Chapter 5

Magnetism and Matter

5.1 Introdution

The word magnet is derived from the name of an island in Greece called magnesia where magnetic ore deposits were found, as early as 600 BC.

Some of the commonly known ideas regarding magnetism are:

- The earth behaves as a magnet with the magnetic field pointing approximately from the geographic south to the north.
- When a bar magnet is freely suspended, it points in the north-south direction. The tip which points to the geographic north is called the north pole and the tip which points to the geographic south is called the south pole of the magnet.
- Similar poles repel and opposite poles attract.
- We cannot isolate the north, or south pole of a magnet. If a bar magnet is broken into two halves, we get two similar bar magnets with somewhat weaker properties. Unlike electric charges, isolated magnetic north and south poles known as magnetic monopoles do not exist.
- It is possible to make magnets out of iron and its alloys

5.2 The Bar Magnet

The magnet has two poles similar to the positive and negative charge of an electric dipole -one pole is designated the North pole and the other, the South pole. When suspended freely, these poles point approximately towards the geographic north and south poles, respectively.

The arrangement of iron filings surrounding a bar magnet. The pattern mimics magnetic field lines. The pattern suggests that the bar magnet is a magnetic dipole. A similar pattern of iron filings is observed around a current carrying solenoid.

The Magnetic Field Lines

- The magnetic field lines of a magnet (or a solenoid) form continuous closed loops.

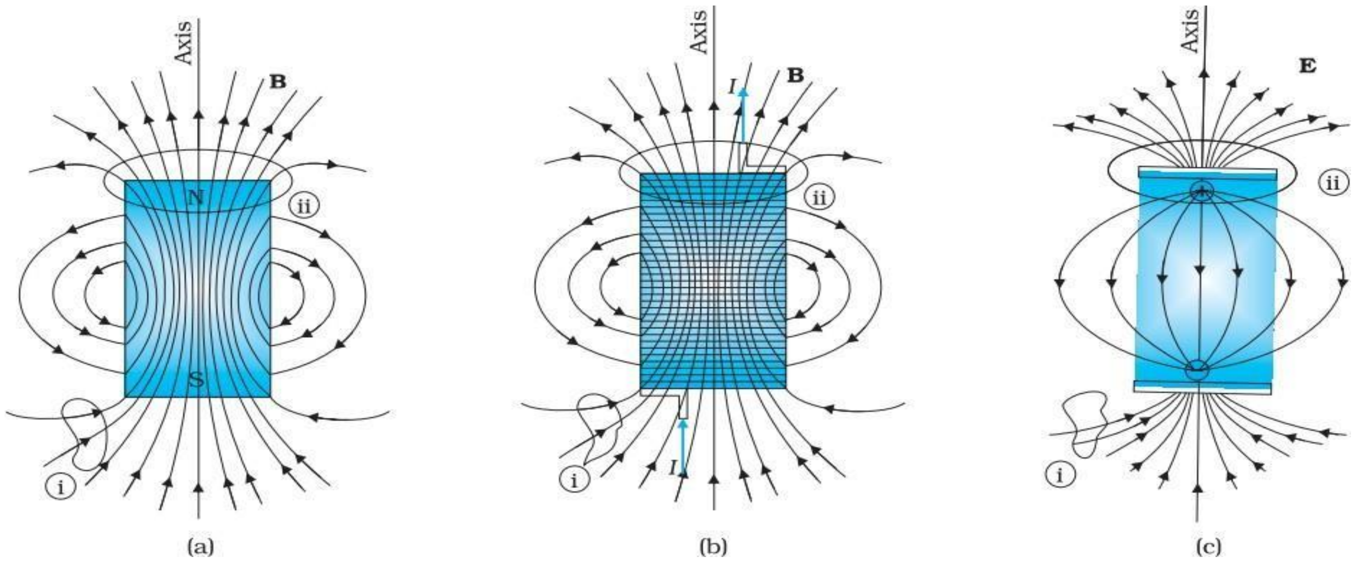
  (This is unlike the electric dipole where these field lines begin from a positive charge and end on the negative charge or escape to infinity.)

- The tangent to the field line at a given point represents the direction of the net magnetic field B at that point.
- The larger the number of field lines crossing per unit area, the stronger is the magnitude of the magnetic field B.
- The magnetic field lines do not intersect.

  (If they intersect, there would be more than one direction for magnetic field at the point of intersection, which is not possible)

The Magnetic field lines of

(a) a bar magnet, (b) a current-carrying finite solenoid and (c) electric dipole

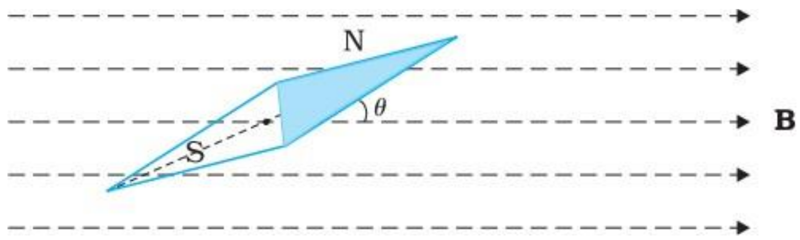


Note:-The magnetic field lines can not be called as magnetic lines of force. Unlike electrostatics (F =qE) the field lines in magnetism do not indicate the direction of the force on a moving charge(F=q(vxB))

Bar magnet as an equivalent solenoid

The resemblance of magnetic field lines for a bar magnet and a solenoid suggest that a bar magnet may be thought of as a large number of circulating currents in analogy with a solenoid.

The dipole in a uniform magnetic field



When a small compass needle of magnetic moment m and moment of inertia I is allowed it to oscillate in a magnetic field B, it executes simple harmonic motion.

Magnetic potential energy

$$\mathbf{U_m} = \int \boldsymbol{\tau}\, d\theta$$

$$\mathbf{U_m} = \int \mathrm{mBsin}\theta \mathrm{d}\theta = -\mathrm{mBcos}\theta$$

$$\mathbf{U_m} = -\mathrm{m.B}$$

Example

(a) What happens if a bar magnet is cut into two pieces:
(i) transverse to its length, (ii) along its length?
In either case, one gets two magnets, each with a north and south pole.

(b) A magnetised needle in a uniform magnetic field experiences a torque but no net force. An iron nail near a bar magnet, however, experiences a force of attraction in addition to a torque. Why?
No force if the field is uniform. The iron nail experiences a non uniform field due to the bar magnet. There is induced magnetic moment in the nail, therefore, it experiences both force and torque. The net force is attractive because the induced south pole (say) in the nail is closer to the north pole of magnet than induced north pole.

(c) Must every magnetic configuration have a north pole and a south pole? What about the field due to a toroid
Not necessarily. True only if the source of the field has a net non zero magnetic moment. This is not so for a toroid or even for a straight infinite conductor.

(d) Two identical looking iron bars A and B are given, one of which is definitely known to be magnetised. (We do not know which one.) How would one ascertain whether or not both are magnetised? If only one is magnetised, how does one ascertain which one? [Use nothing else but the bars A and B.]

Try to bring different ends of the bars closer. A repulsive force in some situation establishes that both are magnetised. If it is always attractive, then one of them is not magnetised.

In a bar magnet the intensity of the magnetic field is the strongest at the two ends (poles) and weakest at the central region. This fact may be used to determine whether A or B is the magnet. In this case, to see which one of the two bars is a magnet, pick up one, (say, A) and lower one of its ends; first on one of the ends of the other (say, B), and then on the middle of B. If you notice that in the middle of B, A experiences no force, then B is magnetised. If you do not notice any change from the end to the middle of B, then A is magnetised.

The electrostatic analog

$\vec{E} \to \vec{B}$, $\vec{p} \to \vec{m}$, $\frac{1}{4\pi\varepsilon_0} \to \frac{\mu_0}{4\pi}$, $\frac{1}{\varepsilon_0} \to \mu_0$

The magnetic field along the axial line of a bar magnet,

Axial filed $B_A = \frac{\mu_0}{4\pi} \frac{2\vec{m}}{r^3}$

The magnetic field along the equatorial l line of a bar magnet,

Equatorial field $B_E = -\frac{\mu_0}{4\pi} \frac{\vec{m}}{r^3}$

The Dipole Analogy

	Electrostatics	Magnetism
	$\frac{1}{\varepsilon_0}$	μ_0
Dipole moment	$\vec{p}$	$\vec{m}$

Axial Field for a short dipole	$\frac{1}{4\pi\varepsilon_0}\frac{2\vec{p}}{r^3}$	$\frac{\mu_0}{4\pi}\frac{2\vec{m}}{r^3}$
Equatorial Field for a short dipole	$\frac{1}{4\pi\varepsilon_0}\frac{\vec{p}}{r^3}$	$\frac{\mu_0}{4\pi}\frac{\vec{m}}{r^3}$
Torque in an external field	$\vec{\tau} = \vec{p} \times \vec{E}$	$\vec{\tau} = \vec{m} \times \vec{B}$
Energy in an external field	$U = -\vec{p}\cdot\vec{E}$	$U = -\vec{m}\cdot\vec{B}$

Example

What is the magnitude of the equatorial and axial fields due to a bar magnet of length 5 cm at a distance of 50 cm from its mid-point? The magnetic moment of the bar magnet is 0.40 A m²,

$B_E = \frac{\mu_0}{4\pi}\frac{m}{r^3} = \frac{10^{-7} \times 0.40}{(0.5)^3} = 3.2 \times 10^{-7}$ T

$B_A = \frac{\mu_0}{4\pi}\frac{2m}{r^3} = 2 \times 3.2 \times 10^{-7} = 6.4 \times 10^{-7}$ T

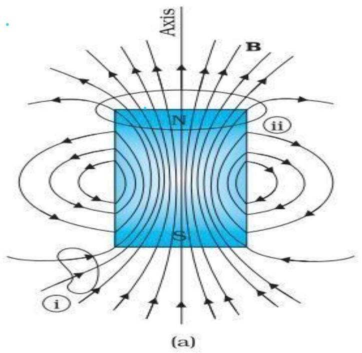
5.3 Magnetism and Gauss's Law

Gauss's law for magnetism states that the net magnetic flux through any closed surface is zero.

$$\phi = \oint \vec{B} \cdot d\vec{s} = 0$$

The difference between the Gauss's law of magnetism and that for electrostatics is due to the fact that isolated magnetic poles (also called monopoles) do not to exist.

There are no sources or sinks of B; the simplest magnetic element is a dipole or a current loop.



For the Gaussian surfaces represented by i or ii , the number of magnetic field lines leaving the surface is balanced by the number of lines entering it. The net magnetic flux is zero for both the surfaces.

Example

(a) Magnetic field lines show the direction (at every point) along which a small magnetised needle aligns (at the point). Do the magnetic field lines also represent the lines of force on a moving charged particle at every point?

No. The magnetic force is always normal to B (remember magnetic force = qv × B). It is misleading to call magnetic field lines as lines of force.

(b) Magnetic field lines can be entirely confined within the core of a toroid, but not within a straight solenoid. Why?

If field lines were entirely confined between two ends of a straight solenoid, the flux through the cross-section at each end would be non-zero. But the flux of field B through any closed surface must always be zero. For a toroid, this difficulty is absent because it has no 'ends'.

(c) If magnetic monopoles existed, how would the Gauss's law of magnetism be modified?

By Gauss's law for magnetism

$$\phi = \oint \vec{B} \cdot d\mathbf{s} = 0$$

If monopoles existed, the right hand side would be equal to the monopole (magnetic charge) q_m enclosed by S.

$$\phi = \oint \vec{B} \cdot d\mathbf{s} = \mu_0 q_m$$

{Analogous to Gauass law in electrostatics , $\phi = \oint \vec{E} \cdot ds = \frac{q}{\varepsilon_0}$}

(d) Does a bar magnet exert a torque on itself due to its own field? Does one element of a current-carrying wire exert a force on another element of the same wire?

No. There is no force or torque on an element due to the field produced by that element itself. But there is a force (or torque) on an element of the same wire. (For the special case of a straight wire, this force is zero.)

(e) Magnetic field arises due to charges in motion. Can a system have magnetic moments even though its net charge is zero

Yes. The average of the charge in the system may be zero. Yet, the mean of the magnetic moments due to various current loops may not be zero. We will come across such examples in connection with paramagnetic material where atoms have net dipole moment through their net charge is zero

5.4 Magnetisation and Magnetic Intensity

Magnetisation(M)

The net magnetic dipole moment developed per unit volume of a material is called Magnetisation(M).

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

Magnetisation is a vector quantity, its unit is Am^{-1},dimensions AL^{-1}

Consider a long solenoid of n turns per unit length and carrying a current I. If the interior of the solenoid is filled with a material with non-zero magnetisation, the total field inside the solenoid will be

$$B = B_0 + B_m \text{ -------------------- } (1)$$

Here $B_0$is the field due to the current in the solenoid and B_m is the field contributed by the material core which is proportional to the magnetisation M of the material.

$$B_0 = \mu_0 nI$$

$$B_m = \mu_0 M$$

$$B = \mu_0 nI + \mu_0 M$$

$$B = \mu_0 H + \mu_0 M$$

$$B = \mu_0 (H + M) \text{ ------------- } (2)$$

Here M is called magnetisation and H is called magnetic intensity

The total magnetic field inside the sample has two parts: one, due to external factors such as the current in the solenoid. This is represented by H. The other is due to the specific nature of the magnetic material, namely M.

Magnetic intensity(H)

The magnetic intensity can be defined as

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

$$B = \mu_0(H + M)$$

$$\frac{B}{\mu_0} = H + M$$

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

H has the same unit and dimensions as M .Its unit is Am^{-1},dimensions AL^{-1}

Magnetic Susceptibility(χ)

The magnetisation can be influenced by external factors(H which is equal to nI). This influence is mathematically expressed as $M = \chi H$

$$\chi = \frac{M}{H}$$

where χ is a dimensionless quantity called as magnetic susceptibility. It is a mesure of how a magnetic material responds to an external field.

- χ is large and positive for ferromagnetic materials.
- χ is small and positive for paramagnetic materials.
- χ is small and negative for diamagnetic materials. For diamagnetic materials M and H are opposite in direction.

Relation connecting Susceptibility and permeability

$$B = \mu_0(H + M)$$

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

$$B = \mu_0(1 + \chi)H) \text{ ------------- } (1)$$

$$B = \mu_0\mu_r H \text{ -------------------- } (2)$$

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

From (1) and (2)

$$\mu_r = 1 + \chi\ \chi$$
$$= \mu_r - 1$$

μ_r is a dimensionless quantity called the relative magnetic permeability of the substance.

The magnetic permeability of the substance is μ can be written as

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

Magnetic permeability

$$B = \mu H$$

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

Example

A solenoid has a core of a material with relative permeability 400. The windings of the solenoid are insulated from the core and carry a current of 2A.If the number of turns is 1000 per metre,calculate (a) H,(b) M,(c) B

a) $H = nI = 1000 \times 2 = 2000$ A/m

b) $M = \chi H = (\mu_r - 1)H$

$= (400-1)2000 = 399 \times 2000$

$= 7.98 \times 10^5 \cong 8 \times 10^5$ A/m

c) $B = \mu_0\mu_r H = 4\pi \times 10^{-7} \times 400 \times 2000$

$= 100.48 \times 10^{-2}$ T $= 1$ T

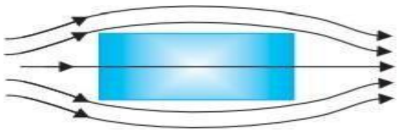
5.5 Magnetic Properties of Materials

In terms of the susceptibility χ , a material is diamagnetic if χ is negative, para- if χ is positive and small, and ferro- if χ is large and positive.

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

Diamagnetism

- Diamagnetic substances are those which get weakly magnetised opposite to the direction of external magnetic field.
- Diamagnetic substances move from stronger to the weaker part of the external magnetic field, i.e.,a magnet would repel a diamagnetic substance.
- Susceptibility **χ** is small and negative for diamagnetic materials. $\chi < 0$
- Relative permeability , μ_r is positive and less than one for diamagnetic materials. $\mu_r < 1$
- When a diamagnetic material is placed in an external magnetic field, the field lines are repelled or expelled and the field inside the material is reduced.



- The resultant magnetic moment of an individual atom of a diamagnetic substance is zero.
- When a magnetic field is applied, the diamagnetic substance develops a net magnetic moment opposite to the direction of applied field and hence repulsion.
- Some diamagnetic materials are bismuth, copper, diamond, gold, lead, mercury,silver, silicon, nitrogen (at STP), water and sodium chloride.
- Super coductors exhibits perfect diamagnetism. Here the field lines are completely expelled. $\chi = -1$ and $\mu_r = 0$.

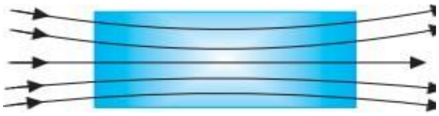
Super conductors

These are metals, cooled to very low temperatures which exhibits both perfect conductivity and perfect diamagnetism. Here the field lines are completely expelled. $\chi = -1$ and $\mu_r = 0$. The phenomenon of perfect diamagnetism in superconductors is called the Meissner effect.

Paramagnetism

- Paramagnetic substances are those which get weakly magnetised in the direction of external magnetic field.
- Paramagnetic substances move from a region of weak magnetic field to strong magnetic field, i.e., they get weakly attracted to a magnet.

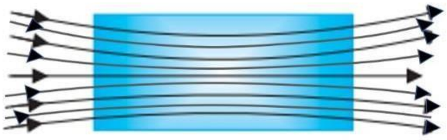
- Susceptibility **χ** is small and positive for paramagnetic materials. $\chi > 0$
- Relative permeability is positive and greater than one for diamagnetic materials. $\mu_r > 1$
- When a paramagnetic material placed in an external field , the field lines gets concentrated inside the material, and the field inside is enhanced.



- The individual atoms of a paramagnetic material possess a permanent magnetic dipole moment of their own.
- When a magnetic field is applied, the individual atomic dipole moments align in the same direction and a net magnetic moment in the direction of applied field and hence attraction.
- Some paramagnetic materials are aluminium, sodium, calcium, chromium, lithium , magnesium, oxygen (at STP) ,copper chloride, platinum, tungsten, niobium.

Ferromagnetism

- Ferromagnetic substances are those which gets strongly magnetised when placed in an external magnetic field.
- Ferromagnetic substances have strong tendency to move from a region of weak magnetic field to strong magnetic field, i.e., they get strongly attracted to a magnet.
- Susceptibility **χ** is large and positive for ferromagnetic materials. $\chi >> 1$
- Relative permeability is greater than one and large. $\mu_r >> 1$
- When a ferromagnetic material placed in an external field , the field lines gets highly concentrated inside the material, and the field inside is enhanced.



- The individual atoms (or ions or molecules) in a ferromagnetic material possess a dipole moment as in a paramagnetic material.

- When a magnetic field is applied, the individual atomic dipole moments align in the same direction and a net magnetic moment in the direction of applied field and hence attraction.
- The ferromagnetic property depends on temperature.At high enough temperature, a ferromagnet becomes a paramagnet.
- Some ferromagnetic materials are iron, cobalt, nickel, gadolinium,Fe_2O_3.

Hard ferromagnets and Soft ferromagnets

The ferromagnetic materials in which the magnetisation persists, ,even when the external field is removed are called hard magnetic materials or hard ferromagnets. Such materials are used to make permanent magnets.
Eg: Alnico(an alloy of iron, aluminium, nickel, cobalt & copper),lodestone

The ferromagnetic materials in which the magnetisation disappears on the removal of the external field are called soft ferromagnetic materials.

Eg: Soft iron .