensity or Magnetising Field (H)</u>

- When a magnetic material is placed in a magnetic field, magnetism is induced in the material. It is known as induced magnetism.
- The field which induces magnetism in a material is called magnetizing field and the strength of that field is called magnetic intensity (H).
- Its SI unit is ampere/ metre
- The magnetizing field is given by

$$\mathbf{H} = \frac{\mathbf{B}}{\mu_0} - \mathbf{M}$$

where, B – net magnetic field, M – Magnetistion, μ_0-permeability of free space

<u>Relation connecting B , M and H</u>

- The total magnetic field B is written as ,

$$\mathbf{B = \mu_0 (H + M)}$$

<u>Relation connecting M and H</u>

- The dependence of M on H is given by $M = \chi H$, Where χ – Magnetic susceptibility

<u>Magnetic susceptibility</u>

- *Magnetic susceptibility* is a measure of how a magnetic material responds to an external field.

- It is *small* and *positive* for *paramagnetic materials*
- *It is small and negative for diamagnetic* materials

Relation connecting B , μ and H

- We have $B = \mu_0 (H + M)$
- Substituting $M = \chi H$, we get

  $$B = \mu_0 (H + \chi H) = \mu_0 H(1+\chi) ,$$

  $$\mathbf{B} = \mu_0 (1+\chi)\mathbf{H} = \mu_0 \mu_r \mathbf{H} = \mu \mathbf{H}$$

- **Thus**
- **where $\mu_r = 1 + \chi$, is a dimensionless quantity called the *relative magnetic permeability of the substance.***
- **The *magnetic permeability of the substance is μ and it has* the same dimensions and units as μ_0**

  $$\mu = \mu_0 \mu_r = \mu_0 (1+\chi)$$

Magnetic permeability (μ)

- It is the ratio of magnetic field to the magnetizing field

  $$\mu = \frac{B}{H}$$

- Its unit is tesla meter/ampere (TmA^{-1})

Relative permeability of medium

- Relative permeability of medium is the ratio of permeability of a medium (μ) to the permeability of air or vacuum (μ_0)

  $$\mu_r = \frac{\mu}{\mu_o}$$

- Also $\mu_r = (1+\chi)$

Magnetic Flux (ϕ)

- It is the number of magnetic field lines passing normally through a surface.
- The SI unit is weber(Wb)

Classification of Magnetic Materials

On the basis of the behavior in an external magnetic field materials can be classified as

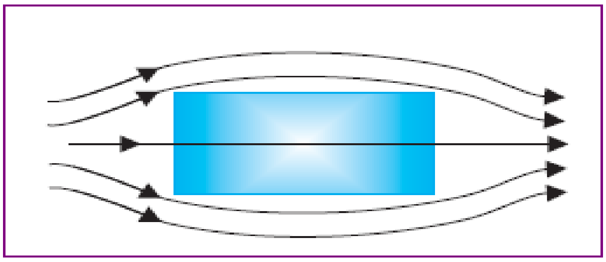
- ***Diamagnetic materials***
- ***Paramagnetic materials***
- ***Ferromagnetic materials***

Diamagnetic	Paramagnetic	Ferromagnetic
$-1 \le \chi < 0$ $0 \le \mu_r < 1$ $\mu < \mu_0$	$0 < \chi < \varepsilon$ $1 < \mu_r < 1+\varepsilon$ $\mu > \mu_0$	$\chi >> 1$ $\mu_r >> 1$ $\mu >> \mu_0$

Diamagnetic materials

- These are substances which experiences weak force of repulsion in a magnetic field.
- The atoms or molecules of a diamagnetic material have no magnetic moments in the absence of external magnetic field.
- The diamagnetic substance develops a net magnetic moment in direction opposite to that of the applied field and hence repulsion
- When freely suspended in a magnetic field it aligns perpendicular to the magnetic field
- Egs:- bismuth, copper, lead, silicon, nitrogen (at STP), water and sodium chloride, glass, marbles, diamond, gold, mercury, silver, zinc, alkali halides etc.

A diamagnetic substance kept in a magnetic field



Superconductors

- These are materials, cooled to very low temperatures which exhibits both *perfect conductivity and perfect diamagnetism.*
- For a super conductor $\chi = -1$ and $\mu_r = 0$.
- Superconducting magnets are used in magnetically levitated superfast trains

Meissner effect

- The phenomenon of perfect diamagnetism in superconductors is called the ***Meissner effect.***

Paramagnetic materials

- These are the substances which experiences a weak force of attraction in a magnetic field
- Paramagnetic substances are those which get weakly magnetized when placed in an external magnetic field.
- The atoms or molecules of a paramagnetic substance have a certain magnetic moment in the absence of external magnetic field.
- In a non-uniform magnetic field, they tend to move from weaker to stronger part of the field.
- When freely suspended in a magnetic field, it aligns parallel to the magnetic field.
- In a uniform magnetic field, a weak magnetisation is induced in the direction of magnetic field
- Egs: aluminium, sodium, calcium,oxygen (at STP) and copper chloride, chromium , lithium, Magnesium, niobium, Platinum, tungsten.
- The individual atoms (or ions or molecules) of a paramagnetic material possess a permanent magnetic dipole moment of their own.
- In the presence of an external field B_0 ,at low temperatures, the individual atomic dipole moment can be made to align and point in the same direction as B_0.

Curie's law

- The magnetization of a paramagnetic material is inversely proportional to the absolute temperature *T.*

$$M = C\frac{B_0}{T}$$

- The constant *C is called **Curie's constant.***
- Or

$$\chi = C\frac{\mu_0}{T}$$

, since M= χH

- As the field is increased or the temperature is lowered, the magnetisation increases until it reaches the saturation value *Ms, at which point all the dipoles are* perfectly aligned with the field. Beyond this, Curie's law is no longer valid.

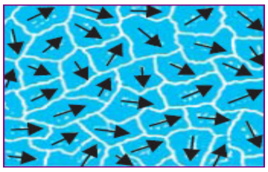
Ferromagnetic materials

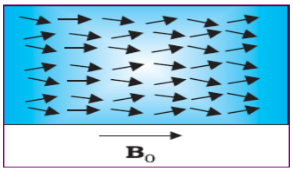
- Ferromagnetic substances are those which gets strongly magnetised when placed in an external magnetic field.
- In a non-uniform magnetic field ferromagnetic material tends to move from weaker to stronger part of the field.
- When freely suspended in a magnetic field, a ferromagnetic material aligns parallel to the magnetic field.
- In a uniform magnetic field, it acquires a large magnetization in the direction of field.
- Egs:- iron, cobalt, nickel, gadolinium,etc.

Origin of Ferromagnetism

- The individual atoms (or ions or molecules) in a ferromagnetic material interact with one another and align themselves in a common direction over a macroscopic volume called ***domain.***

- Each domain has a net magnetisation.
- Typical domain size is 1mm and the domain contains about 10^{11} atoms.





Hard ferromagnetic materials

- The ferromagnetic materials the magnetisation persists even after the removal of external magnetic field are called hard ferromagnetic materials.
- Egs: ***Alnico,*** *an alloy of iron, aluminium, nickel, cobalt* and copper
- Hard ferromagnetic materials are used to make permanent magnets.

Soft ferromagnetic materials

- Materials in which the magnetisation disappears on removal of the external field are called ***soft ferromagnetic materials***.
- Eg: soft iron

Temperature dependence of ferromagnetic materials

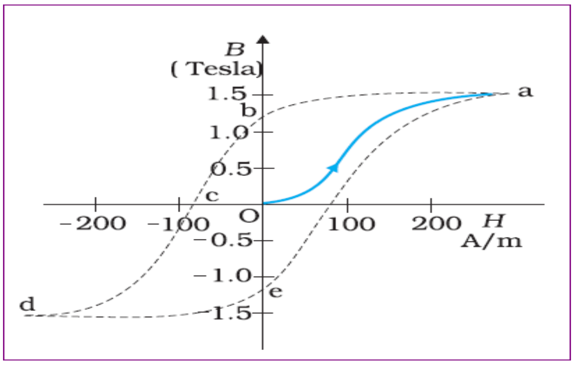
- Ferromagnetic materials lose their magnetism with rise of temperature.
- The temperature at which a ferromagnetic substance gets converted into a paramagnetic substance is called **Curie temperature** or transition temperature.
- The susceptibility above the curie temperature ie, in the paramagnetic phase is given by

$$\chi = \frac{C}{T - T_c} \quad (T > T_c)$$

Magnetic Hysteresis

- When a ferromagnetic sample is placed in a magnetising field, the sample gets magnetized.
- ***The lagging of magnetic induction (B) behind the magnetic intensity (H) is called magnetic hysteresis***.

B-H curve of a ferromagnetic material



- The closed curve **abcdea** which represents a cycle of magnetisation of a ferromagnetic sample is called its ***hysterisis loop.***

Retentivity or Remanence

- The value of magnetic field *B at magnetizing field H = 0, for a ferromagnetic substance is called* ***retentivity or remanence.***
- The magnetic induction (B) left in the material, when the magnetic intensity (**H**) is reduced to zero is called retentivity or residual magnetism.

Coercivity

- The value of magnetizing field H at magnetic field B=0 is called **coercivity.**
- The magnetic intensity (H) that must be applied in the opposite direction so as to cancel the residual magnetism is called coercivity.

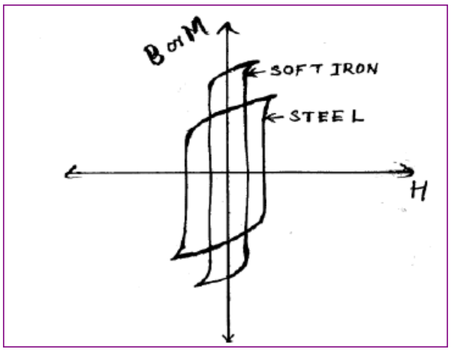
Area of the Hysterisis Loop

- The area within the B-H loops represents the ***energy dissipated per unit volume*** in the material when it is carried through a cycle of magnetization.
- **$BH = B (B/ \mu) = B^2 / \mu_0 \mu_r$**

Importance of hysterisis loops

- A study of hysterisis loop provides us information about retentivity , coercivity and hysterisis loss of magnetic material.
- It helps in proper selection of materials for designing cores of transformers and electromagnets and in making permanent magnets.
- Area of the hysteresis loop gives an idea about the energy loss.
- Helps to select materials used for making core of transformers, electromagnets, permanent magnets etc.

Hysteresis loops of soft iron and steel



Permanent magnets

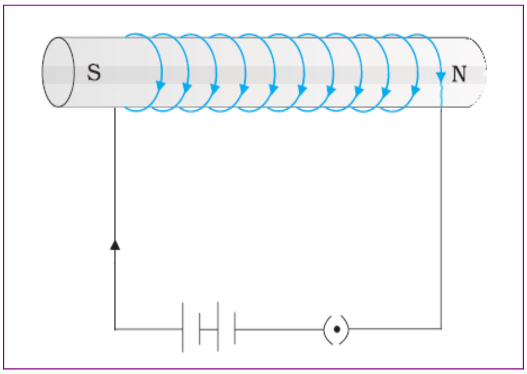
- Substances which at room temperature retain their ferromagnetic property for a long period of time are called ***permanent magnets.***

Properties of permanent magnet

- High retentivity
- **High coercivity**
- **Large area for hysteresis loop**
- High permeability
- Eg: steel, Alnico, cobalt steel, ticonal.

Electromagnets

- ***Electromagnets are used*** in electric bells, loudspeakers and telephone diaphragms.
- Giant electromagnets are used in cranes to lift machinery, and bulk quantities of iron and steel.



Properties of electromagnets

- Low retentivity
- Low coercivity
- Small area for hysteresis loop
- High permeability
- Eg:- soft iron

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