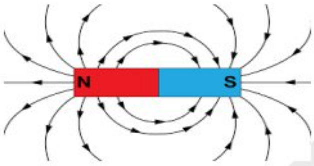
MODULE – 4

Magnetism

Magnetic field

The area around the magnet or any current carrying conductor in which the magnetic force (the force of attraction or repulsion) can be experienced is called Magnetic field.

It is a vector quantity represented by 'B' directed from North Pole to South Pole of a magnet.

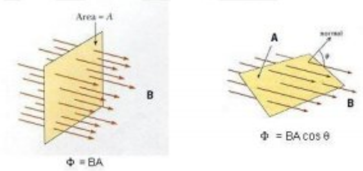
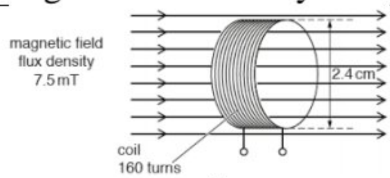


The magnetic field consists of number of invisible magnetic lines of force.

Properties of magnetic lines of force

i. It forms a closed loop in the magnetic field area
ii. The direction of magnetic lines of force from north to south outside the magnet and South to North inside the magnet
iii. They always follows a least reluctance path
iv. The magnetic lines never intersect with each other
v. They repel each other when they are parallel and moves in the same direction
vi. It can be termed as pictorial representation of magnetic field lines

Distinguish between magnetic flux and magnetic flux density

Magnetic flux	Magnetic flux density
The total number of magnetic lines passing through the plane of area 'A' Perpendicular to the field is called magnetic flux	The total amount of magnetic flux passing perpendicularly through a unit area with the Magnetic flux direction is called magnetic flux density.
 It is denoted by $\Phi = BA \cos Ø$ B = Magnetic field intensity A = Area of surface Ø = angle between B and A	 It is denoted by $B = \frac{\Phi}{A}$ Φ = Magnetic flux A = Area of surface
SI unit of 'Φ' is the Webber or Tesla-m^2	SI unit of 'B' is Webber /m^2 or Tesla
Magnetic flux through a closed surface is zero and open surface is nonzero.	Magnetic flux density through a closed surface is nonzero.
It is a Scalar quantity	It is a Vector quantity

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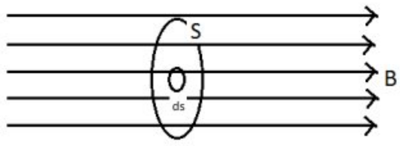
Gauss- Law for magnetic flux

Gauss law states that, the surface integral of magnetic flux over a closed surface is zero,

i.e, $\oint B.ds = 0$

Consider a small area 'ds' of a closed surface 'S'. The magnetic flux passing through this area 'ds' is given by

$\Phi = B.ds = Bds\ Cos\emptyset$



Then the total magnetic flux passing through the entire closed surface is,

$$\oint B.ds$$

By Gauss Law, $\oint B.ds = 0$

This means that, all the magnetic lines of force (magnetic flux) going into the closed surface is equal to magnetic lines of Force coming out from it. i.e, Gauss Law of magnetism tells us that, the magnetic monopoles do not exist. Means magnetic flux has neither a beginning nor an end.

Ampere's Circuital Law

Ampere's Circuital law explains the relationship between the current and magnetic field created by a current-carrying conductor.

It states that, The line integral of magnetic flux density 'B' for a closed path is equal to 'μ_0' times the net current 'I' enclosed by the path.

$$\oint B.dl = \mu_0 I$$

Where, μ_0 - Permeability of free space

I - Total current enclosed by the path

Proof

Consider a current-carrying conductor XY. Let 'I' be the current passing through it. The magnetic field produced around the conductor is as shown.

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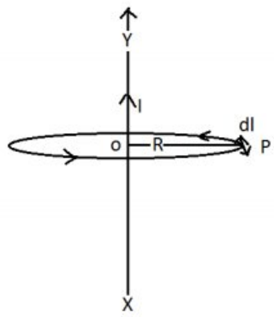

Let us consider the magnetic field 'B' around the conductor with radius 'R' is given by

$$B = \frac{\mu_0 I}{2\pi R}$$

Consider a small element 'dl' of the circle, 'Ø' is the angle between 'B' and 'dl'

$$\oint B.dl = \oint B.dl \cos \emptyset$$

$$\oint B.dl = B \oint dl = B.2\pi R$$

$$\oint B.dl = \frac{\mu_0 I}{2\pi R}.2\pi R = \mu_0 I$$

Hence, Ampere's circuital law is proved

Faraday's law of Electromagnetic Induction

The phenomenon of producing electric current in a closed conducting coil, when it is placed in a changing magnetic field or changing magnetic flux is known as electromagnetic induction.

Whenever the magnetic flux linked with the circuit is changes, an e.m.f is induced in the coil as long as the change in magnetic flux last.

"Faraday's law of electromagnetic induction states that, the magnitude of induced e.m.f in the circuit is equal to the rate of change of magnetic flux linked with the circuit".

$$e = \frac{-d\Phi}{dt}$$

The negative (-) sign indicates the direction of induced e.m.f is Opposite to the change in magnetic flux.

If there are 'n' turns in the coil then,

$$e = -n\frac{d\Phi}{dt}$$

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Intensity of magnetization (M)

It is a measure of monetization of a magnetized material. It is defined as the magnetic dipole moment per unit volume of the material

$$M=\frac{Magnetic\ dipole\ moment}{Volume}=\frac{2ml}{V}$$

Where, m = Pole strength
l= length of magnetic material

Its Unit is Ampere per meter.

Magnetic field intensity (H)

It is defined as the ratio of magnetic field in free space to the permeability of free space

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

Its unit is ampere per meter.

Magnetic susceptibility (χ)

It is defined as the ratio of magnetization 'M' to the magnetic field intensity 'H'. It is a measure of how much the material become magnetized, when it is placed in an applied magnetic field.

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

It is a dimension less quantity. (Since M and H are in Ampere)

Magnetic permeability (μ)

It is defined as the ability of a material to allow magnetic lines of force to pass through it. In other words, it is defined as the ratio of magnetic flux density 'B' to the magnetic field intensity 'H'.

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

Relative permeability (μ_r)

Relative permeability is the comparison of permeability of a material with the permeability of air or vacuum.

Relative permeability, $\mu_r=\frac{\mu}{\mu_0}$

Where μ_0 - Permeability in free space = $4\pi \times 10^{-7}$ Henry/Meter.

When a magnetic material is placed in a uniform magnetic field intensity 'H', then magnetic flux 'B' passed through it and being magnetized 'M' by

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induction. Therefore the net magnetic flux density in the material Is the resultant of External applied magnetic field intensity 'H' and intensity of magnetization 'M'

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

$B = \mu_0 (H + M)$

$B = \mu_0 (H + MH)$ (x^{ly} RHS by $\frac{H}{H}$

$B = \mu_0 H + \mu_0 \chi H$ (Where $\chi = \frac{M}{H}$)

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

$B = \mu H$ [Where, $\mu = \mu_0 (1 + \chi)$ – Permeability of the medium]

In terms of relative permeability,

$$\mu_r = \frac{\mu_0 (1 + \chi)}{\mu_0} = 1 + \chi$$

This implies, $\mu_r = (1 + \chi)$

Classification of Magnetic materials

The magnetic properties of material is due to the orbital and spin motion of electrons present in the atoms by which the materials are made up. Normally Magnetic moments of atoms are oriented randomly, so that the net magnetic moment of the material is zero. When an external magnetic field 'B' is applied to the material, the magnetic moments aligned in the direction of 'B'.

Based on the magnetic properties Induced in the material in the presence of external magnetic field and also based on the effect of temperature on the magnetic properties, all the materials are classified under 3 categories.

Diamagnetic materials	**Paramagnetic materials**	**Ferromagnetic materials**
The materials that are weakly magnetized in a direction opposite to the direction of the applied magnetic field is known as diamagnetic materials	The materials that are weakly magnetized in a direction same as that of the direction of applied magnetic field is known as paramagnetic materials	The materials that are strongly magnetized in a direction same as that of the direction of applied magnetic field is known as ferromagnetic materials
Diamagnetic materials are repelled by a magnetic field	Paramagnetic materials are weakly magnetized by an external magnetic field	Ferromagnetic materials are strongly magnetized and attracted by applied magnetic field

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The net magnetic moment of each atoms of the material is zero	They have a permanent magnetic moment due to the presence of unpaired electrons and normally they aligned in random direction.	They have a permanent magnetic moment due to the presence of unpaired electrons and normally they are aligned in random direction.
Freely suspended diamagnetic material in external magnetic field will be aligned perpendicular to the direction of applied magnetic field	Freely suspended Paramagnetic material in the external magnetic field will be aligned parallel to the direction of applied magnetic field	Freely suspended ferromagnetic material in the external magnetic field will be aligned parallel to the direction of applied magnetic field
In a non-uniform magnetic field, the diamagnetic materials will move from the region of stronger field to the region of weaker field	In a non-uniform magnetic field, the paramagnetic materials will move from a region of weaker field to stronger field	In a non-uniform magnetic field, the ferromagnetic materials will move from a region of weaker field to stronger field
Magnetic susceptibility is negative. (χ - is negative)	Magnetic susceptibility is less and positive. (χ - is positive)	Magnetic susceptibility is very high and positive. (χ - is positive)
Permeability 'μ' is less than 1 ($\mu < 1$)	Permeability 'μ' is greater than 1 ($\mu > 1$)	Permeability 'μ' is much greater than 1 ($\mu >> 1$)
Magnetic flux density inside a diamagnetic material is much less than that of air	Magnetic flux density inside a paramagnetic material is larger than that of air	Magnetic flux density inside a paramagnetic material is much larger than that of air
They are temperature independent	The magnetic property loses when it heated	The magnetic property loses when it heated
No effect on applied magnetic field	Magnetization does not exist when the magnetic field removed	Magnetization exist even after the removal of magnetic field
Egs:- Copper, Bismuth, Lead, Water, Zinc & Rare gases	Egs:- Platinum, Aluminum, Manganese chloride, Salt of iron and nickel	Egs:- Iron, Nickel, Cobalt Erbium, Terbium

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Langevin Theory Of Diamagnetism

The susceptibility of a diamagnetic material is due to the magnetic moment produced by orbital motion of electrons in the material.

$$\chi = \frac{\mu_0 e^2 nz}{6m} < r^2 >$$

μ_0 - Permeability of free space
n - Number of atoms per unit volume
z - Atomic number
e - Electronic charge
m - Mass of electron
< r > - Mean Square distance of electrons from the nucleus

Curie law of Paramagnetism

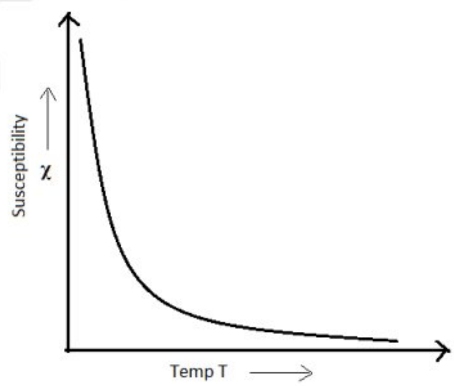
The susceptibility of paramagnetic material is inversely proportional to its temperature.

$$\chi \, \alpha \, \frac{1}{T}$$

ie, $$\chi = \frac{C}{T}$$

Where, $C = \frac{\mu_0 n\mu_e^2}{3k}$ - is a constant called curies constant

k =Boltzmann constant
n = Number of atoms per unit volume
μ_0 = Permeability of free space
μ_e = Magnetic moment of electron, due to its spin and orbital motion.



Curie Temperature (T_{cu})

The Temperature above which a ferromagnetic material changes to paramagnetic is called Curie Temperature 'T_{cu}' of that material.

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Curie – Weiss Law of Ferromagnetism

At the temperature above Curie temperature 'T_{cu}' The magnetic susceptibility 'χ' of ferromagnetic material is inversely proportional to $(T-T_{cu})$

$$\chi \ \alpha \ \frac{1}{(T-T_{cu})}$$

ie, $$\chi = \frac{C}{(T-T_{cu})}$$

Where, C - is the curie constant

T – Absolute Temperature

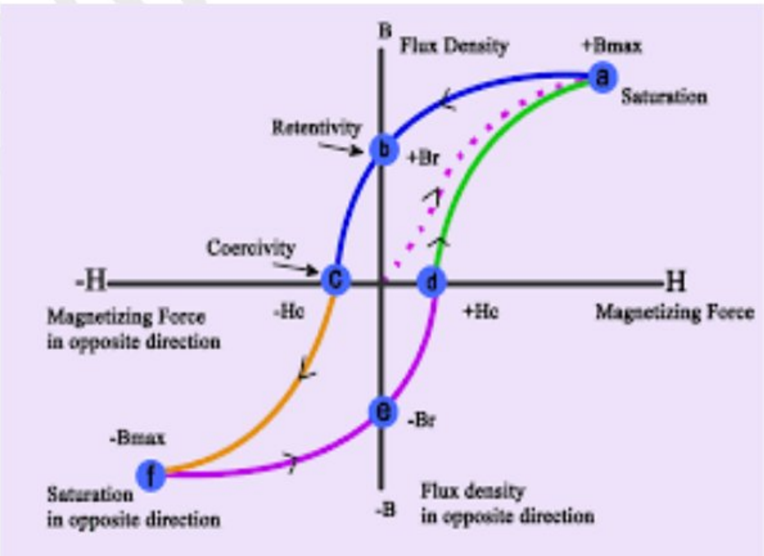
Weiss Theory of Ferromagnetism

When a ferromagnetic material consists of number of magnetic moments is placed in an external magnetic field, the magnetic moment of individual domains oriented by the external field. Hence, the magnitude of spontaneous magnetization of the material is the vector sum of the magnetic moment of individual domains.

Hysteresis Loop in Ferromagnetic materials

'Hysteresis' is a Greek word means nothing to do with the history. ie, Between two saturation point the magnetic flux density 'B' is lagging behind the applied field 'H', We can never get back the actual history.

When a ferromagnetic material is placed in an external magnetic field 'H', it gets magnetized because of the alignment of their individual magnetic domains according to the applied magnetic field 'H'. If the intensity of magnetization 'B' is plotted against the applied magnetic field 'H' over a cycle of variation, Then it can be represented as a closed curve known as Hysteresis curve as shown



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Characteristic features of Hysteresis Loop

i. When the applied magnetic field 'H' increases, Magnetic flux density 'B' inside the material increased and reaches the maximum value (a) is called saturation flux density ($+B_{max}$)

ii. When 'H' decreases to zero, the flux density 'B' is gradually reduced and reaches to the point (b) on graph. ie, The value of magnetic flux density 'B' exhibited by the material, when the applied field 'H' is equal zero(H=0) is called Residual or Retentivity flux density(B_r).

iii. When the magnetic field 'H' is applied in opposite direction, the stage reaches where the magnetic flux density 'B=0'. This negative field intensity 'H' required to make the Residual or Retentivity flux density equal to zero (B_r=0) is called Coercive field 'Hc'

iv. Further increase of applied field 'H' in opposite direction, the saturation flux (–Bmax) in opposite direction is obtained.

v. When the magnetic field 'H' is applied in the original direction, the magnetic flux density also changes and this changes lags behind the changes in the applied field 'H'. This effect is called Hysteresis and the plot is called Hysteresis curve (abcfed)

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