

Important Properties of Ceramic Fiber

The characteristics of ceramic fibers are a remarkable combination of the properties of refractories and traditional insulation material.

- 1. Lower Thermal Conductivity** The low thermal conductivity – 0.1 kCal/m hour deg C at 600° C for 128 kg/m³ density blanket – allows construction of thinner linings with the same thermal efficiency as that of conventional refractories. Hence, for the same outer envelope dimension the furnace volume is much higher. It is 40 % more effective than good quality insulation brick and 2.5 times better than asbestos product. Insulating property of ceramic fiber is better than calcium silicate product.

2. Light Weight Average density of ceramic fiber is 96 kg/m^3 . It is one tenth of the weight of insulating brick and one third that of asbestos / calcium silicate boards. For new furnaces structural supports can be reduced by 40%.

3. Lower Heat Storage Ceramic fiber linings absorb less heat because of lower density. Furnace can be heated and cooled at faster rates. Typically the heat stored in a ceramic fiber lining system is in the range of $2700 - 4050 \text{ kCal/m}^2$ ($1000 - 1500 \text{ Btu/Ft}^2$) as compared to $54200-493900 \text{ kCal/m}^2$ ($20000 - 250000 \text{ Btu/Ft}^2$) for conventionally lined system.

4. Thermal Shock Resistant Ceramic fiber lining resist thermal shock due to their resilient matrix. Also faster heat up and cool down cycles are possible thereby improving furnace availability and productivity.

5. Chemical Resistance Ceramic fiber resist most of the chemical attack and is unaffected by hydrocarbons, water and steam present in flue gases.

6. Mechanical Resilience This property permits fiber lined furnaces to be shop fabricated and shipped to site in assembled form without fear of damage.

7. Low Installation Cost No special skills are required as application practices are standardized. Fiber linings require no dry out or curing times and can be heated to the capacity of the burners after installation is completed without concern for cracking or spalling.

8. Simple Maintenance In case of physical damage the defective section can be quickly removed and a replacement piece added. Whole panel sections can be prefabricated for fast installation with minimal down time.

9. Ease of Handling All product forms are easily handled and most can be quickly cut with a knife or scissors. Vacuum formed products may require cutting with a band saw.

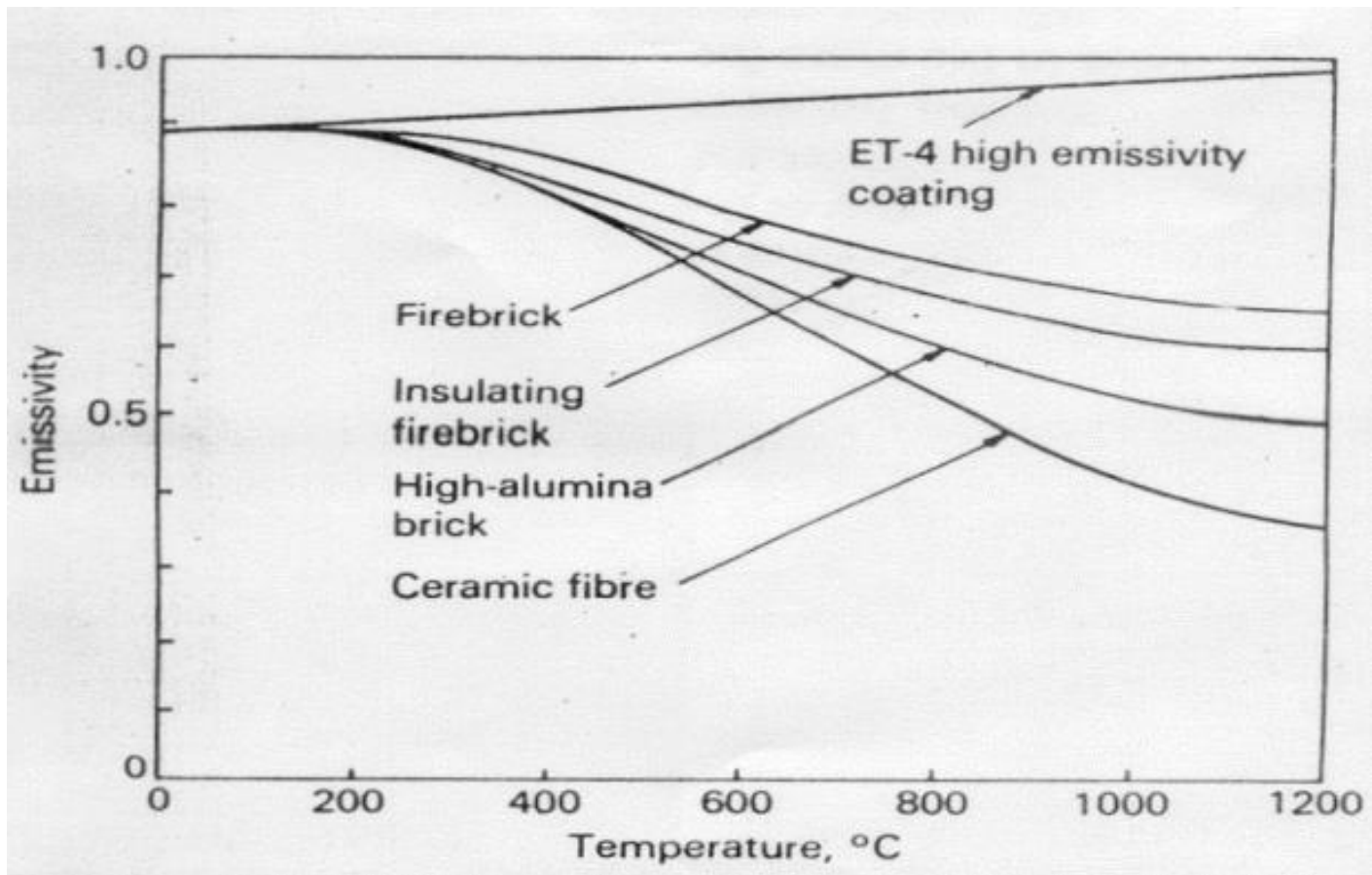
10. Thermal Efficiency The low thermal conductivity of ceramic fibre can be advantageously made use of by the lesser lining thickness and reduced furnace volume. The fast response of ceramic fibre lined furnace also allows for more accurate control and uniform temperature distribution within the furnace.

The other advantages offered by ceramic fibre are summarized below:

- Light weight furnace
- Simple steel fabrication work
- Low down time
- Increased productivity
- Additional capacity
- Low maintenance cost
- Longer service life
- Higher thermal efficiency
- Faster response

High Emissivity Coatings

Emissivity, the measure of a material's ability to both absorb and radiate heat, has been considered by engineers as being an inherent physical property which like density, specific heat and thermal conductivity, is not readily amenable to change. However, the development of high emissivity coatings now allows the surface emissivity of materials to be increased, with resultant benefits in heat transfer efficiency and in the service life of heat transfer components. High emissivity coatings are applied in the interior surface of furnaces. The Figure below shows emissivity of various insulating materials including high emissivity coatings. High emissivity coating shows a constant value over varying process temperatures.



The application of high-emissivity coatings in furnace chambers promotes rapid and efficient transfer of heat, uniform heating, and extended life of refractories and metallic components such as radiant tubes and heating elements. For intermittent furnaces or where rapid heating is required, use of such coatings was found to reduce fuel or power to tune of 25-45%. Other benefits are temperature uniformity and increased refractory life

Furnaces, which operate at high temperature, have emissivities of 0.3. By using high emissivity coatings this can go upto 0.8 thus effectively increasing the radiative heat transfer

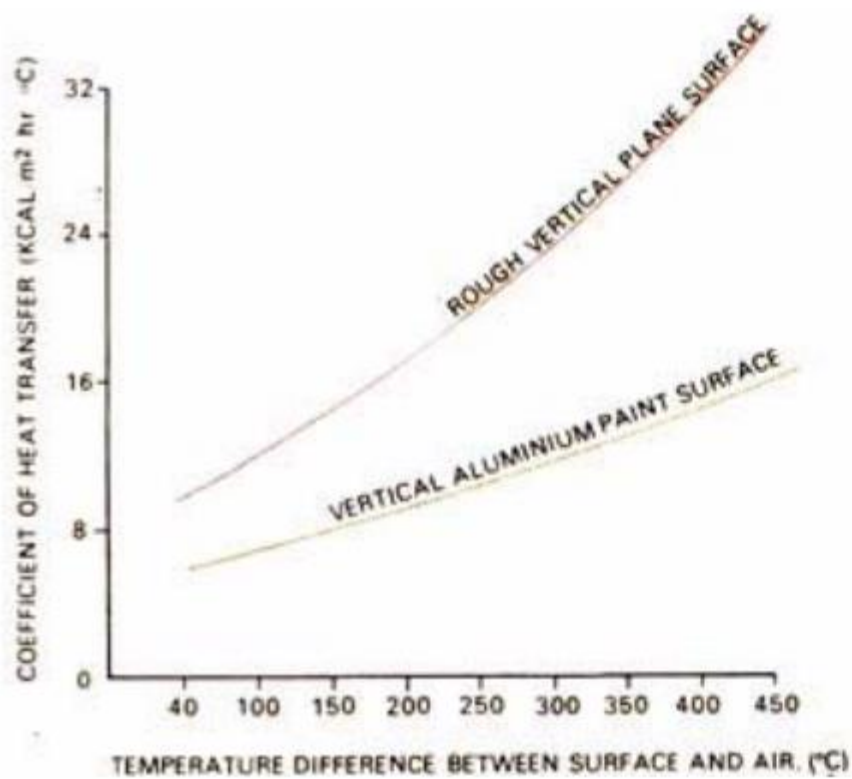
Heat Losses from Furnace Walls

In furnaces and kilns, heat losses from furnace walls, affect the fuel economy substantially. The extent of wall losses depends on:

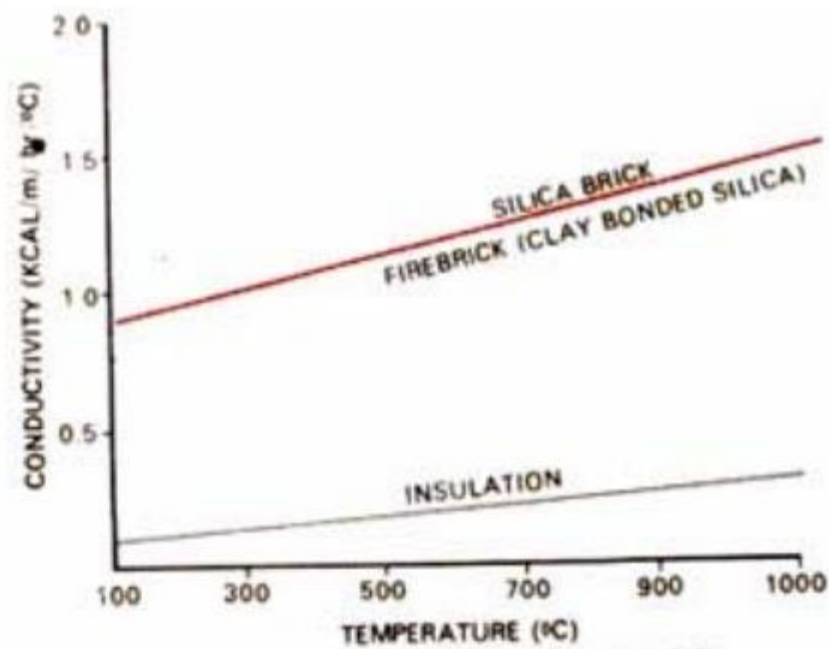
- i) emissivity of walls;
- ii) conductivity of refractories;
- iii) wall thickness;
- iv) whether furnace or kiln is operated continuously or not.

Different materials have different radiation power (emissivity). The emissivity of walls coated with aluminium paint is lower than that of bricks. Figure shows the coefficient of heat dissipation for the following conditions:

- a) rough vertical plane surface. b) Vertical aluminium painted walls



(A)



Average conductivity of refractory material

(B)

The variations of thermal conductivity for typical refractory materials (silica brick, fireclay brick and insulation brick) with temperature is depicted in Figure(B). Thus at a mean temperature of 600°C , conductivity of the insulation brick is only 20% of that for fireclay brick.

Heat losses can be reduced by increasing the wall thickness, or through the application of insulating bricks. Outside wall temperature and heat losses for a composite wall of a certain thickness of firebrick and insulation brick are much lower due to lesser conductivity of insulating brick as compared to a refractory brick.

In the case of batch furnace operation, operating periods (“on”) alternate with idle periods (“off”). During the off period, the heat stored in the refractories in the on-period is gradually dissipated, mainly through radiation and convection from the cold face. In addition, some heat is obstructed by air flowing through the furnace. Dissipation of stored heat is a loss. The lost heat is at least in part again given to the refractories during the next “on” period. If a furnace is operated 24 hr. in every 3 days, practically all of the heat stored in the refractories is lost.

But if the furnace is operated 8 hrs. per day, not all the heat stored in the refractories is dissipated. For a furnace with firebrick wall (350 mm) it is estimated that 55% of the heat stored in the refractories is dissipated from the cold surface during 166 hours idle period.

Furnace walls build of insulating refractories and encased in a shell reduce flow of heat to the surroundings. Inserting a fiber block between the insulating refractory and the steel casing can further reduce the loss. The general question one asks is how much heat loss can be reduced by application of insulation. The answer is that it depends on the thickness of firebricks and of the insulation and on continuity of furnace operation

To sum up, the heat losses from the walls depend on

- Inside temperature.
- Outside air temperature.
- Outside air velocity.
- Configuration of walls.
- Emissivity of walls.
- Thickness of walls.
- Conductivity of walls.

The following conclusions can be drawn:

- Thickness of walls and conductivity of walls can be easily controlled by the furnace fabricator.
- As the wall thickness increases, the heat losses reduce.
- As thickness of insulation is increased, heat losses reduce.
- The effect of insulation in reducing heat losses is more pronounced than the increase of wall thickness. Roughly 1 cm of insulation brick is equivalent to 5 to 8 cm of refractory (firebrick).
- In intermittent (discontinuous) furnaces, thin walls of insulating refractories are preferable to thick walls of a normal refractory for intermittent operation since less heat is stored in them.

- One approach to achieve less heat storage capacity would be to utilise insulating material itself to form the inner refractory lining. Refractories with fairly good strength and spalling resistance can be used for temperatures in the range of 1300°C . They are termed as hot face insulation.
- Hot face insulating bricks are lighter than normal refractories, weighing only one-third to one-half as much. Therefore, heat storage in the hot face insulation is very much reduced.

Refractory Design in Furnaces

Design of Refractory Lining

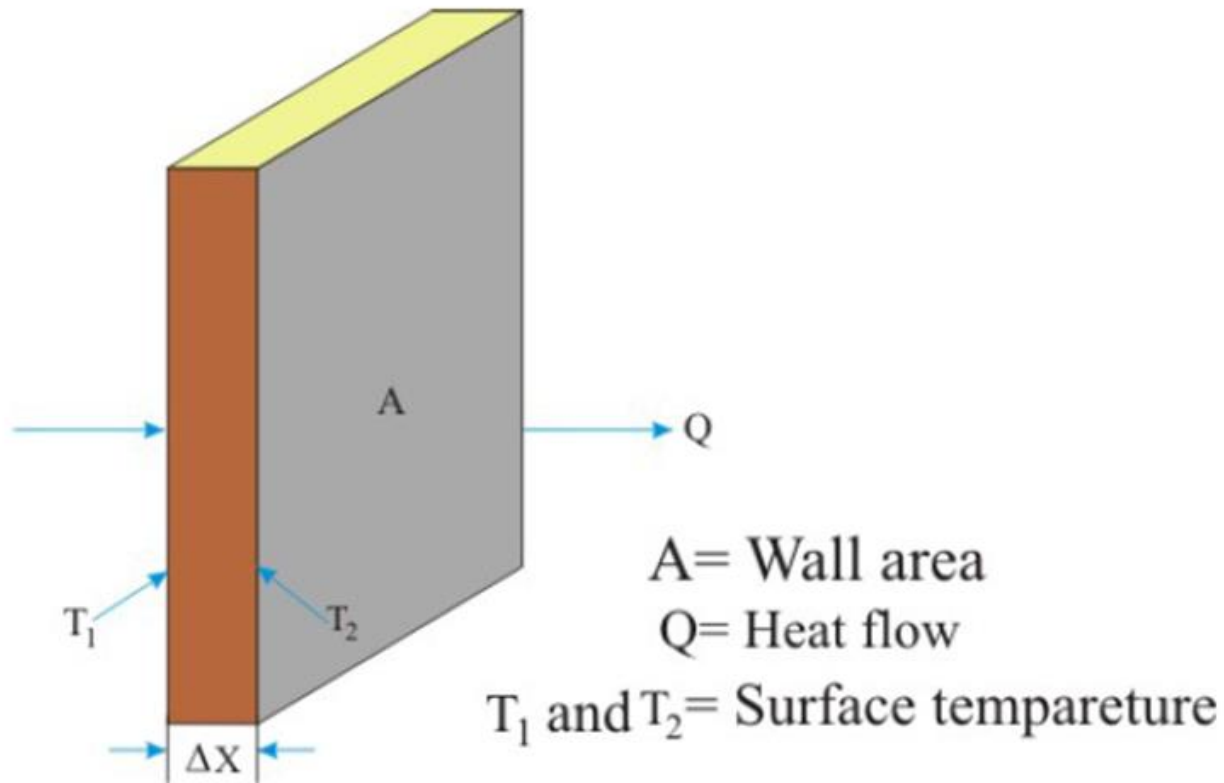
In high temperature furnaces, it is often required to design the refractory lining which is compatible with the physico-chemical-thermal requirements, and energy saving. Mostly, furnaces are multi-layered lining with refractory materials of different thicknesses and thermal conductivities. Whereas the refractory lining facing the reaction chamber should meet different physical, chemical and thermal requirements, like high refractoriness, low porosity, chemically inertness etc.; refractory lining facing the metallic shell must have insulating properties preferably material of low thermal conductivity.

In the design of the multi-layered lining, the thickness of each layer is an important issue. Optimum thickness would not only save cost of the refractory but also control the weight of the vessel.

Several reactors in high temperature furnaces like matte smelters, converters, rotary kiln etc. carry out processes at high temperatures and hence are lined with the refractory materials. An optimum thickness of the lining would be desirable for minimum losses and optimal cost. In most of the reactors the walls are either rectangular or cylindrical. In the following section, dimensional heat flow through flat and cylindrical walls of refractory material is considered at steady state. It is considered that the temperature gradients are across the thickness of the wall whereas the other faces are at uniform temperatures.

Flat wall

Consider heat flow through a flat wall of thickness Δx as shown in the figure. Heat flow through a flat wall of thickness as shown.

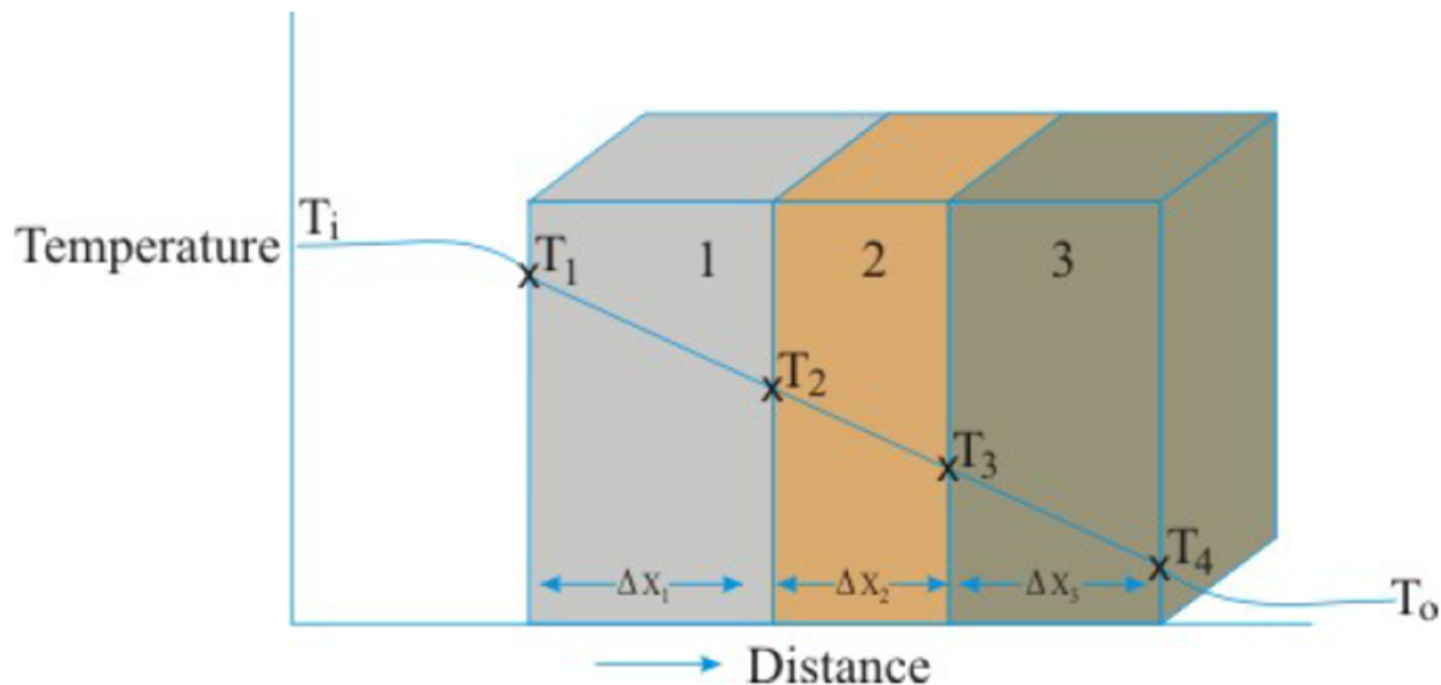


For a constant area along the heat flow path and constant thermal conductivity of the material, the heat flow can be written at steady state

as
$$Q = -\frac{KA}{\Delta x} (T_2 - T_1)$$

Here K , thermal conductivity is assumed to be constant. T_2 and T_1 are surface temperatures.

Consider a simple series wall constructed with materials of different thermal conductivities K_1 , K_2 , and K_3 having thicknesses Δx_1 , Δx_2 and Δx_3 . T_i is the furnace temperature and T_0 is the surrounding temperature. T_1 , T_2 , T_3 and T_4 are the interface temperatures as shown in the figure



One dimensional heat flow across a multilayered wall

As seen in the figure furnace temperature T_i is higher than temperature of the refractory surface facing the combustion chamber of furnace which is T_1 . In such a situation we have to consider the heat flow from the combustion chamber furnace to the refractory surface.

Similar is the case with the exterior wall of the refractory. Here temperature T_4 is greater than the environment temperature T_0 .

In both cases heat flows by convection and heat transfer coefficient should be used to determine respective surface temperatures. In the fuel fired furnaces the reaction chamber is heated by the transfer of heat of products of combustion.

Since no heat is produced in the composite wall, the unidirectional heat flow 'Q' is constant at steady state

$$Q = h_i A (T_i - T_1) = \frac{K_1 A}{\Delta x_1} (T_1 - T_2) = \frac{K_2 A}{\Delta x_2} (T_2 - T_3) = \frac{K_3 A}{\Delta x_3} (T_3 - T_4) = h_0 A (T_4 - T_0)$$

h_i and h_0 are heat transfer coefficients. Note that T_1, T_2, T_3 and T_4 are interface temperatures and there is no air gap between walls. It is also assumed that the contact thermal resistance is zero.

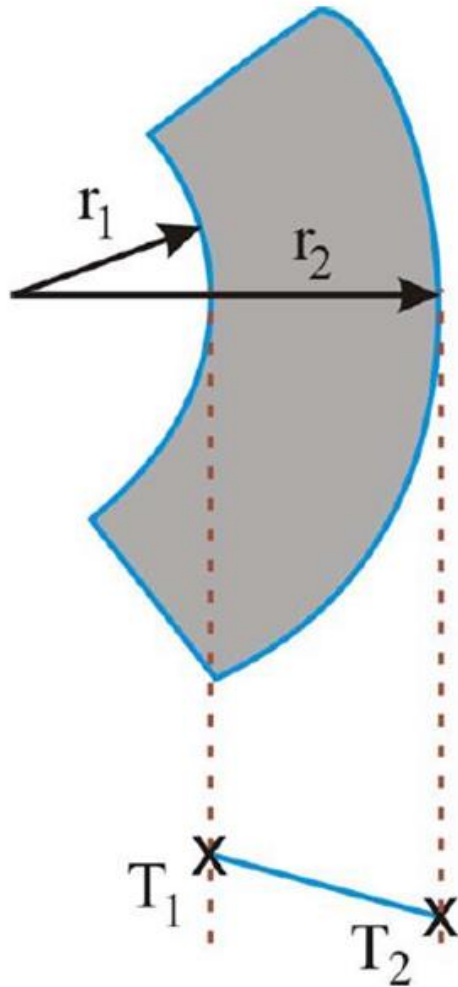
By solving previous equation simultaneously we get;

$$Q = \frac{T_j - T_0}{\frac{1}{h_i A} + \frac{1}{A} \sum \frac{\Delta x_j}{K_j} + \frac{1}{h_o A}}$$

Note $\frac{1}{hA}$ is thermal resistance due to convection. The equation above describes the heat flow through a composite wall lined with the refractory material of different thicknesses and thermal conductivities.

Cylindrical wall

Consider a long cylinder of inside radius r_1 and outside radius r_2 , and length L as shown in the figure



Heat flow, Q is;

$$Q = -K \frac{2\pi L \Delta T}{2.3 \log \frac{r_2}{r_1}}$$

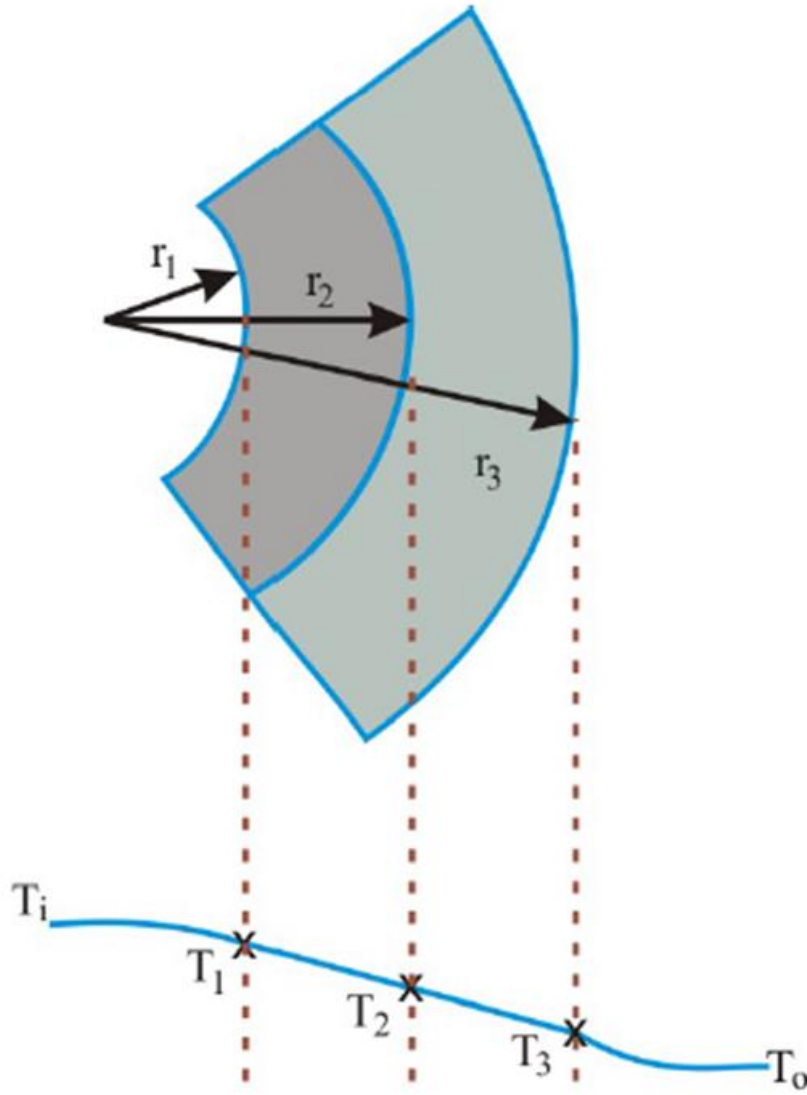
One dimensional heat flow through a hollow cylinder

For some purposes, heat flow through the thickness of the pipe wall or the insulation is required with the inside and outside areas,

$A_1 = \pi d_1 L$ and $A_2 = \pi d_2 L$. In terms of area;

$$Q = -K \left\{ \frac{A_2 - A_1}{2.3 \log\left(\frac{A_2}{A_1}\right)} \right\} \frac{\Delta T}{\Delta r}$$

Figure below is the construction of a composite cylindrical wall having r_2 and r_3 measured from the center of the cylinder of radius r_1 such that $\Delta r_1 = (r_2 - r_1)$ and $\Delta r_2 = (r_3 - r_2)$. The thermal conductivity of the refractory material of thicknesses Δr_1 and Δr_2 is K_1 and K_2 , respectively. The length of the cylinder is L . As in the case of flat wall h_i and h_o are the heat transfer coefficients that determine surface temperatures T_1 and T_3 . The composite wall is placed between furnace temperature T_i and environment temperature T_o .



As no heat is produced in the composite wall, steady state heat flow for the length of the cylinder L is ;

$$Q = h_i 2\pi r_1 (T_i - T_1) = \frac{2\pi K_1 L}{\ln(r_2/r_1)} (T_1 - T_2) = \frac{2\pi K_2 L}{\ln(r_3/r_2)} (T_2 - T_3) = h_o 2\pi r_3 (T_3 - T_o)$$

Adding thermal resistance in series below equation determines the heat flow in a composite wall ;

$$Q = \frac{T_i - T_o}{\frac{1}{2\pi L r_1 h_i} + \frac{\ln(r_2/r_1)}{2\pi L K_1} + \frac{\ln(r_3/r_2)}{2\pi L K_2} + \frac{1}{2\pi L r_3 h_o}}$$

Critical Thickness of Insulation

Consider a single layer of insulation which is put around a cylindrical pipe of length L. The inner temperature of the insulation is fixed at temperature T_1 and the outer surface is exposed to an environment temperature T_0 . Above equation for a single layer of insulation;

$$Q = \frac{2\pi L (T_i - T_o)}{\frac{1}{h_i r_1} + \ln\frac{(r_2/r_1)}{K_1} + \frac{1}{h_o r_2}}$$

As r_2 increases, $\frac{\ln(\frac{r_2}{r_1})}{K_1}$ increases which means there is an increasing resistance to radial conduction. Increase in r_2 increases outer furnace area as well as which means $\frac{1}{h_0 r_2}$ decreases. This dual effect suggests that there exist a particular value of r_2 for which heat loss is maximum. For a given r_1 , the particular value of r_2 can be determined by putting $\frac{dQ}{dr_2} = 0$

$$\frac{dQ}{dr_2} = \frac{-2\pi L(T_i - T_o) \left(\frac{1}{K_1 r_2} - \frac{1}{h_0 r_2^2} \right)}{\frac{1}{h_i r_i} + \frac{1}{K} \ln \frac{r_2}{r_1} + \frac{1}{h_0 r_2}} = 0$$

Solving equation, we get $r_{2c} = \frac{K_1}{h_0}$,

where r_{2c} is critical radius of insulation. This suggests that heat loss does not decrease always with the increase in insulation thickness. Heat loss could increase by increasing the thickness of the insulation beyond r_{2c} because outer surface area increases and hence heat losses increases.

FURNACES

What is a furnace?

A furnace is an equipment used to melt metals for casting or to heat materials to change their shape (e.g. rolling, forging) or properties (heat treatment).

Since flue gases from the fuel come in direct contact with the materials, the type of fuel chosen is important. For example, some materials will not tolerate sulphur in the fuel. Solid fuels generate particulate matter, which will interfere the materials placed inside the furnace. For this reason:

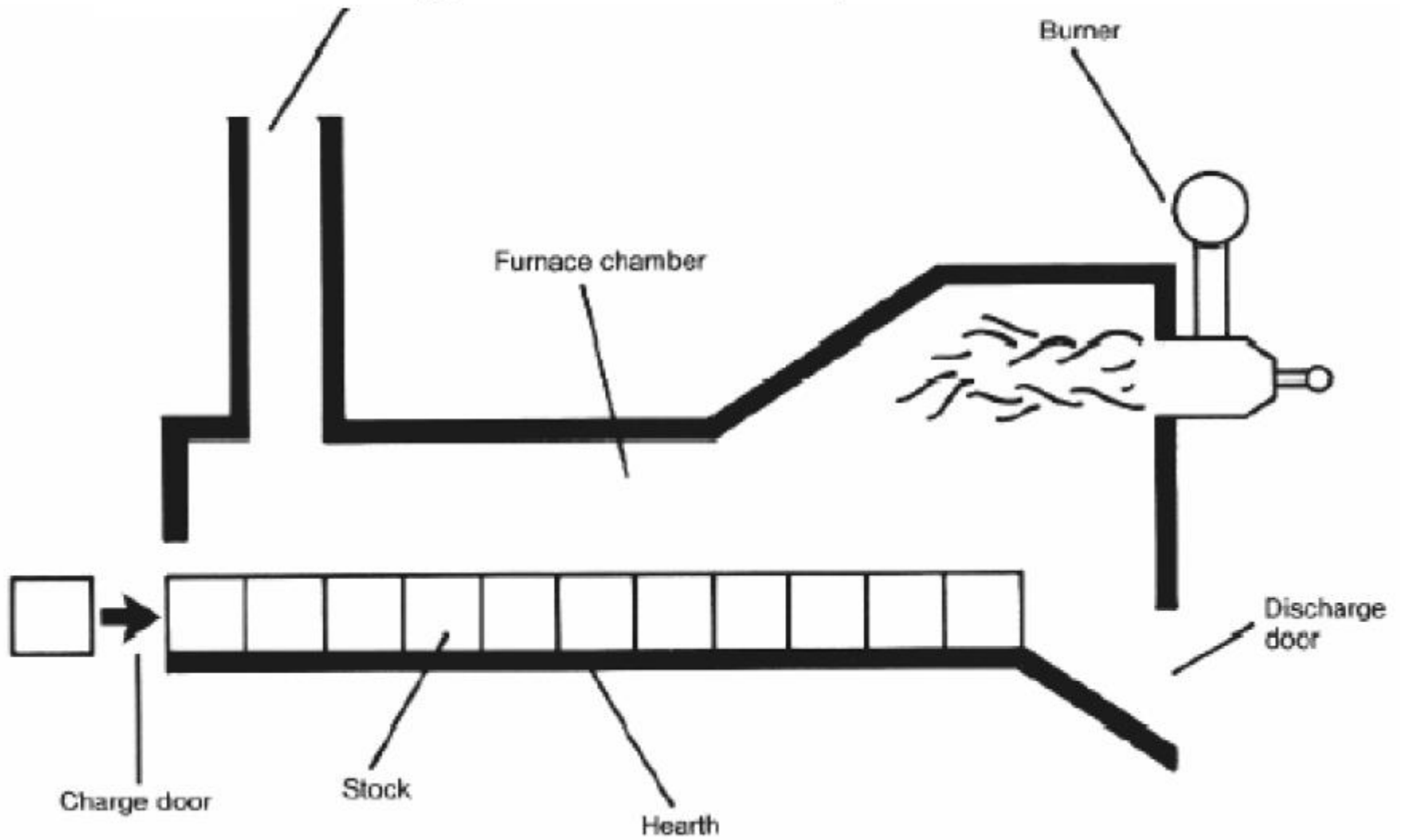
- Most furnaces use liquid fuel, gaseous fuel or electricity as energy input.
- Induction and arc furnaces use electricity to melt steel and cast iron.
- Melting furnaces for nonferrous materials use fuel oil.
- Oil-fired furnaces mostly use furnace oil, especially for reheating and heat treatment of materials.
- Light diesel oil (LDO) is used in furnaces where sulphur is undesirable.

Furnace ideally should heat as much of material as possible to a uniform temperature with the least possible fuel and labor. The key to efficient furnace operation lies in complete combustion of fuel with minimum excess air. Furnaces operate with relatively low efficiencies (as low as 7 %) compared to other combustion equipment such as the boiler (with efficiencies higher than 90 percent). This is caused by the high operating temperatures in the furnace. For example, a furnace heating materials to 1200 °C will emit exhaust gases at 1200 °C or more, which results in significant heat losses through the chimney

All furnaces have the following components as shown in Figure :

- Refractory chamber constructed of insulating materials to retain heat at high operating temperatures.
- Hearth to support or carry the steel, which consists of refractory materials supported by a steel structure, part of which is water-cooled.
- Burners that use liquid or gaseous fuels to raise and maintain the temperature in the chamber. Coal or electricity can be used in reheating furnaces.
- Chimney to remove combustion exhaust gases from the chamber
- Charging and discharging doors through which the chamber is loaded and unloaded. Loading and unloading equipment include roller tables, conveyors, charging machines and furnace pushers.

Typical Furnace Components



Types of furnaces

Furnaces are broadly classified into two types based on the heat generation method: combustion furnaces that use fuels, and electric furnaces that use electricity. Combustion furnaces can be classified in several based as shown in Table : type of fuel used, mode of charging the materials, mode of heat transfer and mode of waste heat recovery.

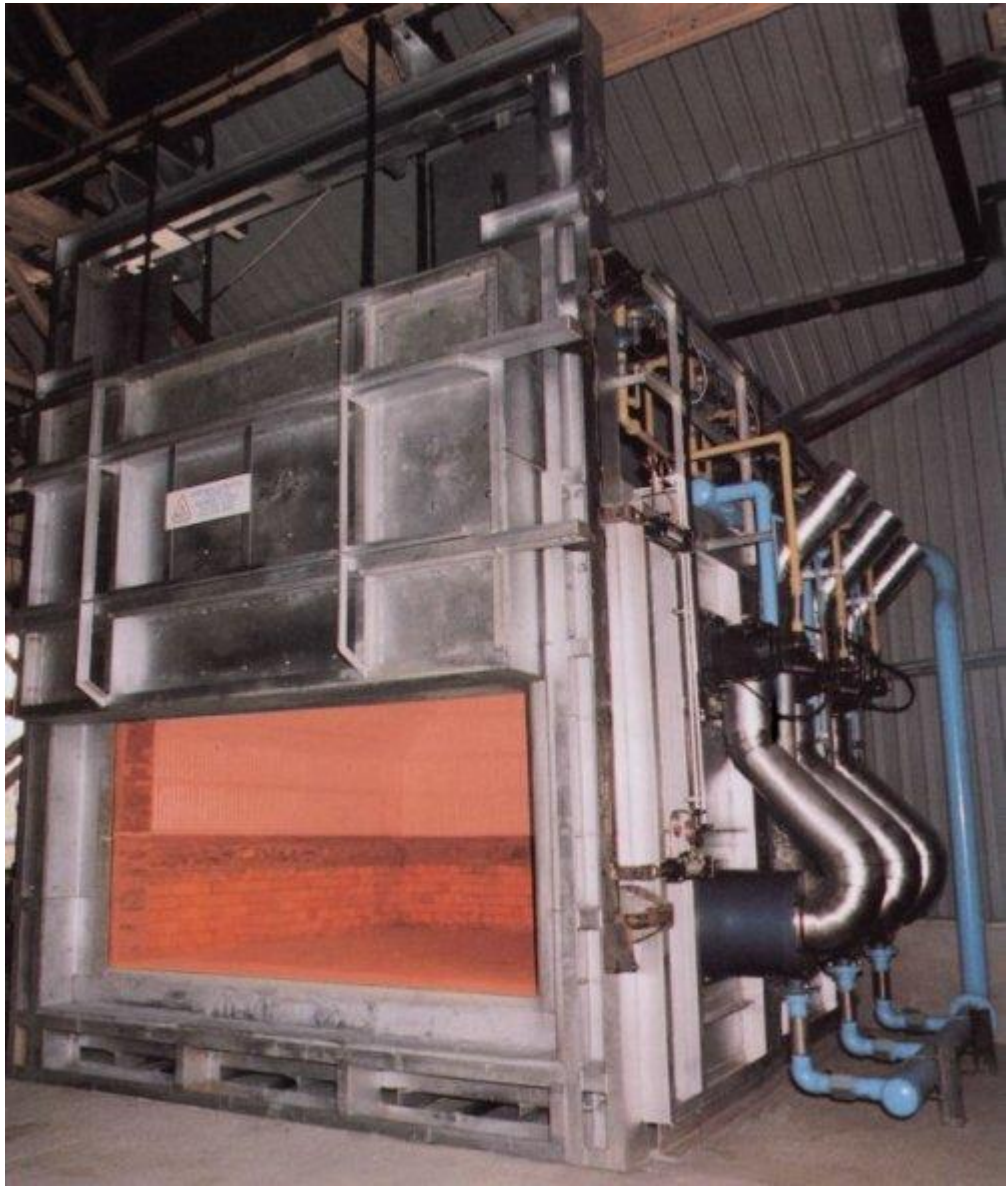
However, it is not possible to use this classification in practice, because a furnace can be using different types of fuel, different ways to charge materials into the furnace etc. The most commonly used furnaces are described in the next sections

Classification of furnaces

Classification method	Types and examples
Type of fuel used	Oil-fired
	Gas-fired
	Coal-fired
Mode of charging materials	Intermittent / Batch
	Periodical <ul style="list-style-type: none"> ▪ Forging ▪ Re-rolling (batch/pusher) ▪ Pot
	Continuous <ul style="list-style-type: none"> ▪ Pusher ▪ Walking beam ▪ Walking hearth ▪ Continuous recirculating bogie furnaces ▪ Rotary hearth furnaces
Mode of heat transfer	Radiation (open fire place)
	Convection (heated through medium)
Mode of waste heat recovery	Recuperative
	Regenerative

Forging Furnace

The forging furnace is used for preheating blocks and ingots to attain a 'forge' temperature. The furnace temperature is maintained at around 1200 to 1250°C. Forging furnaces use an open fireplace system and most of the heat is transmitted by radiation. The typical load is 5 to 6 ton with the furnace operating for 16 to 18 hours daily. The total operating cycle can be divided into (i) heat-up time (ii) soaking time and (iii) forging time. Specific fuel consumption depends upon the type of material and number of 'reheats' required.

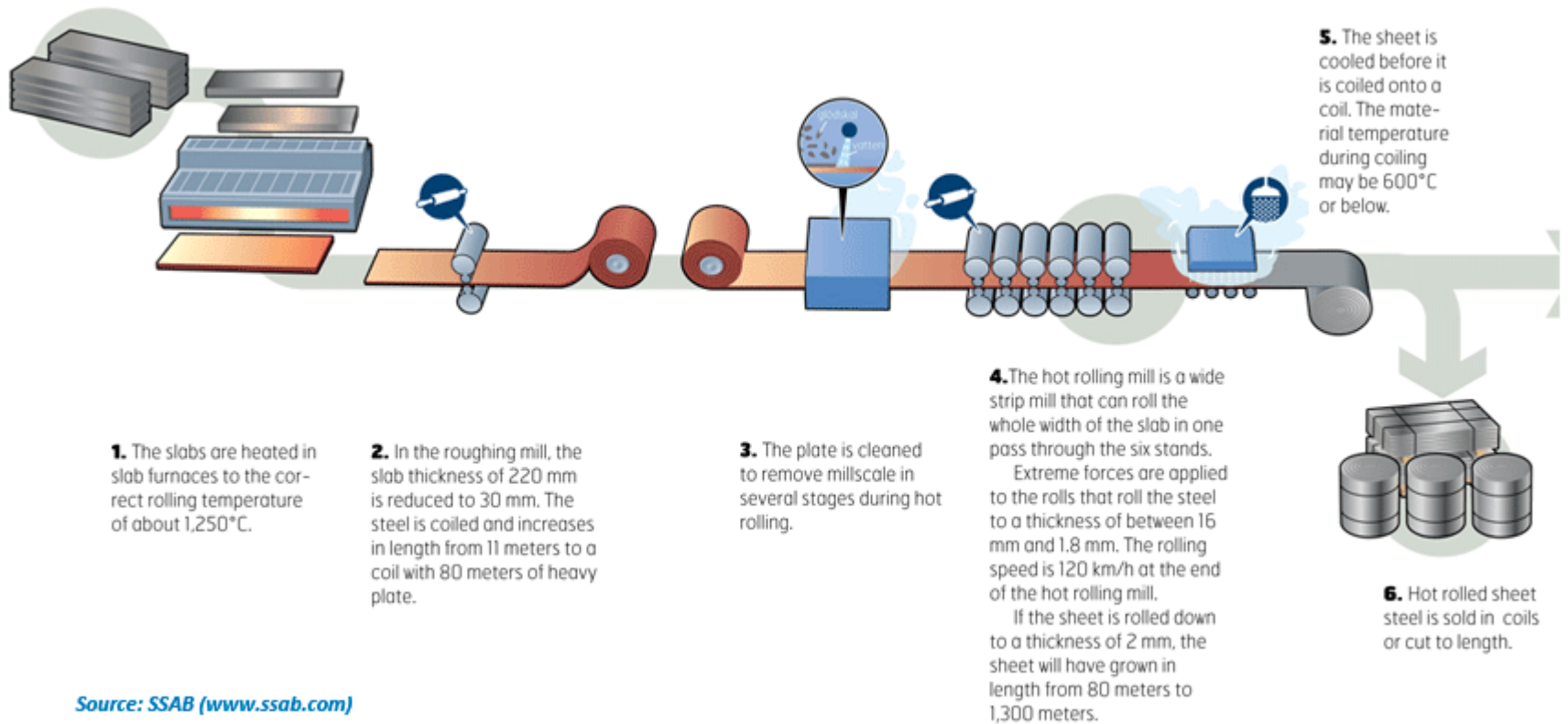


Re-rolling mill furnace

a) Batch type

A box type furnace is used as a batch type re-rolling mill. This furnace is mainly used for heating up scrap, small ingots and billets (blocks) weighing 2 to 20 kg for re-rolling. Materials are manually charged and discharged and the final products are rods, strips etc. The operating temperature is about 1200 °C. The total cycle time can be further categorized into heat-up time and re-rolling time. During heat-up time the material gets heated up-to the required temperature and is removed manually for re-rolling. The average output from these furnaces varies from 10 to 15 tons / day and the specific fuel consumption varies from 180 to 280 kg. of coal / ton of heated material

Re-rolling mill furnace



b) Continuous pusher type

The process flow and operating cycles of a continuous pusher type is the same as that of the batch furnace. The operating temperature is about 1250°C. Generally, these furnaces operate 8 to 10 hours with an output of 20 to 25 ton per day. The material or stock recovers a part of the heat in flue gases as it moves down the length of the furnace. Heat absorption by the material in the furnace is slow, steady and uniform throughout the cross-section compared with batch type.

Continuous reheating furnace

In continuous reheating, the steel stock forms a continuous flow of material and is heated to the desired temperature as it travels through the furnace. The temperature of a piece of steel is typically raised to between 900°C and 1250°C, until it is soft enough to be pressed or rolled into the desired size or shape. The furnace must also meet specific stock heating rates for metallurgical and productivity reasons. To ensure that the energy loss is kept to a minimum, the inlet and outlet doors should be minimal in size and designed to avoid air infiltration.

Continuous reheating furnaces can be categorized by the two methods of transporting stock through the furnace:

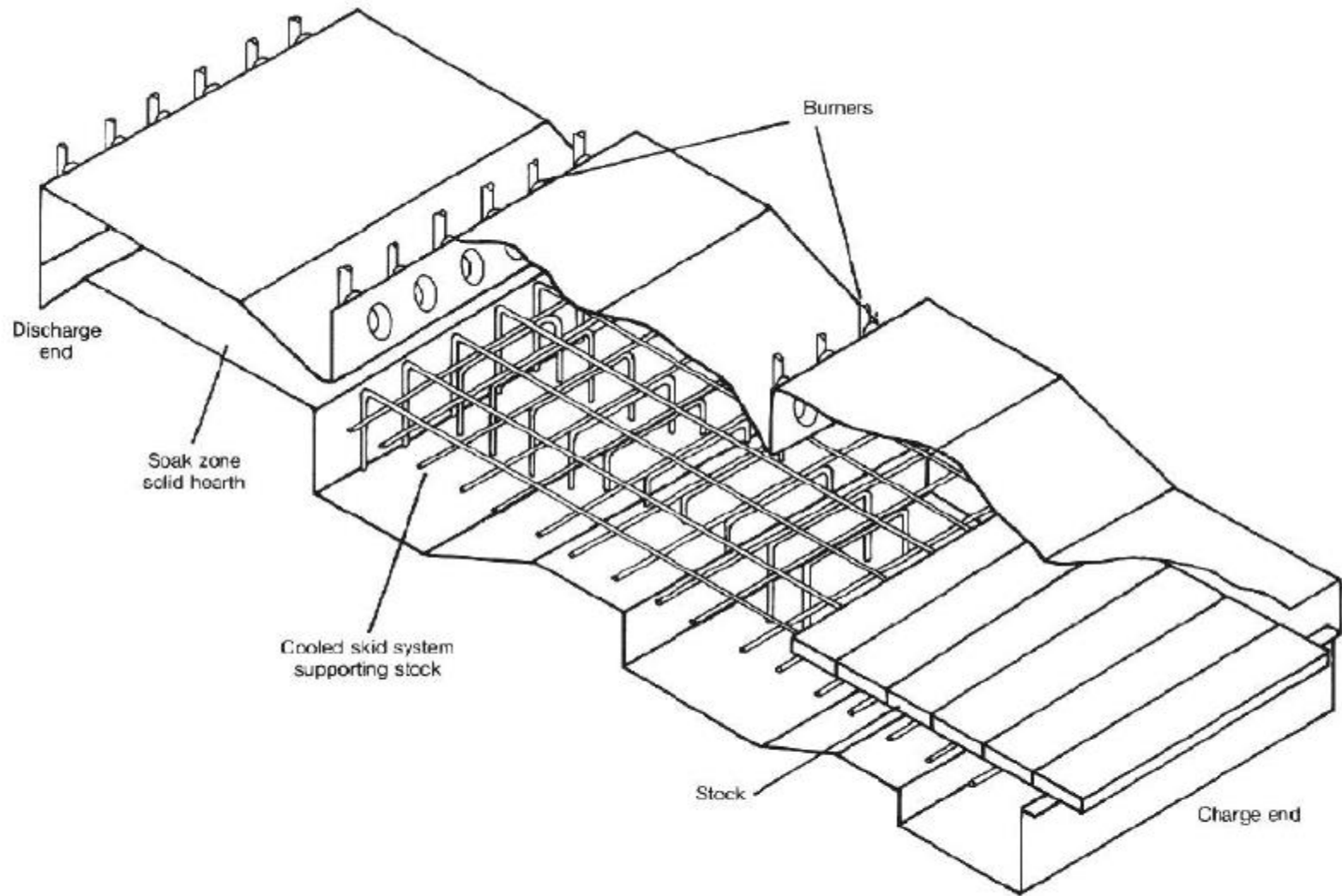
- Stock is kept together to form a stream of material that is pushed through the furnace. Such furnaces are called pusher type furnaces.
- Stock is placed on a moving hearth or supporting structure which transports the steel through the furnace. The furnaces include walking beam, walking hearth, continuous recirculating bogie furnaces, and rotary hearth furnaces.

Table below compares the main types of continuous reheating furnaces used in industry

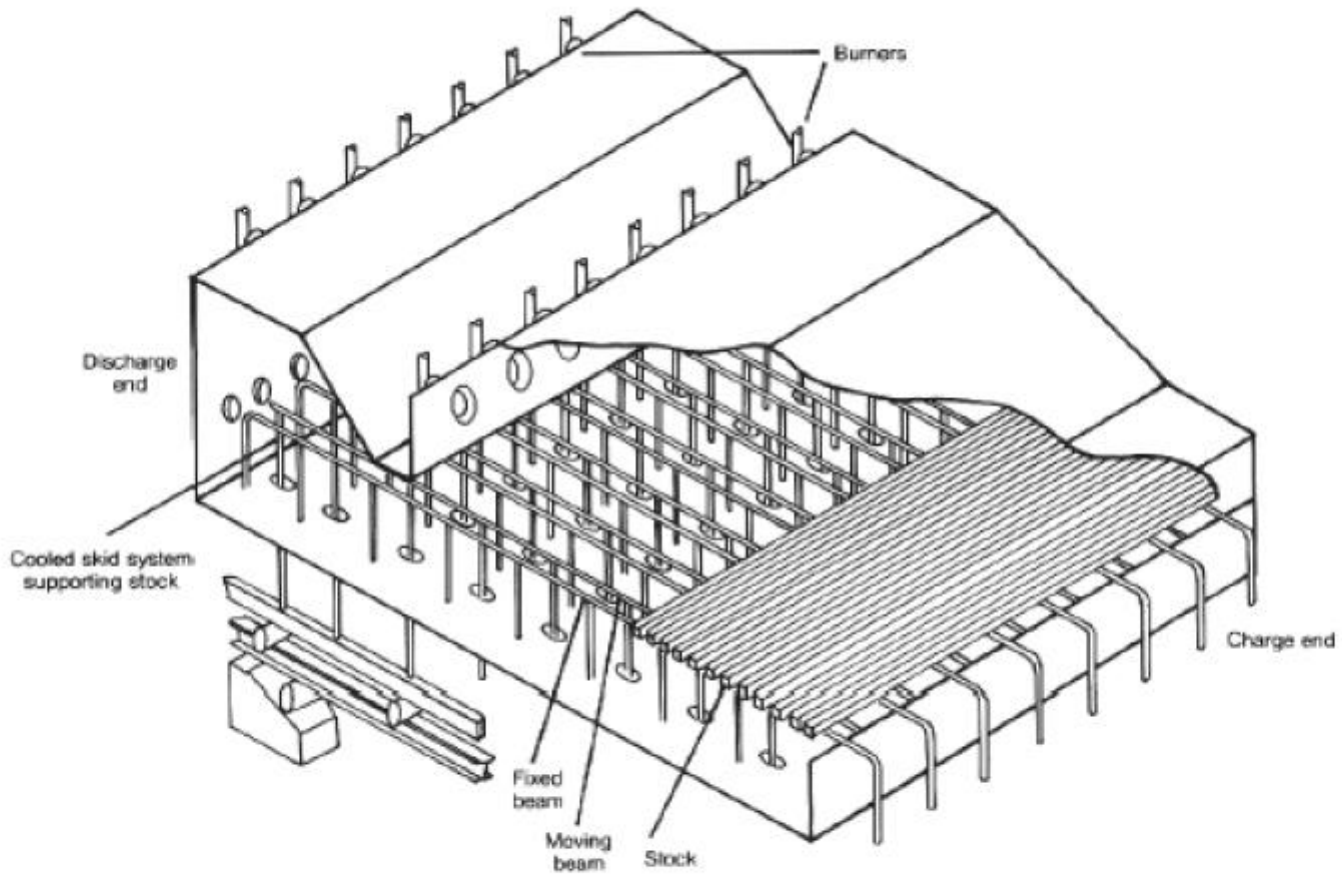
Comparison of Different Continuous Reheating Furnaces (Adapted from The Carbon Trust, 1993 and BEE, 2005)

Type	Description	Advantages	Disadvantages
Pusher furnace	<p>The main features are:</p> <ul style="list-style-type: none"> ▪ Furnaces may have solid hearth, but in most cases pushers are used to charge and discharge stock, that move on “skids” (rails) with water-cooled supports. ▪ These furnaces typically have a hearth sloping towards the discharge end of up to 35 meters divided into five zones in top-fired furnaces. ▪ Firing of furnace by burners located at the discharge end of the furnace, or at top and/or bottom to heat stock from both top and/or bottom ▪ The discharge ends of these furnaces have a chimney with a recuperator for waste heat recovery. 	<p>Low installation and maintenance costs (compared with moving hearth furnaces)</p> <p>Advantages of top and bottom firing:</p> <ul style="list-style-type: none"> ▪ Faster heating of stock ▪ Lower temperature differences within stock ▪ Reduced stock residence time ▪ Shorter furnace lengths (compared to solid hearth furnaces) 	<ul style="list-style-type: none"> ▪ Water cooling energy losses from the skids and stock supporting structure in top and bottom fired furnaces ▪ Discharge must be accompanied by charge ▪ Stock sizes/weights and furnace length are limited by friction and possibility of stock pile-ups ▪ Furnace needs facilities to be completely emptied ▪ Quality reduction by (a) physical marking by skids or ‘skid marks’ (b) temperature differences along the stock length caused by the water cooled supports in top and bottom fired furnaces
Walking beam furnace	<p>These furnaces operate as follows:</p> <ul style="list-style-type: none"> ▪ Stock is placed on stationary ridges ▪ Walking beams are raised from the bottom to raise the stock ▪ Walking beams with the stock move forwards ▪ Walking beams are lowered at end of the furnace to place stock on stationary ridges ▪ Stock is removed from furnace and walking beams return to furnace entrance <p>Initially temperatures were limited 1000 °C but new models are able to reach 1100 °C</p>	<ul style="list-style-type: none"> ▪ Overcomes many of the problems of pusher furnaces (skid marks, stock pile-ups, charge/discharge) ▪ Possible to heat bottom face of the stock resulting in shorter stock heating times and furnace lengths and thus better control of heating rates, uniform stock discharge temperatures and operational flexibility 	<ul style="list-style-type: none"> ▪ High energy loss through water cooling (compared with walking hearth furnaces) ▪ Much of the furnace is below the level of the mill; this may be a constraint in some applications ▪ Sometimes when operating mechanism of beam make it necessary to fire from the sides, this results in non-uniform heating of the stock

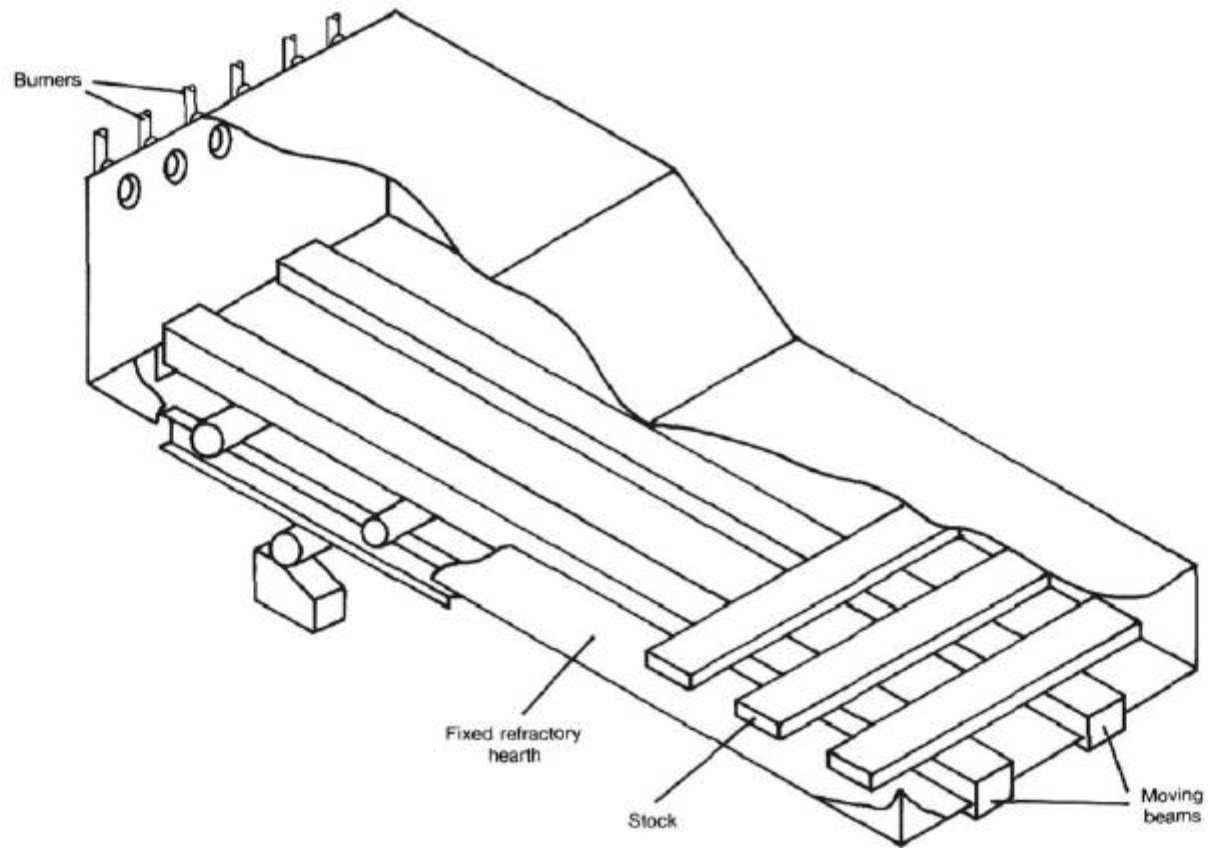
Type	Description	Advantages	Disadvantages
Walking hearth furnace	<p>These furnaces are designed so that the stock rests on fixed refractory blocks, which are extended through openings in the hearth. The stock is transported towards the discharge end in discrete steps by “walking the hearth”, similar to walking beam furnaces</p>	<ul style="list-style-type: none"> ▪ Simplicity of design ▪ Ease of construction ▪ Ability to cater for different stock sizes (within limits) ▪ Negligible water cooling energy losses ▪ Can be emptied ▪ Minimal physical marking of the stock 	<ul style="list-style-type: none"> ▪ Temperatures across the stock are not uniform because the bottom of stock cannot be heated and small spaces between the stock limits heating of the sides. Large spaces between stocks can partially alleviate this. But this increases stock residence time to up to several hours, which affects furnace flexibility and yield
Continuous recirculating bogie furnace	<p>The furnace has the shape of a long and narrow tunnel with rails inside and works as follows:</p> <ul style="list-style-type: none"> ▪ Stock is placed on a bogie (cart with wheels) with a refractory hearth ▪ Several bogies move like a train over the entire furnace length through the furnace ▪ Stock is removed at the discharge end and the bogie returns to the charge end of the furnace 	<ul style="list-style-type: none"> ▪ Suitable for compact stock of variable size and geometry 	<ul style="list-style-type: none"> ▪ The stock in the bogie has to undergo a cycle of heating and cooling then again heating ▪ Heat storage loss through heating and cooling of the bogies ▪ Inadequate sealing of the gap between the bogies and furnace shell, difficulties in removing scale, and difficulties in firing across a narrow hearth width caused by the narrow and long furnace shape
Rotary hearth furnace	<p>More recent developed furnace type that is overtaking the bogie furnace. The walls and the roof of the furnace remains stationary while the hearth moves in a circle on rollers, carrying the stock. Heated gas moves in opposite direction of the hearth and flue gases are discharged near the charging door. The temperature can reach 1300 °C</p>	<ul style="list-style-type: none"> ▪ Suitable for stock of variable size and geometry ▪ Reduced heat storage loss compared to bogie furnace 	<ul style="list-style-type: none"> ▪ More complex design with an annular shape and revolving hearth ▪ Possible logistical problems in layout of some rolling mills and forges because of close location of charge and discharge positions



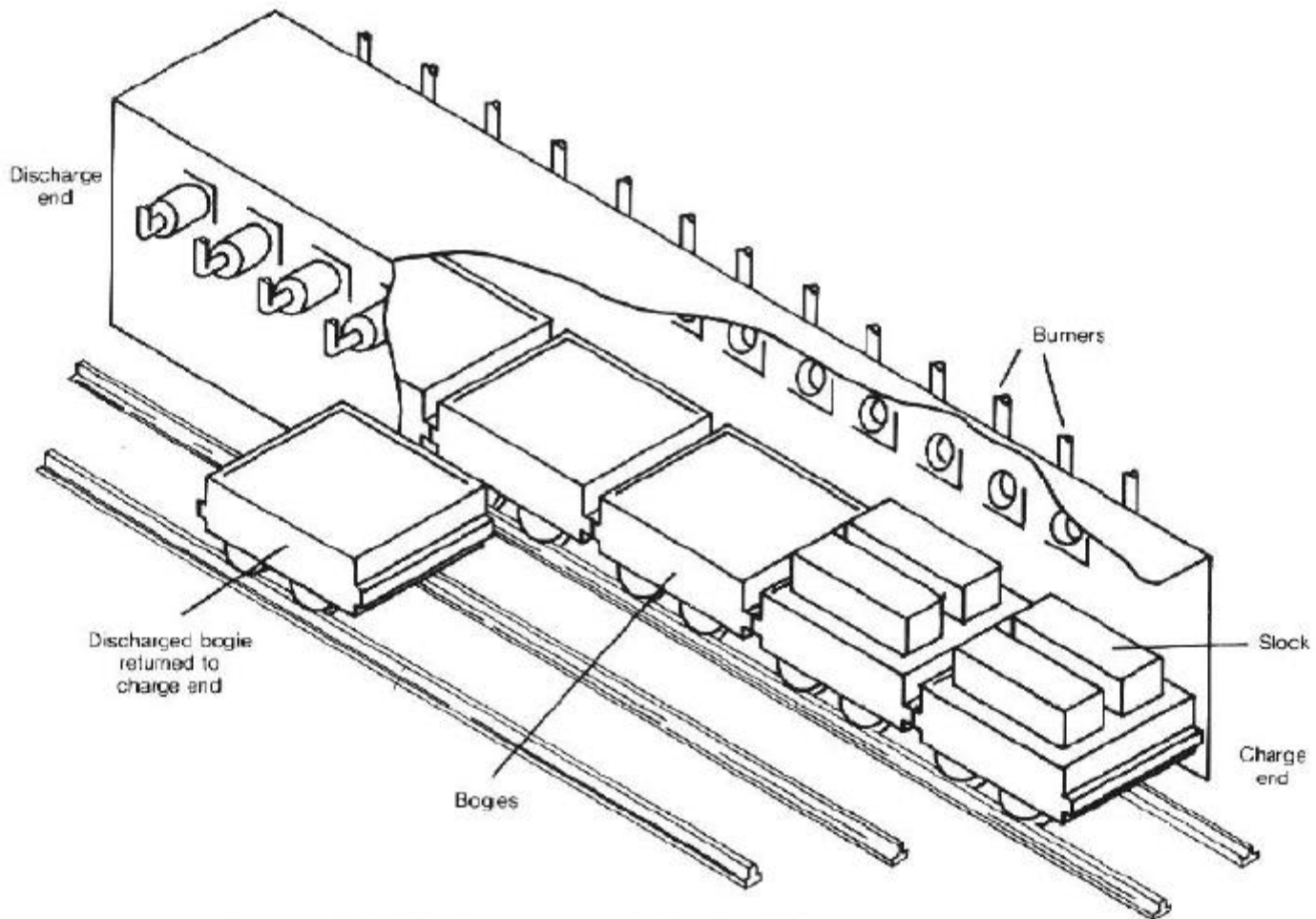
Pusher Furnace (The Carbon Trust, 1993)



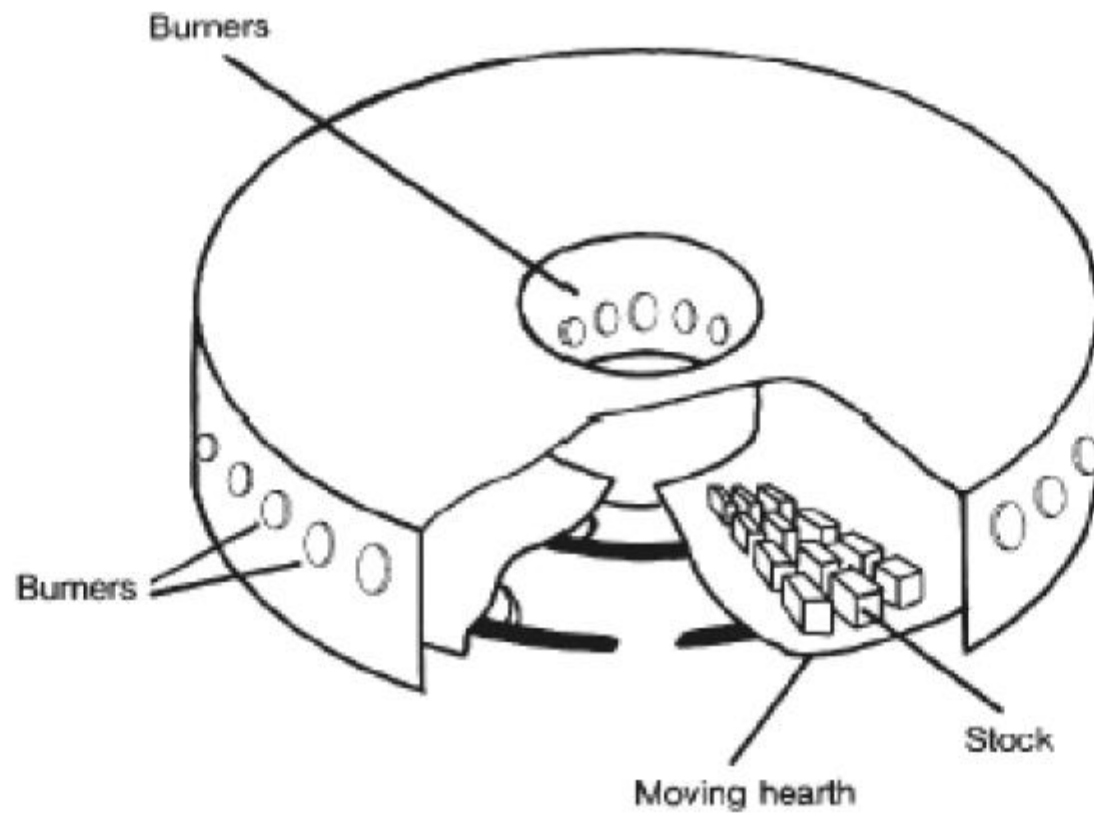
Walking Beam Furnace (The Carbon Trust 1993)



Walking Hearth Furnace (The Carbon Trust, 1993)



Continuous Re-circulating Bogie Furnace (The Carbon Trust, 1993)



Rotary Hearth Furnace (The Carbon Trust, 1993)