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The Features of Aerogel and Prospects for Large-scale Production

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Abstract:

Aerogels play a vital role in industrial applications, attracting significant scientific interest due to their low density, excellent thermal insulation properties, and other unique characteristics. These features have motivated extensive research into the material itself and the expansion of its practical applications. This article begins with a broad overview of the development history of aerogels. It then introduces their fundamental structure and key characteristics—notably, their nanoporous architecture, which results in extremely low density. The Rayleigh scattering effect is introduced to explain their optical behavior, while a microscopic analysis is provided to elucidate their exceptional thermal properties, fully demonstrating their superior physical performance. Subsequently, the article focuses on methods to reduce the production costs of aerogels to enable large-scale commercial manufacturing. Finally, a number of practical application cases are briefly summarized. The overarching aim is to offer perspectives on the future mass production of aerogels based on their structure, properties, real-world applicability, and cost-effective preparation strategies.

Keywords:. Aerogels; nanoporous structure; supercritical drying; ambient pressure drying.

1. Introduction

With the growing global demand for energy efficiency, environmental protection, and cutting-edge technologies, the development of novel multifunctional materials with exceptional properties has become a central focus in materials science. Among various advanced materials, aerogels are hailed as "miraculous materials" due to their unique structure. Aerogels are lightweight, nanoscale porous amorphous materials with a continuous network structure. At the microscopic level, they exhibit nanoscale homogeneity, with both pore sizes and particle diameters falling within the nanometer range. Furthermore, aerogels possess a specific surface area of 200-1000 $m^2 \cdot g^{-1}$ and an ultra-low density as low as 0.02 $g \cdot cm^{-3}$. Since their first synthesis by Kistler in 1931, aerogels have consistently attracted widespread attention from both academia and industry.

Owing to their distinctive nanostructure, aerogels exhibit significantly different mechanical, acoustic, optical, and thermal properties compared to conventional macroscopic glassy materials. These include

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a low refractive index, low elastic modulus, low acoustic impedance, extremely low thermal conductivity, strong adsorption capacity, and a typical fractal structure [1]. Despite their immense application potential, the development of aerogels has long been constrained by complex preparation processes, particularly the traditional supercritical drying technique, which demands sophisticated equipment, high costs, and poses safety risks. These limitations have severely hindered their large-scale commercial adoption.

This paper investigates the fundamental principles and diverse applications of aerogels through an in-depth study of their properties. It elucidates the common characteristics of aerogels as nanoporous materials, including their definition, classification, and key structural features that contribute to their exceptional performance. Special emphasis is placed on analyzing the feasibility of large-scale production. This review primarily focuses on reducing costs from the perspectives of materials and processing technologies to enhance economic and scalable feasibility, while also comparing the resultant differences in performance. The ultimate aim of this review is to delineate the technical development trajectory of aerogels and to propose future research directions based on existing challenges.

2. Aerogel Structure and Characteristics

Aerogels originated in the 1930s and were first invented by the American chemist Kistler, inspired by jelly. The extraordinary properties of aerogels primarily stem from their unique nanoporous structure. The solid framework of an aerogel (such as silica or carbon) is interconnected on the nanoscale, forming a hollow three-dimensional network that creates numerous nanoscale pores. The size of these pores is smaller than the mean free path of air molecules, meaning the air inside the pores becomes "trapped". More than 90% of the volume within an aerogel material consists of air, and such high porosity gives rise to its distinctive properties [2].

Aerogels are closely related to jelly. Jelly is essentially a hydrogel, consisting of two core components: a gelling agent and water. Taking the most common gelling agent, gelatin, as an example, it functions similarly to the silica framework in aerogels, forming a comparable three-dimensional network. Water, which makes up almost the entire volume of jelly, is trapped within the network formed by the gelling agent and cannot flow freely. This structure gives jelly its soft and elastic texture [3].

With nearly 99% of its composition being air, aerogels exhibit extremely low density—only slightly more than three times that of air. Additionally, their high porosity results in unique optical and thermal properties.

Although silica aerogels share the same chemical composition as glass and should theoretically be colorless, their distinct optical characteristics impart a sky-blue appearance. This phenomenon can be explained by Rayleigh scattering, which occurs when light passes through a transparent medium and encounters particles much smaller than its wavelength. The intensity of scattered light is inversely proportional to the fourth power of the wavelength, meaning shorter wavelengths (such as blue and violet light) are scattered more strongly, while longer wavelengths (such as red and orange light) penetrate the medium more easily with minimal scattering. Aerogels, with their highly sparse three-dimensional network structure, feature nanoscale frameworks and pores that are far smaller than the wavelength of visible light (380-780 nm), perfectly satisfying the conditions for Rayleigh scattering by acting as "tiny particles." Thus, when a beam of white light shines on an aerogel: long-wavelength light (e.g., red and orange) penetrates the aerogel directly due to minimal scattering; short-wavelength light (e.g., blue and violet) is scattered in all directions by the nanoscale network structure of the aerogel [4].

Aerogels are hailed as the "ultimate thermal insulation material" due to their exceptional heat resistance, a capability derived from their unique structure that effectively blocks all three heat transfer pathways. First, their extremely high air content (exceeding 99.9%) and minimal solid framework drastically limit heat conduction, while the intricate nanoscale network forces heat to travel through an elongated and tortuous path, making solid-phase heat transfer highly inefficient. Second, the pore size within aerogels (typically 20-50 nm) is smaller than the mean free path of air molecules (~70 nm), restricting air movement and collisions, thereby suppressing convective heat transfer. Third, although pure aerogels are partially transparent to infrared radiation, the incorporation of opacifiers such ascarbon black or titanium dioxide during manufacturing effectively scatters and absorbs infrared radiation, significantly reducing radiative heat transfer [5]. As a result, aerogels exhibit an ultra-low thermal conductivity of 0.012-0.018 W/(m·K) at ambient temperature—lower than that of stationary air (~0.025 W/(m·K)) and substantially superior to traditional insulation materials like polystyrene foam (~0.035 W/(m·K)) and fiberglass (~0.040 W/(m·K)). Moreover, inorganic aerogels (e.g., silica-based) can withstand temperatures as high as 600-800 °C without burning or melting, maintaining stable insulation performance under extreme conditions.

2.1 Aerogel Preparation

The high production cost of aerogels remains a major bottleneck hindering their large-scale commercial applica-

tion. The preparation process consists of two main steps: the sol-gel process and the drying process. Traditional aerogels typically use silicon source compounds such as tetramethyl orthosilicate (TMOS) and tetraethyl orthosilicate (TEOS) as precursors. Technically, the precursor is first mixed with a solvent (usually alcohol and water), and hydrolysis and condensation reactions are initiated under the influence of a catalyst (acid or base). In other words, precursor molecules react with water to form reactive silanol groups (-Si-OH), which then interconnect, releasing water or alcohol, and ultimately form a nano-particulate network of -Si-O-Si- bonds. This results in a solid three-dimensional network that encapsulates the liquid solvent, forming a wet gel [6]. The drying process is the most critical, technically challenging, and cost-intensive stage of aerogel production. Since the nanopores of the wet gel are filled with solvent, direct evaporation drying would generate immense capillary forces that could completely collapse the fragile porous structure, resulting in a dense xerogel rather than an aerogel. Supercritical drying is the earliest and most reliable method to address this [7]. It involves heating and pressurizing the solvent within the wet gel beyond its critical point. In the supercritical state, the gas-liquid interface disappears, and surface tension drops to zero. The supercritical fluid is then slowly released, allowing the intact aerogel structure to be obtained without any capillary force-induced damage.

To reduce the production cost of aerogels, two main strategies are employed. The first is raw material cost control: using sodium silicate ($Na_2O \cdot nSiO_2$, water glass) instead of high-purity organic silicon sources is the most fundamental approach to lowering material expenses. However, the technical challenge lies in the high content of metal ion impurities (e.g., Na^+) in water glass, which interfere with the gelation process and adversely affect the final product's properties (e.g., thermal insulation and hydrophobicity). Therefore, the entire process centers on "purification" and "network strengthening" [8]. A key purification step is ion exchange, wherein diluted water glass solution is passed through a cation exchange resin column. Na^+ ions are exchanged with H^+ on the resin, yielding highly reactive silicic acid (H_2SiO_3) solution. This removes Na^+ ions and produces active silica sol. The exchanged silica sol is then pH-adjusted (usually with a basic catalyst) to trigger condensation, forming a "wet gel." The gel network is subsequently aged in the mother liquor to allow unreacted groups to continue cross-linking, thereby strengthening the network and enhancing its mechanical resistance to capillary forces during drying. This aging process is essential for ambient pressure drying.

Another core research direction for cost reduction is ambient pressure drying. This method does not avoid capillary forces but instead strengthens the gel skeleton and reduces solvent surface tension to withstand them. The process involves three steps: first, solvent exchange replaces the original solvent (e.g., water or alcohol) in the wet gel with a low-surface-tension solvent (e.g., n-hexane or trimethylchlorosilane); next, surface modification is carried out using silylating agents (e.g., trimethylchlorosilane, TMCS) to react with hydroxyl groups (-OH) on the gel skeleton, converting them into hydrophobic and stable organic groups ($-Si-CH_3$). This step is crucial as it eliminates hydrophilic hydroxyl groups, preventing reformation of hydrogen bonds during drying that could cause collapse, while significantly enhancing the mechanical strength of the skeleton; after these treatments, the gel skeleton becomes robust enough, and the pore liquid exhibits very low surface tension, enabling direct drying at ambient pressure and low temperatures without structural collapse [9].

Silica aerogels prepared via ambient pressure drying have been characterized using scanning electron microscopy, pore size distribution analysis, infrared spectroscopy, and thermal conductivity measurements. The results confirm a typical nanoporous structure with a density of 60-300 kg/m^3, an average pore size of ~20 nm, a specific surface area of 400-700 m^2/g, and a thermal conductivity of 0.027-0.031 W/(m·K). These materials represent cost-effective aerogels with controllable density and broad application prospects [10].

2.2 Applications of Aerogels

2.2.1 . Hemostatic materials

Hemostasis plays a critical role in medical practice. Zhang Quanrui et al. utilized the properties of aerogels to develop a novel aerogel-based hemostatic material (hereinafter referred to as OPA). Through experiments on rats, including perforation of internal organs and external tissues, as well as tail amputation, OPA was conclusively demonstrated to exhibit excellent hemostatic efficacy. The results indicated that OPA can adhere tightly to various tissues, achieving rapid and effective bleeding control—reflecting its strong tissue adhesion capability. Moreover, it possesses the unique advantage of easy removal upon rinsing with water after hemostasis is achieved, making it suitable as a next-generation hemostatic material. It significantly reduces blood loss and improves patient survival rates [11]. Furthermore, its favorable biocompatibility and biodegradability provide a safety guarantee for clinical application, preventing complications caused by residual material. Aerogels have already been applied in clinical cases involving nasal hemostasis. For example, in Rhino gel hemostasis applications: no bleeding was observed in 25 cases (13.7%); mild bleeding occurred in 149 cases (81.9%); severe bleeding was noted in only 8 cases (4.4%).

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These data clearly demonstrate the superior hemostatic performance of aerogels, with a very low incidence of severe bleeding, further confirming their high safety profile in clinical use [12].

2.2.2 . Supercapacitors

Supercapacitors (SCs) represent a class of energy storage devices that bridge the gap between conventional capacitors and rechargeable batteries. They are capable of rapid charging and discharging with minimal capacitance loss over thousands of cycles, owing to their exceptional charge-discharge rates and long cycle life. As a result, SCs are increasingly replacing traditional capacitors in various applications. A typical SC consists of two electrodes, an electrolyte, and a separator, with the electrode material playing a decisive role in its performance. Aerogels, when engineered into electrodes, offer a unique structure characterized by ultra-lightweight, high porosity, and large specific surface area. These properties not only facilitate enhanced ion diffusion and charge transfer but also contribute to improved charge-discharge kinetics and extended cycling stability.

In a study conducted by Zhang et al., a polyacrylamide/cellulose hydrogel electrolyte with favorable mechanical and electrochemical properties was synthesized via in-situ polymerization at room temperature. The reaction involved acrylamide and N, N'-methylenebisacrylamide as initiators, and 2-mercaptobenzoic acid as a crosslinking agent, all combined directly in a cellulose aqueous solution. This hydrogel electrolyte was then assembled with activated carbon to form a symmetric supercapacitor. Electrochemical evaluations revealed outstanding performance: a specific capacitance of 163.7 F/g was achieved at a current density of 1.0 A/g, along with a capacitance retention rate of 87.9% after 8,000 charge-discharge cycles [13].

3. Conclusion

This paper focuses on the preparation and application of aerogel materials. The Rayleigh scattering theory is applied to provide a comprehensive explanation of the optical characteristics of aerogels, while experimental data are presented to demonstrate their exceptional thermal insulation performance. A cost-reduction method is introduced, which utilizes ion exchange to initiate a condensation reaction, resulting in the formation of a "wet gel." The gel network is subsequently aged in the mother liquor to allow unreacted functional groups to continue cross-linking. This process strengthens the network structure, enhances its mechanical strength, and improves resistance to capillary forces during drying, thereby reducing the overall production cost of aerogels and offering promising prospects for their large-scale manufacturing. Furthermore, regarding applications, aerogels demonstrate significant potential in medical hemostasis and capacitive energy storage due to their unique structural properties. Their outstanding efficacy in medical bleeding control, coupled with their sustainable performance in supercapacitors, highlights the broad application prospects of aerogels once large-scale production is achieved.

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