5. INSULATION AND REFRACTORIES

Syllabus
Insulation and Refractories: Insulation-types and application, Economic thickness of insulation, Heat savings and application criteria, Refractory-types, selection and application of refractories, Heat loss.

5.1 Purpose of Insulation

A thermal insulator is a poor conductor of heat and has a low thermal conductivity. Insulation is used in buildings and in manufacturing processes to prevent heat loss or heat gain. Although its primary purpose is an economic one, it also provides more accurate control of process temperatures and protection of personnel. It prevents condensation on cold surfaces and the resulting corrosion. Such materials are porous, containing large number of dormant air cells. Thermal insulation delivers the following benefits:

- Reduces over-all energy consumption
- Offers better process control by maintaining process temperature.
- Prevents corrosion by keeping the exposed surface of a refrigerated system above dew point
- Provides fire protection to equipment
- Absorbs vibration

5.2 Types and Application

The Insulation can be classified into three groups according to the temperature ranges for which they are used.

Low Temperature Insulations (up to 90 °C)

This range covers insulating materials for refrigerators, cold and hot water systems, storage tanks, etc. The commonly used materials are Cork, Wood, 85% magnesia, Mineral Fibers, Polyurethane and expanded Polystyrene, etc.

Medium Temperature Insulations (90 – 325 °C)

Insulators in this range are used in low temperature, heating and steam raising equipment, steam lines, flue ducts etc. The types of materials used in this temperatures range include 85% Magnesia, Asbestos, Calcium Silicate and Mineral Fibers etc.

High Temperature Insulations (325 °C – above)

Typical uses of such materials are super heated steam system, oven dryer and furnaces etc. The most extensively used materials in this range are Asbestos, Calcium Silicate, Mineral Fibre, Mica and Vermiculite based insulation, Fireclay or Silica based insulation and Ceramic Fibre.

Insulation material

Insulation materials can also be classified into organic and inorganic types. Organic insulations are based on hydrocarbon polymers, which can be expanded to obtain high void structures

Example: Thermocol (Expanded Polystyrene) and Poly Urethane Form(PUF).

Inorganic insulation is based on Siliceous/Aluminous/Calcium materials in fibrous, granular or powder forms.

Example: Mineral wool, Calcium silicate etc.

Properties of common insulating materials are as under:

Calcium Silicate: Used in industrial process plant piping where high service temperature and compressive strength are needed. Temperature ranges varies from 40 °C to 950 °C.

Glass mineral wool: These are available in flexible forms, rigid slabs and preformed pipe work sections. Good for thermal and acoustic insulation for heating and chilling system pipelines. Temperature range of application is –10 to 500 °C.

Thermocol: These are mainly used as cold insulation for piping and cold storage construction.
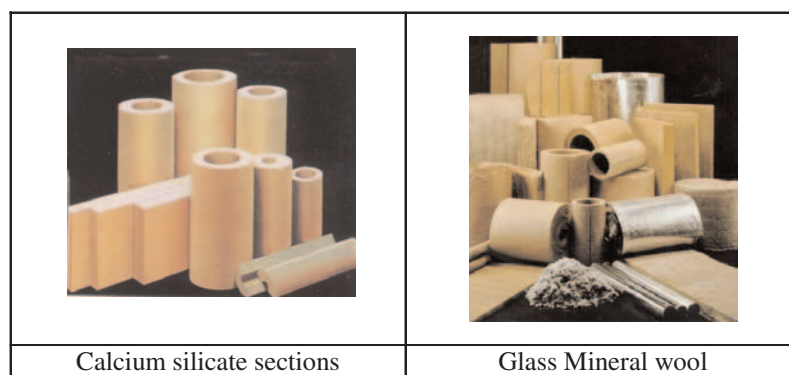

| Calcium silicate sections | Glass Mineral wool |

Figure 5.1

Expanded nitrile rubber: This is a flexible material that forms a closed cell integral vapour barrier. Originally developed for condensation control in refrigeration pipe work and chilled water lines; now-a-days also used for ducting insulation for air conditioning.

Rock mineral wool: This is available in a range of forms from light weight rolled products to heavy rigid slabs including preformed pipe sections. In addition to good thermal insulation properties, it can also provide acoustic insulation and is fire retardant.

Use of Moulded Insulation

Lagging materials can be obtained in bulk, in the form of moulded sections; semi - cylindrical for pipes, slabs for vessels, flanges, valves etc. The main advantage of the moulded sections is the ease of application and replacement when undertaking repairs for damaged lagging.

The *thermal conductivity* of a material is the heat loss per unit area per unit insulation thickness per unit temperature difference. The unit of measurement is W-m^2/m°C or W-m/ °C. The thermal conductivity of materials increases with temperature. So thermal conductivity is always specified at the mean temperature (mean of hot and cold face temperatures) of the insulation material.

Thermal conductivities of typical hot and cold insulation materials are given in Table 5.1 and Table 5.2.

TABLE 5.1 THERMAL CONDUCTIVITY OF HOT INSULATION			
Mean Temperature °C	Calcium Silicate	Resin bonded Mineral wool	Ceramic Fiber Blankets
100	-	0.04	-
200	0.07	0.06	0.06
300	0.08	0.08	0.07
400	0.08	0.11	0.09
700	-	-	0.17
1000	-	-	0.26
Specific heat(kJ/kg/°C)	0.96	0.921	1.07
	(at 40°C)	(at 20°C)	(at 980°C)
Service temp, (°C).	950	700	1425
Density kg/m^3	260	48 to144	64 to 128

TABLE 5.2 THERMAL CONDUCTIVITY OF COLD INSULATION	
MATERIALS	Thermal Conductivity W/m-°C
Mineral Or Glass Fiber Blanket	0.039
Board or Slab	
Cellular Glass	0.058
Cork Board	0.043
Glass Fiber	0.036
Expanded Polystyrene (smooth) - Thermocole	0.029
Expanded Polystyrene (Cut Cell) - Thermocole	0.036
Expanded Polyurethane	0.017
Phenotherm (Trade Name)	0.018
Loose Fill	
Paper or Wood Pulp	0.039
Sawdust or Shavings	0.065
Minerals Wool (Rock, Glass, Slag)	0.039
Wood Fiber (Soft)	0.043

5.3 Calculation of Insulation Thickness

The most basic model for insulation on a pipe is shown in Figure 5.2. r1 show the outside radius of the pipe r2 shows the radius of the Pipe+ insulation.

Heat loss from a surface is expressed as

H = h X A x (Th–Ta)

Where

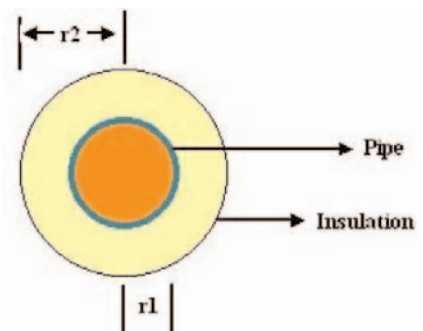h = Heat transfer coefficient, W/m^2–K

H = Heat loss, Watts

Figure 5.2 Pipe Insulation

Ta = Average ambient temperature, °C

Ts = Desired/actual insulation surface temperature, °C

Th = Hot surface temperature (for hot fluid piping), °C & Cold surface temperature for cold fluids piping)

For horizontal pipes, heat transfer coefficient can be calculated by:

$h = (A + 0.005 (T_h - T_a)) \times 10$ W/m²-K

For vertical pipes,

$h = (B + 0.009 (T_h - T_a)) \times 10$ W/m²-K

Using the coefficients A, B as given below.

Surface	ε	A	B
Aluminium , bright rolled	0.05	0.25	0.27
Aluminium, oxidized	0.13	0.31	0.33
Steel	0.15	0.32	0.34
Galvanised sheet metal, dusty	0.44	0.53	0.55
Non metallic surfaces	0.95	0.85	0.87

$$T_m = \frac{(T_h + T_s)}{2}$$

k = Thermal conductivity of insulation at mean temperature of Tm, W/m-°C

tk = Thickness of insulation, mm

r1 = Actual outer radius of pipe, mm

r2 = (r1 + tk)

$$R_s = \text{Surface thermal resistance} = \frac{1}{h} \; °C\text{--m}^2/W$$

$$R_l = \text{Thermal resistance of insulation} = \frac{t_k}{k} \; °C\text{--m}^2/W$$

The heat flow from the pipe surface and the ambient can be expressed as follows:

H = Heat flow, Watts

$$= \frac{(T_h - T_a)}{(R_l + R_s)} = \frac{(T_s - T_a)}{R_s}$$

From the above equation, and for a desired Ts, Rl can be calculated. From Rl and known value of thermal conductivity k, thickness of insulation can be calculated.

$$\text{Equivalent thickness of insulation for pipe, } E_{tk.} = (r_1 + t_k) \times \ln\left(\frac{(r_1 + t_k)}{r_1}\right)$$
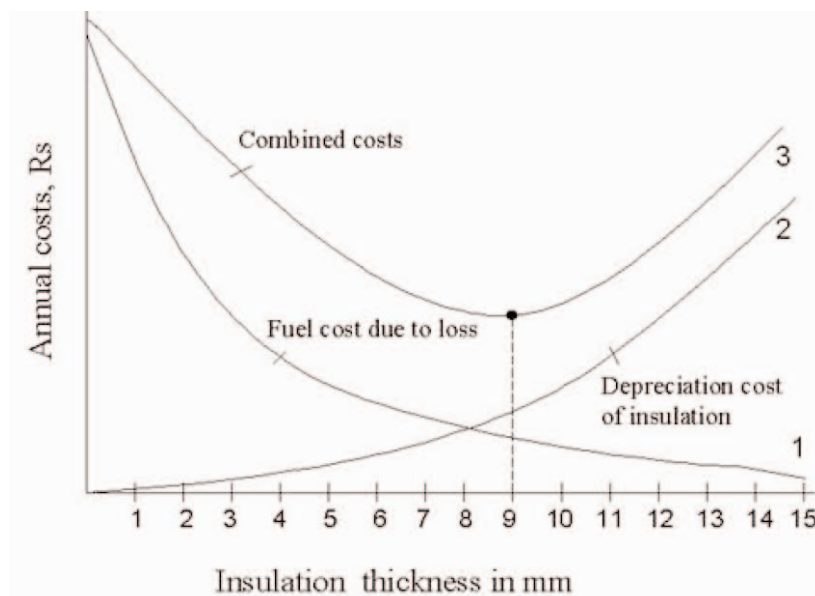
5.4 Economic Thickness of Insulation (ETI)

Insulation of any system means capital expenditure. Hence the most important factor in any insulation system is to analyse the thermal insulation with respect to cost. The effectiveness of insulation follows the law of decreasing returns. Hence, there is a definite economic limit to the amount of insulation, which is justified. An increased thickness is uneconomical and cannot be recovered through small heat savings. This limiting value is termed as economic thickness of insulation. An illustrative case is given in Figure 5.3. Each industry has different fuel cost and boiler efficiency. These values can be used for calculating economic thickness of insulation. This shows that thickness for a given set of circumstances results in the lowest overall cost of insulation and heat loss combined over a given period of time. The following Figure 5.4 illustrates the principle of economic thickness of insulation.
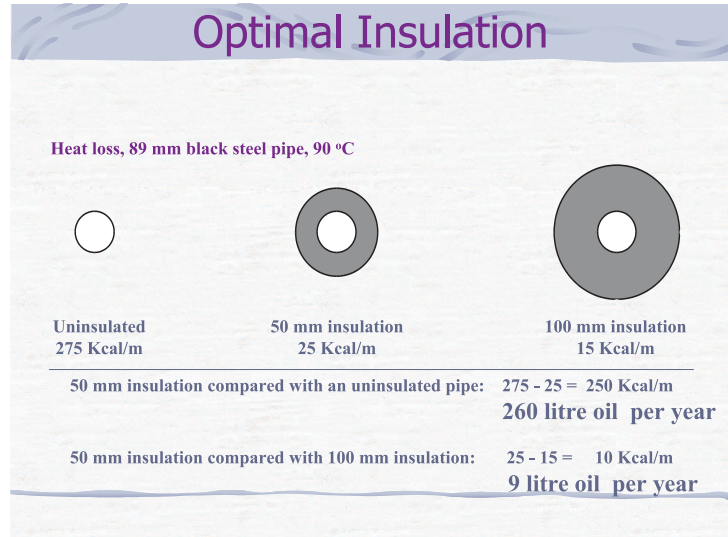
Figure 5.3 Illustration of Optimal Insulation

The simplest method of analysing whether you should use 1" or 2" or 3" insulation is by comparing the cost of energy losses with the cost of insulating the pipe. The insulation thickness for which the total cost is minimum is termed as economic thickness. Refer Figure 5.4 The curve representing the total cost reduces initially and after reaching the economic thickness corresponding to the minimum cost, it increases.

Figure 5.4 Determination of Economic Thickness of Insulation

The determination of economic thickness requires the attention to the following factors.
i. Cost of fuel
ii. Annual hours of operation
iii. Heat content of fuel
iv. Boiler efficiency
v. Operating surface temperature
vi. Pipe diameter/thickness of surface
vii. Estimated cost of insulation.
viii. Average exposure ambient still air temperature

Procedure for Calculating Economic Thickness of Insulation

To explain the concept of economic thickness of insulation, we will use an example. (Refer Table 5.3) Consider an 8 bar steam pipeline of 6" dia having 50-meter length. We will evaluate the cost of energy losses when we use 1", 2" and 3" insulation to find out the most economic thickness.

A step-by-step procedure is given below.
1. Establish the bare pipe surface temperature, by measurement.
2. Note the dimensions such as diameter, length & surface area of the pipe section under consideration.
3. Assume an average ambient temperature. Here, we have taken 30 °C.
4. Since we are doing the calculations for commercially available insulation thickness, some trial and error calculations will be required for deciding the surface temperature after putting insulation. To begin with assume a value between 55 & 65 °C, which is a safe, touch temperature.
5. Select an insulation material, with known thermal conductivity values in the mean insulation temperature range. Here the mean temperature is 111 °C. and the value of k = 0.044 W/m^2 °C for mineral wool.
6. Calculate surface heat transfer coefficients of bare and insulated surfaces, using equations discussed previously. Calculate the thermal resistance and thickness of insulation.
7. Select r2 such that the equivalent thickness of insulation of pipe equals to the insulation thickness estimated in step 6. From this value, calculate the radial thickness of pipe insulation = r2-r1
8. Adjust the desired surface temperature values so that the thickness of insulation is close to the standard value of 1" (25.4 mm).
9. Estimate the surface area of the pipe with different insulation thickness and calculate the total heat loss from the surfaces using heat transfer coefficient, temperature difference between pipe surface and ambient.
10. Estimate the cost of energy losses in the 3 scenarios. Calculate the Net Present Value of the future energy costs during an insulation life of typically 5 years.
11. Find out the total cost of putting insulation on the pipe (material + labor cost)
12. Calculate the total cost of energy costs and insulation for 3 situations.
13. Insulation thickness corresponding to the lowest total cost will be the economic thickness of insulation.

TABLE 5.3 EXAMPLE FOR ECONOMIC INSULATION THICKNESS

Description	Unit	Insulation thickness 1"	2"	3"
Length of pipe, L	m	50	50	50
Bare Pipe outer diameter, d1	mm	168	168	168
Bare pipe surface area, A	m^2	26.38	26.38	26.38
Ambient Temperature, Ta :	°C	30	30	30
Bare Pipe Wall Temperature, Th:	°C	160	160	160
Desired Wall Temperature With Insulation, Tc :	°C	62	48	43
Material of Insulation :		Mineral Wool		
Mean Temperature of Insulation, Tm = (Th+Tc)/2 :	°C	111	104	101.5
Sp.Conductivity of Insulation Material, k (from catalogue) :	W/m°C	0.044	0.042	0.04
Surface Emissivity of bare pipe:		0.95	0.95	0.95
Surface emissivity of insulation cladding(typically Al)		0.13	0.13	0.13

Calculations

Surface Heat Transfer Coefficient of Hot Bare Surface, h :(0.85+ 0.005 (Th – Ta)) x 10	W/m^2°C	15	15	15
Surface Heat Transfer Coefficient After Insulation, h' = (0.31+ 0.005 (Tc – Ta)) x 10	W/m^2°C	4.7	4	3.75
Thermal Resistance, R_{th} = (Th-Tc)/[h' x (Tc-Ta)] :	°C-m^2/W	0.7	1.6	2.4
Thickness of Insulation, t = k x R_{th} :(if surface was flat)	mm	28.7	65.3	96.0
r_1=outer diameter/2 =	mm	84	84	84
t_{eq} = r_2 x ln(r_2/ r_1) = (select r_2 so that t_{eq} = t)	mm	28.7	65.3	106.3
Outer radius of insulation , r_2=	mm	109.2	135.9	161.9
Thickness of insulation	mm	**25.2**	**51.9**	**77.9**
Insulated pipe Area , A :	m^2	34.29	42.66	50.85
Total Losses From Bare Surface, Q = h x A x (Th-Ta) :	kW	51.4	51.4	51.4
Total Loss From Insulated Surface, Q' = h' x A' x (Tc-Ta) :	kW	5.16	3.07	2.48
Power Saved by Providing Insulation, P = Q - Q' :	kW	46.3	48.4	49.0
Annual Working Hours, n :	Hrs	8000	8000	8000
Energy Saving After Providing Insulation, E = P x n :	kWh/year	370203	386892	391634

Economics

Steam cost,	Rs/kg	0.70	0.70	0.70
Heat Energy Cost, p :	Rs./kWh	1.11	1.11	1.11
Annual Monetary Saving, S = E x p :	Rs.	412708	431313	436599
Discount factor for calculating NPV of cost of energy loss	%	15%	15%	15%
Cost of insulation (material + labor)	Rs/m	450	700	1100
Total cost of insulation	Rs/m	22500	35000	55000
Annual Cost of energy loss	Rs/year	46000	27395	22109
NPV of annual cost of energy losses for 5 years	Rs	154198	91832	74112
Total cost (insulation & NPV of heat loss)	Rs	**176698**	**126832**	**129112**

Note that the total cost is lower when using 2" insulation, hence is the economic insulation thickness.

5.5 Simplified Formula for Heat Loss Calculation

Various charts, graphs and references are available for heat loss computation. The surface heat loss can be computed with the help of a simple relation as given below. This equation can be used up to 200 °C surface temperature. Factors like wind velocities, conductivity of insulating material etc has not been considered in the equation.

S = [10+(Ts–Ta)/20] x (Ts–Ta)
Where

$\qquad$ S = Surface heat loss in kCal/hr m^2
$\qquad$ Ts = Hot surface temperature in °C
$\qquad$ Ta = Ambient temperature in °C

Total heat loss/hr (Hs) = S × A
Where A is the surface area in m^2

Based on the cost of heat energy, the quantification of heat loss in Rs. can be worked out as under:

$$\text{Equivalent fuel loss (Hf) (kg/Yr)} = \frac{Hs \times \text{Yearly hours of operation}}{GCV \times \eta_b}$$

Annual heat loss in monetary terms (Rs.) = Hf × Fuel cost (Rs./kg)
$\quad$ Where
$\quad$ GCV = Gross Calorific value of fuel kCal/kg
$\quad\quad$ η_b = Boiler efficiency in %

Case Example

Steam pipeline 100 mm diameter is not insulated for 100 metre length supplying steam at 10 kg/cm2 to the equipment. Find out the fuel savings if it is properly insulated with 65 mm insulating material.

Assumptions:
$\quad$ Boiler efficiency $\qquad\qquad\qquad\qquad\qquad$ – 80%
$\quad$ Fuel Oil cost $\qquad\qquad\qquad\qquad\qquad\qquad$ – Rs.15000/tonne
$\quad$ Surface temperature without insulation $\qquad$ – 170 °C
$\quad$ Surface temperature after insulation $\qquad\quad$ – 65 °C
$\quad$ Ambient temperature $\qquad\qquad\qquad\qquad$ – 25 °C

Existing Heat Loss:
$\quad$ S = [10+ (Ts – Ta)/20] × (Ts – Ta)
$\quad$ T$_s$ = 170 °C
$\quad$ T$_a$ = 25 °C
$\quad$ S = [10 + (170 – 25)/20] × (170 – 25) = 2500 kCal/hr-m^2
$\quad$ S$_1$ = S =Existing heat loss (2500 kCal/hr-m^2)

Modified System:
After insulating with 65 mm glass wool with aluminum cladding the hot face temperature will be 65 °C.

Ts – 65 °C
Ta – 25 °C
Substituting these values

$\quad$ S = [10+(65-25)/20] × (65 – 25)
$\qquad$ = 480 kCal/hr m^2
$\quad$ S2 = S = Existing heat loss (480 kCal/hr – m^2)

Fuel Savings Calculation

Pipe dimension	=	ϕ 100 mm & 100 m length
Surface area existing (A1)	=	3.14 × 0.1 × 100 = 31.4 m^2
Surface area after insulation (A2)	=	3.14 × 0.23 × 100 = 72.2 m^2
Total heat loss in existing system (S1 × A1)	=	2500 × 31.4 = 78500 kCal/hr
Total heat loss in Modified system (S2 × A2)	=	480 × 72.2 = 34656 kCal/hr
Reduction in heat loss	=	78500 – 34656 = 43844 kCal/hr
No. of hours operation in a year	=	8400
Total heat loss (kCal/yr)	=	43844 × 8400 = 368289600
Calorific value of fuel oil	=	10300 kCal/kg
Boiler efficiency	=	80%
Price of fuel oil	=	Rs.15000/Tonne
Yearly fuel oil savings	=	368289600/10300 × 0.8
	=	44695 kg/year

5.6 Refractories

Any material can be described as 'refractory', if it can with stand the action of abrasive or corrosive solids, liquids or gases at high temperatures. The various combinations of operating conditions in which refractories are used, make it necessary to manufacture a range of refractory materials with different properties. Refractory materials are made in varying combinations and shapes and for different applications.

The general requirements of a refractory material can be summed up as :

- Ability to withstand high temperatures.
- Ability to withstand sudden changes of temperatures.
- Ability to withstand action of molten metal slag, glass, hot gases, etc.
- Ability to withstand load at service conditions.
- Ability to withstand load and abrasive forces.
- Low coefficient of thermal expansion.
- Should be able to conserve heat.
- Should not contaminate the material with which it comes into contact.

5.7 Properties of Refractories

Some of the important properties of refractories are:

TABLE 5.4 MELTING POINTS OF PURE COMPOUNDS		
Pure Compound	Formula	Melting Temperature °C
Alumina	A_2O_3	2050
Lime	CaO	2570
Chromite	$FeOCr_2O_3$	2180
Chromium Oxide	Cr_2O_2	2275
Megnesia	MgO	2800
Silica	SiO_2	1715
Titania	TiO_2	1850

Melting point: Pure substances melt sharply at a definite temperature. Most refractory materials consist of high melting particles bonded together. At high temperature, glass fuses and as the temperature rises, the resulting slag increases in quantity by partial solution of the refractory particles. The temperature at which this action results in failure of a test pyramid (cone) to support its own weight is called, for convenience, the melting point of the refractory. Table 5.4 shows the melting point of some pure compounds used as refractories.

Size: The size and shape of the refractories is a part of the design feature. It is an important feature in design since it affects the stability of any structure. Accuracy and size is extremely important to enable proper fitting of the refractory shape and to minimize the thickness and joints in construction.

Bulk density: A useful property of refractories is bulk density, which defines the material present in a given volume. An increase in bulk density of a given refractory increases its volume stability, its heat capacity, as well as resistance to slag penetration.

Porosity: The apparent porosity is a measure of the volume of the open pores, into which a liquid can penetrate, as a percentage of the total volume. This is an important property in cases where the refractory is in contact with molten charge and slags. A low apparent porosity is desirable since it would prevent easy penetration of the refractory size and continuity of pores will have important influences on refractory behaviour. A large number of small pores is generally preferable to an equivalent number of large pores.

Cold crushing strength: The cold crushing strength, which is considered by some to be of doubtful relevance as a useful property, other than that it reveals little more than the ability to withstand the rigors of transport, can be used as a useful indicator to the adequacy of firing and abrasion resistance in consonance with other properties such as bulk density and porosity.

Pyrometric cone equivalent (PCE): Temperature at which a refractory will deform under its own weight is known as its softening temperature which is indicated by PCE. Refractories, due to their chemical complexity, melt progressively over a range of temperature. Hence refractoriness or fusion point is ideally assessed by the cone fusion method. The equivalent

standard cone which melts to the same extent as the test cone is known as the pyrometric cone equivalent. Thus in the Figure 5.5 refractoriness of Sample A is much higher than B and C. The pyrometric cone equivalent indicates only the softening temperature. But, in service the refractory is subjected to loads which would deform the refractory at a much lower temperature than that indicated by PCE. With change in the environmental conditions, such as reducing atmosphere, the P.C.E. value changes drastically.
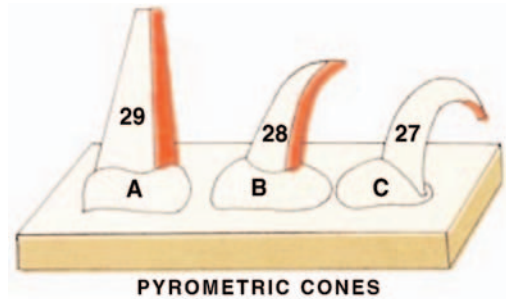

PYROMETRIC CONES

Figure 5.5

Refractoriness under load (RUL): The refractoriness under load test (RUL test) gives an indication of the temperature at which the bricks will collapse, in service conditions with similar load.

Creep at high temperature: Creep is a time dependent property which determines the deformation in a given time and at a given temperature by a material under stress.

Volume stability, expansion, and shrinkage at high temperatures: The contraction or expansion of the refractories can take place during service. Such permanent changes in dimensions may be due to:

i)   The changes in the allotropic forms which cause a change in specific gravity.
ii)   A chemical reaction which produces a new material of altered specific gravity.
iii)   The formation of liquid phase.
iv)   Sintering reactions.
v)   It may also happen on account of fluxing with dust and stag or by the action of alkalies on fireclay refractories, to form alkali-alumina silicates, causing expansion and disruption.

This is an example which is generally observed in blast furnaces.

Reversible Thermal Expansion: Any material when heated, expands, and contracts on cooling. The reversible thermal expansion is a reflection on the phase transformations that occur during heating and cooling.

Thermal Conductivity: Thermal conductivity depends upon the chemical and mineralogical compositions as well as the glassy phase contained in the refractory and the application temperature. The conductivity usually changes with rise in temperature. In cases where heat transfer is required though the brick work, for example in recuperators, regenerators, muffles, etc. the refractory should have high conductivity. Low thermal conductivity is desirable for conservation of heat by providing adequate insulation.

The provisions for back-up insulation, conserves heat but at the same time it increases the hot face temperature and hence the demand on the refractory quality increases.

Accordingly, insulation on the roof in open hearth furnaces is normally not provided, otherwise it would cause failure due to severe dripping. Depending on the characteristic of the refractory used in the hot face, such as the high temperature load bearing capacity, it may be required that the quality of the brick be increased to match the rise temperature caused by over insulation.

Light weight refractories of low thermal conductivity find wider applications in the moderately low temperature heat treatment furnaces, where its primary function is usually conservation of energy. It is more so in case of batch type furnaces where the low heat capacity of the refractory structure would minimize the heat storage during the intermittent heating and cooling cycles.

5.8 Classification of Refractories

Refractories can be classified on the basis of chemical composition and use and methods of manufacture as shown below:

Classification based on Chemical composition	Examples
ACID which readily combines with bases.	Silica, Semisilica, Aluminosilicate.
BASIC which consists mainly of metallic oxides which resist the action of bases.	Magnesite, chromemagnesite, Dolomite.
NEUTRAL which doesn't combine; neither with acids nor bases.	Chrome, Pure. Alumina
Special	Carbon, Silicon Carbide, Zirconia.
Classification based on end use	Blast furnace Casting Pit
Classification based on method of manufacture	- Dry Press Process - Fused Cast - Hand Moulded - Formed Normal, fired or Chemically bonded.) - Unformed (Monolithics – plastics, Ramming Mass, Gunning Castable, Spraying.)

Mineral-based refractories are classified according to their chemical composition:
   i.   Acid bricks contain at least 92%~ silicon oxide (SiO_2);
   ii. Semi-basic bricks contain at least 65% silicon oxide. but less than 30% alumina (Al_2O_3);
   iii. Neutral bricks contain at least 30% alumina;
   iv. Basic bricks contain at least 60% magnesium oxide (MgO).
   v.   Synthetic refractories e.g. silicon carbide are produced by melting and casting processes.

The structure of the furnace consists mainly of refractory bricks and cement, which must be able to withstand the high furnace temperatures and must be carefully selected and constructed. The furnace structure may contain monolithic refractories, which can be shaped in situ, e.g. those used for burner quarls. There are three basic types of monolithic refractories:
   •   Castables;
   •   Mouldables;
   •   Ramming mixtures
Different furnace zones normally operate at different temperatures. The correct selection

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of refractory materials for the various parts of the furnace and for various components e.g. hearths, walls, etc, is important. This process is governed not only by properties like thermal conductivity, expansion, etc, but also by the experience of the furnace designer or builder.

The hearth is the most important and the most severely treated region of a furnace. It should be able to bear the required load and withstand chemical attack and mechanical wear. The selection of hearth refractories is less critical for top and bottom fired furnaces, than for top fired only pusher types.

For optimum strength and thermal insulation, the walls, roof and hearth of most furnaces are constructed using layers of refractory materials. Thermal insulation is determined by the thermal properties of the refractory, and these properties are important in minimising transmission and storage heat losses. Table 5.5 compares the thermal properties of typical high density and low density refractory materials. Structural heat losses can be reduced by using low thermal mass refractory materials in the construction of the furnace.

TABLE 5.5 TYPICAL REFRACTORY PROPERTIES

Property	High Thermal Mass(High Density Refractories)	Low Thermal Mass (Ceramic Fibre)
Thermal Conductivity, W/m K	1.2	0.3
Specific Heat, J/kg K	1000	1000
Density ,kg/m^3	2300	130

5.9 Typical Refractories in Industrial Use

Depending on the area of application such as boilers, furnaces, kilns, ovens etc, temperatures and atmospheres encountered different types of refractories are used. Typical installations of refractories are shown in Figure 5.6
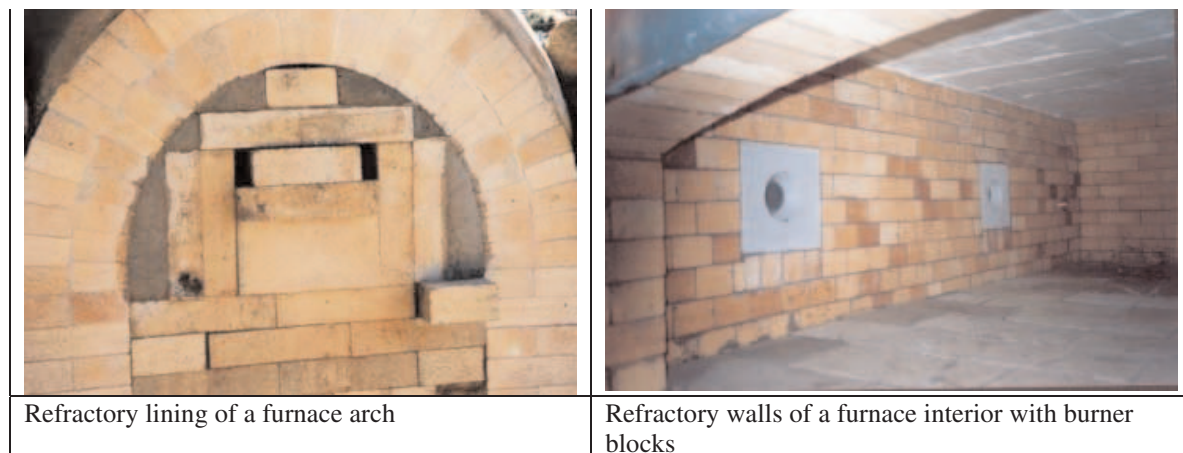

| Refractory lining of a furnace arch | Refractory walls of a furnace interior with burner blocks |

Figure 5.6

Fireclay Refractories

Fireclay refractories, such as firebricks, siliceous fireclays and aluminous clay refractories consist of aluminium silicates with various amounts of silica ranging from SiO_2 content of less than 78% and containing less than 44% of Al_2O_3.

Table 5.6 shows that as the quantity of impurities increases and the amount of Al_2O_3

decreases, the melting point of fireclay brick decreases. Owing to its relative cheapness and widespread location of the raw materials used to manufacture firebricks, this material finds use in most furnaces, kilns, stoves, etc.

Firebrick is the most common form of refractory material. It is used extensively in the iron and steel industry, nonferrous metallurgy, glass industry, pottery kilns, cement industry, and by many others.

TABLE 5.6 PROPERTIES OF TYPICAL FIRECLAY BRICKS				
Brick	Percent SiO_2	Percent Al_2O_3	Other Constituents	PCE °C
Super Duty	49-53	40–44	5-7	1745-1760
High Duty	50-80	35-40	5-9	1690-1745
Intermediate	60-70	26-36	5-9	1640-1680
HighDuty (Siliceous)	65-80	18-30	3-8	1620-1680
Low Duty	60-70	23-33	6-10	1520-1595

High Alumina Refractories

Alumino silicate refractories containing more than 45% alumina are generally termed as high alumina materials. The alumina concentration ranges from 45 to 100%. The refractoriness of high alumina refractories increases with increase in alumina percentage. The applications of high alumina refractories includes the hearth and shaft of blast furnaces, ceramic kilns, cement kilns, glass tanks and crucibles for melting a wide range of metals.

Silica Brick

Silica brick (or Dinas) is a refractory material containing at least 93% SiO_2. The raw material is quality rocks. Various grades of silica brick have found extensive use in the iron and steel melting furnaces. In addition to high fusion point multi-type refractories, the other important properties are their high resistance to thermal shock (spalling) and their high refractoriness. It finds typical use in glass making and steel industry.

The outstanding property of silica brick is that it does not begin to soften under high loads until its fusion point is approached. This behaviour contrasts with that of many other refractories, for example alumino silicate materials, which begin to fuse and creep at temperatures considerably lower than their fusion points. Other advantages are flux and stag resistance, volume stability and high spalling resistance.

Magnesite

Magnesite refractories are chemically basic materials, containing at least 85% magnesium oxide. They are made from naturally occurring magnesite ($MgCO_3$). The properties of magnesite refractories depend on the concentration of silicate bond at the operating temperatures. Good quality magnesite usually results from a $CaO-SiO_2$ ratio of less than 2 with a minimum ferrite concentration, particularly if the furnaces lined with the refractory operate in oxidizing and reducing conditions. The slag resistance is very high particularly to lime and iron rich slags.

Chromite Refractories

Here, a distinction must be made between chrome-magnesite refractories and magnesite-chromite-refractories. Chromemagnesite material usually contain 15-35% Cr_2O_3 and 42-50% MgO whereas magnesite-chromite refractories contain at least 60% MgO and 8-18% Cr_2O_3.

Chrome-magnesite refractories are made in a wide range of qualities and are used for building the critical parts of high temperature furnaces. These materials can withstand corrosive slags and gases and have high refractoriness. The magnesite-chromite products are suitable for service at the highest temperatures and in contact with the most basic slags used in steel melting. Magnesite-chromite usually ahs a better spalling resistance than chrome-magnesite.

Zirconia Refractories

Zirconium dioxide (ZrO_2) is a polymorphic, material. There are certain difficulties in its usage and fabrication as a refractory material. It is essential to stabilize it before application as a refractory. This is achieved by incorporating small quantities of calcium, magnesium and cerium oxide, etc. Its properties depend mainly on the degree of stabilization and quantity of stabilizer as well as the quality of the original raw material. Zirconia refractories have a very high strength at room temperature which is maintained upto temperatures as high as 1500 °C. They are, therefore, useful as high temperature constructional materials for furnaces and kilns. The thermal conductivity, of zirconium dioxide is found to be much lower than that of most other refractories and the material is therefore used as a high temperature insulating refractory.

Since Zirconia exhibits very low thermal losses and does not react readily with liquid metals, it is particularly useful for making refractory crucibles and other vessels for metallurgical purposes. Zirconia is a useful refractory material for glass furnaces primarily since it is not easily wetted by molten glasses and because of its low reaction with them.

Oxide Refractories (Alumina)

Alumina refractory materials which consist of aluminium oxide with little traces of impurities are often known as pure alumina. Alumina is one of the most chemically stable oxides known. It is mechanically very strong, insoluble in water and super heated steam, and in most inorganic acids and alkalies. Its properties make it suitable for the shaping of crucibles for fusing sodium carbonate, sodium hydroxide and sodium peroxide. It has a high resistance in oxidizing and reducing atmosphere. Alumina is extensively used in heat processing industries. Highly porous alumina is used for lining furnaces operating up to 1850 °C.

Monolithics

Monolithic refractories (single piece cast in the shape of equipment such as one for a ladle shown in Figure 5.7) are replacing the conventional type fired refractories at a much faster rate in many applications including those of industrial furnaces. The main advantages being:

- It eliminates joints which is an inherent weakness
- Method of application is faster and skilled measures in large number are not required
- Transportation and handling are simple
- Offers better scope to reduce downtime for repairs
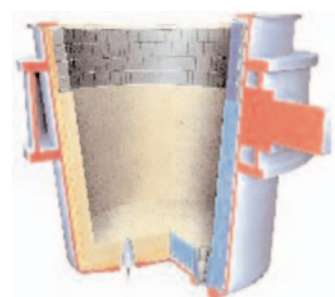
Figure 5.7 Monolithic Lining for a Ladle

- Offers considerable scope to reduce inventory and eliminate special shapes
- It is a heat saver
- Has better spalling resistance
- Has greater volume stability

Various means are employed in the placement of monolithics like ramming, casting, gunniting, spraying, sand slinging, etc. Ramming masses are used mostly in cold applications where proper consolidation of the material is important. The same practice can be adopted with both air setting and heat setting materials. Proper ramming tools need to be selected.

Castables by name implies a material of hydraulic setting in nature. Calcium aluminate cement being the binder, it will have to be stored properly to prevent moisture absorption. Further its strength starts deteriorating after a period of 6 to 12 months.

Insulating Materials

Insulating materials greatly reduce the heat losses through walls. Insulation is effected by providing a layer of material having a low heat conductivity between the internal hot surface of a furnace and the external surface, thus causing the temperature of the external surface reduced.

The insulating materials may be classified into the following groups:
- Insulating bricks
- Insulating Castables
- Ceramic fibre
- Calcium silicate
- Ceramic coating

Insulating materials owe their low conductivity to their pores while their heat capacity depends on the bulk density and specific heat. Structure of air insulating material consists of minute pores filled with air which have in themselves very low thermal conductivity, excessive heat affects all insulation material adversely, but the temperatures to which the various materials can be heated before this adverse effect occurs differ widely. Clearly, therefore, the choice of an insulating material must depend upon its effectiveness to resist heat conductivity and upon the temperature that it will withstand.

One of the most widely used insulating materials is diatomite, also known as kiesel guhr which is made up of a mass of skeletons of minute aquatic plants deposited thousands of years ago on the beds of seas and lakes. Chemically this consists of silica contaminated with clay and organic matter. A wide range of insulating refractories with wide combinations of properties are now available.

The important physical properties of some insulating refractories are shown in the Table 5.7.

TABLE 5.7 PHYSICAL PROPERTIES OF INSULATING REFRACTORIES					
Type	Thermal conductivity at 400 °C	Max. safe temperature °C	Cold Crushing Strength Kg/cm²	Porosity %	Bulk density Kg/m³
Diatomite Solid Grade	0.025	1000	270	52	1090
Diatomite Porous Grade	0.014	800	110	77	540
Clay	0.030	1500	260	68	560
High Aluminia	0.028	1500–1600	300	66	910
Silica	0.040	1400	400	65	830

Castables and Concretes

Monolithic linings and furnace sections can be built up by casting refractory insulating concretes, and by stamping into place certain light weight aggregates suitably bonded. Other applications include the formation of the bases of tunnel kiln cars used in the ceramic industry. The ingredients are similar to those used for making piece refractories, except that concretes contain some kind of cement, either Portland or a high-alumina cement.

Ceramic Fibre

Ceramic fibre is a low thermal mass insulation material, which has revolutionalised the furnace design lining systems.

Ceramic fibre is an alumino silicate material manufactured by blending and melting alumina and silica at temperature of 1800 - 2000 °C and breaking the molten stream by blowing compressed air or dropping the melt on spinning disc to form loose or bulk ceramic fibre. The bulk fibre is converted to various products including blanket, strips, veneering and anchored modules, paper, vacuum formed boards and shapes, rope, wet felt, mastic cement etc. for insulation applications.

Figure 5.8 Ceramic Fibre Insulation

Fibres are usually produced in two temperature grades based on Al_2O_3 content. A recent addition is ZrO_2 added alumino silicate fibre, which helps to reduce shrinkage levels thereby rating the fibre for higher temperatures. Continuous recommended operating temperature for fibres are given in the following Table 5.8:
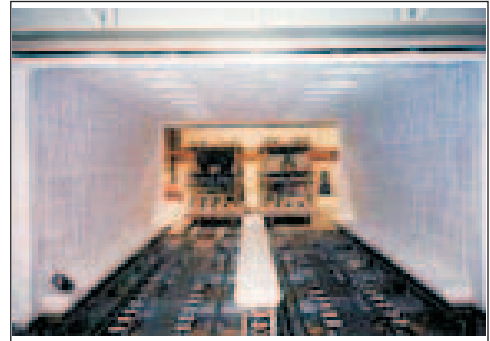
TABLE 5.8 CONTINUOUS RECOMMENDED OPERATING TEMPERATURE FOR FIBRES			
	Al_2O_3	SiO_2	ZrO_2
1150 °C	43 – 47%	53 – 57%	–
1250 °C	52 – 56%	44 – 48%	–
1325 °C	33 – 35%	47 – 50%	17 – 20%

These fibres are generally produced in bulk wool form and needled into blanket mass of various densities ranging from 64 to 190 kg/m^3. Converted products and over 40 different forms are made from blankets to suit various requirements.

Important Properties of Ceramic Fibre

The characteristics of ceramic fibres 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/m^3 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 fibre is better than calcium silicate product.

2.   Light Weight
Average density of ceramic fibre 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 fibre linings absorb less heat because of lower density. Furnace can be heated and cooled at faster rates. Typically the heat stored in a ceramic fibre lining system is in the range of 2700 - 4050 kCal/m^2 (1000 - 1500 Btu/Ft^2) as compared to 54200-493900 kCal/m^2 (20000 - 250000 Btu/Ft^2) for conventionally lined system.

4.   Thermal Shock Resistant
Ceramic fibre 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 fibre resist most of the chemical attack and is unaffected by hydrocarbons, water and steam present in flue gases.

6.   Mechanical Resilience
This property permits fibre 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 standardised. Fibre 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 5.9 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.
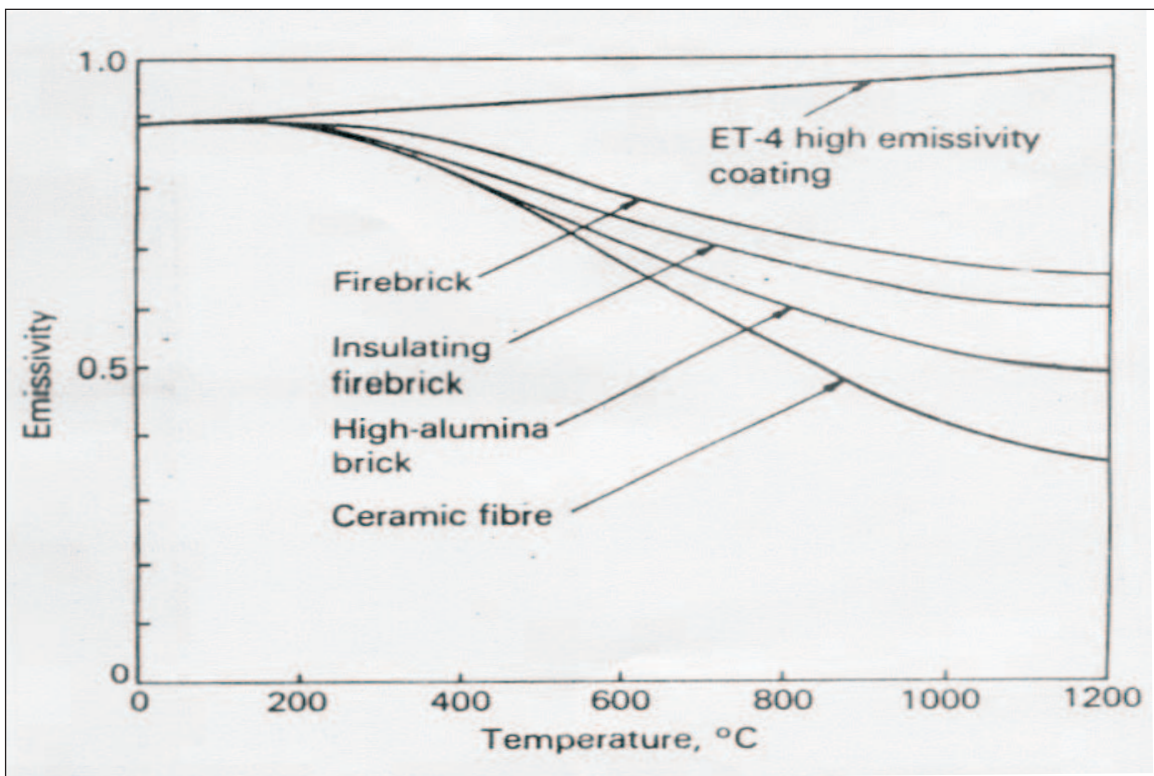

Figure 5.9 Emissivity of Refractory Materials at Different Temperatures

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.

5.10 Selection of Refractories

The selection of refractories for any particular application is made with a view to achieve the best performance of the equipment furnace, kiln or boiler and depends on their properties. Further, the choice of a refractory material for a given application will be determined by the type of furnace or heating unit and the prevailing conditions e.g. the gaseous atmosphere, the presence of slags, the type of metal charge etc. It is, therefore, clear that temperature is by no means the only criterion for selection of refractories.

Any furnace designer or industry should have a clear idea about the service conditions which the refractory is required to face. The furnace manufacturers or users have to consider the following points, before selecting a refractory.

i)   Area of application.
ii) Working temperatures.
iii) Extent of abrasion and impact.
iv) Structural load of the furnace.
v)   Stress due to temperature gradient in the structures and temperature fluctuations.
vi) Chemical compatibility to the furnace environment.
vii) Heat transfer and fuel conservation
viii) Cost considerations.

It is therefore, essential to have an objective evaluation of the above conditions. A proper assessment of the desired properties would provide guidelines for selection of the proper refractory materials.

It would be important to mention here that the furnace manufacturer or a user is also concerned with the conservation of energy. Fuel can be saved in two ways: either by insulation or by faster working. Both these methods give low energy cost per tonne of product.

5.11 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 intermittently.

Different materials have different radiation power (emissivity). The emissivity of walls coated with aluminium paint is lower than that of bricks. Fig. 5.10(A) shows the coefficient of heat dissipation for the following conditions:
a)   rough vertical plane surface.
b)   Vertical aluminium painted walls

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

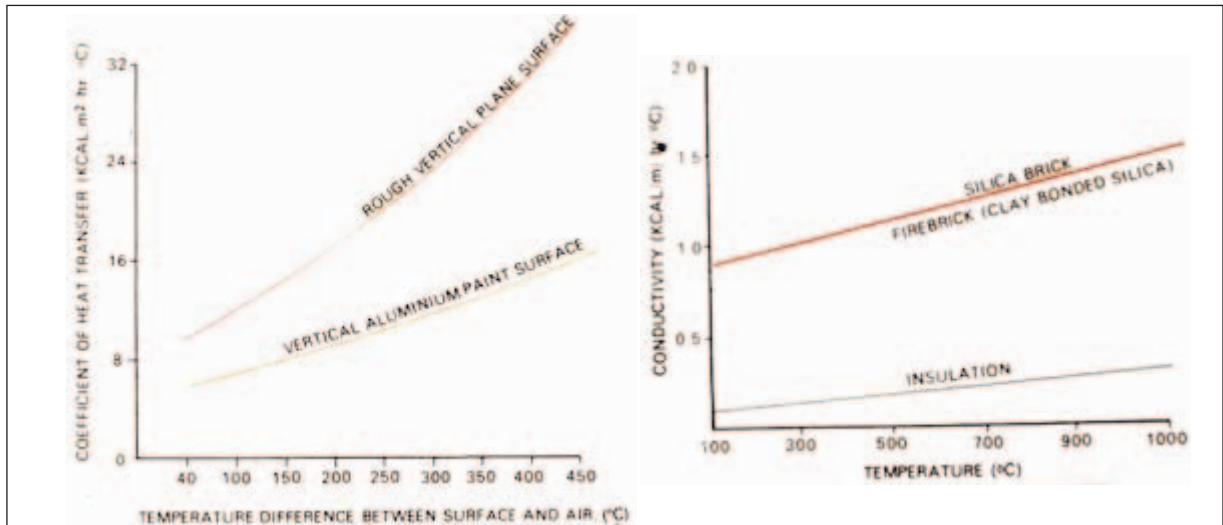temperature of 600 °C, conductivity of the insulation brick is only 20 per cent of that for fireclay brick.

Figure 5.10 (A) Coefficient of Heat Transfer for Different Conditions in Still Air at 40 °C

Figure 5.10 (B) Average Conductivity of Refractory Material

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, because the lost heat is at least in part again imparted to the refractories during the next 'on' period, thus expending fuel to generate the heat. If a furnace is operated 24 hr. every third day, 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 per cent 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 fibre 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 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. Robust 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.

	QUESTIONS
1.	A thermal insulator has (a) low thermal conductivity (b) high thermal conductivity (c) high convection co-efficient (d) low convection co-efficient
2.	What are the benefits of insulation other than heat loss / heat gain?
3.	Give examples of materials for medium temperature insulations.
4.	Give examples of materials for high temperature insulations.
5.	State the advantages of moulded insulations.
6.	Explain the term economic thickness of insulation.
7.	Of the following which are the property is most important for an insulating brick (a) Porosity (b) Mechanical strength (c) Chemical property (d) Compact strength
8.	What are castables ?
9.	Explain briefly how ceramic fibre is made.
10.	Which of the following when added to alumino silicate helps to reduce the shrinkage level of ceramic fibre (a) $Zr O_2$ (b) SiO_2 (c) Al_2O_3 (d) $CaSO_4$
11.	The term blanket refers to (a) Ceramic fibre (b) Refractory brick (c) Insulating brick (d) Castables
12.	Explain the advantages of ceramic fibre with respective properties.
13.	Find out from the figure given in this chapter, the emissivity at 1000 °C for the following: (a) fire brick (b) high alumina brick (c) ceramic fibre (d) high emissivity coatings
14.	Name the three classifications of refractories on the basis of chemical composition.
15.	The most common refractory used in furnaces is (a) fire brick (b) zirconia brick (c) magnesite brick (d) silica brick
16.	State briefly the criteria of selection of refractories.

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