Research Progress on Aerogels as Transparent Insulation Materials

Qunzhi Zhu*, Yongguang Li**, and Zhongzhu Qiu+
School of Energy Sources & Environment Engineering, Shanghai University of Electric Power, Shanghai 200090, China
(E-mail: zhuqunzhi@shiep.edu.cn*, liyongguang@shiep.edu.cn**, qzhzhu@163.com+)

Abstract: Solar Energy is a clean and renewable source. Transparent insulation materials are essential for high solar transmittance and low thermal loss in passive solar usage such as building window systems and solar collectors. This paper gives a short review on aerogel, an excellent candidate for transparent insulation materials due to its unique properties. Synthesis of monolithic and granular forms of aerogels is briefly described. Optical and thermal properties of aerogels are discussed. Typical applications and demonstration projects are summarized. The outlook of research and applications is also provided.

Keywords: Aerogel, Transparent insulation materials, Glazing, Solar energy

1 INTRODUCTION

About 40% of the primary energy is consumed in producing low-temperature thermal energy for building heating, domestic water and industrial process heat[1]. Building windows allow day light and solar energy come inside, meanwhile, they are the weakest place for thermal loss in building envelopes. Solar heat collectors are widely used in residential houses to provide domestic water in many countries including China. The efficiency of flat-plate collectors is low in winter because of large thermal loss from the glazing of the solar collector. In order to reduce the thermal loss and enlarge the solar gain through windows and glazings, it is essential to use transparent insulation materials (TIMs).

Glass is a conventional transparent insulation material. A single glass pane can transmit 90% of solar radiation and absorb most of thermal radiation in the infrared spectra. However, because thermal conductivity of glass is much higher than air, heat loss coefficient from a single glass pane is only reduced by a factor of two[2]. In order to further decrease the heat loss, double glazings or triple glazings are necessary. However, reflections by glass/air surfaces of multiple glazings can reduce transmission of solar energy and daylight and in the meantime, deteriorate outdoor view.

Aerogel is a sponge-like open-pore nano-structure material with porosities up to 98%. The transmittance of aerogel is high because silica particles are much smaller than the wavelength of visible light. Aerogel is a super thermal insulation material. Thermal conductivity of aerogel can be smaller than that of still air[3]. The first aerogel was produced by Kistler and it was well-known until in the 1980s. Since then it has been used in many fields including high-energy physics, chemistry, and engineering. Many applications and several demonstration projects have been completed using monolithic and granular aerogels in glazings. It has been shown that the heat insulation can be improved by a factor of 40 without a large decrease of transmittance by using aerogels[1]. Inorganic aerogels can be stable against temperature up to 600°C, which is a great advantage compared to synthetic TIMs like PMMA or polycarbonate[4].

This paper gives a short review on aerogels as transparent insulation materials. In Section 2, synthesis of monolithic and granular forms of aerogels is briefly described. Optical and thermal properties of aerogels are discussed. In Section 3, typical applications and demonstration projects are summarized. Finally, the outlook of research and applications is provided in Section 4.

2 OVERVIEW OF AEROGELS

2.1 Synthesis and structure

Aerogel is a high porosity material. Around 75-98 percent of its volume is occupied by air and the remainder is volume of the skeleton. Diameter of skeletal particles is about 5 - 10 nm and pore size is in the range of 10 - 100 nm[5]. Therefore aerogel is very light with a density as low as a few times air density. Various kinds of inorganic aerogels have been produced, such as silica aerogel and aluminum oxide aerogel. Organic aerogels, for instance, carbon aerogel, have also been synthesized. Among them silica aerogel is very common so that “aerogel” generally refers to silica aerogel.

Aerogels are synthesized by the sol-gel method. The first process in this method can be considered as a chemical process. Precursors of silica aerogels are comprised of inorganic and organic precursors. Waterglass (Na2SiO3) is a relatively cheap inorganic precursor. Two common organic precursors are tetraethyl orthosilicate (TEOS) and tetramethyl orthosilicate (TMOS). The latter is more toxic than the former. Equations (1) and (2) describe the acid-catalyzed hydrolysis and condensation reactions. TEOS is hydrolyzed in ethanol with HCl and HF as catalysts, yielding monosilicic acid,

\[ \text{Si(CH}_3\text{CH}_2\text{O)}_4 + 4\text{H}_2\text{O} \xrightarrow{\text{catalyst}} \text{Si(OH)}_4 + 4\text{CH}_3\text{CH}_2\text{OH} \] (1)

The monosilicic acid condenses to form colloidal silica[3],
\[ n \cdot \text{Si(OH)}_3 \longrightarrow n \cdot \text{Si(OH)}_2 + 2n \cdot \text{H}_2\text{O} \quad (2) \]

Small particles in the colloidal silica agglomerate to large spheres and then to cross-linked branches, resulting in a networked wet gel. The second step is a physical step. Water and other solvent such as ethanol should be taken out of the wet gel and the left voids are filled with gas. Because the receding interface between vapor and liquid introduces extraordinarily strong force inside the gel, the skeleton can collapse, causing serious shrink or even fracture. Therefore, drying is usually carried out under a supercritical condition where the interface between vapor and liquid disappears.

Both acidic and basic catalysis can be used to make wet silica gels. Dependent on how many catalyses used, the sol-gel method can be divided into one-step and two-step process. In the one-step process, either acidic or basic catalyst is added. In the two-step process both acidic and basic catalysts are used in different stages. Acid catalysis can help the reaction of hydrolysis and the structure of the gel is polymer-like. Basic catalysis can promote the reaction of condensation and the structure of the gel is displays colloidal[6]. A hierarchy model can be applied to the structure of base-catalyzed aerogels. The primary structure is compact silica particles with diameters around 1 nm. The secondary structure consists of massive particles and accommodates almost all the surface area. The final structure is branching and cross-linking of chains in the length scale of 50-100 nm[7].

Aerogel is available in different forms. The wet gel can be put into an autoclave and a crack-free transparent or translucent monolithic aerogel can be obtained under well-controlled conditions. Granular aerogel can be produced as follows. Mixed waterglass and sulfuric acid are sprayed from a nozzle and transforms into hydrogel beads or spheres with diameters in the range of 1-8 mm. After solvent replacement, supercritical drying granular aerogels can be obtained[8, 9]. The granular aerogel is translucent due to imperfection in the bulk and surface. Powder aerogel can be produced by grinding fractures of monolithic aerogels and granular aerogels.

Several manufactures can provide commercial products. For example, Airglass (Sweden) once produced 60×60×1(2) cm monolithic aerogel slabs. BASF (Germany) sales granular and powder aerogels. The second generation of granular aerogel is hydrophobic and can even float on water[2]. Thermalux (USA) produces opacified aerogels.

### 2.2 Optical properties

When electromagnetic waves pass through aerogels, pores and silica particles can act as scatters. The size of individual particles is small compared to the wavelength of visible spectra, satisfying one criterion of Rayleigh scattering. However, the distance between particles in aerogel is not large enough for scattering to be considered as independent scattering. Nevertheless, bulk scattering from aerogel shows some characteristic features of Rayleigh scattering. Therefore, a monolithic aerogel slab looks bluish when viewed against a dark surrounding and yellowish when viewed in a bright surrounding. Since aerogel absorbs little in the visible spectra and near ultraviolet, bulk scattering dominates optical loss in these spectra. At the wavelength range of 200 nm < \( \lambda < 600 \) nm spectral scattering coefficient, \( S_{\text{bulk}} \), is dependent on the wavelength with a relation of \( S_{\text{bulk}} \propto \lambda^{-4} \)[10]. When \( \lambda > 600 \) nm, spectral scattering coefficient deviates from the \( \lambda^{-4} \) dependence[11]. Besides bulk scattering caused by mesopores and inhomogeneities in aerogel, scratch and crack in the surface also scatter the incoming radiation. Therefore, total scattering is comprised by bulk scattering and surface scattering. Bulk scattering is dependent on wavelength while surface scattering is independent of wavelength. Since the bulk scattering is approximately isotropic but the surface scattering is favorably forwarded, the pattern of total scattering is forwarded.

The spectral transmittance and reflectance are commonly measured with a UV/VIS/NIR spectrometry. Measurement of directional-directional properties is straightforward. By the means of an integration sphere, directional-hemispherical transmittance and reflectance can also be quantified. Figure 1 displays the measurement results by the authors[12]. The normal-hemispherical transmittance is around 90% at 800 nm < \( \lambda < 1800 \) nm. The direct part and diffuse part of the normal-hemispherical transmittance are also shown. The dips around 1400 nm and 1900 nm are attributed to absorption bands of water.

![Fig.1](image)

**Fig.1** normal-hemispherical transmittance and its two components (monolithic aerogel, 11 mm thick).

Solar transmittance is evaluated by averaging the spectral transmittance with the standard reference data (Air Mass 1.5). Generally solar transmittance of monolithic aerogels is better than that of granular aerogels. Luminous transmittance is essential to compare the optical quality of different aerogel glazings. It can be calculated from the spectral transmittance by weighting with the dimensional standard data (EN 410). Transparency ratio (TR) is defined by normal-normal transmittance \( T_{v-n} \) and normal-hemispherical transmittance \( T_{v-h} \) as