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Advances of thermal conductivity models of nanoscale silica aerogel insulation material

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HIGHLIGHTS

- The heat transfer mechanisms of nanoporous aerogel material are analyzed.
- The heat transfer models for the nanoporous aerogel material are reviewed.
- Illustration of establishing thermal conductivity model of the material are given.
- Future interests for heat transfer of aerogel material are pointed out.

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ABSTRACT

This paper summarized the development of the effective thermal conductivity models for the nanoporous silica aerogel insulation material. Firstly, the nanoscale heat transfer characteristics inside aerogel material was introduced. Secondly, the existing models and methods to calculate the thermal conductivity of each heat transfer mode at the nanoscale were reviewed. Next, the advances and developments of the effective thermal conductivity models for the nanoporous silica aerogel materials as well as its composite insulation material were also discussed. Then the procedure of establishing the effective thermal conductivity model of the aerogel insulation material from nanoscale to macroscale was introduced by taking our previous work as an illustration. Finally, it should be noted that for the nanoporous silica aerogel insulation material, there are still some key issues that need to be investigated to get deep understanding of the mechanism of nanoscale heat transfer inside the material, such as the coupled heat transfer behavior at the gas–solid contact interface, the influence of scale effect/interfacial effect on the thermal conductivity of nanoscale solid particles, etc. Thus it is necessary to keep on investigating these questions thoroughly to provide help for establishing more accurate heat transfer model as well as optimizing the insulation performance of the material.

1. Introduction

Thermal insulation material is a kind of material that can significantly reduce the heat flux through it. The utilization of the thermal insulation material can save energy on one hand and meet the temperature requirement of equipment/building on the other hand. Thus insulation material is of great importance for many engineering applications, such as energy, building, aeronautics and astronautics and so on. Thermal conductivity is one of the most important parameter that reflect the insulation performance of the thermal insulation material. With the rapid development of high technology(hypersonic vehicle, space shuttle), the requirement for high efficient thermal insulation material become more and more urgent. Traditional thermal insulation material (fiberglass, asbestos, rock wool, etc) become difficult to meet the requirement for these high-tech equipment. Therefore, developing new-type thermal insulation material become a major trend in the development of thermal insulation materials. Among them, aerogel is one of the most promising new-type high efficient thermal insulation material.

Aerogel usually refers to such a kind of lightweight nanoscale solid material that is constituted by the aggregation of nanoscale particles to form a nanostructured solid network. Aerogel has nanoporous structure with 1–20 nm particle diameter and

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2–50 nm pore diameter, and its porosity can be up to 90% [1]. The special nanoscale porous network structure (Fig. 1) brings about a lot of excellent properties of aerogel material and makes it applicable to a widely fields in industry such as thermal insulation, energy, building, chemical industry, catalysis, aeronautics and astronautics and so on. Hrubesh [2] had summarized the special properties and the corresponding application of aerogel material, see Table 1.

As a kind of new type nanoporous heat insulation material, aerogel has the advantages of lightweight and highly efficient heat insulation performance, so it has attracted more and more attentions, especially in the rapidly developed aerospace area [3–6]. In the 1990s, NASA applied aerogel material in two Space exploration programs: *Mars Pathfinder* and *Stardust*; this opened the aerogel application in the field of space exploration [3]. In 2003, the *Sample Collection for the Investigation of Mars (SCIM)* and *Satellite Test of the Equivalence Principle (STEP)* in NASA's *Mars Exploration Rovers* both used aerogel material as insulation material, and it was considered to be one of the key factors of the success of the plans [3]. In 2005, NASA prepared to use aerogel material in the thermal protection system of Venus spacecraft [6]. Up to now, NASA has never stopped the efforts in aerogel research. Besides, as the new type insulation material, aerogel also has more and more applications in civilian field and modern industry [7–10]. Cuce et al. [11] gave a comprehensive review on aerogel and its utilization in buildings. An economic analysis and future potential of aerogel were also considered in their study.

Since the traditional thermal insulation materials can hardly meet the high demand in modern industrial, aerospace and other fields, the development of the nanoporous aerogel insulation material becomes important. Because of its nanostructure, aerogel has some special heat transfer phenomenon which makes heat transfer inside the material much more complex. Therefore, analyzing the heat transfer modes and the internal heat transfer mechanisms, constructing a suitable thermal conductivity model for aerogel material and studying the influence of various influencing factors on the heat transfer performance of material, have significant values in the performance prediction, optimization as well as practical application for the silica aerogel composite insulation material. And this could also provide theoretical foundation for the further development of new heat insulation material with high temperature resistant, lightweight and high efficiency.

Recently, many scholars have studied and discussed the heat transfer models of silica aerogel nanoporous insulation material. The object of this paper is to review the current heat transfer models for the aerogel material and to help the subsequent studies of aerogel material. The structure of this paper is as follows: In Section 2, the nanoscale heat transfer features inside nanoporous aerogel material and the heat transfer features of composite aerogel insulation material will be introduced. In Section 3, the current thermal conductivity models for the three basic heat transfer modes inside aerogel material, which are gaseous heat transfer, solid heat transfer and radiative heat transfer, are discussed, respectively. Afterward, on the basis of models of each heat transfer mode, the total effective thermal conductivity models for the nanoporous aerogel material and its composite insulation material are reviewed. Our previous work on the effective thermal conductivity of aerogel insulation material is then introduced as an illustration of establishing the effective thermal conductivity model of the material. Finally, as a fast developed molecular simulation method, the molecular dynamics (MD) plays an important role in the simulation of aerogel materials and we will make a briefly introduction of MD.

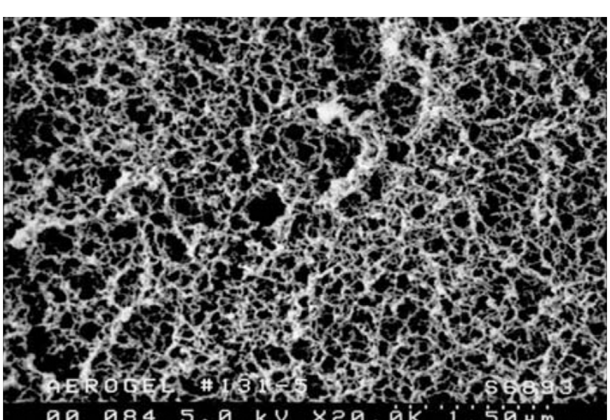

Fig. 1. Scanning electron micrograph of silica aerogel network [3].

Table 1
Properties, features and applications of aerogel material [2].

Properties	Features	Applications
Thermal	• Best insulation solid • Transparent • High temperature • Lightweight	Building insulation materials, Space vehicles and detection, casting molds
Density/porosity	• Lightest synthetic solid • Homogeneous • High specific surf. area • Multiple compositions	Catalysts, sorbers, sensors, fuel storage, ion exchange
Optical	• Low refractive index solid • Transparent • Multiple compositions	Cherenkov detectors, lightweight optics, special effect optics
Acoustic	• Lowest sound speed	Sound absorption materials, 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

2. Aerogel heat transfer mechanism analysis of aerogel material

2.1. Nanoscale heat transfer inside nanoporous aerogel material

In porous materials, there are three basic modes of heat transfer, which are convection, conduction and radiation heat transfer.

Convection is the macroscopic movement of the fluid, which leads to a relative displacement and mixes the cold part and hot part of the fluid to produce the heat transfer in the fluid. For porous media, it was reported that when the pore diameter is lower than 4 mm, heat transfer by the convection could be neglected [12,13]. Since the internal pore diameters of aerogel material are all nanoscale [1,14], convection is neglected when studying heat transfer characteristics of aerogel.

Conduction is a kind of heat transfer mode which is caused due to the motion of microscopic energy carriers, such as molecular, atom as well as free electron and phonon [15]. Porous media has solid phase composition and gas phase composition, so the conduction heat transfer mode could be subdivided into the gaseous heat conduction and solid heat conduction.

Gaseous heat conduction is caused due to the collision between gas molecules. The pore diameter of aerogel is about 5–100 nm and the mean diameter of pore is about 20–40 nm [1], while the mean free path of air under the standard temperature and pressure is