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Coupling model for heat transfer between solid and gas phases in aerogel and experimental investigation

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ABSTRACT

The coupling heat conduction between the aerogel solid and gas phases is of important contribution to the total effective thermal conductivity of aerogel. Based on the assumption of spherical particles in the aerogel backbone, a theoretical model is proposed to calculate the coupling thermal conductivity in aerogel which relates aerogel mean pore size, mean particle size, gaseous thermal conductivity and solid particle thermal conductivity. An experimental study on the thermal conductivity of silica aerogel is carried out to validate the coupling model, and good agreement between the measured data and the coupling model is found. The present coupling model is also verified by available data including experimental results, numerical results and theoretical predictions in the literature. The comparison among the coupling models shows that the present model is of high accuracy without complex and difficult calculations.

1. Introduction

Aerogel, a typical nanoporous material, is well known for its excellent performance of thermal insulation [1–5]. The ultra low thermal conductivity of aerogel can be attributed to its complex micro/nano-structure, e.g., an ideal structure of aerogel presents a three-dimensional network skeleton consisting of interconnected spherical solid nano-particles [1,5], see Figs. 1(a) and (b). Such a structure creates numerous nanopores reducing the mean free path of the filled gas and simultaneously increases the heat flux path and the thermal resistance when the heat is transported via the aerogel solid backbones. The mechanism of the heat transfer in aerogel is usually attributed to three modes: (1) heat conduction via the aerogel backbone (red particle chain), (2) heat transfer via the gas molecules (gray dots), and (3) thermal radiation (wave purple arrows), see Fig. 1(c). According to the three heat transfer modes, the widely used prediction formula for the effective thermal conductivity of aerogel is expressed as [1]

$$\lambda_{\text{eff}} = \lambda_s + \lambda_r + \lambda_g \tag{1}$$

where λ_s, λ_r and λ_g are solid thermal conductivity, radiative thermal conductivity and gaseous thermal conductivity, which denote the contributions of the solid phase, radiation, and gas phase to the effective/total thermal conductivity of aerogel, respectively.

Compared with available experimental data, the effective thermal conductivity of aerogel is often found to be underestimated if using Eq. (1). It is usually believed that the coupling effect is ignored. The coupling effect denotes that the coupling heat transfer between the aerogel solid and gas phases also contributes to the effective thermal conductivity [6–9]. Reichenauer et al. [7] considered the coupling effect and revised Eq. (1) as

$$\lambda_{\text{eff}} = \lambda_s + \lambda_r + \lambda_g + \lambda_c \tag{2}$$

where λ_c is the coupling thermal conductivity and denotes the contribution of the coupling effect to the aerogel total thermal conductivity. Though there are a lot of researches on the gaseous, solid and radiative thermal conductivities [10–14], few studies have discussed the coupling thermal conductivity in detail. Swimm et al. [8] investigated the coupling effect on the effective thermal conductivity of aerogel, and proposed a model of the coupling thermal conductivity, but their model still underestimates the data. Zhao et al. [15] developed the model of Swimm et al. by taking into account the micro-morphology of aerogel to improve the prediction accuracy. Both models of Swimm et al. and Zhao et al. are based on the mechanism of thermal-bridge effect, i.e., the heat flux along the aerogel solid backbone is enhanced by the gas molecules in the gap of linked particles, see Fig. 2. However, too many parameters are involved in the two models and numerical integration is required

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Nomenclature

a	contact diameter of aerogel interconnected particles, m
A	area, m^2
c_p	specific heat at constant pressure, J/kg K
C_V	volume specific heat, J/m^3 K
d_p	aerogel particle diameter, m
D	mean pore size of aerogel, m
E_s/ρ_s	specific extinction coefficient of aerogel, m^2/kg
h	length of heat flux path in the solid phase, m
L_g, L_s	heat conduction length in the gas and solid phases in Eq. (3), m
n	refractive index in Eq. (18)
p	gas pressure, Pa
q	heat flux, W/m^2
R	aerogel particle radius, m
s	distance between the centers of two linked particles, m
$\mathbf{s}$	direction vector with respect to s
S	specific surface area, m^2/kg
T	temperature, K
v	sound velocity, m/s
V_{pore}	pore volume, m^3/kg

Greek symbols

β	parameter in Eq. (6)
θ	angle between z-direction and the direction of vector $\mathbf{s}$, rad
λ	thermal conductivity, W/m K
Λ	mean free path, m
ρ	density, kg/m^3
σ	area of integral domain in Eq. (9), m^2
σ'	standard deviation in Eq. (8), m
ϕ	angle between x-axis and the direction of $\mathbf{s}_i$ projected on x–y plane, rad
Φ	porosity

Subscripts

0	aerogel backbone
bulk	bulk parameters
c	coupling heat transfer
eff	effective
g	gaseous
g–s	gas–solid
n	nanowire-like aerogel backbone
p	particle
r	radiative
s	solid
total	total heat flux

to deal with the thermal-bridge effect, which result in much difficulty for the calculation. In addition, compared with the theoretical model Eq. (1), numerical simulations [16–19] present improved accuracy for predicting the effective thermal conductivity of aerogel. However, the numerical methods in [16–19] are based on macroscopic heat conduction law (Fourier's law), and the limits in these numerical approximations will also affect the prediction accuracy as the aerogel particle dimension falls in nanoscale. Therefore, the nanoscale numerical methods can help us to obtain more accurate predictions, e.g., the use of Molecular Dynamics simulation [20–22], Monte Carlo method [23–27] and solving the phonon Boltzmann equation [27,28] to improve the prediction of thermal

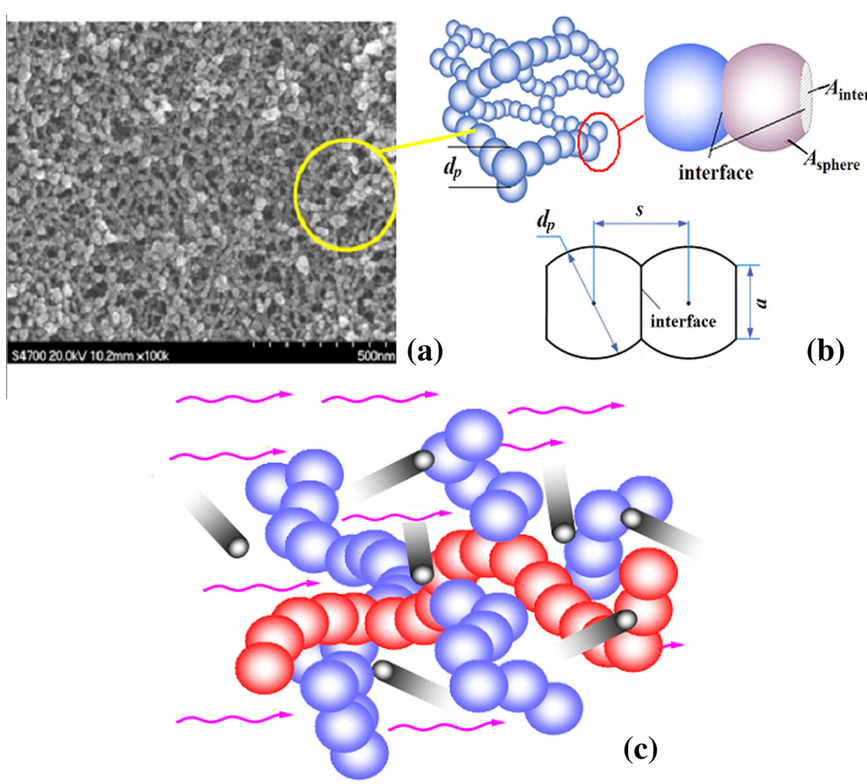

Fig. 1. Aerogel structure. (a) SEM image. (b) Schematic of base-catalyzed aerogel structure. (c) Heat transfer modes in aerogel.