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Thermal Insulation Materials: A Tool for Energy Conservation

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Abstract

Energy conservation is an increasingly important issue for the dairy and food industry. Therefore, attention towards thermal insulation systems for plant equipment has grown in recent years. 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. In this study, a literature review on different thermal insulation material with their properties, types and applications. The selection of optimal thermal insulation has great potential towards the energy saving.

Keywords: Energy; Insulation materials

Introduction

Insulation materials are very basic and important requirement in any industry dealing with various heat transfer unit operations. It is very important in dairy and food industry to maintain the temperature of chilled water and steam supply, store the products at low temperature either in cold storages or in tanks and transportation of the products at lower temperature. The basic aim of insulation is to retard the rate of heat flow in order to prevent/minimize the change of temperature of the system or the space. It has been reported that in dairy industry 50% of the energy is consumed in heating and cooling of milk [1]. As dairy and food industry involves several unit operations, either at higher temperature or lower temperature as compared to ambient conditions of the air, the use of insulation materials in dairy and food industry is inevitable for the conservation of energy. There are several insulation materials available in the market having different insulating properties. It is very important to select right type of insulation material considering temperature of the system and mode of heat transfer involved. The selection of insulating material, deciding the thickness, correct method of performing the insulation of steam and chilled water pipelines, milk storage tanks, silos, bulk milk coolers, cold storages, etc. are some of the important considerations to achieve optimum results.

Thermal insulation

Thermal insulation is defined as a material or combination of materials which on application retards the flow of heat and adapted to any size, shape and surface [2,3]. Thus, the insulation is the outcome of performing the process to thermally isolate the system using insulating materials to reduce the heat transfer rate drastically between the system and the adjacent body or the environment. The term 'thermal insulation' is applied in the temperature range from -75°C to 815°C and applications below -75°C are termed 'cryogenic' while above 815°C are termed as 'refractory' [4].

A thermal insulator is a poor conductor of heat having very low thermal conductivity. Insulation is used in dairy and food industries to prevent heat loss or heat gain. Such materials are porous, containing large number of air cells [5]. Glass wool, polystyrene and polyurethane foam are widely used as insulating materials in dairy and food plants. However, there are few other types of insulation materials which are available as a potential option as an insulating material for dairy and food industry.

Advantages of insulation

The primary purpose of insulation is to prevent/minimize thermal energy losses for the conservation of energy. However, insulation helps in several ways as indicated below;

I. It provides more accurate control of process temperatures and protection of the product.

II. It prevents condensation on cold surfaces and the resulting corrosion.

III. It helps in saving of energy and reduction in Green House Gases (GHGs) in environment.

IV. It minimises the formation of condensate in steam pipeline and related problems.

V. It provides fire protection and absorbs vibration.

Many direct and indirect advantages of insulation have been reported [4,6]. Thermal insulation delivers lots of benefits like; reducing over-all energy consumption, better process control by maintaining process temperature, prevents corrosion, provides fire protection and absorbs vibration [4]. Enhanced thermal protection is the most cost-effective way to reduce energy loss and operational costs [7]. Substantial quantity of heat energy is wasted in industrial plants nationwide because of uninsulated, under maintained or under insulated heated or cooled surfaces [2]. Properly designed and installed insulation systems reduce the consumption of energy. Some recent studies demonstrated that application of thermal insulations may result heating and cooling energy savings up to 25% [8,9]. Some reports also inferred that, insulation materials have the potential to reduce energy consumption between 18-34% depending upon the type of insulation and the ambient temperature [10].

Important properties of insulation materials

There are many properties of insulating materials which are important to consider for the selection of insulation materials from the market. The final selection not only depends on the properties of the material but on the basis of economics and structural considerations.

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An ideal insulating material should fulfil a number of criteria such as low thermal conductivity, non corrosive, non toxic, non flammable and exhibit little or no decomposition at long period of time [11]. The five key properties of an insulating material to be considered have been described; these properties are compressive strength, service temperature range, thermal conductivity, water absorption and thickness tolerance [2,3,12]. The compressive strength of most insulating materials decreases as temperature increases and therefore it is necessary to consider the compressive strength at the service temperature. The service temperature is the highest temperature at which the insulation material can perform reliably in long-term application. Thermal conductivity (K) is the most important in determining a material's ability to resist the flow of heat. The absorption of water in insulating material increases conductivity of the material and causes swelling of the material. Thickness tolerance is important for achieving alignments and product quality. A low value of thermal expansion at operating temperatures is required for the insulation.

Types of insulation materials

Insulation is well known to humans from a long time. Egyptians used earth as an insulator for their comfort [13]. The first use of insulation using cellulose was patented in England in 1893. It is reported that more applications of insulation started from the 1920's [14].

There are three types of insulation materials in general [3]:

a. Fibrous insulations (e.g. Ceramic fibre, glass mineral wool, rock mineral wool, etc.)

b. Cellular insulations (e.g. Polyurethane, polystyrene and polypropylene, etc.)

c. Granular insulations (e.g. Calcium silicate, perlite expanded and vermiculate)

There are many insulation materials available for hot and cold insulations in dairy and food industry. The following are the insulation materials that are accepted by the process industries [15].

Hot insulation materials

Glass mineral wool: Glass mineral wool is available in a wide range of forms ranging from flexible rolls, rigid slabs and preformed pipe sections. It is particularly suitable for thermal insulation in steam pipeline, hot water line and other industrial applications such as high performance insulation in the aircraft industry [16]. It is generally used for high temperature insulations as it is cost effective and steady in performance. It is popular in dairy and food industry for steam pipeline insulation. The thermal conductivity is 0.031 to 0.042 W/mK. The density of the insulation material ranges from 10 to 80 kg/m^3 with service temperature range of -200°C to 450°C. The compressive strength of the glass mineral wool is 1 to 8 kN/m^2, the water vapour transmission is 346 to 417 µgm/Nh and it is non-combustible by nature, which is acceptable for high temperature applications [17].

Cellulose glass: Cellulose glass as an insulating material is available with relatively high density and 40 to 160 mm thickness. The thermal conductivity ranges from 0.034 to 0.081 W/mK with the service temperature of -260°C to 430°C. The water vapour transmission is zero with a compressive strength of 700 kN/m^2. It is a non-combustible insulation material [18].

Calcium silicate: It is suitable to use in superheated steam lines and hot water pipe lines, fitments and vessels. It is also used in furnace insulation or in boiler insulation. It is generally available in 240 kg/m^3 density and a thickness ranging from 25 to 100 mm. The thermal conductivity range is 0.054 W/mK. The maximum service temperature of calcium silicate is 1000°C with no water vapour penetration under normal conditions. It is a non-combustible material and has a compressive strength of 600 kN/m^2 [19].

Ceramic fibre: Ceramic fibre is a refractory grade material suitable for use up to 1400°C. It is generally used for thermal insulation within dairy and food processing industries such as in boilers. The density of the Ceramic Fibre is in the range of 64 to 192 kg/m^3 with a thickness of 6 to 50 mm. The thermal conductivity is from 0.030 to 0.079 W/mK with the water vapour transmission of zero. The compressive strength 2.5 kN/m^2 and they are non-combustible [15].

Melamine foam: Melamine foam involves a fibre free insulation, suitable for use on low and medium temperature heating. It has applications in food processing, breweries and pharmaceutical industries. Melamine foams are commercially available with 11 kg/m^3 density and 10 to 50 mm thickness. The thermal conductivity is 0.034 W/mK with the service temperature range of 10°C to 150°C. Melamine foams have the water vapour transmission of 350 µgm/Nh and a compressive strength of 5 to 20 kN/m^2. The melamine foams are combustible [20].

Perlite expanded: Perlite expanded can be used as structural insulation in cold stores and for storage tanks. It is suitable for use above 180°C as it contains no organic materials and can be used insulating refractory materials. Perlite expanded is available with the density of 80 kg/m^3 and of 25 to 300 mm thickness. It has a thermal conductivity of 0.057 W/mK. The service temperature range of the perlite expanded is -250°C to 1000°C and it is a non-combustible insulating material [15]. Since it contains a hydrophobic agent, it repels water which confirms a zero water vapour transmission rate [21].

Rock mineral wool: Rock mineral wool is used as a thermal insulation and fire protection of plant, equipment and in structures in the commercial and industrial sectors. It has density of 80 kg/m^3 with 20 to 120 mm thickness. It also has thermal conductivity of 0.033 W/mK and a service temperature range of -200°C to 900°C. It has the water vapour transmission rate of 385-400 µgm/Nh and a compressive strength of 7.5 to 10.5 kN/m^2, which is significantly higher than other insulating materials. It is non-combustible insulating material [16].

Vermiculate: Vermiculate is used as a loose fill granular insulate. It is used in hazardous goods packaging, insulating concretes and with plasters. Sometimes it contains asbestos in it which is not suitable for human health. It is used as both, for general purpose and for fire resistivity. It is used to insulate fitments like steam pipe line as it can bear a high level of vibration. Vermiculate has the density ranging from 50 to 150 kg/m^3 with a thermal conductivity of 0.066 to 0.083 W/mK. The service temperature range is from 0°C to 1300°C with a water vapour transmission of Vermiculate is 350 µgm/Nh. The thickness range varies according to the use. Vermiculate are non-combustible [22].

Cold insulation

Cork: Cork is a resilient material and it is suitable for use on chilled water and industrial refrigeration pipe work, as it involves higher vibrations. Oak wood is generally used in cork. It is available with 112 kg/m^3 density and a thermal conductivity of 0.038 W/mK. Corks have a service temperature range of -180°C to 100°C. It has water vapour transmission of 20 to 40 µgm/Nh and a very less compressive strength compared to other materials. Corks are available in Slabs and Pipe insulation form with available thickness of 13 to 305 mm. Corks are highly combustible [22].

Nitrile rubber expanded: Nitrile rubber expanded is a closed cell, flexible integral vapour barrier insulation. It is widely used for condensation control and reducing heat gain on air conditioning, chilled water and refrigeration services. It is also used for frost protection and energy conservation in chilled water pipe work. Nitrile rubber expanded is having a density of 60 to 90 kg/m^3 with thickness of 6 to 32 mm. Its thermal conductivity ranges from 0.033 to 0.044 W/mK with a service temperature of -40°C to 116°C. This type of insulation materials permits around 0.25 µgm/Nh water vapour transmission. The compressive strength of nitrile rubber expanded is 14 to 35 kN/m^2 and they are combustible by nature [20].

Phenolic foam: Phenolic foam is used in commercial and industrial insulation applications where high insulation standards are required but space is less. It can also work as a substitute for PUF in low temperature applications like cold stores and storage tanks. Phenolic foams are having a density range from 35 to 120 kg/m^3 with a thickness of around 10 to 600 mm. The thermal conductivity of this material is between 0.018 to 0.022 W/mK and the service temperature range is from -180°C to 120°C. It has a water vapour transmission of 10 µgm/Nh with a compressive strength of 172 kN/m^2. Phenolic foams are non-combustible [23,24].

Polyethylene foam: Polyethylene foams are closed cell insulation materials, refinements to cell structure have made to improve thermal conductivity. It is widely used in the form of pipe insulation for frost protection and energy conservation. Polyethylene foams are available with a density of 30 to 60 kg/m^3 and a thickness range of 6 to 32 mm. The thermal conductivity of polyethylene foam is from 0.033 to 0.045 W/mK with the service temperature range of -50°C to 105°C. The water vapour transmission from this insulation material is 0.5 µgm/Nh and the compressive strength is between 19 to 168 kN/m^2 which are higher than some other insulation materials. That is why this type of insulation material is not used where the operating pressure is higher. Polyethylene foams are combustible by nature [5].

Polypropylene: Polypropylene is used for thermal insulation in tank container industry where a lightweight product with low water absorption rate is required. The higher density gives improved mechanical properties and lower thermal conductivity at low temperatures. These types of insulations are widely used in rail or road containers' insulation. Polypropylene is one of the widely used insulation material. It is available with a density of 20 kg/m^3 and a thickness of 43 and 50 mm and a thermal conductivity of 0.034 W/mK. This type of insulation materials are high performance insulators. The service temperature range of polypropylene is from -40°C to 130°C. The water vapour transmission is around 0.45 µgm/Nh and it is non-combustible insulation material [20].

Polystyrene: Polystyrene is used in construction of floor, wall, and roof insulations in cold stores and industrial premises. It is also used as a pipe insulation material in commercial and industrial refrigeration applications. Polystyrene expanded are popularly known as thermocole. This type of insulation materials are widely used and accepted by every industry for the insulation purpose, as it is very cheap. Polystyrenes are available in form of polystyrene expanded and polystyrene extruded. Polystyrene is generally available in 15 to 30 kg/m^3 density and 5 to 610 mm thickness with a thermal conductivity of 0.033 to 0.038 W/mK. The service temperature range of polystyrene is from -150°C to 80°C and the water vapour transmission rate is 25 µgm/Nh. The compressive strength of polystyrene is 15 kN/m^2 and it is highly combustible insulation material [25].

Polyurethane foam (PUF): Polyurethane Foams are also known as PUF. It is used in medium to heavy-duty refrigeration systems to reduce heat gain and provide condensation control and in low temperature tanks of carbon dioxide, propane, etc. Laminated panels of PUFs are used in cold stores and refrigerated vehicles. Polyurethane foams are very popular insulation material it is available with thickness of 10 to 15 mm. It has a density ranging from 35 to 50 kg/m^3 with a thermal conductivity ranging from 0.016 to 0.023 W/mK. The service temperature range of PUF is in the range of -180°C to 110°C. PUF has a water vapour transmission of 20 µgm/Nh with a maximum compressive strength of 350 kN/m^2. These types of insulation materials are combustible by nature [26,27].

Synthetic rubber expanded: Synthetic rubber expanded is used as closed cell, flexible, integral vapour barrier insulant. Different grades suitable for low temperature applications such as for medium or low temperatures and for low-pressure ammonia lines are available. Synthetic rubber expanded is having a thermal conductivity ranging from 0.038 W/mK with a density of 60 kg/m^3. The service temperature range of this insulation material is from -50°C to 150°C. The water vapour transmission rate of this insulation material is 0.1 µgm/Nh with maximum compressive strength of 14 to 35 kN/m^2. The synthetic rubber expanded is available with the thickness of 9 to 25 mm. These types of materials are combustible [15].

Method of Insulation

There is a basic need for insulation at any surface which is in contact with hot or cold surrounding. To insulate a surface, there are few points that are required to be taken care of like cleaning of surface [28,29] and application of corrosion repellents like chloride, fluorine and magnesium to have least amount of water gain to prevent corrosion [30]. Thompson [31] reported that, each product has a different temperature for storage, according to this temperature, the optimum operating temperature and the type of insulation material and thickness of insulation is selected. The designing is a very important which involves location of the plant, temperature conditions and service conditions [32]. Thickness of insulation is also very important in designing, there is a thickness below which the insulation is insufficient and the loss of heat is more [33] Higher thickness results into higher cost input with a little thermal savings [34,35]. Thus, economical thickness has to be calculated for given insulation material.

The water vapour barriers like bituminous, epoxy and aluminium foils of minimum 0.06 mm are required on the cold side of the insulation [15,36,37]. Hart and Yarbrough [21] noticed that, once the insulation system started to absorb significant quantities of greater than 2% volume, the performance might find unsatisfactory. Among all insulation materials, Polyurethane Foam (PUF) is the most commonly used insulation material in diary and food industry. It can be applied through blocks or spray of the foam which hardens instantly for in-situ or crevice insulation. PUF contains a viscous cream-colored liquid containing a polyether polyol, a silicone surfactant and a catalyst. Another solution is a dark brown viscous liquid containing diphenylmethane di-isocyanate and higher oligomers of di-isocyanate. When the polyether polyol is mixed with the di-isocyanate, an exothermic reaction occurs, producing polyurethane foam. This foam is either sprayed on the wall or filled into a structure where it makes a rigid structure. Prefabricated polyvinyl sheets are applied on it if it is a sprayed insulation [38-40]. Next step is application of insulation material either in-situ insulation or panel insulation with a glue to the surface in a staggered manner and with a wire mash placed above it for better holding of plaster or tiles [15,39].

Conclusion

Insulation is one of the essential requirements for conservation of energy in dairy and food industries as many unit operations involve heating and cooling processes. The saving of energy is not only important to reduce the cost of processing, but also helps in reducing the emission of green house gases in the environment. Increased awareness towards the environment and public health is leading to an integrated evaluation of insulation materials and whilst no one questions their positive action, there is still significant potential for improving their overall performance. There are various types of insulation materials which can be used in dairy industry at several places like cold stores, steam and chilled water pipelines, milk silos and tanks, etc. to save the energy loss. The appropriate insulation must be selected on the basis of temperature, thermal conductivity and other factors that might limit application. The optimisation of insulation considering saving of energy, cost of insulation and its installation is one of the basic requirements to achieve optimum benefit. There is a need to develop more efficient insulating materials in terms of heat transfer, water repellent properties, ease of application, strength, etc. The thickness must be determined for the particular application according to the type and temperature range. Insulation materials not only saves the heat loss and energy, but it also helps to protect the contained structure which makes it an essential input required for dairy and food industry.

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