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Thermal Insulation and Refractory Material

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Thermal Insulation and refractory material

Sonal Desai, Ph.D.

COURSE CONTENT

Introduction

Insulation is defined as a material or combination of materials, which retards the flow of heat. The materials can be of any size, shape or surface. Thermal insulations are materials that insulate the components of mechanical systems in commercial buildings and industrial processes.

In buildings, insulations are installed to improve the energy consumption of the buildings' cooling and heating systems, domestic hot and chilled water supply, and refrigerated systems including ducts and housings.

For industrial facilities, such as power plants, refineries, and paper mills, thermal insulations are installed to control heat gain or heat loss on process piping and equipment, steam and condensate distribution systems, boilers, smoke stacks, bag houses and precipitators, storage tanks etc.

More about Insulation

Thermal insulations are one or more materials providing resistance to heat flow and thereby prevent heat loss. Most insulating materials have low thermal conductivity, air pockets and are heterogeneous. Temperature difference creates heat transfer between two different temperature bodies for an example steam pipe exposed to atmosphere or liquid nitrogen tank in ambient air. To slow down heat transfer between two bodies “barrier” in a form of thermal insulation is required.

As the insulation reduces heat loss and thus saves fuel or energy invested in the process and thus it pays for itself in due course of time. For most of the applications payback period is less than two years and in major cases it is less than few months, hence applying thermal insulation is first and foremost energy conservation measure taken up by an engineer.

Role of thermal insulations

1. Energy saving: First reason to apply insulation on hot body or a cold body is to conserve energy. Properly insulated systems will immediately reduce the need for energy. Benefits to industry include enormous cost savings, improved productivity, and enhanced environmental quality.
2. Reduces Emission: Due to reduced need of energy, CO_2 and NO_x production from power plant reduces.
3. Protection: Too hot or too cold surfaces are dangerous to people who are working in nearby area. According to safety standards, the hot surfaces temperature should be less than 60ºC. Thermal insulation is one of the most effective means of protecting workers from second and third degree burns resulting from skin contact for more than **5** seconds with surfaces of hot piping and equipment.
4. Maintains process temperature: It is necessary to maintain exact temperature in certain temperature sensitive process, which is achieved by proper insulation. By reducing heat loss or gain, insulation can help to maintain process temperature to a pre-determined value or within a predetermined range. The insulation thickness must be sufficient to limit the heat transfer in a dynamic system or limit the temperature change with time in a static system.
5. Minimize temperature variation and fluctuation: If not insulated, temperature may vary between mid section and ends and also affected by temperature of surroundings.
6. Prevents condensation: If the surface temperature is less than dew point temperature, moisture from surrounding air will condense on the surface, which may promote algae growth and corrosion.
7. Fire protection: Keeping the temperature in lower and safer zone reduces fire hazards.
8. Freezing protection: In low ambient, water / fluid may freeze, this can slow down by providing proper insulation.
9. Reduced level of vibration and noise: Insulation helps to damp vibration as well as noise.

Heat transfer mechanism in thermal insulation

Conduction, convection and radiation are three modes of heat transfer and due to them heat loss occurs from high temperature body to low temperature body. Thermal insulations are designed to reduce heat transfer by all three modes. Efficiency of thermal insulation is measured by physical property, known as thermal conductivity. Following section describes basic modes of heat transfer and thermal conductivity.

1 Conduction

Conduction is the mode of energy transfer from more energetic particle of a substance to the less energetic one, as a result of interaction between the particles. It may take place in solids, liquids or gases. As conduction is due to collisions and diffusion of the molecules during their random movement, it is less significant in liquids and gases. In solids conduction is due to combined effect of lattice vibration and movement of free electrons. Mathematically it is represented by Fourier's law of heat conduction, given in equation 1.

$$\dot{Q} = -k\,A\,\frac{dT}{dx}$$

where *dT/dx* represents temperature gradient,
k stands for thermal conductivity in W/m ºC
and *A* stands for area perpendicular to the direction of heat transfer in m^2.

2 Convection

Convection is the mode of energy transfer between a solid surface and adjacent fluid or energy transfer among the fluid. It includes heat transfer due to conduction and fluid motion. More is the fluid motion, higher is the convection. If fluid motion is by external means such as pump, fan or blower, it is known as forced convection and in contrast, if the fluid motion is due to buoyancy force which is induced due to density difference then it is known as free convection. In some typical applications like condenser, evaporator etc convection also involves phase change process. Mathematically, connection is expressed by Newton's law of cooling as given in equation 2.

$$\dot{Q} = h\,A\,(T_s - T_\infty)$$

where *h* represents convection heat transfer coefficient in W/ m^2 ºC and decided by many parameters like surface geometry, fluid motion, properties of fluid etc and $(T_s - T_\infty)$ is temperature difference.
A stands for surface area in m^2 through which convection takes place.

3 Radiation

Radiation is energy emitted by high temperature body in form of electromagnetic waves. Conduction and convection requires medium to transfer heat but radiation does not require any intermediate medium, in contrast radiation will be faster in absence of medium (vacuum). Radiation is considered as surface phenomenon and quality of surface (black, white, transparent, opaque etc.) decides quantum of radiation. Radiation heat exchange between two surfaces at different temperature is given mathematically as per Stefan-Boltzman's law (equation 3). It is important to note here that heat transfer by conduction and convection depends upon temperature difference *(ΔT)* while radiation heat transfer depends upon fourth power of temperature difference $(Ts^4 - T\infty^4)$ and hence at higher temperature level, heat transfer by radiation is prominent than conduction and convection.

$$\dot{Q} = \varepsilon \sigma A \left(T_s^4 - T_\infty^4\right)$$

where ε is emissivity of the surface. (1 for blackbody)
A is surface area in m2
and Stefan-Boltzman's constant ε is 5.67 *10-8 W/m^2 K^4

4 Properties of Insulation material

Material	Thermal conductivity W/m°C
Silver	429
Copper	401
Aluminium	237
Iron	80.2
Mercury	8.54
Glass	0.78
Brick	0.72
Water	0.613
Wood	0.17
Soft rubber	0.13
Glass fibre	0.043
Air	0.026
Urethane foam	0.026

Table 1 Thermal conductivity values of some common material

Thermal conductivity

Thermal conductivity is rate of heat transfer through a unit thickness of the material per unit area per unit temperature difference (W/m°C). It is a measure of heat transfer rate. High thermal conductivity indicates that the material is good conductor of heat and low conductivity indicates material is poor conductor of heat i.e. insulator. Thermal conductivity of some common materials is given in table 1. Normally good thermal conductors are also good electric conductors e.g. silver, copper etc and similarly poor thermal conductors are poor electric conductors e.g. rubber, wood etc.

When we talk about heat transfer in insulation material, it is through conduction in solid thermal insulators and from the surface of insulators it is by combination of convection and radiation. Materials having high density are good thermal conductors and those with low density have voids containing air or gas, which restricts heat transfer by conduction. The gap in voids is too small for convection or radiation heat transfer but at elevated temperature heat transfer by radiation and convection is not small and hence for high temperature applications, insulation material of high density are used. General properties of insulating material are tabulated in table 2.

R value of insulation

Some manufacturers provide the data of different insulating materials as its R value which is thermal resistance of the material per unit surface area.

$$R\ value\ for\ flat\ surface = L/k$$

where L is thickness and k is thermal conductivity

$$R\ value\ for\ pipe = \frac{r_2}{k}\ln\frac{r_2}{r_1}$$

where r1 and r2 are inside and outside radius of insulation

Once R value of insulating material is known, heat transfer rate through insulating material can be determined by following equation

$$\dot{Q} = \frac{\Delta T}{R\ value} \times area$$

Property of material	Condition required
Thermal Conductivity	As low as possible.
Mechanical Stability	Able to withstand vibration, expansion and contraction.
Durability	Able to withstand extreme operating temperature.
Weight	As less as possible or else additional support is required.
Thickness	As small as possible for compactness.
Water absorption	Water increases thermal conductivity of insulation and reduces its effectiveness hence it should be less.
Effect of chemicals	Able to resist chemicals / fumes used in surrounding environment.
Effect of microbes	Able to resist vermin and fungal growth – specially in food storage and factory applications.
Emissivity	Low surface emittance is required.
Health hazards	It should be asbestos free to reduce danger of inhalation of fine particles.
Fire hazards	The material itself should be non combustible in case of fire prone or smoke involved applications.
Corrosion	In case of wetted insulation (due to leak or internal condensation) the insulation soluble compounds should not promote corrosion.

Table 2 Required properties of insulating material.

R values for some material is given in table 3

Material	R value (m^2 K/ W)
Silica aerogel	1.76
Polyurethane rigid panel	1.3
Urea foam	0.92
Fibreglass rigid panel	0.44

Table 3 R values of common insulating materials

Density

This is the weight of a specific volume of insulation material measured in pounds per cubic foot or kilograms per cubic meter.

Surface Burning Characteristics

These are comparative measurements of flame spread and smoke development with that of select red oak and inorganic cement board. Results of this test may be used as elements of a fire-risk assessment which takes into account all of the factors which are pertinent to an assessment of the fire hazard or fire risk of a particular end use.

Compressive Resistance

This is a measure of the material to resist deformation (reduction in thickness) under a compressive load. It is important when external loads are applied to an insulation installation.

Thermal Expansion/Contraction and Dimensional Stability

Insulation systems are installed under ambient conditions that may differ from service conditions. When the operating conditions are imposed, metal surfaces may expand or contract differently from the insulation and finish applied. This can create openings and parallel heat flow and moisture flow paths that can degrade system performance. Long term satisfactory service requires that the insulating materials, closure materials, facings, coating, and accessories withstand the rigors of temperature,

Water Vapor Permeability

This is the time rate of water vapor transmission through unit area of flat material of unit thickness induced by unit vapor pressure difference between two specific surfaces, under specified temperature and humidity conditions. It is important when insulation systems will be operating with service temperatures below the ambient air. Materials and systems with low water vapor permeability are needed in this service.

Temperature Resistance

Ability of a material to perform its intended function after being subjected to high and low temperatures which the material might be expected to encounter during normal use.

Weather Resistance

Ability of a material to be exposed for prolonged periods of time to the outdoors without significant loss of mechanical properties.

Abuse Resistance

Ability of a material to be exposed for prolonged periods of time to normal physical abuse without significant deformation or punctures.

Corrosion Resistance

Ability of a material to be exposed for prolonged periods of time to a corrosive environment without significant onset of corrosion and the consequential loss of mechanical properties.

Fire Resistance/Endurance

Capability of an insulation assembly exposed for a defined period of exposure to heat and flame (fire) with only a limited and measurable loss of mechanical properties. Fire endurance is not a comparative surface burning characteristic for insulation materials.

Fungal Growth Resistance

Ability of a material to be exposed continuously to damp conditions without the growth of mildew or mould.

Classification of thermal insulation

Different insulating material available in market (both natural and manmade type) is broadly classified as capacitive, reflective and resistive materials and respective examples are bricks, aluminum and mineral wool Out of these mentioned categories we use resistive insulation widely. They have low thermal conductivity and can be grouped as fibrous insulation, cellular insulation, granular insulation and reflective insulation.

Capacitive insulation is named so, because they slow down rate of heat transfer by absorbing and releasing it slowly. It is not practical to use in present applications as they require thick brick work. The only application of capacitive insulation is burying water pipe lines below thick layer of earth where atmospheric low temperature will not freeze the water in colder locations.

Reflective insulation material like aluminum foil is effective thermal insulation to prevent radiation because of high reflectivity, but is not used for conduction and convection heat loss. Their use is limited for evacuated space where conduction and convection heat loss are absent. Multilayer insulators (super insulators) have very low conductivity – as low as 0.0001W/mºC.

1 Fibrous insulation

It consists of small diameter fibers that have air in small gaps. It can be organic if made from wool, cotton, wood, cloth, cane, vegetable fibers etc. or inorganic if made from mineral wool, glass wool and ceramic fibers.
Rock and glass mineral wool is resilient, fibrous, wool like, light weight insulating material. It is made from molten slag, rock or other material by bonding mineral fibers with medium or high temperature binders (organic type).

Rock mineral wool		
Density	60 to 160 kg/m^3	
Thermal conductivity W/mº C		
	Mean temperature	Density 80 kg/m^3
	10	0.033
Service temperature ºC	-200 to 900	
Fire characteristics	Non combustible	
Water vapour transmission	Non permeable	
Compressive strength	10.5 kN/m^2 for 80 kg/m^3 density	
Shapes available	Loose fill, mats, pipe section, rolls, slabs	
Thickness available	20 to 120 mm	
Applicaitons	Used as a thermal and acoustic insulation and fire protection of plant, equipment, marine, offshore, HVAC, Industry, commercial, domestic sectors	

Table 4 Properties of rock mineral wool

They are available in loose blanket, board, pipe section and molded shapes. They are more heat resistance and hence used for high temperature applications, however in mineral fiber, the length of fiber is shorter than glass fibers and hence, they do not retain properties well after burnout. Ceramic fiber have alumina-silica compound and hence can be used at very high temperature range. Properties of Rock mineral wool, Glass mineral wool and ceramic fibers are listed in table 4 to 6 respectively.

Ceramic fiber is blown alumina silica made from different types of high purity alumina and silica. As the fiber is non crystalline, hence can be formed in any shape. It can withstand high operating temperatures. It is suitable for applications having cyclic heating and cooling. Its cost is higher than mineral wool.

Glass Mineral Wool			
Density	10 to 80 kg/m^3		
Thermal conductivity W/mº C			
	Mean temperature ºC	Density 48 kg/m^3	Density 80 kg/m^3
	-20	0.028	0.028
	10	0.030	0.031
	20	0.032	0.032
	50	0.035	0.035
	100	0.044	0.042
Service temperature ºC	-200 to 450		
Fire characteristics	Non combustible		
Water vapour transmission	Non permeable		
Compressive strength	1 to 8 kN/m^2 at 5 % deformation		
Shapes available	Blown fibre, pipe section, rolls, slabs		
Thickness available	15 to 150 mm		
Applications	Widely used for thermal and acoustic insulation in HVAC applications, transport, shipping, building etc.		

Table 5 Properties of glass mineral wool

Ceramic fibre (blanket)			
Density	64 to 192 kg/m^3		
Thermal conductivity W/mº C			
	Mean temperature ºC	Density 96kg/m^3	Density 128 kg/m^3
	100	0.041	0.03
	300	0.079	0.06
	600	0.14	0.12
	800	0.22	0.18
	1000	0.36	0.28
Maximum temperature ºC	1250		
Fire characteristics	Non combustible		
Water vapour transmission	Permeable		
Compressive strength	2.5kN/m^2 at 10 % deformation		
Shapes available	Logs, sections, slabs		
Thickness available	6 to 50 mm		
Applications	Thermal and acoustic insulation for motor, petrochemical and power generation, fire protection of commercial buildings and offshore structures		

Table 6 Properties of ceramic fibre

2 Cellular insulation

It is made of cellular material like cork, foamed plastic, glass, polystyrene, polyurethane and have cellular like structure. These types of insulating material are very popular as they are impermeable and non combustible. Since it is made of closed cell they are impermeable to moisture and non combustible and can be used for both indoor and outdoor applications. Cellular glass is an alumina silicate glass that contains carbon monoxide or carbon dioxide. It is water vapour resistant and has high compressive strength. Glass being somewhat brittle creates problem in vibration and flexing applications. Properties of cellular glass are listed in table 7.

Cellular glass			
Thermal conductivity W/mº C			
	Mean temperature ºC	Density 120 kg/m^3	Density $135 kg/m^3$
	-100	0.034	-
	0	0.038	0.044
	10	0.04	0.046
	100	0.081	-
Temperature range ºC	-260 to 430		
Fire characteristics	Non combustible		
Water vapour transmission	Non permeable		
Compressive strength	700 kN/m^2		
Shapes available	Board, pipe shells, slabs		
Thickness available	40 to 160 mm		
Applications	Cold storage and marine applications, tank and vessel bases, buildings etc.		

Table 7 Properties of cellular glass

3 Granular insulation

They are made of small nodules of lime, silica and various reinforcing fibers. Generally they do not have organic fibers and hence they are able to maintain physical integrity at high temperature and non combustible. Calcium silicate, vermiculate and perlite (also known as volcanic rock glass) are known granular insulation. Calcium silicate is a dense granular insulation material made of lime and silica. It is reinforced with organic or inorganic fibers and set into molded forms. Calcium silicate has exceptional strength and durability at medium and high temperature applications.

Vermiculite is a natural material with main constituent of magnesium silicate. It is mostly used with cement binders to produce spray and formed as a board, which is popular as fire protection product.

Similarly expanded perlite are made from naturally occurring minerals and are expanded at high temperature to form a structure of tiny air cells surrounded by vitrified products. Properties of calcium silicate, vermiculate and perlite are tabulated in table 8 to 10.

Calcium Silicate		
Thermal conductivity W/mºC		
	Mean Temperature ºC	Thermal Conductivity
	100	0.054
	150	0.058
	200	0.063
	250	0.068
	300	0.074
	350	0.082
Maximum temperature ºC	1000	
Fire characteristics	Non combustible	
Compressive strength	600 kN/m^2 at 1.5% deformation	
Shapes available	Logs, sections, slabs	
Thickness available	25 to 100 mm	
Applications	Steam pipe and vessels, ovens, petrochemical, furnace, general heating process insulation and food processing plants	

Table 8 Properties of calcium silicate

Figure 1 Images of different insulating material

Vermiculite	
Density	50 to 150 kg/m^3
Thermal conductivity	0.067 W/m° C for density of 104 kg/m^3
Service temperature °C	0 to 1300
Fire characteristics	Non combustible
Water vapour transmission	Permeable
Compressive strength	10.5 kN/m^2 for 80 kg/m^3 density
Shapes available	Depends upon type of application
Applications	Loose fill granular insulations are used in loft insulation, steel works, foundries, packing, plasters, building boards etc.

Table 9 Properties of vermiculite

Perlite expanded	
Density	50 to 150 kg/m^3
Thermal conductivity	0.057 W/m° C for density of 80 kg/m^3
Service temperature °C	-250 to 1000
Fire characteristics	Non combustible
Water vapour transmission	Non permeable
Shapes available	Loose fill granular material
Thickness available	25 to 300 mm
Applications	Used as a structural insulation for domestic and commercial buildings. Also used for low temperature applications.

Table 10 Properties of expanded perlite

Different forms of insulation materials available in the market.

Thermal insulations are required in different forms as their end applications are different. Some common forms of insulations available in market are discussed here:

1. Preformed / prefab – Insulating materials are available in different preformed or prefab shapes where its one or more than one surface exactly

fits on application surface. Common prefabs available are board, block, sheet, pipe fitting etc.

2. Materials like magnesia, calcium silicate are also available in plastic compositions which are prepared by mixing with water.

Insulating material	Board	Block	Sheet	Pipe Fitting
Calcium silicate	√	√		√
Cellular glass		√		√
Fibre glass	√		√	√
Mineral wool	√	√	√	√
Polystyrene and polyurethane	√		√	√
Perlite		√		√

Table 11 Shapes available for different insulating material

3. Mineral wool, perlite and vermiculite are available in loose fill form which can be applied on expansion joints.
4. Flexible insulation material is applicable on any shape of applications by wrapping around it. Low density mineral wool, fibre glass are available in flexible form.
5. Some materials like polyurethane are available in foam shapes, which can be mixed with liquid and applied on irregular shapes. It expands and hardens on the applied surface.
6. Asbestos and ceramic fibres are available in rope or cloth form.

COLD INSULATION

Cold insulation are used where operating temperatures are below ambient and where protection is required against heat gain, condensation or freezing. Cold insulation economically and technically plays very important role at low range of temperature. Heat loss of one watt at low range of temperature is equal to heat loss of hundred to thousand watts at room temperature. To prevent heat gain from atmospheric surrounding to cold end of the system, insulating materials, vacuum, radiation shield or combination of these are used depending on lowest temperature of the application. Different cold insulation material are discussed here:

Perlite (loose granular material of volcanic origin) is suitable material for low temperature applications e.g. air separation plant and storage tanks. 80kg/m^3 density Perlite has thermal conductivity of 0.057 W/mK. A Perlite-vacuum and fibre –vacuum are widely used in cryogenic storage and transport vessels. Multilayer insulation is preferably used in liquid hydrogen, liquid helium and liquid nitrogen range of temperatures.

Foam insulation is suitable above 200K and does not require vacuum. It includes polyurethane foam, polyamide foam and foam glass. It prevents heat transfer by conduction and convection due to low density and thermal conductivity. Presence of moisture drastically decreases performance of foam. Thermal cycling and environmental exposure creates crack in foam over a period of time which becomes source of moisture to enter and freeze.

Multilayer insulation or super insulation consists of many Mylar aluminized shields stacked as close as possible and separated by spacers having low thermal conductivity. It works well between 77K to 4K and usually 20 layers/cm are selected.

Selection of insulating material.

Following factors are to be considered while selecting insulation material.

1. Purpose / application : For most of the applications the insulation is applied to save energy but sometimes it may be used for safety, to prevent freezing or condensation, to prevent sound transmission or to control process temperature. Thickness of insulation is decided based on economic thickness and energy saving potential in first case but in other cases it is used as much as possible as it satisfy the requirement.
2. Type of surface: A rigid board type of insulation cannot be used on pipe, thus a type of surface where insulation is to be applied decides type of insulation.
3. Surrounding condition: Insulation material on steam pipe will be different for underground and over ground applications. Thus moisture content of the room, chemical vapour in the vicinity of insulating material, vibrations, strength required are important parameters that decides type of insulation used.
4. Ease of applying / frequent removal : Some application areas are very complex where applying insulation is very difficult and certain applications requires frequent maintenance, hence selection of material is done accordingly.
5. Cost: After narrowing down the choice the next and important criteria to select the insulation material is its cost and availability.

Calculation of insulation thickness

Computer programs are readily available to do calculate the thickness of insulation and basics of these calculations are explained here:

In case of insulation applied on a cylinder pipe, heat transfer through the pipe and insulating material takes place due to conduction and convection. Considering them equation is written for overall heat transfer coefficient as:

$$U = \frac{1}{\frac{D_3}{D_1\ h_i} + \frac{D_3\ \ln\left(\frac{D_2}{D_1}\right)}{2\ k_W} + \frac{D_3\ \ln\left(\frac{D_3}{D_2}\right)}{2\ k_i} + \frac{1}{h_o}}$$

Where D_1, D_2 and D_3 are diameter of pipes, where D_1 represents inner diameter of pipe, D_2 represents outer diameter of pipe and D_3 represents diameter inclusive of insulation thickness,
h_i and h_o stands for inside and outside convective coefficients,
k_w and k_i stands for conductivity of pipe insulation material.

First two parameters in above equation counts for very low value and can be neglected. Hence equation can be used for calculating overall heat transfer coefficient is given as below:

$$U = \frac{1}{\frac{D_3\ \ln\left(\frac{D_3}{D_2}\right)}{2\ k_i} + \frac{1}{h_o}}$$

Heat transfer through unit length of pipe is calculated as per equation

$$\frac{Q}{L} = \pi\ D_3\ \ U\ (T_{in} - T_{out})$$

where T_{in} and T_{out} stands for inside fluid temperature and outside air temperature.

Example: Compare heat loss and calculate annual saving due to application of insulation in following case:

Outer diameter of pipe 4.5” (114.3 mm) and thickness 3.05 mm
Steam is passing through it at 4 bar and 0.0824kg/s flow rate at 144°C

Thermal conductivity of pipe material is 30 W/m ºC
Ambient temperature 25ºC
Inside and outside convection coefficient is 1000 W/m^2 ºC and 10 W/m^2 ºC.
Type of insulation is mineral wool and thermal conductivity is 0.06 W/m ºC
Insulation thickness is 32 mm
Operating hours are 8760 hrs per year

Calculate overall heat transfer coefficient for a bare pipe using following equation

$$U = \frac{1}{\frac{D_2}{D_1 h_i} + \frac{D_2 \ln\left(\frac{D_2}{D_1}\right)}{2 k_w} + \frac{1}{h_o}} = 9.89\ W\ {}^{W}/_{m^2 K}$$

Calculate overall heat transfer coefficient for a pipe with insulation material

$$U = \frac{1}{\frac{D_3 \ln\left(\frac{D_3}{D_2}\right)}{2 k_i} + \frac{1}{h_o}} = 1.314\ {}^{W}/_{m^2 K}$$

Calculate heat transfer for bare pipe and insulated pipe using equation

$$\frac{Q}{L} = \pi\ D_3\ U\ (T_{in} - T_{out})$$

$$\frac{Q}{L}\ for\ bare\ pipe = 422.60\ W$$

$$\frac{Q}{L} for\ insulated\ pipe = 87.58\ W$$

$$Qloss\ per\ anum = \Delta\ Q\ \times 8760 = 2934 \times 10^3$$

$$Fuel\ required = \frac{\Delta\ Q}{\eta_{boiler}} = \frac{\Delta\ Q}{0.8} = 3668\ kWh$$

These calculations do not include radiation heat loss from outer surface, effect of wind velocity, applying cost of insulation and service life of insulation. This example is just an illustration to understand heat transfer through pipe with and without insulation and its impact on fuel consumption.

Economic thickness of insulation

In above example it is sited that applying insulation on a steam pipe saves considerable amount of fuel and hence money. What thickness of insulation saves most and at minimum cost is always critical question to answer because economic benefits of insulation vary according to application and method of financial evaluation. Simple payback is a commonly used term to evaluate financial appraisal. Payback increases with insulation thickness and cost. Normally projects having payback of less than two years are viable. The economic benefit of insulation follows the law of diminishing returns. With addition in insulation thickness, cost of insulation as well as saving due to insulation increases. There is a limiting value of insulation thickness above which saving is very small against the cost involved and that is defined as economic thickness of insulation.

Following factors affect economic thickness of insulation.

- Cost, heat content and efficiency of fuel and firing system
- Hours of operation
- Average ambient temperature and wind velocity
- Heat loss per unit length or unit area of insulated surface
- Initial, applying and maintenance cost of insulation and availability

An example given below explains method to calculate economic thickness of insulation for previous numerical.

Software to calculate insulation thickness

Various softwares are available to select and calculate thickness of thermal insulation. Some of them are 3E plus, Armacell, Techcalc, Trocellen etc. Use of such software makes insulation selection process easy and gives on hand solution of different parameters like economic thickness, available options in different insulation material, payback time, annual heat loss, financial analysis etc.

Following example gives calculation of heat loss and compared with the same calculated with 3E plus software.

Two pipes are shown in Figure 2. First one is bare pipe and the second one has got Mineral wool insulation of 25mm. Thermal conductivity of insulation is 0.06 W/(m K)

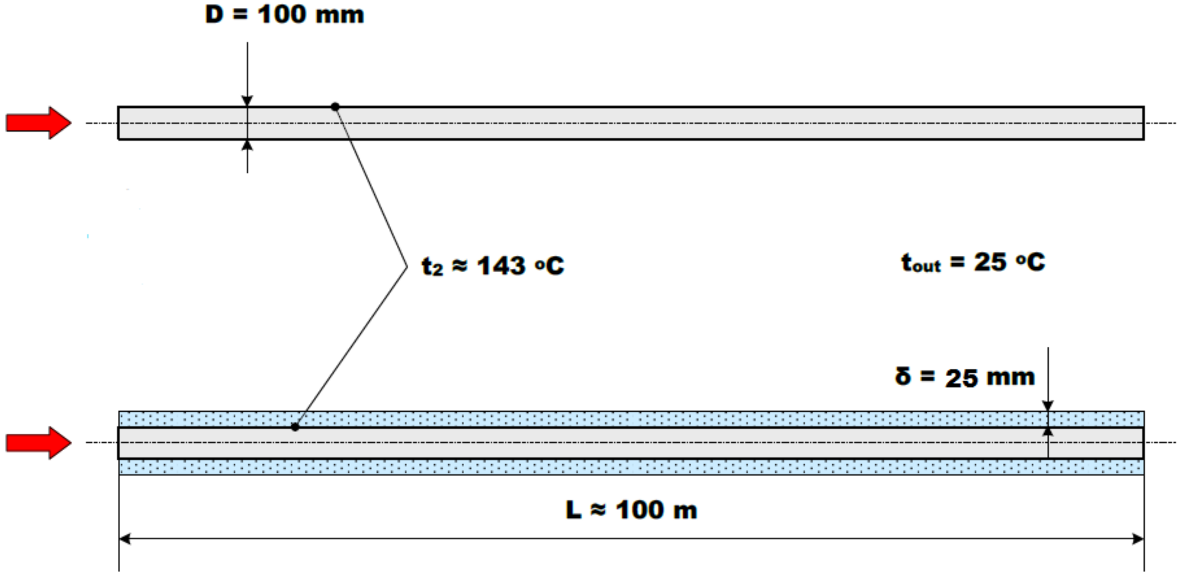

Figure 2 Bare and Insulated pipes

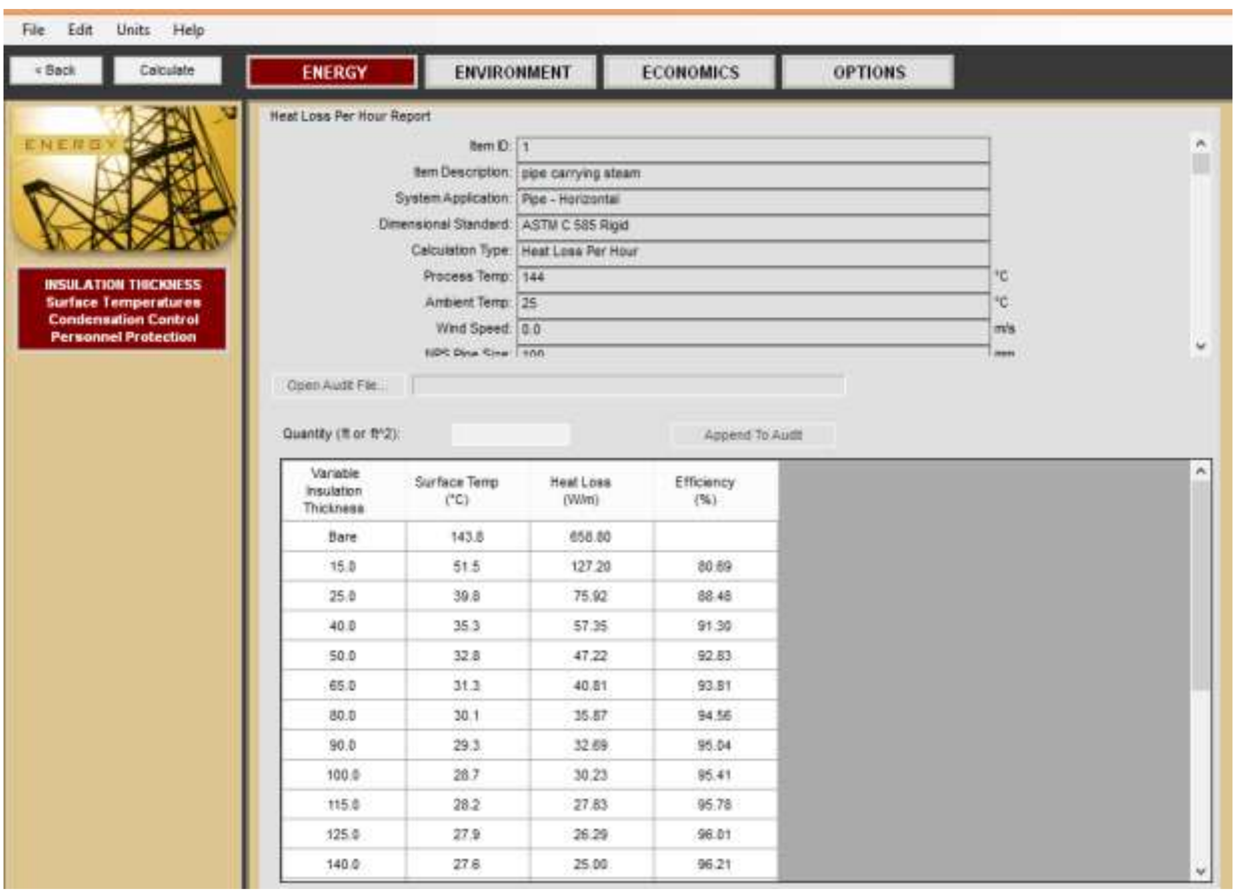

Figure 3 Screen shot of Insulation calculator software

Figure 3 shows screen shot of Insulation calculator software. It shows that for an insulation thickness of 15mm, heat loss is 127.2 W and same for 25 mm, heat loss is 75.92. Beyond this thickness of insulation, saving in energy is negligible. The same is represented in a Figure 4. Figure 5 represents annual heat loss and Figure 6 shows comparison of different insulation material. Aerogel gives minimum heat loss but its cost is also very high.

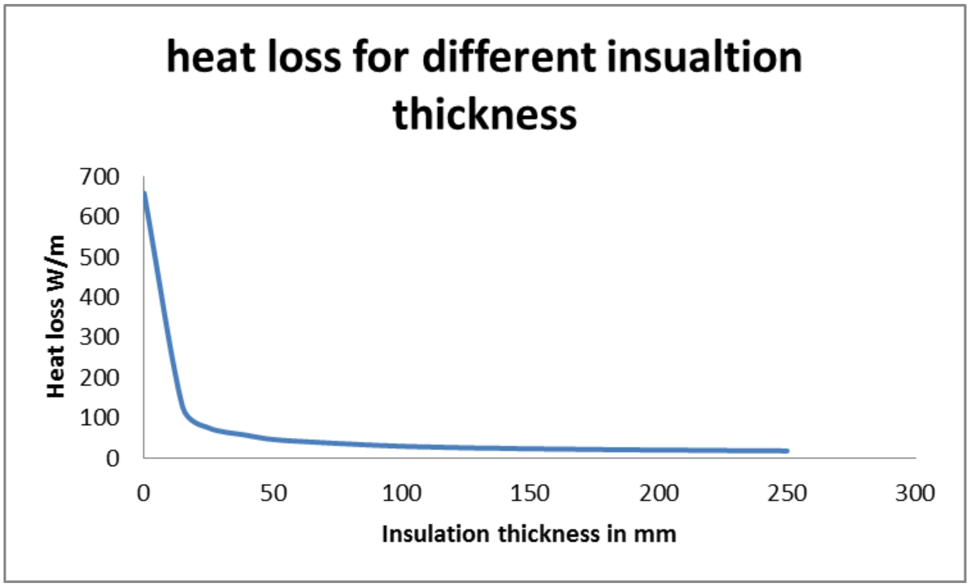

Figure 4 Heat loss for different insulation thickness

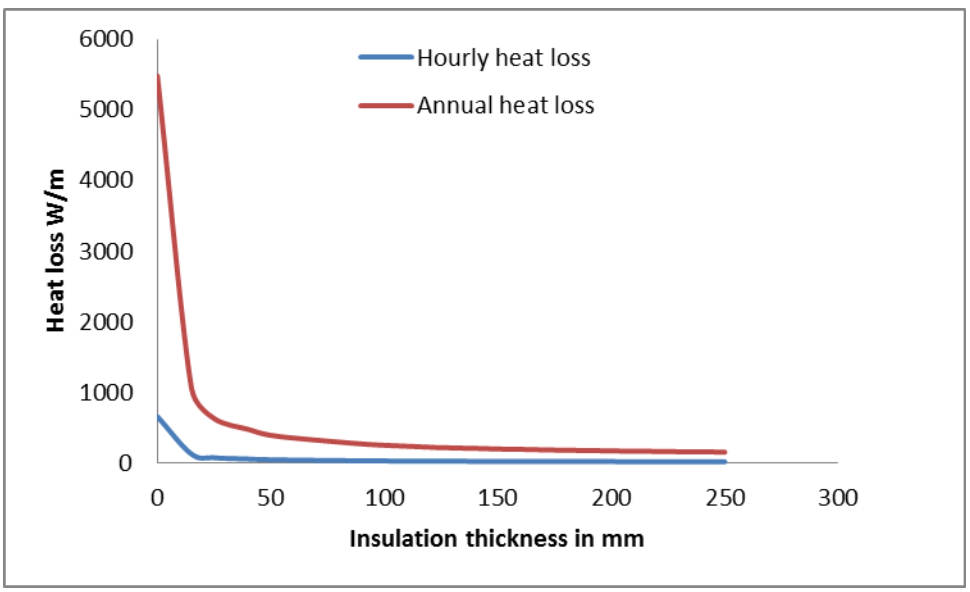

Figure 5 Heat loss calucation on hourly and annual basis

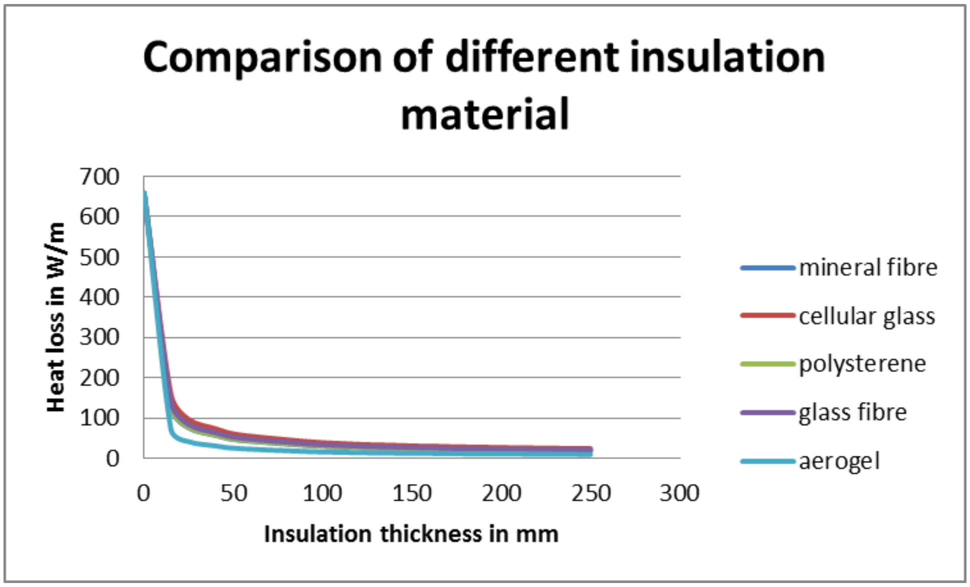

Figure 6 Comparison of different insuaton material

Some of the features of 3E plus software are:

1. Determines economic thickness of insulations based on return on investment for chosen fuel cost, installed cost, tax rates, maintenance, etc.
2. Calculates the amount of insulation needed for personnel protection for various design conditions.
3. Calculates the thickness of insulation needed for condensation control.
4. Calculates greenhouse gas emissions and reductions.
5. Determines surface temperature and heat loss/gain calculations of individual insulation thickness up to 10 inches (250 mm).
6. Solves for outside insulated surface temperatures for all types of insulation applications at different process temperatures and various configurations.
7. Calculates bare vs. insulated heat loss efficiency percentages for horizontal and vertical piping, ducts and flat surfaces.
8. Performs calculations for various flat surfaces, selected pipe sizes and all standard iron pipe sizes from 1/2" to 48" (15 - 1200 mm).
9. Calculates heat loss/gain and outside insulated surface temperatures for any insulation material provided the thermal conductivity, associated mean temperatures, and temperature limit are entered by the user.

Refractory material

Refractory material is used to withstand high temperature and is made of inorganic, non metallic, porous and heterogeneous material, which is highly stable at elevated temperature. Fireclay, alumina, magnesite, dolomite are commonly used refractory material in high temperature applications like furnaces, metal extraction, cement making, glass making, ceramics etc. A good refractory material has to withstand physio-chemical attack of different phases of material during reaction processes performing at high temperature (500ºC to 1600ºC), where source of heat can be electricity or fossil fuel depending upon the process and application.

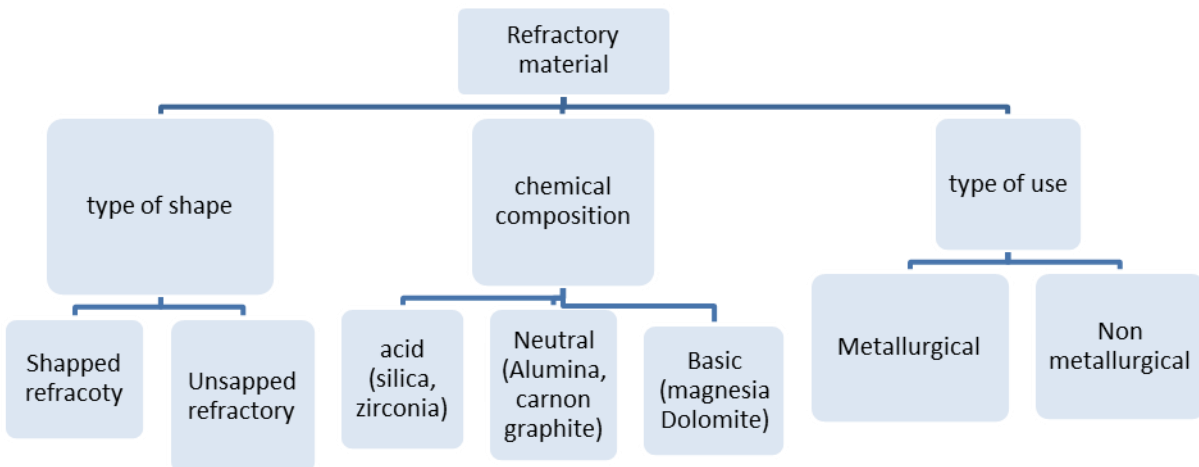

Chart - Classification of refractory material

Based on application refractory materials are classified as used by metallurgy industry or other than metallurgy industry. Metallurgy industry includes furnace, kiln, reactor etc. and non metallurgy industry includes heater, reformer, incinerator, boiler, cracking unit, claciner etc.

Properties of refractory material

Like insulation materials, refractory materials are characterized by their properties. They are listed below:

Melting point
This temperature indicates ability of material to withstand the process without any deformation and change in properties. Normally refractory material is a blend of different materials so melting point depends upon its constituents and

compositions. Temperature of different constituents used in refractory material is listed in table 12.

Porosity

This property represents the volume fraction of pores or voids present and termed as "% apparent porosity". Generally porous material has low thermal conductivity, low density and poor strength. More porous material has poor load bearing capacity and corrosion resistance as more slag can penetrate through it.

Constituents of refractory material	Melting temperature ºC
Graphite	3500
Magnesia	2800
Lime	2570
Magnesia	2200
Alumina	2050
Fireclay	1870
Silica	1715

Table 12 Melting temperature of different constituent of refractory material

Bulk density

It is the ratio of weight to the volume and is expressed in kg per cubic meter and is a measure similar to porosity. A refractory material having high bulk density indicates low porosity and is better in quality, volume stability, heat capacity and resistance to abrasion and slag penetration.

Pyrometric cone equivalent (PCE)

Refractory material melts progressively over a range of high temperature and is measured by cone fusion method. Pyrometric cone equivalent is a measure of refractoriness and state of maturity of material composition during high temperature exposure. Standard cone which melts to the same extent as the test cone is known as pyrometric cone equivalent which depends upon time and temperature.

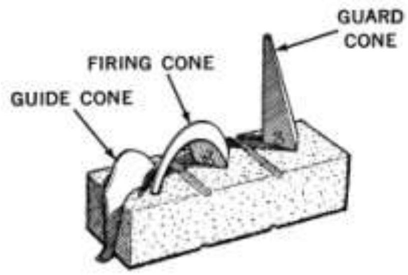

Figure 7 Pyrometric cone preparations

Thermal expansion

A material expands when heated and contracts when cooled and so it is for refractory material. Term used to express expansion of refractory material is "permanent linear change %". Dimensional change due to thermal expansion is linear with rising temperature gradient but nonlinear for extended period of holding and soaking and results into plastic deformation. The plastic deformation occurring due to heat is known as creep. Refractory material should be able to withstand dimensional stability under extreme temperature (including cyclic loading), high temperature corrosive liquids and gases.

Thermal conductivity

As defined in earlier section of this chapter thermal conductivity is a property of material, which decides quantity of heat that will flow through a unit area in a direction perpendicular to the surface. It is recommended that refractory material have thermal conductivity as low as possible except some applications where thermal contact is essential (e.g. coke oven, regenerators, muffles and water cooled furnace walls). Thermal conductivity of material depends upon composition of material, and as porosity increases, value of thermal conductivity decreases.

Cold crushing strength

It is a capacity of refractory to resist compressive load at room temperature and is measured in kg/cm^2 at which refractory material breaks.

Commonly used refractory materials

Fireclay bricks

Major refractory material used is fireclay bricks which is made of aluminum silicate (SiO_2 and Al_2O_3) Reasons for its popularity are multipurpose applicability and low cost. Fireclay bricks are sub grouped as super duty, high duty, medium duty and low duty based on fusion temperature (PCE Index) and % alumina – silica in the composition of brick. High alumina bricks have less impurity and has high melting point.

Figure 8 A sample of fireclay brick.

High Alumina Refractory

It consists of aluminium oxide and other materials. It is chemically stable, has excellent hardness, strength and spalling resistance (resistance to chip or break off), insoluble with water and superheated steam, acids and alkalis. Based on compositions, they are available as 50%, 60%, 70% and 80% alumina classes.

Silica bricks

Second known refractory material after fireclay material is silica bricks. They have more than 93% SiO_2. Most of the refractory material looses their properties at fusion temperature but silica brick is opposite to them, It has excellent mechanical strength at fusion point. Additional advantages are good flux resistance, volume stability and spalling resistance. Due to these benefits, silica bricks are used in iron, steel and glass making industry.

Magnesite refractory

It is made of minimum 85% magnesium oxide, basic in nature and is available in bricks form. The prime advantage of this material is excellent resistance to slag, which makes it very useful for steel making processes, glass tank checkers and in lime and cement kilns.

Dolomite, Chromite, Zirconia and Monolithic refractory

Dolomite ($CaCO_3$ + $MgCO_3$) is useful refractory for cement kiln clinker as it provides excellent coating stability, thermal shock and alkali resistant. Chrome magnesite refractory can withstand corrosive slag and gasses. Zirconia refractory is difficult to make but they have high strength up to 1500 ºC and thermal conductivity is much lower than other refractory material. It is useful for glass furnaces as it is not wetted by molten glass. Monolithic refractory are available in loose form and can be set into required form either by ramming, casting, spraying etc. Advantages of monolithic refractory are, they are joint less, skilled labours are not required and properties are better than refractory bricks.

Figure 9 Monolithic refractory casted in required shape

Ceramic fiber – an insulating refractory

Some application requires refractory material of low thermal conductivity to reduce heat loss. Ceramic fiber is one such insulating refractory. It is white, fluffy, cotton like fiber and available in fabric, board or block forms. Ceramic fibers have very low thermal conductivity, are extremely light weight and resistant to thermal shocks and are chemically stable. Other advantages of ceramic fibers are listed below:

1. Long life of furnace and reduced maintenance cost due to long life of refractory material.
2. Upto 60% fuel saving due to better insulation quality compared to other refractory material.
3. Less heat storage increases productivity of furnaces.
4. Easy to apply compared to other materials.

Limitations of ceramic fibers are listed below:

1. It shrinks at higher temperature.
2. Poor mechanical strength- they cannot be used as structural material and proper support is required.
3. They tend to sag at higher temperature.
4. Dust, fog and fumes can easily get deposited on ceramic fibers and hence are not suitable for such environment.
5. Costlier than other refractory material.

Selection of refractory material

Low thermal conductivity and capacity to withstand operating conditions are basic requirement from a refractory material. Following points are to be considered while deciding refractory material.

1. Type of material to be melted in furnace.
2. Temperature and time span for which material will be melted.
3. Additives and alloys used for melting and their effects on refractory material.
4. Area of application, thickness requirement etc.
5. Workmanship

Looking at above factors, cost and availability, refractory material is selected for a particular application.

How to improve life of refractory material

Adopt following practices to extend life of refractory material.

1. Use of consistent quality of refractory material.
2. Use of large refractory blocks instead of small ones, as large blocks have less number of joints.
3. The quality of mortar used in furnace lining should be similar to refractory material.
4. It is advisable to use dimensionally accurate and warpage (dimensional distortion) free blocks.
5. It is likely that some spillage of charge material may damage floor of the furnace so it is advisable to apply anti corrosive coating material on floor surface.

Checklist for energy saving in insulation material

Energy saving measures are given herewith:

1. Always insulate pipes of steam, hot oil, hot water (both high and low pressure), condensate.
2. Use removable flexible insulations on valves, flanges and other fittings.
3. Regularly check for water logging as this reduces insulation effectiveness.
4. Check for tightness of insulation on surface as the air gap between insulation and hot / cold surface increases convection heat loss.
5. As cost of energy increases, thicker insulation is required. Always check thickness of insulation with respect to cost of energy and if found suitable increase thickness of insulation.
6. Cover hot liquid surfaces with lid.
7. If hot pipes are passing through air conditioned space it adds heating load on the system. Apply necessary insulation on them.
8. Steam or other fluids leaking from pipe degrades insulation.

9. Failure to replace or repair insulation after site maintenance degrades insulation.
10. Carry out heat balance regularly to count for heat loss in a system.
11. Use thermographic equipment to measure outer surface temperature of insulation material.
12. Due to difficulty in application, complex shapes like valves, fittings, reducers are overlooked while applying insulation. Use special insulation available for such shapes.