NANOTECHNOLOGY AND ENERGY EFFICIENCY IN BUILDINGS
Nano - based Insulation Materials

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ABSTRACT

Building sector is responsible for high energy consumption, and its global demand is expected to grow in the next decades. Nanotechnology may play a role in conserving energy through improved building insulation. Recent advances in the development of insulating materials due to the progress in nanotechnology and material sciences have allowed the production of high- performance thermal insulators with low thermal conductivity. Nowadays, the current products range from nano-based- insulation varies among paints, coatings, thin films or rigid panels. , such as aerogel, Vacuum insulation panels (VIP). This paper investigates applications of aerogel and Vacuum insulation panels VIP as new advanced high-performance insulating materials able to provide exceptional heat flow resistance performance due to their low thermal conductivity

Key words: Energy Consumption, Energy Efficiency, nanotechnology, nanomaterials, thermal insulation materials

PROBLEM

As the global population is expected to increase by 2.5 billion people by 2050 and economic development and living standards are improving worldwide, hence energy use in the building sector is set to rise greatly: with no improvements in the energy efficiency of the building sector, its energy demand is expected to grow by 50% by 2050.[1]

INTRODUCTION

Increasing standards of living and rising population numbers are leading to inevitable increases in global energy consumption. Worldwide energy usage is on track to increase by roughly 40% in the next 20 years (Fig. 1) and to nearly double by 2050.[1]

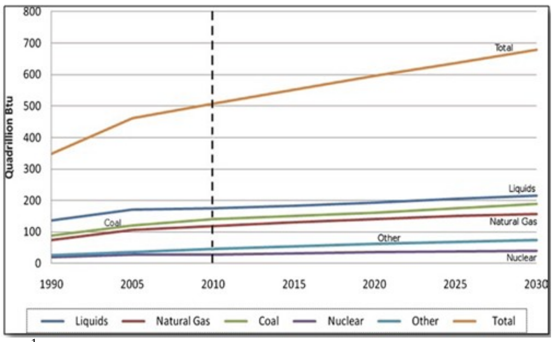

Fig. 1[1] -World total energy consumption in quadrillion BTUs (1990 - 2030) (From U.S. Energy Information Administration, http://www.eia.doe.gov/oiaf/forecasting.html

Building sector is responsible for high energy consumption, and its global demand is expected to grow in the next decades, hence, a crowd of research in the areas of advanced technologies for building energy efficiency. In 2012 buildings globally accounted for 32% of final energy consumption, 53% of electricity consumption, and one-third of direct and indirect CO_2 and particulate matter emissions.[2] In Egypt buildings account for more than 58.6% of total final energy use.[3](Fig. 2).

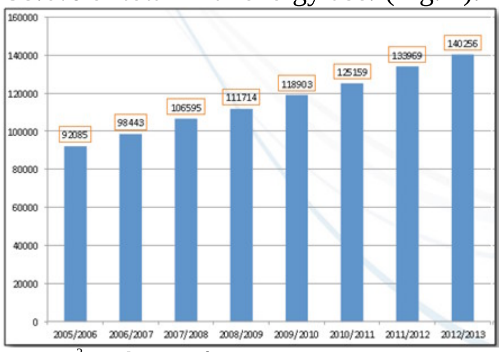

Fig. 2[3]- Evaluation of Energy Consumption in Egypt

Space cooling still accounts for less than 5% of final energy demand, but this value is dramatically rising worldwide, with an increase of 43% in the last 10 years compared to a 34% increase in building floor area and a 13% growth of world population.[2] Energy consumption for cooling is set to increase by almost 150% globally, and by 300-600 % in developing countries, by 2050[2].

Thermal insulation in buildings contributes reducing the size of the heating and cooling systems and the annual energy consumptions. Traditional insulation materials, such as cork, mineral wool, cellulose, polystyrene or polyurethane (PUR), are capable of preserving energy to certain extents. New building materials and technologies are

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needed to increase energy efficiency and energy savings at much lower cost than is possible today (IEA 2013).

Nano science and nanotechnology may yield important improvements in the energy efficiency of the building envelope, allowing advanced materials with fixed or dynamic high performance response able to balance performance requirements with aesthetic requirements and architectural constraints. Recent advances in the development of insulating materials due to the progress in nanotechnology and material sciences, have allowed production of high performance thermal insulators with a thermal conductivity below 0.02 W/mK.

1- Why Energy Efficiency in Buildings?

Energy efficiency in buildings is intensely coupled with the amount of energy actually required to generate or produce the desired comfort conditions in the indoor environment. In other words, energy efficiency refers to the usage of energy at a minimum level for performing an associated task.

An improvement of energy performance of buildings, along with reducing carbon emissions, would also yield important benefits to building owners and occupants, such as improved durability, reduced maintenance, greater comfort, lower costs, higher property values, increased habitable space, increased productivity, and improved health and safety.

2- State-Of-The-Art Insulators

Thermal insulation in buildings contributes to reduce the size of cooling systems and the annual energy consumptions. The application of innovative solutions can be therefore a useful tool not only for new constructions, but also for the refurbishment of existing buildings, in order to reduce the heat gains of the envelope. Many transparent insulating systems have been proposed and their optical, thermal, and acoustic properties have been investigated at the University of Perugia since 2003, with both experimental campaigns and simulation codes.[5]

3- Nanotechnology and Nanomaterials

Nanotechnology is the control and restricting of matter at nanoscale, at atomic and molecular levels in the size range of about 1-100 nm, in order to create materials, devices and systems with fundamentally new properties and functions due to their small structure.

Recent advances in the development of insulating materials due to the progress in nanotechnology and material sciences, have allowed production of high performance thermal insulators with a thermal conductivity below 0.02 W/mK, compared to an average value of conventional insulating materials in the range of 0.025 - 0.040 W/mK[4]. Contemporary paper mentions types of such materials: aerogels and vacuum insulation panels (VIPs).

4- Nano Based Insulating Materials

As an alternative to traditional thermal insulators, nanotechnology can be used to create new advanced high performance insulating materials able to provide exceptional heat flow resistance performance due to their low thermal conductivity (l < 0.02 W/mK), with very low thickness, allowing architectural quality to be combined with energy efficiency, there are innovative products in the form of panels, rolls, or loose granulates that exploit the latest advances of nanotechnology in the fields of materials science, and are thus able to provide high levels of thermal protection (Fig. 4)

4-1- Nano porous insulating materials: aerogels

4-1-1-Thermal insulation; Aerogel[4]:

- High-performance thermal insulation.
- Light and airy nano foam.

Aerogel is a synthetic, porous ultra light material derived from a gel, in which the liquid component of the gel has been replaced with a gas. The result is a solid with extremely low density and low thermal conductivity. It is considered to be the most low-density solid material and has several unique physical properties (e.g. as thermal insulation[6]).

Aerogel was first created by an American chemist, Samuel Stephens Kistler (1900- 1975), in 1931, as the result of a bet with Charles Learned over who could replace the liquid in jellies with gas without causing shrinkage. The first aerogels were produced from silica gels (Fig. 3). Since then it has been proven that aerogels can be prepared from a number of different materials like alumina, chrome, tin dioxide and carbon[7].

Aerogel has since the 1990s found significant applications in the highest-tech aerospace, chemical, and pharmaceutical sectors. In the last 10 years it has been employed in the sports sector, and more recently in the building industry. Aerogel can be obtained from gels made of different inorganic or organic materials for applications such as insulators, sensors, actuators, electrodes, and thermoelectric devices, or to trap space-dust particles. Among different aerogels, those based on silica (dubbed silica aerogels) are the most widely used for all applications, and in particular for thermal insulation, due to their properties and relatively simple and reliable preparation method.

Fig. 3[4] - Monolithic Silica Aerogel. Courtesy of Aspen Aerogels Inc.

Fig.4 [4] Aeropan Basic And Space Loft Fiber-Reinforced Aerogel Blankets. Courtesy Of AMA Composites And Aspen Aerogels Inc

4-1-2- Properties of Aerogel Insulators[8]

* Aerogel is especially very interesting as a translucent or transparent insulation material because of its combination of a low thermal conductivity and a high transmittance of daylight and solar energy.

* Aerogel insulators have an overall thermal conductivity at ambient pressure down to 0.012 W/(mK) at ambient pressure and to 0.004 W/(mK) at a pressure of 50 mbar or less, whereas comercial aerogel thermal insulators for building purposes have a thermal conductivity of around 0.014 W/(mK) at ambient temperature and are very little affected up to a temperature of 200°C. (Fig. 7)

* Silica aerogels have a high transmittance of radiation within the range of visible light. Heat treatment of aerogels can increase their transparency, and the optical properties can be influenced further by selecting optimal synthesis parameters in the sol-gel process.

* In contrast to combustible organic foam insulation that emits deadly fumes and smoke when burning, silica aerogel materials are non-combustible due to their non-organic SiO_2 structure and withstand heat up to 1400°C.

* Due to their physical solid structure, aerogels show a low tensile strength and a brittle nature, whereas its porous structures make it very sensible to moisture due to high surface tensions.

* Compared to conventional insulation materials (Table 1; Figs.6, 7 and 8), such as vegetal (cork, wood fiber, hemp fiber, coconut fiber, etc.), animal (sheep wool), mineral (fiberglass, rock wool, expanded vermiculite, pumice, etc.), or synthetic materials (polyurethane (PUR), polystyrene, polyethylene foams, etc.), aerogels have important advantages as well as offering greater thermal insulation values (l ¼ 0.015 W/m K^2):

• Constant thermal performance regardless of operating temperature;

• High hydrophobicity values while maintaining high water vapor permeability

• Low flammability (Euro class C to A2: fire-resistant materials);

• mold proofing and ultraviolet (UV) and element resistance;

Fig.5[5]- Aerogel, the world's lightest solid

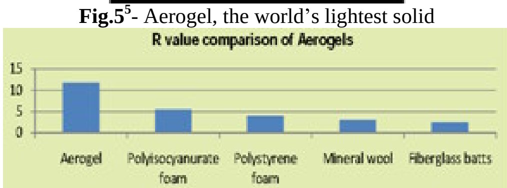
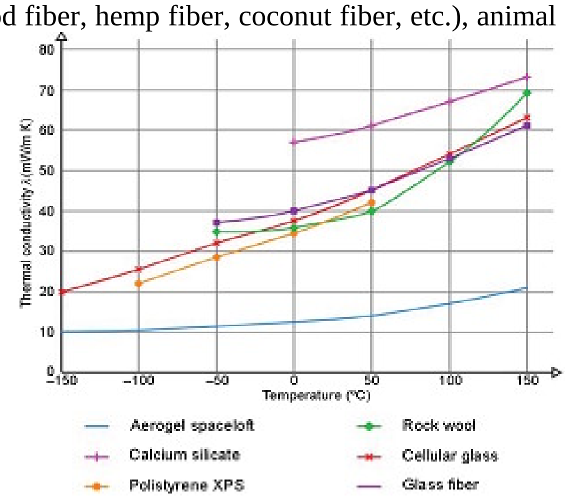


Fig. 6[5]- R value comparison of Aerogels (Elvin, 2007)

Despite these advantages, the cost per square meter of aerogel insulating material is still high, about 8e10 times more than the traditional insulation.



Fig,7[2]- Thermal conductivity of insulating materials related to operating temperature

Fig.8[2]: Thickness comparison between rock wool, polyurethane, and fiber-reinforced

Table 1- Comparison Between Aerogel And Traditional Insulating Material[2]

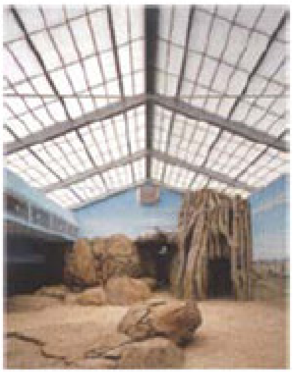
Insulating material	Thermal conductivity λ (W/m^2 K)	Equivalent thickness (cm)	Reaction to fire Euroclass	Vapor resistance μ	Specific heat (J/kg K)
Fiber-reinforced aerogel blanket	0.013	1.00	C	5	1000
Phenolic resins	0.023	1.77	C	35	1400
Polyisocyanurate foam	0.026	2.00	E	60	1464
Expanded PUR	0.027	2.08	E	60	1400
Extruded expanded polystyrene (EPS)	0.034	2.62	E	150	1450
Molded EPS	0.035	2.69	E	60	1450
Stone wool	0.036	2.77	Al	1	1030
Cork	0.042	3.23	F	10	1560
Calcium silicate	0.044	3.38	Al	3	1300
Mineralized spruce wood--wool	0.068	5.23	B	5	1810

4-1-3- Building Applications

The main building applications may be divided into two groups, i.e., as traditional thermal insulators by means of aerogel blankets, and in translucent form for high performance glazing.

First example: County Zoo[9]

Milwaukee, WI. USA



ARCHITECTURE:
Zimmerman Design Group, USA
PRODUCT: Kalwall+ Nanogel glazing
MANUFACTURER:
Kalwall Corporation
COMPLETION: 2005
AREA: Approx. 840 m^2 glazing

The Florence Mila Borchert Big Cat Country building, constructed mostly of stone and concrete, was beginning to show its age. Better natural lighting was needed to improve conditions for the big cats. A key problem in this respect was the fulfillment of thermal performance and energy efficiency legislation. This was solved through the installation of aerogel-filled glass panels, which provide glare-free natural daylight whilst ensuring greater energy efficiency

Second example: Factory[9]

Zaisertshofen, Germany

CLIENT: Ruf Maschinenbau GmbH & Co KG
PRODUCT: Aerogel-filled multi-wall polycarbonate panels
MANUFACTURER: E.M.B. Products AG Licht- und Lufttechnik GmbH

A factory in Bavaria needed glare-free light in its workshops. 16mm thick translucent aerogel-filled multiwall polycarbonate panels were installed in the skylights to provide uniform glare-free natural illumination in the workspace beneath. With a U-value of 1.31 W/m'K, this is a practical and relatively straightforward application of an aerogel-based product.

4-2- Thermal insulation: Vacuum insulation panels (VIPs)[9]:

-Maximum thermal insulation.
-Minimum insulation thickness.

4-2-1- Vacuum insulation panels (VIP):

A Vacuum Panel is a composite of a core material in vacuum and a gas impermeable enclosure retaining that vacuum (fig. 10), together creating a panel with a thermal conductivity that can be as low as 0.004 W/(m·K) or less. The extremely low conductivity is reached by optimization of the core material in combination with the low internal pressure which, if it is lost, will lead to panel failure and the thermal conductivity will raise to about 0.020 W/(m\p;[·K).

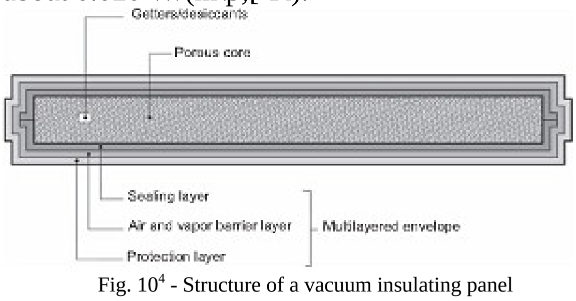


Fig. 10[4] - Structure of a vacuum insulating panel

Vacuum insulation panels (VIP) represent a state-of-the-art high-performance thermal insulation solution. Vacuum insulation panels (VIPs) are ideally suited for providing very good thermal insulation with a much thinner insulation thickness than usual. In comparison to conventional insulation materials such as polystyrene, the thermal conductivity is up to ten times lower.

As any other material for thermal insulation of buildings on the market, VIPs have its advantages and disadvantages. On the positive side, they have the lowest thermal conductivity rate, and they allow for significant space economy. On the negative side, they are relatively fragile; their performance significantly decreases with time and they are not adaptable for construction sites without losses in thermal conductivity. VIPs are also relatively expensive to produce, costing €168/m^2 on average.

Despite the current difficulties that VIPs are facing in becoming a thermal building insulation material of choice, they represent one of the most promising building insulation material technologies. Two main types shall be distinguished, i.e. VIPs with fumed (pyrogenic) silica cores and VIPs with glass fiber cores. The VIPs with fumed silica cores have a centre-of-panel thermal conductivity which normally ranges from 0.004 W/(mK) in pristine condition to typical 0.008W/(mK) after 25 years of ageing. This is 5–10 times better, depending on ageing, than traditional insulation used in buildings today[5]; therefore, VIPs enable highly insulated constructions for walls, roofs and floors.

4-2-2- Properties of Vacuum Insulation Panels (VIP)

* The main benefit of vacuum insulation panels is the reduction of the required thickness of the insulation layers. With a pristine center-of-panel thermal conductivity *k* of 0.004–0.005 W/(mK), equal thermal resistances are achieved within a thickness 5–8 times lower than traditional thermal insulators[8].

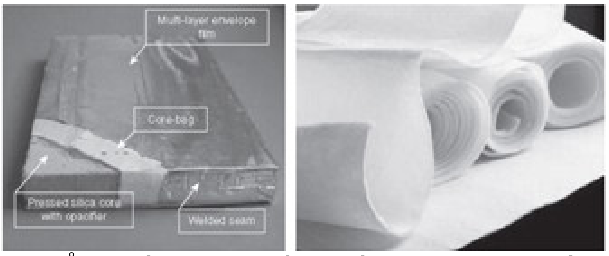


Fig. 11[8]- Typical VIP structure showing the main components and an example of aerogel as a high performance thermal insulation material for building applications,

Fig. 12[8]- Thickness comparison between rock wool polyurethane, and fiber-reinforced

* Maximum thermal resistance can be achieved with minimum insulation thinness. The thickness of these VIPs ranges from 2mm to 40mm. Scientific testing such as that conducted by NRC-IRC in Canada over seven years on 20 VIP products showed an average loss of thermal resistance of 2% per year, enough to ensure a service life of at least 25 years[10].

* VIP panels perform significantly better than all other insulation products (including aerogel), with thermal conductivity values (λ) of 0.004 - 0.005 W /m K at manufactured pressure of 0.5 mbar for panels with a silica core and 0.002 - 0.004 W/m K for those with an aerogel core[(2)]. Vacuum insulating panels (VIPs) today hold the record for thermal insulation, with thermal resistance values up to 20 times higher than conventional insulating materials such as polystyrene foam or mineral wool (Fig. 13).

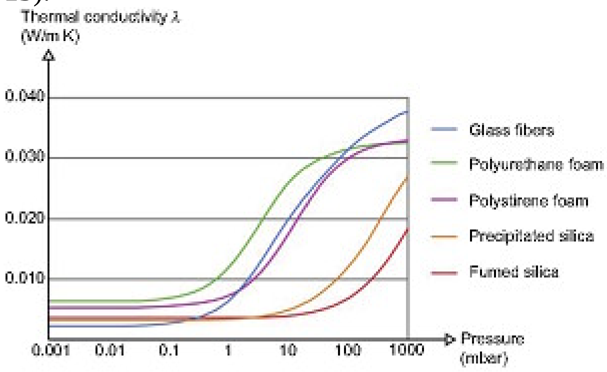


Fig. 13[4]-Thermal conductivity of vacuum insulating panels related to operating pressure and core material

4-2-3-Building Applications

As with aerogel, VIPs are suitable for any type of building, but are ideal for external and/or internal restructuring or building restoration interventions, especially of historic buildings subject to architectural constraints, and in all cases where it is necessary to increase energy efficiency and living comfort while using as little space as possible.

First example: Science to Business Center Nanotronics & Bio, Marl, Germany[9]:

The seven-storey mixed-use residential and commercial building in Munich is the first building of a substantial size to be fully clad with vacuum insulation panels (VIPs). The compact rectangular form of the white building is punctured by large windows that wrap around its corners. At between 8 and 10 times greater efficiency than conventional insulation materials, the ultra-slim VIPs are extremely good insulators.

4-2-4-Disadvantages of VIPs

* A VIP requires a low pressure inside. If the panel is perforated or broken in any way which leads to a loss of this vacuum, the thermal conductivity will increase to about 0.020 W/(mK) for VIPs containing fumed silica. Cutting and adapting the panel on-site is not possible.

* Insulating a building with VIPs therefore requires detailed planning from an early stage and a layout plan of how and where the panels shall be put into place.

* Practice also shows that the most common cause of damage to the panels occurs before and during installation. Extra precautionary matters need to be taken with the handling of VIPs as they are a fragile construction material.

* Damaged panels do not only decrease the thermal resistance of the building, but depending on how the VIPs are implemented there is also a risk of condensation and possibly mould growth large-scale use of VIPs is still hindered by both cost (100e300 V/m2) and lack of versatility, due to the fact that they must be sized in the factory and cannot be adapted during installation.

CONCLUSION

With the demand for energy efficient buildings rising, insulating building materials play a key role in meeting the requirements to increase building energy efficiency. Significant research activities are being undertaken in order to improve the properties of materials and to introduce the most advanced thermal insulation materials with high nanotechnology-based performance. Advanced insulating materials such as aerogel and VIPs are beginning to enter the market in various niche applications.

Aerogels are made from silica and have the highest insulation rating known. They offer significant energy savings for buildings. As discussed before, aerogels have important advantages as well as offering greater thermal insulation values (l ¼ 0.015 W/m K) compared to the conventional insulating materials. Aerogel-filled glass panels can provide glare-free natural daylight whilst ensuring greater energy efficiency. Despite the advantages of aerogel, the cost per square meter of aerogel insulating material is still high, about 8e10 times more than the traditional insulation.

Vacuum insulation panels represent one of the most promising building insulation material technologies. They offer great potential in the general context of improving energy efficiency through better insulation and accordingly contribute to reducing the amount of CO_2 emissions. It is ideal for external and/or internal restructuring or building restoration interventions, especially of historic buildings. As shown in the previous example, vacuum insulation panel can increase energy efficiency in buildings at between 8 and 10 times greater than conventional insulation materials. Despite VIPs' advantages, they must be sized in the factory and cannot be adapted during installation since cutting and adapting the panel on-site is not possible.

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