Nano-Based Thermal Insulating Materials for Building Energy Efficiency

Aerogel- Vacuum Insulation Panels (VIPs)

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Abstract:

The construction industry consumes a lot of energy, and its demand is expected to grow in the next decades all over the world. Nanotechnology may be used to generate new advanced high performance insulating materials with reduced thermal conductivity as a replacement for existing thermal insulators. This paper intends to give a state-of-the-art review of aerogels and vacuum insulation panels in order to provide a scientific overview of the most promising nano-based thermal insulation material for building applications in order to achieve energy efficiency. Firstly, the paper is used an inductive inference approach and includes reviewing general characteristics of these two nano-based insulating materials, as well as their types, applications and qualities that affect building energy consumption. Then, the analytical approach to analyze some international examples of buildings applications to illustrate the potential energy efficiency with using nano based thermal insulators. It is found that, aerogel thermal insulation products have two to three times less thermal conductivity than typical thermal insulation materials; either for opaque insulators or the transparent-translucent one. Regarding Vacuum Insulation Panels (VIPs); it can increase building energy efficiency by 8 to 10 times with very thin layers.

Keywords:

Energy Consumption, Energy Efficiency, Nanotechnology, Nanomaterials, Thermal Insulation Materials

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1. Introduction

Increases in global energy consumption are unavoidable as living standards rise and the population growth. In the next 20 years, global energy consumption is expected to rise by around 40% in the next 20 years (Fig. 1), and by 2050, it will have nearly doubled [1].

The construction industry consumes a lot of energy, and its worldwide demand is anticipated to increase in the next decades, hence, a crowd of research in the areas of advanced technologies for building energy efficiency. Buildings consumed 32 percent of global final energy, 53 percent of electricity, and one-third of direct and indirect CO_2 and particulate matter emissions in 2012 [(2)]. Buildings account for around 58.6% of total final energy consumption in Egypt [(3)] (Fig. 2)

Although space cooling currently accounts for less than 5% of total energy consumption, but it is rapidly increasing globally, with a 43 percent rise in the previous ten years, despite a 34% increase in building floor area and a 13% increase in global population. Moreover, by 2050, worldwide cooling energy consumption is expected to rise by almost 150 percent and by 300 to 600 percent in emerging nations [(2)].

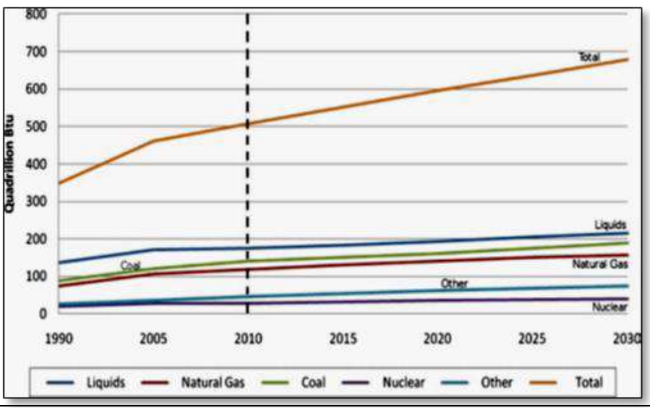


Fig. 1: Total global energy usage in quadrillion BTUs (1990–2030) [(1)]

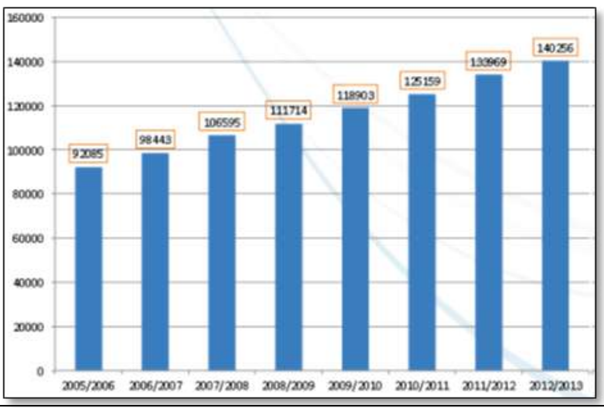


Fig. 2: Evaluation of Energy Consumption in Egypt [(3)]

Building thermal insulation helps to make heating and cooling systems smaller as well as yearly energy consumption. Traditional insulating materials including cork, mineral wool, cellulose, polystyrene, and polyurethane (PUR) can help save energy to some extent. To improve energy efficiency and save money at a far lower cost than is now possible, new construction materials and technologies are required.

Nano science and nanotechnology has the potential to significantly enhance building envelope energy efficiency by providing innovative materials. Recent advancements in the manufacture of insulating materials, owing to improvements in material sciences and nanotechnology, have enabled the manufacturing thermal insulators of high performance with thermal conductivities of less than 0.02 W/mK. the main objective of this study is reviewing the most promising nano-based thermal insulating materials with the greatest promise for energy-efficient building applications today, aerogels and vacuum insulation panels (VIPs) for construction purposes.

Problem

According to the expectation of increasing the global population by 2.5 billion people by 2050, and the development of economic and improving of living standards worldwide, energy consumption in building sector is expected to increase significantly; its demand is expected to rise by 50% by 2050 [(1)]

Objective

This paper intends to give a state-of-the-art review of aerogels and vacuum insulation panels in order to provide a scientific overview of the most promising nano-based thermal insulation material for building applications in order to achieve energy efficiency through:

1- Illustrate their types, applications and qualities that affect building energy consumption.
2- Investigate the applicability of nano-based thermal insulating materials in buildings to achieve energy efficiency

Research methodology

1- the paper is used an inductive inference approach and includes reviewing general characteristics of the nano-based thermal insulating materials, as well as their types, applications and qualities that affect building energy consumption.
2- Analytical approach to analyze some international examples of buildings applications to illustrate the potential energy efficiency with using nano based thermal insulators.

Significance

Several studies have been discussed the advanced thermal insulating materials in order to improve building energy efficiency. This paper focuses on reviewing the most promising nano-based thermal insulating, aerogel and vacuum insulation panel (VIP), their general characteristics as well as their types, applications and qualities that affect building energy consumption.

2. Building Energy Efficiency

Efficiency in Energy refers to using the least amount of energy possible for heating, cooling, equipment, and lighting in order to maintain comfort conditions in a building. It is a measurement of how efficiently energy is used to fulfill basic necessities.

Building energy efficiency is intimately linked to the quantity of energy essentially requisite to develop or create the required levels of comfort in the interior environment. In other words, energy efficiency refers to utilizing the least amount of energy possible to complete a task.

3. State-of-the-Art Insulators

Building thermal insulation helps to minimize the size of cooling systems and the amount of energy consumed annually. Novel solutions might thus be useful not just for new projects, but also for renovating existing structures to decrease heat gains via the exterior. Since 2003, at the University of Perugia, a number of insulating systems that are transparent have been developed, and their optical, thermal, and acoustic characteristics have been investigated using both experimental campaigns and simulation models [(5)].

4. Nanotechnology and Nanomaterials

Nanotechnology is defined as the manipulation and containment of matter at the nanoscale, at the atomic and molecular levels, in the size range of 1 to 100 nanometers, with the goal of developing materials, systems, and devices with fundamentally novel properties and functionalities as a result of their microscopic structure.

The advancement of nanotechnology and material sciences has been resulted in developing of insulating materials with high performance, nano based insulating materials with a thermal conductivity of less than 0.02 W/mK, compared to an average value of 0.025 - 0.040 W/mK for traditional insulating materials ([(4)]. The most promising nano-based thermal insulating materials that show the most potential for energy-efficient building applications today, aerogels and vacuum insulation panels (VIPs) for construction purposes, are reviewed in this paper.

5. Nano Based Thermal Insulating Materials

As a substitute for conventional thermal insulators, nanotechnology may be utilized to develop new sophisticated high performance insulating materials with minimal thermal conductivity (0.02 W/mK) and very low thickness alternatively to existing thermal insulating materials, enabling the combination of architectural elegance and energy efficiency.

There are revolutionary products that take advantage of the most recent innovation in nanotechnology in material science field to provide excellent thermal insulation in the shape of panels, rolls, or loose granulate (Fig. 3, Fig. 4).

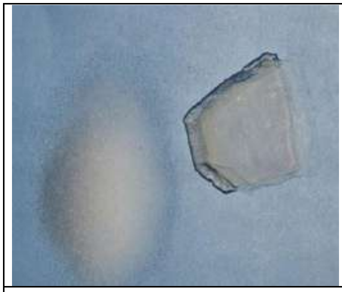


Fig. 3: Silica aerogels: monolithic pane (right) and granular (left) [5].

Fig. 4: Spaceloft fibers-reinforced blankets and Aeroplan Basic Aerogel [4].

Fig. 5: silica aerogel (Monolithic) [4].

5.1 Nano porous insulating materials: Aerogel [4]:

-High-performance thermal insulation.

-Light and airy nano foam.

Aerogel is a porous, ultra-light synthetic material made from a gel with a gas component in place of the liquid component. As a consequence, a solid with exceptionally low density and thermal conductivity has been created. It has the lowest density of all solids and a variety of properties (e.g. as thermal insulation) [6]

Samuel Stephens Kistler (1900-1975), an American scientist proved, won in 1931, that liquid in jellies could be replace with gas without the jelly shrinking. Silica gels were the initial material used to create aerogels (Fig. 6). Aerogels may now be made of a variety of substances, including alumina, chromium, tin dioxide, and carbon, according to research published since then [4, 7].

Due to their characteristics and relatively easy and consistent manufacturing technique, aerogel silica based (called aerogels of silica) is perhaps the most extensively utilized for every purpose, particularly for thermal insulation.

5.1.1. Properties of Aerogel Insulators [8]

- Aerogel is particularly desirable as a translucent or transparent insulating material due to its low heat conductivity and excellent daylight and solar energy transmission.
- Commercial aerogel thermal insulators for building applications have a thermal conductivity of around 0.014 W/(mK) at ambient temperature and are barely affected up to 200°C
- Within the visible light spectrum, silica aerogels exhibit a high permeability of radiation. The transparency of aerogels can be improved by heating them, and appropriate synthesis parameters in the process of sol-gel can further impact optical characteristics.

Fig. 6: Aerogel, the world's lightest solid [5]

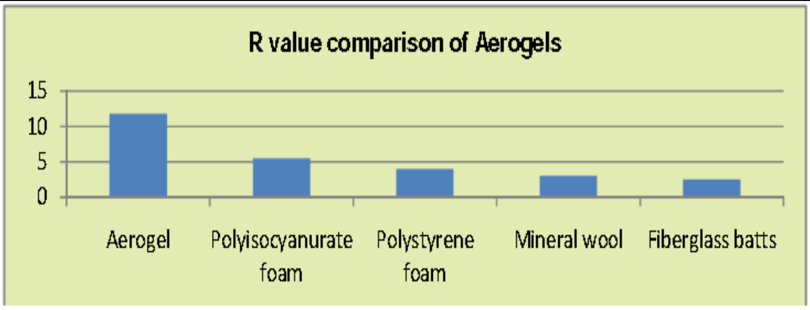


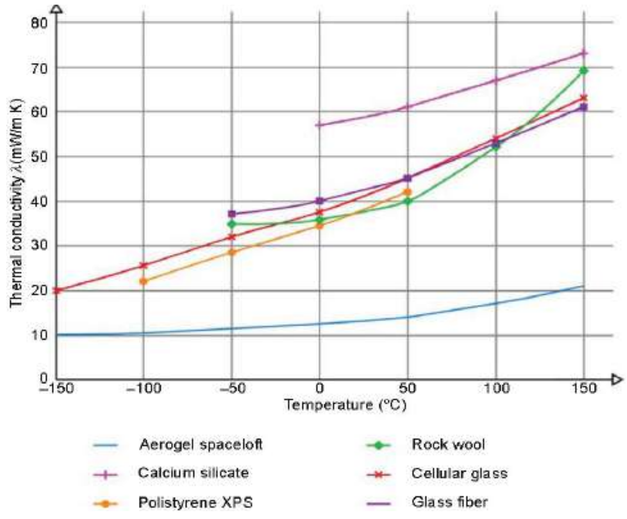
Fig. 7: R value comparison of Aerogels (Elvin, 2007) [5]

- Unlike flammable organic foam insulation, which releases lethal gases and smoke when burned, silica aerogel materials are non-combustible and can tolerate heat up to 1400°C due to their non-organic SiO_2 structure.
- Aerogels have a low tensile strength and brittle character due to their physical solid structure, but their porous architectures make them very susceptible to moisture due to high surface tensions.

Ccomparing to conventional insulating materials (Table 1; Figs. 7, 8, and 9) such as vegetal (cork, wood fiber, hemp fiber, coconut fiber, etc.), animal (sheep wool), mineral (fiber glass, rock wool, expanded vermiculite, pumice, etc.), or synthetic (polyurethane (PUR), polystyrene, polyethylene foams, etc.), aerogels have several significant advantages as follows: [2]

- Thermal performance is constant independent of operational temperature;
- High water vapor permeability while retaining high hydrophobicity values;

- Flammability is low.



Fig, 8: The relationship between thermal conductivity and operating temperature in insulating materials [(2)].

Fig. 9: Rock wool, polyurethane, and fiber-reinforced polymer thickness comparison [(2)]

Table (1) Aerogel vs. conventional insulating materials [(2)]

Insulating material	Thermal conductivity λ (W/m^2 K)	Equivalent thickness (cm)	Specific heat (J/kg K)
Fiber-reinforced aerogel blanket	0.013	1.00	1000
Phenol resins	0.023	1.77	1400
Polyisocyanurate foam	0.026	2.00	1464
Expanded PUR	0.027	2.08	1400
Extruded expanded polystyrene (EPS)	0.034	2.62	1450
Molded EPS	0.035	2.69	1450
Stone wool	0.036	2.77	1030
Cork	0.042	3.23	1560
Calcium silicate	0.044	3.38	1300
Mineralized spruce wood--wool	0.068	5.23	1810

Despite these benefits, the cost per aerogel square meter insulation is quiet expensive, approximately 8 to10 times that of conventional insulation.

5.1.2. Types of Aerogel Insulators

Aerogels have been produced that are Opaque, Transparent, or Translucent.

On the market, aerogel mostly exists as monolithic blocks or blankets, loose granular form [(4)].

1- Opaque Aerogel Insulations Materials

- Aspen Aerogels is currently developing Spaceloft, which is an aerogel-based insulating material. Spaceloft is a flexible aerogel blanket that has a two-to-three-times lower thermal conductivity than typical thermal insulation materials. It is now available in 10 mm thicknesses [(9)].
- Aerogel is frequently incorporated in a fibrous support structure made of polyethylene terephthalate (PET) to increase its mechanical properties and make it easier to employ in insulating opaque enclosure, resulting in aerogel blanket with fiber reinforcement (FRAB) [(4)].

2- Translucent Aerogel Insulation Materials

Translucent or transparent form of aerogel is intriguing as an insulation material due to its low thermal conductivity combined with excellent daylight and solar energy transmittance. Aerogel in granular form is also employed in the manufacture of transparent insulating materials due to its optical characteristics (TIMs). ZAE (Germany) Bayern has created a granular aerogel-based window [(9)]

3- Transparent Aerogel Insulation Materials

Aerogel monolithic forms offer remarkable optical features, such as high light and solar transmission and excellent thermal insulation. As a result, they are employed in office buildings as translucent walls

5.1.3. Building Applications

The two most popular architectural applications are opaque form of aerogel blankets and transparent forms for high-performance windows.

- Opaque aerogels might be utilized as insulation to reduce the thickness of the walls in the building envelope and achieve a low thermal transmittance. Spaceloft, an aerogel-based insulating material, is a flexible aerogel blanket that comes in 10 mm thicknesses (Fig. 10).

- Aerogel granules can be used to fill wall voids with hydrophobic processing or combined with cement to make insulating plaster for internal or exterior usage.
- Translucent or transparent form of aerogel can be used in energy efficient windows (Fig. 11).

Simulations have been carried out on the windows of an office building, based on Cairo climate conditions, the reduction in the cooling energy consumption 7.41 %. And by applying the two nano-based building envelope materials, both the opaque and transparent, the reduction in the cooling energy consumption reaches 10.78% (10)

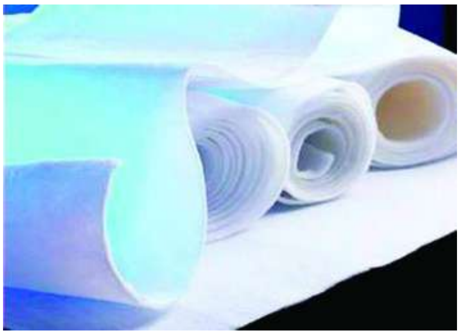


Fig. 10: An example of aerogel for opaque building applications (9).

Fig. 11: **a** monolithic aerogel prototype; **b** a prototype of a PMMA system using granular aerogel.

The following are two examples illustrate the implementation of aerogel as opaque and transparent insulation materials in the buildings.

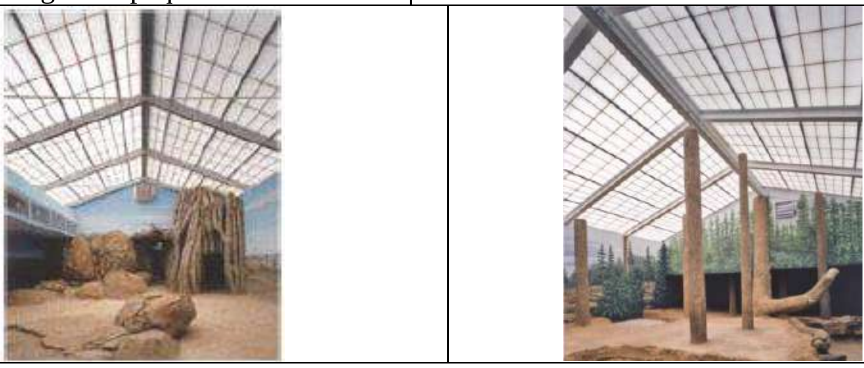


Fig.12: Milwaukee County Zoo Florence Mila Borchert Big Cat Country, Milwaukee, WI (11)

- **First Example: County Zoo** (11)

Milwaukee, WI. USA
Product : Kalwall+ Nanogel glazing
Manufacturing: Kalwall Corporation
Area: Approx. 840 m^2 glazing

In this building it was needed to provide natural lighting to enhance the large cats' living circumstances. The main issue in this regard was ensuring compliance with thermal efficiency and Legislation on energy efficiency. This was rectified by installing aerogel-filled glass panels, (Fig. 12), which ensure glare-free natural light while increasing energy efficiency.

- **Second Example: School Extension** (11)

London, England
Product : Kalwall. Nanogel glazing
Manufactory: Stoakes Systems Ltd

Fig.13: an extension to an existing school, London, England (11)

The building is an extension to an existing school. Classrooms, the assembly hall, an internet café, and a dance studio are all housed on the building's south elevation, which is completely covered with 70 mm thick translucent aerogel-filled panels. The panels diffuse the light, creating a pleasing and bright environment inside while blocking exterior views. Its exceptional thermal insulation characteristics (U-value 0.28 W/m2K) save energy, lowering the school's operating expenses and compensating the initial expenditure required to fund such huge transparent panels (Fig. 13).

5.2 VIPs, Vacuum insulation panels :

-High Performance thermal insulation.

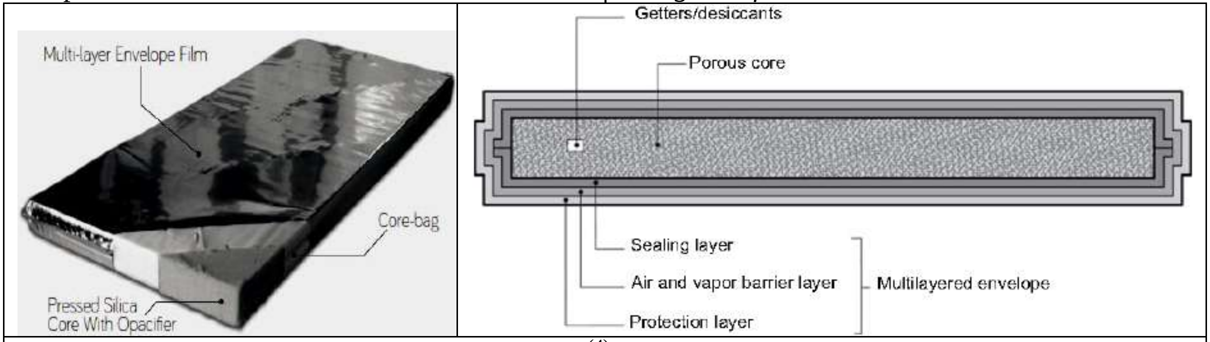


Fig. 14: Structure of a vacuum insulating panel [4].

-Lowest insulation thickness.

Fig. 15: Different insulating material thicknesses compared to attain the same U-value.[14]

A Vacuum Panel consists of a vacuum-filled inner material and a gas-tight shell that maintains the vacuum (Fig. 14), yielding in a panel with a thermal conductivity of less than 0.004 W/(m·K).

The ultra-low conductivity is achieved by optimizing the core material in conjunction with a low internal pressure that, if removed, would cause panel collapse and raise thermal conductivity to around 0.020 W/(m•K) [13].

VIPs (vacuum insulation panels) are a cutting-edge, high-performance thermal insulation system. VIPs (vacuum insulation panels) can provide excellent thermal insulation with a much thinner insulation layer than is typically used, (Fig. 15). Thermal conductivity might be as low as ten times lower than traditional insulating materials such as polystyrene.

VIPs, like any other buildings' thermal insulation material on the market, have benefits and drawbacks. On the helpful side, they have the lowest rate of thermal conductivity, and can save a substantial amount of space. On the other hand, they are somewhat brittle; their efficiency deteriorates as time goes on, besides incompatible with building sites due to thermal conductivity losses. In addition, VIPs are quite costly to manufacture, with an average cost of €168/m2.

Despite the challenges that VIPs have in becoming the preferred thermal building insulation material, they remain one of the most promising building insulators. After 25 years of ageing, the thermal conductivity of VIPs with fumed silica cores varies from 0.004 W/(mK) to a typical 0.008 W/(mK). As a result, VIPs make it possible to build highly insulated walls, roofs, and floors, which are, depending on the age of the building, 5–10 times better than standard insulation used nowadays [5].

5.2.1 Vacuum Insulation Panels (VIPs) Properties

- The fundamental advantage of vacuum insulation panels is that the needed insulation layer thickness is reduced, since these VIPs' thickness varies from 2mm to 40mm. Equal thermal resistances are attained within a thickness 5–8 times smaller than typical thermal insulators with a thermal conductivity k of 0.004–0.005 W/(mK) [8].
- According to scientific testing undertaken by NRC-IRC in Canada over a seven-year period on 20 VIP products, the service life of VIP is at least 25 years. The results indicated an average thermal resistance loss of 2% per year [12].
- Thermal conductivity values of VIP panels with an aerogel core are 0.002 - 0.004 W/m K [2].

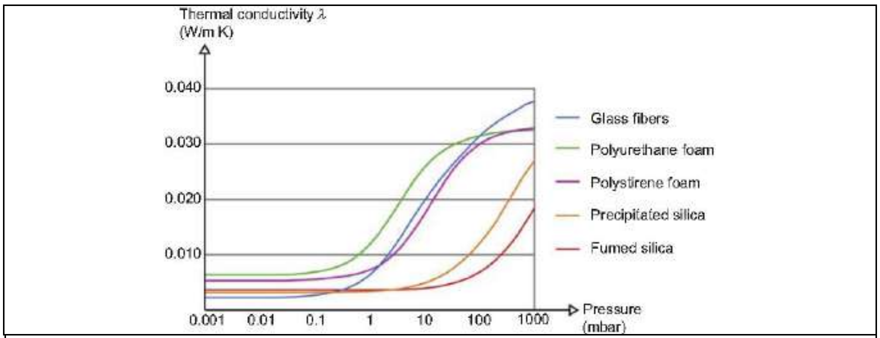


Fig. 16: Vacuum insulating panels' thermal conductivity is affected by operating pressure and core material. [4]

- Vacuum insulating panels (VIPs) now hold the record for thermal insulation with thermal resistance values up to 20 times greater than typical insulating materials such as polystyrene foam or mineral wool. (Fig. 16)

5.2.2. Types of Vacuum Insulation Panels (VIPs)

There are two basic types to consider:

- VIPs with fumed silica: after 25 years of ageing, VIPs with fumed silica as the core material commonly achieve thermal conductivity values ranging from 0.004 W/(mK) to 0.008 W/(mK). This is 5–10 times better than the standard insulation used in buildings today, depending on age [5]. Fumed silica cores have a thermal conductivity at the panel's center of roughly 0.008 W/(mK). This increases the estimated lifetime of VIPs with fumed silica cores. Despite the fact that fumed silica is more expensive than glass fiber, it is required for building applications.
- VIPs with glass fibers cores.

Although the initial heat conductivity of glass fiber VIP cores is the same as that of silica core VIPs, their predicted duration is shorter.

Building Applications

VIPs, like aerogel, are appropriate for any building type, but they are particularly well suited to interventions in exterior and/or interior restructure or building restoration, particularly in historic buildings with architectural limitations. VIPs are appropriate for both outdoor and indoor applications where increased living comfort and energy efficiency are required while using the least amount of space feasible.

VIPs can be used in a variety of ways throughout a building. A large-scale study on the potential of vacuum insulation panels in insulated building envelopes was conducted, and several construction VIPs' applications were suggested and/or tried out. Accordingly VIPs make it possible to build highly insulated walls, roofs, and floors.

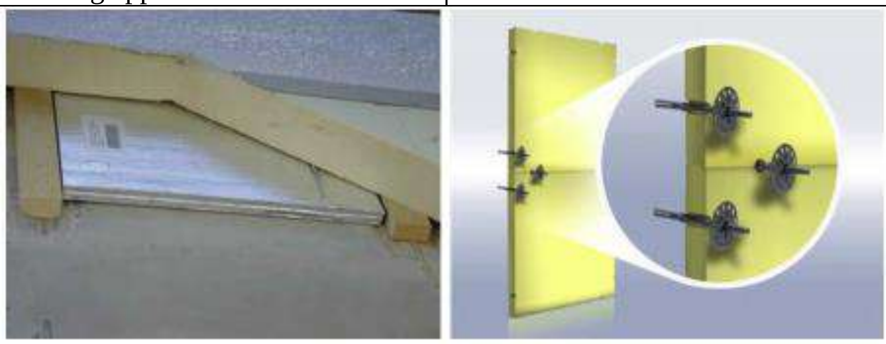


Fig. 14: Structure of a vacuum insulating panel [4].

Walls

Fig. 15: The Sun Ship building, Freiburg [5].

With specific products, like VakuVIP SP, va-Q-safe, or Vacupor PS/XPS, which have a thick polystyrene layer on one or both sides, Fig. 14, or Vaku VIP Bauplatte, VIPs may be used in high-performance exterior thermal insulation composite systems (ETICS). All have a 2-cm polystyrene perimeter frame to allow safe mechanical fastening with dowels.

The following are two examples illustrate the implementation of aerogel as opaque and transparent insulation material in the buildings.

- **First example; Sonnenschiff centre, Freiburg, Germany** [11]

The forward-thinking idea of the Sonnenschiff, Fig. 15, blends cost-effective and efficient energy utilization. The insulating material utilized was vacuum insulation panels (VIPs). The V1Ps are responsible for the insulation of the main facade's exterior walls and window parapets, as well as the ventilation flaps.

They provide 10 times greater insulation than conventional insulation materials of the same thickness.

- **Second Example: Science to Business Center Nanotronics & Bio, Marl, Germany:** [11]

Munich's seven-story residential and commercial mixed-use building, Fig. 16, is the first of its scale being completely covered in vacuum insulation panels (VIPs). The very-thin VIPs are extraordinarily excellent insulators, with an efficiency of 8 to 10 times that of typical insulating materials.

Fig. 16: Residential and office building in Munich [11]

5.2.3 Disadvantages of VIPs

- A VIP demands a modest level of pressure. For VIPs containing fumed silica, the thermal conductivity will rise to around 0.020 W/(mK) if the panel is pierced or damaged in any manner, vacuum will be lost. Cutting and adapting the panel on-site is not possible.
- Using VIPs to insulate a structure necessitates meticulous planning from the start, as well as a layout design for how and where the panels will be installed.
- Because VIPs are a fragile building material, extra precautions must be used when handling them.
- Damaged panels not only reduce the building's heat resistance, but they also provide a risk of moisture and perhaps mould growth, depending on how the VIPs are installed.
- Large-scale application is still restricted by both cost and lack of adaptability because VIPs must be sized at the manufacturer and cannot be adjusted after installation.

Table 2 illustrates a comparison between aerogel and VIPs insulation materials.

Table (2): A comparison between aerogels and VIPs advantages and disadvantages building applications

	Advantages	Disadvantages
Aerogel Insulation Material	• Relative low thermal conductivity	• Very expensive
	• Possible transparency	• Long-term physical characteristics are unknown.
	• On-site use similar to traditional materials	
Vacuum Insulation Panels (VIPs)	• Very low thermal conductivity with thinner thickness	• Very expensive and lack of adjustability
		• Increased thermal conductivity as a result of ageing
		• No adaptation on-site

Conclusion

With the growing need for energy-efficient structures, insulating construction materials are becoming increasingly important in addressing those demands. Nanotechnology might be used to create new high-tech, high-performance insulating materials that resist heat flow. Aerogels and vacuum insulation panels (VIPs) are two emerging high-performance materials for thermal insulation that might be employed in the future.

Aerogel thermal insulation products have thermal conductivity two to three times lower than traditional thermal insulation materials. Because transparent or translucent silica aerogel has very low heat conductivity, nanogel windows are ensuring greater energy efficiency for buildings.

- Despite its benefits, the cost of aerogel insulating material per square meter remains high, around 8 to10 times that of standard insulation.

Vacuum insulation panels consider one of the most promising advancements in the field of building insulation. They have a lot of promise in terms of increasing energy efficiency through improved insulation with a considerably smaller insulation thickness .in general. When compared to traditional insulation materials, vacuum insulation panels can increase building energy efficiency by 8 to 10 times with no need of extremely thick building envelopes.

- Despite its benefits, VIPs must be sized at the manufacturer and cannot be altered during installation due to the inability to cut and adjust the panel on-site.

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