

HEAT TRANSFER , FLUID FLOW & FURNACE

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HEAT FLOW/HEAT TRANSFER

DEFINITION-Heat transfer is the process of transfer of heat from high temperature system to a low temperature system.

In the thermodynamics system, heat transfer is the movement of heat across the boundary of the system due to temperature difference between the system and surrounding.

APPLICATION OF HEAT TRANSFER-

- 1.Civil Engineering-Buildings,Railway Tracks.
- 2.Electrical Engineering-Transformers,Motors.
- 3.Metallurgical Engineering-Furnaces,Heattransfer
- 4.Mechanical Engineering-Boilers,IC Engines.

MODES OF HEAT TRANSFER-

There are 3 modes of heat transfer;(i)Conduction

(ii)Convection

(iii)Radiation

STEADY STATE AND UNSTEADY STATE FLOW-

Steady state

It is defined as that types of flow in which the fluid characteristics like velocity,pressure,density etc at a point doesn't change with respect to time.

$$dv/dt=0 \quad dp/dt=0 \quad \rho/dt=0$$

Unsteady state

It is that types of flow on which the velocity pressure and density at a point changes with respect to time.This is called unsteady state flow.

UNIFORM AND NON-UNIFORM FLOW-

Uniform flow

It is defined that type of flow in which the velocity at any given time doesn't change with respect to space[length of flow in the direction(s)]

$$dv/ds=0$$

Non-uniform flow

It is that type of flow in which the velocity at given time changes with respect to space.

$$dv/ds \neq 0$$

LAMINAR AND TARBULANT FLOW-

COMPRESSIBLE AND INCOMPRESSIBLE FLOW-

LAMINAR

Laminar flow is that type of flow in which the fluid

Particles moves along well defined paths or steam lines are straight and parallel.

This type of flow is also called steam line flow or viscous flow.

TARBULANT FLOW

Tarbulant flow is that type of flow in which fluid particles moves in a zigzag way.

Due to the movement of fluid particles in zizag way the eddies formation takes place which is responsible for high energy loss.

A laminar flow changes to tarbuant when,

- i.Velocity is increased
- ii.Diameter of pipe increased
- iii.The viscosity of fluid increased

COMPRESSIVE AND INCOMPRESSIVE FLOW

COMPRESSIVE FLOW

Compressive is that type of flow in which the density of fluid changes from point to point w.r.t time.

$$dp/dt \neq 0$$

INCOMPRESSIVE FLOW

In compressive flow is that type of flow in which the density of fluid does not changes from point to point w.r.t to time.

$$dp/dt = 0$$

Rotational flow-Flow an own axis

Irrotational Flow-Does not flow an own axis

REYNOLD NUMBER-

Reynold number is defined as the ratio of inertia force of the flowing fluid and the viscous force of the fluid.

$$R_N = \text{Inertia force} / \text{Viscous force}$$

$$= \rho v^2 / \mu v / d \quad (\rho = \text{ROH})$$

$$= \rho dv / \mu$$

$\Rightarrow \rho dv / \mu$ is dimension less quantity and is called R_N

R_N is < 2000 is said to be laminar flow

R_N is > 4000 is said to be turbulent flow

If the R_N lies between 2000-4000 are said to be mixed flow.

RATE OF FLOW OR DISCHARGE-

It is defined as the quantity of flowing per second through a section of pipe or a channel.

i) For a incompressible fluid the rate of flow or discharge is expressed as the volume of the fluid flowing across the section per second.

ii) For compressible fluid the rate of flow is expressed as the weight of the fluid across the section.

$$Q = A \times V$$

$$Q=AV$$

CONTINUITY EQUATION-

In an incompressible fluid/liquid is continuously flow through a pipe or channel which cross-sectional area may or may not be constant.

The quantity of liquid passing per second is equal in all section.

The process in which there is no transfer of heat between the system and its surrounding is called **ADIABATIC PROCESS**.

(i)CONDUCTION-

- a) The transfer of heat from one substance to another due to direct contact.
- b) It is a microscopic phenomenon.
- c) Conduction can occur in solids, liquids and gases.
- d) $Q \propto A \cdot (Dt/dX)$ [Fourier's Law]
Where, Q =Heat Transfer
 A =Area
 dT/dX =Temperature Gradient
- e) Ex-Flow of heat through metal shell of a boiler takes place by conduction as far as solid wall or shell is considered.
- f) The flow of heat is depends on the transfer of VIBRATIONAL ENERGY one molecule to another, and in case of metal the MOVEMENT OF FREE ELECTRONS.

(ii)CONVECTION-

- a) The transfer of heat through a fluid caused by molecular motion.
- b) It is also a microscopic phenomenon.
- c) It is of 2 types; 1. Natural or Free Convection
2. Forced Convection
- d) Mathematically,
 $Q_{\text{convection}} = h \times A \times \Delta T$ [NEWTON'S LAW]
Where, A =Surface Area
 H =Heat transfer coefficient

ΔT =Change in temperature

- e) Ex-Heating of water by hot surface is mainly by convection.
- f) In Natural convection(free convection)
Heat transfer occurs due to density differences.
- g) In Forced convection,the heat transfer occurs with the help of external agent,fan or pump.SOURCE;Natural wind and fans

(iii)RADIATION

a)Energy that is radiated or transmitted in the form of rays or waves or particles.

b)Radiative heat transfer occurs when the emitted radiation strikes another body and is absorbed.We all experience radiative heat transfer every day;solar radiation, absorbed by our skin,is why we feel warmer in the sun in the shadow.

c)Mathematically,

$$E=\sigma T^4$$

Where,E=emissivity(which is
equal to absorptive power)

$$\sigma=5.67$$

T=Temperature(Kelvin)

d)Ex-Solar water heaters,solar cookers,
microwave ovens,microwave cookers
etc.

APPLICATION-

a)EVAPORATION-Heat is supplied in order to convert a liquid into vapour.

b)DISTILLATION-Heat is supplied to liquid mixture for converting the liquid into vapour so that individual vapour components are condensed at another place.

c)DRYING-In the production of tablets,heat is passed through a carrier gas over a bed of wet solid mass for achieving drying.

d)CRYSTALLISATION-Saturated solution is heated to bring about supersaturation,which promotes the crystallisation of drugs.

e) STERILISATION-For the sterilisation of pharmaceuticals, AUTOCLAVES are used with steam as a heating medium.

FOURIER'S LAW-It states that the rate of heat transfer (dt) is directly proportional to the negative temperature gradient.

Q is called rate of heat transfer

dt=temperature difference(t_1-t_2)between hot and cold part

dx=thickness of the material

A=Area of the material through which heat exchange occurs

$$Q \propto A$$

$$Q \propto t_2 - t_1$$

$$Q \propto 1/dx$$

$$Q \propto A(t_2 - t_1)/dx$$

$$Q = -KA(t_2 - t_1)/dx$$

K=Thermal conductivity of

The medium

$$\Rightarrow Q/A = -K(t_2 - t_1)/dx$$

$$\Rightarrow Q/A = \text{Heat flux}$$

$$\Rightarrow q = -K(t_2 - t_1)/dx$$

$$q \propto -dt/dx$$

This shows that heat transfer flux is directly proportional to the -ve temperature gradient.

$$q = \text{cal/sec.cm}^2$$

$$Q = q.A \text{ cal/sec.cm}^2 \times \text{cm}^2$$

$$= \text{cal/sec}$$

DERIVATION-

a) Fourier law can be applied to a metal wall through which the conduction of heat taking place.

b) Area of wall = A, m^2

c) Thickness of wall = L, m

d) Face of wall (HH) is maintained at uniform, definite and higher temperature = t_1, K

e) Face of wall (CC) is maintained at a lower, but uniform temperature = t_2, K

f) The heat flow will be at right angle to the plane A and is assumed to be in steady state.

g) Consider thin section of thickness dL at an intermediate point in the wall.

h) For this section, FOURIER'S LAW may be applied as given:

$$dQ/d\theta = -k \times A \times dt/dL$$

Where, Q = Heat transfer

θ = Time, s

k = Proportionality constant, $W/m \times K$

t = Temperature, K

The 'minus' sign indicates the decrease in temperature in direction of flow.

In equation (dt/dL) represents temperature gradient.

i) For the steady state heat transfer, this equation changes to: $dQ/d\theta = \text{constant} = q = -K \times A \times dt/dL$

Where, q = rate of heat transfer, J/s (or W)

Re-arranging this equation

$$q = -K_m \times A \times \Delta t / L$$

Where, K_m = mean proportionality constant, $W/m \times K$

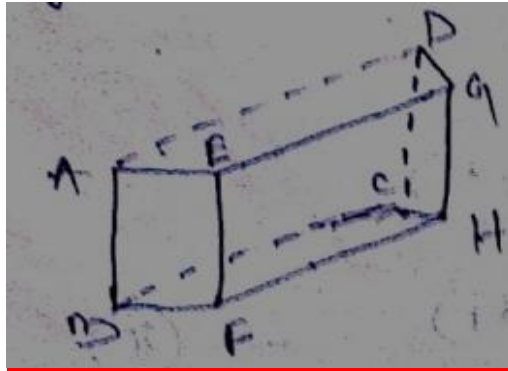
In steady state heat transfer, ' q ' remains constant.

Rearranging this equation by comparing it with rate equation

$$q = \Delta t / L / K_m \times A$$

HEAT CONDUCTION THROUGH FLAT WALLS

IN STEADY STATE



Consider a rectangular flat wall ABCDEFGH in which heat is conducted from ABCD to EFGH.

Let here A = Area of the face ABCD

T_1 = Temperature of face ABCD

T_2 = Temperature of face EFGH

h = Distance betⁿ two faces

K = thermal conductivity of the
Material wall

Applying Fourier's law of heat conduction

$$q = Q/A = -K(t_2 - t_1)/h$$

$$Q = -KA(T_2 - T_1)/h$$

$$Q = KA(T_1 - T_2)/h$$

$$Q = KA / KA(T_1 - T_2)/h / KA$$

$$Q = (T_1 - T_2)/R \quad [h/KA = R]$$

HEAT FLOW THROUGH FURNACE WALL

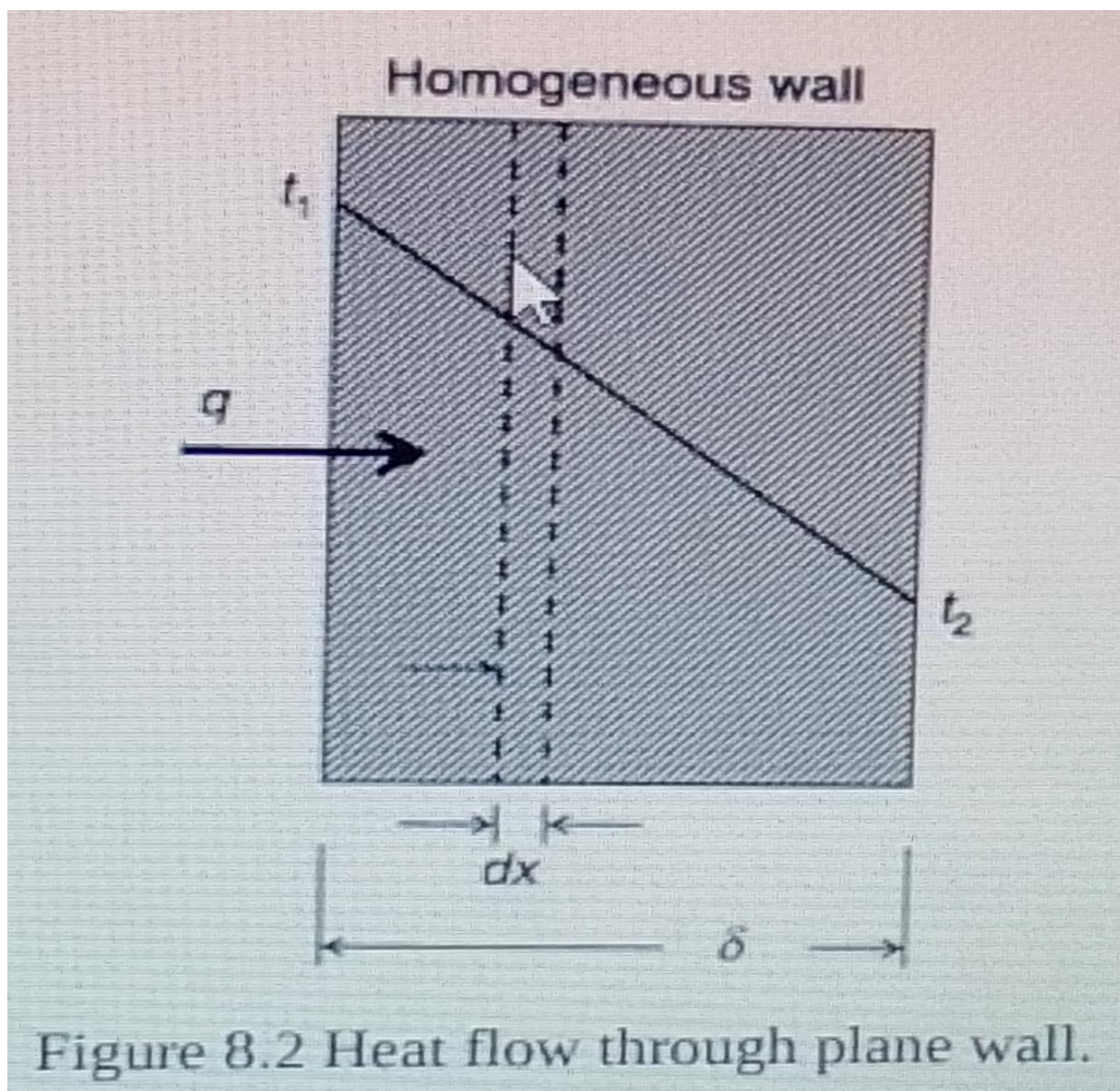
Let us consider the following conditions of heat flow:

1. The wall is homogeneous in nature having width δ .
2. The faces of the wall have steady state condition of heat flow having temperatures t_1 and t_2 which do not change with time.

3. Temperature t_1

is higher than t_2 and the heat flow direction is from surface temperature t_1 to t_2

4. This is a case of one dimensional heat flow with isothermal surface. In such case, the temperature is changing only in one direction (say x -axis) perpendicular to wall.



The heat flow direction, wall thickness and surface temperatures are illustrated in Figure 8.2 for better understanding.

Now, let us consider a small thickness of wall (dx) is located at distance x from the wall having temperature t_1

The rate of heat flow per unit area through this thin layer (thickness dx) is given by Fourier Law

$$q = \lambda \left(\frac{dx}{dt} \right) \quad (8.2)$$

This can be written as, $dt = - (q/\lambda) dx$ (8.3)

The integration of equation (8.3) gives

$$t = - (q/\lambda) x + c \quad (8.4)$$

The constant c can be determined by using boundary conditions, i.e., when $x = 0$, then $t = t_1$
Substituting the boundary conditions in equation (8.4), we get

$$c = t_1 \quad (8.5)$$

When the value of $x = \delta$, then $t = t_2$. Substituting these values of x and t along with value of c in equation (8.4), we get

$$t_2 = - (q/\lambda) \delta + t_1 \quad (8.6)$$

Thus, the rate of heat flow per unit area through the wall can be expressed by rearranging equation (8.6) as

$$q = - (\lambda/\delta) (t_1 - t_2) \quad (8.7)$$

The ratio (λ/δ) is known as 'thermal conductance' and the ratio (λ/δ) is termed

as 'thermal resistance' of the wall.

Using equation (8.7), the total quantity of heat transferred (Q) through a plane wall having surface area A (in m^2) in τ hours is given by

$$Q = q \cdot A \cdot \tau = - (\lambda/\delta) A \cdot \tau \cdot (t_1 - t_2) \text{ kcal}$$

(ii) Heat conduction through composite plane furnace wall

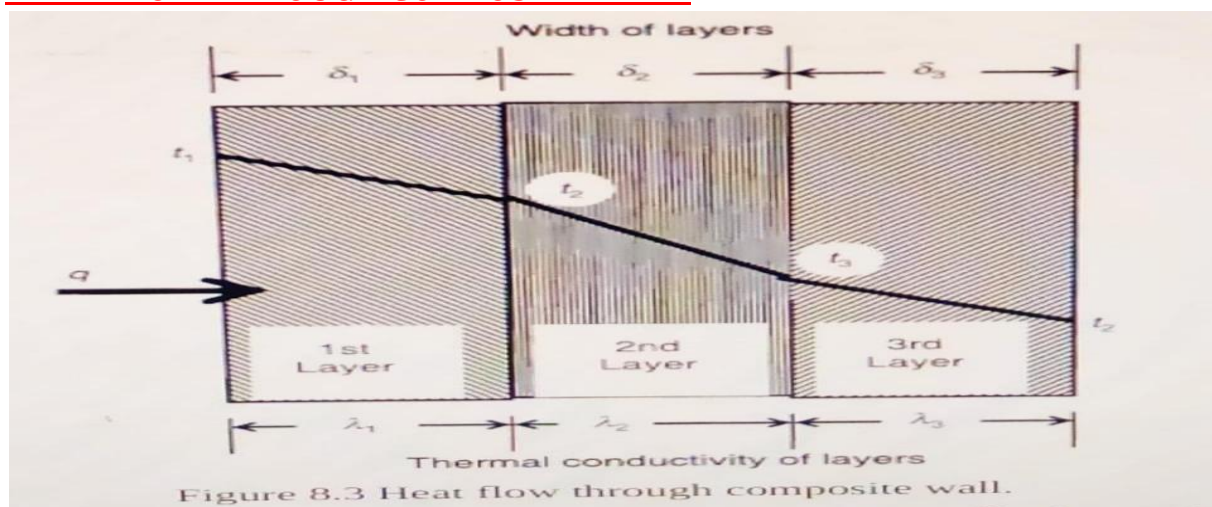
The walls of furnaces and other heat devices are generally made of wall having

two, three or more layers of different materials to have better furnace efficiency.

It is common to have a refractory layer backed with insulating bricks on the outer side. The heat flow in such cases can be done with the following assumptions (Figure 8.3) to simplify the calculation:

1. The composite wall under consideration has three layers of different materials.
2. The thicknesses of 1st, 2nd and 3rd layer walls are δ_1 , δ_2 and δ_3 respectively.
3. The thermal conductivities of 1st, 2nd and 3rd layer are λ_1 , λ_2 and λ_3 respectively.
4. The temperatures t_1 (inner higher temperature) and t_4 (outer lower temperature) are known.
5. The layers in the wall are in close contact with each other and adjacent junction surfaces have same temperature, but the values of t_2 and t_3 are not known.
6. The rate of heat flow per unit area under steady state condition is same for all the layers.

HEAT FLOW THROUGH COMPOSITE WALL



Under these assumptions the rate of heat flow for all these layers could be written (using equation (8.7)) as:

$$q = -(\lambda_1/\delta_1)(t_1 - t_2) \quad (8.9)$$

$$q = -(\lambda_2/\delta_2)(t_2 - t_3) \quad (8.10)$$

$$q = -(\lambda_3/\delta_3)(t_3 - t_4) \quad (8.11)$$

Equations (8.9), (8.10) and (8.11) help in knowing temperature difference at each layer, hence we can write them as:

$$(t_1 - t_2) = q(\lambda_1/\delta_1) \quad (8.12)$$

$$(t_2 - t_3) = q(\lambda_2/\delta_2) \quad (8.13)$$

$$(t_3 - t_4) = q(\lambda_3/\delta_3) \quad (8.14)$$

The sum of temperature difference at each layer is the temperature difference of the composite wall

$$\text{i.e.,} \quad (t_1 - t_4) = (t_1 - t_2) + (t_2 - t_3) + (t_3 - t_4) \quad (8.15)$$

Equation (8.15) can be written as:

$$(t_1 - t_4) = q[(\delta_1/\lambda_1) + (\delta_2/\lambda_2) + (\delta_3/\lambda_3)] \quad (8.16)$$

Hence, the rate of heat flow,

$$q = \frac{t_1 - t_4}{[(\delta_1/\lambda_1) + (\delta_2/\lambda_2) + (\delta_3/\lambda_3)]} \text{ kcal/m}^2 \text{ hr} \quad (8.17)$$

By analogy, the rate of heat flow for wall having n number of layers can be written as:

$$q = \frac{t_1 - t_{n+1}}{[(\delta_1/\lambda_1) + (\delta_2/\lambda_2) + (\delta_3/\lambda_3) + \dots + (\delta_n/\lambda_n)]} \text{ kcal/m}^2 \text{ hr} \quad (8.18)$$

CONVECTION

Convection ;

- **Convection** , is process in which heat flow is achieved by actual mixing of warmer portions with cooler portions of same material.
- It is the heat transfer due to bulk movement within fluid such as gases and liquids.
- For example , heating of water by hot surface is mainly by convection.
- **Natural convection(or free convection)** refers to a case where the fluid movement is created by the warm fluid itself. **The density of fluid decreases as it is heated. Thus , hot fluids are lighter than cool fluid.**

FORCED CONVECTION

Cont ..

- **Forced convection** uses external means of producing fluid movement.
- Forced convection is what in winter days , heat loss from your body is increases due to the **constant replenishment of cold air by the wind.**
- Natural wind and fans are two most common sources of forced convection.

Forced convection

- Forced convection is a heat transfer convection process in which mixing of fluid may be obtained by the **use of stirrer or agitator or pumping the fluid** for recirculation.
- Consider a case of heat flowing from a hot fluid through a metal wall into cold fluid .
- Variation of temperature at a specific point is observed.

NATURAL/FREE CONVECTION

Fluid in Natural Convection/Free convection

- **Natural convection** is defined as heat transfer convection process in which a fluid is heated , the currents set up may cause mixing of fluid .
- This is type of heat transport , in which fluid motion is not generated by external source (like pump, fan, suction device etc)
- In natural convection, fluid surrounding heat source receives heat and by thermal expansion becomes less dense and rises.
- The surrounding ,cooler fluid is then moves to replace it .
- This cooler fluid is then heated and the process continues, forming convection current:

Cont..

- This process transfers heat energy from the bottom of the convection cell to top.
- The driving force for natural convection is **buoyancy**, a result of difference in fluid density.
- This process continues thereby effecting the mixing of hot and cold fluids.
- **Application :**
- Natural convection is observed when extracts are evaporated in open pans.

NATURAL VS FORCED CONVECTION

<h1>Natural vs Forced Convection</h1> <p>More Information Online WWW.DIFFERENCEBETWEEN.COM</p>		
	Natural Convection	Forced Convection
DEFINITION	A method of heat transfer in which the motion of fluid is influenced by natural means.	A method of heat transfer in which the motion of fluid is influenced by external means.
INITIATION OF FLUID MOTION	Fluid motion generates as a result of the change of the density of fluid when heated.	Fluid motion generates as a result of an external source such as pumping, fan, suction devices.
FACTORS AFFECTING HEAT TRANSFER	No external factors affect the heat transfer.	Only external factors can cause heat transfer.
EXAMPLES	Cooling down a boiled egg when kept in the normal air, loss of cool of a cool drink can, etc.	Air conditioning, steam turbines, etc.

HEAT TRANSFER CO-EFFICIENT

Heat transfer coefficient is the heat transfer per unit area per kelvin.

Thus area is included in the equation as it represents the area over which the transfer of heat takes place.

The areas for each flow will be different as they represents the contact area for each fluid side.

OR

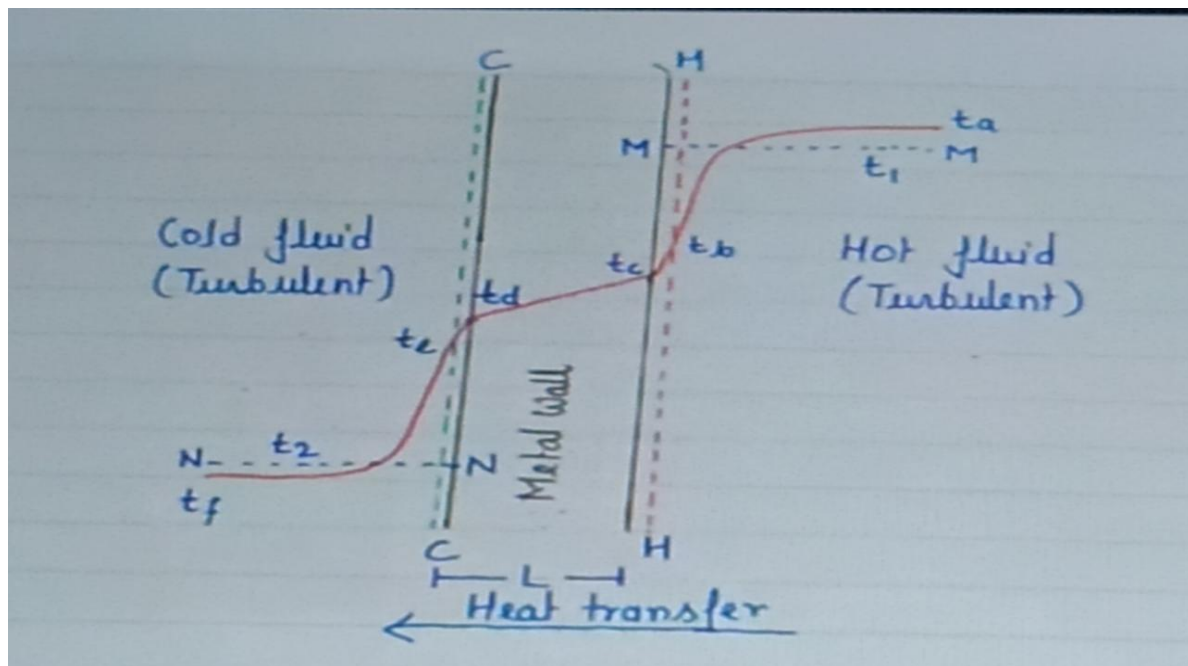
Consider a case of heat flowing from hot fluid

↓

Through a metal wall

↓

Into a cold fluid



FREE(NATURAL)CONVECTION HEAT TRANSFER

CO-EFFICIENT

$$N_U = C(Gr.Pr)^n = CRa^n$$

OR

$$h.L/k = C(p^2 g_c \beta c_p \Delta T L^3 / \mu^2 \times \mu / c_p k)^n$$

where

C_p = Specific heat constant pressure

G_c = Gravitational acceleration

G_R = Grashof number (dimensionless)

h = Heat transfer coefficient

k = Thermal conductivity of air

L =Height or length of plate

N_U =Nusselt number(dimensionless)

P_R =Prandtl number(dimensionless)

R_a =Rayleigh number(dimensionless)

T_a =Temperature of ambient air

T_s =Temperature of heated surface

ΔT =Temperature difference from
Surface to air

B =Coefficient of thermal expansion for air

ρ =Density of air

μ =Dynamic viscosity of air

FORCED CONVECTION HEAT TRANSFER

CO-EFFICIENT

q =Heat flux

W/m^2 =Thermal power per unit area

$q=d/dA$

h =Heat transfer coefficient

$W/(m^2.K)$

RADIATION

Radiation :

- Radiation is a energy transfer process in which heat is transferred through space by means of electromagnetic waves .
- **Thermal radiation :**
 - Heat transfer by radiation is known as **thermal radiation** .
 - Radiation is effective across perfect vacuum and also through layers of air.
 - All solid bodies radiates energy when their temperature are above the absolute zero.
 - The amount and kind of thermal energy radiated increases rapidly with temperature.

Cont...

- Thermal radiation usually occurs simultaneously with heat transfer by **convection** and **conduction** .
- **Advantages :**
 - The radiation source corresponding to wavelength from **0.8 to 400 μm** is used for the thermal radiation.
 - Radiants energy penetrates a short distance (1 to 2 μm) into material.

RATE OF RADIATION

Rate of radiation:

- Normally , hot bodies emit radiation. *Stefan –Boltzman law* gives the total amount of radiation emitted by a black body.

$$q = bAT^4$$

Where, q = energy radiate per second. W (or J/s)

A = Area of radiating surface, m^2

T = Absolute temperature of the radiating surface, K

b = Constant, $W/m^2.K^4$

Kirchoff's law :

This law establishes relationship between **emissive power of surface to its absorptivity.**

Cont..

- E , emissive power of the body is the **radiant energy emitted from unit area in unit time.**
- It states that , the ratio of emissive power to the absorptivity is same for all bodies in thermal equilibrium .

$$\frac{E_1}{\alpha_1} = \frac{E_2}{\alpha_2}$$

E_1 and E_2 = Emissive power of two bodies

α_1 and α_2 = Absorptivity of two bodies

STEFAN BOLTZMAN'S LAW

This law states that amount of radiant heat emitted black body which is proportional to the forth power of absolute temperature.

$$F_0 \propto T^4$$

$$F_0 \propto \sigma_0 T^4$$

$\therefore \sigma_0$ = radiation co-efficient of black body

EMISSIVITY OF BLACK AND GREY BODIES

A black body that absorb all the radiation falling upon it, is called black body. without regarding the wavelength of incident ray.

There is no material which is perfectly black since every body lose part of incident radiation by reflecting or transmitting.

But, it is possible to increase the absorbing of body upto 90-95% of artificial creative black body.

Consider a large hollow sphere/cylinder provided with only one small opening and let it be maintained at uniform temperature. The inner surface of cylinder is coated with black which absorbs about 95% of the incident radiation. When the radiation is allowed to incident through the opening. The incident rays are internally reflected several times on the inner surface and hence an amount of radiation is absorbed and only a small part escapes out.

GREY BODY

A body whose absorptivity doesn't vary with temperature and wavelength of incident ray is called grey body.

For grey body, the emissivity power is less than 1.

The emissivity power of the body is the thermal energy radiated from a unit surface of the body in a unit time for electromagnetic wave.

Length ranging from $\lambda=0$ to $\lambda=\infty$

FURNACES

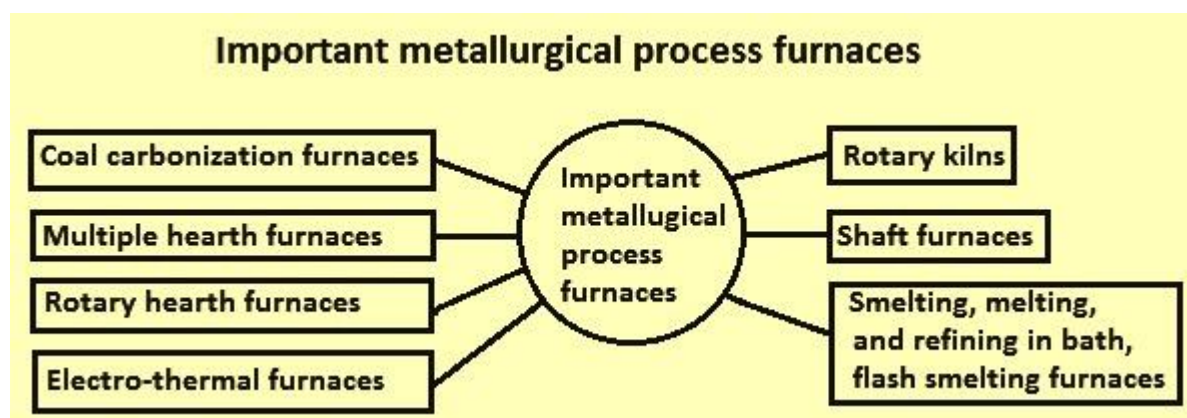
Metallurgical Industrial Furnaces

An industrial furnace is essentially a thermal enclosure and is employed to process raw materials at high temperatures both in solid state and liquid state. The principle objectives of an industrial furnace are (i) to utilize heat efficiently so that losses are minimum, and (ii) to handle the different phases (solid, liquid or gaseous) moving at different velocities for different times and temperatures such that erosion and corrosion of the refractory are minimum.

Industrial furnaces which used in the metallurgical industry for carrying out various metallurgical processes are known as metallurgical industrial furnaces. Metallurgical furnaces are mostly used for (i) extraction of metals from ores, (ii) calcining and sintering of ores, (iii) melting, refining and alloying of metals, (iv) heating of metals, (v) carbonizing of coals, and (vi) heat treatment of metals etc. Energy sources for metallurgical furnaces are (i) combustion of fossil fuels, such as solid, liquid and gaseous fuels, (ii) electric energy such as resistance heating, induction heating or arc heating, and (iii) chemical energy such as exothermic reactions.

Important metallurgical furnaces

Important metallurgical furnaces used in various metallurgical processes are (i) coal carbonization furnaces, (ii) rotary kilns, (iii) multiple hearth furnaces, (iv) shaft furnaces, (v) rotary hearth furnaces, (vi) smelting, melting, and refining in bath and flash smelting furnaces, and (vii) electro-thermal furnaces.



Coal carbonization furnaces

Coal carbonization furnaces are popularly known as coke ovens, where the coal carbonization process takes place. The process consists of thermal decomposition of coals either in the absence of air or in controlled atmosphere to produce a carbonaceous residue known as coke. 3 types of coke ovens are used for coal carbonization. These are (i) beehive ovens, (ii) by-product ovens, and (iii) non- recovery ovens.

A beehive oven is a simple firebrick chamber built with an arched roof so that the shape inside is that of an old-fashioned beehive. Its dimensions are typically 4 m wide and 2.5 m high. Beehive ovens are usually built in rows, one oven beside another with common walls between neighboring ovens. Such a row of ovens is termed a battery. A battery usually consists of many ovens, sometimes hundreds, in a row.

The beehive oven is a simple domed brick structure into which coal can be charged through an opening at the top and then leveled through a side door to form on a bed of around 600 mm to 900 mm thick. Heat is supplied by burning the volatile matter (VM) released from the coal, and carbonization progresses from the top down through the charge. Around 5 tons to 6 tons of coal can be charged, and a period of 48 hours to 72 hours is needed for the carbonization.

By-product coke ovens are the chambers made of refractories to convert coal into coke by carbonizing coal in absence of air and there by distilling the VM out of coal. Byproduct coke ovens are also arranged in a battery containing number of coke ovens (can vary from 20 to 100 in each battery).

Modern by product coke ovens are comprised of chambers 15 metres (m) to 20 m long, 6 m to around 9 m high, 500 mm to 600 mm wide and having a wall thickness of around 100 mm. A number of these chambers alternating with similar cells that accommodate heating flues form as a battery. Crushed coal is loaded along the top of the ovens using a charging car on rails and is leveled by a retractable bar.

Rotary kilns

A rotary kiln is an inclined, rotating cylindrical reactor through which a charge moves continuously. The rotary kiln is used when thermal processing of solids which is more severe than drying is required. The furnace walls (normally lined) make intermittent contact with the flue gas and the charge. Heat required for the various physical and chemical processes is delivered to the charge by lifting and overturning the charge as it moves through the interior of the rotary kiln. The most widespread usage of rotary kiln is in the production of cement clinker, limestone calcining, production of calcined and dead burnt dolomite, calcined magnesite, and iron ore reduction for the production of direct reduced iron (DRI) etc.

The rotary kiln consists of a lined hollow cylinder, mounted in an inclined position on rolls and rotated slowly by a drive. The charge material moves from the feed end to the discharge end because of the rotary motion and gravity. The inclination is between 1.5 % and 5 %. Speed is between 0.2 rpm (rotations per minute) and 2 rpm. Variable-speed drives are normally used to control the residence. Kiln diameter is usually constant over the full length. Some rotary kilns have internals such as conveying or lifting flights, built in crossed-hanging link chains, or ring dams. In some processes, air-feed pipes or burner tubes for gas or oil are installed on the furnace shell. Air or other gases can also be introduced through ports in the lining.

Rotary kiln carries out several functions simultaneously. It is equipment for conveying, mixing, heat transfer, and reaction. These functions are to be in harmony. The charge in the kiln moves both radially and axially. Radial motion is determined by the degree of filling (percentage of cross-sectional area occupied by the charge) and the rotational speed. The angle of repose and the kiln inclination govern the axial motion.

The interior of the charge tends to have a higher bulk density than the exterior, and grain size increases toward the outside. This tendency can be counteracted by the internals, which also improve heat transfer into the charge. Dust production can be limited by pelletizing the feed.

Heat transfer occurs principally from the combustion gas (generated by a burner usually installed at the discharge end of the kiln) to the charge. The driving force is generally the temperature difference. The gas can move co- or counter-current to the longitudinal movement of the charge. Cocurrent gas flow is advantageous only when the charge temperature does not have to exceed a certain value. The counter-current arrangement is preferred because it involves increased total energy consumption.

Multiple hearth furnaces

Multiple hearth furnaces used to be in a dominant position as a roasting furnace for sulphide ores (mainly pyrites in sulphuric acid production). It has now been almost completely replaced by fluidized-bed roasting equipment since the 1960s. Fluidized-bed furnaces allow much higher throughputs than multiple hearth furnaces, with substantially better control of reaction temperature and O₂ partial pressure in the roasting gas. However, the multiple hearth furnaces continue to find use in some special areas of process engineering.

A multiple hearth furnace consists of an internally lined steel cylinder with a number of horizontally mounted, lined platforms called hearths. The circular hearths are thinner near the centre, which has an opening for a vertical shaft. An adjustable-speed drive with overload protection turns the shaft at 0.2 rpm to 5 rpm. From 1 to 4 rabble arms per hearth are latched to the shaft in a gastight manner. These arms bear oblique stirring teeth to move the solids over the hearth. On one hearth, the motion is from centre to edge, on the next from edge to centre depending on the inclination of the stirring teeth. The openings in the hearths, through which the charge travels from the top of the furnace to the bottom, thus alternate from central to peripheral.

Shaft furnaces

A shaft furnace is a furnace which has an upright working chamber of circular, elliptical, or rectangular cross section in which a fixed bed (or descending column) of solids is maintained, and through which an ascending stream of

hot gas is forced . It is used to smelt or roast lumped materials. The heat required for smelting or roasting process is produced by the combustion of a fuel either directly in the furnace or in an external firebox from which the combustion products are supplied to the furnace. There is counter current movement of gases and the solids in the furnace.

Moderate velocities of the gaseous combustion products are characteristic of shaft furnaces. At such velocities, the bulk of the lumped materials (the charge) is not entrained by the ascending gas stream and, in contrast to the case of a fluidized- bed furnace, maintains aerodynamic stability. The counter current motion of the charge (from the top to the bottom) and of the gases forced through the charge (from the bottom to the top) and the direct contact between the charge and the hot gases result in good heat exchange and the generation of low-temperature exhaust gases. Thus, shaft furnaces are characterized by a high thermal efficiency and a relatively high output. Such furnaces are widely used to smelt iron ores (blast furnace and direct reduction furnace) as well as non-ferrous ores.

The shaft furnaces are designed for continuous operation. The main components of shaft furnace consist of (i) a top, through which the charge is loaded and the gaseous combustion products are discharged, (ii) a shaft equipped with tuyeres, through which either a blast for fuel combustion or hot gases are supplied, and (iii) an inside crucible with a refractory lining, where the liquid products collect. The furnace is tapped at intervals.

Rotary hearth furnaces

Rotary hearth furnaces are also known as rotating table furnaces. They are very useful for many purposes. Besides being utilized for the heating of circular loads (for example in the pipe rolling mills), the rolling hearth furnaces are also being used for the reduction processes. In these furnaces materials are placed on the merry-go-round-like hearth. The materials travel on a circular track and undergo reduction reactions while travelling. The reduced product is later removed after the materials have completed almost a whole revolution. The furnaces have several zones.

Special features of the rotary hearth furnace are (i) they are of simple design and have good reliability, (ii) the separated zones allow accurate process control, (iii) less thermal and mechanical stressing of batch carriers, (iv) loading/offloading can take place at a single location, (v) allows high degrees of flexibility in configuring feed and take-off lines and no extra grates needed for emptying runs, and (vi) better net throughputs, resulting from the use of lighter base grates or ceramic batch carriers for individual parts handling.

Rotary hearth furnaces are utilized for heat treating of large pipes, carbon baking, calcining of coal and carbon products, direct reduction of ores, and processing of iron nuggets.

Smelting, melting, and refining in bath and flash smelting furnaces

Fine concentrates can be smelted without agglomeration in flash (after drying) or bath smelting furnaces. The heat of exothermic chemical reactions provides the energy for autogenous smelting. All these furnaces are operated continuously. A wide variety of such smelting furnaces and converters are being used. The smelting furnaces represent a modern approach of intensive metal smelting under environmentally 'clean' conditions.

In bath smelting furnaces and converters, O₂ or O₂-enriched air is blown into the liquid metal or matte baths via tuyeres, lances, or injectors to oxidize elements which are to be removed as impurities. Coal or reducing gases can also be blown into liquid slags via tuyeres, lances, and injectors for slag reduction. In the case of aluminum (Al) smelting, chlorine (Cl) is blown through pipes and stirrers into the liquid metal bath to remove alkaline and alkaline-earth elements. Bath smelting furnaces are used for smelting of copper (Cu), and lead (Pb). Bath smelting furnaces are in development for the direct steel production from iron ores.

Satyendra December 9, 2019 0 Comments Bath Smelting, Coal Carbonation Furnaces, Converters, EAF, Electro Thermal Furnaces, Flash Smelting, heating Furnaces, IF, Metallurgical Furnaces, Multiple Hearth Furnaces, process Furnaces, Rotary Hearth Furnaces, Rotary Kilns, Shaft Furnaces, VAR Furnaces

Metallurgical Industrial Furnaces

An industrial furnace is essentially a thermal enclosure and is employed to process raw materials at high temperatures both in solid state and liquid state.

The principle objectives of an industrial furnace are (i) to utilize heat efficiently so that losses are minimum, and (ii) to handle the different phases (solid, liquid or gaseous) moving at different velocities for different times and temperatures such that erosion and corrosion of the refractory are minimum.

Industrial furnaces which used in the metallurgical industry for carrying out various metallurgical processes are known as metallurgical industrial furnaces. Metallurgical furnaces are mostly used for (i) extraction of metals from ores, (ii) calcining and sintering of ores, (iii) melting, refining and alloying of metals, (iv) heating of metals, (v) carbonizing of coals, and (vi) heat treatment of metals etc. Energy sources for metallurgical furnaces are (i) combustion of fossil fuels, such as solid, liquid and gaseous fuels, (ii) electric energy such as resistance heating, induction heating or arc heating, and (iii) chemical energy such as exothermic reactions.

Process heating metallurgical furnaces are insulated enclosures designed to deliver heat to the charge. Melting ferrous metals needs very high temperatures (higher than 1250 deg C), and can involve erosive and corrosive conditions. Shaping operations use high temperatures (1050 deg C to 1250 deg C) to soften the materials for processing such as forging, rolling, pressing, bending, drawing, and extruding etc. Treating can use midrange temperatures (600 deg C to 1050 deg C) to physically change crystalline structures or chemically (metallurgically) alter surface compounds, including hardening or relieving strains in metals, or modifying their ductility. These include aging, annealing, austenitizing and carburizing, hardening, malleabilizing, martinizing, nitriding, sintering, spheroidizing, stress-relieving, and tempering. Processes which use low temperatures (less than 600 deg C) include drying, polymerizing, and other chemical changes.

Metallurgical furnaces which do not show colour, that is, in which the temperature is below 650 deg C, are generally called 'ovens'. However, the dividing line between ovens and furnaces is not sharp. For example, coke ovens operate at high temperatures (higher than 900 deg C). Many of the furnaces are termed ovens, kilns, heaters, afterburners, incinerators, or destructors. The furnace of a boiler is its 'firebox' or 'combustion chamber', or a fire-tube boiler's 'Morrison tube.'

Industrial heating operations encompass a wide range of temperatures, which depend partly on the material being heated and partly on the purpose of the heating process and subsequent operations. In any heating process, the maximum furnace temperature always exceeds the temperature to which the furnace charge is to be heated.

Classification of metallurgical industrial furnaces

Metallurgical industrial furnaces are classified in several ways. These are described below.

Furnace classification by heat source – Heat is generated in the furnace to increase the furnace temperature to a level which is higher than the temperature needed for the process, either (i) by the combustion of a fuel, or (ii) by conversion of electric energy to heat. Some furnaces also utilize the waste heat from the metallurgical process. Fuel-fired furnaces are most widely used, but electrically heated furnaces are also used where they offer advantages which cannot always be measured in terms of fuel cost. In fuel-fired furnaces, the nature of the fuel can make a difference in the furnace design, but that is not much of a problem with modern industrial furnaces and combustion equipment. Additional basis for classification can relate to the place where combustion begins and the means for directing the products of combustion (POC).

Furnace classification by the method handling materials into, through, and out of the furnace – Furnaces can be batch type or continuous type.

Batch-type furnaces are often termed as 'in-and-out furnaces. These furnaces have one temperature set point, but have usually 3 zones of control for maintaining uniform temperature throughout, because of a need for more heat at a door and at the ends. These furnaces can be charged manually or by a manipulator. After placing the charge in the furnace, both the furnace and its charge are brought up to the required temperature together, and depending on the process, the furnace may or may not be cooled before it is opened and the charge is removed from the furnace usually through a single charging and discharging door. Batch furnace configurations include box, slot, car-hearth, shuttle, bell, elevator, and bath (including immersion). For long solid loads,

crosswise piers and top-left/bottom-right burner locations circulate for better uniformity. Bell and elevator kiln furnaces are often cylindrical. Furnaces for pot, kettle, and dip-tank containers can be fired tangentially with high velocity, low swirl flames instead of flat flame with very high swirl. There are many types of batch furnaces. Examples are crucible, pot, kettle, dip-tank furnaces, and movable hearth furnace etc.

Continuous furnaces move the charged material while it is being heated. Material passes over either a stationary hearth or the hearth itself moves. If the hearth is stationary, the material is pushed or pulled over skids or rolls, or is moved through the furnace by wire ropes or mechanical pushers. Except for delays, a continuous furnace operates at a constant heat input rate, burners being rarely shut off. A constantly moving (or frequently moving) conveyor or hearth eliminates the need to cool and reheat the furnace (as is the case with a batch furnace), thus it saves energy. Horizontal straight-line continuous furnaces are more common than rotary hearth furnaces, rotary drum furnaces, vertical shaft furnaces, or fluidized bed furnaces. Common examples of continuous furnaces are reheating furnace in rolling mill, continuous belt-conveyor type heat treat furnace, roller hearth furnace, and tunnel furnaces / tunnel kilns.

Alternatives to straight-line horizontal continuous furnaces are rotary hearth (disc or donut) furnaces, inclined rotary drum furnaces, tower furnaces, shaft furnaces, fluidized bed furnaces, and liquid heaters and boilers. Rotary hearth or rotating table furnaces are very useful for many purposes. Charges are placed on the merry-go-round-like hearth, and later removed after they have completed almost a whole revolution. The rotary hearth, disc or donut (with a hole in the middle), travels on a circular track. The rotary hearth or rotating table furnace is especially useful for cylindrical charges, which cannot be pushed through a furnace, and for shorter pieces which can be stood on end or laid end to end. The central column of the donut type helps to separate the control zones.

Multi hearth furnace is a variation of the rotary hearth furnace with many levels of round stationary hearths with rotating rabble arms which gradually

plow granular or small lump materials radially across the hearths, causing them to eventually drop through ports to the next level.

Inclined rotary drum furnaces, kilns, incinerators, and dryers often use long type luminous flames. If drying is involved, substantially more excess air than normal can be justified to provide greater moisture pickup ability.

Tower furnaces conserve floor space by running long strip or strand materials vertically on tall furnaces for drying, coating, curing, or heat treating (especially annealing). In some cases, the load can be protected by a special atmosphere, and heated with radiant tubes or electrical means.

Shaft furnaces are usually refractory-lined vertical cylinders, in which gravity conveys solids and liquids to the bottom and by-product gases to the top. Examples are cupolas, blast furnaces, and lime kilns.

Fluidized bed furnaces utilize intense gas convection heat transfer and physical bombardment of solid heat receiver surfaces with millions of rapidly vibrating hot solid particles. The furnaces are of several types as given below.

A refractory-lined container, with a fine grate bottom, filled with inert (normally refractory) balls, pellets, or granules which are heated by POC from a combustion chamber below the grate. Loads or boiler tubes are immersed in the fluidized bed above the grate for heat processing or to generate steam.

Similar to above, but the granules are fuel particles or sewage sludge to be incinerated. The space below the grate is a pressurized air supply plenum. The fuel particles are ignited above the grate and burn in fluidized suspension while physically bombarding the water walls of the upper chamber and water tubes immersed in its fluidized bed.

The fluidized bed is filled with cold granules of a coating material (e.g. polymer), and loads to be coated are heated in a separate oven to a

temperature above the melting point of the granules. The hot loads are then dipped (by a conveyor) into the open-topped fluidized bed for coating.

Furnace classification by fuel – In fuel-fired furnaces, the nature of the fuel can make a difference in the furnace design, but this is not much of a problem with modern industrial furnaces and burners, except if solid fuels are involved. Similar bases for classification are air furnaces, oxygen (O₂) furnaces, and atmosphere furnaces. Related bases for classification can be the position in the furnace where combustion begins, and the means for directing the POC. Examples are internal fan furnaces, high velocity furnaces, and baffled furnaces.

Electric furnaces for industrial process heating can use resistance or induction heating. Theoretically, if there is no gas or air exhaust, electric heating has no flue gas loss.

Resistance heating usually involves the high electricity costs, and can require circulating fans to assure the temperature uniformity achievable by the flow motion of the POC in a fuel-fired furnace. Silicon (Si) control rectifiers have made input modulation more economical with resistance heating. Various materials are used for electric furnace resistors. Most are of a nickel–chromium (Ni-Cr) alloy, in the form of rolled strip or wire, or of cast zigzag grids (mostly for convection). Other resistor materials are molten glass, granular carbon (C), solid C, graphite, or silicon carbide (SiC) (glow bars, mostly for radiation). It is sometimes possible to use the charge which is being heated as a resistor.

In induction heating, a current passes through a coil that surrounds the piece to be heated. The electric current frequency to be used depends on the mass of the piece being heated. The induction coil (or induction heads for specific charge shapes) is to be water cooled to protect them from overheating themselves. Although induction heating generally uses less electricity than resistance heating, some of that gain can be lost due to the cost of the cooling water and the heat which it carries down the drain. Induction heating is easily

adapted to heating only localized areas of each piece and to mass production methods.

Many recent developments and suggested new methods of electric or electronic heating offer ways to accomplish industrial heat processing, using plasma arcs, lasers, radio frequency, microwave, and electromagnetic heating, and combinations of these with fuel firing.

Furnace classification by recirculation – For medium or low temperature furnaces/ovens/dryers operating below 750 deg C, a forced recirculation furnace or recirculating oven delivers better temperature uniformity and better fuel economy. The recirculation can be by a fan and duct arrangement, by ceiling plug fans, or by the jet momentum of burners (especially high-velocity low swirl flame burners). In these furnaces, the requirement is thoughtful circulation design and careful positioning relative to the furnace charges.

Furnace classification by direct-fired or indirect-fired – If the flame is developed in the heating chamber proper, or if the POC are circulated over the surface of the workload, then the furnace is said to be direct-fired. In most of the furnaces, ovens, and dryers, the charge is not harmed by contact with the POC. Indirect-fired furnaces are used for heating materials and products for which the quality of the finished products can be inferior if they have come in contact with flame or POC.

In such cases, the charge can be (a) heated in an enclosing muffle (conducting container) which is heated either from the outside by the POC from burners or heated by radiant tubes which enclose the flame and POC. In case of a double muffle arrangement, not only the charge is enclosed in a muffle but the POC are confined inside muffles called radiant tubes. This use of radiant tubes to protect the inner cover from uneven heating is being replaced by direct-fired with flat (very high swirl) or high velocity (low swirl) flames to heat the inner cover, thereby improving thermal conversion efficiency and reducing heating time. The radiant tube furnace is for charges which require a special

atmosphere for protection of the material from oxidation, decarburization, or for other purposes. The indirect-fired furnace is built with a gas-tight outer casing surrounding the refractory lining so that the whole furnace can be filled with a prepared atmosphere. Heat is supplied by fuel-fired radiant tubes or electric resistance elements.

Classification by furnace Use (including the shape of the material to be heated) – These are soaking pit or ingot-heating furnace, usually in a vertical position. There is forge furnace for heating whole pieces or for heating ends of bars for forging or welding. Slot forge furnace has a horizontal slot instead of a door for inserting the many bars which are to be heated at one time. The slot also often serves as the flue. Furnaces named for the material being heated include bolt heading furnaces, plate furnaces, wire furnaces, rivet furnaces, and sheet furnaces. Some furnaces are also classified by the process of which they are a part, such as hardening, tempering, annealing, melting, and polymerizing. In carburizing furnaces, the charge to be case-hardened is packed in a C-rich powder and heated in pots/boxes, or heated in rotating drums in a carburizing atmosphere.

Classification by type of heat recovery (if any) – Most heat recovery efforts are aimed at utilizing the 'waste heat' leaving through the flues. Some forms of heat recovery are air preheating, fuel preheating, charge preheating, recuperative, regenerative, and waste heat boilers. Preheating combustion air is accomplished by recuperators or regenerators. Recuperators are steady-state heat exchangers which exchange heat from hot flue gases to cold combustion air. Regenerators are non-steady state devices which temporarily store heat from the flue gas in many small masses of refractory or metal, each having considerable heat-absorbing surface. Then, the heat absorbing masses are moved into an incoming cold combustion air stream to give it their stored heat. Furnaces equipped with these devices are sometimes termed recuperative furnaces or regenerative furnaces.

Regenerative furnaces in the past have been very large, integrated refractory structures incorporating both a furnace and a checker work refractory regenerator, the latter often much larger than the furnace portion. However,

most regeneration is now accomplished with integral regenerator/burner packages which are used in pairs.

Both preheating the charge and preheating combustion air are used together in steam generators, rotary drum calciners, metal heating furnaces, and tunnel kilns.

Other furnace type classifications – There are stationary furnaces, portable furnaces, and furnaces which are slowly rolled over a long row of loads. Many kinds of continuous ‘conveyor furnaces’ have the charge carried through the heating chamber by a conveying mechanism. Some forms of conveyors are wire ropes, rollers, rocker bars, and self-conveying catenary strips or strands.

Oxygen furnace is the furnace which uses O₂ enriched air or near-pure O₂. In many high-temperature furnaces, productivity can be increased with minimum capital investment by using O₂ enrichment or 100 % O₂ (oxy-fuel firing). Either method reduces the nitrogen (N₂) concentration, lowering the percentage of diatomic molecules and increasing the percentage of triatomic molecules. This raises the heat transfer rate (for the same average gas blanket temperature and thickness) and thereby lowers the stack loss. O₂ use reduces the concentration of N₂ in a furnace atmosphere (by reducing the volume of combustion air needed), so it can reduce NO_x emissions.

Important metallurgical furnaces

Important metallurgical furnaces used in various metallurgical processes (Fig 1) are (i) coal carbonization furnaces, (ii) rotary kilns, (iii) multiple hearth furnaces, (iv) shaft furnaces, (v) rotary hearth furnaces, (vi) smelting, melting, and refining in bath and flash smelting furnaces, and (vii) electro-thermal furnaces.

Fig 1 Important metallurgical process furnaces

Coal carbonization furnaces

Coal carbonization furnaces are popularly known as coke ovens, where the coal carbonization process takes place. The process consists of thermal decomposition of coals either in the absence of air or in controlled atmosphere to produce a carbonaceous residue known as coke. 3 types of coke ovens are used for coal carbonization. These are (i) beehive ovens, (ii) by-product ovens, and (iii) non-recovery ovens.

A beehive oven is a simple firebrick chamber built with an arched roof so that the shape inside is that of an old-fashioned beehive. Its dimensions are typically 4 m wide and 2.5 m high. Beehive ovens are usually built in rows, one oven beside another with common walls between neighboring ovens. Such a row of ovens is termed a battery. A battery usually consists of many ovens, sometimes hundreds, in a row.

The beehive oven is a simple domed brick structure into which coal can be charged through an opening at the top and then leveled through a side door to form on a bed of around 600 mm to 900 mm thick. Heat is supplied by burning the volatile matter (VM) released from the coal, and carbonization progresses from the top down through the charge. Around 5 tons to 6 tons of coal can be charged, and a period of 48 hours to 72 hours is needed for the carbonization.

By-product coke ovens are the chambers made of refractories to convert coal into coke by carbonizing coal in absence of air and there by distilling the VM out of coal. Byproduct coke ovens are also arranged in a battery containing number of coke ovens (can vary from 20 to 100 in each battery).

Modern by product coke ovens are comprised of chambers 15 metres (m) to 20 m long, 6 m to around 9 m high, 500 mm to 600 mm wide and having a wall

thickness of around 100 mm. A number of these chambers alternating with similar cells that accommodate heating flues form as a battery. Crushed coal is loaded along the top of the ovens using a charging car on rails and is leveled by a retractable bar.

The operation of each oven is cyclic, but the battery contains a sufficiently large number of ovens to produce an essentially continuous flow of raw coke oven gas. The individual ovens are charged and emptied at approximately equal time intervals during the coking cycle. Coking proceeds for 15 hours to 18 hours to produce BF coke. During this period, VM of coal distills out as coke oven gas. The time of coking is determined by the coal blend, moisture content, rate of under firing, and the desired properties of the coke. Coking temperatures generally range from 900 deg C to 1100 deg C and are kept on the higher side of the range to produce blast furnace (BF) coke. Air is prevented from leaking into the ovens by maintaining a positive back pressure in the collecting main. The ovens are maintained under positive pressure by maintaining high hydraulic main pressure of around 10 mm water column in batteries. The gases and hydrocarbons which evolve during the thermal distillation are removed through the off take system and sent to the by-product plant for recovery.

Non-recovery ovens are generally of horizontal design and operate under negative pressure unlike by-products ovens which operate under positive pressure. Primary combustion air, introduced through ports in the oven doors, partially burns directly the volatiles (Including tar and benzol) in the oven space above the coal. This generates the heat needed for the process. The mixture of the crude and the waste gases is led through the vertical ducts in the side walls to the heating flue system under the oven sole. Secondary air is introduced into the sole flues, which runs in the serpentine fashion under the coal bed and completes the combustion of the gases. The design of the flues and the control of the air flow allow the coking rate at the top and bottom of the coal bed to be equalized. Due to the temperatures generated, all the hydro-carbons and by-products are burned within the oven. The time of coking varies from 48 hours to 72 hours depending upon the design of the non-recovery coke ovens. Hot gases pass in a waste tunnel to heat recovery steam

generators (HRSG), where high pressure steam is produced which is normally utilized for power generation.

Rotary kilns

A rotary kiln is an inclined, rotating cylindrical reactor through which a charge moves continuously. The rotary kiln is used when thermal processing of solids which is more severe than drying is required. The furnace walls (normally lined) make intermittent contact with the flue gas and the charge. Heat required for the various physical and chemical processes is delivered to the charge by lifting and overturning the charge as it moves through the interior of the rotary kiln. The most widespread usage of rotary kiln is in the production of cement clinker, limestone calcining, production of calcined and dead burnt dolomite, calcined magnesite, and iron ore reduction for the production of direct reduced iron (DRI) etc.

The rotary kiln consists of a lined hollow cylinder, mounted in an inclined position on rolls and rotated slowly by a drive. The charge material moves from the feed end to the discharge end because of the rotary motion and gravity. The inclination is between 1.5 % and 5 %. Speed is between 0.2 rpm (rotations per minute) and 2 rpm. Variable-speed drives are normally used to control the residence. Kiln diameter is usually constant over the full length. Some rotary kilns have internals such as conveying or lifting flights, built in crossed-hanging link chains, or ring dams. In some processes, air-feed pipes or burner tubes for gas or oil are installed on the furnace shell. Air or other gases can also be introduced through ports in the lining.

Rotary kiln carries out several functions simultaneously. It is equipment for conveying, mixing, heat transfer, and reaction. These functions are to be in harmony. The charge in the kiln moves both radially and axially. Radial motion is determined by the degree of filling (percentage of cross-sectional area occupied by the charge) and the rotational speed. The angle of repose and the kiln inclination govern the axial motion.

The interior of the charge tends to have a higher bulk density than the exterior, and grain size increases toward the outside. This tendency can be counteracted by the internals, which also improve heat transfer into the charge. Dust production can be limited by pelletizing the feed.

Heat transfer occurs principally from the combustion gas (generated by a burner usually installed at the discharge end of the kiln) to the charge. The driving force is generally the temperature difference. The gas can move co- or counter-current to the longitudinal movement of the charge. Cocurrent gas flow is advantageous only when the charge temperature does not have to exceed a certain value. The counter-current arrangement is preferred because it involves increased total energy consumption.

Multiple hearth furnaces

Multiple hearth furnaces used to be in a dominant position as a roasting furnace for sulphide ores (mainly pyrites in sulphuric acid production). It has now been almost completely replaced by fluidized-bed roasting equipment since the 1960s. Fluidized-bed furnaces allow much higher throughputs than multiple hearth furnaces, with substantially better control of reaction temperature and O₂ partial pressure in the roasting gas. However, the multiple hearth furnaces continue to find use in some special areas of process engineering.

A multiple hearth furnace consists of an internally lined steel cylinder with a number of horizontally mounted, lined platforms called hearths. The circular hearths are thinner near the centre, which has an opening for a vertical shaft. An adjustable-speed drive with overload protection turns the shaft at 0.2 rpm to 5 rpm. From 1 to 4 rabble arms per hearth are latched to the shaft in a gastight manner. These arms bear oblique stirring teeth to move the solids over the hearth. On one hearth, the motion is from centre to edge, on the next from edge to centre depending on the inclination of the stirring teeth. The openings in the hearths, through which the charge travels from the top of the furnace to the bottom, thus alternate from central to peripheral.

Since the temperature in the furnace is high, the shaft and rabble arms are air cooled. The shaft has double walls. Cold air supplied by a fan enters the outside space, passes through the shaft and arms, and leaves the furnace at 200 deg C to 300 deg C by way of the centre space. Each hearth has several doors, which allow monitoring of the reaction and replacement of the rabble arms. The doors can be sealed tightly or can have adjustable air slots to admit cooling or combustion air if a slight sub atmospheric pressure is maintained in the furnace.

Appropriate reactions for the multiple-hearth furnace are (i) slow reactions (since long residence times can be achieved), (ii) reactions between solids and quantities of gas which are too small to maintain a fluidized bed, (iii) processes in which the solid is inlet in slurry form and the slowest and most gentle drying possible is desired, (iv) processes in which solids are to be exposed to a stepwise varying reaction temperature during thermal processing, and (v) reactions in which the solid undergoes slight softening, agglomeration, or sintering so that fluidized-bed processes cannot be employed.

Further, since the roasting reactions are exothermic, the furnace is normally to be heated only at the start of the process. The material fed to the top most hearth is distributed by the teeth on the rabble arms, slowly transported to the centre of the hearth, and dried. Then the ore falls into the first roasting zone, where it is heated in contact with hot roasting gas until it ignites. The reaction goes to completion as the charge is transported further over the hearths. On the last hearth, roasting air drawn or blown into the furnace from the bottom is preheated by cooling the residue. The progress of the reaction is monitored by measuring the temperature on the individual hearths.

Shaft furnaces

A shaft furnace is a furnace which has an upright working chamber of circular, elliptical, or rectangular cross section in which a fixed bed (or descending column) of solids is maintained , and through which an ascending stream of

hot gas is forced . It is used to smelt or roast lumped materials. The heat required for smelting or roasting process is produced by the combustion of a fuel either directly in the furnace or in an external firebox from which the combustion products are supplied to the furnace. There is counter current movement of gases and the solids in the furnace.

Moderate velocities of the gaseous combustion products are characteristic of shaft furnaces. At such velocities, the bulk of the lumped materials (the charge) is not entrained by the ascending gas stream and, in contrast to the case of a fluidized- bed furnace, maintains aerodynamic stability. The counter current motion of the charge (from the top to the bottom) and of the gases forced through the charge (from the bottom to the top) and the direct contact between the charge and the hot gases result in good heat exchange and the generation of low-temperature exhaust gases. Thus, shaft furnaces are characterized by a high thermal efficiency and a relatively high output. Such furnaces are widely used to smelt iron ores (blast furnace and direct reduction furnace) as well as non-ferrous ores.

The shaft furnaces are designed for continuous operation. The main components of shaft furnace consist of (i) a top, through which the charge is loaded and the gaseous combustion products are discharged, (ii) a shaft equipped with tuyeres, through which either a blast for fuel combustion or hot gases are supplied, and (iii) an inside crucible with a refractory lining, where the liquid products collect. The furnace is tapped at intervals.

The shaft furnaces have a variety of uses in metallurgy. The Rachette furnace is employed in lead production. The distinguishing feature of the lead blast furnace is that the throat widens upward. The iron smelting blast furnace is the most important type of shaft furnace. The blast furnace has the form of two truncated cones set with their large bases together. The widening of the stack from top to bottom reduces the frictional resistance as the burden moves downward. The blast furnace is divided into the several sections namely throat, stack, bosh, and hearth. The shaft furnaces are also used for smelting of copper, melting of pig iron for production of castings (cupola).

Ores concentrates, or metals for shaft furnaces are to be lumpy or to be agglomerated by sintering, pelletizing, or briquetting. To some extent, fine ores or secondaries can be blown through the tuyeres directly into the raceway for very fast reduction.

Rotary hearth furnaces

Rotary hearth furnaces are also known as rotating table furnaces. They are very useful for many purposes. Besides being utilized for the heating of circular loads (for example in the pipe rolling mills), the rolling hearth furnaces are also being used for the reduction processes. In these furnaces materials are placed on the merry-go-round-like hearth. The materials travel on a circular track and undergo reduction reactions while travelling. The reduced product is later removed after the materials have completed almost a whole revolution. The furnaces have several zones.

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Smelting, melting, and refining in bath and flash smelting furnaces

Fine concentrates can be smelted without agglomeration in flash (after drying) or bath smelting furnaces. The heat of exothermic chemical reactions provides the energy for autogenous smelting. All these furnaces are operated continuously. A wide variety of such smelting furnaces and converters are being used. The smelting furnaces represent a modern approach of intensive metal smelting under environmentally 'clean' conditions.

In bath smelting furnaces and converters, O₂ or O₂-enriched air is blown into the liquid metal or matte baths via tuyeres, lances, or injectors to oxidize elements which are to be removed as impurities. Coal or reducing gases can also be blown into liquid slags via tuyeres, lances, and injectors for slag reduction. In the case of aluminum (Al) smelting, chlorine (Cl) is blown through pipes and stirrers into the liquid metal bath to remove alkaline and alkaline-earth elements. Bath smelting furnaces are used for smelting of copper (Cu), and lead (Pb). Bath smelting furnaces are in development for the direct steel production from iron ores

The first flash smelting furnace started operation in 1949. By now, several flash smelting furnaces treat Cu concentrates, and smelt nickel (Ni) concentrates. The flash smelting furnace consists of a circular reaction shaft for roasting and smelting of dry concentrates in suspension with highly enriched air, a settling hearth for collection of the droplets and separation of matte (metal) and slag, and an off-take shaft for waste gas and flue dust.

Bath smelting and refining furnaces are often used for melting, refining, and alloying metals. These furnaces are operated batch wise and are fed with solid and liquid metal. They are of the stationary, tilting, or rotary type. Their applications include (i) electric arc furnaces (EAFs) and induction furnaces (IFs) for steel and cast iron smelting and refining, stationary and tilting hearth furnaces and rotary for Al melting, refining, and alloying, (iii) stationary hearth furnaces for Cu matte and ferronickel smelting, rotary furnaces for anode Cu smelting and refining, stationary and tilting hearth furnaces for Cu scrap melting and refining, and (vi) rotary furnaces for secondary Pb smelting. For mixing the melt, such furnaces are stirred mechanically, inductively, or by gas.

Converters are mainly used for (i) conversion of hot metal (HM) together with scrap into steel, (ii) conversion of Cu matte into blister Cu and the refining of secondary black Cu, (iii) refining of secondary Al, and (iv) conversion of Ni matte into Ni.

Majority of global steel production is carried out in converters. HM together with steel scrap (for cooling) is transformed to steel in the converter. Accompanying elements, particularly C, are oxidized to a desired level by O₂. In the past, air was used for converting in the Bessemer (since 1855) and Thomas (since 1877) converters. Nowadays only O₂ converters are in use which employs lances for top blowing and injectors for bottom blowing or side blowing. The LD process was developed in 1952 in Linz and Donawitz, Austria. O₂ is blown onto the bath of liquid iron from above through a water-cooled O₂ lance. The AOD (argon-oxygen-decarburization) converter permits oxidation and degassing of steel before casting. Loading always takes place through the mouth of the converter. Steel is tapped via a taphole situated in the upper side by tilting the converter. Another development of melting and converting of scrap is the energy-optimizing furnace (EOF) which combines preheating, melting, side blowing, and direct heat recovery from the reactor gases.

Electro-thermal furnaces

The use of electricity for metallurgical applications started in at the beginning of the nineteenth century. As early as 1810, Davy performed experiments in which he produced alkali metals via fused salt electrolysis. In 1888 Hérault patented a small electric furnace for the production of Al, which formed the basis of the present-day electrolytic recovery of Al from alumina (Al₂O₃). The use of induction as a heating method was patented by de Ferranti in 1887. Although the experimental use of an electric arc can be traced back to 1810, the development of the first EAF is attributed to Siemens, who developed a small arc furnace in 1878 – 1879. From this modest beginning, the use of an arc for melting and smelting in furnaces progressed from an arc furnace

(developed by H'eroult in 1900) to the ultrahigh power (UHP) technology (developed in 1960 – 1962), with which very high melting rates can be attained.

The earliest recorded application of electro-slag refining dates back to 1892. By the time of Hopkins' development of the electro-slag process in 1935, vacuum arc refining was making great headway. Vacuum melting was introduced as a plant-scale operation in 1917 when Rohn melted Ni-base alloys by resistance heating. In 1923, vacuum induction furnaces are being operated. By about 1956 the potential of vacuum arc remelting for steels, as well as Ni- and titanium (Ti) -base alloys had been used for the production of improved gas turbine disks, shafts, and casings.

The use of electron-beam technology for smelting and melting is as young as plasma metallurgy, although experiments with electron beams (at the time known as cathode rays) commenced as early as 1852. This technology was patented in 1907. Semi continuous electron-beam melting was first performed in a cold mould crucible in 1954. By 1957 facilities were available for processing Ti ingot.

Electro thermal furnaces can be used for the production of metals from raw materials by reduction. They can also be applied during metal refining. If cheap electrical energy is available heating in electro-thermal furnaces has many advantages over heating with fossil fuels.

Electro-thermal reduction furnaces use electric energy to heat the feed to the required operating temperature. In conventional reduction furnaces, heat liberated during the exothermic reaction between, for example, coke and O₂ is utilized to heat the feed. In electro-thermal furnaces, coke is only needed for reduction.

Arc furnaces – An electric arc can be produced and sustained between two electrodes or an electrode and a liquid melt if the voltage is high enough. The transformation of electric energy to heat takes place through the current in the ionized plasma of the arc, in which the temperatures can reach 6000 deg C.

EAfs are classified according to whether transfer of heat from the arc to the furnace feed is indirect or direct. In indirectly heated furnaces, the arc burns

between two electrodes without contact with the feed and the heat is transferred only by radiation and convection. This technique has been employed in single-phase rotary furnaces, which are, however, no longer in use because of economic reasons. In directly heated furnaces an arc burns between the electrode and the melt. Heat is transferred via the fire point produced by the arc by conduction, radiation, and convection to the melt. Directly heated arc furnaces can be used for melting and refining. The arc-resistance and submerged-arc furnaces are mainly used for reduction and their construction is similar to that of resistance furnaces.

The principal application of EAFs is for the production of steel. One-electrode furnaces generally operate in the DC mode with the electrode forming the cathode and the bottom of the furnace forming the anode. 3-electrode furnaces are mostly AC furnaces. The electrodes are switched into a 3-phase circuit and are usually placed on the vertices of an equilateral triangle in a round furnace. Maximum furnaces are equipped with removable roofs. The required atmosphere can be provided inside the furnace which can be tilted during tapping. Dolomite and magnesite refractories are used for lining the lower walls and the bottom of the steel shell of the arc furnaces.

The upper walls and the roof of the furnaces are water-cooled to provide good resistance against high temperature and temperature changes. The high temperature obtained in arc furnaces allows high production capacities. When scrap is melted down, crater-type holes are burnt into the scrap which protects the furnace roof and walls from overheating.

The advantages of EAFs are (i) high temperatures can be reached within a short time, (ii) continuous temperature adjustment is possible via computer control systems which control the level of the arc, (iii) the atmosphere in the furnace can be tightly controlled, (iv) in contrast to conventionally heated furnaces, impurities are not brought into the steel by the energy input, (v) the furnace can easily be brought on- or offline with relatively little energy and time, furnace operation can be controlled to meet the production requirements of the continuous casting machines, (vi) oxidation, reduction, and alloying can be carried out in one charge with little loss, and (vii) desulphurization is possible.

Modern furnaces can be tilted only 12 degrees during slagging off operations. Liquid steel tapping is done by eccentric bottom tapping. Sometimes the mixing in the furnace is improved by an induction stirring coil underneath the furnace or by bubbling gas through a porous plug.

Induction furnaces – The increasing demand for high-quality metals and alloys under ecologically clean conditions has increased the application of IFs in foundries for cast iron, steel, and nonferrous metals (mainly Al, Cu, Mg, Ni, precious metals and their alloys). There are two basic types of IF. These are the crucible IF and the channel IF. IFs are mainly used for melting and refining of metals and alloys. Special applications are zone refining and levitation melting. Inductive heating is also used for brazing and welding, different types of heat treatment (e.g. surface treatment, heating and annealing), metal transport and dosing, and electromagnetic casting.

Electromagnetic induction heating is a direct method for contactless heating with a high power density which implies that the material to be heated (melted) is not contaminated by heating gases or electrode materials. However, contact and reactions with the crucible (graphite or refractories) can take place. Advantages of these types of furnaces are excellent alloying and mixing conditions, good temperature control of the melt, a low slag formation, and low off-gas volume.

The heating takes place since an AC coil induces a potential in an electrical conductor (in IFs solids and/or melts) situated inside the coil due to the changing magnetic field, which creates eddy currents (Lenz's law). The eddy currents or induced current produce heat according to Joule's law

The resistivity and relative magnetic permeability of the material to be heated and the frequency of the primary current circuit are the most important parameters of induction heating. The induced current within the conductor is not evenly distributed, but mostly located near the surface (skin effect).

Plasma furnaces – Plasma is a partially ionized (upto 50 %) gas which contains electrons, ions, energized molecules, dissociated molecules, neutral molecules, and atoms. The plasma operates at atmospheric pressure and is sufficiently conducting to permit stable transfer of electric power between two or more electrodes.

The principal difference between plasma furnaces and arc furnaces is the use of a plasma torch instead of electrodes. In a plasma torch thermionic electrons are emitted from a cathode and accelerated towards the anode. They collide with gas molecules and ionize them. The positively charged gas ions are accelerated in the opposite direction towards the cathode with which they collide, releasing their energy and hence sustaining the thermionic emission. Depending on the type of torch and its construction materials, water cooling can be applied. Several types of AC and DC torches are available. They include transferred arc, non-transferred arc, and superimposed arc.

Crucible IFs are used for melting and refining numerous metals and alloys. They are usually applied in cast iron, steel, and nonferrous metal foundries (Al, Mg, Cu, brass, bronze, Zn, Ni, precious metals, and super alloys). They are unsuitable for slag metallurgical operations since only the metal is heated by induction and not the slag. In addition, the advantages of numerous crucible designs (e.g. rammed or brick lining; ceramic, graphite, steel, or Cu crucible) render them very attractive. They also permit various operations, such as alternative or continuous melting, continuous melting and pouring, quick alloy changes, and application of vacuum or controlled atmosphere. They are sometimes used as buffer furnaces or grading furnaces.

Channel IFs – In the channel IFs the induction coil is located under or beside the crucible and has an iron core. The coil is enclosed in a channel. This construction acts as a transformer with a short circuit secondary coil producing the best power transfer efficiency (0.95 to 0.98 with furnace efficiency around 0.9). The metal in the channel is heated and pumped back to the metal reservoir in the crucible by the repulsive force of the coil and the induced currents. This means that the furnace is always to be charged with a certain amount of liquid metal.