Utilization Of Electrical Energy‘

Electric Heating

Dr Gamal Swoilam

1 INTRODUCTION

Heat plays a major role in everyday life. All heating requirements in domestic purposes such as cooking, room heater, immersion water heaters, and electric toasters and also in industrial purposes such as welding, melting of metals, tempering, hardening, and drying can be met easily by electric heating, over the other forms of conventional heating.

Heat and electricity are interchangeable. Heat also can be produced by passing the current through material to be heated. This is called electric heating; there are various methods of heating a material but electric heating is considered far superior compared to the heat produced by coal, oil, and natural gas.

ADVANTAGES OF ELECTRIC HEATING

(i) Economical

They do not require much skilled persons; therefore, maintenance cost is less.

(ii) Cleanliness

Since dust and ash are completely eliminated in the electric heating, it keeps surroundings cleanly.

(iii) Pollution free

As there are no flue gases in the electric heating, atmosphere around is pollution free; no need of providing space for their exit.

(iv) Ease of control

In this heating, temperature can be controlled and regulated accurately either manually or automatically.

(v) Uniform heating

With electric heating, the substance can be heated uniformly, throughout whether it may be conducting or non-conducting material.

(vi) High efficiency

In non-electric heating, only 40–60% of heat is utilized but in electric heating 75–100% of heat can be successfully utilized. So, overall efficiency of electric heating is very high.

(vii) Automatic protection

Protection against over current and over heating can be provided by using fast control devices.

(viii) Heating of non-conducting materials

The heat developed in the non-conducting materials such as wood and porcelain is possible only through the electric heating.

(ix) Better working conditions

No irritating noise is produced with electric heating and also radiating losses are low.

(x) Less floor area

Due to the compactness of electric furnace, floor area required is less.

(xi) High temperature

High temperature can be obtained by the electric heating except the ability of the material to withstand the heat.

(xii) Safety

The electric heating is quite safe

MODES OF TRANSFER OF HEAT

The transmission of the heat energy from one body to another because of the temperature gradient takes place by any of the following methods:

1. conduction,
2. convection, or
3. radiation.

1. Conduction

The heat transfers from one part of substance to another part without the movement in the molecules of substance. The rate of the conduction of heat along the substance depends upon the temperature gradient.

The amount of heat passed through a cubic body with two parallel faces with thickness 't' meters, having the cross-sectional area of 'A' square meters and the temperature of its two faces T_1°C and T_2°C, during 'T' hours is given by:

$$Q = \frac{k\,A}{t}(T_1 - T_2)\;T \text{ MJ},$$

where k is the coefficient of the thermal conductivity for the material and it is measured in $MJ/m^3/°C/hr$.

Ex: Refractory heating, the heating of insulating materials, etc.

2. Convection

The heat transfer takes place from one part to another part of substance or fluid due to the **actual motion of the molecules**. The rate of conduction of heat depends **mainly on the difference in the fluid density at different temperatures.**

Ex: Immersion water heater.

The mount of heat absorbed by the water from heater through convection depends mainly upon the temperature of heating element and also depends partly on the position of the heater. Heat dissipation is given by the following expression.

$$H = a\,(T_1 - T_2)^b \ W/m^2,$$

where 'a' and 'b' are the constants whose values are depend upon the heating surface and T_1 and T_2 are the temperatures of heating element and fluid in °C, respectively.

3.Radiation

The heat transfers from source to the substance to be heated **without heating the medium in between. It is dependent on surface.**

Ex: Solar heaters.

The rate of heat dissipation through radiation is given by Stefan's Law.

$$\text{Heat dissipation, } H = 5.72 \times 10^4 k\, e \left[\left(\frac{T_1}{1,000} \right)^4 - \left(\frac{T_2}{1,000} \right)^4 \right] \text{W/m}^2$$

where T_1 is the temperature of the source in kelvin, T_2 is the temperature of the substance to be heated in kelvin, and k is the radiant efficiency:

= 1, for single element

= 0.5–0.8, for several elements

e = emissivity = 1, for black body

= 0.9, for resistance heating element.

From Equation, the radiant heat is proportional to the difference of fourth power of the temperature, so it is very efficient heating at high temperature.

ESSENTIAL REQUIREMENTS OF GOOD HEATING ELEMENT

The materials used for heating element should have the following properties:

- **High-specific resistance**

  Material should have **high-specific resistance** so that small length of wire may be required to provide given amount of heat.

- **High-melting point**

  It should have **high-melting point** so that it can withstand for high temperature, a small increase in temperature will not destroy the element.

- **Low temperature coefficient of resistance**

  From above Equation, the radiant heat is proportional to fourth powers of the temperatures, it is very efficient heating at high temperature.

  For accurate temperature control, **the variation of resistance with the operating temperature should be very low**. This can be obtained only if the material has low temperature coefficient of resistance

- **Free from oxidation**

  The element material **should not be oxidized when it is subjected to high temperatures**; otherwise the formation of oxidized layers will shorten its life.

- **High-mechanical strength**
  The material should have **high-mechanical strength and should withstand for mechanical vibrations.**
- **Non-corrosive**
  The element should **not corrode when exposed to atmosphere or any other chemical fumes.**
- **Economical**
  The cost of **material should not be so high**.

CAUSES OF FAILURE OF HEATING ELEMENTS

Heating element may fail due to any one of the following reasons.

1. Formation of hot spots.

2. Oxidation of the element and intermittency of operation.

3. Embrittlement caused by gain growth.

4. Contamination and corrosion.

DESIGN OF HEATING ELEMENTS

By knowing the voltage and electrical energy input, **the design of the heating element for an electric furnace** is required to determine the **size and length of the heating element**. **The wire employed may be circular or rectangular like a ribbon.** The ribbon-type heating element permits the use of **higher wattage per unit area compared to the circular-type element.**

1. Circular-type heating element

Initially when the heating element is connected to the supply, the temperature goes on increasing and finally reaches high temperature.

Let *V be the supply voltage of the system and R be the resistance of the element, then electric* power input

$$P = \frac{V^2}{R} \text{ W}$$

If *ρ is the resistivity of the element, l is the length, 'a' is the area, and d is the diameter of the* element, then:

$$R = \rho \frac{l}{a} = \frac{\rho l}{\frac{\pi d^2}{4}}$$

Therefore, power input $\rightarrow$ $$P=\frac{V^2\pi d^2}{4\rho l} \quad (1)$$

By rearranging the above equation, we get: $\rightarrow$ $$\frac{l}{d^2}=\frac{\pi V^2}{4P\rho}, \quad (2)$$

where *P is the electrical power input per phase (watt), V is the operating voltage per phase* (volts), *R is the resistance of the element (Ω), l is the length of the element (m), a is the area of* cross-section (m*m), *d is the diameter of the element (m), and ρ is the specific resistance (Ω-m)*

According to Stefan's law, heat dissipated per unit area is

$$H=5.72\times10^4\ k\ e\left[\left(\frac{T_1}{1,000}\right)^4-\left(\frac{T_2}{1,000}\right)^4\right]\ \mathrm{W/m^2} \quad (3)$$

where *T1 is the absolute temperature of the element (K), T2 is the absolute temperature of the* charge (K), *e is the emissivity, and k is the radiant efficiency.*

The surface area of the circular heating element: $\rightarrow$ $$S=\pi dl.$$

∴ Total heat dissipated = surface area × $H = H\pi dl$.

Under thermal equilibrium,

Power input = heat dissipated

$$P = H \times \pi dl.$$

Substituting *P from Equation (1) in above equation:*

$$\frac{V^2}{\rho l}\left(\frac{\pi d^2}{4}\right) = H \times \pi dl$$

$$\therefore \frac{d}{l^2} = \frac{4\rho H}{V^2}. \qquad (4)$$

By solving Equations (2) and (4), the length and diameter of the wire can be determined.

2. Ribbon-type element

Let '*w*' *be the width and* '*t*' *be the thickness of the ribbon-type heating element*. for ribbon or rectangular element, ***a* = *w* × *t***

$$R = \frac{\rho l}{a} = \frac{\rho l}{w \times t}$$

Electrical power input → $P = \frac{V^2}{\left(\frac{\rho l}{w \times t}\right)}$

$$\therefore \frac{l}{w} = \frac{V^2 t}{P \rho} \quad (5)$$

The surface area of the rectangular element $(S) = 2\, l \times w$.

∴ Total heat dissipated = $H \times S = H \times 2\, lw$.

∴ Under the thermal equilibrium,

Electrical power input = heat dissipated

$$P = H \times 2\, lw$$

$$lw = \frac{P}{2H} \quad (6)$$

By solving Equations (5) and (6), the length and width of the heating element can be determined.

Example 1:

A 4.5-kW, 200-V, and 1-*φ resistance oven is to have nichrome wire heating* elements. If the wire temperature is to be 1,000°C and that of the charge 500°C. Estimate the diameter and length of the wire. The resistivity of the nichrome alloy is 42.5 μΩ-*m. Assume the* radiating efficiency and the emissivity of the element as 1.0 and 0.9, respectively.

Temperature of the source (*T1)* = *1,000* + *273* = 1,273 K.
Temperature of the charge *T2* = *500* + *273* = 773 K.

According to the Stefan's law,

$$\text{The amount of heat dissipation } (H) = 5.72 \times 10^4 \times k\, e \left[\left(\frac{T_1}{1,000} \right)^4 - \left(\frac{T_2}{1,000} \right)^4 \right] \text{W/m}^2$$

$$H = 5.72 \times 10^4 \times 0.1 \times 0.9 \left[\left(\frac{1,273}{1,000} \right)^4 - \left(\frac{773}{1,000} \right)^4 \right]$$

$$= 11.68 \times 10^3 \text{ W/m}^2.$$

$$\text{Power, } P = \frac{V^2}{R} = \frac{V^2 A}{\rho\, l} = \frac{V^2 \pi d^2}{4\rho l} \qquad \left[\therefore \text{ The area of circular type element} = \frac{\pi}{4} d^2 \right]$$

$$\frac{d^2}{l} = \frac{4P\rho}{V^2\pi} = \frac{4 \times 42.5 \times 10^{-6} \times 4.5 \times 10^3}{(200)^2\, 3.14} = 6.09 \times 10^{-9}. \Longrightarrow (1)$$

The heat dissipation is given by: $P = H \times S$ (S = circular full-face area)

$$P = H \times \pi d l$$

$$dl = \frac{P}{H\pi} = \frac{4.5 \times 10^3}{3.14 \times 11.68 \times 10^3}$$

$$dl = 0.1226. \longrightarrow (2)$$

By solving Equations (1) and (2):

$$d^3 = 0.7466 \Longrightarrow d = 0.907 \text{ mm.}$$

Substitute the value of 'd' *in Equation (2):* ⇒

$$l = 135.14 \text{ m.}$$

Example 2: A20-kW, 230-V, and single-phase resistance oven employs nickel—chrome strip 25-mm thick is used, for its heating elements. If the wire temperature is not to exceed 1,200°C and the temperature of the charge is to be 700°C. Calculate the width and length of the wire. Assume the radiating efficiency as 0.6 and emissivity as 0.9. Determine also the temperature of the wire when the charge is cold.

Let '*w*' *be the width in meters, t be the thickness in meters, 'l' be the length also in* meters *and A= w*t*. Then:

$$P = \frac{V^2}{R} = \frac{V^2}{\frac{\rho 1}{A}} = \frac{V^2 \times wt}{\rho l}$$

$$\frac{w}{l} = \frac{P\rho}{V^2 t} = \frac{20 \times 10^3 \times 1.016 \times 10^{-6}}{(230)^2 \times 0.25 \times 10^{-3}} = 1.536 \times 10^{-3}. \qquad (1)$$

$$H = 5.72 \times 10^4 \times ke\left[\left(\frac{T_1}{1,000}\right)^4 - \left(\frac{T_2}{1,000}\right)^4\right] \text{W/m}^2$$

$$H = 5.72 \times 10^4 \times 0.6 \times 0.9\left[\left(\frac{1,200+273}{1,000}\right)^4 - \left(\frac{700+273}{1,000}\right)^4\right]$$

$$\Rightarrow H = 117.714 \text{ kW/m}^2.$$

The total amount of the heat dissipation × the surface area of strip = power supplied

$$P = H \times S$$

$$= H \times 2\ lw\ (S = surface\ area\ of\ strip = 2lw)$$

$$lw = \frac{P}{2H} = \frac{20 \times 10^3}{2 \times 117.714 \times 10^3} = 0.0849. \qquad (2)$$

From Equations (1) and (2):

$$\frac{w}{l} \times lw = 1.536 \times 10^{-3} \times 0.0849 \longrightarrow w^2 = 1.304 \times 10^{-4}$$

$$w = 11.42 \text{ mm.}$$

and $l = 7.435$ m.

When the charge is cold, it would be at normal temperature, say 25°C.

$$117.714 \times 10^3 = 5.72 \times 10^4 \times 0.6 \times 0.9 \left[\left(\frac{T_1}{1{,}000} \right)^4 - \left(\frac{273 + 25}{1{,}000} \right)^4 \right]$$

$$\left(\frac{T_1}{1{,}000} \right)^4 - 0.00788 = 3.8109 \Rightarrow \left(\frac{T_1}{1{,}000} \right)^4 = 3.818$$

$$T_1 = 1{,}397.9169 \text{ K absolute}$$

$$T_1 = 1{,}124.9\text{°C.}$$

Example 3 Determine the diameter and length of the wire, if a 17-kW, 220-V, and 1-*φ resistance oven employs nickel-chrome wire for its heating elements. The temperature is not* exceeding to 1,100°C and the temperature of the charge is to be 500°C. Assume the radiating efficiency as 0.5 and the emissivity as 0.9, respectively.

For a circular element:

$$\frac{d^2}{l} = \frac{4P\rho}{V^2\pi} = \frac{4 \times 17 \times 10^3 \times 1.016 \times 10^{-6}}{(220)^2 \times 3.14} = 4.545 \times 10^{-7} \qquad (1)$$

$$H = 5.72 \times 10^4\, ke\left[\left(\frac{T_1}{1,000}\right)^4 - \left(\frac{T_2}{1,000}\right)^4\right] \mathrm{W/m^2}$$

$$H = 5.72 \times 10^4 \times 0.5 \times 0.9 \left[\left(\frac{1,100+273}{1,000}\right)^4 - \left(\frac{500+273}{1,000}\right)^4\right] = 82.28\ \mathrm{kW/m^2}.$$

At steady temperature, crucial power input = heat output:

$$P = H \times \pi dl$$

$$dl = \frac{P}{H \times \pi}$$

$$dl = \frac{7 \times 10^3}{3.14 \times 62.28 \times 10^3}$$

$$= 0.0658. \longrightarrow (2)$$

Solving Equations (1) and (2), we get:

$$\frac{d^2}{l} \times dl = 4.545 \times 10^{-7} \times 0.0658$$

$$d^3 = 2.99 \times 10^{-8}$$

$$d = 3.1 \text{ mm.}$$

Substitute the value of '*d' in Equation (2) gives:*

$$l = 21.198 \text{ m.}$$

METHODS OF ELECTRIC HEATING

Electric heating can be broadly classified as follows.

(i) Direct resistance heating

In this method, the electric current is made to pass through the charge (or) substance to be heated. This principle of heating is employed in electrode boiler.

(ii) Indirect resistance heating

In this method, the electric current is made to pass through a wire or high-resistance heating element, the heat so developed is transferred to charge from the heating element by convection or radiation. This method of heating is employed in immersion water heaters.

Infrared (or) radiant heating

In this method of heating, the heat energy is transferred from source (incandescent lamp) and focused upon the body to be heated up in the form of electromagnetic radiations. Normally, this method is used for drying clothes in the textile industry and to dry the wet paints on an object.

Direct arc heating

In this method, by striking the arc between the charge and the electrode or electrodes, the heat so developed is directly conducted and taken by the charge. The furnace operating on this principle is known as direct arc furnaces. The main application of this type of heating is production of steel.

Indirect arc heating

In this method, arc is established between the two electrodes, the heat so developed is transferred to the charge (or) substance by radiation. The furnaces operating on this principle are known as indirect arc furnaces. This method is generally used in the melting of non-ferrous metals.

Direct induction heating

In this method of heating, the currents are induced by electromagnetic action in the charge to be heated. These induced currents are used to melt the charge in induction furnace.

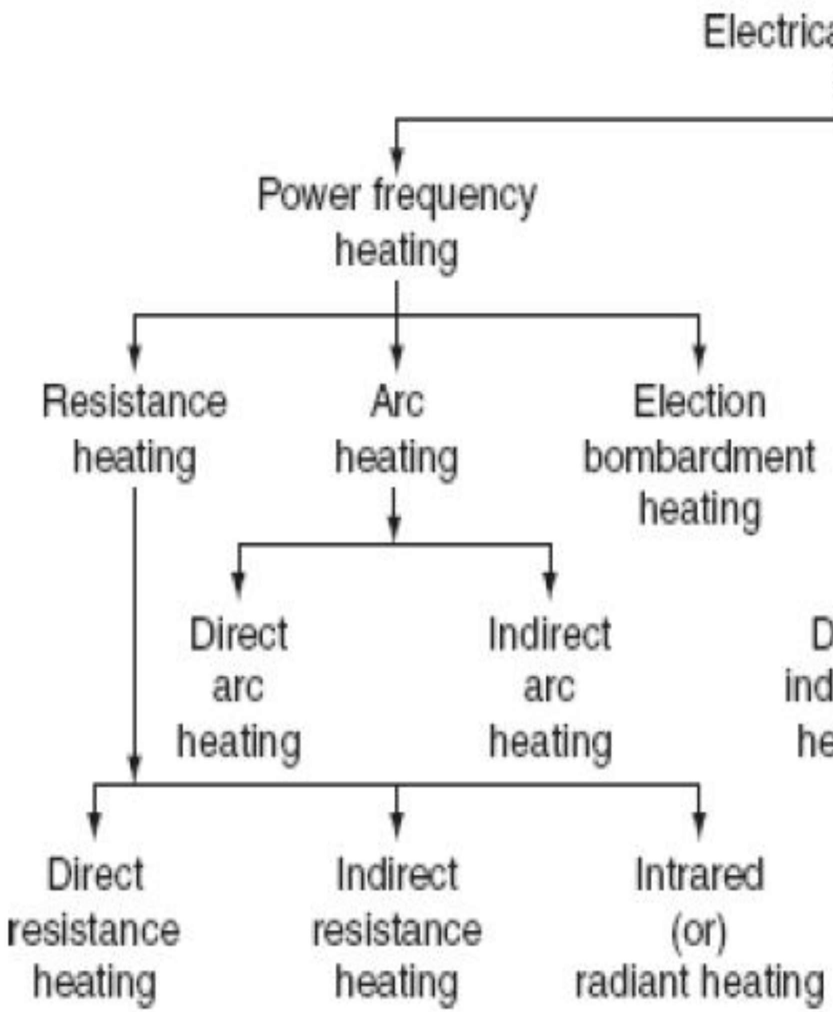
Indirect induction heating

In this method, eddy currents are induced in the heating element by electromagnetic action. Thus, the developed heat in the heating element is transferred to the body (or) charge to be heated by radiation (or) convection. This principle of heating is employed in induction furnaces used for the heat treatment of metals.

Dielectric heating

In this method of electric heating, the heat developed in a non-metallic material due to inter-atomic friction, known as dielectric loss. This principle of heating usually employed for preheating of plastic performs, baking foundry cores, etc.

Classification of electrical heating



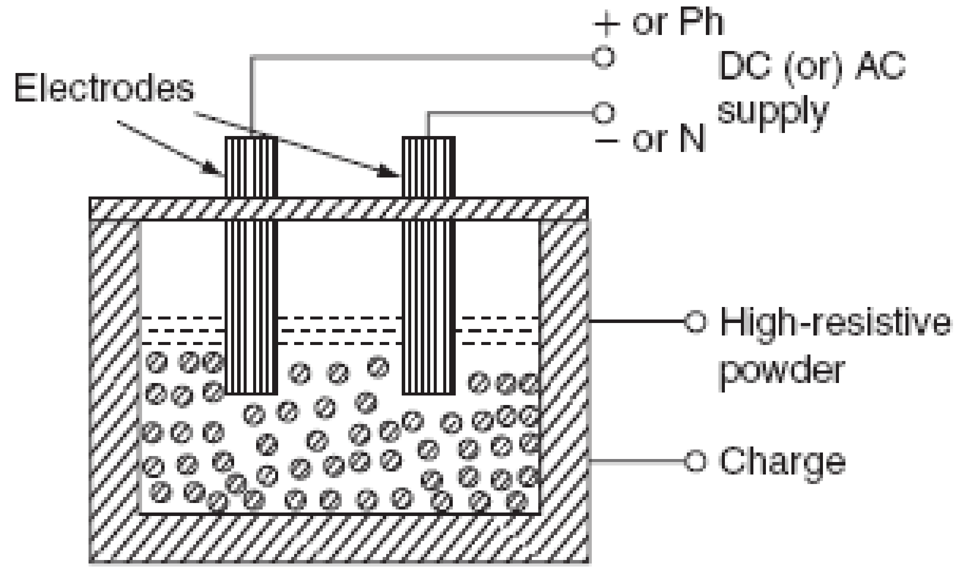
RESISTANCE HEATING

When the electric current is made to pass through a high-resistive body (or) substance, a power loss takes place in it, which results in the form of heat energy, i.e., resistance heating is passed upon the I^2R effect. **This method of heating has wide applications such as drying, baking of potteries, commercial and domestic cooking, and the heat treatment of metals such as annealing and hardening.** In oven where wire resistances are employed for heating, temperature up to about 1,000°C can be obtained.

The resistance heating is further classified as:

1. direct resistance heating,
2. indirect resistance heating, and
3. infrared (or) radiant heating.

1. Direct resistance heating



In this method, electrodes are immersed in a material or charge to be heated. The charge may be in the form of powder, pieces, or liquid. The electrodes are connected to AC or DC supply as shown in Figure.

In case of DC or 1-φ AC, two electrodes are immersed and three electrodes are immersed in the charge and connected to supply in case of availability of 3-φ supply.

When metal pieces are to be heated, the powder of lightly resistive is sprinkled over the surface of the charge (or) pieces to avoid direct short circuit. The current flows through the charge and heat is produced in the charge itself. So, this method has high efficiency. As the current in this case is not variable, so that automatic temperature control is not possible. This method of heating is employed in salt bath furnace and electrode boiler for heating water.

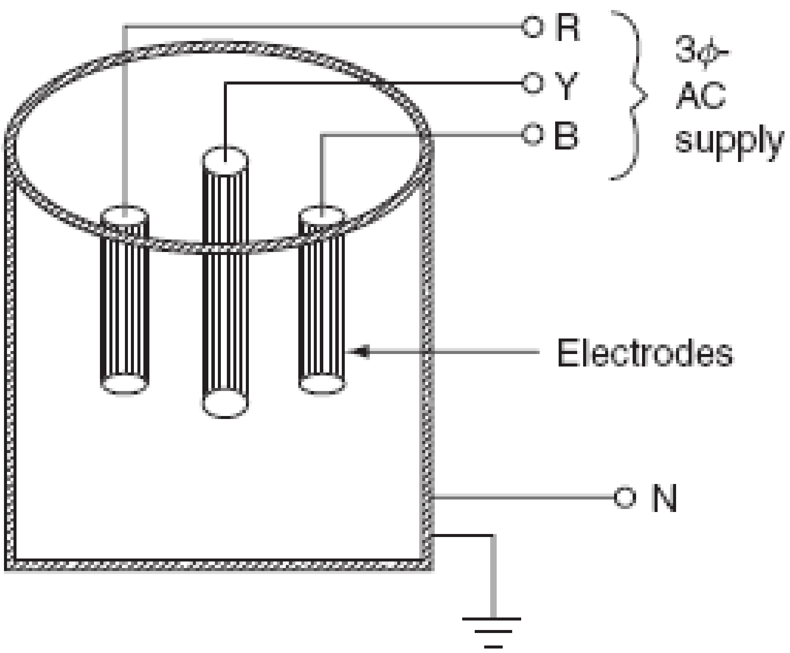
(i) Salt bath furnace

This type of furnace consists of a bath and containing some salt such as molten sodium chloride and two electrodes immersed in it.
Such salt have a fusing point of about 1,000–1,500°C depending upon the type of salt used.

When the current is passed between the electrodes immersed in the salt, heat is developed and the temperature of the salt bath may be increased. Such an arrangement is known as a salt bath furnace.

(ii) Electrode boiler

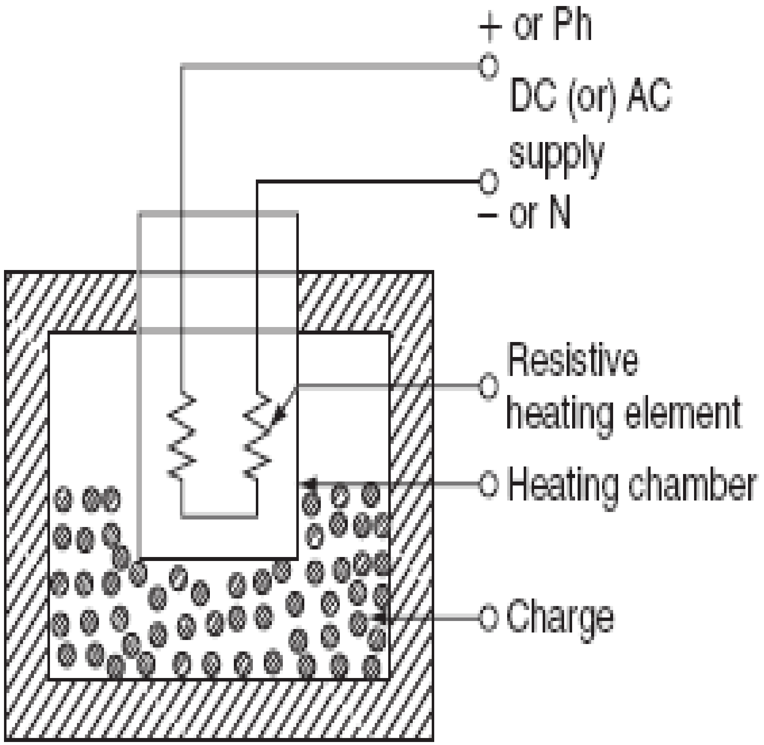
It is used to heat the water by immersing three electrodes in a tank as shown in Figure. This is based on the principle that when the electric current passed through the water produces heat due to the resistance offered by it.



This is based on the principle that when the electric current passed through the water produces heat due to the resistance offered by it. For DC supply, it results in a lot of evolution of H_2 at negative electrode and O_2 at positive electrode. Whereas AC supply hardly results in any evolution of gas, but heats the water. Electrode boiler tank is earthed solidly and connected to the ground. A circuit breaker is usually incorporated to make and break all poles simultaneously and an over current protective device is provided in each conductor feeding an electrode.

2. Indirect resistance heating

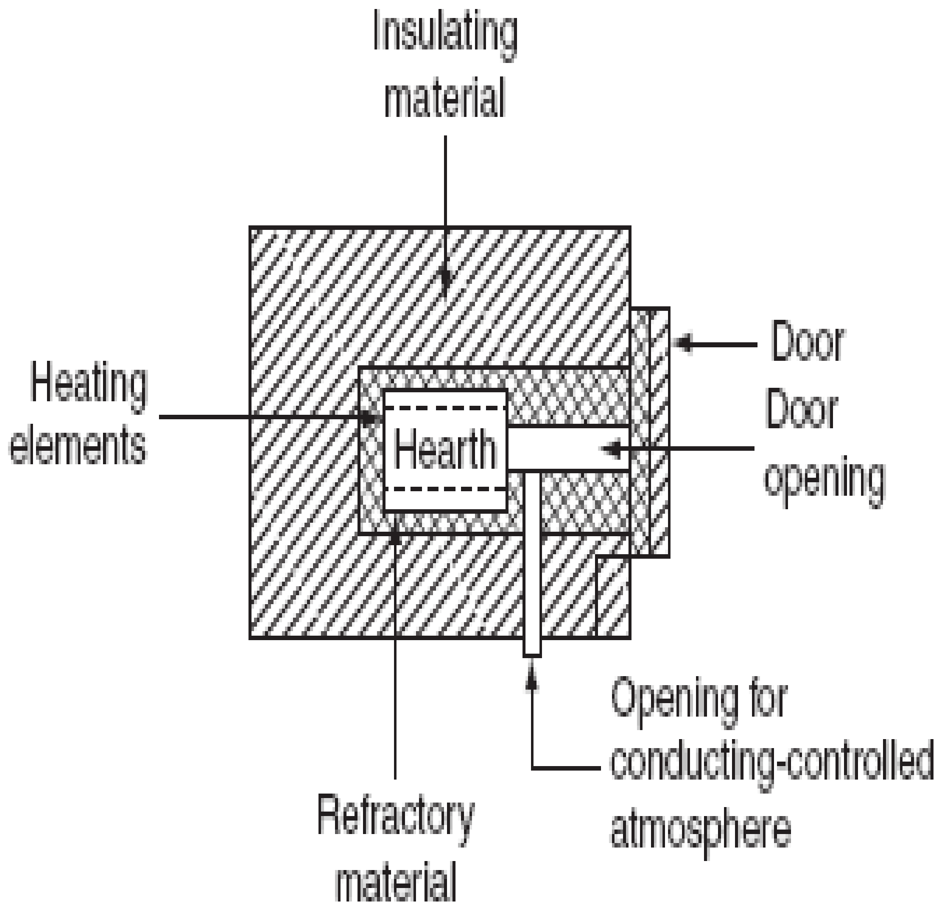
In the indirect resistance heating method, high current is passed through the heating element. In case of industrial heating, some times the heating element is placed in a cylinder which is surrounded by the charge placed in a jacket is known as heating chamber is shown in Figure.



The heat is proportional to power loss produced in the heating element is delivered to the charge by one or more of the modes of the transfer of heat viz. conduction, convection, and radiation.

This arrangement provides uniform temperature and automatic temperature control. Generally, this method of heating is used in immersion water heaters, room heaters, and the resistance ovens used in domestic and commercial cooling and salt bath furnace.

Resistance ovens



According to the operating temperatures, the resistance furnaces may be classified into various types. Low-temperature heating chamber with the provision for ventilation is called as oven. For drying varnish coating, the hardening of synthetic materials, and commercial and domestic heating, etc., the resistance ovens are employed.

The operating temperature of medium temperature furnaces is between 300°C and 1,050°C. These are employed for the melting of nonferrous metals, stove (annealing), etc. Furnaces operating at temperature between 1,050°C and 1,350°C are known as high-temperature furnaces. These furnaces are employed for hardening applications. A simple resistance oven is shown in Figure.

Resistance oven consists of a heating chamber in which heating elements are placed as shown in the Figure. The inner surface of the heating chamber is made to suit the character of the charge and the type of furnace or oven. The type of insulation used for heating chamber is determined by the maximum temperature of the heating chamber.

3. Infrared or radiant heating

In this method of heating, the heat transfer takes place from the source to the body to be heated through radiation, for low and medium temperature applications. Whereas in resistance ovens, the heat transfers to the charge partly by convection and partly by radiation.

In the radiant heating, the heating element consists of tungsten filament lamps together with reflector and to direct all the heat on the charge. Tungsten filament lamps are operating at 2,300°C instead of 3,000°C to give greater portion of infrared radiation and a longer life.

The radiant heating is mainly used for drying enamel or painted surfaces. The high concentration of the radiant energy enables the heat to penetrate the coating of paint or enamel to a depth sufficient to dry it out without wasting energy in the body of the workpiece.

The main advantage of the radiant heating is that the heat absorption remains approximately constant whatever the charge temperature, whereas with the ordinary oven the heat absorption falls off very considerably as the temperature of the charge raises. The lamp ratings used are usually between 250 and 1,000 W and are operating at voltage of 115 V in order to ensure a robust filament