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Introduction:

Insulation is defined as those materials or combinations of materials, which retard the flow of heat energy by performing one or more of the following functions:

1. Conserve energy by reducing heat loss or gain.
2. Control surface temperatures for personnel protection and comfort.
3. Facilitate temperature control of a process.
4. Prevent vapor flow and water condensation on cold surfaces.
5. Increase operating efficiency of heating/ventilating/cooling, plumbing, steam, process and power systems found in commercial and industrial installations.
6. Prevent or reduce damage to equipment from exposure to fire or corrosive atmospheres.
7. Assist mechanical systems in meeting food and drugs standards criteria in food and cosmetic plants.

Resistance to heat is only one of several criteria to be considered while selecting an insulation material for a particular service. The choice is generally a compromise arrived at to a great extent by the total cost of insulation and its installation. However, due to increasing cost of energy a new parameter – life cycle cost based on the initial cost plus maintenance and operating cost for a reasonable life expectancy rather than initial low cost is gaining importance in making decision. This paper deals with making decision on selection of insulating material based on various criteria. Before considering economic criteria, the insulation material must pass through technical criteria.

Technical Criteria for Insulation material:

The basic technical criteria in selecting a suitable insulating material for a particular service are to meet minimum safety and process conditions. To meet the criteria material of particular type, form and properties of the material is selected.

Types

1. **Fibrous Insulation:** Composed of small diameter fibers, which finely divide the air space. The fibers may be perpendicular or horizontal to the surface being insulated and they may or may not be bonded together. Silica, rock wool, slag wool and alumina silica fibers are used. The most widely used insulations of this type are glass fiber and mineral wool.

2. **Cellular Insulation:** Composed of small individual cells separated from each other. The cellular material may be glass or foamed plastic such as polystyrene (closed cell), polyurethane, polyisocyanurate, polyolefin, and elastomers.

3. **Granular Insulation:** Composed of small nodules, which contain voids or hollow spaces. It is not considered a true cellular material since gas/ air can be transferred between the individual spaces. This type may be produced as a loose or pourable material, or combined with a binder and fibers to make a rigid insulation. Examples of these insulations are calcium silicate, expanded vermiculite, perlite, cellulose, diatomaceous earth and expanded polystyrene.

Forms

Insulation is produced in a variety of forms suitable for specific functions and applications. The combined form and type of insulation determine its proper method of installation. The forms most widely used are:

1. Rigid boards, blocks, sheets, and pre-formed shapes such as pipe insulation, curved segment, lagging, etc.: Cellular, granular, and fibrous insulations are produced in these forms.

2. Flexible sheets and pre-formed shapes: Cellular and fibrous insulations are produced in these forms.

3. Flexible blankets: Fibrous insulations are produced in flexible blankets.

4. Cements (insulating and finishing): Produced from fibrous and granular insulations and cement, they may be of the hydraulic setting or air-drying type.

5. Foam: Poured or froth foam used to fill irregular areas and voids. Spray used for flat surfaces.

Properties

1) Conductivity: It is the most important property of an insulation – lower the value of conductivity less will be thickness of the insulation. In many applications, thermal conductivity of mass insulation is a combination of following heat transfer mechanisms: thermal conductivity of air, thermal conductivity of the solid structure of insulating material, convective heat transfer within the pore structure, the radiation heat transfer within the structure and interaction of these mechanisms. Other derived property based on conductivity is conductance, which is a measure of rate of heat flow for a particular thickness of insulation material.

2) Temperature limitations: Insulating materials are normally classified according to service-temperature ranges they are suitable for. However, at many times they tend to be arbitrary. When operating temperatures reach a certain upper limit, the materials may become structurally unstable or become uncompetitive because of a relatively high conductivity. Within each

temperature range choice among material available is generally based on other properties and cost. Normally temperature ranges and types of insulation materials used are as follows:

Cryogenic range (-270 ^{0} C to –75 ^{0} C): In this range insulations fall within two types- vacuum and massive. The later consisting of one or more solid phase distributed with a gas like dry air.

Low temperature range (-75 ^{0} C to 100 ^{0}C): At lower end of the range foam insulations are used more. The main problems are moisture permeation and fire hazards. Since the cost of refrigeration is greater than the cost of heating, more insulation is often justified. At the upper end of the range, insulation is of normally used for safety and personal protection.

Intermediate Range (100 ^{0} C to 550 ^{0} C): This is the normally encountered in most of chemical process industry and steam systems. The most important type insulation in this range include:

- Calcium silicates.
- Diatomaceous silica.
- Cellular glass (up to 450 ^{0} C) .
- Glass fibers bonded with high temperature binders.
- Magnesium carbonate with asbestos or other fibers and binders (up to about 300 ^{0} C).
- Rock wool or mineral derived fibers.
- Expanded perlite with binders.

Selection of insulation material in this temperature range is strongly dictated by value of thermal conductivity, mechanical properties, forms available and the cost of installation.

High temperature Range (550 ^{0} C and above): This range approaches refractory range of materials. The materials used in this range are:

- Mineral fiber: 550 to 1000 ^{0} C.
- Calcium silicate :650 to 1100 ^{0} C.

- Ceramic fibers based on Al_2O_3-SiO_2 systems: 850 to 1450 ^{0} C.
- Castable ceramic insulating refractories: 1000 to 1650 ^{0} C.
- Oxide fibers primarily Al_2O_3 or ZrO_2 : 1500 to 1650 ^{0} C.
- Rigid ceramic insulating brick : 1000 to 1750 ^{0}C.
- Carbon fibers: up to 2000 ^{0} C.

3) Thermal-shock resistance: The insulation material should resist the attack of heat particularly at high temperatures.
4) Coefficient of expansion: This is required to be considered while designing the design and spacing of expansion/contraction joints and/or the use of multiple layer insulation applications.
5) Abrasion and erosion resistance: In case of refractory materials erosion occurs more rapidly in turbulent zones rather than non-turbulent zones.

6) Compressibility: it is Important if the insulation must support a load or withstand mechanical abuse without crushing. If, however, cushioning or filling in space is needed as in expansion/contraction joints, low compressive strength materials are specified.
7) Chemical resistance: Leakages from fluid should not affect the insulating material. Also Potential fire hazards exist in areas where volatile chemicals are present. Corrosion resistance must also be considered. Particularly chloride concentration of insulating material has to be below acceptable limit in case of use in SS piping or vessels.
8) Environmental resistance : This factor is significant when the atmosphere is salt or chemical laden.
9) Alkalinity (pH or acidity): It is important when corrosive atmospheres are present. Also insulation must not contribute to corrosion of theIt system.
10) Density and strength: In a number of applications densities of an insulating material containing solid structure can be modified to get a suitable apparent conductivity (“k_a”) by creating dead air spaces (porosity). But more porosity reduces strength of the insulating material such as insulating firebricks. Therefore, a careful assessment of strength and apparent “k_a” required is done with data provided by insulation manufacturers.
11) Appearance: It is important in exposed areas and for coding purposes.

12) **Capillarity:** It must be considered when material may be in contact with liquids.

13) **Fire retardancy:** Flame spread and smoke developed ratings of the material should be considered.

14) **Combustibility:** One of the measures of a material's contribution to a fire hazard has to be taken into account.

15) **Dimensional stability:** It has significance when the material is exposed to atmospheric and mechanical abuse such as twisting or vibration from thermally expanding pipe.

16) **Hygroscopicity**: Tendency of a material to absorb water vapor from the air needs to be considered.

17) **Resistance to ultraviolet light:** It is important if application is outdoors.

18) **Resistance to fungal or bacterial growth:** It is necessary in food or cosmetic process areas.

19) **Shrinkage:** Its significance in applications involving cements and mastics.

20) **Sound absorption coefficient:** It must be considered when sound attenuation is required, as it is in radio stations, some hospital areas, etc.

21) **Sound transmission loss value:** It is important when constructing a sound barrier.

22) **Toxicity:** It must be considered in food processing plants and potential fire hazard areas.

23) **Ease of application**: Installation of insulating material on valves, pipe- fittings should be as easy as possible. This is important in case of thermal insulation.

Not all properties are significant for all materials or applications. Therefore, many are not included in manufacturers' published literature. In some applications, however, omitted properties may assume extreme importance (i.e. when insulations must be compatible with chemically corrosive atmospheres.)

If the property is significant for an application and the measure of that property cannot be found in manufacturers' literature, effort should be made to obtain the information directly from the manufacturer, testing laboratory, or insulation contractors association.

While technically selecting insulations, it is possible to make use of combinations – layers of different insulating materials to get optimum size, weight and damage resistance. Some insulations are available in prefabricated forms for piping, valves and fittings. It is possible to reduce application/ installation cost of insulation by procuring prefabricated forms.

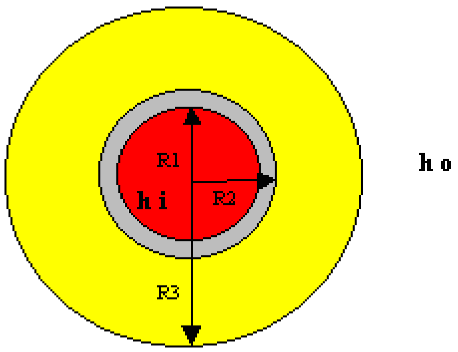
In case of thermal insulations, barrier system has to be effective. It should allow little or no water leakage. Any penetration of water or for that matter any other liquid seriously diminishes its insulating properties till it dries out. It is noticed that in case of steam turbines, sometimes due to ineffective barrier system, insulation material on steam lines get soaked in oil due to leakage in lube oil system and pose fire hazards. Jacketing of insulating material protects insulation against mechanical abuse as well as against weather and other damage. In selection of jacketing material corrosion resistance is an important factor.

Economic Criteria

It is based on calculation of the amount of insulation that would save enough energy over a set period of time period to justify the investment. Economic thickness calculations based on equations first published in 1926 have been refined over the years taking into consideration new inputs particularly with respect to methods for developing investment return analyses. Interest in economic thickness increased more with the rise in energy costs. Earlier, cookbook approach based on some design standards was prevalent. However, nowadays insulation costs are not considered as expenses but as investment. Therefore, methods used in economic feasibility of a project are also used in determining economic thickness of insulation.

Basic Model and Theory in Economic Insulation calculation

The most basic model for insulation on a pipe is shown below. R1 and R2 show the inside and outside radius of the pipe respectively. R3 shows the radius of the insulation. Typically when dealing with insulations, engineers must be concerned with linear heat loss or heat loss per unit length.



$$U = \frac{1}{\frac{R3}{R1\,hi} + \frac{R3\ LN(R2/R1)}{k_{pipe}} + \frac{R3\ LN(R3/R2)}{k_{insulation}} + \frac{1}{ho}} \quad \textbf{(1)}$$

Generally, the heat transfer coefficient of ambient air is about 40 W/m^2 K. This coefficient can of course increase with wind velocity if the pipe is outside The total heat loss per unit length can then be calculated by:

$$\frac{Q}{L} = 2\pi R3\ U\ \Delta T$$

$$\text{where } \Delta T = T_{insidepipe} - T_{ambient} \qquad (2)$$

Safety

Pipes that are readily accessible by workers are subject to safety constraints. The recommended safe "touch" temperature range is from 55 ^{0}C to 65 ^{0}C. Insulation calculations should aim to keep the outside temperature of the insulation around 60 ^{0}C. An additional tool employed to help meet this goal is aluminum covering wrapped around the outside of the insulation. Aluminum's thermal conductivity of 209 W/m K does not offer much resistance to heat transfer, but it does act as another resistance while also holding the insulation in place. Typical thickness of aluminum used for this purpose ranges from 0.2 mm to 0.4 mm. The addition of aluminum adds another resistance term to Equation 1 when calculating the total heat loss

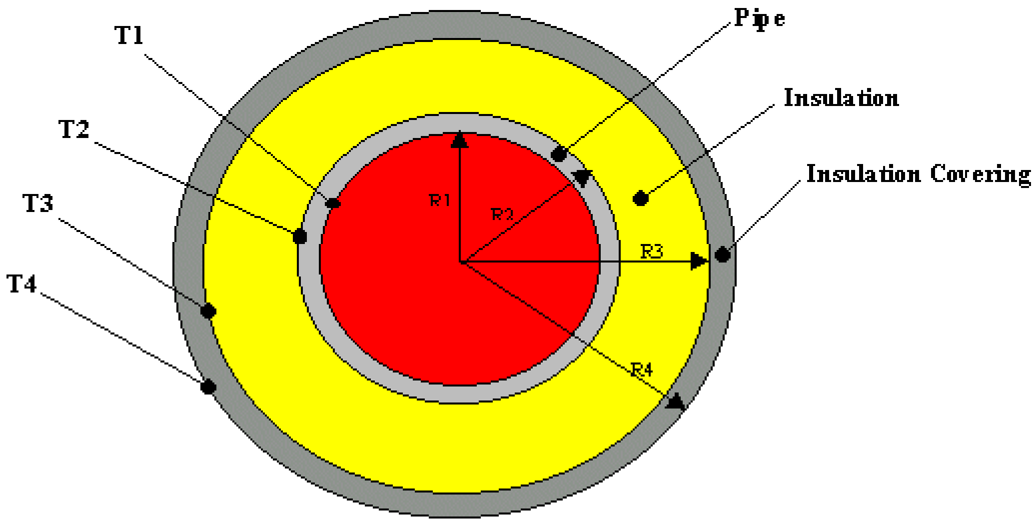
$$U = \frac{1}{\frac{R4}{R1\,hi} + \frac{R4\ LN(R2/R1)}{k_{pipe}} + \frac{R4\ LN(R3/R2)}{k_{insulation}} + \frac{R4\ LN(R4/R3)}{k_{aluminum}} + \frac{1}{ho}}$$

and Equation 2 becomes :

$$\frac{Q}{L} = 2\pi R4\ U\ \Delta T$$

where R4 is the radius of the pipe, insulation , and aluminum cover combined. (3)

However, when considering safety, engineers need a quick way to calculate the surface temperature that will come into contact with the workers. This can be done with equations or the use of charts. This can be done by looking at another diagram:



At steady state, the heat transfer rate will be the same for each layer:

$$Q = \frac{T1 - T2}{(R2 - R1)/(k_{pipe} A_{LMpipe})} = \frac{T2 - T3}{(R3 - R2)/(k_{ins} A_{LMins})} = \frac{T3 - T4}{(R4 - R3)/(k_{inscover} A_{LMinscover})}$$

where :

$$A_{LMpipe} = \frac{(2\pi\ R2\ L) - (2\pi\ R1\ L)}{LN\left(\frac{2\pi\ R2\ L}{2\pi\ R1\ L}\right)},$$

$$A_{LMins} = \frac{(2\pi\ R3\ L) - (2\pi\ R2\ L)}{LN\left(\frac{2\pi\ R3\ L}{2\pi\ R2\ L}\right)},$$

$$A_{LMinscover} = \frac{(2\pi\ R4\ L) - (2\pi\ R3\ L)}{LN\left(\frac{2\pi\ R4\ L}{2\pi\ R3\ L}\right)} \qquad (4)$$

Rearranging Equation 4 by solving the three expressions for the temperature difference yields:

$$Q = \frac{T1 - T4}{\left(\frac{R2 - R1}{k_{pipe} A_{LMpipe}}\right) + \left(\frac{R3 - R2}{k_{ins} A_{LMins}}\right) + \left(\frac{R4 - R3}{k_{inscover} A_{LMinscoverr}}\right)} \qquad (5)$$

Each term in the denominator of Equation 5 is referred to as the "resistance" of each layer. This can be defined as Rs and rewrite the equation as:

$$Q = \frac{T1 - T4}{R_{Spipe} + R_{Sins} + R_{Sinscover}} \qquad (6)$$

Since the heat loss is constant for each layer, use Equation 4 to calculate Q from the bare pipe, then solve Equation 6 for T4 (surface temperature). Use the economic thickness of your insulation as a basis for your calculation, after all, if the most affordable layer of insulation is safe, that's the one you'd want to use. If the economic thickness results in too high a surface temperature, repeat the calculation by increasing the insulation thickness by 1/2 inch each time until a safe touch temperature is reached.

As can be seen, using heat balance equations is certainly a valid means of estimating surface temperatures, but it may not always be the fastest. Charts are available that utilize a characteristic called "equivalent thickness" to simplify the heat balance equations. This correlation also uses the surface resistance of the outer covering of the pipe

Economic thickness of insulation is a well documented calculation procedure. The calculations typically take in the entire scope of the installation including plant depreciation to wind speed. Data charts for calculating the economic thickness of insulation are widely available.

It may be noted that economic thickness for same service will differ due to a number of factors, which may be considered in evaluation. These factors are:

1) Type and cost of fuel.
2) Heating value of fuel.
3) Expected annual fuel price increase.
4) Efficiency of conversion of fuel to heat.
5) Capital investment for heat plant.
6) Cost of investment to finance the plant.
7) Heating equipment depreciation period.
8) Expected annual heat production.

9) Income tax rate.
10) Insulation depreciation period.
11) Insulating material.
12) Jacket emmisivity.
13) Surface resistance.
14) Installed insulation prices/ rates.
15) Pipe size.
16) Piping complexity factor.
17) Average ambient temperature to be considered in economic thickness calculation.
18) Process temperature.
19) Annual operating hours.
20) Previous thickness if specified.

To calculate economic insulation thickness considering all above factors, many times computer models in Excel spreadsheets are used. It is possible to simplify computer models ignoring factors having less impact. Some simple methods with an example are presented below:

For the sake of demonstrating applications of different methods, a system where present investment on insulation based on standards for safety and process requirements is taken at Rs. 200,000. By increasing thickness in steps to arrive at economic thickness, investment is Rs. 250,000. Annual fuel requirements-existing at Rs. 40,000 and for economic thickness at Rs. 30,000 are considered. The life of insulation is taken as 20 years. The cost of capital investment in insulation is considered as 10%.

Payback period: It is essentially the time required to repay the capital investment with savings accrued through operation.

	Thickness based on current standard	Economic thickness	Difference (Incremental)
Insulation investment, Rs.	200,000	250,000	50,000
Annual fuel	40,000	30,000	10,000

cost, Rs.			

Simple payback period will be 5 years (50,000/10,000).

Above method does not take into account time value of money. Also it does not take into account cash inflows beyond the payback period.

Investment is done first and benefits are accrued later over a number of years. Therefore, methods based on time value of money are more appropriately used in economic insulation calculations. Minimum annual cost and maximum net present value are methods normally used.

Minimum annual cost:

In this method discounted (at an assigned rate) annualized cost of insulation and the costs of heat lost through the insulation are considered to arrive at minimum annual cost.

Example:

Basis: Investment for standard insulation thickness: Rs. 200,000

Investment for economic insulation thickness: rs. 250,000

Life of insulation: 20 years

.	Item	@std. Current thickness	@Economic thickness	Comments
1	Annual energy cost	40,000	30,000	
2	Insulation depreciation	10,000	12,500	20,000/20 and 250,000/20
3	Annual cash cost	30,000	17,500	(1) – (2)
4	Capital recovery factor for 20	0.1175	0.1175	1/ 8.514

	years* @10%			
5	Equivalent annual insulation cost	23,491	29,363	200,000 x 0.1175 and 250,000 x.1175
6	Total Annual cost	53,491	46,863	(3) plus (5)

Conclusion: The lowest annual cost (Rs. 46,863) is better of two investment options.

Maximum Net present value

		@Std. thickness	@ Economic Ins. thickness	Comment s
1	Annual energy cost	40,000	30,000	
2	Annual Ins. depreciatio n	10,000	12,500	
3	Annual cash cost	30,000	17,500	(1) – (2)
4	Net present value factor for 20 years	8.514	8.514	
5	Present value of annual cash cost	255,42 0	148,99 5	
6	Initial cost of investment	200,00 0	250,00 0	
7	Net present value of cost	455,42 0	398,99 5	(5) plus (6)

Conclusion: Net present value of cost at Economic Insulation thickness is less than at standard thickness. Therefore, it is better of two investment options.

It may be noted that in annulised discounted cost and NPV method depreciation is not considered as it is not cash outflow.

There are computer programs available based on this method. To find out economic insulation thickness, the program increases the insulation thickness from the current thickness and finishes the finding when the insulation thickness reaches the Maximum thickness of the last layer.

During the thickness increase the selected economic insulation thickness is the thickness of one step before where the annual total cost changes from decrease to increase.