Aerogel insulation for building applications: A state-of-the-art review

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Abstract

Aerogels are regarded as one of the most promising high performance thermal insulation materials for building applications today. With a thermal conductivity down to 13 mW/(mK) for commercial products they show remarkable characteristics compared to traditional thermal insulation materials. Also the possibility of high transmittances in the solar spectrum is of high interest for the construction sector. With the proper knowledge they give both the architect and engineer the opportunity of re-inventing architectural solutions. Within this work, a review is given on the knowledge of aerogel insulation in general and for building applications in particular.

Keywords: *Aerogel, High performance thermal insulation material, Building application, Review.*

1. Introduction

In 2005, buildings emitted 8.3 Gt carbon dioxide each year accounting for more than 30 % of the greenhouse gas emissions in many developed countries. Residential and commercial retrofit insulation has been found as one of the most cost effective actions for greenhouse gas abatement [47]. Herefore, Traditional insulation materials [46] were and are being used in thicker or multiple layers which result in more complex building details, an adverse net-to-gross floor area and possible heavier load bearing constructions. But simultaneously, a second strategy won interest. It became clear that *air as an insulator had reached his limit* [22] and that there was a need to research and develop high performance thermal insulation materials and solutions.

Although yet discovered in the early 1930s [40], aerogels are - together with vacuum insulation panels - one of these *new* promising high performance thermal insulation materials for possible building applications [61,30], but only limited commercial products are available so far [3,12-14]. However, aerogel technologies is of strategic importance for the 29 G$ global insulation market. The last five years, the global market for aerogels tripled to 83 M$ in 2008 and is expected to reach up to 646 M$ by 2013 [15]. Here, aerogel manufacturers put the emphasis on cost reduction, developing new types of aerogels and targeting very large commercial markets where the overall growth for aerogels is mainly driven by applications as thermal and acoustic insulation [15]. Two examples of aerogels for building applications are shown in Fig. 2 .

In this review, a state-of-the-art is made on the most representative information on aerogels as a thermal insulation material for building applications. This is carried out in 2 main parts: Firstly, aerogels are discussed in general: How come they have such a high thermal quality? And what are their physical properties? The remarkable properties of aerogels are due to its extraordinary physical and chemical structure, which is the result of an advanced and complicated production process. Therefore, the production process of aerogels will be explained first. Secondly, a review is given on current building applications of aerogels. Building applications as thermal and acoustic insulation materials is currently the main market for aerogels, whereas also a wide range of other applications is possible [28,67], e.g. as absorbents, shock absorbers, nuclear waste storage, batteries and catalysts.

Fig. 1 An example of aerogel as a high performance thermal insulation material for building applications (Aspen Aerogels, Inc.) [**Error! Reference source not found.**].

Fig. 2 Translucent aerogel insulation used in a curtain wall at the *Sculpture* building and gallery of *Yale University* (New Haven, Connecticut - USA) [77].

2. Synthesis

Aerogels are dried gels with a very high porosity [30] and were discovered in the early 1930s by Samuel Kistler [40]. Silica aerogels are synthesized in a first step by traditional low-temperature sol-gel chemistry [84], but in contrast to xerogels where wet gels are often dried by evaporation, aerogels are essentially dried often by supercritical drying. As a result, dried samples keep the porous texture of the wet stage. In general, aerogels have a high specific surface area, a very low apparent density and a low refraction index [20,80,52]. Furthermore, the thermal properties of aerogels may undertake a structural evolution when aged in a liquid medium and/or heat treated during the synthesis process.

The synthesis of (silica) aerogels may be divided in three general steps: Gel preparation by sol-gel processes, ageing of the gel in its mother solution to prevent the gel to shrink during drying, and drying of

the gel under special conditions to prevent the gel structure to collapse. A simplified reaction for silica aerogels, i.e. the most common type of aerogels for insulation purposes, may be presented as [51]:

$$Si(OCH_3)_4 + 2\ H_2O \leftrightarrow SiO_2 + 4\ CH_3OH \qquad [1]$$
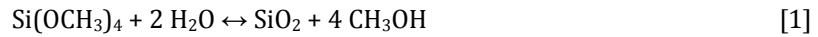
A detailed comprehensive review on the synthesis of silica aerogels has been written recently by Dorcheh & Abbasi [19] and it is referred to this work for a more extensive analysis of aerogel synthesis and recent developments.

2.1. Gel preparation

The *sol-gel* process is a process in which solid nanoparticles dispersed in a liquid agglomerate together to form a continuous three-dimensional network extending throughout the liquid. The process is extensively described by Brinker & Scherer [8]. Aerogels are essentially the solid framework of such a gel isolated from its liquid medium. For silica aerogels, nanoparticles are grown directly in a liquid.

The main precursors for silica aerogels are silicon alkoxides. Tetramethoxysilane $Si(OCH_3)_4$ or TMOS [50], tetraethoxysilane $Si(OC_2H_5)_4$ or TEOS [73] and polyethoxydisiloxane $SiO_n(OC_2H_5)_{4-2n}$ or PEDS-P_x [16] are most often used, where PEDS-P_x can be obtained by reacting TEOS with a substoichiometric quantity of water in an acidic alcoholic medium according to

$$Si(OC_2H_5)_4 + n\ H_2O \leftrightarrow SiO_n(OC_2H_5)_{4-2n} + 2n\ C_2H_5OH \qquad [2]$$
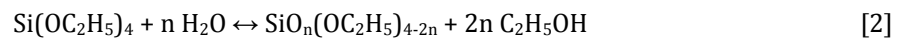
for *n* lower than 2. From the point of view for application as thermal insulation, the thermal conductivities of PEDS and TMOS aerogel monoliths will be found lower compared to TEOS aerogel monoliths [81], whereas high-quality transparent aerogels have been developed [75] based on TEOS. Additional solvents such as ethanol are needed too much water will yield low-porosity gels.

Hydrolysis of silicon alkoxides is performed with a catalyst, i.e. mostly acid or base catalysis, or a two-step [79] catalysis. The sol becomes a gel when the solid nanoparticles dispersed in it stick together to form a network of particles spanning the liquid. This requires that the solid nanoparticles in the liquid collide with each other and stick together. This is easy for some nanoparticles since they contain reactive surface groups that make them stick together after colliding by bonding or by electrostatic forces, whereas this may require the addition of an additive to make them stick together when colliding by bonding or by electrostatic forces. In general, acid hydrolysis and condensation results in linear or weakly branched chains and microporous structures in silica sols [38] and the resulting gelation times are generally long. On the opposite, uniform particles are easily formed in base catalysis (i.e. mostly NH$_4$OH-based) and leads to a broader distribution of larger pores, which is less favourable for thermal insulation materials [66].

Alkoxides are described in some literature as expensive educts prohibiting mass production. A solution to the cost of alkoxides is found in the use of water glass or sodium silicate Na_2SiO_3 as a cheaper raw material for silica [68] which is now used as general precursor for commercial aerogel synthesis for technical applications. Here, a silica hydrogel is generated by acidification of the aqueous sodium silicate solution with e.g. HCl or H_2SO_4 [31,32].

2.2. Ageing

The moment a sol reaches the gel point, the polymerizing silica species span the container containing the sol. However, the silica spine of the gel still contains a significant number of unreacted alkoxide groups. Hydrolysis and condensation may continue and sufficient time must be given for the strengthening of the silica network, enhanced by controlling the pH, concentration and water content of the covering solution [24,25,70].

During ageing, two different mechanism (might) affect the structure of the gel: Transport of material to the neck region and dissolution of small particles into larger ones. Common ageing procedures typically involves ethanol-siloxane mixtures [25], thus adding new monomers to the solid SiO network and increasing the degree of cross-linking. The result is a higher stiffness and strength of the resulting gel. This ageing is diffusion controlled: transport of material is unaffected by convection or mixing due to the solid silica network, while diffusion itself is affected by the thickness of the gel. As a result, the time required for each processing step increases as the thickness of the gel increases, limiting the practical production of aerogels.

After ageing the gel, all water still within the pores must be removed before drying, which can easily be achieved by washing the gel with ethanol and heptanes [25]. Any water left in the gel will not be removed by supercritical drying and will lead to an opaque and very dense aerogel.

2.3. Drying

Drying of the gel is the final and most critical step in the production process of aerogels. Drying is ruled by capillary pressure (except for supercritical drying and freeze-drying), causing consequent shrinking and possible fracture due to the small pore sizes and the resulting capillary tension. As a result, two different drying processes are most often used: Ambient pressure drying (APD), were capillary tension can not be avoided, and supercritical drying (SCD), where the pore liquid is removed above the critical temperature T_{cr} and pressure P_{cr} to avoid capillary tension.

2.3.1 Supercritical drying

Supercritical drying (SCD) is the first and most commonly used method for silica aerogels:

> *"Obviously, if one wishes to produce an aerogel, he must replace the liquid with air by some means in which the surface of the liquid is never permitted to recede within the gel. If a liquid is held under pressure always greater than the vapour pressure, and the temperature is raised, it will be transformed at the critical temperature into a gas without two phases having been present at any time."* [42]

Two different SCD methods can be distinguished: High temperature supercritical drying (HTSCD) [42] and low temperature supercritical drying from carbon dioxide (LTSCD) or the Hunt Process [74]. The method of HTSCD is not relevant for aerogels for building applications, though will be described to give a complete image and allow comparison.

HTSCD is carried out in three steps: Firstly, the aged gel is placed in an autoclave filled half-way with the same solvent held in the gel's pores. The vessel is then sealed and heated slowly past the solvent's critical temperature and pressure (i.e. most-used organic solvents have a relatively high T_{cr} or 300-600 K with a P_{cr} of 30-80 atm [45]). Secondly, the fluid is isothermally depressurized. Finally, at ambient pressure, the autoclave is cooled to room temperature. In the case of silica aerogels, methanol is most frequently used as solvent for HTSCD. At its critical point (i.e. T_{cr} = 512.6 K, P_{cr} = 79.783 atm [45]), methanol can react with OH groups on the surface of the gel backbone to form CH_3O groups, which make the silica aerogels partially hydrophobic and is the reason why HTSCD silica aerogels are generally of higher quality. Furthermore, HTSCD has been found the best way to minimize shrinkage of the gel. For each possible solvent, drying pressures are known for which shrinkage of the aerogels stays below 5 % [39].

The process of LTSCD [74] is similar to that of HTSCD and is also carried out in three steps: Firstly, the aged gel is placed in an autoclave, but now filled with the saver, non-flammable liquid carbon dioxide (i.e. T_{cr} = 304.2 K, P_{cr} = 72.786 atm [45]) at 4 to 10°C until 100 bar to replace the solvent in the pores of the gel. When all solvents are replaced, the autoclave is heated to 313 K while maintaining 100 bar. Secondly, the fluid is isothermally depressurized. Finally, at ambient pressure, the autoclave is cooled to room temperature. Also aerogels dried by LTSCD show shrinkage but, compared to HTSCD, not caused by the SCD process but by replacement of the original solvent with liquid carbon dioxide.

2.3.2 Ambient pressure drying

Ambient pressure drying (APD) is of most interest to lower the costs compared to the expensive drying processes of HTSCD or LTSCD. APD is generally carried out in two steps: Firstly, silylation of all OH groups must take place for preventing adsorption of water resulting by formation of a hydrophobic aerogels. This is carried out by replacing the present solvent with a water-free solvent and a sylilating agent (e.g. hexamethyldisilazane HMDS) [44], resulting in a replacement of H from OH groups by an alkyl such as CH_3. Secondly, drying is carried out by ambient pressure evaporation [11] and consists of three steps: After a warming period, the first drying period occurs where the volume loss of the gel balances those of the evaporated liquid as free water moves continuously to the external surface by capillary forces. In the second drying period or falling rate period, diffusive vapour transport will dominate allowing liquid to escape slowly to the exterior.

3. Solid properties of silica aerogel

The high potential of silica aerogels is due to their unusual solid material properties. Silica aerogels consist of a cross-linked internal structure of SiO_2 chains with a large number of air-filled pores. These pores of aerogel are very small: Pure aerogel has an average pore diameter between 10 and 100 nm [85], but silica aerogels in general will have pore sizes between 5 and 70 nm, depending on the purity and the fabrication method (see Fig.3) [10] which will take from 85 up to 99.8 % of the total aerogel volume.

Due to its extraordinary small pore sizes and high porosity, the aerogel achieves its remarkable physical, thermal, optical and acoustical properties, while on the other hand this also results in a very low mechanical strength. The high porosity makes aerogels the lightest solid material known at the moment. It has a skeleton density of approximately 2 200 kg/m^3, but the high porosity can result in a bulk density as low as 3 kg/m^3, e.g. compare with the density of air of approximately 1.2 kg/m^3 [29]. Current aerogels for building applications have an overall density of 70 to 150 kg/m^3.

Silica aerogels are also load bearing with a high compression strength up to 3 bar, but they have a very low tensile strength making the material very fragile. If not well hydrophobised, contact with water could demolish an aerogel structure because of the surface tension in the pores [33]. In this case, aerogel is often used in combination with a vacuum, where the envelope prevents water inclusion and the vacuum reduces the thermal conductivity furthermore. However, the weak tensile properties are solved for commercial aerogel insulation materials by incorporating it in a fibre matrix.

3.1. Thermal conductivity

Aerogels have a very low thermal conductivity λ_{tot} (W/(mK)) [41], resulting from as well a low solid skeleton conductivity, a low gaseous conductivity λ_g and a low radiative infrared transmission T_{IR} [54]. However, an attempt to come to an overall thermal conductivity by summing all factors may be difficult, because the modes are strongly coupled, e.g. a change in the infrared absorbance will also result in a change of the solid skeleton conductivity.

The intrinsic solid thermal conductivity λ_s of dense silica is relatively high, but silica aerogels have only a small fraction of solid silica. Furthermore, the inner skeleton structure has many 'dead-ends' resulting in an ineffective and long tortuous path of thermal transport. A typical minimum does exist in the thermal conductivity's dependence on density for aerogels: With a density below this optimum, the pore diameter increases followed by an increase of λ_g (see Eqns.2-3) [27], whereas (ideally) a low mass density may also be envisioned with small pores.

The low gaseous thermal conductivity λ_g of aerogels in general can be explained by the Knudsen effect, expressing the gaseous conduction in a porous media as function of the air pressure and the characteristic pore size [37] (see also Fig. 3.):

$$\lambda_g = \frac{\lambda_{g,0}}{1 + 2\beta K_n} \qquad [3]$$

where

$$K_n = \frac{l_{mean}}{\delta} \quad \text{and} \quad l_{mean} = \frac{k_B T}{\sqrt{2}\pi d_g^2 P_g} \qquad [4]$$

where K_n is the Knudsen number, i.e. the ratio between the mean free path l_{mean} of air molecules and the characteristic size of pores δ (e.g. pore diameter), where d_g is the diameter of the gas molecules, k_B the Boltzmann constant, T the temperature, P_g the gas pressure and β a constant between 1.5 and 2.0 characterising the efficiency of energy transfer when gas molecules hit the solid structure of the material. The constant β depends on the gas type, the solid material and the temperature.

Silica aerogels have both an intrinsic low characteristic pore size δ and a very high porosity. As a result, the gaseous thermal conductivity will have large influence on the overall thermal conductivity of aerogels, but will at the same time be strongly reduced at ambient pressure due to the Knudsen effect. The gaseous thermal conductivity can be further reduced (i) by filling the aerogel with a low-conductive gas (e.g. noble gases), (ii) by decreasing the maximum pore size or (iii) by applying a vacuum on the aerogel. Hereby, an

overall thermal conductivity of 8 mW/(mK) can be reached for silica aerogels by applying a pressure of 50 mbar or less, if no further attempts are made to decrease the radiation transfer [29,69,83].

Silica aerogels are reasonable transparent in the infrared spectrum (see Fig.4). The radiative transfer will become a dominant factor of the thermal conductivity at high temperatures, i.e. above 200°C, but will represent no problem at low temperatures. Furthermore, the radiative transfer can be suppressed by adding an additional component such as carbon black to the aerogel, i.e. before or after the critical drying, that either absorbs or scatters infrared radiation. In this way, the overall thermal conductivity at ambient pressure can be decreased to a value of 13.5 mW/(mK) at ambient pressure and to 4 mW/(mK) at a pressure of 50 mbar or less, whereas state-of-the-art commercially available aerogel insulation for building purposes has a thermal conductivity between 13.1 and 13.6 mW/(mK) at ambient temperature [1] and very little affected up till a temperature of 200°C.
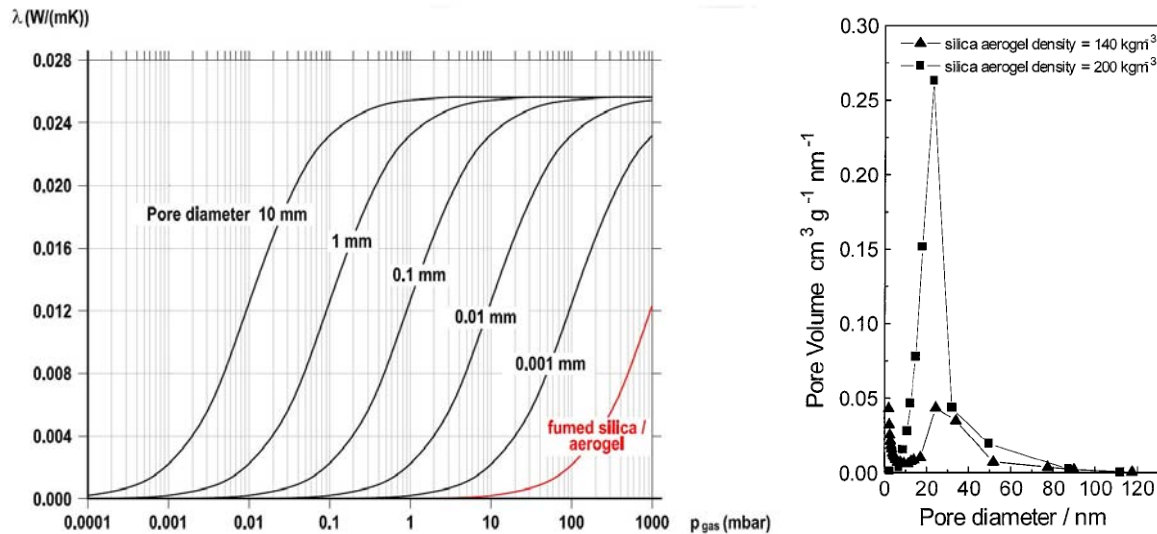

Fig. 3. [left] The thermal conductivity of air as a function of the air pressure and the average pore diameter of the medium. The small pore size of aerogel reduces the gaseous conductivity even at the atmospheric pressure of 1 000 mbar (redrawn from [65]). [right] Pore size distribution of silica aerogels prepared from industrial silicon derivative polyethoxydisiloxanes E-40 [17].

3.2. Optical properties

Silica aerogels have interesting optical properties. In Fig.4, one can notice the high transmittance of radiation within the range of visible light (i.e. radiation with a wavelength between 380 and 780 nm). Monolith translucent silica aerogel in a 10 mm thick packed bed has a solar transmittance T_{SOL} of 0.88 [58]. Heat treatment of the aerogels can increase their transparency further, i.e. currently by up to 6 % [33], because of water desorption and burning of organic components. The optical properties can be influenced furthermore by parameters of the sol-gel process, i.e. by selecting optimal synthesis parameters [54].

Light reflected by (silica) aerogels appears bluish and transmitted light appears slightly reddened. This scattering of the light can be explained by bulk- or Rayleigh scattering and by exterior surface scattering. Rayleigh scattering is caused by the interaction with inhomogeneities in solids, liquids or gases such as dust particles in the atmosphere, and becomes more effective when the size of the particles is similar to the wavelength of the incident light. The presence of a certain number of pores within this range in aerogels can act as so-called 'scattering centres'. The efficiency of scattering will depend on the size of the scattering centres, while different wavelengths of radiation will scatter with different magnitudes.

Silica aerogels can also have a high transparency in the infrared spectrum, i.e. a T_{IR} of 0.85. This transparency increases the overall thermal conductivity of silica aerogels, especially at higher temperatures. If transparency is not desired, the direct-hemispherical transmission in the visible range can be strongly reduced with up to 50 % by adding only a few vol% isopropanol [56] or other opacifiers to the aerogel.
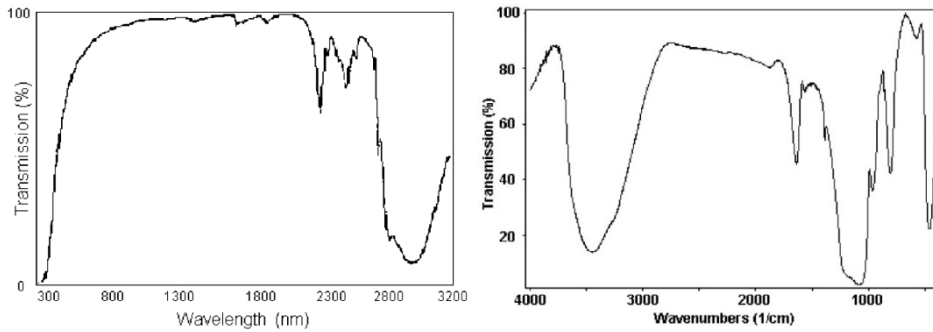
Fig. 4 The transmittance of a silica aerogel in the ultraviolet, visible and near infrared spectrum (left) and the infrared spectrum (right) showing IR-bans of alcohol at 3200-3600 cm^{-1} , of carbonyl at 1690-1760 cm^{-1} and of carboxyl between 1080-1300 cm^{-1} [54].

3.3. Acoustic properties

Monolith silica aerogels have a lower speed of sound than air. Sound velocities down to 40 m/s have been measured [21], whereas (non-monolith) commercial products claim to have a sound velocity of ~100 m/s through the structure [4]. Granular aerogels are exceptional reflectors of audible sound, making excellent barrier materials [18,23]. By combining multiple layers with different granular sizes, average attenuations of -60 dB has been found for a total thickness of only 7 cm [60].

3.4. Safety aspects and fire behaviour

Aerogel insulation sheets suffer from dust production. As most of the commercial aerogel insulation products consist of complete amorphous (and thus 0 % crystalline) silica, exposure limits in the range of 5 mg/m^3 for respirable dust count in the US OSHA. However, the International Agency for Research on Cancer (IARC) considers synthetic amorphous silica to be not classifiable as to its carcinogenicity to humans (i.e. group 3). No evidence of silicosis has been found from epidemiological studies of workers with long-term exposure to synthetic silica, whereas studies of various animal species show that amorphous silica can be completely cleared from the lungs [48,82].

Monolith silica aerogels consists of SiO_2 with a -CH_3 treated surface for hydrophobisation. They are generally non-flammable and non-reactive. Also commercial products containing silica aerogels are considered to have the same properties [71]. Even more, aerogel insulation is used as fire-protecting material [1,55] where the PET fibers generally used for reinforcement are replaced [2].

4. Building applications of aerogels

Silica aerogels are an innovative alternative to traditional insulation due to their high thermal performance, although the costs of the material remain high for cost-sensitive industries such as the building industry. Research is continuing to improve the insulation performance and lowering the production costs of aerogels.

Presently, two different groups of building applications can be noticed for aerogel insulation: (i) Insulation materials which only use the high thermal performance of silica aerogels and (ii) granular aerogel-based translucent insulation materials or (iii) transparent monolithic aerogel. Two examples of translucent aerogel insulation applied over large areas in new buildings for daylighting purposes are depicted in Fig. 5 [35]. Aerogel insulation applied as retrofitting of an old brick building is shown in Fig. 6. , which in another example also shows a timber wall with aerogel insulated studs (top floor), demonstrating by infrared thermography the thermal bridge differences to the non-aerogel insulated studs (ground floor) in the same building.

Fig. 5 Two examples of translucent aerogel insulation as a high performance thermal insulation solution for daylighting [35].

Fig. 6. [left] Aspen aerogel insulation for retrofitting of an old brick dwelling and [right] a thermographic image of a timber wall where the studs of the top floor are insulated with a thin layer of aerogel insulation whereas the ground floor is not [3].

4.1. Opaque aerogel insulation materials

Currently, an aerogel based insulation material is developed called Spaceloft® by *Aspen Aerogels, Inc.* (Northborough, MA, US) [71]. Spaceloft® is a flexible aerogel blanket currently available in thicknesses of 10 mm and has a thermal conductivity of 13.1 mW/(mK) at 273 K, 2 to 2.5 times lower than traditional thermal insulation materials. Interesting is also the preparation procedure for the aerogel in [18]. Whereas monolith silica aerogels are very fragile, *Aspen* aerogel insulation products are textile-like blankets. The aerogel composite may be prepared by adding fibres or a fibrous matrix to a pre-gel mixture containing gel precursors, whereafter the gel can be dried. The product may be used to reduce the thermal bridges due to studs in wood-frame or steel-frame building envelopes [43]. The current cost the product is in the range of 25 €/m² or 4 000 \$/m³ (November 2008), whereas the material cost of a conventional insulation material is about 10 times lower for the same thermal resistance. Nevertheless, wherever space is an important topic, aerogel may be an option to be considered.

The aerogel insulation material consists of amorphous silica instead of crystalline silica, reducing possible health risks at exposure.

Another aerogel-based insulation material is developed for pipe insulation called Nanogel® Compression Pack™ by *Cabot Aerogel* (Massachusettes, USA) [12] with a thermal conductivity 'half the value of that from polyurethane' or 14 mW/(mK). The product can be 'activated' whereafter it will expand to fill all gaps. The product is at the moment only available for pipe insulation and delivered as a normal flat blanket, while no performance durability over time is assured by the manufacturer.

4.2. Translucent aerogel insulation materials

Aerogel is especially very interesting as a translucent or transparent insulation material [36,83] because of its combination of a low thermal conductivity and a high transmittance of daylight and solar energy. Within this purpose, research has been conducted in the last decade on the development of highly insulating windows based on granular aerogel and monolithic aerogel, e.g. [63,64].

A granular aerogel based window was developed by *ZAE Bayern* (Germany) [57-59,83]. Here, two types of granular aerogel are used in prototype windows: Semi transparent spheres with a solar transmittance T_{SOL} of 0.53 for a 10 mm packed bed and highly translucent granulates with a T_{SOL} of 0.88. This granular aerogel is stacked in a 16 mm wide polymethylmethacrylate (PMMA) double skin-sheet, between two gaps (i.e. of either 12 or 16 mm in width and respectively filled with krypton or argon) and glass panes (see Fig.5 [left]). Based on this principle, three different high performance thermal insulation solutions have been developed:

i. A daylighting system was developed by applying two low-e coatings with an emissivity ε of 0.08 onto the glass panes. A visual directional-hemispherical transmittance T_{VIS} between 0.24 and 0.54 and a total T_{SOL} between 0.33 and 0.45 were achieved, while the complete system had an U-value between 0.44 and 0.56 W/(m²K).

ii. A sun protecting system was developed by applying two low-e coatings with an ε of 0.03 onto the glass panes. Here, a T_{VIS} between 0.19 and 0.38 and a T_{SOL} between 0.17 and 0.23 were obtained, while the complete system had a U-value between 0.37 and 0.47 W/(m²K).

iii. An evacuated solar collector has been proposed, stacking a heat exchanger between a layer of aerogel and a layer of fumed silica and two glass panes.

A monolithic aerogel-based window was developed by the *HILIT⁺* project of the European Union. This window is developed in combination with the technology of vacuum glazing by applying a pressure between 1 and 10 mbar . An overall heat loss coefficient U_{window} of 0.66 W/(m²K) and a T_{SOL} of more than 0.85 were measured for an evacuated glazing with 13.5 mm thick aerogel, while the noise reduction of the glazing was measured to be 33 dB [34]. Increasing the aerogel thickness to 20.0 mm will lower the U-value further more to approximately 0.5 W/(m²K), while the solar transmittance will still stay above 0.75 [64]. Simulations have been done on the window based on Danish climate conditions, and an energy saving of 19 and 34 % respectively for 13.5 and 20 mm have been found replacing triple glazed argon-filled glazing for a house built according to the Danish standard and for a house insulated to the passive house standard. However, scattering becomes strongly visible if the aerogel window is exposed to direct sunlight, making the present quality of aerogel most suitable for north face windows and for daylight components in general.

At the present, two commercial types of such aerogel-based daylight systems, i.e. Scoba-lit and Okagel windows, are developed and manufactured by Okalux, resp Scobalit where-fore the aerogel is produced by Cabot Aerogel under the name NanogelTM and Okagel® [13,14]. The aerogel product has a thermal conductivity of 18 mW/(mK) and the fabricator offers skylights with a heat transmittance coefficient between 0.6 and 0.3 W/(m²K) for layers of 30 and 60 mm Okagel® respectively. The visible light transmission T_{vis} is 0.40 and the sound reduction is 52 dB.
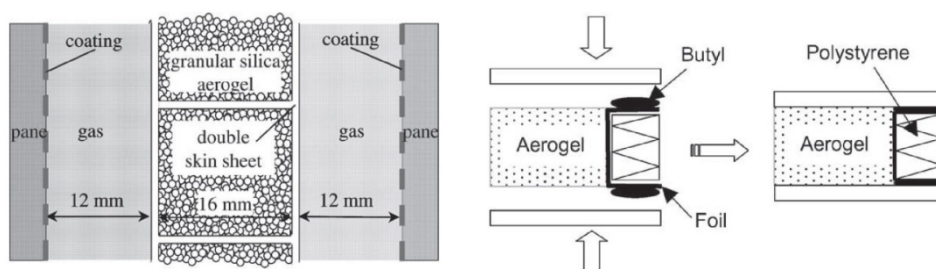

Fig. 7 Cross-section through the granular aerogel based glazing, consisting of two glass panels with a low-e coating on the inside, two gaps and an aerogel-filled PMMA double-skin-sheet [left] [59] and cross-section of the monolithic aerogel based evacuated glazing [right] [33].

5. Other high performance thermal insulation materials and solutions

Other state‑of‑the‑art high performance thermal insulation materials or solutions do exist. In principle close to aerogels, is the technology of vacuum insulated panels (VIPs) [5,9,65] among others. Such VIPs apply a vacuum to a material, i.e. mainly fumed silica, in order to drastically reduce the gaseous thermal conductivity. Although an air-tight metal or metallized (thus highly thermal conducting) envelope is necessary to maintain the applied vacuum, centre-of-panel thermal conductivities of 4 mW/(mK) [78] are achieved for VIPs in pristine conditions. Envelope-related aspects as well as ageing raises the overall thermal conductivity to a range of 7 to 10 mW/(mK) [5,7]. Compared to aerogels, VIPs have advantages and disadvantages for possible building applications. In general, VIPs obtain a much lower thermal conductivity and as a result can strongly reduce the applied thickness of the thermal insulation material, but the thermal conductivity of VIPs will increase through time due to intake of air and moisture. Even more, damageing the envelope will increase the VIPs overall thermal conductivity to that of fumed silica, i.e. 20 mW/(mK), far above the thermal conductivity of silica aerogels. Furthermore, VIPs can not be adapted or cut at the building site.

Also gas-filled panels (GFPs) [6] could been seen as a another state‑of‑the‑art thermal insulation materials. However, no commercial products for building applications do yet exist and their effectiveness may be questioned.

6. Conclusions

Aerogel is one of the most if not the most promising thermal insulation material of the last decades. If one can be able to manufacture aerogel for a fraction of the current economic and environmental cost, aerogel insulation may become a decent alternative to current traditional building insulation materials combining the benefit of most traditional building insulation materials - i.e. a robust bulk material - with a thermal conductivity 2 to 2.5 times lower than that of conventional mineral wool. The high potential for aerogels may be especially found in its translucency and possible transparency, as the aerogels may provide large energy savings in future windows and skylights.

Acknowledgements

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