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An analytical model for combined radiative and conductive heat transfer in fiber-loaded silica aerogels

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ABSTRACT

An improved analytical model for the total thermal conductivity of fiber-loaded silica aerogels was developed based on the complex refractive index, size, orientation, volume fraction and morphology of the fibers and silica aerogel. A cubic array of spherical porous secondary nanoparticles and a modified parallel-series model were proposed to model the combined solid and gaseous thermal conductivities. An anomalous diffraction theory (ADT) was used to predict the fiber extinction coefficient. Five common fiber types in the composites were studied including amorphous SiO_2 glass, silicon glass, common float glass, soda lime silica glass and borosilicate glass. The results show that the total extinction coefficient of the silica aerogel system is largest by loading with the common float glass fiber and lowest by loading with the soda lime silica glass among the five fiber types. The model provides theoretic guidelines for material designs with optimum parameters, such as the type, inclination angle, volume fraction and diameter of the fibers as well as the aerogel nanoparticle and pore sizes. The optimum fiber for improved thermal insulation should have a large spectral complex refractive index throughout the infrared region.

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1. Introduction

Silica aerogels are transparent, highly porous and open-cell thermal insulating materials made of nanoporous matrices with interconnected 3-D random aggregates of amorphous silica nanoparticles [1–11]. However, pure silica aerogels are fragile with low mechanical strength and are transparent in the infrared wavelength range between 3 and 8 μm [9–11]. Thus, microscale fibers or other hard materials are usually added into the aerogel matrix to provide mechanical reinforcement [2,3,5,9]. Some mineral powders, such as TiO_2, SiC and carbon black, are usually loaded into the aerogels as opacifiers to reduce the radiative heat transfer [1–3,8]. Properly selected fibers can both strengthen the material and be used as opacifiers to reduce the radiative heat transport in aerogels at high temperatures [9]. These nanoporous thermal insulating composites have extremely low thermal conductivities of about 0.02 $W\,m^{-1}\,K^{-1}$ at ambient conditions and small densities of 50–300 $kg\,m^{-3}$ [1–11]. Thus, these composites have great potential for applications in heat storage and transport systems as well as heat protection of space vehicles and nuclear reactors [1–13].

Accurate heat transfer models of fiber-loaded silica aerogel composites can facilitate system thermal analyses and guide the design of new materials for better thermal insulation. The heat transfer mechanisms in these highly porous materials include solid conduction, gas convection and conduction, and radiation. The gas convection can always be neglected as the pore sizes in the nanoporous composite are much smaller than 1 mm [12]. Since the sample thickness in practical thermal insulation applications is typically very large, about 1–5 cm, the sample can be considered to be optically thick [9,11–15]. The total thermal conductivity of the composite, k_{total}, can then be expressed as the linear superposition of the conductive, k_c, and radiative, k_r, thermal conductivities as $k_{\mathrm{total}} = k_c + k_r$ [5,9].

The radiative thermal conductivity, k_r, dramatically increases with temperature while k_r can be reduced by a larger extinction coefficient [8–18]. Thus, the extinction coefficient is a key radiative property that determines the thermal insulation ability of the composite at high temperatures. Mie theory for an infinitely long circular cylinder is always used to obtain the extinction efficiency of a single fiber [9]. However, the Mie theory calculation for a cylinder is complicated, time-consuming and slow to converge due to the calculation of the infinite series in Mie theory [19]. A suitable approximation to Mie theory is the anomalous diffraction theory (ADT) introduced by van de Hulst [20], which can predict the extinction efficiency of spheres, spheroids and cylinders within an

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acceptable degree of accuracy [19–21]. The ADT gives a clearer mathematical formulation of the fiber extinction efficiency based on the incident angle, fiber geometric and optical properties [19–21]. The fiber extinction efficiencies are then integrated over the fiber sizes and orientation distributions together with the fiber volume fraction to obtain the extinction coefficient of fiber assemblies [9].

The conductive thermal conductivity of the composite, k_c, includes the gas conduction in aerogel nanopores and the solid conduction via the aerogel skeleton and the fibers [22–26]. The combined solid and gaseous thermal conductivities of silica aerogels are usually based on a density empirical equation [1,3] or an analytical solution for a cubic array of intersecting spherical full density nanoparticles [5,25,26]. However, the helium pycnometry experiment shows that the measured skeletal density of silica aerogels is smaller than the amorphous silica density [10]. The density difference indicates that the aerogel nanoparticles are not full density. The combined aerogel and fiber thermal conductions are usually based on a density empirical equation [9], which is not very accurate due to the neglected fiber geometry and orientation.

To the best of the authors' knowledge, there is limited information available on the thermal properties of various fibers and the fundamental relationship between the total thermal conductivity and the actual composition and morphology of fiber-loaded aerogel composites [9,27]. This paper improves the analytical heat transfer models to investigate the effects of the fiber type and the micro- and nanoscale morphologies of the fiber and silica aerogel on the total thermal conductivity of the composite. The combined solid and gas thermal conductions in the aerogel matrix are developed based on a cubic array of spherical porous secondary nanoparticles while previous studies are all based on full density primary nanoparticles [5,25,26]. An improved parallel-series model is proposed here to combine the aerogel and fiber thermal conductions while previous studies are usually based on the density empirical equation [9]. The radiative and conductive heat transfer of five common types of fibers, which include amorphous SiO_2 glass, silicon glass, common float glass, soda lime silica glass and borosilicate glass [28–30], as well as the corresponding composites is investigated in this study.

2. Preparation and characterization

After the sol was prepared using a tetraethylorthosilane (TEOS)–water–ethanol system, the fibers were dispersed in the sol with an aqueous ammonia solution to base-catalyze the fiber–sol composite into the fiber–gel composite. The fiber-loaded silica aerogel composites were then prepared based on this two step sol-gel process and the supercritical drying. The five kinds of most common fibers loaded into the silica aerogel to strengthen the material are amorphous SiO_2 glass [28], silicon glass [29], common float glass [30], soda lime silica glass [30] and borosilicate glass [30].

Table 1
Fiber types and compositions [28–30].

Fiber type	Composition
Amorphous SiO_2 glass fiber [28]	100 wt.% SiO_2
Silicon glass fiber [29]	60–65 wt.% SiO_2, 14–16 wt.% Na_2O, 7–10 wt.% CaO, 4–7 wt.% B_2O_3, 2–4 wt.% Al_2O_3 and MgO
Common float glass fiber [30]	73 wt.% SiO_2, 15 wt.% Na_2O, 10 wt.% CaO, and 2 wt.% Al_2O_3
Soda lime silica glass fiber [30]	72 wt.% SiO_2, 14 wt.% Na_2O, 9 wt.% CaO, and 4 wt.% MgO
Borosilicate glass fiber [30]	81 wt.% SiO_2, 4 wt.% Na_2O, 13 wt.% B_2O_3, and 2 wt.% Al_2O_3

These five types of fibers are investigated in the present study with the fiber compositions listed in Table 1. The complex refractive indices of the five types of fibers, $m_f = n_f - i\kappa_f$, are shown in Fig. 1 [28–30]. The real part, n, accounts for the radiation refraction and determines the phase velocity in the medium. The imaginary part, κ, accounts for the absorption and determines the radiation attenuation through the medium. n and κ are often referred to as the optical constants.

A Brunauer–Emmett–Teller (BET) sorption analyzer, a FTIR spectrometer and a scanning electron microscope (SEM, Hitachi S-5500) were used to analyze the fiber-loaded silica aerogel composite. Fig. 2(a) shows that a fiber-loaded aerogel composite is more opaque to visible light than a pure silica aerogel. The upper and lower surfaces were assumed to have constant wall temperature boundary conditions with the other side faces under zero heat flux conditions. The A-A cutting plane is parallel to the top and bottom surfaces or perpendicular to the heat flux. Fig. 2(b) shows that the fibers are well dispersed in the aerogel matrix, criss-crossing the A-A cutting plane with a few distributed perpendicular to the A-A cutting plane. The fiber volume fractions in different A-A cutting planes are almost the same, about 5% [26]. The inclination angle, ϕ, as shown in Fig. 3 is the angle that describes the extent of a fiber deviating from the A-A cutting plane. If the fiber is in the A-A cutting plane, then $\phi = 0°$.

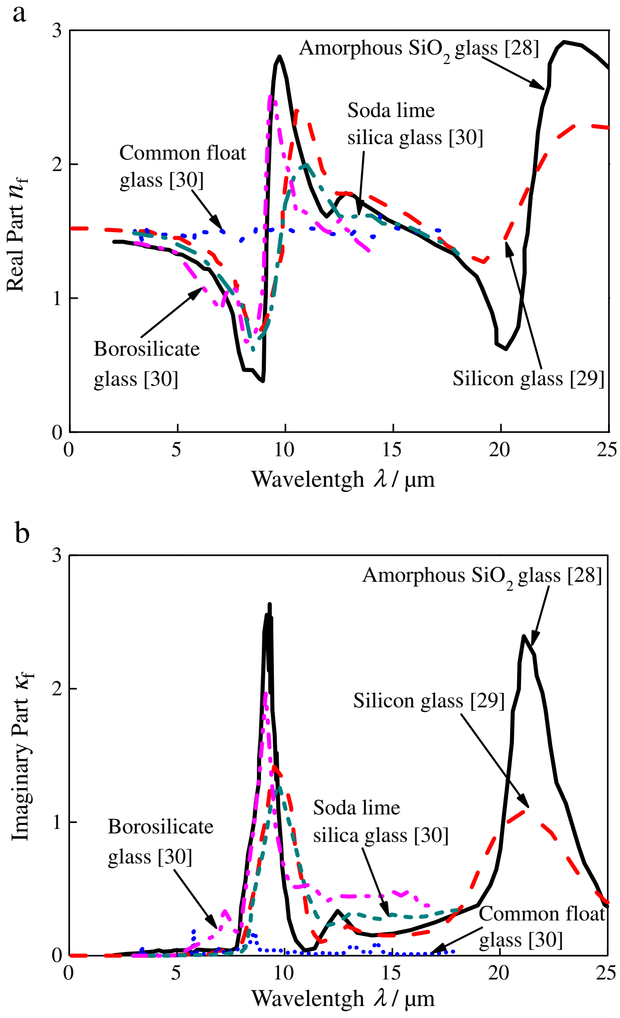

Fig. 1. Experimental data of complex refractive indices of the five types of fibers [28–30]. (a) Real part; (b) imaginary part.

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