(c) Ferromagnetic Substances: Examples of such substances are iron, nickel, steel, cobalt and their alloys. These substances resemble to a higher degree the paramagnetic substances with regards to their behaviour. They have the following additional properties:

(i) These substances are strongly magnetized by even a weak magnetic field.

(ii) The relative permeability is very large and is of the order of hundreds and thousands.

(iii) The susceptibility is positive and very large.

(iv) Susceptibility remains constant for very small values of $\vec{H}$, increases for larger values of $\vec{H}$ and then decreases for very large values of $\vec{H}$.

(v) Susceptibility decreases steadily with the rise of the temperature. Above a certain temperature, known as Curie temperature, the ferromagnetic substances become paramagnetic. For iron, it is 1000°C, 770°C for steel, 360°C for nickel, and 1150°C for cobalt.

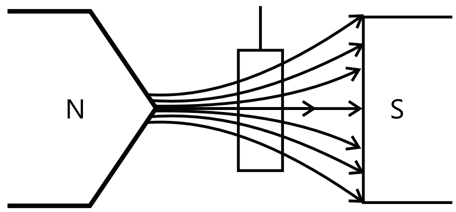

Figure 21.49: Diamagnetic substance in magnetic field

21. HYSTERESIS

Hysteresis is the dependence of the magnetic flux density B in a ferromagnetic material not only on its current magnetizing field H, but also on its history of magnetization or residual magnetization.

When a ferromagnetic material is magnetized in one direction, and then the applied magnetizing field is removed, then its magnetization will not be reduced to zero. It must be driven back to zero by a field in the opposite direction. If an alternating magnetic field intensity is applied to the material, its magnetization will trace out a loop called a hysteresis loop.

The phenomena in which magnetic flux density (B) lags behind the magnetizing field (H) in a ferromagnetic material during cycles of magnetization is called as hysteresis.

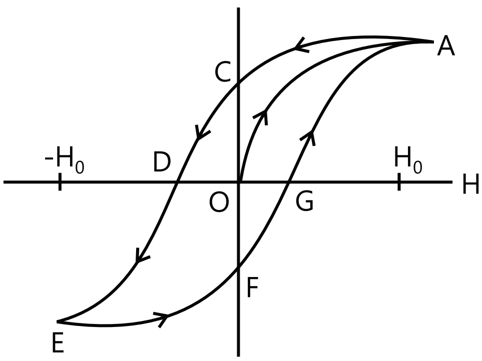

Figure 21.50: Hysteresis loop of I vs H

PROBLEM-SOLVING TACTICS

(a) General advice for this section involves learning of formulae and avoiding silly mistakes. Also it would be better to go by the usual algorithm of noting down known and unknown quantities and linking them.

(b) Much of manipulation and mathematical complexity is involved here which can't be avoided.

FORMULAE SHEET

(a) Magnetic Force on a charge moving with velocity $\vec{v}$ in magnetic field $\vec{B}$ is $\vec{F}_m = q\vec{v} \times \vec{B}$. Magnitude is $F_m = qvB\sin\theta$.

(b) Charged particle moving in uniform magnetic field

(i) Angular velocity $\omega = 2\pi f = \frac{|q|B}{m}$

(ii) Time period $T = \frac{2\pi m}{|q|B}$

(iii) Radius $r = \frac{mv}{qB} = \frac{m}{qB}\sqrt{\frac{2qV}{m}} = \frac{1}{B}\sqrt{\frac{2mV}{q}}$

(c) Helical Paths: Radius $r = \frac{mv_\perp}{qB}$ Pitch: $p = v_\perp T = v_\perp \frac{2\pi m}{|q|B}$

(d) The cyclotron $|q|B = 2\pi m f_{osc}$

(e) Crossed Fields: Lorentz Force $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$

(f) Trajectory of a charged particle in electric field $y = \frac{|q|Ex^2}{2mv^2}$

(g) Magnetic force on current element $d\vec{F} = Id\vec{\ell} \times \vec{B}$

(h) Magnetic force on a conductor in uniform field $\vec{F} = I\vec{L} \times \vec{B}$

(i) Magnetic dipole moment of a current coil having N turns $\vec{p}_m = NIA\hat{n}$

(j) Torque on a current coil $\vec{\tau} = \vec{p}_m \times \vec{B}$

(k) Potential energy of current coil $U = -\vec{p}_m.\vec{B}$

(l) Biot-Savart Law $d\vec{B} = \frac{\mu_0}{4\pi}\frac{Id\vec{\ell} \times \vec{r}}{r^3}$, $dB = \frac{\mu_0}{4\pi}\frac{Id\ell\sin\theta}{r^2}$

(m) Magnetic field at center of an arc subtending angle θ, $B = \left(\frac{\mu_0}{4\pi}\right)\frac{I\theta}{R}$

(n) Magnetic field at a point on the axis of a N turn coil $B = \frac{\mu_0}{2}\frac{NIR^2}{\left(z^2 + R^2\right)^{3/2}}$

(o) Magnetic field at center of N turn coil $B = \frac{\mu_0}{2}\frac{NI}{R}$

(p) Concentric coils with equal turns

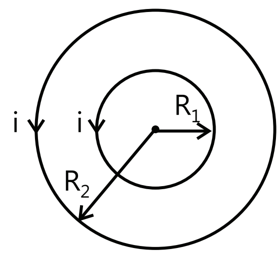

Figure 21.51

(i) Similar currents flowing in the same direction

Net magnetic field, $B = \frac{\mu_0}{2}\frac{NI}{R_1} + \frac{\mu_0}{2}\frac{NI}{R_2} = \frac{\mu_0}{2}NI\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$

(ii) Similar currents flowing in the opposite direction

Net magnetic field, $$B = \frac{\mu_0}{2}\frac{NI}{R_1} - \frac{\mu_0}{2}\frac{NI}{R_2}$$

$$= \frac{\mu_0}{2} NI\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

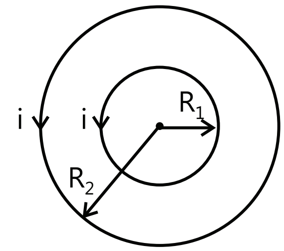

Figure 21.52

(q) Mutually perpendicular coils

Net Magnetic field, $$B = \sqrt{2}\left(\frac{\mu_0}{4\pi}\right)\frac{2\pi I}{R}$$

(r) Dispatched coils

Net Magnetic Field, $$B = \sqrt{2}\frac{\mu_0}{2}\frac{IR^2}{(R^2 + x^3)^{3/2}}$$

$$= \frac{\mu_0 IR^2}{\sqrt{2}(x^2 + R^2)^{3/2}}$$

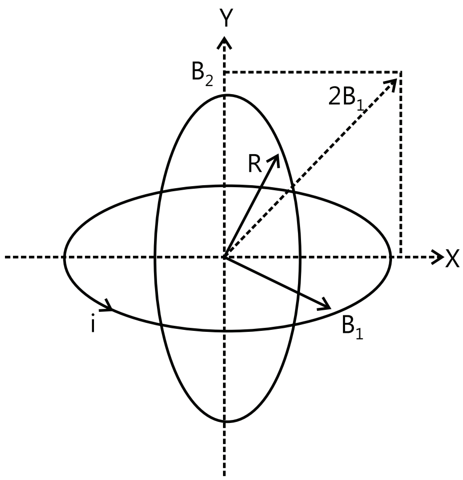

Figure 21.53

(s) Infinite straight wire $B = \frac{\mu_0 I}{2\pi R}$

(t) Semi-infinite straight wire $B = \frac{\mu_0 I}{4\pi R}$

(u) Force per unit length between two parallel currents separated by distance d, $\frac{dF}{d\ell} = \frac{\mu_0 I_1 I_2}{2\pi d}$

(v) Ampere's law $\oint \vec{B}.d\vec{\ell} = \mu_0 I_{enc}$

(w) Field inside infinite straight wire of circular cross-section $B = \frac{\mu_0 I}{2\pi R^2} r$

(x) Magnetic Field inside long solenoid having n turns per unit length $B = \mu_0 nI$

(y) Magnetic Field inside toroid having N turns $B = \frac{\mu_0 NI}{2\pi r}$

(z) Magnetic field due to bar magnet at end-on position $B = \frac{\mu_0}{4\pi}\frac{2M}{d^3}$

(aa) Magnetic field due to bar magnet at broadside-on position $B = \frac{\mu_0}{4\pi}\frac{M}{d^3}$

(ab) Moving Coil Galvanometer $I = \frac{k\phi}{NAB}$

(ac) Magnetic field Intensity H, in vacuum is, $H = \frac{B}{\mu_0}$

(ad) Magnetic field Intensity H, in a medium is, $H = \frac{B}{\mu_r \mu_0}$

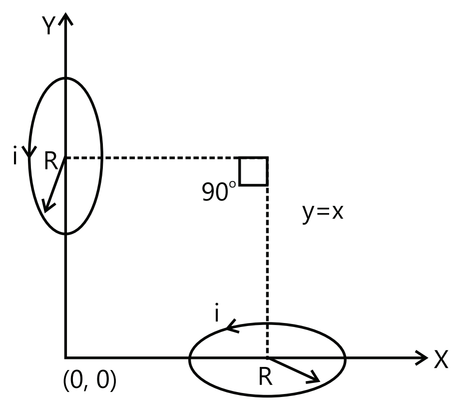

Figure 21.54