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Section 8. Applications

Aerogel applications

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Abstract

Aerogel materials possess a wide variety of exceptional properties, hence a striking number of applications have developed for them. Many of the commercial applications of aerogels such as catalysts, thermal insulation, windows, and particle detectors are under development and new applications have been publicized since the ISA4 Conference in 1994: e.g., supercapacitors, insulation for heat storage in automobiles, electrodes for capacitive deionization, etc. More applications are evolving as the scientific and engineering community becomes familiar with the unusual and exceptional physical properties of aerogels. In addition to growing commercial applications of aerogels, there are also scientific and technical applications, as well. This paper discusses a variety of technical applications of aerogels. It reports current technical applications under development for which several types of aerogels are formed in custom sizes and shapes.

Keywords: Aerogel; Property; Dielectric

1. Introduction

Each ISA conference brings renewed hope and speculation about continued growth of aerogel technology. There is anticipation by some of the developers of the technology, that aerogels will be popular and commonly used some day, because the materials have such exceptional properties and so many potential applications. That anticipation is most evident within the prefaces of the proceedings for each of the previous ISA conferences [1–4]. The fact that these symposia not only continue, but that they draw increasing numbers of attendees from worldwide to report their work, gives testimony to the expansion of this technology. And indeed, more new applications, both commercial and technical, are reported at each of these conferences, including ISA5. Over the past fifteen years, many applications have been identified for aerogels, ranging from pesticides [5] to cosmic dust capture [6], but commercialization has been slow. However, the number of companies producing aerogels is increasing to address markets in insulation, electronics, and high energy physics. Importantly, these companies are also providing aerogel materials for evaluation by other manufacturers and users, for their applications.

Certainly, the popularity of aerogels has increased and continues to grow, especially as the materials are used in space applications which capture the imagination of the public. For example, the number of requests for information at Lawrence Livermore National Laboratory (LLNL), jumps with each new public release about aerogels. Also, requests for technical information about aerogels are increasing. As more scientists and engineers become aware of

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the exceptional properties of aerogels, they seek to utilize them in their experiments and designs. Another sign of growth of the technology is the increasing number of patents involving aerogels. So, there is reasonable expectation for the continued use of aerogels in commercial and technical applications, in the near future.

Although it is not a complete one, in a sense this is a review paper, because it identifies most of the applications that have been published or formally proposed, it reviews historical applications, and discusses some recent technical applications for which custom aerogels have been developed in the past decade.

2. Survey of aerogel applications

It is difficult to separate 'technical' applications from 'commercial' applications, because with few exceptions, all applications result from some technical property or feature of aerogel material. Therefore, all applications are considered technical for purposes of this paper. However, the main purpose is to emphasize applications of aerogels in scientific experiments and engineering designs, rather than commercial products.

It is interesting to compare the various exceptional properties and features of aerogels with their real or prospective applications. This gives an idea of the tremendous variety of aerogel applications and hints at the impact that these materials will have as we view their future uses. Table 1 shows some applications, both general and specific, which result from particular properties of the aerogels. Most of the applications discussed in this paper will employ one or more of the listed properties. In fact, the technical applications can be generally categorized by the properties being utilized, as will be seen in the following sections.

The large number and variety of aerogel applications are truly impressive. New technical applications were reported for aerogels at each of the prior ISA symposia [1–4] and more new applications are mentioned in recent reviews [7–9]. Some of the interesting reported commercial applications include: wastewater treatment [10], molds for casting aluminum metal [11], aerocapacitors [12], and heat storage device for automobiles [13]. Very exciting new technical applications employing aerogels include:

Table 1
Identification of aerogel properties and features, with their applications

Property	Features	Applications
• thermal conductivity	• best insulating solid • transparent • high temperature • lightweight	• architectural and appliance insulation, portable coolers, transport vehicles, pipes, cryogenic, skylights • space vehicles and probes, casting molds
• density/porosity	• lightest synthetic solid • homogeneous • high specific surf. area • multiple compositions	• catalysts, sorbers, sensors, fuel storage, ion exchange • targets for ICF, X-ray lasers
• optical	• low refractive index solid • transparent • multiple compositions	• Cherenkov detectors, lightweight optics, lightguides, special effect optics
• acoustic	• lowest sound speed	• impedance matchers for transducers, range finders, speakers
• mechanical	• elastic • lightweight	• energy absorber, hypervelocity particle trap
• electrical	• lowest dielectric constant • high dielectric strength • high surface area	• dielectrics for ICs, spacers for vacuum electrodes, vacuum display spacers, capacitors

cosmic dust capture [6], muonium atom studies [14], and helium phase transition studies [15]. Several companies are making aerogels for applications including; thermal insulation, electronic devices, filters, particle detectors and catalysts. Many applications have been identified for aerogels where they are employed within other devices to enhance the performance (e.g., solar windows, dielectrics for circuits, and catalyst supports). Also, many others utilize the aerogel as the main functional material (e.g., casting molds, capacitors, and particle detectors). Some of these specific applications and other general applications, will be discussed in the following sections.

3. Applications of aerogels

Clearly, aerogels are among the most versatile materials available for technical applications, where they are used or considered for use, in laser experiments, sensors (ultrasonic and gas), nuclear particle detection (Cherenkov), thermal insulation (cryogenic to high temperatures), waste management (gas absorption, radioactive waste confinement), molds for molten actinides, optics and light-guides, electronic devices, capacitors, energy storage, high explosive research, imaging devices, catalysts, X-ray laser research.

Aerogels were recognized in the early nineteen eighties for their exceptional properties, particularly homogeneity and uniformity, which were especially important for primary applications. As scientists and engineers became aware of aerogel properties and considered designs for utilizing them, they requested custom aerogels.

3.1. Cherenkov (particle detection and counters)

Earliest recorded use of aerogels was for particle detection using the Cherenkov effect in the early 1980s. High energy physics studies relied on aerogels having specific refractive indexes for threshold detectors. Solid aerogels, though fragile, were much easier and safer to apply than high pressure gas alternatives. There are many references using aerogels for nucleonic particles [16–22] and this was the primary application driving commercialization [23]. Aerogel use for particle detectors and counters continues in space, at accelerators around the world, and in upper atmosphere balloon borne experiments [24].

3.2. Targets for laser experiments

An important early application of aerogel material was as fuel capsules for direct-drive, inertial confinement fusion experiments. The requirement was for a very homogeneous, high purity, low density porous material (i.e., < 0.05 g/cm^3), available as near perfect spherical shells. The average pores need to be smaller than 1 μm to stably hold the liquid fuel and to ensure homogeneity. Also the material needed to be wettable by liquid deuterium–tritium, radiation stable, and strong enough to be machined and coated.

Initial experiments used silica aerogels to test concepts [25]. The silica aerogel was purchased from a commercial source, and hemispherical shells were machined from monolithic pieces for the first experiments. Later, the requirement for low atomic weight material led to the development of borate based aerogels [26], organic aerogels [27,28], and carbon aerogels [29]. New methods were developed to directly fabricate the microspheres [30,31], to eliminate machining.

Aerogel materials were thoroughly characterized for this application and they have been used successfully in experiments through the 1980s; but since then, they have been replaced by stronger, microporous polymeric materials.

3.3. Shock compression experiments

One of the earliest experiments with aerogels was to measure shock compression in silica aerogels [32]. The low density of the silica aerogel allowed higher compression and thus more internal energy could be deposited in it. The specimens had to be very uniform, with < 50 nm sized pores and particles, in order to achieve thermal equilibrium in a time short compared to the lifetime of the shockwave. The purposes of this work were to investigate silica aerogel as a very low shock impedance equation-of-state standard, to explore the possibility of using aerogels to generate few-electron-volt plasmas inertially confined in a well-defined thermodynamic state, and to examine aerogels as a capture medium for freezing states of other minerals generated from 100 Mbar shock pressures.

3.4. Radiation-driven shock-induced mixing studies

Two experimental programs carried out on the Nova laser at LLNL, explored the physics of the instabilities which occur when a dense fluid is accelerated by a less dense fluid [33–36]. Perturbations initially residing at the interface of the two fluids, grow under the influence of this acceleration, leading to mixing of the two fluids. This process is important in a number of situations, including the implosion of inertial confinement fusion capsules and the explosions of supernovae. The experiments are carried out using multibeams from the Nova laser at LLNL to produce X-rays which cause a rapid ablation of the target material (doped aerogels or plastics) which launches a shock wave into a tube and impinges on the interfacing materials. The mixing was followed using gated X-ray imaging.

Custom aerogels are developed for these studies [37]. Both low density (<0.1 g/cm^3) carbon aerogels from resorcinol, and silica aerogels (<0.03 g/cm^3) are used in these studies and they typically have dimensions less than a few millimeters.

3.5. Geiger tube

In the mid-1980s a low density silica aerogel was used in radiation detection vacuum tubes to support the high voltage wire coaxially with the cathode sheath, in a Geiger tube. The aerogel provided both the support for the wire and voltage standoff, yet its porosity allowed ion transport after radiation ionizing events in the tube. A method was developed to fabricate the monolithic, low density aerogel directly within the tube, surrounding the wire [38].

3.6. Energy-loss radiography using Cherenkov imaging

An exciting new application for aerogel is the development of an energy-loss camera based on near-threshold Cherenkov radiation [39,40]. Here, the aerogel refractive index is selected for energy threshold as usual, and a monoenergetic charged particle beam is used to illuminate the object to be imaged. The particle interactions with the object cause an energy loss and reduced particle velocity. Near threshold, the number of Cherenkov photons emitted is nearly linear with particle velocity, so that a measurement of the Cherenkov photons gives a measure of the density of the object. Images of the object can thus be directly formed from the emitted light. The main advantage of this method is its speed, which rivals flash X-ray techniques. Once fully developed, this technique should be relatively inexpensive because it can utilize electron or proton beams.

3.7. Studies of superfluid transitions and phase separation of ^{3}He–^{4}He

Low density silica aerogels are used to study the superfluid transition of ^{4}He and phase separation of ^{3}He–^{4}He mixture. Here, the fractal aerogels provide a random disordered structure that modifies the normal superfluid and phase separation behavior with helium. There has been published work on ^{3}He–^{4}He phase transition anomalies in aerogels due to the extremely small pores [41–45].

3.8. Aerocapacitors

The carbon aerogels, being electrically conductive with very large surface areas for double layer charge separation, are an almost ideal material for capacitors [46,47]. The aerocapacitor is a high power density, high energy density, electrochemical double layer capacitor that uses carbon aerogels as electrodes. The electrodes possess very high surface per unit volume and are electrically continuous in both the carbon and electrolyte phases. The stored energy in these devices can be released rapidly with high power densities (e.g., 7.5 kW/kg).

3.9. Capacitive deionization

One of the promising new applications for aerogels is in a cost-effective purification process [48]. The carbon aerogel capacitive deionization process works by sending solutions with various positively and negatively charged ions through an electrochemical cell consisting of numerous electrodes containing carbon aerogels. The aerogel is in the form of sheets used as electrodes. The electrodes are stacked and alternate electrodes are oppositely polarized so that each attracts ions of opposite charge as they pass by and through the aerogel sheets. The polarization and flow are reversed to drive off the collected ions after the surfaces are saturated, thus obtaining a net purification of the processed water. The aerogel process can have a variety of uses ranging from extracting harmful contaminants from industrial wastewater to desalinizing sea water.

3.10. Optical fiber cladding for efficient light-guiding

In a patented application, aerogel films have been applied to the outside of fiber optics to improve the light collection and propagation efficiency [49]. The refractive index of the aerogel is close to that of air, which provides a high numerical aperture to the fiber-optic, maximizing its collection angle at the fiber ends. A wavelength shifting optical fiber, coated with a silica aerogel film (~ 20 μm thick), has demonstrated a factor of four increase in the light trapping fraction, over commercially available fibers.

3.11. Aerogels as energetic materials

A new and exciting application for aerogels is their potential use as energetic materials. The tremendous internal energy stored on the surfaces within aerogels has been discussed previously [50]. The uniform dispersion of extremely small energetic particles that could be produced in such materials, is particularly of interest for potential explosives. There are a variety of possibilities; e.g., making composites of aerogels and explosives, making aerogels directly from energetic molecules, and aerogels that contain oxidizer and reducer together, are a few. A report of work-in-progress, including experimental results with explosive containing aerogels, is presented in another ISA5 paper.

4. Applications by property or category

The following applications for aerogels, which have either been demonstrated or proposed, are associated with certain properties or features of aerogel materials. In many cases, the application is associated with a single property even if the aerogels have a combination of properties appropriate to the given application. The applications are listed by property or category, and the reference to the work is included wherever possible.

4.1. Optical property applications

Aerogels have been used to prepare ultrapure, full density silica glass by sintering at temperatures below the melting temperature of silica [51]. Lanthanide-doped aerogels are considered for laser glass [52–54] and dye-doped aerogels have actually demonstrated lasing action [55]. Silica aerogel, doped with radioactive tritium and a phosphor, makes an efficient radioluminescent light source [56]. There is also evidence for quantum confinement in nanoparticle-loaded silica aerogels [57] for producing blue light emission.

Translucent aerogels have been proposed for solar covers and collectors [58,59] and transparent aerogels have been considered by many for use in solar windows [60–66]. Ultralow density aerogels have been proposed as lightweight mirror backings [67].

4.2. Thermal insulator applications

Aerogel materials exhibit the lowest thermal conductivities of any of the solid or porous materials. This key property of the material leads to many applications including insulation for architectural purposes [68], piping, heat and cold storage appliances and devices [69], automotive exhaust pipes, transport vehicles and vessels. Commercial sources of aerogels have characterized their materials for thermal insulation applications [13].

4.3. Acoustical and mechanical applications

All of the aerogel varieties have unusual acoustic and mechanical behavior, which could be exploited for various applications. The two applications that have been used or proposed are: acoustic impedance matching for more efficient ultrasonic devices [70–72], and sound absorption (anechoic chambers) [73,74]. Aerogels have also been proposed as a shock absorbing material.

4.4. Porosity and surface area applications

The high porosity ($>85\%$) and very large surface areas ($>400\ m^2/g$) available in aerogel materials, lead to applications as filters [75], absorbing media for desiccation [76–78] and waste containment [79], encapsulation media [80], and hydrogen fuel storage [81]. Aerogels have been recognized for many years as excellent catalysts and catalyst supports [5] and there are numerous references of this application for various aerogels and doped aerogels [82–87].

4.5. Electrical and electronic applications

The metal oxide and organic aerogels are excellent dielectrics. The bulk aerogels can be used for microwave electronics and high voltage insulators [88]. Thin aerogel films are almost ideal dielectrics for ultrafast integrated circuits [89–91]. Carbon aerogels are electrically conductive, so they have applications as electrodes for batteries and capacitors [92]. Other metal oxide aerogels have been made, which exhibit superconducting behavior [93], thermoelectric behavior [94], and piezoelectric properties [95].

4.6. Space applications

Aerogels have already captured cosmic dust while on the European Retrieval Carrier (EURECA) satellite and in Space Shuttle experiments [6] and they are now proposed for a mission to capture cometary dust in NASA's STARDUST project. Lightweight silica aerogels have also been proposed as a contaminant collector to protect space mirrors from volatile organics [96].

5. Conclusions

This review does not include all applications for aerogels, by any means. However, it has shown that aerogels as a class of materials, have already demonstrated an incredible versatility of applications; probably having no comparable competitor in recent years. It can be said that the full impact of these materials for public use is yet to come. It is doubtful that it will happen until the cost of producing these materials is reduced and the price becomes competitive with other polymer materials. While this may still be a few years away, this author believes that the common use and availability of aerogels is inevitable. There is also little doubt that each future ISA conference we will include more applications for aerogels, both technical and commercial.

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