

Abstract

Silica aerogels have emerged as a groundbreaking material in the 21st century, distinguished by their extraordinarily porous structure. These advanced materials boast a wide range of specific surface areas from 100 to 1600 m²/g and exhibit low refractive index ranging from 1.007 to 1.240. The versatility of silica aerogels extends to a multitude of uses, including their role as adsorbents for harmful substances, elements in sensor technology, dielectrics, filtration systems, detectors for Cherenkov radiation, energy absorption mechanisms, bases for catalysis, transporters, extraction agents and protective wear.

Aerogel encapsulates air within the chain of linked pearls and enables aerogels to contain between 80% and 99.8% air, making them among the lightest solids available and providing them with exceptional insulating properties. The air trapped in these voids significantly reduces heat transfer through both conduction and convection, contributing to aerogel's status as one of the best insulating materials available. The air inside the aerogel's pores is immobilized, limiting the movement of air molecules and thus reducing the ability of heat to transfer through the material. When the ambient air pressure is reduced at higher altitudes, the already low thermal conductivity of the trapped air decreases even further. Consequently, the thermal insulation effectiveness of aerogels is amplified in these conditions.

The effectiveness of aerogel in acoustic insulation is also influenced by its porosity, pore size distribution, and the density of the material. The ability to engineer aerogels with specific properties allows for the customization of the material to target specific sound frequencies, enhancing its utility across a broad range of applications. For instance, aerogels can be designed to have a higher performance in absorbing low, medium, or high-frequency sound waves, making them suitable for various environments, from industrial settings to residential and commercial buildings where noise reduction is desired.

Silicon dioxide, the constituent material of silica aerogels, is inherently non-flammable. Unlike organic materials, silica does not combust, nor does it support combustion. This makes silica aerogel a particularly effective material for fire resistance, as it can withstand exposure to high temperatures without igniting or degrading. This combination of attributes establishes silica aerogel as an exceptionally suitable material for scenarios demanding substantial thermal insulation and fire resistance capabilities.

However, the integration of silica aerogels into everyday uses faces limitations due to their inherent brittleness, which presents challenges in processing. The nanostructured network that gives aerogels their lightweight and insulating properties also makes them fragile and prone to cracking or shattering under mechanical stress. This brittleness restricts the use of aerogels in applications where materials may be subject to impact, vibration, or bending forces. Aerogel releases fine dust particles, which are fragments of the aerogel structure. This dust can be an irritant, posing health risks when inhaled and necessitating protective measures during handling and processing. The propensity to emit dust also complicates the integration of aerogels into environments where air purity is critical.

Many aerogels, especially silica-based ones, are naturally hydrophilic, meaning they readily absorb water. This absorption can significantly affect their structural integrity and insulating properties. In environments with high humidity or direct exposure to water, the performance of aerogels can be compromised unless they are properly treated or coated to repel water.

The manufacturing of aerogels involves sophisticated processes, including supercritical drying, which requires specialized equipment and conditions to avoid the collapse of the aerogel structure. The complexity of these processes contributes to higher production costs and limits the ability to produce aerogels on a large scale. Perhaps the most significant limitation to the widespread adoption of aerogels is their cost. The intricate manufacturing process, coupled with the need for specialized materials and equipment, makes aerogels significantly more

expensive than traditional insulating materials like polyurethane foam. The high cost is a barrier for many potential applications, especially where large quantities of material are required. Research has identified multiple methods to reinforce the mechanical properties of silica-based aerogels, including extending the ageing process, applying polymers for silica network cross-linking, introducing additional phases or flexible precursors to the silica sol, and incorporating strong covalent bonds between particles. Challenges associated with aerogels involve their propensity to emit dust, inherent attraction to water, risk of shrinking in volume, the need for complex processing, and importantly, their price, which is considerably higher than that of traditional materials such as polyurethane foam. Overcoming these obstacles is crucial for expanding the range of practical applications for these promising materials.

This thesis presents a detailed investigation into the synthesis of silica aerogels using sol-gel technology under ambient pressure drying, with a strong emphasis on optimizing the entire synthesis process. The research meticulously optimized catalytic conditions using both acid and base catalysts to fine-tune the hydrolysis and condensation reactions of the silica precursor, crucial for controlling the gelation process and achieving the desired structural integrity and porosity. Additionally, the molar concentration of the precursor to solvent was adjusted to influence the aerogel's microstructure directly, targeting optimal pore size and distribution for improved insulating and mechanical properties. A significant focus was also placed on making the aerogels hydrophobic through surface modification, which involved optimizing the concentration of hydrophobic agents to enhance moisture resistance without compromising structural integrity. Process times for each synthesis step, including gelation, aging, and hydrophobic treatment, were optimized for ideal properties. Furthermore, multiple solvent exchanges were employed to mitigate capillary pressure during drying, preventing shrinkage and preserving the aerogel's microstructure. Through these comprehensive optimizations, the research succeeded in producing silica aerogels with controlled porosity, superior mechanical

properties, and effective hydrophobicity, paving the way for their broader application across various industries.

The next chapter investigates a streamlined method for producing silica aerogels, focusing on the use of a precursor containing unhydrolyzed methyl groups. This approach notably omits the process of surface modification, a step typically involved in enhancing the hydrophobicity of aerogels. In addition, it details the optimization of acid-base catalysts, crucial for effectively controlling the sol-gel reaction that forms the aerogel structure. A significant innovation in this method is the avoidance of multiple solvent exchanges, a procedure traditionally necessary to minimize capillary forces during drying, which can lead to structural shrinkage and compromise the aerogel's integrity. The chapter further presents a detailed comparison of the properties of aerogels produced using this novel approach with those of conventional aerogels. The development of aerogel-embedded glass and ceramic blankets through the in-situ synthesis of aerogel under ambient pressure conditions is explored for use in aero-engine applications. Utilizing a two-step acid-base synthesis process with tetraethyl orthosilicate (TEOS) as the silica source, this approach addresses the inherent fragility of aerogels by incorporating them into a fibrous matrix.

This network imparts the composite material with comprehensive structural integrity and macroscopic flexibility, overcoming the brittleness typically associated with aerogels. The aerogel blanket demonstrates superior thermal and acoustic insulation properties post-synthesis, signifying a substantial improvement over traditional insulation materials. Furthermore, the aerogel blanket meets stringent fire-resistance standards, making it suitable for critical applications such as thermal shielding in aero-engines.

In the subsequent chapter, the in-situ production of aerogel for the creation of an aerogel-embedded blanket is explored, utilizing methyltrimethoxysilane (MTMS) as the silica source and employing ambient pressure drying for synthesis. This process omits surface modification

steps, leading to the formation of an aerogel that is both flexible and compressible, making it suitable for application in aeroengine insulation. The influence of the MTMS precursor concentration on the characteristics of the aerogel-embedded blankets is thoroughly investigated, with particular attention to how variations in precursor concentration impact the aerogel's physical properties, including its degree of shrinkage. This analysis extends to examine the effects of aerogel shrinkage on the overall physical attributes of the developed blankets. The incorporation of aerogel into the blanket matrix significantly enhances its thermal and acoustic insulation properties, attributed to the aerogel's ability to trap air within its structure. Furthermore, the aerogel-embedded blankets demonstrate enhanced fire resistance, a critical requirement for their application as insulation shields in aeroengines.

The challenge of dusting associated with aerogel-embedded blankets has led to the exploration of a novel solution: the development of 3D woven spacer fabrics. These three-dimensional textiles are crafted by intertwining two distinct layers of fabric with pile yarns, using advanced weaving or knitting techniques. Renowned for their lightweight, superior formability, and adaptability, spacer fabrics have found widespread applications in industries such as aerospace, shipbuilding, and automotive. The customizable nature of these substrate allows for tailored adjustments to pile height and frequency by altering yarn types and fabrication methods. This flexibility enables precise control over the fabric's density and air permeability, making 3D woven spacer fabrics a promising alternative to traditional porous materials for various protective applications.

In the last chapter, the development of aerogel-embedded 3D woven basalt spacer fabrics is presented, achieved through ambient pressure drying with the use of both precursors. This innovative technique showcases outstanding mechanical strength, enhanced thermal stability, remarkable sound insulation, and unparalleled thermal insulation efficacy. The inclusion of pile structures within these fabrics significantly contributes to their structural integrity,

effectively preventing aerogel particles from shedding. The exceptional thermal insulation observed in these 3D woven blankets can be attributed to the synergistic effect of the aerogel's nano-3D network structure and the inherent thermal insulating qualities of basalt fibers. Adjustments in pile height and the overall thickness of the spacer fabrics directly influence the mechanical properties, demonstrating the customizable nature of these materials. Furthermore, variations in the sol-gel parameters, particularly the dilution ratio of precursor to solvent, were found to impact the aerogel's characteristics, thereby affecting the overall performance of the resulting blankets. This comprehensive exploration highlights the potential of aerogel-embedded 3D woven basalt spacer fabrics in providing effective insulation solutions with enhanced durability and performance.

This research presents a methodical strategy for engineering robust and lightweight aerogel-embedded blankets, specifically designed for advanced insulation applications. These innovative materials are adept at providing effective thermal insulation, soundproofing, and fire protection, making them highly suitable for a diverse range of practical uses across various sectors including building, aerospace, and construction industries.