**Unit 7 Insulations and Refractories**

**Objectives:** At the end of this chapter the reader would be able to describe what insulation is, what are its types and where different types of insulations are used. The reader would also be able to describe the R value of insulation, the optimum thickness of insulation. A step by step procedure used to calculate the optimum thickness of insulation is also described.

The chapter also aims to give an introduction to different types of refractories used in industries along their properties. A discussion on heat losses from furnace walls is also included at the end of the chapter.

**Pre-requisites:** Understanding of basic thermodynamic and heat transfer principles, basic understanding of material properties, basics of inorganic and physical chemistry.

**7.1 Purpose of insulations, Types and applications**

*Thermal Insulations*are basically materials used to reduce the heat flow to and from a body. As such insulations are made of low thermal conductivity materials, and they involve air pockets. Air is used because it is one of the least thermally conductive materials. *Mineral Wool, Styrofoam, Clay, etc.* are common examples of insulators. The main driving force for heat flow is the temperature difference. Greater the temperature difference greater is the heat flow. To prevent the heat flow we have to put some barriers in the path of flow. These barriers used to prevent the flow of heat are known as thermal insulators.

One interesting fact about insulations is that they pay for itselffrom the energy it saves. Insulation involves one time capital investment but the savings generated are long term. The insulation payback period is generally less than one year i.e. the savings insulation generates in the first year itself is usually greater than its initial material and installation costs. Proper insulation results in reduced primary energy consumption and as a result helps in reducing pollution and emission of greenhouse gases.

Insulation also helps in saving energy by reducing heat loss from cold surfacessuch as chilled water lines, cryogenic storage tanks, refrigerated trucks, and air-conditioning ducts. If a cold canned drink is wrapped in a blanket it stays colder much longer. A refrigerator with well-insulated walls will consume much less electricity than a similar refrigerator with little or no insulation. Insulation plays a major role in air-conditioning. Proper insulation helps in lowering the air-conditioning load.

Insulations are extensively used for

* Energy Conservation
* Personal Protection and Comfort
* Maintaining Process Temperature
* Reducing Temperature Variation and Fluctuations
* Condensation and Corrosion Prevention
* Fire Protection
* Freezing Protection
* Reducing Noise and Vibration
* Design of energy efficient buildings

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 superheated 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.

Some commercially used insulation materials, their area of application and operating temperature ranges are summarised in table 7.1 below.

Table 7.1 Insulations and their properties[[1]](#footnote-1)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Sl. No.** | **Type** | **Name of Insulation Material** | **Temperature** | **Areas of application** | **Remarks** |
| 1 | Organic foam | Polystyrene foam | Upto and not more than +75°C | Roofing, cold storage, refrigerated transport | Non-toxic & non-irritant. Resistant to water penetration, low cost (i.e. lower than mineral wools) |
| 2 | Organic | PUR (mixture of agents and additives) | (-)185°C to +110°C |  | Very low thermal conductivity. Slightly more expensive but installation costs are much lower |
| 3 | Organic foam | PIR | (-)185°C to +140°C | Petrochemical equipment, buildings, refrigerated vehicles, tankers and ducting | More expensive, better fire performance |
| 4 | Organic foam | Phenolic foam | (-)180°C to +120°C | Air conditioning ducting, dry lining, sandwich panels insulation | Very low thermal conductivity. Does not melt when exposed to flame. |
| 5 | Organic foam | ENR | limit around +150°C | Industrial H&V, domestic heating and plumbing. | More expensive than mineral wools but is normally used in thinner layer |
| 6 | Organic foam | Polyethylene foam | Limit around +100°C | Domestic heating and plumbing | Unsuitable for process plant |
| 7 | Inorganic material | Calcium silicate | 37.8°C to 648.9°C | Back up insulation in the refractory industry, boilers, ducting and process pipe work | More expensive than mineral wool |
| 8 | Inorganic material | Cellular glass | (-)267.8°C to 482.2°C | Process plant application and wide range of building application. | Resistant to water vapour, high compressive strength and good chemical resistance. Non-combustible. High production cost. |
| 9 | Inorganic material | Microporous silica | 400°C to 1000°C | Refractory industry, aerospace and process plant | Its structure can be designed to prevent the passage of infra-red radiation. Low thermal conductivity. Higher cost than mineral wool. |
| 10 | Inorganic material | Ceramic fibre | Upto 1600°C | It can be used in application where rapid heating is followed by immediately by rapid cooling. Refractory industries | Low density and good resistance to thermal shock. Its cost is considerably higher than that of mineral wool. |
| 11 | Inorganic material | Expanded vermiculate | Upto 1000°C | Cementitious binders to produce sprays or boards as a fire protection product | Naturally occurring material, light weight, granular material, inert and high melting point. |
| 12 | Inorganic material | Perlite | Upto 650°C | It is often used as a form of loose fill insulation | Naturally occurring material, Cheaper than mineral wool |

**7.2 Calculation of insulation Thickness; Economic thickness of insulations**

**The R-value of Insulation**

The ***R*-value** gives the effectiveness of insulation materials. It is basically the *thermal resistance* of the material *per unit surface area.* For *flat insulation* the *R-*value is obtained by simply dividing the thickness of the insulation by its thermal conductivity i.e.

----------(7.1)

where *L* is the thickness and *k* is the thermal conductivity of the material.

For *pipe insulation,* the *R-*value is determined using relation 7.2 below

----------(7.2)

the thermal resistance relation from where *r1* is the inside radius of insulation and *r2* is the outside radius of insulation. Once the *R-*value is available, the rate of heat transfer through the insulation can be determined from relation 7.3

----------(7.3)

where Δ*T* is the temperature difference across the insulation and Area is the outer surface area for the cylinder.

**Optimum Thickness of Insulation**

It is observed that more the thickness of insulation less is the thermal energy loss. But as we go on increasing the thickness of the insulation the cost also increases. So a balance has to be maintained in order to minimise the combined cost of insulation and heat lost. The thickness of the insulation so chosen is known as the optimum thickness of insulation. Figure 7.1 shows the simplest method of determination of optimum thickness of insulation.

It is noticed heat loss decreases exponentially while the cost of insulation increases roughly linearly. It is also observed that the total cost (insulation cost + lost heat cost), decreases first, reaches a minimum, and then increases. The thickness which corresponds to the minimum total cost is the optimum thickness of insulation.

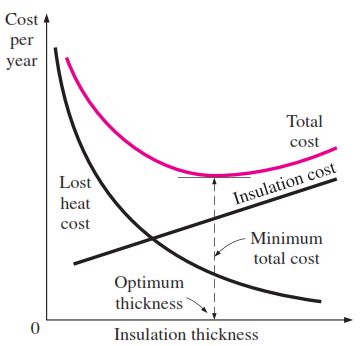


Figure 7.1 Optimum Thickness of Insulation[[2]](#footnote-2)

A more holistic approach for determination of the optimum thickness of insulation involves the consideration of the following factors

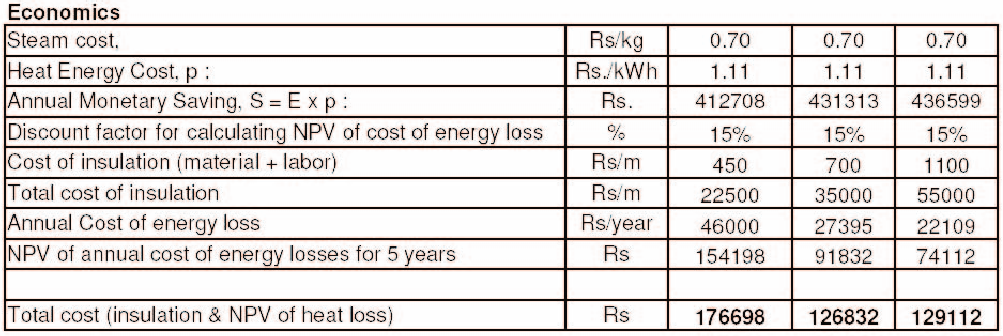
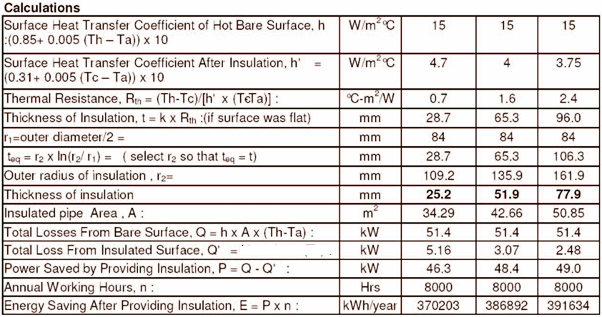
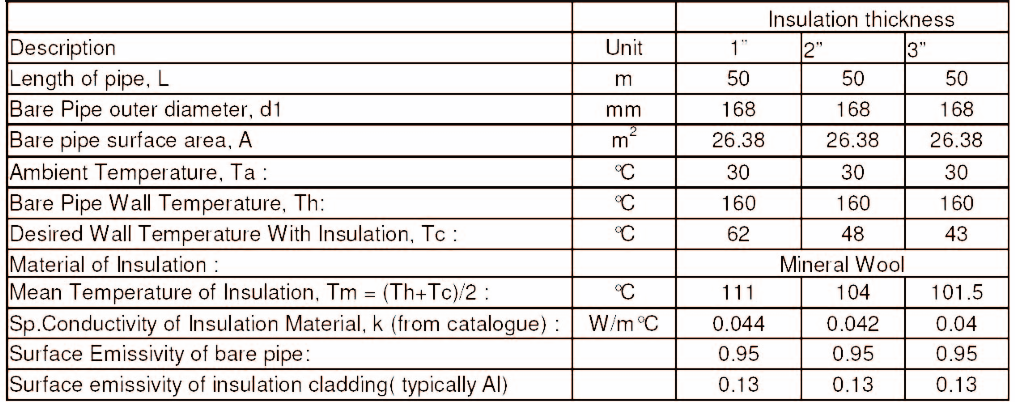
* Cost of fuel
* Annual hours of operation
* Heat content of fuel
* Boiler efficiency
* Operating surface temperature
* Pipe diameter/thickness of surface
* Estimated cost of insulation.
* Average exposure ambient still air temperature

**Procedure for Calculating Economic Thickness of Insulation[[3]](#footnote-3)**

To explain the concept of economic thickness of insulation, we will use an example. (Refer Table 7.2) Consider an 8 bar steam pipeline of 6" diameter 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/m2 °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 7.2 Calculation of Economic Thickness of Insulation



Hence economic thickness of insulation = 2”

**7.3 Types and properties of refractories; Industrial use of refractories**

A refractory material is one that retains its strength at high temperatures. ASTM C71 defines refractories as "non-metallic materials having those chemical and physical properties that make them applicable for structures, or as components of systems, that are exposed to environments above 1,000 °F (811 K; 538 °C)"[[4]](#footnote-4).

Refractory materials are used in linings for furnaces, kilns, incinerators and reactors. They are also used to make crucibles. Refractories can be classified on the basis of chemical composition, end use and methods of manufacture as shown in table 7.3.

**Table 7.3: Classification of refractories based on chemical composition (Adapted from Gilchrist)**

|  |  |
| --- | --- |
| **Classification method** | **Examples** |
| ***Chemical composition*** | |
| ACID, which readily combines  with bases | Silica, Semisilica, Aluminosilicate |
| BASIC, which consists mainly of  metallic oxides that resist the action of bases | Magnesite, Chrome-magnesite, Magnesite-chromite,  Dolomite |
| NEUTRAL, which does not  combine with acids nor bases | Fireclay bricks, Chrome, Pure Alumina |
| Special | Carbon, Silicon Carbide, Zirconia |
| ***End use*** | Blast furnace casting pit |
| ***Method of manufacture*** | Dry press process, fused cast, hand moulded, formed normal,  fired or chemically bonded, unformed (monolithics, plastics, ramming mass, gunning castable, spraying) |

**Some important properties of refractories**

**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.

**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 are 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. 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.

**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:

1. The changes in the allotropic forms which cause a change in specific gravity.
2. A chemical reaction which produces a new material of altered specific gravity.
3. The formation of liquid phase.
4. Sintering reactions.
5. 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.

Some commonly used refractory materials; their properties and application are discussed in the following section.

**Fireclay Bricks**

The most commonly used refractory material is the fireclay brick. It is used extensively in industries such as iron and steel, glass, pottery kilns, cement and many others.

Fireclay refractories, such as firebricks, siliceous fireclays and aluminous clay refractories consist of aluminium silicates with varying silica (SiO2) content of up to 78% and Al2O3 content of up to 44%. Table 7.4 shows that the melting point (PCE) of fireclay brick decreases with increasing impurity and decreasing Al2O3. Fireclay brick finds wide application in furnaces, kilns and stoves because of its availability and cost effectiveness.

**Table 7.4. Properties of typical fireclay bricks[[5]](#footnote-5)**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Brick type** | **Percentage SiO**2 | **Percentage Al**2**O**3 | **Percentage of other constituents** | **PCE (oC)** |
| 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 |
| High Duty (Siliceous) | 65-80 | 18-30 | 3-8 | 1620-1680 |
| Low Duty | 60-70 | 23-33 | 6-10 | 1520-1595 |

**High alumina refractories**

High alumina refractories contain more than 45% alumina. The alumina concentration varies from 45% to 100%. As the alumina percentage increases the refractoriness also increases. High alumina refractories find extensive application in 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 is a type of refractory brick formed of at least 90% silica cemented with, for example, slurried lime. Silica bricks are used extensively in the iron and steel melting furnaces and the glass industry. These bricks are characterised by high fusion point, high resistance to thermal shock (spalling) and high refractoriness. Until its fusion point is approached, silica brick does not begin to soften even under high loads. Other important characteristics are flux and stag resistance, volume stability and high spalling resistance.

**Magnesite**

Magnesite refractories are made from naturally occurring magnesite (MgCO3) containing at least 85% magnesium oxide. The concentration of silicate bond at the operating temperatures dictates the properties of the magnesite refractories. Magnesite refractories of good quality have a CaO-SiO2 ratio of less than two with a minimum ferrite concentration.

Chrome-magnesite refractories usually contain 15-35% Cr2O3 and 42-50% MgO and are made in a wide range of qualities. They are used for building the critical parts of high temperature furnaces as they can withstand corrosion and have high refractoriness.

Magnesite-chromite refractories contain at least 60% MgO and 8-18% Cr2O3 and have a better spalling resistance than chrome-magnesite. They are extensively used in the steel industry because of their usability at high temperatures and ability to withstand the most basic slags.

**Zirconia refractories**

Zirconia refractories basically contains Zirconium dioxide (ZrO2. Zirconium dioxide is a polymorphic material and as such it to be stabilised before its application as a refractory, which is achieved by incorporating small quantities of calcium, magnesium and cerium oxide, etc. Degree of stabilization, quantity of stabilizer and quality of the original raw material determines the properties of the refractory. Zirconia refractories maintain their strength at temperatures as high as 15000C. Zirconia refractories are used as a high temperature insulating refractory because their thermal conductivity is much lower than other refractory materials. Zirconia is extensively used in making refractory crucibles and other vessels for metallurgical purposes as it exhibits very low thermal losses and does not react readily with liquid metals.

**Oxide refractories (Alumina)**

Alumina mainly consists of aluminium oxide with little traces of impurities. Alumina is characterised by its high chemical stability, high mechanical strength, insolubility in water, superheated steam and most inorganic acids and alkalies. These properties make it suitable for the shaping of crucibles for fusing sodium carbonate, sodium hydroxide and sodium peroxide. Alumina is extensively used in heat processing industries. Highly porous alumina is used for lining furnaces operating at up to 1850oC.

**Monolithics**

Monolithic refractories as the name suggests are single piece casts in the desired shape. Monolithics are now being used in place of conventional refractories because of their inherent advantages as listed below:

* Elimination of joints which is an inherent weakness
* Faster application method
* Special skill for installation not required
* Ease of transportation and handling
* Better scope to reduce downtime for repairs
* Considerable scope to reduce inventory and eliminate special shapes
* Heat savings
* Better spalling resistance
* Greater volume stability

**7.4 Heat losses from furnace walls**

Furnaces being high temperature equipment there is heat loss from their walls. If these wall heat losses are successfully contained then a substantial amount of primary fuel can be saved which in turn will lead to economic stability. The extent of wall losses depends on the emissivity of walls; conductivity of refractories; wall thickness and whether the furnace or kiln is being operated continuously or intermittently.

Emissivity depends upon the type of the material and its shape. It is observed that the emissivity of a wall coated with aluminium has a lower conductivity than bricks.

Thermal conductivity of refractory materials depends upon the temperature. Thus for different temperature applications different types of bricks are used. It is observed that at a mean temperature of 600 °C, conductivity of the insulation brick is only 20 per cent of that for fireclay brick.

As discussed earlier, 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 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 for 8 hours daily, 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 built 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.

Thus, it may summarised that the heat losses from walls depends upon the inside temperature, outside air temperature, outside air velocity, configuration of walls, emissivity of walls, thickness of walls and conductivity of walls.

The following observations are made regarding heat losses from walls of furnaces and kilns[[6]](#footnote-6).

* 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.

**Self-Assessment Exercise**

**Q1.** What do you understand by the R-value of insulation?

**Q2.** Why is it necessary to calculate the economic thickness of insulation? Explain briefly how the economic thickness of insulation can be calculated.

**Q3.** How refractories differ from insulations? Explain how refractories are categorised?

**Q4.** Explain how heat losses from furnace walls can be minimised?

1. . Sethuraman C., *Proper Selection of Insulating Material is an Art*, CSIO [↑](#footnote-ref-1)
2. . Cengel, Y. A., *Thermodynamics: An Engineering Approach*, 5th Edition, Tata McGraw Hill [↑](#footnote-ref-2)
3. . This section has been adapted from *Bureau of Energy Efficiency Guide Books*, Chapter: Insulation and Refractories. [↑](#footnote-ref-3)
4. . ASTM Volume 15.01 *Refractories; Activated Carbon, Advanced Ceramics* [↑](#footnote-ref-4)
5. . *Bureau of Energy Efficiency Guide Books*, Chapter: Insulation and Refractories. [↑](#footnote-ref-5)
6. . *Bureau of Energy Efficiency Guide Books*, Chapter: Insulation and Refractories. [↑](#footnote-ref-6)