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The Importance of Thermal Insulation: Characteristics, Properties and Applications

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Abstract–

Thermal insulation is used to ensure that there is no loss or gain of heat in a medium, and therefore must be very well chosen considering the properties, applications and costs. It is used for protection, prevention, comfort and economy. The choice of insulation, the thickness and the method of application are extremely important to obtain good technical and economic results. The objective of the present article was to compile characteristics and properties of thermal insulation, exposing its applications in thermal products companies. Thus, information and research results were collected from articles, and grouped into insulation originating from animal, synthetic, vegetal, animal, vacuum compounds and gases. A questionnaire was also applied to manufacturers and users of thermal insulation, reporting on each insulation and its applications. The differences of each thermal insulation, its advantages and applications are noted. There is no insulator that fully has all the advantageous properties and characteristics. Therefore, the choice of the insulation should be thorough, opting for one which shows greater propensity to the desired application.

Keywords - thermal insulation, applications, properties, characteristics.

I. INTRODUCTION

Thermal insulation restricts the flow of heat between different temperature media [1]. It is used to protect people and equipment, process control, prevention of possible condensation and saving energy [2]. For construction, in addition to energy saving, insulation offers comfort on hot summer and/or cold winter days. There is also a decrease in external noises and a decrease in condensations that damage furniture [3].

The use of suitably designed and installed heat insulation in a process can reduce energy consumption by about 18-34% depending on the type of insulation and media temperatures [4].

Since they are usually solid materials, the heat is transferred mainly by conduction, with the values of convection and radiation being negligible [5]. According to Diamant (1986), the insulation coefficient is defined as the heat flux in watts (W) that occurs through a cube of one square meter (m^2) cross-section and one meter (m) thickness, if the temperature difference between the two faces is 1 °C, receiving as dimension W/m °C or W/m·K [1]. A good thermal insulation has the lowest thermal conductivity compared to other materials [6].

Environmental impacts caused by these insulators should also be known. These include their non-recyclable and non-renewable nature that pollutes the environment, and the emission of polluting and toxic gases through the process of manufacturing, burning or putrefaction of the material [7], [8]. One parameter to quantify these impacts is the incorporated energy (unit: kWh/m^3), which evaluates the energy spent from its manufacturing to its application. Another parameter is the carbon dioxide balance, an indicator of direct and indirect CO_2 emissions, referred to as kg equivalent CO_2/m^3 [7].

This article associates information on different thermal insulation, such as manufacturing, properties, characteristics and applications in industries. It also shows the insulators used and manufactured in Brazilian and multinational industries, and shows some results obtained by researchers in the thermal insulation sector.

II. THERMAL INSULATION, PROPERTIES AND CHARACTERISTICS

Insulators have little molecular interaction because they have a stable molecular structure, making their heat exchange difficult [9].

For higher performance, the insulating material needs to have low density, permeability, durability, mechanical resistance and easy handling [10].

According to INMETRO [11], regulation will be drafted on information about combustibility in insulation products where it will classify the reaction to fire, evaluating aspects such as flame propagation, fire growth, smoke development and the dripping of flaming particles. The classification of the materials in relation to fire resistance is [7]:

- Class M0 - non-combustible materials;
- Class M1 - non-flammable materials;
- Class M2 - rarely flammable materials;
- Class M3 - moderately flammable materials;
- Class M4 - easily flammable materials;
- Class M5 - very easily flammable materials.

Table I lists several types of insulation materials with their characteristics and properties.

Table I - Characteristics Of Some Insulators. Adapted From: [7], [12]

Insulation	***Density (Kg/m³)***	***Thermal Conductivity (W/mºC)***	***Reaction to fire***	***Incoporated energy (kWh/ m³)***	**Emission of CO_2 (Kg/m³)**
Glass wool	13-100	0.039	M1	225	75
Rock Wool	20-150	0.037	M1	150	45
Cellular Glass	100-165	0.035-0.048	M0	1600	45
Vermiculite	75-130	0.06-0.08	M0	230	69
Perlite	90	0.045-0.05	M0	230	69
Expanded clay	290-700	0.103-0.108	M0	300	average value
Expanded polystyrene	10-40	0.04	M1	450	70
Extruded polystyrene	10-40	0.032	M1	850	70
Polyurethane	40	0.023	M1-M3	1200	High value
Urea formaldehyde	8-14	0.026	M0		
Hemp wool	Detached: 20 Rolls: 25 Panel: 30	0.039		30	9
Wood Wool	40-55	0.039		50	15
Coconut wool	Detached/Rolls: 20 Panel: 50	0.047 0.05	M1	average value	High value
Linen Wool	Detached/Rolls:18-20 Panel: 30-35	0.047	M1-M2	30	High value
Wood Fiber	110-160	0.05		800	240
Cotton Fiber	Rolls: 20 Detached: 25-30	0.04	M1	average value	High value
Cork	Panel: 60-75 Detached: 70-160	0.032-0.045	M1	450	average value
Cellulose Ouate	Detached: 50-75 Panel: 75-100	0.038	M1	6	2-3
Straw	70-120	0.045-0.07	M1-M2	low value	low value
Sheep wool	10-20	0.03-0.045	M1	55	average value
Duck feathers	26-34	0.033-0.042	M2	50	average value

Any material should not be classified as better or worse insulator, but rather as more appropriate for a specific application [13]. Insulators can be of mineral, synthetic, vegetal and animal origin[7].

A. Mineral origin

These are materials obtained through natural raw materials such as sand, volcanic rock, and recycled glass. They have excellent fire behavior and good resistance. Glass wool, rock wool, cell glass, vermiculite, perlite and expanded clay are among these materials [7]. They can usually be found in the form of blankets or panel and in some cases in bulk or rolls, blocks in the case of cell glass, and granulated for perlite and vermiculite [7], [12].

Its main characteristics are:

- ✓ Resistant to insects, microorganisms and rodents;
- ✓ Chemically inert;
- ✓ Permeable, except cell glass and expanded clay;
- ✓ High cost, except for glass wool and rock wool;
- ✓ Non - renewable, with vermiculite and perlite being reusable;
- ✓ They may have an impact on health and the environment.

Glass wool is composed of crushed recycled glass, which passes through the rotary kiln sintering and expansion process [14]. It has easy application due to its flexibility and elasticity, poor mechanical and thermal performance in the presence of moisture [7].

On the other hand, the cellular glass, according to Silva [7], "is made from carbon and glass, and contains an inert gas in its micro-cells that gives this material good insulating properties."

As raw material for rock wool, granite, diabase, calcite, slate, basalt, and gabbro among others can be used [15]. The raw material is melted at temperatures above 1400 °C and then spun on abrupt quenching with water or liquid nitrogen, generating the mineral rock fibers that are blended into a binder mixture, usually phenol-formaldehyde resin [16], [17]. The choice of the binder mixture depends on the mechanical properties desired [17]. Besides being a good thermal insulation it can also be used in acoustic insulation, it is resistant to vibrations, and stable at high temperature [12]. It may be carcinogenic to humans, therefore, contact with the product is not advisable [7].

Another rock-based material is expanded perlite, in which the volcanic rock undergoes heating at 1200 °C, evaporating its free water and dilating the rock particles by increasing its volume 20-fold [12].

Vermiculite is a non-metallic mineral (clay-mineral) composed of silica, aluminum, iron and magnesium. It has this name because when heated, its particles move similarly to worms [8], [18]. According to Peralta [18], vermiculite is a non-abrasive, odorless, neutral pH, inert material that does not decompose, has low density, is acoustic and thermal insulation, has high liquid absorption and high surface area. Silva [7] claims that it is a toxic-emitting material, releasing substances in the form of bitumen and silicone.

Expanded clay is obtained by baking the coarse clay at 1100 °C [7].

B. Synthetic origin

These are produced from hydrocarbons, with raw materials that are neither renewable nor recyclable. They have good impermeability to water vapor, are light, poor acoustic insulation, their fabrication and burning releases toxic and polluting gases [7]. They are usually marketed in the form of slabs, bulk or '*in situ*'. These are: expanded and extruded polystyrene, polyurethane and urea - formaldehyde [12].

Expanded polystyrene is obtained by the polymerization of styrene under the action of water vapor and an expansion agent, the resultant is in the form of small beads. It can be used in bulk or, after processing, in plates. Like expanded polystyrene, extruded polystyrene undergoes polymerization of styrene, but is extruded under the action of a filler, which may be CO_2 or HFC gases. They are light products with 98% air and absorb minimal amounts of water [12]. They are light products, easy to apply and inexpensive, highly flammable and manufacturing produces many pollutants [7], [12].

Polyurethane is generally obtained by reacting polyisocyanate and polyol in the presence of a blowing agent, flame retardants, surfactants, stabilizers and catalysts can also be used [12], [19]. Initially CFC (chlorofluorocarbon) was used as a blowing agent for polyurethane foams, being very harmful a compound to

the ozone layer, it was replaced by HCFCs (hydrochlorofluorocarbons), and subsequently by HFC and HC (cyclopentane), but these still cause environmental damages, besides the energy disadvantage, the high cost of the change of line and the lack of safe operation in the case of cyclopentane [20], [21]. It has compressive strength, great adhesion to most materials, and does not feed fungi and bacteria, has bad behavior with strong mineral acids and acetone [7], [12]. In addition to being used in thermal insulation, this compound can be used in cushioning, buoyancy, energy absorption (packaging), among others [22]. It is usually used in insulation of refrigerators and freezers [23].

The rigid urea-formaldehyde foam is based on resin obtained by condensing the urea with aqueous formaldehyde solution, the resin is then mixed with a foaming agent containing an expansion agent, a surfactant and an acid catalyst [12], [24].

C. Vegetable origin

This type of insulation is produced with vegetable fibers, it has a lower environmental impact, is renewable and recyclable, biodegradable, does not release toxic gases in cases of fire, it is harmless to health, energy consumption and of low costs [7], [8]. Wood wool, wood fiber, cotton fiber, cork, and straw among others are in this category [7].

Cork is the bark of species of some trees, mainly cork oak (*Quercus suber* L.), where it is generally associated with flolem tissue [25], [26]. The extraction is done through a layer of thick outer shell that is removed periodically [25]. For the production of thermal insulation, the cork goes through cooking at 300°C [13].

Wood wool and fiber are obtained from compressed waste, mainly sawdust, there is no need for addition of a binder since the wood contains lignin that exerts this action. This material presents better protection against the cold than against the heat during the summer [7]. If wet, they ferment and decompose to release odors, worms and rats also proliferate [13].

There is also insulation obtained through fibers not used in the textile industry (flax wool); recycled paper (cellulose wadding); cereal by - products (straw); coconut (coconut fiber); hemp (hemp wool); raw or recycled cotton (cotton fiber); charcoal (coal fiber) [7], [27].

D. Animal origin

These are derived from animal fluff and, like those from plant origin, have little environmental impact compared to others, they are recyclable and renewable, do not emit toxic gases, are harmless to health and have good hygroscopic capacity, but present high costs and need additives. These include sheep wool and duck feathers [7].

In the manufacture of sheep wool, a binder of polyester fiber is added to the raw material to ensure the cohesion of the material [7]. It has a natural characteristic of regulating temperatures and resistance to fire. For animal health, the wool is annually removed generating 2.3 to 3.6 kg on average [28].

For insulation with duck feathers, these are washed, treated, dried and mixed with sheep wool (10%) and fibers (20%) to provide elasticity to the material [7].

III. OTHER TYPES OF THERMAL INSULATION

Vacuum insulation panels (VIPs) are made of highly porous, open cell material between a chemically stable barrier film. The porosity is obtained by synthesizing the material or stacking microfibers, and the vacuum is maintained by the impermeability of the barrier film and by the presence of an absorber from within the shell [29], [30]. In the high vacuum, the thermal conductivity is proportional to the pressure [13]. According to SILVA [7], the thermal conductivity of a VIP with a silica fumed core has a value λ of 0.004 W/m.K.

Gas-filled panels (GFPs), other than VIPs, have highly porous materials filled with gas of lower thermal conductivity than air, such as Argon, Krypton (Kr), Xenon (Xe). For the best performance, there can be no air or moisture penetration. Its prototype showed a thermal conductivity of 40 Mk/m.k, but theoretically this value may be lower with the improvement of the technique [31].

In the case of dynamic insulation materials (DIM), the thermal conductivity can be controlled for a desired time. This happens by changing the concentration or gas content in the pores, emissivity of the internal pore surfaces, the thermal conductivity in the solid state of the network. The latter can be described by the vibrations of the structure of the atom and the thermal conductivity of the free electrons [31].

IV. ECONOMICAL THICKNESS OF INSULATION - ETI

After choosing the insulation, the economical thickness of insulation (ETI) must be calculated, so that there is no over-dimensioning or undersizing, because with the increase of insulation thickness, the application cost will increase, and a decrease in heat loss means the cost will be lower. In Fig. 1, it is seen that with the sum of the installation costs and heat loss the total cost is obtained. The economic thickness of insulation is at the point where the latter is lowest [2].

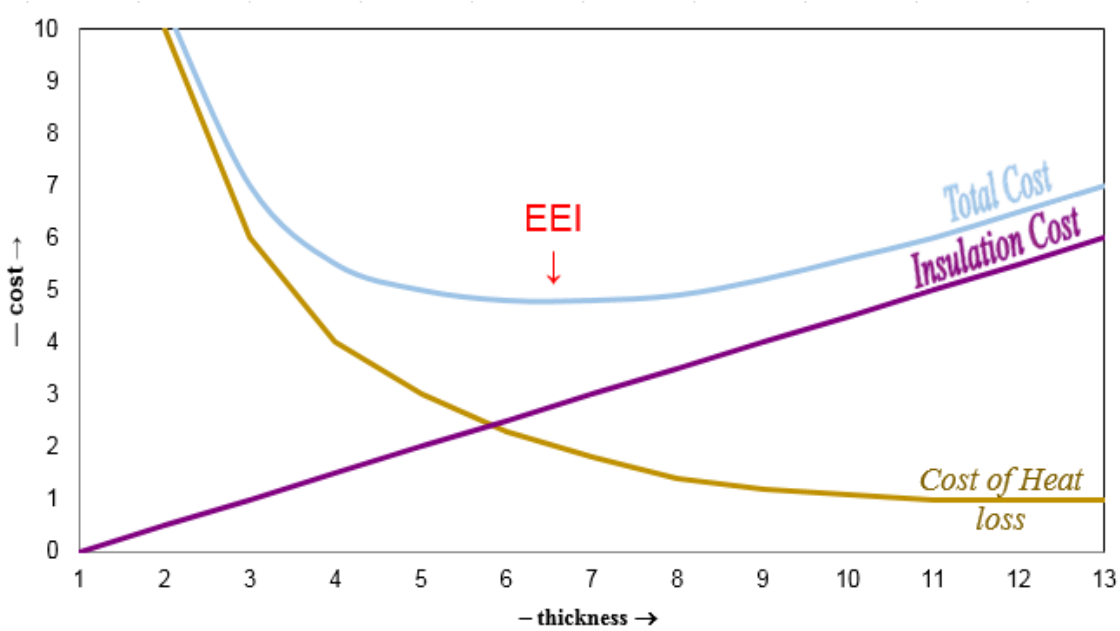

Fig. 1 - Variation of total cost associated to thermal insulation thickness of an element and the loss of heat of the medium. source: [2].

V. COMPANIES THAT PRODUCE AND USE THERMAL INSULATION

A questionnaire was prepared in Google Forms and sent to 130 Brazilian and multinational companies that produce or use thermal insulation in some part of their final product, from January 13, 2017 to March 4, 2017. The following questions were used:

- Company name (optional field)
- It is a company that:
  - ✓ Manufactures thermal insulation
  - ✓ Uses thermal insulation during the process

- What insulation is/are produced or used?
- What is the reason for choosing this insulation (s)?
- What is each insulation mentioned in question 3 used for?

Only 15 companies answered the questionnaire developed, in which nine (60%) were companies that used and six (40%) were producers of thermal insulation. Table 2 shows the information given by the producing companies, while table 3 shows the information of companies that use thermal insulation.

Through Tables II and III, the use of thermal insulators of synthetic and mineral origin is mainly observed, both for manufacturing and for their use. These are low density, low thermal conductivity and non-flammable insulators, but with a high environmental impact since they are non-recyclable, non-renewable and emitters of polluting gases. The materials cited in the results made from wool and fibers are most often used as insulation in higher temperature media, with the synthetic material being used in lower temperature media. It can be noticed that the most used and manufactured insulator is polyurethane, a material that can be used in various sectors, due to easy adhesion to various materials and simple application.

Table II - Table of Results of Companies That Produce Thermal Insulators

Company Name	Insulator (s) produced / used?	What is the reason for choosing this insulation (s)?	What is each insulation mentioned in question 3 used for?
Erviegas Instrumental Cirurgicos Ltda	Thermo boxes with polyurethane filling	Greater conservation	The boxes are marketed for transporting blood bags, biological materials, vaccines, food and beverages.
Indústrias Brasileiras de Artigos Refratários - IBAR	Rock Wool and Ceramic Fiber	The company's flagship is refractory, so the need was seen to expand the range to better meet the needs of customers.	Rock wool, material for thermal insulation for up to 750ºC and also acoustic in both the industrial and civil construction sectors. Ceramic fiber, thermal insulation at higher temperatures 1,425ºC, generally used in ovens.
RK componen_ tes Industrial LTDA EPP	Isol Board	Experience and knowledge	For thermal insulation in machinery
	Polyurethane	Add to the company product line	Polyurethane is recommended for the following applications: Thermal insulation of pipelines, pipelines, storage tanks, cold rooms, etc. Thermal insulation of roofs and roofs Thermal insulation of trucks, railway wagons, cargo ships, containers, etc. Manufacture of refrigerated panels or thermal tiles (sandwich): Due to its lightness and flutuality is ideal for the construction of small boats
Isopur Isolantes Térmicos e Acústicos	We produce glass wool, rock wool, ceramic fiber, floor insulation.	Better thermal and acoustic performance	Civil engineering, insulation of machinery, insulation of air conditioning ducts, etc.
Selena Sulamericana (Tytan)	Expansive Polyurethane Foam	Several factors may lead to the choice of this product, the most important of which is the ease of application.	For door and window fences.

Table III - Results of Companies That Use In Any Way the Thermal Insulators

Company Name	Insulator (s) produced / used?	What is the reason for choosing this insulation (s)?	What is each insulation mentioned in question 3 used for?
	Injected Polyurethane	Finishing, durability, process ease.	Insulation of refrigeration equipment.
	(PUR, PIR, EPS, LDR) *	Miscellaneous applications	Low, medium and high temperatures and in case PIR* (flammable extinguishable)
FORAN Industrial Technology	EPS * and PU *	Better thermal insulation	Cold rooms and climate chambers
	Isocyanate + polyol = expanded polyurethane	Used for insulation of thermal boxes and	Thermal insulation and conditioning of food products.

		isothermal products.	
Soprano	PU and EPS *	Application of each product and the thermal efficiency it should withstand due to the use	PU- thermal products that need to conserve the temperature for longer (thermal boxes, thermal and isothermal plates); EPS - products that do not require such a long shelf life.
Acital	AcistopFoil, rock wool, glass wool, ceramic fiber, polyester wool, special fiberglass fabrics, among others, XPS*.	Performance and applicability	Roof insulation (AcistopFoil, XPS, Glass wool, rock wool and polyester wool), Thermal insulation of pipes, tanks and motors (rock wool, glass wool, Ceramic fiber, special fiberglass fabrics, ceramic fiber , Among others), Wall insulation (Glass wool, rock wool and polyester wool), Insulation of slabs (XPS*)
Divicenter Divisórias	We resell the product for insulation installers Brand ISOVER	Because it is an acceptable product in the market that guarantees customer safety	The insulation is intended to reduce sound and heat.
	Ceramic Fiber	Low thermal conductivity.	Ovens, stoves and boilers.
Reframax	Basalt rock wool, calcium silicate, ceramic fiber.	According to the project.	Energy conservation, personal protection, cold and hot insulation.

* PUR/PU - polyurethane, PIR - polyisocyanurate, EPS - Expanded polystyrene, LDR - rock wool, XPS - extruded polystyrene.

VI. OTHERS APPLICATIONS

Jelle [31] carried out a study on traditional thermal insulation and the most recent ones at the time, finally concluding that there was no insulation capable of supplying the needs of thermal conductivity, vulnerability to perforation, ease of cutting and application on the site, mechanical resistance, fire protection, smoke emission during fire, robustness, resistance to aging caused by the weather, resistance to freeze/thaw cycles, water resistance, and impact. Confirming the affirmation of Torreira [13] that a material cannot be classified as better or worse insulator, but as to which is the most appropriate for a distinctive application.

The analysis of Specht *et al.* [32] on heat transfer in composite walls with different configurations, using ceramic brick, laying mortar, coating mortar and, in some cases, expanded polystyrene can be observed. It denotes a better thermoeconomic performance on the wall that has greater thickness of bricks, insulated in the outside with polystyrene and wrapped with coating mortar. While the one of lesser thermoeconomic yield is the wall which only has a coating in the inner part with exposed bricks on the outside. This study is very important for building constructions that use air conditioners, providing considerable energy savings.

Lin and Chang [27] studied the use of bamboo charcoal fibers along with PET fibers, in the manufacture of textile products, such as clothing, ski boots, upholstery, insulation for cars, among others. Greater thermal insulation was achieved with PET fiber coated carbon fiber.

Felizardo *et al.* [33] proposed the increase of pores in a geopolymer (inorganic polymer rich in silica and aluminum) thus obtaining a lower thermal conductivity of the same. Despite making the geopolymer more fragile, this exploration allows greater use of the same since there was an increase in its efficiency as an insulator.

Arcaro *et al.* [34] produced a thermal insulation from industrial waste, clear bottle glass, effluent treatment plant sludge and calcium carbonate. At suitable proportions and temperatures this combination generated a porous material of thermal conductivity between 1.25 to 0.5 W/m.K. An advantageous product in question of recycling and effective in the insulation function.

VII. FINAL CONSIDERATIONS

It has been seen that thermal insulation is very important in environments with different temperatures, because in addition to increasing efficiency, we also obtain savings. However, each insulation has its own property, advantage and disadvantage, and each must be chosen according to the desired application.

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