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Research Paper

# Radiative heat attenuation mechanisms for nanoporous thermal insulating composites

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## HIGHLIGHTS

- Nanoporous thermal insulating composites are prepared by a dry molding method.
- SiC as an opacifier can reduce radiation heat transfer at higher temperatures.
- Radiation attenuation mechanisms are explained by calculating optical parameters.
- The calculation results are verified by thermal conductivity measurement.

## ARTICLE INFO

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## ABSTRACT

Nanoporous thermal insulating composites of fumed silica, opacifier, and fiber have been prepared by a dry molding method. SiC is adopted as an opacifier to improve thermal insulating performance at higher temperatures where radiation heat transfer plays an important role in entire heat transfer system. Radiative heat attenuation mechanisms have been illuminated by calculating thermal radiation optical parameters including scattering, absorption, and attenuation factors. The result shows fumed silica has low attenuation factor in infrared wavelength range, only 0.00188 for infrared radiation with a wavelength of 3.14 μm. The introduction of SiC can remarkably restrain radiative heat transfer, and the maximum attenuation factor reaches up to 5.848 for infrared radiation with a wavelength of 8.646 μm. The effect of SiC particle size on thermal radiation optical parameters is also studied. The choice of SiC particle size should match up with serving temperature of this insulation. In addition, thermal conductivity measurement has been employed to verify the accuracy of calculation results. Thermal conductivity can significantly decrease from 0.119 to 0.041 W/(m K) at 773 K when 25 wt% SiC (0.877 μm) is added into the composites.



## 1. Introduction

Nanoporous thermal insulating composites belong to a new generation of super thermal insulations, which have drawn great attention due to extremely low thermal conductivity. The most typical aerogel thermal insulations have been researched for many years, mainly focusing on the improvements of processing method, thermal property and mechanical strength. Zhao et al. [1] and Zhu et al. [2] utilized low cost silica materials to synthesize granular silica aerogel insulations via ambient pressure drying process instead of ethanol supercritical drying [3]. Wang et al. [4] developed trimethylethoxysilane (TMEO)-modified alumina aerogels to enhance heat resistance of aerogel insulations during sol–gel and supercritical fluid drying process. In He's work [5], aerogels/fibrous ceramic composites have been prepared with a high compressive strength of up to 1.05 MPa. However, because of the combination of extremely high porosity and the unprecedented small pore size, aerogel insulations require very complicated processing schemes. Even up to this date, the processing complexity and consequential lack of mass production have remained as the biggest hurdle for commercialization. If we can manufacture this new generation of thermal insulation by a process competitive to current insulation production process, the new technology could be broadly applied and contribute appreciably to energy savings in every sector of our economy.

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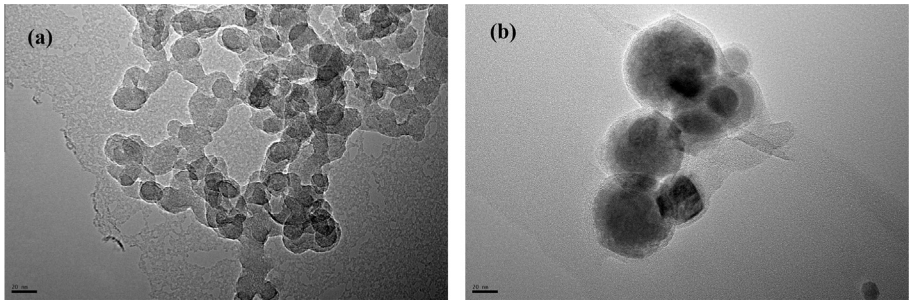


**Fig. 1.** Field emission scanning electron microscopy (FESEM) images of fumed silica.

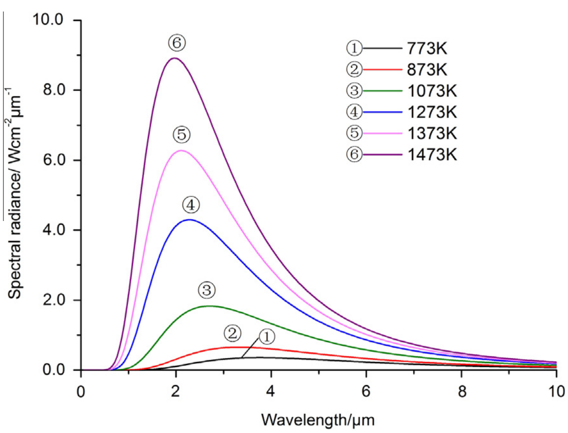


**Fig. 2.** The spectral radiance of thermal radiation for all wavelengths from a black body at different temperatures.

**Table 1**
The corresponding wavelength of energy density peak value at different temperatures.

| *T*/K | 773 | 873 | 1073 | 1273 | 1373 | 1473 |
|---|---|---|---|---|---|---|
| $\lambda_m$/μm | 3.76 | 3.31 | 2.71 | 2.26 | 2.11 | 1.96 |

With the development of nanotechnology, this interesting idea has been turned into reality that fumed silica, as an amorphous nanoparticle, has successfully realized industrial production by fusing naturally occurring quartz crystals of high purity at approximately 2000 °C [6–8]. Fumed silica has many excellent properties to be applied in rubber, concrete and insulation. By means of this low-cost nanoproduct, Lian et al. [9] and Feng et al. [10] have prepared fumed silica based thermal insulating composites, which exhibit superior thermal insulating performance at ambient temperature. However, at higher temperatures heavy infrared radiation heat transfer causes obvious deterioration in thermal insulation. Therefore, researchers are trying to find some approaches to solve this problem. Actually there are many ways for heat transfer optimization. In Kim's et al. work [11], an insulation system composed of an inner mineral wool layer, a steel liner, an outer mineral wool layer, and a concrete lining was proposed as the optimal design for underground thermal energy storage (TES) systems. Hao et al. [12] adopted entransy theory to establish a mathematical model for porosity distribution optimization of insulation materials by a variational method, and Najafi et al. [13] used genetic algorithm to optimize energy and cost of a plate and fin heat exchanger. On this basis, for fumed silica based thermal insulating composites system we proposed a new optimization approach of infrared radiation heat transfer by the introduction of opacifier because it has been successfully used in aerogel insulations [14]. Xu et al. [15] prepared infrared-opacified $Al_2O_3$–$SiO_2$ aerogel composites reinforced by SiC-coated mullite fibers for thermal insulations and Wang et al. [16] studied radiative characteristics of opacifier-loaded silica aerogel composites to prove that opacifiers can significantly reduce radiation heat transfer. Zhao et al. [17] presented a theoretical method for determining the optimal carbon doping in silica aerogel to minimize the energy transfer. In addition, there are similar physical and chemical properties between $SiO_2$ aerogel and fumed silica [18]. Therefore, in this work, SiC is chosen as an opacifier to reduce radiation heat transfer of fumed silica based thermal insulating composites. Radiation optical parameters of fumed silica and SiC are respectively calculated including scattering, absorption, and attenuation factors to explain radiative heat attenuation mechanisms. Finally, thermal conductivity measurement is employed to verify the accuracy of calculation results.

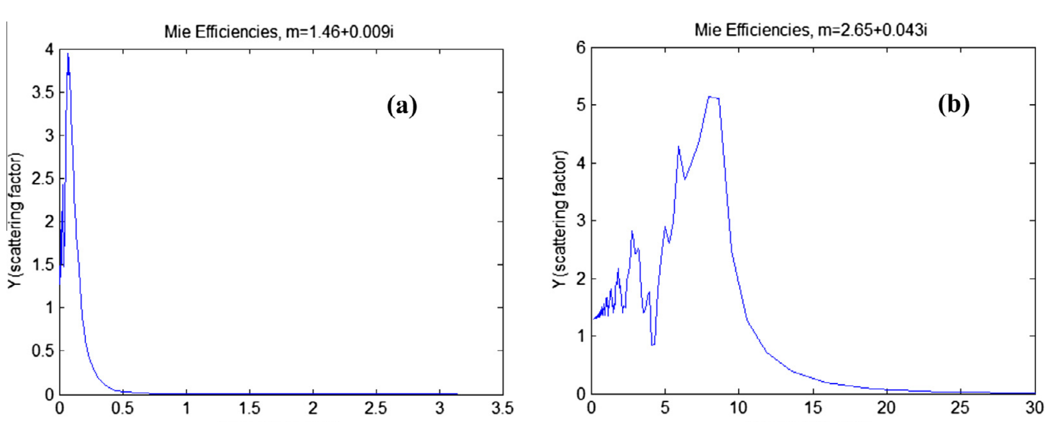


**Fig. 3.** The scattering factor of fumed silica (a) and SiC (b) versus radiative waves with different wavelengths.