ELECTRICAL HEATING

Introduction: The process of heating using electrical energy is known as electrical heating. Heating is required for both domestic and industrial purposes. The following are some of the applications of electrical heating:

1. **Domestic purposes** – The heating in general is required for the following purposes in case of domestic scenario: -
   - Hot plates for cooking
   - Room heaters
   - Immersion heaters for water heating
   - Electric irons
   - Electric toasters
   - Electric ovens for baking etc.

2. **Industrial purposes** – The heating in general is required for the following purposes in case of industrial scenario: -
   - Melting of metals
   - Moulding of glass
   - Heat treatment processes
   - Baking of insulators
   - Enamelling of copper wires etc.

Advantages of electric heating – The following are some of the advantages of electric heating:

1. **Cleanliness** – In the absence of dust and ash of the fuel, charge never gets contaminated.
2. **Absence of flue gases** – In the absence of flue gases and soot, atmosphere and charge are not polluted. Therefore the operation is clean and hygienic.
3. **Ease of control** – In case of electrical heating the temperature of charge can be easily controlled easily manually or fully automatic. Also it is possible to adopt any heating and cooling cycle.
4. **Better working conditions** – As the radiation losses are low, working with electric furnaces is convenient and cool as well as these furnaces provide noiseless operation.
5. **Ease of adaptation** – In case of electric heating there is greater adaptability as heating can be done locally at certain local spots or the material can be uniformly heated as per the requirements.
6. **Very high efficiency of utilization** – In case of electric heating, the source of heat can be brought directly to the point where heat is required thereby reducing transfer losses and increases the efficiency. Since there are no products of combustion which result in heat losses in their removal from combustion chamber.
7. **Uniform heating** – In all the methods of heating by burning fuels, heat is conducted from the outer surface of material to inside of the material due to which the inside core relatively remains cold. However in case of electrical heating it is possible to generate heat inside the core of the material thereby resulting in uniform heating.

8. **Heating of non conducting materials** – A non – conducting (or insulating) material can be heated uniformly only with electric heating since heat is generated inside the material itself.
9. **Cheap furnaces** – Since there are no chimney and grating, the electric furnaces specially do not require protective atmospheres and hence are cheap. Also the maintenance required by these furnaces is very small.
10. **No limit to upper maximum temperature** – There is no limit of the maximum upper temperature limit. The maximum temperature which can be obtained using electrical heating depends on the heat handling capability of the material used for heating.

Modes of heat transfer – Heat transfer is defined as the transmission of energy from one region to another as a result of temperature gradient and it takes place by three modes – conduction, convection and radiation. In majority of practical cases the heat transfer takes place due to the combination of all the modes of heat transfer.

i. **Conduction** – It is the transfer of heat from one part of a substance to another part of the same substance, or from one substance to another in physical contact with it, without appreciable displacement of molecules forming the substance. In solids, the heat is conducted by the two mechanisms (a) by lattice vibration (b) by transport of free electrons. In case of gases, the kinetic energy of molecules is exchanged by their collision due to continuous random motion. In case the mechanism is closer to gases except that in this case the molecules are more closely packed and intermolecular forces also affect the process. The thermal conductivity of a material is defined as the amount of energy conducted through a body of unit area, and unit thickness in unit time when the difference between the faces causing heat flow is unit temperature difference. Thermal conductivity of a material depends on material structure, moisture content, density of the material and pressure and temperature.

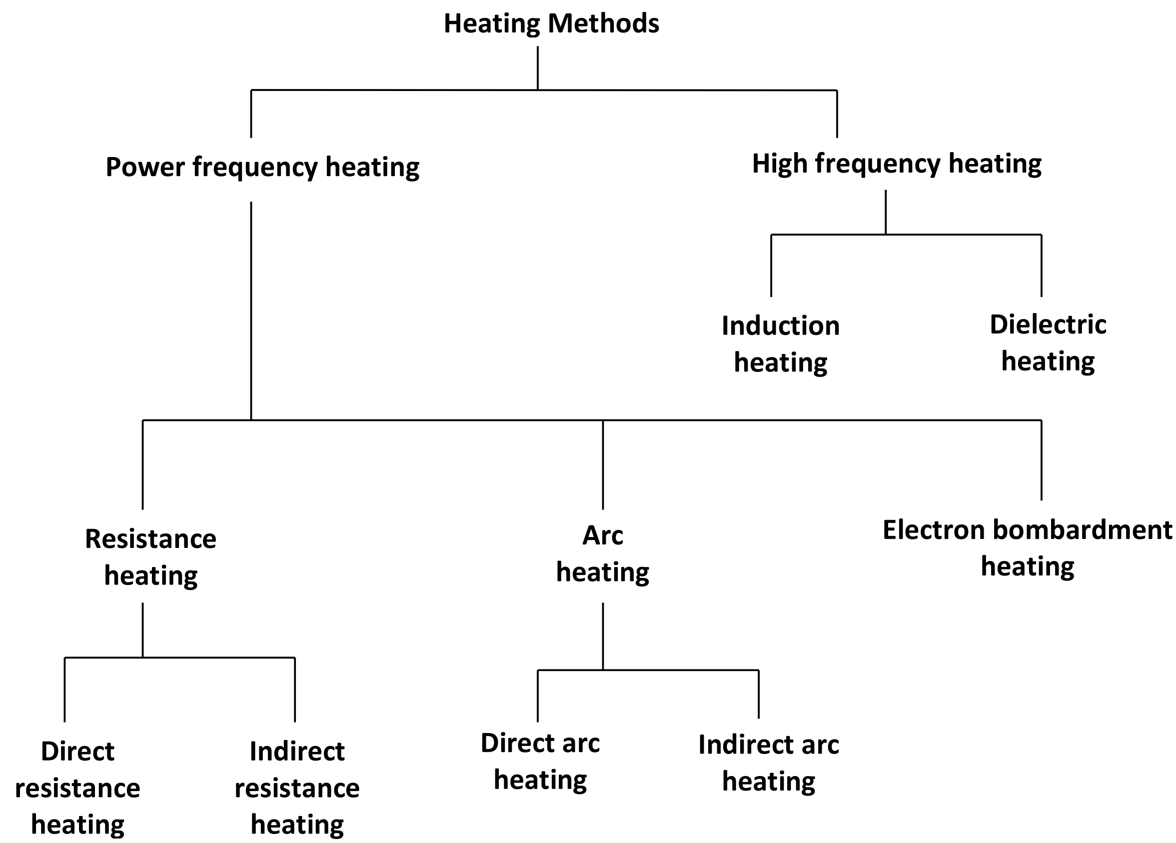
ii. **Convection** - It is the transfer of heat within a fluid by mixing of one portion of the fluid with the other. This mode of heat transfer is only possible in fluid medium. This mode is basically conduction in a very thin fluid layer at any surface and then mixing caused by the flow. The heat flow depends on the properties of fluid and is independent of the properties of the material of the surface. It however depends on the shape of the surface which influences the heat flow and hence heat transfer.

iii. **Radiation** – It is the transfer of heat through space or matter by means other than conduction and convection. The heat transferred by radiation can be considered as electromagnetic waves or quanta similar in nature to light and radio waves. All bodies radiate heat and hence transfer of heat by radiation occurs because hot body emits more heat than it receives and a cold body receives more heat than it emits. The radiant energy requires no medium for propagation and will pass through vacuum. The following are the properties of radiant heat in general:
   a. It does not require the presence of a material medium for its transmission.
   b. It can be reflected from the surfaces and obeys ordinary laws of reflection.
   c. It travels with the speed of light.

d. It shows interference, diffraction and polarization etc. just like light waves.
e. If follows the law of inverse square.

The wavelength of heat radiations is longer than that of light waves, hence they are invisible to the eyes.

Methods of Heating – The following are the different methods of electric heating



Direct resistance heating – In this method of heating, the material or charge to be heated is taken as resistance and current is passed through it. The charge may be in the form of powder, pieces or a liquid. Two electrodes are immersed in the charge and connected to supply in case of d.c. or single phase a.c. supply. Three electrodes are immersed in the charge and connected to supply in case of three phase a.c. supply. When some pieces of metal are to be heated then some highly resistive powder is sprinkled over the surface of pieces to avoid direct short circuit.

The current flows through the charge and heat is produced. This method has high efficiency since heat is produced in the charge itself. As the current in this case is not easily variable, therefore automatic temperature control is not possible. However uniform and high temperature can be obtained. This method of heating is used in salt bath furnaces and in the electrode boiler for heating water. The fig. A shows a direct resistance furnace.

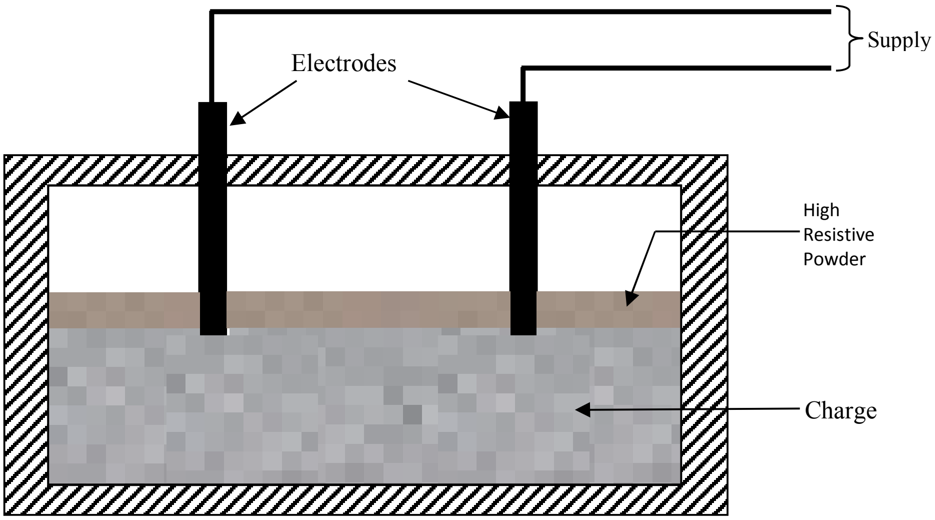


Fig. A Direct Resistance Heating

Indirect resistance heating – In this method of heating, electric current is passed through a wire or other high resistance material forming a heating element. The heat proportional to I^2R loss produced in the heating element is delivered to the charge by one or more of the modes of transfer of heat i.e. conduction, convection and radiation. If the heat is transferred by conduction the resistor must be in contact with the charge. An enclosure known as heating chamber is required for heat transfer by radiation and convection for the charge. For industrial purposes, where a large amount of charge is to be heated then the heating element is kept in a cylinder surrounded by jacket containing the charge.

The fig. B shows indirect resistance heating. This arrangement provides a uniform temperature. Automatic temperature control can be provided in this case. This method of heating is used in room heaters, immersion water heaters and in various types of resistance ovens employed in domestic and commercial cooking and salt bath furnaces.

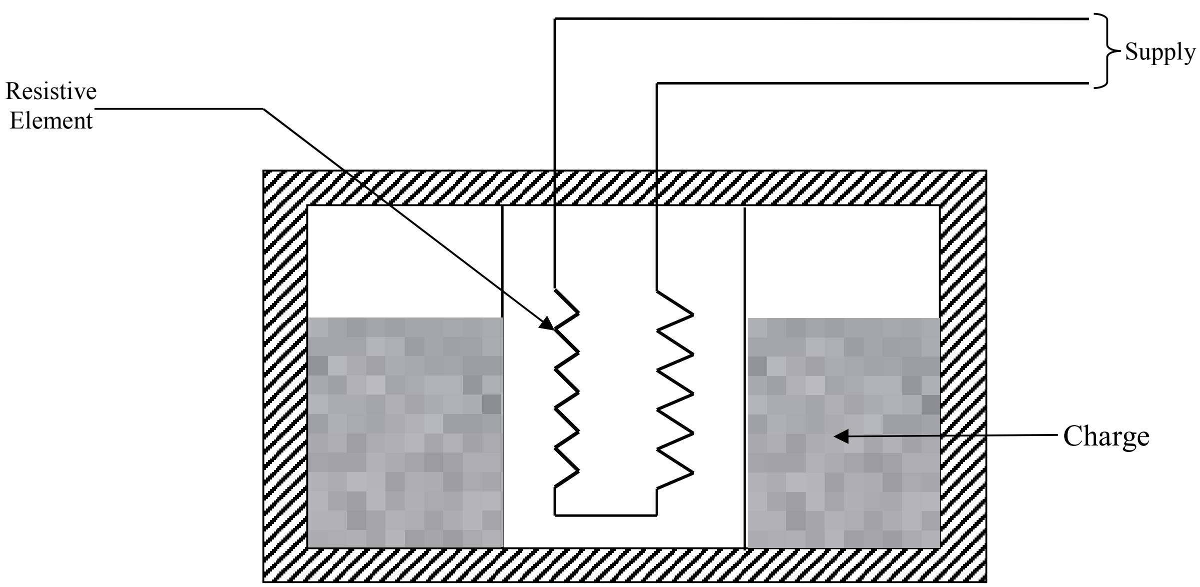


Fig.B Indirect Resistance Heating

Requirements of a good heating element – A good heating element should process the following properties:

1. It should have high specific resistance so that small length of wire may be required to produce given amount of heat.
2. It should have high melting temperature.
3. It should not oxidize at the temperature of the furnace otherwise we will require frequent replacement of element.
4. It should have low temperature coefficient of resistance so that at starting from cold it should not take heavy current.
5. It should have positive temperature coefficient of resistance.
6. It should have high ductility and flexibility.
7. It should have high mechanical strength of its own.

Different types of heating material – There are different types of alloys used for heating elements. The choice of the material depends upon the service conditions such as maximum operating temperature. These alloys are mainly divided into four classes as follows:

Type of Alloy	Nickel Copper	Nickel Chromium Iron	Nickel Chromium	Iron Chromium Aluminium
Composition	45% Ni, 55% Cu	60% Ni, 24% Fe, 16% Cr	80% Ni, 20% Cr	20-30% Cr, 5% Al, 65 – 75% Fe
Maximum temperature of operation	400^0C	950^0C	1150^0C	1150^0C to 1350^0 C
Specific resistance at room temp. of 20^0 C	49 $\mu\Omega/cm^3$	110 $\mu\Omega/cm^3$	109 $\mu\Omega/cm^3$	140 $\mu\Omega/cm^3$
Specific gravity	8.88	8.28	8.36	7.2

Temperature Control of resistance furnace: The temperature of the resistance furnace depends on voltage of supply and current through the element both of which are independent parameters. Hence the temperature of the resistance furnace can be controlled by the following methods:

1.) By varying voltage across element – This can be achieved by the following methods:
   i. By using auto transformer or induction regulator
   ii. By using a series impedance
   iii. By using a variable voltage supply

2.) By varying the resistance of elements – This can be achieved by the following methds:
   i. By using variable number of heating elements
   ii. By using series parallel or star delta arrangement of elements.

3.) By periodically switching on and off the electric supply

Varying voltage using auto transformer or induction regulator – The temperature of the resistance furnace can be controlled by auto transformer by providing different taps on the auto transformer as shown in fig.1 or by varying the position of the rotor of an induction regulator as shown in fig.2 to get a variable voltage supply.

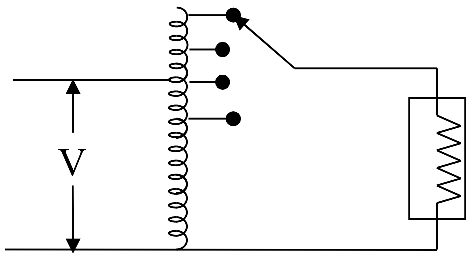


Fig. 1 Auto transformer for temperature control of resistance furnace

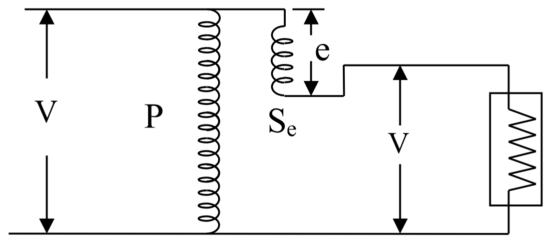


Fig.2 Equivalent circuit of induction regulator

Varying voltage by using series impedance – The temperature of the resistance furnace is varied by connecting impedance in series with the element and a reduced voltage is applied to the element and hence the current also gets reduced as shown in fig.3 However this method results in wastage of energy and hence it is used only for small furnaces.

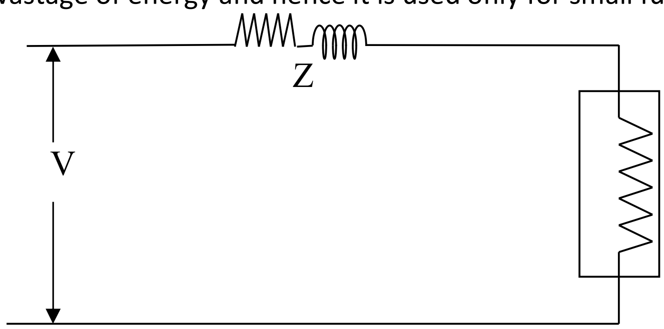


Fig. 3 Using Series Impedance

Varying voltage by using variable number of elements – If **R** is the resistance of one element and **n** be the number of elements working in parallel. The total resistance can be varied by putting or removing more resistances in parallel. In this method the temperature can be changed by putting more and more resistances in parallel in circuit. However the heating would be uneven if the elements used are not well distributed which results in complicated wiring.

Varying voltage by using series parallel or star delta arrangement – In case of single phase supply, the heating elements can be arranged is series (for low temperature) or in parallel (for high temperature) by means of a series parallel switch. In case of three phase supply, the heating element can be arranged in star (for low temperature) or in delta (for high temperature) by means of a star delta switch.

Varying voltage by periodically switching on or off electric supply – The temperature of a oven can also be controlled by periodically switching on or off electric supply particularly in case of small ovens. Here supply is given to the oven through a thermostat switch which switches on and switches off the supply at particular temperatures. The final temperature is proportional to the ratio of

$$\left(\frac{time\ interval\ switch\ remains\ on}{total\ time\ interval\ of\ on\ off\ cycle}\right)$$

The advantage of this method is that it is more efficient than series impedance method.

Design of heating element – The heating elements are normally made of wires of circular cross – section or rectangular conducting ribbons. Under steady state conditions, a heating element dissipates as much heat from its surface as it receives the power from the electric supply. If P is the power input and H is the heat dissipated by radiation, then under steady state conditions P = H.

Heat radiated by a body, as per Stefan's law of radiation is given by

$$H = 5.67\ K\ e\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right]\ W/m^2$$

where T_1 and T_2 are absolute temperatures in Kelvin of hot and cold bodies respectively. e = emissivity whose values is unity for black body and 0.9 for heating elements. K = radiating efficiency whose values is unity for single element and may go down upto 0.5 for many elements. Both e and K are dimensionless.

$$Since\ P = \frac{V^2}{R} \quad therefore\ R = \frac{V^2}{P}$$

$$Also\ R = \rho\frac{L}{A} \quad or\ R = \frac{\rho L}{\pi/4 d^2}$$

$$therefore\ P = \frac{\pi d^2 V^2}{4\rho L}$$

$$or\ \frac{L}{d^2} = \frac{\pi}{4}\frac{V^2}{P\rho} \qquad (1)$$

If H is the heat dissipated by radiation per second per unit surface area of the wire then heat radiated per second = (πd) x L x H

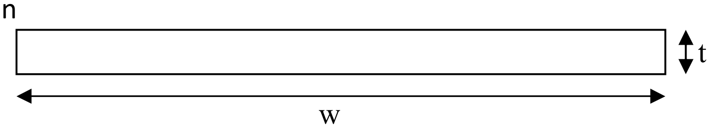
Under steady state conditions P = (πd) x L x H

$$\text{Therefore}\ \frac{\pi d^2 V^2}{4\rho L} = (\pi d)\times L\times H$$

$$or\ \frac{d}{L^2} = \frac{4\rho H}{V^2} \qquad (2)$$

From equation no. (1) and (2) we can find the values of L and d.

In case of ribbon type element if 'w' and 't' are the width and thickness of the ribbon respectively then



$$P = \frac{V^2}{R} = \frac{V^2}{\rho L/A} = \frac{V^2}{\rho L(w \times t)} = \frac{V^2 wt}{\rho L} \qquad (3)$$

$$\text{Or } \frac{L}{wt} = \frac{V^2}{\rho P} \qquad (4)$$

Heat lost from ribbon surface = 2(w + t)LH Since in case of the ribbon type of element the thickness 't' is negligible in comparison with respect to width. Therefore heat lost from the ribbon surface is given by = 2wLH (5)

From equation (3) and (5) we have

$$\frac{V^2 wt}{\rho L} = 2wLH \qquad (6)$$

$$\text{Or } \frac{t}{L^2} = \frac{2\rho H}{V^2} \qquad (7)$$

The values of L and w can be found by solving equation (6) and (7)

Infra-red or Radiant Heating – In the ordinary resistance furnaces the heat is transferred from heating elements to the charge partly by radiation and partly by convection. For low or medium temperatures purely radiant or infra-red heating is used. In this method of heating, the heating element consists of tungsten filament lamps together with reflectors to direct the whole of the heat emitted on to the charge. The lamps are operated at 2300^0 C instead of 3000^0 C giving greater proportion of infra-red radiation and a longer life. The reflectors are plated with rhodium which being harder has a longer life and is easier to maintain.

The lamps employed are usually rated between 250 and 1000 watts operating at 115 volts. The operation at low voltage results in a robust filament. The plant sizes range from a single lamp to chambers containing several hundred kW of lamps. This arrangement results in charge temperature between 200^0 C and 300^0 C. The following are the advantages of infra-red heating:

i. Rapid heating
ii. Compactness of heating units
iii. Flexibility

This type of heating method is used in (i) paint stoving (ii) drying of radio cabinets and wood furniture (iii) pre heating of plastics prior to moulding (iv) softening of thermo plastic sheets (v) drying of pottery, paper, textiles etc. where moisture content is not large.

The best results by using infra-red heating are obtained when the infra-red lamps are located at a distance of 25 to 30 cm from the object to be heated.

Electric Arc Furnace – When voltage across two electrodes separated by an air gap is increased, a stage is reached when the voltage gradient in the air gap is such that the air in the gap becomes good conductor of electricity. The arc is said to exist when electric current passes through the air gap. A very high voltage is required to establish an arc across an air gap but to maintain an arc small voltage may be sufficient. An arc can also be established by short circuiting the two electrodes momentarily and then withdrawing them back. In this method of striking an arc, high voltage is not required. The arc drawn between two electrodes produces heat and has a temperature between 10000 C and 35000 C depending upon the material of the electrodes used.

Usually arc furnaces are of cylindrical shape but recently conical shaped shells have been used. However even in conical shapes the horizontal cross-section is cylindrical. The advantage of a cone shape is less power consumption, less radiation losses, reduced melting time. The arc furnaces are of two types – direct arc furnace and indirect arc furnace.

Direct arc furnace – In this type of furnace, the charge itself acts as one of the electrodes. The arc is made to strike between one electrode and charge itself. As a result the current flows through the body of the charge developing heat due to electrical resistance of the charge in addition to the heat radiated from the arc. There are two types of direct arc furnaces namely those with non conducting bottom as shown in fig.4 (a) and those with conducting bottom as shown in fig.4 (b).

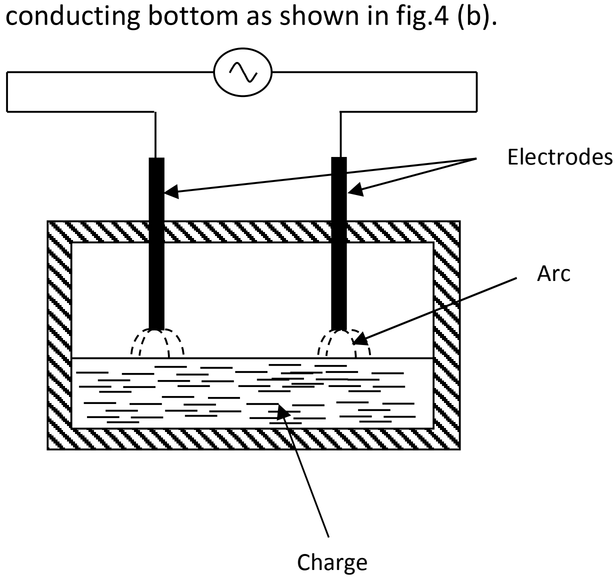


Fig.4 (a) Non Conducting Bottom Direct Arc Furnace

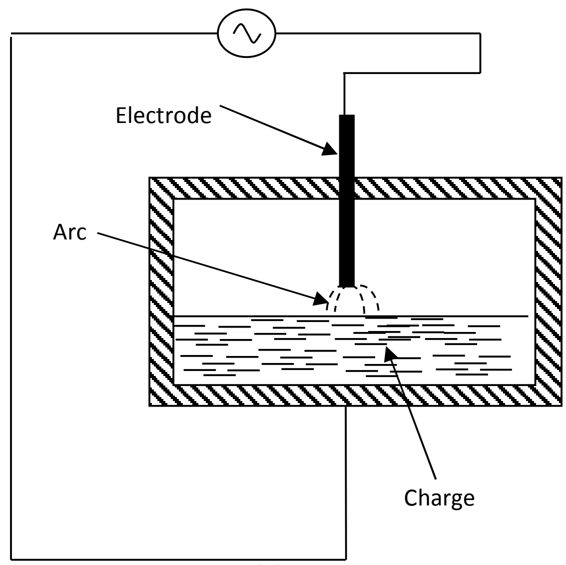


Fig.4 (b) Conducting Bottom Direct Arc Furnace

In case of a single phase arc furnace having non conducting bottom, two electrodes are taken vertically downward through the roof of the furnace to the surface of the charge and in case of 3 phase furnace three electrodes put at the corners of an equilateral triangle are projected on the charge through the roof and three arcs are formed. The current passing through the charge develops electromagnetic field and necessary stirring action is automatically obtained by it. Thus uniform heating is obtained. In case of a single phase arc furnace having conducting bottom, one electrode is taken vertically downward through the roof of the furnace to the surface of the charge and the one part of the supply is connected directly to the bottom of the furnace.

This type of furnace is commonly used for production of steel having size between 5 and 10 tonnes. The main advantage of direct arc furnace is that purer production is obtained and the composition can be exactly controlled during refining process. This furnace can be used both for melting and refining but due to its higher cost it is used for refining than melting.

Indirect arc furnace – In an indirect arc furnace arc is formed between two electrodes above the charge and heat is transmitted to the charge by radiation. The fig.5 shows a single phase indirect arc furnace which is cylindrical in shape. The arc is struck by short – circuiting the electrodes manually or automatically for a moment and then withdrawing them apart. The heat from the arc and the hot refractory lining is transferred to the top layer of the charge by radiation. The heat from the hot top layer of the charge is further transferred to other parts by conduction.

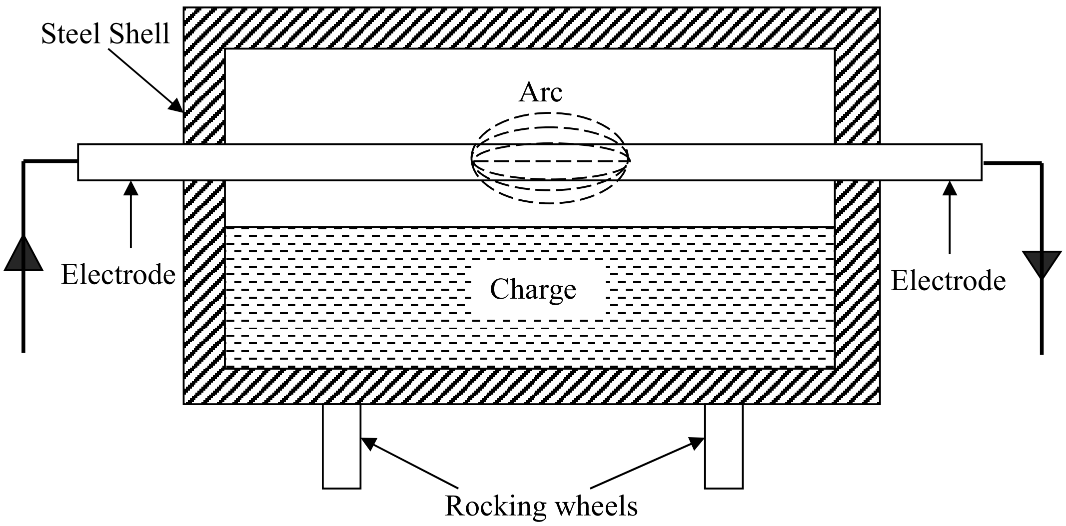


Fig.5 Indirect Arc Furnace

In this type of furnace, since no current passes through the body of the charge, there is no inherent stirring action due to electromagnetic forces setup by the current. Hence such furnaces have to be rocked continuously in order to distribute heat uniformly by exposing different layers of the charge to the heat of the arc. An electric motor is employed to operate suitable grinders and rollers to impart rocking motion to the furnace. Rocking motion provides thorough mixing of the charge and also increases the furnace efficiency in addition to increasing the life of the refractory lining material. In this furnace, since the charge is heated by radiation only, its temperature is lower than that obtainable in a direct arc furnace. The following are the advantages of indirect arc furnace:

- Lower overall production cost per tonne of molten metal.
- Sound castings in thin and intricate designs can be produced.
- Metal losses due to oxidation and volatilization are quite low.
- Flexible in operation.

Submerged arc furnace – It is a cylindrical furnace in which arc is formed between the carbon electrodes (from the top) and hearth electrodes. The hearth lining is of magnetite which becomes comparatively good electrical conductor when hot. It is also mixed with coke or graphite. Sometimes a conducting hearth is used as electrode. The number of electrodes taken from the roof depends on the type of supply. For single phase 1 electrode, for 3 phase 3 electrode and bottom conductor is connected to neutral. The power is controlled by varying distance between electrodes or by varying the voltage applied to the electrodes.

In this type of furnace better distributed heating is obtained since charge behaves as the resistance. Similarly, better mixing of charge takes place and the current under short circuit is limited to charge which otherwise in indirect furnace is very high.

Power Supply and Control of Arc Furnaces – In case of arc furnaces the power consumption is very high and the arc voltages lies between 50 – 150 V therefore the current required is of the order of several hundred amperes. The following are the reasons for low voltage high current power supply for arc furnaces:

(i) As the heating effect is proportional to the square of the current, therefore to achieve higher temperature heavy currents are essential.
(ii) From view point of insulation and safety considerations the maximum secondary voltage is also limited to 275 V (line to line open circuit voltage).
(iii) Due to the use of low voltage and high current the electrodes are kept very near to the charge as the arc is of small length. Since the arc remains away from the roof and therefore life of the roof refractory is increased.
(iv) The use of higher voltage causes higher voltage gradient between the electrode and the charge resulting in ionization of nitrogen of furnace atmosphere which gets absorbed by the charge resulting in embrittlement.

The fig. 6 shows the equivalent circuit of an arc furnace

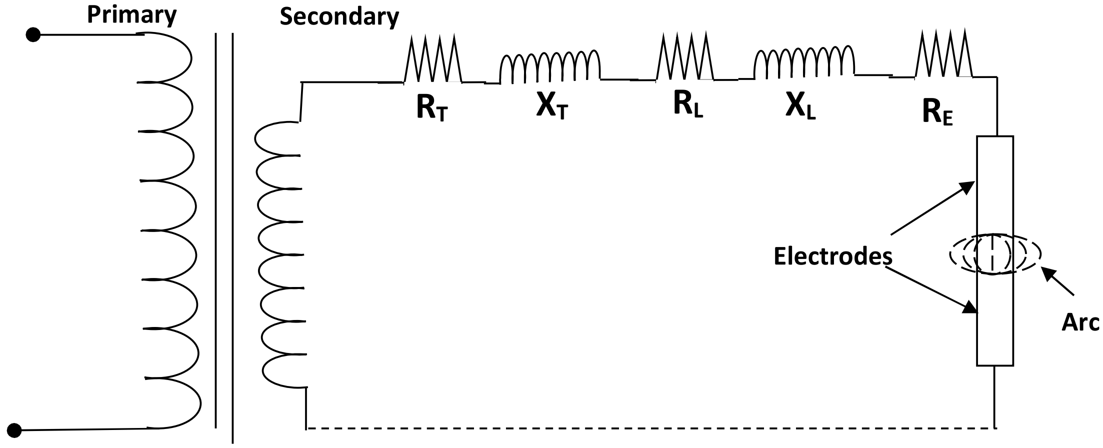


Fig.6 Equivalent Circuit of an Arc

Where

R_T = Equivalent resistance of the furnace (referred to secondary side)
X_T = Equivalent reactance of the furnace (referred to secondary side)
R_L = Resistance of the load
X_L = Reactance of the load
R_E = Resistance of the electrodes
R_A = Arc resistance
E_A = Voltage drop across the arc

In order to achieve complete control of furnace temperature and best operating conditions both voltage and electrode controls are employed.

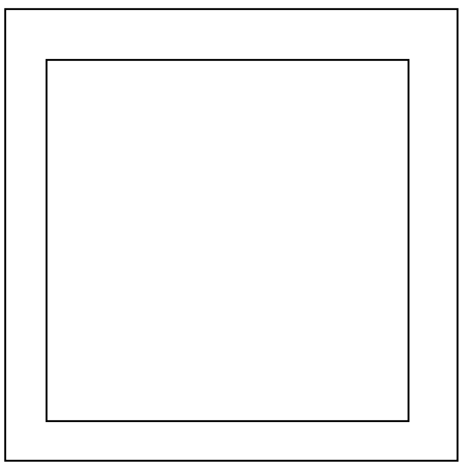
Induction Heating – The process of induction heating makes use of the currents induced by the electromagnetic action in the charge to be heated. It is based on the principle of transformer working. The primary winding is supplied from an a.c. source which is magnetically coupled to the charge which acts as a short circuited secondary of a single turn. When A.C. voltage is applied to the primary, it induces voltage in the secondary i.e. charge. The secondary current heats up the charge in the same way as any electric does while passing through a resistance. The induction furnace are of two types

1. Core type or low frequency induction furnace – It is again of the following types:

   (i) Direct core type
   (ii) Vertical core type
   (iii) Indirect core type

2. Coreless type or high frequency induction furnace

Direct Core Type Induction Furnace – It is shown in fig. 7. It consists of a transformer in which charge to be heated forms a single turn short circuited secondary and is magnetically coupled to the primary by iron core the furnace consists of a circular hearth which contains the charge to be melted in the form of an annular ring.



When there is no molten metal in the ring, the secondary becomes open circuited thereby cutting off the secondary current. Hence to start the furnace, molten metal has to be poured in the annular. Due to very poor magnetic coupling between the primary and secondary, it results in high leakage and low power factor. Therefore to nullify the effect of increased leakage reactance low primary frequency of the order of 10 Hz or so is used.