

Mechanics and thermal transport in nanostructured porous polyimides

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Abstract

Aerogels are ultra-light, nanostructured solids with extremely high porosity. Their high specific surface area and very low density result in unique thermal, mechanical, and optical properties compared to conventional materials. Aerogels can be synthesized from variety of materials, including inorganic compounds, organic polymers, biopolymers, or hybrid systems, forming a three-dimensional network of interconnected nanoscale building blocks. This combination of structural and physical features makes aerogels a versatile class of advanced materials used in applications ranging from aerospace to energy, environmental, and biomedical technologies. Their performance depends not only on chemical composition but also on nanoscale architecture, making them valuable for both fundamental research and innovative, application-driven material design. Understanding the structure–property relationships of aerogels is crucial for tailoring their performance across a wide range of applications. Even small variations in pore size, connectivity, density, or skeletal morphology can significantly affect heat transport,

mechanical strength, optical transparency, and acoustic behavior. A major focus of our research group is the development of advanced thermal insulation materials for space and aerospace applications, where extreme temperatures, strict weight limits, and long-term reliability are critical. In this context, polymer-based aerogels, particularly those derived from high-performance polymers such as polyimides, offer key advantages, including low thermal conductivity, high thermal stability, and mechanical resilience. Understanding how the structural features of these aerogels relate to application-relevant performance is therefore essential for targeted material optimization. We investigated how nanoscale morphology affects the thermal, mechanical, and acoustic properties of fibrous polyimide aerogels. A systematic series of aerogels with identical chemical composition but varying morphology was synthesized, and comprehensive characterization examined how fiber diameter, network connectivity, and pore architecture influence heat transfer, mechanical, and acoustic behavior. These experimental results were complemented by nanoscale theoretical modeling, providing deeper insight into the underlying physical processes and enabling quantitative structure–property relationships to guide the rational design of high-performance thermal insulation materials.

Keywords:

aerogel polyimide thermal conductivity structure-property