Chapter 11: Magnetic Materials

EXERCISES [PAGES 263 - 264]

Exercises | Q 1.1 | Page 263

Choose the correct option:
Intensity of the magnetic field of the earth at the point inside a hollow iron box is.

1. less than that outside
2. more than that outside
3. same as that outside
4. **zero**

SOLUTION

Zero

Explanation: No magnetic lines of force passes through the steel box.

Exercises | Q 1.2 | Page 263

Choose the correct option:
Soft iron is used to make the core of the transformer because of its

1. **low coercivity and low retentivity**
2. low coercivity and high retentivity
3. high coercivity and high retentivity
4. high coercivity and low retentivity

SOLUTION

low coercivity and low retentivity

Exercises | Q 1.3 | Page 263

Choose the correct option:
Which of the following statements is correct for diamagnetic materials?

1. $\mu_r < 1$
2. χ is negative and low
3. χ does not depend on temperature
4. **All of the above**

SOLUTION

All of the above

Exercises | Q 1.4 | Page 263
Choose the correct option:

A rectangular magnet suspended freely has a period of oscillation equal to T. Now it is broken into two equal halves (each having half of the original length) and one-piece is made to oscillate freely. Its period of oscillation is T′, the ratio of T′/T is.

$\frac{1}{2\sqrt{2}}$

$\frac{1}{2}$

2

$\frac{1}{4}$

SOLUTION

$\frac{1}{2}$

Explanation:

Time period for the oscillating magnet is

$T = 2\pi\sqrt{\frac{I}{MB}}$ ....(1)

where I is the moment of inertia,

M is the magnetic moment

M = x × l

x = pole strength

When the magnet is broken in two equal parts, the new magnetic dipole moment is

$M' = \frac{x \times l}{2} = \frac{M}{2}$

$I' = \frac{ML^{12}}{2}$

$= \frac{\frac{M}{2} \times \left(\frac{L}{2}\right)^2}{12}$

$$= \frac{ML^2}{12 \times 8}$$

$$= \frac{I}{8}$$

New time period is

$$T' = 2\pi\sqrt{\frac{I\prime}{M\prime B}}$$

$$\frac{T\prime}{T} = \sqrt{\frac{1}{4}} = \frac{1}{2}$$

Exercises | Q 1.5 | Page 263

Choose the correct option:

A magnetising field of 360 Am^{-1} produces a magnetic flux density (B) = 0.6 T in a ferromagnetic material. What is its permeability in Tm A^{-1}?

$\frac{1}{300}$

300

$\frac{1}{600}$

600

SOLUTION

$\frac{1}{600}$

Explanation:

Given: Magnetising field = 360 Am^{-1}

Magnetic flux density (B) = 0.6T

To find: Permeability

$$\text{Permeability} = \frac{B}{\text{Magnetising field}}$$

$$= \frac{0.6}{360 \times 10}$$

$$= \frac{1}{600} \frac{\text{Tm}}{\text{A}}$$

Exercises | Q 2.1 | Page 263

Answer in brief.

Which property of soft iron makes it useful for preparing electromagnet?

SOLUTION

An electromagnet should become magnetic when a current is passed through its coil but should lose its magnetism once the current is switched off. Hence, the ferromagnetic core (usually iron-based) used for an electromagnet should have high permeability and low retentivity, i.e., it should be magnetically 'soft'.

Exercises | Q 2.2 | Page 263

Answer in brief.

What happens to a ferromagnetic material when its temperature increases above curie temperature?

SOLUTION

A ferromagnetic material is composed of small regions called domains. Within each domain, the atomic magnetic moments of nearest-neighbor atoms interact strongly through exchange interaction, a quantum mechanical phenomenon, and align themselves parallel to each other even in the absence of an external magnetic field. A domain is, therefore, spontaneously magnetized to saturation.

The material retains its domain structure only up to a certain temperature. On heating, the increased thermal agitation works against the spontaneous domain magnetization. Finally, at a certain critical temperature, called the Curie point or Curie temperature, thermal agitation overcomes the exchange forces and keeps the atomic magnetic moments randomly oriented. Thus, above the Curie point, the material becomes paramagnetic. The ferromagnetic to paramagnetic transition is an order to disorder transition. When cooled below the Curie point, the material becomes ferromagnetic again.

Exercises | Q 2.3 | Page 263

Answer in brief.

What should be retentivity and coercivity of permanent magnet?

SOLUTION

A permanent magnet should have a large zero-field magnetization and should need a very large reverse field to demagnetize. In other words, it should have a very broad hysteresis loop with high retentivity and very high coercivity.

Exercises | Q 2.4 | Page 263

Answer in brief.

Discuss the Curie law for paramagnetic material.

SOLUTION

Curie's law: The magnetization of a paramagnetic material is directly proportional to the external magnetic field and inversely proportional to the absolute temperature of the material.

If a paramagnetic material at an absolute temperature T is placed in an external magnetic field of induction $\vec{B}_{ext}$, the magnitude of its magnetization

$$M_z \propto \frac{B_{ext}}{T}$$

$$\therefore M_z = C\frac{B_{ext}}{T}$$

where the proportionality constant C is called the Curie constant.

Exercises | Q 2.5 | Page 263

Answer in brief.

Obtain an expression for the orbital magnetic moment of an electron rotating about the nucleus in an atom.

SOLUTION

In the Bohr model of a hydrogen atom, the electron of charge - e performs a uniform circular motion around the positively charged nucleus. Let r, v and T be the orbital radius, speed and period of motion of the electron. Then,

$$T = \frac{2\pi r}{v} \quad ...(1)$$

Therefore, the orbital magnetic moment associated with this orbital current loop has a magnitude,

$$I = \frac{e}{T} = \frac{ev}{2\pi r} \quad ...(2)$$

Therefore, the magnetic dipole moment associated with this electronic current loop has a magnitude

M_0 = current × area of the loop

$$= I(\pi r^2) = \frac{ev}{2\pi r} \times \pi r^2 = \frac{1}{2}evr \quad ....(3)$$

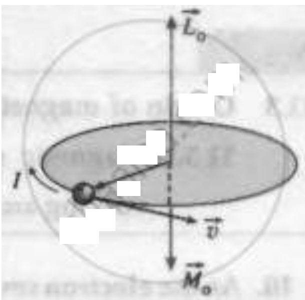
Multiplying and dividing the right-hand side of the above expression by the electron mass m_e,

$$M_0 = \frac{e}{2m_e}(m_e vr) = \frac{e}{2m_e} L_0 \quad ....(4)$$

where L_0 - $m_e vr$ is the magnitude of the orbital angular momentum of the electron. $\overrightarrow{M}_0$ is opposite to $\overrightarrow{L}_0$.

$$\therefore \overrightarrow{M}_0 = -\frac{e}{2m_e}\overrightarrow{L}_0 \quad ....(5)$$

which is the required expression.



According to Bohr's second postulate of stationary orbits in his theory of hydrogen atom, the angular momentum of the electron in the nth stationary orbit is equal to n $\frac{h}{2\pi}$, where h is the Planck constant and n is a positive integer. Thus, for an orbital electron,

$$L_0 = m_e vr = \frac{nh}{2\pi} \quad ...(6)$$

Substituting for L_0 in Eq. (4),

$$M_0 = \frac{enh}{4\pi m_e}$$

For n = 1, $M_0 = \frac{eh}{4\pi m_e}$

The quantity $\frac{eh}{4\pi m_e}$ is a fundamental constant called the Bohr magneton, $\mu_B \cdot \mu_B = 9.274 \times 10^{-24} J/T$ (or Am^2)=5.788 x 10^{-5} eV/T.

Exercises | Q 2.6 | Page 263

Answer in brief.

What does the hysteresis loop represent?

SOLUTION

A magnetic hysteresis loop is a closed curve obtained by plotting the magnetic flux density B of a ferromagnetic material against the corresponding magnetizing field H when the material is taken through a complete magnetizing cycle. The area enclosed by the loop represents the hysteresis loss per unit volume in taking the material through the magnetizing cycle.

Exercises | Q 2.7 | Page 263

Answer in brief.

Explain one application of electromagnet.

SOLUTION

Electromagnets are used for various purposes on a day to day basis. For example, electromagnets are used in the large cranes which are used in waste yards. Electromagnets are also widely used in numerous electromechanical and electronic devices. Some of the common uses are given below.

- **Uses in Home Appliances:** Most of the electric appliances used in the home use electromagnetism as the basic working principle. Some electromagnet uses in the home include the electric fan, electric doorbell, induction cooker, magnetic locks, etc. In an electric fan, the electromagnetic induction keeps the motor rotating on and on making the blade of the fan to rotate. Also in an electric doorbell when the button is pressed, due to the electromagnetic forces the coil gets energized and the bell sounds.

- **Uses in Medical Field:** The uses of electromagnets are also seen in the medical field. MRI scan which is short for Magnetic Resonance Imaging is a device that uses electromagnets. The device can scan all the tiny details in the human body with the help of electromagnetism.
- **Uses in Memory Storage Devices and Computer Hardware:** The data in ebook gadgets and phones are stored in the electromagnetic format in the form of bytes and bits. The computer hardware is also having a magnetic tape which works on the principle of electromagnetism. Even in the olden days' electromagnets had a huge role in the data storage of VCP and VCR.

Exercises | Q 3 | Page 263

When a plate of magnetic material of size 10 cm x 0.5 cm × 0.2 cm (length, breath, and thickness respectively) is located in a magnetizing field of 0.5×10^4 A/m, then a magnetic moment of 5 $A{\cdot}m^2$ is induced in it. Find the magnetic induction in the rod.

SOLUTION

Data: l = 10 cm, b = 0.5 cm, h = 0.2 cm, $H = 0.5 \times 10^4\ Am^{-1}$, $M = 5\ A.m^2$

The volume of the plate,

$V = 10 \times 0.5 \times 0.2 = 1\ cm^2 = 10^{-6}\ m^2$

$$B = \mu_0(H + M_2) = \mu_0\left(H + \frac{M}{V}\right)$$

The magnetic induction in the plate,

$$\therefore \text{B} = 4\pi \times 10^{-7}\left(0.5 \times 10^{4} + \frac{5}{10^{-6}}\right)$$

= 6.290 T

Exercises | Q 4 | Page 264

A rod of magnetic material of cross-section 0.25 cm^2 is placed in a magnetizing field of intensity 4000 A/m. The magnetic flux passing through the rod is 25 x 10^{-6} Wb. Find out

(a) relative permeability

(b) magnetic susceptibility and

(c) magnetisation of the rod.

SOLUTION

Data: A= 0.25 cm^2 = 25 x 10^{-6} m^2

H = 4000 A m^{-1}, Φ = 25 x 10^{-6} Wb

Magnetic induction is

$$\text{B} = \frac{\phi}{\text{A}} = \frac{25 \times 10^{-6}}{25 \times 10^{-6}} = 1\ \text{Wb/m}^2$$

(a) B = $\mu_0\mu_r$H

∴ The relative permeability of the material,

$$\mu_\text{r} = \frac{\text{B}}{\mu_0\text{H}} = \frac{1}{4 \times 3.142 \times 10^{-7} \times 4000}$$

$$= \frac{10000}{50.272} = 198.91 = 199$$

(b) $\mu_\text{r} = 1 + \chi_\text{m}$

∴ The magnetic susceptibility of the material,

$$\chi_\text{m} = \mu_\text{r} - 1 = 199 - 1 = 198$$

(c) $\chi_m = \frac{M_z}{H}$

The magnetization of the rod,

$$M_z = \chi_m H = 198 \times 4000 = 7.92 \times 10^5 \text{A/m}$$

Exercises | Q 5 | Page 264

The work done for rotating a magnet with magnetic dipole moment m, through 90° from its magnetic meridian is n times the work done to rotate it through 60°. Find the value of n.

SOLUTION

Data: $\theta_0 = 0°$, $\theta_1 = 90°$, $\theta_2 = 60°$, $W_1 = nW_2$

The work done by an external agent to rotate the magnet from θ_0 to θ is

$W = MB (\cos \theta_0 - \cos \theta)$

$\therefore W_1 = MB (\cos \theta_0 - \cos \theta_1)$

$= MB (\cos 0° - \cos 90°)$

$= MB (1 - 0)$

$= MB$

$\therefore W_2 = MB (\cos 0° - \cos 60°)$

$$= MB \left(1 - \frac{1}{2}\right)$$

$= 0.5\ MB$

$\therefore W_1 = 2W_2 = MB$

Given $W_1 = nW_2$. Therefore $n = 2$

Exercises | Q 6 | Page 264

An electron in an atom is revolving around the nucleus in a circular orbit of radius 5.3×10^{-11} m, with a speed of 2×10^6 m/s. Find the resultant orbital magnetic moment and angular momentum of the electron. [$e = 1.6 \times 10^{-19}$ C, $m_e = 9.1 \times 10^{-31}$ kg]

SOLUTION

Data: $r = 5.3 \times 10^{-11}$ m, $v = 2 \times 10^{6}$ m/s,

$e = 1.6 \times 10^{-19}$ C, $m_e = 9.1 \times 10^{-31}$ kg

The orbital magnetic moment of the electron is

$$M_0 = \frac{1}{2} evr$$

$$= \frac{1}{2}\left(1.6 \times 10^{-19}\right)\left(2 \times 10^{6}\right)\left(5.3 \times 10^{-11}\right)$$

$= 8.48 \times 10^{-24}$ A.m^2

The angular momentum of the electron is

$L_0 = m_e vr$

$= (9.1 \times 10^{-31})(2 \times 10^{6})(5.3 \times 10^{-11})$

$= 96.46 \times 10^{-36} = 9.646 \times 10^{-35}$ kg.m^2/s

Exercises | Q 7 | Page 264

A paramagnetic gas has 2.0×10^{26} atoms/m with atomic magnetic dipole moment of 1.5×10^{-23} A m^2 each. The gas is at 27°C.

a. Find the maximum magnetization intensity of this sample.

b. If the gas in this problem is kept in a uniform magnetic field of 3 T, is it possible to achieve saturation magnetization? Why?

SOLUTION

Data: $\frac{N}{V} = 2.0 \times 10^{26}$ atoms/m^3,

$\mu = 1.5 \times 10^{-23}$ Am^2, T = 27 + 273 = 300 K, B = 3 T, $k_B = 1.38 \times 10^{-23}$ J/K, 1 eV = 1.6×10^{-19} J

(a) The maximum magnetization of the material,

$$M_z = \frac{N}{V}\mu = \left(2.0 \times 10^{26}\right)\left(1.5 \times 10^{-23}\right)$$

$= 3 \times 10^3$ A/m

(b) The maximum orientation energy per atom is

$$\upsilon_{max} = -\mu B \cos 180^\circ = \mu B$$

$$= \left(1.5 \times 10^{-23}\right)(3) = \frac{4.5 \times 10^{-23}}{1.6 \times 10^{-19}}$$

$= 2.8 \times 10^{-4}$ eV

The average thermal energy of each atom,

$$E = \frac{3}{2}k_B T$$

where k_B is the Botzmann constant.

$\therefore E = 1.5(1.38 \times 10^{-23})(300)$

$$= 6.21 \times 10^{-21} \text{ J} = \frac{6.21 \times 10^{-21}}{1.6 \times 10^{-19}}$$

$= 3.9 \times 10^{-2}$ eV

Since the thermal energy of randomization is about two orders of magnitude greater than the magnetic potential energy of orientation, saturation magnetization will not be achieved at 300 K.

Exercises | Q 8 | Page 264

A magnetic needle placed in uniform magnetic field has magnetic moment of 2×10^{-2} A·m^2, and a moment of inertia of 7.2×10^{-7} kg·m^2. It performs 10 complete oscillations in 6 s. What is the magnitude of the magnetic field?

SOLUTION

Data: $M = 2 \times 10^{-2}$ Am^2, $I = 7.2 \times 10^{-7}$ kg.m^2,

$$T = \frac{6}{10} = 0.6 \text{s}$$

$$T = 2\pi\sqrt{\frac{I}{MB}}$$

The magnitude of the magnetic field is

$$B = \frac{4\pi^2 I}{MT^2}$$

$$= \frac{(4)(3.14)^2(7.2 \times 10^{-7})}{(2 \times 10^{-2})(0.6)^2}$$

$= 3.943 \times 10^{-3}$ T = 3.943 mT

Exercises | Q 9 | Page 264

A short bar magnet is placed in an external magnetic field of 700 gauss. When its axis makes an angle of 30° with the external magnetic field, it experiences a torque of 0.014 Nm. Find the magnetic moment of the magnet, and the work done in moving it from its most stable to the most unstable position.

SOLUTION

Data: B = 700 gauss= 0.07 tesla, θ = 30°, τ = 0.014 Nm, τ = MB sin θ

The magnetic moment of the magnet is

$$M = \frac{\tau}{B\ \sin\theta} = \frac{0.014}{(0.07)(\sin 30^\circ)} = 0.4 A.m^2$$

The most stable state of the bar magnet is for θ = 0°. It is in the most unstable state when θ = 180°. Thus, the work done in moving the bar magnet from 0° to 180° is

W =MB (cos θ_0 - cos θ)

= MB (cos 0° - cos 180°)

= MB [1 - (- 1)]

= 2 MB = (2)(0.4)(0.07)

= 0.056 J

Exercises | Q 10 | Page 264

A magnetic needle is suspended freely so that it can rotate freely in the magnetic meridian. In order to keep it horizontal position, a weight of 0.2 g is kept on one end of the needle. If the pole strength of the needle is 20 Am, find the value of the vertical component of the Earth's magnetic field.

SOLUTION

Data: M = 0.2 g = 2×10^{-4} kg, q_m = 20 A·m, g = 9.8 m/s^2

Without the added weight at one end, the needle will dip in the direction of the resultant magnetic field inclined with the horizontal. The torque due to the added weight about the vertical axis through the center balances the torque of the couple due to the vertical component of the Earth's magnetic field.

$$\therefore (\mathrm{Mg})\left(\frac{\mathrm{L}}{2}\right) = (\mathrm{q_m B_v})\mathrm{L}$$

The vertical component of the Earth's magnetic field,

$$\mathrm{B_v} = \frac{\mathrm{Mg}}{2\mathrm{q_m}} = \frac{(2 \times 10^{-4})(9.8)}{2(20)} = 4.9 \times 10^{-5}\mathrm{T}$$

Exercises | Q 11 | Page 264

The susceptibility of a paramagnetic material is χ at 27° C. At what temperature its susceptibility be χ/3?

SOLUTION

Data: $\chi m_1 = \chi$, T_1 = 27°C = 300 K, $\chi m_2 = \frac{\chi}{3}$

By Curie's law,

$$\mathrm{M_z} = \mathrm{C}\frac{\mathrm{B_0}}{\mathrm{T}}$$

Since $M_z = \chi_m H$ and $B_0 = \mu_0 H$

$$\chi_m H = C\frac{\mu_0 \mathrm{H}}{\mathrm{T}}$$

$$\therefore \chi_m = C\,\frac{\mu_0}{\mathrm{T}}$$

$$\therefore \chi_m \propto \frac{1}{\mathrm{T}}$$

$$\therefore \frac{\chi_{m1}}{\chi_{m2}} = \frac{T_2}{T_1}$$

$$\therefore T_2 = \frac{\chi_{m1}}{\chi_{m2}} \times T_1 = 3\frac{\chi}{\chi} \times 300 = 900K = 627^{\circ}C$$