A Review on Thermal Insulation and Its Optimum Thickness to Reduce Heat Loss

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Abstract

An understanding of the mechanisms of heat transfer is becoming increasingly important in today's world. Conduction and convection heat transfer phenomena are found throughout virtually all of the physical world and the industrial domain. A thermal insulator is a poor conductor of heat and has a low thermal conductivity. In this paper we studied that Insulation is used in buildings and in manufacturing processes to prevent heat loss or heat gain. Although its primary purpose is an economic one, it also provides more accurate control of process temperatures and protection of personnel. It prevents condensation on cold surfaces and the resulting corrosion. We also studied that critical radius of insulation is a radius at which the heat loss is maximum and above this radius the heat loss reduces with increase in radius. We also gave the concept of selection of economical insulation material and optimum thickness of insulation that give minimum total cost.
Keywords: Heat, Conduction, Convection, Heat Loss, Insulation

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I. INTRODUCTION

Heat flow is an inevitable consequence of contact between objects of differing temperature. Thermal insulation provides a region for insulation in which thermal conduction is reduced or thermal radiation is reflected rather than absorbed by the lower temperature body. To change the temperature of an object, energy is required in the form of heat generation to increase the temperature, or heat extraction to reduce the temperature. Once the heat generation or heat extraction is terminated a reverse flow of heat occurs to reverse the temperature back to ambient. To maintain a given temperature considerable continuous energy is required. Insulation will reduce this energy loss.

Heat may be transferred in three mechanisms: conduction, convection and radiation. Thermal conduction is the molecular transport of heat under the effect of temperature gradient. Convection mechanism of heat occurs in liquids and gases, whereby the flow processes transfer heat. Free convection is flow caused by the differences in density as a result of temperature differences. Forced convection is flow caused by external influences (wind, ventilators, etc.). Thermal radiation mechanism occurs when thermal energy is emitted similar to light radiation.

Heat transfers through insulation material occur by means of conduction, while heat loss to or heat gain from atmosphere occurs by means of convection and radiation. Materials, which have a low thermal conductivity, are those, which have a high proportion of small voids containing air or gases. These voids are not big enough to transmit heat by convection or radiation, and therefore reduce the flow of heat. Thermal insulation materials come into the latter category. Thermal insulation materials may be natural substances or man-made.

II. THE NEED FOR INSULATION

A thermal insulator is a poor conductor of heat and has a low thermal conductivity. Insulationis used in buildings and in manufacturing processes to prevent heat loss or heat gain. Although its primary purpose is an economic one, it also provides more accurate control of process temperatures and protection of personnel. It prevents condensation on cold surfaces and the resulting corrosion. Such materials are porous, containing large number of dormant air cells. Thermal insulation delivers the following benefits: [1][2]

A. Energy Conservation
Conserving energy by reducing the rate of heat flow (fig 1) is the primary reason for insulating surfaces. Insulation materials that will perform satisfactorily in the temperature range of -268°C to 1000°C are widely available.

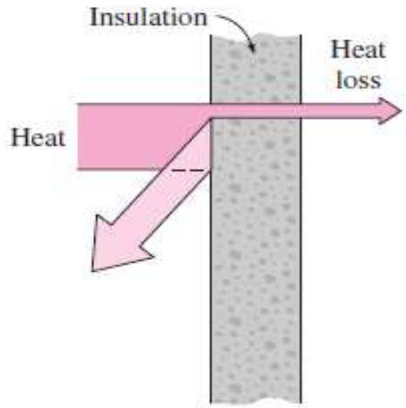

Fig. 1: Thermal insulation retards heat transfer by acting as a barrier in the path of heat flow

B. Personnel Protection and Comfort
A surface that is too hot poses a danger to people who are working in that area of accidentally touching the hot surface and burning themselves. To prevent this dangerand to comply with the OSHA (Occupational Safety and HealthAdministration) standards, the temperatures of hot surfaces should be reduced to below 60°C (140°F) by insulating them.

C. Maintaining Process Temperature
Some processes in the chemical industry are temperature-sensitive, and it may become necessary to insulate the process tanks and flow sections heavily to maintain the same temperature throughout.

D. Reducing Temperature Variation and Fluctuations
The temperature in an enclosure may vary greatly between the midsection and the edges if the enclosure is not insulated. Insulation minimizes temperature non-uniformity in an enclosure and slows down fluctuations.

E. Condensation and Corrosion Prevention
Water vapor in the air condenses on surfaces whose temperature is below the dew point, and the outer surfaces of the tanks or pipes that contain a cold fluid frequently fall below the dew-point temperature unless they have adequate insulation. The liquid water on exposed surfaces of the metal tanks or pipes may promote corrosion as well as algae growth.

F. Fire Protection
Damage during a fire may be minimized by keeping valuable combustibles in a safety box that is well insulated. Insulation may lower the rate of heat flow to such levels that the temperature in the box never rises to unsafe levels during fire.

G. Freezing Protection
Prolonged exposure to subfreezing temperatures may cause water in pipes or storage vessels to freeze. Also, a molten metal or plastic in a container will solidify on the inner surface if the container is not properly insulated.

H. Reducing Noise and Vibration
An added benefit of thermal insulation is its ability to dampen noise and vibrations. The insulation materials differ in their ability to reduce noise and vibration, and the proper kind can be selected if noise reduction is an important consideration.

III. GENERIC TYPES AND FORMS OF INSULATION
Insulations will be discussed in this section according to their generic types and forms. The type indicates composition (i.e. glass, plastic) and internal structure (i.e. cellular, fibrous). The form implies overall shape or application (i.e. board, blanket, pipe covering). [3]

A. Types of Insulations
1) Fibrous Insulation
They are composed of small diameter fibers which finely divide the air space. The fibers may be perpendicular or parallel 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. Glass fiber and mineral wool products usually have their fibers bonded together with organic binders that supply the limited structural integrity of the products.

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), and elastomeric.

3) Granular Insulation

Composed of small nodules which may contain voids or hollow spaces. It is not considered a true cellular material since gas 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 or undergo a chemical reaction to make a rigid insulation. Examples of these insulations are calcium silicate, expanded vermiculite, perlite, cellulose, diatomaceous earth and expanded polystyrene.

B. Forms of Insulations

Insulations are 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 segments, 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) Foams. Poured or froth foam used to fill irregular areas and voids. Spray used for flat surfaces.

IV. INSULATION MATERIALS AND PROPERTIES

A. Thermal Properties of Insulation

Thermal properties are the primary consideration in choosing insulations. Refer to the following Glossaryfor definitions. [3]

1) Temperature limits: Upper and lower temperatures within which the material must retain all its properties.
2) Thermal conductance "C": The time rate of steady state heat flow through a unit area of a material or construction induced by a unit temperature difference between the body surfaces.
3) Thermal conductivity "K": The time rate of steady state heat flow through a unit area of a homogeneous material induced by a unit temperature gradient in a direction perpendicular to that unit area.
4) Emissivity "E": Significant when the surface temperature of the insulation must be regulated as with moisture condensation or personnel protection.
5) Thermal resistance "R": The overall resistance of a "material" to the flow of heat.
6) Thermal transmittance "U": The overall conductance of heat flow through an "assembly".

B. Insulation Material

Properties of common insulating materials are as under: [1]

1) Calcium Silicate: Used in industrial process plant piping where high service temperature andcompressive strength are needed. Temperature ranges varies from 40 °C to 950 °C.
2) Glass mineral wool: These are available in flexible forms, rigid slabs and preformed pipe work sections. Good for thermal and acoustic insulation for heating and chilling system pipelines. Temperature range of application is –10 to 500 °C.
3) Thermocol: These are mainly used as cold insulation for piping and cold storage construction.
4) Expanded nitrile rubber: This is a flexible material that forms a closed cell integral vapourbarrier. Originally developed for condensation control in refrigeration pipe work and chilled water lines; now-a-days also used for ducting insulation for air conditioning.
5) Rock mineral wool: This is available in a range of forms from light weight rolled productsto heavy rigid slabs including preformed pipe sections. In addition to good thermal insulation properties, it can also provide acoustic insulation and is fire retardant.

V. CALCULATION FOR INSULATION THICKNESS

A. Fundamentals of Heat Transfer

Heat flows from a hot or warm medium to a cold medium in three ways: [4][5]

- By radiation from a warm surface to a cooler surface through an air space or vacuum.
- By conduction through solid or fluid materials
- By convection, this involves the physical movement of air.

1) Conduction

Conduction is the direct flow of heat through a material resulting from physical contact. The transfer of heat by conduction is caused by molecular motion in which molecules transfer their energy to adjoining molecules and increase their temperature.
Heat transfer by conduction is governed by a fundamental equation known as Fourier's Law.

$$Q_{cond} = - k\, A \frac{dT}{dx}$$

The factor k is called thermal conductivity or in the case of many insulation materials "apparent thermal conductivity". This property is characteristic of the material and it varies with temperature, density (degree of compaction), and composition. Some typical thermal conductivity and thermal resistivity data are given in the following table for the purpose of comparison.

2) Convection

Convection in buildings is the transfer of heat caused by the movement of heated air. In a building space, warm air rises and cold air settles to create a convection loop and is termed free convection. Convection can also be caused mechanically, (termed forced convection), by a fan or by wind. The convection heat transfer is given by

$$Q_{conv} = h\, A_s\, (T_s - T_\infty) \qquad (2)$$

Where h is the convection heat transfer coefficient in W/m^2, A_s is the surface area through which convection heat transfer takes place, T_s is the surface temperature, and T_∞ is the temperature of the fluid sufficiently far from the surface.

3) Radiation

Radiation is the transfer of heat (infra-red radiant energy) from a hot surface to a cold surface through air or vacuum. All surfaces including a radiator, stove, a ceiling or roof and ordinary insulation radiate to different degrees. The radiant heat is invisible and has no temperature, just energy. When this energy strikes another surface, it is absorbed and increases the temperature of that surface.

B. Critical Radius of Insulation for Cylinder and Sphere

We know that adding more insulation to a wall or to the attic always decreases heat transfer. The thicker the insulation, the lower the heat transfer rate. This is expected, since the heat transfer area *A* is constant, and adding insulation always increases the thermal resistance of the wall without increasing the convection resistance.
Adding insulation to a cylindrical pipe or a spherical shell, however, is a different matter. The additional insulation increases the conduction resistance of the insulation layer but decreases the convection resistance of the surface because of the increase in the outer surface area for convection. The heat transfer from the pipe may increase or decrease, depending on which effect dominates.

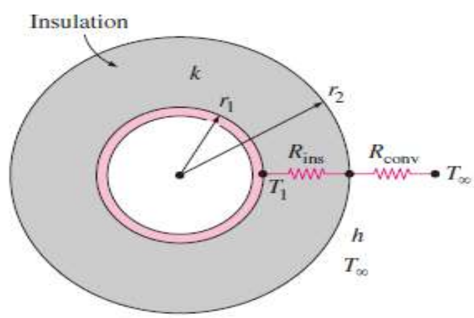

Fig. 2: An insulated cylindrical pipe exposed to convection from the outer surface and the thermal resistance network associated with it.

Consider a cylindrical pipe of outer radius r_1 whose outer surface temperature T_1 is maintained constant (Fig. 3). The pipe is now insulated with a material whose thermal conductivity is *k* and outer radius is r_2. Heat is lost from the pipe to the surrounding medium at temperature T_∞, with a convection heat transfer coefficient *h*. The rate of heat transfer from the insulated pipe to the surrounding air can be expressed as (Fig. 3)

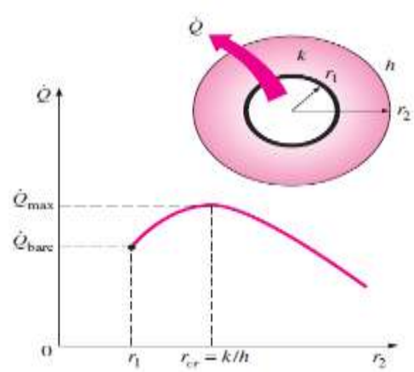

Fig. 3: The variation of Q with the outer radius of the insulation r_2

$$Q = \frac{T_1 - T_\infty}{R_{ins} + R_{conv}} = \frac{T_1 - T_\infty}{\frac{\ln(r_1/r_2)}{2\pi Lk} + \frac{1}{h(2\pi r_2 L)}}$$

The variation of Q with the outer radius of the insulation r_2 is plotted in Fig. 3. The value of r_2 at which Q reaches a maximum is determined from the requirement that $dQ/dr_2 = 0$ (zero slope). Performing the differentiation and solving for r_2 yields the critical radius of insulation for a cylindrical body to be [4]

$$r_{cr,cylinder} = \frac{k}{h}$$

Note that the critical radius of insulation depends on the thermal conductivityof the insulation k and the external convection heat transfer coefficient h.The rate of heat transfer from the cylinder increases with the addition of insulation for $r_2 < r_{cr}$, reaches a maximum when $r_2 = r_{cr}$, and starts to decrease for $r_2 > r_{cr}$. Thus, insulating the pipe may actually increase the rate of heat transfer from the pipe instead of decreasing it when $r_2 < r_{cr}$.

The discussions above can be repeated for a sphere, and it can be shown ina similar manner that the critical radius of insulation for a spherical shell is

$$r_{cr,\ sphere} = \frac{2k}{h}$$

Where k is the thermal conductivity of the insulation and h is the convection heat transfer coefficient on the outer surface.

VI. OPTIMUM THICKNESS OF INSULATION

It should be realized that insulation does not eliminate heat transfer; it merely reduces it. The thicker the insulation, the lower the rate of heat transfers but also the higher the cost of insulation. Therefore, there should be an optimum thickness of insulation that corresponds to a minimum combined cost of insulation and heat lost. The determination of the optimum thickness of insulation is illustrated in Figure 4. Notice that the cost of insulation increases roughly linearly with thickness while the cost of heat loss decreases exponentially. The total cost, which is the sum of the insulation cost and the lost heat cost, decreases first, reaches a minimum, and then increases. The thickness corresponding to the minimum total cost is the optimum thickness of insulation, and this is the recommended thickness of insulation to be installed. [2]

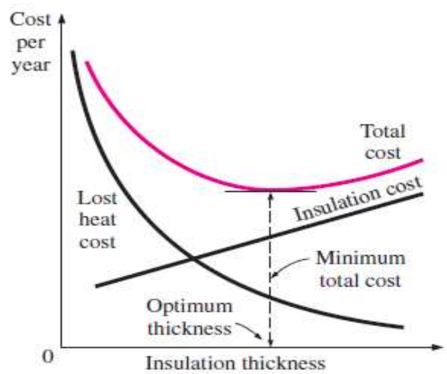

Fig. 4: Determination of the optimum thickness of insulation on the basis of minimum total cost.

The discussion above on optimum thickness is valid when the type and manufacturer of insulation are already selected, and the only thing to be determined is the most economical thickness. But often there are several suitable insulations for a job, and the selection process can be rather confusing since each insulation can have a different thermal conductivity, different installation cost, and different service life. In such cases, a selection can be made by preparing an annualized cost versus thickness chart like figure 5 for each insulation, and determining the one having the lowest minimum cost. The insulation with the lowest annual cost is obviously the most economical insulation, and the insulation thickness corresponding to the minimum total cost is the optimum thickness. When the optimum thickness falls between two commercially available thicknesses, it is a good practice to be conservative and choose the thicker insulation.

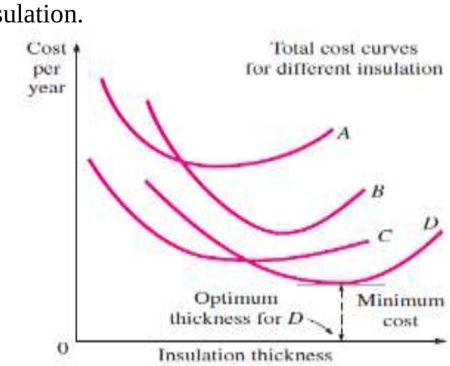

Fig. 5: Determination of the most economical type of insulation and its optimum thickness.

The extra thickness will provide a little safety cushion for any possible decline in performance over time and will help the environment by reducing the production of greenhouse gases such as CO2.

The determination of the optimum thickness of insulation requires a heat transfer and economic analysis, which can be tedious and time-consuming. The primary inputs required for using these tables or chartsare the operating and ambient temperatures, pipe diameter (in the case of pipe insulation), and the unit fuel cost.

VII. RESULTS AND DISCUSSIONS

This paper gives the detailed study of insulation materials, there needs, types, thermal properties and there selection in respect to economic consideration. Heat may be transferred in three mechanisms: conduction, convection and radiation. Heat transfers through insulation material occur by means of conduction, while heat loss to or heat gain from atmosphere occurs by means of convection and radiation. We also studied that adding more insulation to a wall or to the attic always decreases heat transfer. The thicker the insulation, the lower the heat transfer rate. We studied that critical radius of insulation depends on the thermal conductivity of the insulation k and the external convection heat transfer coefficient h. we also studied that the economic thickness of insulation depends on the minimum combined cost of insulation and heat lost.

VIII. CONCLUSIONS

In conclusion, we have successfully outlined the process of setting up and analyzing the thermal insulation and there optimum thickness selection. We were studied the critical radius of insulation for maximum heat transfer in cylindrical and spherical geometry and suggest that at radius, maximum than the critical radius always gives the reduction in heat transfer. We also outlined the method of selection of most economical type of insulation and there optimum thickness. The determination of the optimum thickness of insulation requires a heat transfer and economic analysis, which can be tedious and time-consuming. The primary inputs required are the operating and ambient temperatures, pipe diameter (in the case of pipe insulation), and the unit fuel cost.

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