EXHAUSTIVE REVIEW OF THERMAL INSULATIONS IN ROUTINE APPLICATIONS

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ABSTRACT

This paper gives the detailed review of thermal insulation from the history to the development of different insulations and insulating materials. It also gives the detailed classification of the types, forms and various major materials used for thermal insulation purpose. The properties of the insulation, functions and benefits of insulation help in selection of insulation for any particular application.

Keyword: - *thermal insulation, history and development, types, forms, insulating materials, routine applications.*

1. INTRODUCTION

The energy sources used are limited in magnitude and those will be exhausted by the end of 21st century even if the present rate of demand is continued. These energy resources can be used for a longer time if proper conservation methods are used and available resources are properly managed. In general energy can be conserved by avoiding the waste. Therefore to reduce the wastage of energy in form of heat, furnaces, and pipes carrying fluids at elevated temperature and turbines are insulated. Thermal insulation is the reduction of heat transfer (the transfer of thermal energy between objects of differing temperature) between objects in thermal contact or in range of radiative influence. Thermal insulation can be achieved with specially engineered methods or processes, as well as with suitable object shapes and materials. Heat flow is an inevitable consequence of contact between objects of differing temperature. Thermal insulation provides a region of insulation in which thermal conduction is reduced or thermal radiation is reflected rather than absorbed by the lower-temperature body. The insulating capability of a material is measured with thermal conductivity (k). Low thermal conductivity is equivalent to high insulating capability (r-value). In thermal engineering, other important properties of insulating materials are product density (ρ) and specific heat capacity (c) which are taken into account while selecting the insulators.

2. HISTORY AND DEVELOPMENT

The history of thermal insulation is not as long as that of other building constructions. Long ago thermal insulation did not form a separate layer in building construction because there was no need to build in extra materials to assure the insulating function. The process of building activity appeared when prehistoric human beings first created shelters themselves. The main reason for this activity was protection against wild animals and the elements (cold winters, hot summers), i.e. insulation from the surroundings. Accordingly we can reasonably assume that one of the most important requirements for building construction is the necessity of adequate thermal insulation which is as old as building activity itself and has existed since prehistoric times[1].

The first prehistoric peoples built temporary dwellings from same materials that they used for clothing. The most common materials were animal skins, fur, wool and plant related products like reed, flax or straw, but their lifespan was limited. Later because of the settled lifestyle and the development of agriculture they needed more durable materials for housing, like stone, wood and earth.

Both earth-sheltered houses and cave dwellings were built at the same time and it appears they were very popular because of their inherent benefits. Their implementation was cheap and an earth covering assured excellent protection against wild animals, fire and during periods of fighting. In addition earth houses use soil as a magnificent insulating blanket, as due to the high density of earth, the inside temperature changes very slowly. This phenomenon is called thermal lag which is why earth covering keeps the interior warm in winter and cool in summer.

The houses in the Neolithic village of Skara Brae (Orkney Island, Scotland) are the oldest known – nearly 5.000 years old – earth-sheltered, green roofed dwellings in the world (Fig. 1) but we can come across similar buildings in cold climatic areas like Scandinavia, Iceland, Russia, Greenland and Alaska.

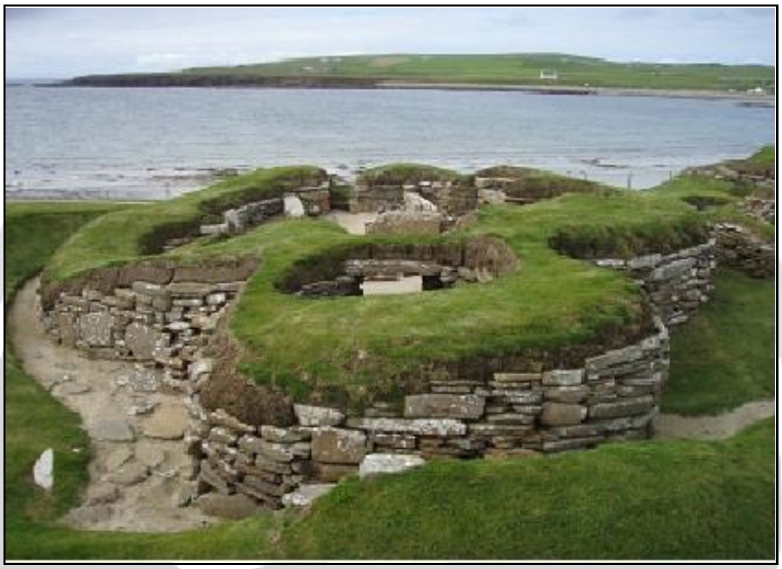

Fig. 1: The Neolithic village of Skara Brae (Orkney Island, Scotland)

At the end of the 19th century the techniques of planning and construction had developed and changed dramatically over a relatively short period. New building materials emerged (cast-iron, glass structures, concrete, and steel) and structural systems were planned not in empirical ways but on calculative methods [6, 7].

At first, the main problem was caused by the unusual thermal expansion of these new materials. To avoid the cracks and resulting damage it became obvious, that these structures needed extra thermal protection [6, 7].

Furthermore the thermal insulation capacity of the slight cast-iron, concrete and steel constructions was much lower than a thick wall made of adobe or bricks resulting in greater heat loss and higher heating demands. By turn of the 20th century, it was clear that flat roofs made of reinforced concrete, and the light frame structures made of steel and wood also needed extra thermal protection.

Rising energy consumption and the relatively high costs of fossil fuels (coal, crude oil) during the worldwide economic crisis (Long Depression, 1873-1896) forced thermal power plants to reduce the heat losses from steam engines, heating equipment, chimneys and also building structures around them [8]. This and light frame construction were some of the reasons why industrial architecture started to utilize thermal insulation materials.

A focus of the developing technologies and their innovations was to improve human comfort in buildings. It was evident that the task soon became how to keep the heat in, with the role of thermal insulation becoming significant in residential buildings [6, 7]. Heating and ventilation equipment showed extraordinary development in the 1880s and the calibration of them became necessary. The calculation of heat loss and heat gain of buildings became the key problem for building mechanical engineers with the first theories on thermal insulation and building physics appearing at the same time [8].

From this time people started to use thermal insulation materials. At first they processed materials that were found in nature, but later other specific artificial materials were discovered that were suitable for thermal insulation.

3. TYPES OF INSULATIONS

3.1. Fibrous Insulation

It is composed of small diameter fibres which finely divide the air space. The fibres 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 fibres are used. The most widely used insulations of this type are glass fibre and mineral wool. Glass fibre and mineral wool products usually have their fibres bonded together with organic binders that supply the limited structural integrity of the products.

3.2. Cellular Insulation

It is composed of small individual cells separated from each other. The cellular material may be glass or foamed plastic such as polystyrene (closed cell), polyisocyanurate and elastomeric.

3.3. Granular Insulation

It is 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 fibres 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 [2].

4. FORMS OF INSULATION

4.1 Board

Rigid or semi-rigid self-supporting insulation formed into rectangular or curved shapes.

- Calcium silicate
- Fiber glass or mineral fiber
- Mineral wool or mineral fiber
- Polyisocyanurates
- Polystyrene

4.2 Block

Rigid insulation formed into rectangular shapes.

- Calcium silicate
- Cellular glass
- Mineral wool or mineral fiber
- Perlite

4.3 Sheet

Semi-rigid insulation formed into rectangular pieces or rolls.

- Fiber glass or mineral fiber
- Elastomeric foam
- Mineral wool or mineral fiber
- Polyurethane

4.4 Flexible Fibrous Blankets

A flexible insulation used to wrap different shapes and forms.

- Fiber glass or mineral fiber
- Mineral wool or mineral fiber
- Refractory ceramic fiber

4.5 Pipe and Fitting Insulation Pre-formed insulation to fit piping, tubing and fittings

- Calcium silicate
- Cellular glass
- Elastomeric foam
- Fiber glass or mineral fiber
- Mineral wool or mineral fiber
- Perlite
- Phenolic foam
- Polyethylene
- Polyisocyanurates
- Polyurethanes

4.6 Foam

Liquid mixed at the time of application which expands and hardens to insulate irregular areas and voids.

- Polyisocyanurates
- Polyurethane

4.7 Spray Applied Insulation

Liquid binders or water introduced to insulation while spraying on to flat or irregular surfaces for fire resistance, condensation control, acoustical correction and thermal insulation.

- Mineral wool or mineral fiber

4.8 Loose fill Granular insulation used for pouring expansion joints.

- Mineral wool or mineral fiber
- Perlite
- Vermiculite

4.9 Cements (Insulating and Finishing Muds)

Produced with mineral wool and clay insulation, these cements may be hydraulic setting or air drying types.

4.10 Flexible Elastomeric Foam

Foam sheets and tubing insulation containing vulcanized rubber [2].

5. PROPERTIES OF INSULATION

5.1 Thermal Properties

Thermal properties are the primary consideration in choosing insulations [2].

- Temperature limits: Upper and lower temperatures within which the material must retain all its properties.

- 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.

- 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.

- Emissivity "E": The emissivity of a material (usually written ε or e) is the relative ability of its surface to emit energy by radiation. It is the ratio of energy radiated by a particular material to energy radiated by a black body at the same temperature.

- Thermal resistance "R": Resistance of a material to the flow of heat.

- Thermal transmittance "U": The overall conductance of heat flow through an "assembly".

5.2 Mechanical and Chemical Properties

Properties other than thermal must be considered when choosing materials for specific applications. Among them are:

- Alkalinity (pH) or acidity: Significant when moisture is present. Also insulation must not contribute to corrosion of the system.

- Appearance: Important in exposed areas and for coding purposes.

- Breaking load: In some installations the insulation material must "bridge" over a discontinuity in its support. This factor is however most significant as a measure of resistance to abuse during handling.

- Capillarity: Must be considered when material may be in contact with liquids.

- Chemical reaction: Potential fire hazards exist in areas where flammable chemicals are present. Corrosion resistance must also be considered.

- Chemical resistance: Significant when the atmosphere is salt or chemical laden and when pipe content leaks.

- Coefficient of expansion and contraction: Enters into the design and spacing of expansion/contraction joints and/or use of multiple layer insulation applications.

- Combustibility: One of the measures of a material's contribution to a fire hazard.

- Compressive strength: 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.

- Density: A material's density may affect other properties of that material, such as compressive strength. The weight of the insulated system must be known in order to design the proper support.

- Dimensional stability: Significant when the material is exposed to temperature; expansion or shrinkage of the insulation may occur resulting in stress cracking , voids, sagging or slump.

- Fire retardancy: Flame spread and smoke developed ratings are of vital importance; referred to as "surface burning characteristics".

- Resistance to ultraviolet light: Significant if application is outdoors and high intensity indoors.

- Resistance to fungal or bacterial growth: Is important in all insulation applications.
- Shrinkage: Significant on applications involving cements and mastics.
- Sound absorption coefficient: Must be considered when sound attenuation is required, as it is in radio stations, some hospital areas where decibel reduction is required.
- Sound transmission loss value: Significant when constructing a sound barrier.
- Toxicity: Must be considered in the selection of all insulating materials.

6. MAJOR INSULATION MATERIALS

6.1 Calcium Silicate

Calcium silicate insulation is composed principally of hydrous calcium silicate which usually contains reinforcing fibers; it is available in molded and rigid forms. Service temperature range covered is 35°C to 815°C. Flexural and compressive strength is good. Calcium silicate is water absorbent. However, it can be dried out without deterioration. The material is non-combustible and used primarily on hot piping and surfaces. Jacketing is field applied.

6.2 Mineral Fibre

- Glass: Available as flexible blanket, rigid board, pipe covering and other pre-molded shapes. Service temperature range is -40°C to 232°C. Fibrous glass is neutral; however, the binder may have a pH factor. The product is non-combustible and has good sound absorption qualities.
- Rock and Slag: Rock and slag fibers are bonded together with a heat resistant binder to produce mineral fiber or wool. Upper temperature limit can reach 1035°C. The same organic binder used in the production of glass fiber products is also used in the production of most mineral fiber products. Mineral fiber products are non-combustible and have excellent fire properties.

6.3 Cellular Glass

Available in board and block form capable of being fabricated into pipe covering and various shapes. Service temperature range is -273C to 200°C and to 650°C in composite systems. Good structural strength, poor impact resistance. Material is non-combustible, non-absorptive and resistant to many chemicals.

6.4 Expanded Silica or Perlite

Insulation material composed of natural or expanded perlite ore to form a cellular structure; material has a low shrinkage coefficient and is corrosion resistant; non-combustible, it is used in high and intermediate temperature ranges. Available in pre-formed sections and blocks.

6.5 Elastomeric Foam

Foamed resins combined with elastomers to produce a flexible cellular material. Available in preformed sections or sheets, Elastomeric insulation offer water and moisture resistance. Upper temperature limit is 105^{o}C. Product is resilient. Fire resistance should be taken in consideration.

6.6 Foamed Plastic

Insulations produced from foaming plastic resins create predominately closed cellular rigid materials. "K" values decline after initial use as the gas trapped within the cellular structure is eventually replaced by air. Check manufacturers' data. Foamed plastics are light weight with excellent cutting characteristics. The chemical content varies with each manufacturer. Available in pre-formed shapes and boards, foamed plastics are generally used in the lower intermediate and the entire low temperature ranges. Consideration should be made for fire retardancy of the material.

6.7 Refractory Fiber

Refractory Fiber insulations are mineral or ceramic fibers, including alumina and silica, bonded with extremely high temperature inorganic binders, or a mechanical interlocking of fibers eliminates the need for any binder. The material is manufactured in blanket or rigid form. Thermal shock resistance is high. Temperature limits reach 1750°C. The material is non-combustible.

6.8 Insulating Cement

Insulating and finishing cements are a mixture of various insulating fibers and binders with water and cement, to form a soft plastic mass for application on irregular surfaces. Insulation values are moderate. Cements may be applied to high temperature surfaces. Finishing cements or one-coat cements are used in the lower intermediate range and as a finish to other insulation applications. Check each manufacturer for shrinkage and adhesion properties [3].

7. FUNCTIONS OF INSULATIONS

The insulation is used to perform one or more of the following functions[3].

- Reduce heat loss or heat gain to achieve energy conservation.
- Protect the environment through the reduction of CO_2, NO_x and greenhouse gases.
- Control surface temperatures for personnel and equipment protection.
- Control the temperature of commercial and industrial processes.
- Prevent or reduce condensation on surfaces.
- Increase operating efficiency of heating/ventilation/cooling, plumbing, steam, process and power systems.
- Prevent or reduce damage to equipment from exposure to fire or corrosive atmospheres.
- Reduce noise from mechanical systems.

8. BENEFITS OF INSULATION

8.1 Energy Savings

Substantial quantities of heat energy are wasted daily in industrial plants nationwide because of under insulated, under maintained or uninsulated heated and cooled surfaces. Properly designed and installed insulation systems will immediately reduce the need for energy. Benefits to industry include enormous cost savings, improved productivity, and enhanced environmental quality.

8.2 Process Control

By reducing heat loss or gain, insulation can help 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. The need to provide time for owners to take remedial action in emergency situations in the event of loss of electrical power, or heat sources is a major reason for this action in static systems.

8.3 Personnel Protection

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 operating at temperatures above 136.4°F (ASTM C 1055). Insulation reduces the surface temperature of piping or equipment to a safer level as required by OSHA, resulting in increased worker safety and the avoidance of worker downtime due to injury.

8.4 Fire Protection

Used in combination with other materials, insulation helps provide fire protection in:

- Fire stop systems designed to provide an effective barrier against the spread of flame, smoke, and gases at penetrations of fire resistance rated assemblies by ducts, pipes, and cable.
- Electrical and communications conduit and cable protection.

8.5 Sound Attenuation

Insulation materials can be used in the design of an assembly having a high sound transmission loss to be installed between the source and the surrounding area. Aesthetics

8.6 Greenhouse Gas Reduction

Thermal insulation for mechanical systems provides immediate reductions in CO2, NOx and greenhouse gas emissions to the outdoor environment in flue or stack emissions by reducing fuel consumption required at the combustion sites because less heat is gained or lost by the system [3].

9. ROUTINE APPLICATIONS OF THERMAL INSULATIONS

9.1 Clothing

Clothing can help control the temperature of the human body. To offset high ambient temperature, clothing can enable sweat to evaporate (thus permitting cooling by evaporation). The billowing of fabric during movement can create air currents that increase evaporation and cooling. A layer of fabric then insulates slightly and can help keep skin temperatures to a cooler level.

To combat low ambient temperatures, a thick insulation is desirable to reduce conductive heat loss. Other things being equal, a thick sleeping bag is warmer than a thin one. At the same time, evacuating skin humidity remains important: several layers of materials with different properties may be used to achieve this goal while lowering heat losses so they match the body's internal heat production. Clothing heat loss occurs due to wind, radiation of heat into space, and conductive bridging. The latter is most apparent in footwear where insulation against conductive to the ground is most important.

9.2 Buildings

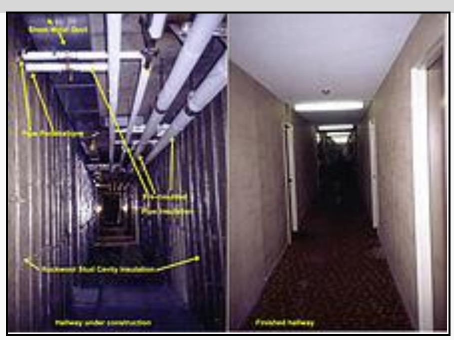

Fig. 2: Insulation in apartment building in Ontario, Canada.

Maintaining acceptable temperatures in buildings (by heating and cooling) uses a large proportion of global energy consumption. When well insulated, a building:

- Is energy-efficient, thus saving the owner money.

- Provides more uniform temperatures throughout the space. There is less temperature gradient both vertically (between ankle height and head height) and horizontally from exterior walls, ceilings and windows to the interior walls, thus producing a more comfortable occupant environment when outside temperatures are extremely cold or hot.
- Has minimal recurring expense. Unlike heating and cooling equipment, insulation is permanent and does not require maintenance, upkeep, or adjustment.
- Lowers the Tripton rating of the carbon footprint produced by the house.

Many forms of thermal insulation also reduce noise and vibration, both coming from the outside and from other rooms inside a building, thus producing a more comfortable environment. Window insulation film can be applied in weatherization applications to reduce incoming thermal radiation in summer and loss in winter.

In industry, energy has to be expended to raise, lower, or maintain the temperature of objects or process fluids. If these are not insulated, this increases the energy requirements of a process, and therefore th e cost and environmental impact.

9.3 Mechanical systems

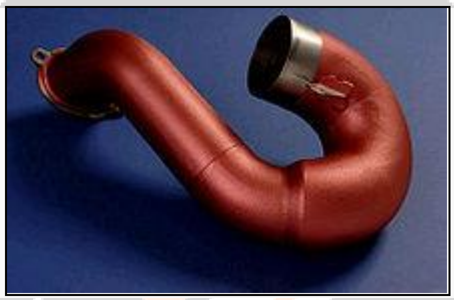

Fig.3: Pipe insulation

Thermal insulation applied to exhaust component by means of plasma spraying Space heating and cooling systems distribute heat throughout buildings by means of pipe or ductwork. Insulating these pipes using pipe insulation reduces energy into unoccupied rooms and prevents condensation from occurring on cold and chilled pipe work [4]. Pipe insulation is also used on water supply pipework to help delay pipe freezing for an acceptable length time.

9.4 Spacecraft

Launch and re-entry place severe mechanical stresses on spacecraft, so the strength of an insulator is critically important (as seen by the failure of insulating foam on the Space Shuttle Columbia).

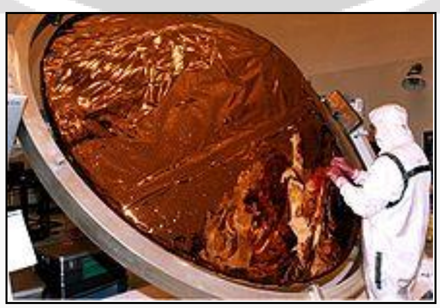

Fig. 4: Thermal insulation on the Huygens probe

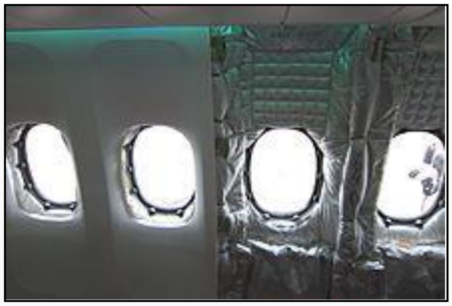

Fig. 5: Cabin insulation of a Boeing 747-8airliner

Re-entry through the atmosphere generates very high temperatures due to compression of the air at high speeds. Insulators must meet demanding physical properties beyond their thermal transfer retardant properties. E.g. reinforced carbon-carbon composite nose cone and silica fiber tiles of Space Shuttle. See also insulative paint.

9.5 Automotive

Internal combustion engines produce a lot of heat during their combustion cycle. This can have a negative effect when it reaches various heat-sensitive components such as sensors, batteries and starter motors. As a result, thermal insulation is necessary to prevent the heat from the exhaust reaching these components. Therefore Insulation is used in Exhaust Heat Management [5]. High performance cars often use thermal insulation as a means to increase engine performance.

10. CONCLUSION

The thermal insulation helps in reduction of heat transfer between objects in thermal contact or in range of radiative influence. The types, forms of insulation and insulating materials are selected according the requirement of application based on the properties and functions. The various routine applications as discussed above uses the above mentioned criteria for each application. The thermal insulation also helps in enhancing the surface where it is applied also it is used to increase life and efficiency of the system.

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