17

THERMAL AND CHEMICAL EFFECTS OF ELECTRIC CURRENT

17.1 INTRODUCTION

In the earlier lessons we have learnt about the various characteristics of electric charges when at rest, for example the electric field and electrostatic potential. We must remember that these features, refer to the behavior of charges at macroscopic level. We have also learnt that when a charged body is connected to another uncharged body via a metal wire, the charge of the former is transferred to the latter through the metal wire. The flow of charge is said to constitute an electric current. However the electric resistances have an ability to oppose the flow of current through them. The flow of current and resistance in its flow causes variety of interesting phenomenons such as chemical effect, thermal effect etc.

In this lesson we shall learn about chemical and thermal effects of current and some of their applications in our daily life.

17.2 OBJECTIVES

After studying this lesson, you should be able to :

- *explain Joule's law of heating;*
- *calculate electric power consumed in heating process;*
- *discribe process of electrolysis;*
- *explain the Faraday's laws of electrolysis;*
- *mention the practical applications of electrolysis;*
- *understand the thermo-electric effect;*
- *state Seeback, Paltier and Thomson effects;*
- *make distinction between the different thermo-electric effects.*

17.3 THE THERMAL EFFECTS OF ELECTRIC CURRENT

Many modern household appliances such as electric heater, electric iron etc. utilize the heating effect of an electric current. Because of the resistance of the conductors the work must be done to maintain the flow of electrons (current) through them. Just like the mechanical energy used in overcoming mechanical friction, the energy used in overcoming electrical resistance is transformed into heat energy. Thus, when an electric current is passed through a resistor, work is done against the resistance resulting a heating effecting.

We know that in metals electric current is due to free electrons. These free electrons frequently collide with the atoms of the metals in lattice. At each collision they lose some of their kinetic energy and give it to the atoms which they strike. Thus, as the current flows through a wire or a conductor, it increases the kinetic energy of vibrations of the atoms and hence, it generates the heat in metal wire. The electric resistance of the metal is due to the atoms of lattice obstructing the drift of electrons.

To calculate the heat produced due to flow of current, we consider a circuit consisting of a resistor having resistance 'R' and a battery as shown in Fig. 17.1. Let a potential difference 'V' exists across the two ends 'a' and 'b' of the resistor and current I is flowing through it from 'a' to 'b'. As you are familiar that the flow of electrons is in opposite direction of current. So electrons are flowing in the circuit from 'b' to 'a'. Electrons entering at 'b' possess more energy than electrons leaving at 'a'. Hence there is a loss in potential energy of the electron while passing from 'b' to 'a' and this loss of potential energy appears as the heat energy during the flow of current through resistor 'R'.

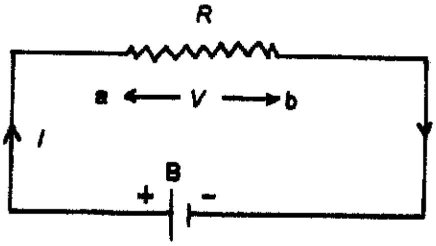

Fig. 17.1

You know that the potential energy of an electron at 'b' $= -eV_b$ and the potential energy of electron at 'a' $= -eV_a$. Where 'e' is the charge on the electron and V_a and V_b are the potentials of ends 'a' and 'b' respectively. Loss of potential energy per electron $= [-eV_b - (-eV_a)]$.

Further, the number of electrons crossing the section of wire in time 't' is,

$$= \frac{\text{total charge}}{\text{charge of each electron}} = \frac{Id}{e}$$

Thus, the total loss in potential energy of electrons in time 't' is,

$$W = \frac{It}{e}[-eV_b - (-eV_a)].$$

$$= It\,(V_a - V_b)$$

As you see from the Fig. 17.1 $V = (V_a - V_b)$

Thus, $W = I\,V\,t$ ...(17.1)

or $W = I\,(IR) \times t$ (From Ohm's law $V = IR$)

or $\boxed{W = I^2 Rt}$

As already said above, this work done is converted into heat, therefore the heat produced due to flow of electrons (electric current) through the resistor in time 't' will be,

$$H = W/J, \text{ where } J = 4.2\ J/\text{cal};\ J \text{ is mechanical equivalent of heat}$$

$$H = I^2 Rt \text{ Joule} = \frac{I\,Rt\ cal}{J} \;\ldots\ldots \qquad \ldots(17.2)$$

This relation is known as ***Joule's law of heating***. It clearly expressed the following facts that the heat produced is proportional to:

i) the square of current strength (I^2).
ii) the resistance (R).
iii) the time (t) for which the current flows.

This heating effect of electric current has many applications. Electric iron, the incandescent lamp (electric bulb), electric fans, electric furnace/oven, electric arc, electric welding, safety fuse, are some of the examples.

17.3.1 Electrical Power

You know that power is the rate of doing work, thus *energy liberated per second in an electric device is called electric power.* The electric power P, using the Eq 17.1 can be written as,

$$P = \frac{W}{t} = I\,V \text{ (Equation 17.1 } W = IVt)$$
$$P = I^2 R \quad (\text{where } V = IR, \text{ Ohm's law})$$
$$P = V^2/R \quad (\text{where } I = V/R, \text{ Ohm's law})$$

Here power P is in watt when I is in ampere, R is in ohm and V is in volt; larger units of power are often found to be more useful.

1000 watts = 1 Kilowatt

746 watts = 1 Horsepower

17.3.2 Calculation of Electrical Energy Consumed

You know that almost all household appliances are marked with their power-rating. The electrical bulbs (incandescent lamps), may be marked 15W, 25W, 60W or 100W or even higher. An automatic transistor may be rated at 1250 W, an electronic iron at 2000 watts, a small radio receiver at 25 W and a television set at 350 W.

When appliance is in use, you pay for the account of power, it requires for the time you use it. If the power of one watt is provided for one hour, the consumer pays for 1 watt-hour of energy. Similarly, if one kilowatt (1000 watts) is used for one hour, then you have to pay for one kilowatt-hour (kwh) of energy.

Electric energy used in kwh = Power (kw) × time in hr.

$$\begin{aligned} 1 \text{ kwh} &= 1000 \text{ Wh} \\ &= 1000 \text{ W} \times 60 \times 60 \text{ sec.} \\ &= 3600 \times 1000 \text{ W s} \\ &= 36 \times 100000 \text{ W s} \end{aligned}$$

$$\boxed{1 \text{ kwh} = 36 \times 10^5 \text{ J}}$$

Example. 17.1 : *Find the cost of operating an electric iron for 2 hours, if it draws 4 A on 220 volts circuit. The electric energy costs one rupee per kilowatt hour.*

Solution : $I = 4$ A, $t = 2$h. Because $P = IV$.
$V = 220$ volts. $P = 4 \times 220 = 880$ W
$= 0.88$ kW

Electric energy used in 2 hrs = $0.88 \times 2 = 1.76$ kwh
Now, 1.76 kwh cost = $1 \times 1.76 = 1.76$ rupees.
Thus, the cost of operating the iron = Rs. 1.76

INTEXT QUESTIONS 17.1

1. *Which of the two bulbs 25W and 100 W will have more resistance when both are operating at same voltage ?*

   ....

2. *On what factors does the thermal effect of electric current depend ?*

   ....

3. *List three appliances that works on the heating effect of an electric current in your house.*

   ....

4. *Answer whether the following statements are 'True' or 'False.'*
   a) Fuses work on the heating effect of an electric current.
   b) Electrical energy is measured in kilowatt.
   c) Electric power $P = I^2/R$ where I is current in Ampere and R is resistance in ohm.
   d) Electric appliances are usually marked in watt as per their power rating.

   ....

17.4 THERMO-ELECTRICITY

We know that electric energy can be converted into heat energy. From the principle of physical symmetry, it is natural to expect the existence of phenomenon in which heat energy can be converted into electrical energy. It turns out that such process is possible. This effect, *where electricity is produced by the direct conversion of heat energy into electrical energy, is known as* ***thermo-electric effect****. As you know that heating effect of an electric current is an irreversible effect while thermo-electric effect is reversible effect.* If a circuit contains conductors of different materials, and the junctions between those conductors are maintained at different temperatures, then electric current are found to flow in the circuit. Three related effects of this kind are found. They are :

a) Seebeck effect
b) Peltier effect, and
c) Thomson effect

17.4.1 Seebeck Effect

Seeback discovered in 1826 that an *electric current could be produced by* thermal means alone. When two dissimilar metals are connected as in Fig. 17.2 and one of the junction is heated, there is a current in the circuit. This current is known as thermo-electric current. The emf developed in the circuit, which can be determined from the current and resistance, is called the thermo-electric emf and is of the order of a few millivolts. This effect is called ***Seebeck effect.*** The pair of metals in Fig. 17.2 constitutes a thermocouple.

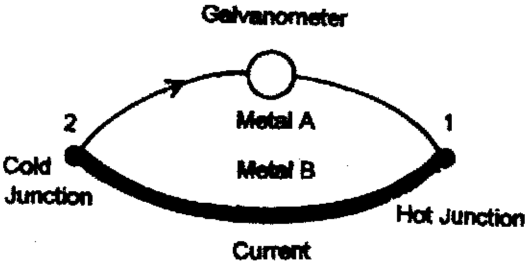

Fig. 17.2: Seebeck Effect

Seebeck studied the behavior of many pairs of metals and arranged them in a series in such a way that *when two metals from this series were connected to form a thermo-couple, the current at the hot junction was from the metal occurring earlier in the series to the one occurring later.* Further its magnitude, depends upon the extent of separation of the metals in the series.

The ***Seebeck series*** is :

Bi, Ni, Co, Pd, Pt, U, Cu, Mn, Ti, Hg, Pb, Sn, Cr, Mo, Rh, Ir, Au, Ag, Zn, W, Cd, Fe, As, Sb, Te.

This series indicate that Bismuth (Bi) and Tungston (Tc) thermo-couple is the most sensitive as it will produce large thermo-emf. The current in this thermo-couple will flow from Bismuth to Tungston across the hot junction.

If one of the thermo-couple junction is kept at a fixed temperature and other one is heated, the Seebeck thermo emf in the circuit will vary with temperature difference of the junctions. The variation of thermo emf with this difference of temperature is shown in Fig 17.3. The temperature T_n of the hot junction at which there is maximum current in the circuit, is called ***neutral temperature***. The temperature T_i of the hot junction at which there is zero current at which reversal of current is about to begin, is called the ***temperature of inversion***. For copper-iron thermo-couple, the neutral temperature is 275° C and the inversion temperature is 550° C, when the cold junction is at 0° C. If the temperature of the cold junction is raised to 10° C, the neutral temperature will remain the same

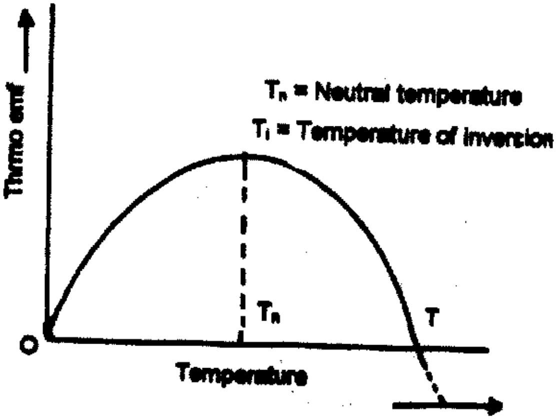

Fig. 17.3: Variation of thermo-emf with temperature difference

as before but the inversion temperature will become 540° C. Thus, *neutral temperature for a given thermo-couple is constant while the inversion temperature is as much* above it as the cold junction temperature is below it. For majority of thermo-couple, the temperature-thermo emf graph (as shown in Fig. 17.3) is very nearly a parabola. In general the Seebeck emf (E) can be expressed as.

$$E = aT + bT \qquad \text{....(17.3)}$$

Where T is the temperature difference of two junctions in K and a and b are constants, and they show the characteristics of the given thermo-couple.

The rate of change of thermo electric emf (E) with temperature difference T is known as the *thermoelectric power* (P). Thus,

$$P = \frac{dE}{dT}$$

$$= \frac{d(aT + bT^2)}{dT}$$

$$P = a + 2bT.$$

Thus P varies with T in a linear way.

If T_c is the temperature of the cold junction, T_n is the neutral temperature and T_i the temperature of inversion for a given thermo-couple then, it is found that

$$\boxed{(T_i - T_c) = 2(T_n - T_c)} \qquad \text{....(17.4)}$$

17.4.2 Peltier Effect

Peltier in 1834 discovered that whenever a current flows in a thermo-couple, heat is absorbed at the hot junction and liberated at the cold junction. *This absorption or evolution of heat at a junction when a current is sent through a thermo-couple is known as the **Peltier effect**.* To study the Peltier effect, insert a battery in the circuit of Fig. 17.2 and pass a current as shown in 17.4. It is observed that heat is absorbed at junction 1. while it is generated at junction 2. On compiring Fig. 17.3 and 17.4 you may note that particular junction is cooled which must be heated in order to give a thermo-couple current in the same direction as the battery current.

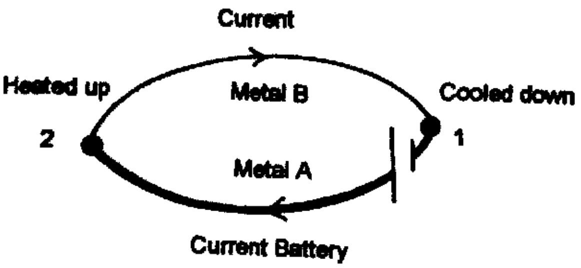

Fig. 17.4: Peltier effect

The phenomena on of Peltier effect is the under lying principle of thermo-electric refrigerators. The energy absorbed (or evolved) at a junction, when a unit charge passes through it is called the ***Peltier coefficient*** and is denoted by π the usual practice is to measure charge in coulomb and heat in joule and hence π will be expressed as joule/coulomb i.e. volt. This coefficient depends on the temperature and material of the junction. The rate at which Peltier heat is transferred is proportional to the power of the current or equal to πIt.

The Peltier effect is reversible. When the direction of the current is reversed, the Peltier heat is same but in the opposite direction.

Important difference between Joule heating effect and Peltier thermo-electric effect are listed below :

a) Peltier effect takes place at a junction only but the Joule heating is distributed along the entire length of the conductor.
b) Peltier effect is reversible while the Joule heating is irreversible.
c) Heat generated is proportional to I^2 in Joule heating effect while it is proportional to I in Peltier effect.
d) In Joule effect, heat is always generated while in Peltier effect heat is absorbed at one junction and evolved at other.

17.4.3 Thomson Effect

Thomson discovered that when a temperature gradient exists along the conductor and a current is allowed to pass through the conductor, then the absorption or evolution of heat can take place in the conductor itself. This phenomenon is known as ***Thomson effect.***

Consider a copper rod AB. Let a symmetrical temperature gradient be maintained along the length of the rod by heating it at the central point C to a temperature T^2 and keeping the ends A and B at the lower temperature T_1 (see Fig. 17.5). In this figure, the height of ordinates at each point is a measure of temperature of the rod at that point. Now if the current is passed along the copper rod in the direction ACB, it is observed that heat is absorbed when the current flows from A to C i.e. from cold to hot parts whereas heat is evolved when current flows from C to B i.e. from hot to cold parts. Thus, there is a transfer of heat due to current in the flow direction. Metals like silver, zinc, antimony and cadminium etc. shows similar behavior as that shown by copper. All these metals are said to posses a ***positive Thomson effect.***

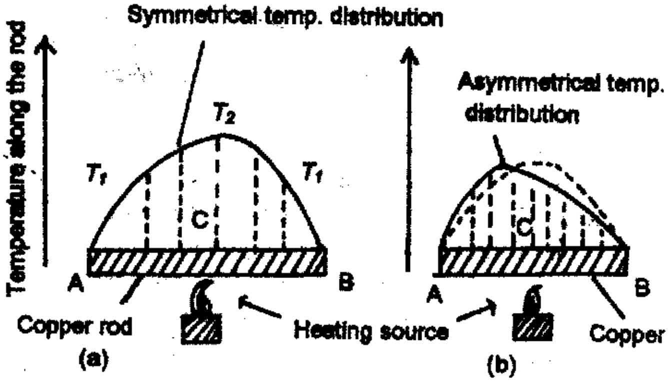

Fig. 17.5

Metals like iron, bismuth, cobalt, platinum and nickel evolve heat, when current flows from cold to hot and heat is absorbed, when current flows from hot to cold parts. Obviously, for such metals, the transfer of heat due to passage of current take place in the direction opposite to the direction of current flow. These metal behave differently then copper and effect shown by them is termed as ***negative Thomson effect.***

It is worth while to note that in either of the two cases (i.e. positive or negative), Thomson's effect gets reversed when the current flows in reversedirection. Following important point had been established on the basis of extensive experimental studies.

(i) The rate at which Thomson heat is transferred (H) into a small region of a wire carrying current I and having temperature difference dT, is proportional to IdT i.e.

$$H = \sigma I \, dT \qquad \text{.....(17.5)}$$

Where σ is Thomson coefficient. It is measured in joule and some time called the ***specific heat of electricity.*** It is regarded as positive when a current opposite to the direction of temperature gradient causes an absorption of heat by the conductors.

(ii) The Thomson effect is reversible. If the direction of current is reversed, heat is absorbed in the region where it was previously evolved or vice-versa.

(iii) The Thomson coefficient is characteristic of a particular metal under consideration. For metals like copper it is positive and for metal like iron it is negative. The Thomson coefficient for lead is practically zero.

(iv) Thomson coefficient is a function of temperature and is not constant.

INTEXT QUESITONS 17.2

1 *Distinguish between seebak effect and Peltier effect.*

....

2. *What do you mean by the fact that the Pelter effect is reversible ?*

....

3. *If the cold junction of a thermo-couple is $0^{\circ}C$ and the temperature of inversion in $60^{\circ}C$, what is the value of neutral temperature ?*

....

17.5 ELECTROLYSIS

Aqueous solutions of inorganic salts, acids and bases, conduct electricity and these are called ***electrolytes.*** The process of conduction of electricity through solutions and through molten salts is called ***electrolyis.*** The phenomenon of electrolysis i.e. the passage of current through a conducting liquid solutions, is different from the conduction of electricity through metals in following two important a spects.

1) Flow of current causes a chemical reactions. Chemical reactions at the anode are different from those at cathode.

2) Conduction in electrolytes is due to ions which are produced by the dissociation of electrolyte in the solvent. Unlike conduction in metal, here matter is actually transported through the solution.

17.5.1 Laws of Electrolysis

The phenomenon of electrolysis was first studied in detailed and systematic way by Faraday, whose observations led him to make two statements. These are known as Faraday's Laws of electrolysis.

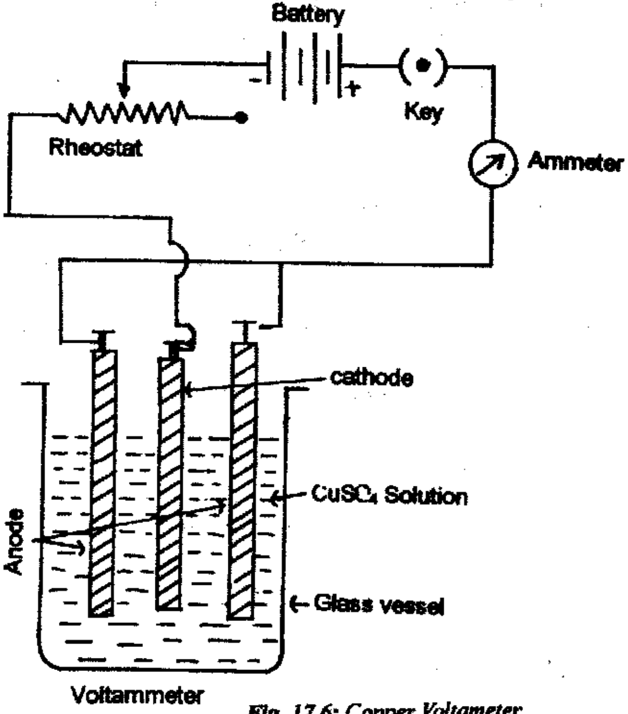

Fig. 17.6: Copper Voltameter

The Fig. 17.6 shows a setup called voltameter consisting of the cathode in centre, surrounded by two electrodes (connected together) which form the anode. The outer vassel, generally of glass, contains the electrolyte. The choice of the metal electrodes depends upon the nature of the electrolyte and chemical change it is likely to undergo. Using the copper voltameter as shown in Fig 17.6. Faraday observed that the mass of copper (m) deposited on the cathode is proportional both to current (I), and to the time (t) for which the current (I) was allowed to flow through the voltameter. From the result, it follows that,

$$m \propto It$$

$$m = Z\,It = Z\,Q \qquad \text{......(17.6)}$$

where Z is the constant of proportionality.

(since $I \times t = Q$ where Q is the amount of charge flowing through the electrolyte)

Thus, *the mass of an element or radical deposited or liberated at an electrode is proportional to the quantity of electricity flowing through the electrolyte*. It is known as ***Faraday's First law of electrolysis.***

The constant Z is known as the ***electrochemical equivalent*** of the element or radical and may be *defined as the mass liberated by the passage of a unit quantity of electricity through the electrolyte.*

Faraday connected number of voltameter in series so that the same quantity of electricity could pass through all the electrolytes placed in different voltameter. When he measured the amounts of element liberated in such a situation, it was always found them to be in the same ratio as their chemical equivalent weights. He was thus led to frame his ***second law*** in the form as :

When the same quantity of electricity passes through the solutions of different electrolytes, the masses of the elements or radicals liberated at the electrodes are in the same ratio as their chemical equivalent weights

Thus, if masses m_1, m_2, m_3 .... of the equivalent weights E_1, E_2, E_3.............. are liberated by the passage of the same quantity of electricity. We have

$m_1.\, m_2.\, m_3$ .... $= E_1.\, E_2.\, E_3$ . ...

From Faraday's second law of electrolysis it follows that the same quantity of electricity is needed to liberate 1 kg equivalent at any substance. Precise measurements have shown that this quantity is 96500×10^3 coulomb which is also known as ***one Faraday*** i.e

$$1 \text{ Faraday} = 96500 \times 10^3 \text{ coulomb}$$

Form the Eq. 17.6 we get $Z = m/Q$

Thus, Z, *the electrochemical equivalent is the amount of substance liberated by passage of* 1 coulomb of charge. Hence,

$$Z = \frac{E}{96500 \times 10^3} \text{ kg}$$

where E is the ***chemical equivalent weight***. Using this value of Z in Eq. 17.6 we can easily obtain:

$$m = Z\,It = \frac{E}{96500 \times 10^3} \times I \times t$$

Above relation may be considered as the expression incorporating ***both laws of electrolysis.***

17.5.2 Explanation of the Process of Electrolysis

The theory of ionic dissociation can be used to explain Faraday's law of electrolysis. Considering the case of $CuSO_4$ we know that this molecule will split into Cu^{++} and SO_4 ions. Now every time a SO_4 ions reaches the anode under the influenced of electric field, it dissolves one copper atom from the anode. At the same time, one copper atom is deposited at the cathode. Thus, the mass of $CuSO_4$ in solution is unaltered and the loss in mass of the anode equals to the gain in mass of cathode. Further, the mass of copper deposited in this case is proportional to the number of ions reaching it. Since all the ions carry the same charge, the mass deposited will be proportional to the quantity of electricity depositing them as stated by Faraday's first law.

17.5.3 Applications of Electrolysis

Electrolysis is one of the very important chemical effect of electrical current and has many applications. Some of these are mentioned below :

(i) ***Electroplating*** : You all have seen shinning handle of your bicycle made of iron. Do you know how it is made to shine ? It is electroplated with cromium or nickel. *The process of depositing a thin layer of one metal over another metal by the method of electrolysis is known as electroplating*. The article of cheap metals are coated with precious metals to make their look more attractive. The article to be electroplated is made the cathode and the metal to be deposited is made anode. A soluble salt of the precious metal is taken as the electrolyte. When current is passed, a thin layer of metal is deposited on the article made cathode.

(ii) ***Extraction of metals from the ores :*** Certain metals like Na, Aℓ, Ca, Mg, Zn, Cu etc. are extracted from their ores by electrolysis. Ores solution acts as electrolyte and metal ions are collected at electrodes. You will learn more about it in your chemistry lessons.

(iii) ***Purifications of metals :*** Metals can be purified by electrolysis. The impure metal sheet is made the anode and a pure metal sheet as the cathode in a large electrolytic cell. The soluble salt to the pure metal is used as electrolyte. When current is passed, pure metal out of anode dissolves into electrolyte solutions and get deposited on the pure metal sheet acting as cathode. Copper is purified in this manner.

(iv) ***Electrotyping :*** The exact copies of the metallic type used in the printing work and the engraved blocks on the metal can be prepared by the process of electrolysis. A sheet of wax is first pressed against the type set or block. The impression optained on wax is made conducting by coating it with graphite powder. Then it is copper plated by the process of electrolysis. The sheet so obtained is a copy of the type of the block.

(v) ***Anodising :*** It is the process of coating aluminium with its oxide, electrochemically to protect it against corrosion. In dilute sulphuric acid as electrolyte, the aluminium article is made the anode. Sometime, to give the surface of the article beautiful colours, dyes are mixed in the electrolyte.

(vi) ***Medical Applications :*** Electrolysis is finding applications in medical science too. It is used for nerve stimulation especially for polio, for removing unwanted hair on any part of the body etc.

INTEXT QUESTIONS 17.3

1. *On what factors does the mass of radical deposited at electrode depends ?*

   ....

2. *For an electrolysis process if we plot a graph between mass deposited and time, then what will be the shape of curve?*

   ....

3. *One Faraday is equal to how many coulomb?*

   ....

4. *In CuSO voltameter, on which electrode will the copper ions will deposit.*

   ....

5. *Answer whether the following statement are True or False.*
   - a) *In an electrolyte solution, current is maintained by the flow of electron.*
   - b) *The matter is actually transported through the solution in electrolysis.*
   - c) *There are only two laws of electrolysis.*
   - d) *Electroplating is based on electrolysis.*

   ....

17.6 WHAT YOU HAVE LEARNT

- The electric current through the conductor can produce heating.
- The electron on their way collide frequently with atoms. In each collision, kinetic energy is lost and converted into heat energy.
- Heat generated in a simple electric circuit is proportional to (i) square of the current (ii) the resistance, and (iii) the time during which current flows.
- The unit of power is watt.
- The difference between conduction of electricity through a metallic wire and an electrolyte.

- The definitions of Faraday, electro-chemical equivalent.
- The electrolysis has various practical application.
- Thermo-electricity-phenomenon involves the conversion of heat energy into electrical energy.
- According to Seebeak effact if two junctions of a thermo-couple are kept at different temperaturs an emf is generated in the circuit.
- If an electric current is passed through a thermo-couple, heat is absorred at one junction and liberated at the other junction. This is called Peltier effect.
- According to thomson effect when temperature gradient exist along the conductor and current is allowed to pass through the conductor then the absorption or evolution of heat can take place across the conductor itself.
- The variations of Seebeck emf with temperature difference of the junctions is generally parabolic.
- The neutral temperature, is the maximum temperature beyond which thermo emf starts decreasing.
- Peltier effect is reversible and different from Joule's effect.
- The Thomson coefficient can be positive or negative depending upon the nature of metal. It is practically zero for lead.
- Thomson effect is again reversible effect.
- The Thomson coefficient is a function of temperature and not constant.

17.7 TERMINAL QUESTIONS

1. State and explain Joule's law for the rate of production of heat for a coil of wire carrying an electric current. Define Electric power and state its units.
2. Discuss the phenomenon of electrolysis. State and explain the Faraday's law of electrolysis.
3. Explain some practical applications of electrolysis.
4. Explain the terms : Electrolysis, electrolyte, electrodes, voltmeter.
5. How does the conduction of electricity in a metallic conductor differ from that in electrolyte? Why is the conductivity of an electrolyte law as compared to a metal at room temperature?
6. What is a Seebeck effect? Discuss the variation of Seebeak emf with temperature.
7. What is meant by Peltier effect? How does it differ from Joule effect?
8. What is Thomson effect? Explain it by giving proper diagram.
9. Define Thomson coefficient of an metal. Give its unit. Is it a constant?