A review of state-of-the-art aerogel applications in buildings

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Abstract

Aerogels are a special type of solid material with nanometre-scale pores <1/3000th the width of a human hair. Porosity is in excess of 90%, in some cases as high as 99.9%, and densities can be as low as 3 kg/m^3. Aerogels are essentially 'puffed-up sand' and are often termed 'frozen smoke'. Their thermal conductivity (0.014 W/m K at room temperature) is the lowest of any solids, and they also have good transparency. The acoustic properties of aerogels make them effective insulators against noise, and aerogels have the lowest refractive index, and dielectric constant of all solid materials. The unusual properties of aerogels open the way to a new range of opportunities for their application in buildings. This paper provides information on their unique features and reviews the potential applications for aerogels in buildings as well as latest developments in the field.

Keywords: aerogel; porosity; superinsulating glazing; aerogel blanket; sound insulation; fire retardation

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1 INTRODUCTION

In most developed countries, buildings account for around 40% of the total energy consumption. In the UK, this figure is 46% (domestic 29%; commercial and public buildings 13%; industrial buildings 4%) [1]. The building sector offers significant potential for improved energy efficiency through the use of high-performance insulation and energy-efficient systems, and it is estimated that, in some cases, up to 80% of a building's energy consumption can be saved. The walls, roof and windows of a building account for the majority of its heat loss in winter and heat gain in summer. Windows need to be designed to maximize daylighting without compromising energy efficiency, and although double and triple glazing partly meet these requirements, these are expensive and require maintenance. An aerogel is a special type of solid material with nanometre-scale pores <1/3000th the diameter of a human hair. Figure 1 shows the structure of a typical aerogel, which has an extremely low density, in the region of 3 kg/m^3, compared with other solids (density of air is 1.29 kg/m^3). The porosity of an aerogel is in excess of 90% and can be as high as 99.9%. Essentially, an aerogel is 'puffed-up sand' and the term 'frozen smoke' is often used to describe its appearance (Figure 2) [2]. Typically, an aerogel is made using sol–gel chemistry to form a solvent filled with high-porosity gel. The gel is then dried by removing the solvent without collapsing the tenuous solid phase through a process called supercritical drying [3]. The aerogel is fragile, but if care is taken, it can be handled and shaped effectively.

The unique structure of an aerogel gives it special properties, including the lowest thermal conductivity (0.014 W/m K at room temperature), lowest density, lowest refractive index and lowest dielectric constant of all solid materials [4, 5]. Table 1 summarizes the key physical properties of silica aerogels. A range of values is given for each property because the exact value is dependent on the preparative conditions and, in particular, on density.

The unusual properties of the aerogels afford their suitability for many applications in commercial and high-tech fields, such as waste management (gas absorption, radioactive waste confinement), thermal insulation (cryogenic to high temperatures), superinsulating jackets, laser experiments, sensors (ultrasonic and gas), nuclear particle detection (Cherenkov), optics and light-guides, electronic devices, capacitors, high explosive research and catalysts [2, 5–13]. This paper reviews the applications of aerogels in buildings.

2 AEROGEL APPLICATIONS IN BUILDINGS

The unique properties of aerogels offer many new applications in buildings [14]. The extraordinary low thermal insulation

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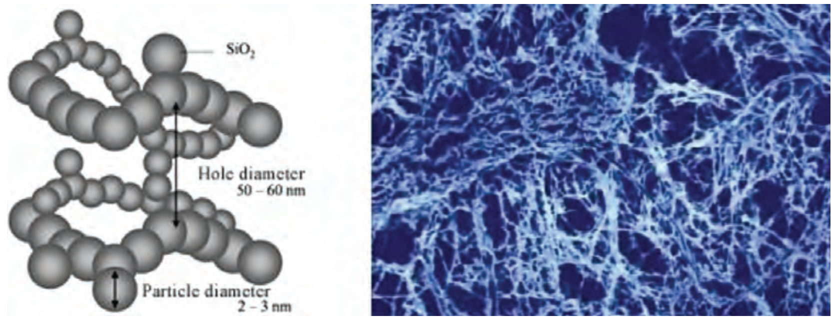

Figure 1. *Nanometre-scale particles and pores in an aerogel. (**a**) Network architecture of an aerogel [15]. (**b**) Electron micrograph of a silica aerogel [2].*

Figure 2. *Aerogel 'puffed-up sand' or 'frozen smoke' [2].*

and optical transparency of aerogels allow its applications in window panes and solar collector covers. Due to their low thermal conductivity and acoustic property for noise abatement, aerogels could be used in buildings, as well as for adsorption and catalysis in indoor air purification, photocatalysis in environmental clean-up, non-combustibility (inorganic aerogels) in fire retardation boards in kitchens.

2.1 Superinsulating glazings and aerogel blankets

Any thermal insulation material aims to reduce heat loss, and so a low thermal conductivity or high *R*-value is of prime importance. A high *R*-value means that a thinner layer of insulation can be used, leading to a smaller space requirement. Omer *et al.* [16] evaluated various insulation materials and compared their thermal conductivities (Table 2). An aerogel has the lowest thermal conductivity, and its manufacturing cost can be reduced drastically, if it is produced under normal pressure [13, 17]. Super-insulating glazing and aerogel blankets are becoming more available in the insulation market.

2.1.1 *Superinsulating glazing*

Due to its large thermal resistance and high transmittance of sunlight, silica aerogel is an attractive material for the construction of window panes with high thermal performance (Figure 3) [18, 19]. Duer and Svendsen [20] developed silica aerogel superinsulating glazing with a solar transmittance of 84–92% and a *U*-value below 0.5 W/m^2K; its thickness was 7–12 mm. However, an aerogel is vulnerable to moisture and tensile stress and could be spoiled rapidly, if water or water vapour comes into contact with the material. Waterproof protection is therefore needed for aerogels used in building components, such as window panes and covers for solar collectors. Fortunately, the aerogel is very strong in compression and so can be used as a sandwich construction, e.g. between two sheets of glass or plastic [20]. Reim *et al.* [18] applied granular silica aerogel sandwiched between two sheets of PMMA to make window glazing with a solar transmittance of 35% and a *U*-value below 0.5 W/m^2 K under a total glazing thickness of 50 mm (Figure 3a).

Another type of transparent superinsulation window glazing, sandwiched by glass slides coated with a silica aerogel film, is synthesized by means of an ambient drying process (1 atm, 270°C) [17]. This type of aerogel-window glazing has a higher transmittance of over 90%, that is, 12% higher transmittance than the uncoated glass slide, because aerogels have

Table 1. *Physical properties of silica aerogels [4, 5].*

Properties	Value	Properties	Value
Density (kg/m^3)	3–350 (most common ~100)	Primary particle diameter (nm)	2–5
Pore diameter (nm)	1–100 (~20 on average)	Surface area (m^2/g)	600–1000
Porosity (%)	85–99.9 (typical ~95)	Index of refraction	1.0–1.05
Thermal conductivity (W/m K)	0.01–0.02	Thermal tolerance temperature (°C)	500 (m.p > 1200)
Transmittance in 0.5–2.5 μm, 3.7–5.9 μm	0.80–0.95	Coefficient of linear expansion (1/°C)	$2.0–4.0 \times 10^{-6}$
Longitudinal sound speed (m/s)	100–300	Tensile strength (kPa)	16

Table 2. *Properties of various thermal insulation materials ranked by thermal conductivity [16].*

Insulation material	Thermal conductivity (W/m K)	Temperature range (°C)	Applications	Availability and cost
Vacuum insulation panel (0.01 bar)	0.005–0.015	−200 to 120	Refrigeration an d cold storage	Expensive to produce
Microporous aerogel	0.0136–0.038	Room to 1400	Cryogenic, aerospace, fire protection	Raw material is abundant, but expensive to produce
Polyisocyanurate (PIR)	0.019–0.022	−185 to 140	Petrochemical, buildings, refrigeration	Abundant and very cheap
Rigid phenolic	0.019–0.024	10–120	Pipe work sector	Cheap
Microporous silica	0.019–0.028	Up to 400	Refractory industry and heat shield	Expensive to produce
Microporous ceramic	0.019–0.030	Room to 1000	Storage heater, gas boilers, ceramic hobs	Relatively expensive compared to PU, EPS&PIR
Polyurethane (PU)	0.020–0.030	0–100	Refrigeration, building	Cheap to produce
Expanded polystyrene (EPS)	0.026–0.033	Room to 90	Refrigeration, casing, building	Abundant and very cheap
Fibreglass	0.0345–0.040	Room to 250	Furnaces, heat exchangers	Relatively expensive compared to PU, EPS and PIR

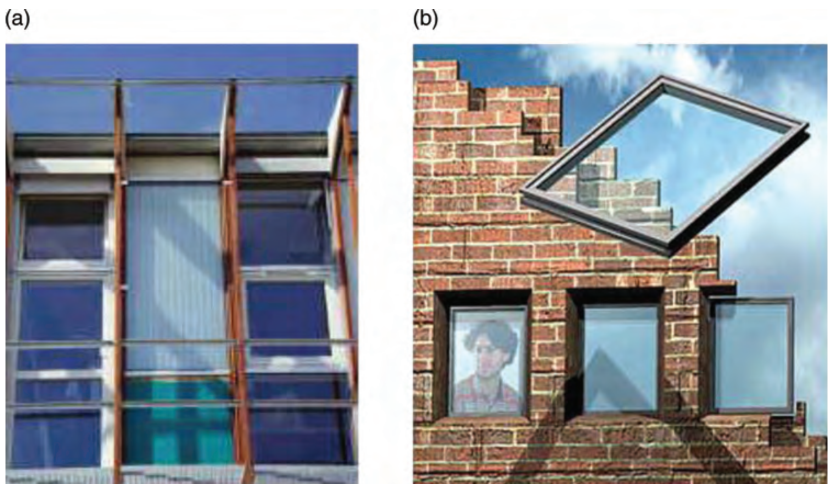

Figure 3. *View of translucent aerogel-glazed windows. (**a**) Translucent aerogel glazing [18]. (**b**) Transparent aerogel glazing [19].*

Figure 4. *Translucent aerogel roof in a pharmacy of Switzerland [21].*

an anti-reflective property, as shown in Figure 3b [19]. The transmittance value is particularly high in the visible region (0.38–0.78 μm) as a result of the Rayleigh scattering.

The development of the superinsulating glazing would lead to significant energy savings in both existing and new residential and commercial buildings. The light transmittance and *U*-value of aerogel-glazed windows, ∼40% and 0.85 W/m^{2}K, respectively, present new opportunities for the use of daylighting in buildings and the architectural design of building façades (Figure 4) [21]. In addition to glazing, aerogels have also been used in solar collector covers [22].

2.1.2 *Aerogel blankets*

Aerogel materials may also be applied to a building's walls, attics, grounds and appliances. Aerogel blankets/panels have been developed to meet various demands, as shown in Figure 5, and commercial manufacture of aerogel blankets began around the year 2000 [2, 23]. An aerogel blanket/panel is a composite of a silica aerogel and fibrous reinforcement that turns the brittle aerogel into a durable, flexible/solid and hydrophobic material, useful for building envelopes, inside or

Figure 5. *Flexible aerogel blankets and solid aerogel boards. (**a**) Aerogel blankets [2], (**b**) aerogel panel [23] and (**c**) superinsulating aerogel blanket [2].*

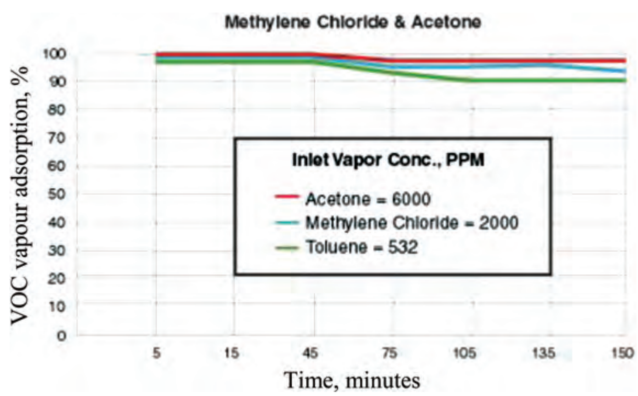

Figure 6. *Removal by adsorption of VOCs from air with Pristina^{TM} Aerogel [14].*

outside. The aerogel blanket/panel products have been manufactured and sold in USA [2], Australia [24] and China [23, 25].

2.2 Air purification

Many pollutants are released into the indoor environment, including chloride from tap water, hydrocarbons (CH_3CHO and CH_3CHOH) from cigarettes, formalin (preservative) from furniture and paints, NO_x and SO_x from the incomplete burning of gas and VOC from organic solvents. Some allergies and respiratory problems, such as asthma, are exacerbated by airborne contaminants and their conversion into non-toxic compounds is an effective route for their removal [26]. The first stage of this process is the rapid adsorption of the contaminants by a multi-porous material. The concentrated contaminants can then be destroyed by a catalytic process. Thermal desorption from such sorbents is now practical, and commercialized on a large scale.

An aerogel has a much higher porosity and larger specific surface area (m^2/g) than activated carbon, thus much better adsorption. However, some metal oxides are required if the adsorbed contaminants are converted into non-toxic chemicals under conventional atmospheric conditions. Aerogel-prepared nanocrystals of MgO, CaO and Al_2O_3, with high surface area/gram of up to 500 m^2/g, have shown remarkably high capacity to destructively adsorb VOCs rather than physisorb them under the atmospheric pressure and temperature [27]. Aerogel-prepared metal oxide semiconductors (e.g. TiO_2, ZnO) which have both high adsorption and photocatalytic oxidation (PCO) under conventional atmospheric conditions. Operating at room temperature, PCO can degrade a wide range of contaminants into innocuous final products such as CO_2 and H_2O without significant energy input.

In the presence of air or oxygen, UV-irradiated TiO_2 is capable of destructing many organic contaminants completely [28]. For instance, Pristina^{TM} aerogel products by TAASI corporation are capable of selective and efficient removal of many pollutants/contaminants from air [14]. Figure 6 shows the removal by adsorption of VOCs from air with Pristina^{TM} aerogel [14].

2.3 Fire retardation

Being of non-organic structure, silica aerogel materials are non-combustible and withstand heat up to 1400°C. This is in contrast to combustible organic foam insulation that emits deadly fumes and smoke when burning. High-temperature applications include the insulation of exhaust systems and reactors, and protection of sensitive electronic components. The continuous operating temperature range for a silica aerogel is from −273 to 650°C [2]. Shrinkage begins slowly at 500°C and increases with increasing temperature. Figure 7 illustrates the excellent thermal insulation and heat endurance properties of silica aerogels and fire-retarding blankets made of this material would be very effective in halting the spread of fire in kitchens and elsewhere.

2.4 Sound insulation

Audible sound waves have a frequency ranging from ~20 to 20 000 Hz. Sound absorption increases with the surface area facing the sound. As aerogels have high porosity and high specific surface area, sound waves are strongly absorbed and attenuated. Sound velocity through a silica aerogel can be as low as 100 m/s, compared with 332 m/s in air at 0°C. Sound absorption and attenuation are related to wave frequency, material density and the size of pores (granules) etc. [29–31]. Sound absorption is significantly enhanced with fibre reinforcement and decrease in pore size, as shown in Figure 8 [30]. Aerogels are therefore useful products for control of sound in environments such as offices or sound rooms. Aerogels have also been proposed as shock-absorbing materials.

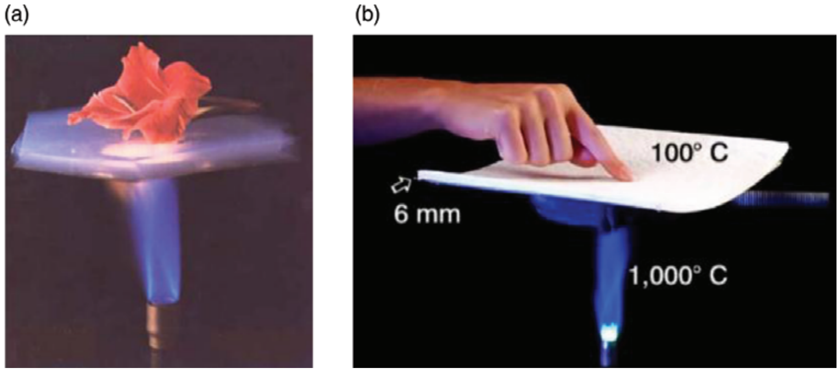

Figure 7. *Aerogel/aerogel blanket placed over Bunsen flame [2]. (a) Rose shielded by the aerogel over a Bunsen. (b) Temperature difference of 900°C through flame a 6 mm aerogel blanket.*

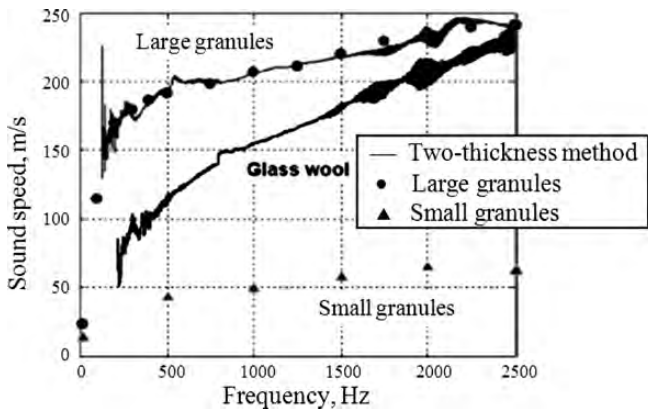

Figure 8. *Sound velocity measurements in large and small aerogel granules and glass wool [30] (aerogel granules: large, 3.5 mm; small, 80 μm).*

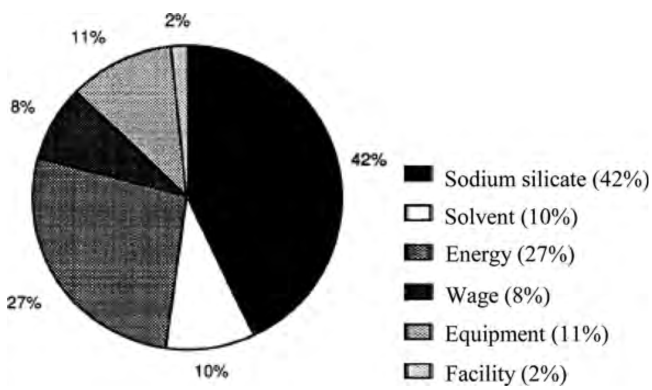

Figure 9. *Aerogel cost distribution (sodium silicate) [32].*

3 ECONOMIC ANALYSES

Aerogels have a broad range of applications in buildings, but their wide-scale use has been limited due to their high cost, manufacturability and market competition. Aerogel production technology is well established but small scale at present, leading to relatively high cost. Figure 9 shows relative silica aerogel production cost, using sodium silicate as the precursor, with respect to six analysed factors [32]. Aerogel production commonly uses supercritical drying, which results in a long process time and leads to high production cost compared with the established insulation materials, such as polystyrene and fiberglass [33]. However, it is also possible to manufacture aerogels using ambient drying [17]. This has the effect of lowering the energy requirement, simplifies equipment and reduces labour cost (Figure 9). Even so, aerogels are still relatively expensive, e.g. the cost of an aerogel window is six times that of a conventional double-glazed window [19]. Although aerogel blankets are more expensive than commonplace foam insulation panels [16], the price of aerogel blankets is acceptable in industrial and some residential applications. Yingde [23] stated that the cost is about £20/m^2, while Shaoxing [25] estimated the cost at £35/m^2 for an aerogel blanket of 1 cm thickness.

4 CONCLUSIONS

Aerogels are a unique and versatile category of materials suitable for a range of applications in buildings. Their main benefits can be summarized as follows:

(1) Excellent insulating properties provide energy and cost savings due to reduced loss of heated or conditioned indoor air.
(2) Healthier indoor environment due to removal of airborne contaminants.
(3) Heat- and sound-retarding properties due to the non-combustibility and acoustic properties of the aerogel.
(4) User-friendly, recyclable and reusable.

The future applications of aerogel products are expected to increase significantly as both the demand for energy and its cost increase. The scale-up of aerogel production to large-scale manufacturing plants will lead to a reduction in unit cost and thus increase the competiveness of aerogel products with conventional materials.

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