

Insulation helps in efficient use of energy

Introduction

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

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

Resistance to heat is only one of the several criteria to be considered while selecting an insulation material. The choice is generally a compromise between the total cost of insulation and its installation. However, due to increasing cost of energy a new parameter is gaining importance in making a decision. This is called life-cycle cost based on the initial cost plus maintenance and operating cost for a reasonable life expectancy rather than initial low cost.

This article deals with making decision on selection of insulating material based on various criteria. Before considering the economic criteria, the insulation material must pass through the 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 a particular type, form and properties of the material is selected.

Types

Fibrous Insulation

This insulation is 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.

Cellular Insulation

This insulation is 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.

Granular Insulation

This insulation is 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 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.

This 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:

- Rigid boards, blocks, sheets, and pre-formed shapes such as pipe insulation, curved segment, lagging, etc: Cellular, granular, and fibrous insulations are produced.
- Flexible sheets and pre-formed shapes: cellular and fibrous insulations are produced.
- Cements (insulating and finishing): produced from fibrous and granular insulations and cement, they may be of the hydraulic setting or air drying type.
- Foam: Poured or froth foam used to fill irregular areas and voids. Spray used for flat surfaces.

Properties

- **Conductivity:** The most important property of an insulation – lower the value of conductivity less will be the thickness of the insulation. In many applications, thermal conductivity of mass insulation is a combination of the 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 a particular thickness of insulation material.
- **Temperature limitations:** Insulating materials are normally classified according to service-temperature ranges they are suitable for. However, at many times they tend to 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 °C to -75 °C): In this range, insulation falls within two types, vacuum and massive, the latter consisting of one or more solid phase distributed with a gas like dry air.

Low temperature range (-75 °C to 100 °C): At the 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 normally used for safety and personal protection.

Intermediate range (100 °C to 550 °C): This is normally encountered in most chemical process industries and steam systems. The most important type of insulation in this range include:

- Calcium silicates
- Diatomaceous silica
- Cellular glass (up to 450 °C)
- Glass fibers bounded with high temperature binders
- Magnesium carbonate with asbestos or other fibers and binders (up to about 300 °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 °C and above): This range approaches the refractory range of materials. The materials used in this range are:

- Mineral fiber: 550 to 1,000 °C
 - Calcium silicate: 650 to 1,100 °C
 - Ceramic fibers based on $\text{Al}_2\text{O}_3\text{-SiO}_2$ systems: 850 to 1,450 °C
 - Castable ceramic insulating refractories: 1,000 to 1,650 °C
 - Oxides fibers primarily Al_2O_3 or ZrO_2 : 1,500 to 1,650 °C
 - Rigid ceramic insulating brick: 1,000 to 1,750 °C
 - Carbon fibers: up to 2,000 °C
- **Thermal-shock resistance:** The insulation material should resist the attack of heat particularly at high temperatures.
 - **Coefficient of expansion:** this is required to be considered while creating the design and spacing of expansion/contraction joints and/or the use of multiple layer insulation applications.
 - **Abrasion and erosion resistance:** in case of refractory materials erosion occurs more rapidly in turbulent zones rather than non-turbulent zones.
 - **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.
 - **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 the acceptable limit in case of use in SS piping or vessels.

- Environmental resistance: this factor is significant when the atmosphere is salty or chemical laden.
- Alkalinity (pH or acidity): It is important when corrosive atmospheres are present. Also, insulation must not contribute to corrosion of the shell system.
- 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.
- Appearance: It is important in exposed areas and for coding purposes.
- Capillarity: It must be considered when material may be in contact with liquids.
- Fire retardancy: Flame spread and smoke developed ratings of the material should be considered.
- Combustibility: One of the measures of a material’s contribution to a fire hazard has to be taken into account.
- Dimensional stability: it has significance when the material is exposed to atmospheric and mechanical abuse such as twisting or vibration from thermally expanding pipe.
- Hygroscopicity: Tendency of a material to absorb water vapor from the air needs to be considered.
- Resistance to ultraviolet light: It is important if application is outdoors.
- Resistance to fungal or bacterial growth: It is necessary in food or cosmetic process areas.
- Shrinkage: Its significance in applications involving cements and mastics.
- Sound absorption coefficient: It must be considered when sound attenuation is required, as it is in radio stations, some hospital areas, etc.
- Sound transmission loss value: It is important when constructing a sound barrier:
- Toxicity: It must be considered in food processing plants and potential fire hazard areas.
- 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 the manufacturer’s publishing 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 the manufacturer’s literature, effort should be made to obtain the information directly from the manufacturer, testing laboratory, or insulation contractors association.

While selecting insulations on technical grounds, 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 a prefabricated form for piping, valves and fittings. It is possible to reduce application/installation cost of insulation by procuring prefabricated forms.

In case of thermal insulations, the barrier system must 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. In case of steam turbines, sometimes due to an 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 the insulation against mechanical abuse as well as against weather and other damage. Consider corrosion resistance as important in selection of the jacketing material.

$$U = \frac{1}{\frac{R3}{R1 h_i} + \frac{R3 \text{ LN } (R2/R1)}{k_{\text{pipe}}} + \frac{R3 \text{ LN } (R3/R2)}{k_{\text{insulation}}} + \frac{1}{h_o}} \quad (1)$$

Economic Criteria

It is based on calculation of the amount of insulation that would save enough energy over a set period of time 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. The earlier cookbook approach based on some design standards was

prevalent. However, insulation costs today are not considered as expense but as investment. Therefore, methods used in calculating the economic feasibility of a project are also used in determining the economic thickness of the insulation.

Basic Model and Theory in Economic Insulation Calculation

The most basic model for insulation on a pipe is shown in the figure above (1). 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 look at linear heat loss or heat loss per unit length.

Generally, the heat transfer coefficient of ambient air is about 40 W/m² K. this coefficient can of course increase with wind velocity if the pipe is outside. The total heat loss per unit length can be calculated by:

$$\frac{Q}{L} = 2\pi R_3 U \Delta T \quad (2)$$

Where $\Delta T = T_{\text{inside pipe}} - T_{\text{ambient}}$

Safety

Pipes that are readily accessible by workers are subject to safety constraints. The recommended safe "touch" temperature range is from 55 °C to 65 °C. Insulation calculations should aim to keep the outside temperature of the insulation around 60 °C. an additional tool employed to help meet this goal is aluminum covering wrapped around the outside of the insulation.

$$U = \frac{1}{\frac{R_4}{R_1 h_i} + \frac{R_4 \ln(R_2/R_1)}{k_{\text{pipe}}} + \frac{R_4 \ln(R_3/R_2)}{k_{\text{insulation}}} + \frac{R_4 \ln(R_4/R_3)}{k_{\text{aluminum}}} + \frac{1}{h_o}}$$

And Equation 2 becomes:

$$\frac{Q}{L} = 2\pi R_4 U \Delta T \quad (3)$$

Where R4 is the radius of the pipe, insulation, and aluminum cover combined

$$Q = \frac{T_1 - T_2}{(R_2 - R_1)/(k_{\text{pipe}} AL_{\text{Mpipe}})} = \frac{T_2 - T_3}{(R_3 - R_2)/(k_{\text{ins}} AL_{\text{Mins}})} = \frac{T_3 - T_4}{(R_4 - R_3)/(k_{\text{inscover}} AL_{\text{Minscover}})}$$

Where:

$$AL_{\text{Mpipe}} = \frac{(2\pi R_2 L) - (2\pi R_1 L)}{\ln \left\{ \frac{2\pi R_2 L}{2\pi R_1 L} \right\}}$$

$$AL_{\text{Mins}} = \frac{(2\pi R_3 L) - (2\pi R_1 L)}{\ln \left\{ \frac{2\pi R_2 L}{2\pi R_1 L} \right\}} \quad (4)$$

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

$$Q = \frac{T_1 - T_4}{\frac{(R_2 - R_1)/(k_{\text{pipe}} AL_{\text{Mpipe}})} + \frac{(R_3 - R_2)/(k_{\text{ins}} AL_{\text{Mins}})} + \frac{(R_4 - R_3)/(k_{\text{inscover}} AL_{\text{Minscover}})}} \quad (5)$$

Aluminum's thermal conductivity of 209 W/m K does not offer much resistance to heat transfer, but it does act as another resistance to heat transfer, but it does act as another resistance while also holding the insulation in place. The 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.

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 by looking at another diagram (see above):

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

$$Q = \frac{T_1 - T_4}{(R_{\text{pipe}} + R_{\text{ins}} + R_{\text{inscover}})}$$

Since the heat loss is constant for each layer, use Equation 4 to calculate Q from the bare pipe, then solve Equation 6 for T_4 (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 half an 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.

Economic thickness for same service will differ due to a number of factors, which may be considered during evaluation. These factors are:

- Type and cost of fuel
- Heating value of fuel
- Expected annual fuel price increase
- Efficiency of conversion of fuel to heat
- Capital investment for heat plant
- Cost of investment to finance the plant
- Heating equipment depreciation period
- Expected annual heat production
- Income tax rate
- Insulation depreciation period
- Insulating material
- Jacket emissivity
- Surface resistance
- Installed insulation prices/rates
- Pipe size
- Piping complexity factor
- Average ambient temperature to be considering in calculating economic thickness
- Process temperature
- Annual operating hours
- Previous thickness if specified

To calculate the economic insulation thickness considering all the above factors, 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 the economic thickness, the 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 percent.

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

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

Investment is done first and benefits accrued later over a number of years. Therefore, methods based on time value of money are more appropriately used in calculating the economic insulation. Minimum annual cost and maximum net present value are methods that are 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 the minimum annual cost. See tables for example:

	Thickness Based on Current Standard	Economic Thickness	Difference (Incremental)
Insulation investment Rs.	200,000	250,000	50,000
Annual cost. Rs.	40,000	30,000	10,000

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

Item	@std. Current Thickness	@Economic Thickness	Comments
Annual energy cost	40,000	30,000	
Insulation depreciation 250,000/20	10,000	12,500	20,000/20 and
Annual cash cost	30,000	17,500	(1) – (2)
Capital recovery factor for 20 years @10%	0.1175	0.1175	1/8.514
Equivalent annual insulation cost	23,491	29,363	200,000 x .1175 and 250,000 x .1175
Total Annual cost	53,491	46,863	(3) plus (5)

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

Maximum net present value

	@Std. Thickness	@ Economic Ins. Thickness	Comments
Annual energy cost	40,000	30,000	
Annual Ins. Depreciation	10,000	12,500	
Annual cash cost	30,000	17,500	(1) – (2)
Net present value factor for 20 years	8.514	8.514	
Present value of annual cash cost	255,420	148,995	
Initial cost of investment	200,000	250,000	
Net present value of cost	455,420	398,995	(5) plus (6)

Basis

- Investment for standard insulation thickness: Rs. 200,000
- Investment for economic insulation thickness: rs. 250,000
- Life of insulation: 20 years

Conclusion

The Net present value of cost at economic insulation thickness is less than at standard thickness. Therefore, it is the better or the two investment options.

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

There are computers available based on this method. To find out economic insulation thickness, the program increases the insulation thickness from the current 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.

Courtesy: Ramchandra V. Nesari, Dy. General Manger (chemicals),
Rashtriya Chemicals & Fertilizers Ltd
E-mail: nesarirv@vsnl.net

Reference Book:

Indian National Science Academy
April 2006