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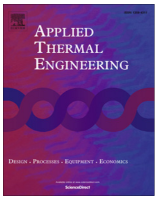

Research Paper

Prediction and optimization of radiative thermal properties of ultrafine fibrous insulations

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HIGHLIGHTS

- Radiative thermal conductivities of ultrafine fibrous insulations were predicted.
- Infrared optical constants of ultrafine fibrous insulations were determined.
- Critical diameter of PVDF fibrous insulations was deduced with 1.06 μm.
- Fiber diameters were optimized for minimum radiative thermal conductivity.
- Optimized radiative thermal conductivity is 25% lower than that by as-prepared.

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ABSTRACT

Predicting and optimizing radiative thermal properties have been acknowledged as an efficient way to improve thermal insulation performance of fibrous materials with high porosity. Based on experimental investigation of infrared spectral of ultrafine fibrous insulations with diameters of 520–650 nm, a method of calculating radiative thermal properties was presented by combining Rosseland equation, Mie scattering theory, Beer's law and Subtractive Kramers–Kronig (SKK) relation. To ensure the calculation correct the uniqueness analysis was performed for Poly(vinylidene fluoride) (PVDF) fibers, which indicated the valid fiber diameter was less than 1.06 μm. The calculated thermal radiative conductivities by using the method agreed well with the measured data. The effect of fiber diameter on the thermal properties of the fibrous insulations was also investigated to minimize the radiative thermal conductivity. The results indicated that the minimized radiative thermal conductivities by regulating fiber diameters could be approximately 25% smaller than those for experimental fiber diameters. The method of predicting and minimizing radiative thermal conductivities of fibrous insulations demonstrated in this paper could be of great advantage to thermal engineering applications aiming to reducing heat loss and saving energy.

0. Introduction

Fibrous materials with low thermal conductivity and high porosity have widely been used as thermal insulations [1] so as to reduce heat loss in aerospace crafts, industrial equipment, building construction [2] and textiles [3]. Owning to the high porosity (commonly greater than 80%) of fibrous insulations [4], the radiative thermal flux may be acknowledged as an important part of the total heat flux within fibrous insulations (e.g. superfine polyvinyl alcohol textiles [5] and metallic foams [6]). The radiative thermal flux in lightweight fibrous insulations could be up to 30% [7] of the total heat flux even at moderate temperatures (300–400 K). Therefore, reducing the radiative heat flux is an efficient way to improve the thermal insulation performance of fibrous material with high porosity.

Extensive investigations have been conducted on decreasing the radiative thermal conductivity of the fibrous insulations [8,9]. With given optical constants of fibers, numerical method predicting the minimum effective thermal conductivity by optimizing the structure parameters (e.g. diameter, volume fraction [10]) of fibrous insulations was one of the most important approach. In the numerical method the spectral optical constants (m_λ) of fibers are the fundamental data [11] to calculate thermal radiative conductivities of fibrous insulations. The spectral optical constants are constituted by real part n_λ (viz., spectral refractive index) [12] and imaginary part κ_λ (viz., spectral absorption index) [13], which indicates the

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scattering and absorption capability of fibrous insulations, respectively [14].

However, it is very difficult or extremely time-consuming to experimentally measure the spectral optical constants of fibers for each wavelength in the whole infrared spectrum generally in infrared wavelengths (λ) of 2.5–25 μm. In fact the data of the spectral optical constants of fibrous insulations were extremely insufficient besides several specific data in few separate wavelengths. Therefore, the efforts on exploring spectral optical constants of fibrous insulations are needed to predict and optimize thermal insulation performance.

In the past few years, a method by combining experimental infrared transmittances and thermal radiation model had been reported to calculate the optical constants of particles in some certain wavelengths, such as Bhattacharyya et al. [15] for $Zn_{1-x}Mg_xO$ films in 0.4–0.8 μm, Gushterova and Sharlandjiev [16] for GeSe films in 0.4–1.2 μm and Dombrovsky for ceramic microspheres et al. [17] in 2.6–18 μm. Very recently Ruan et al. [18] calculated spectral optical constants of spherical particles in wide wavelengths of 2.5–25 μm by combining spectral transmittances, Mie scattering theory and SKK relations. The calculated results of optical constants were found to be feasible as the diameter of the spherical particles was smaller than the critical diameter of 1–2 μm by performing uniqueness analysis. Similarly, a certain critical diameter of fibers may exist to calculate the optical constants. As a comparison the commonly used fibers in fibrous insulations had the diameters of several dozen micrometers which were much greater than the critical fiber diameter. Herein, the previous numerical method may not be feasible for the commonly used fibrous insulations.

Recently new-type fibrous materials with finer diameters have successfully been prepared by using the newly developed micro and nano technology. Electrospinning is one of the most attractive nanotechnologies to fabricate ultrafine fibrous materials [19]. By engineering electrospinning parameters [20] the electrospun fiber diameters could be regulated from 10 nm to 10 μm [21]. Herein, electrospun fibers have well acknowledged as a type of ultrafine fibers with diameters smaller than 10 μm, which are much finer than the commonly used fibers with diameters of several dozen micrometers. The electrospun ultrafine fibers provides a possibility to calculate the unique optical constant of materials by combining experimental infrared transmittance and thermal radiation model.

Therefore, this paper was aiming to obtain the spectral optical constants of fibrous insulations with ultrafine diameters by using the numerical method combining experimental infrared transmittance and thermal radiation model. Firstly, ultrafine fibrous insulations were experimentally fabricated by using electrospinning. The spectral transmittance of the as-fabricated ultrafine fibrous insulations were experimentally investigated. Concerning the experimental results, the optical constants of fibrous insulations were then calculated by using the radiation model and SKK relation. Uniqueness analysis to ensure the calculation correct was performed and the calculated results were validated with the experimental measurements. Eventually, effect of fiber diameters on thermal conductivities were explored so as to minimize thermal conductivity by optimizing fiber diameters for improving thermal insulation performance.

1. Theoretical model of radiative thermal conductivity

1.1. Radiative thermal properties of fibrous insulations

Taking ultrafine Poly(vinylidene fluoride) (PVDF) fibers as an example of fibrous materials their microstructure characterized scanning electronic microscope (SEM) was shown in Fig. 1. The image was obtained by a field emission scanning electron microscopy (FESEM, JSM-7001F, JEOL, Japan). The preparation process of ultrafine PVDF fibers is presented in Section 2.1. It can be observed from Fig. 1 that PVDF fibers are in infinite cylinders [22] with the radio of length to diameter greater than 100 and ultrafine diameters (d) of 0.2–1.0 μm. The directions of their axis are randomly distributed in plane. Fig. 2 shows the scattering geometry of a PVDF fiber with incident radiation. The inclination angle (ϕ) describes the extent of the fiber direction deviating from the radiation heat flux direction. As the plane of the fiber axis is perpendicular to the direction of radiation heat flow, ϕ equals to 0.

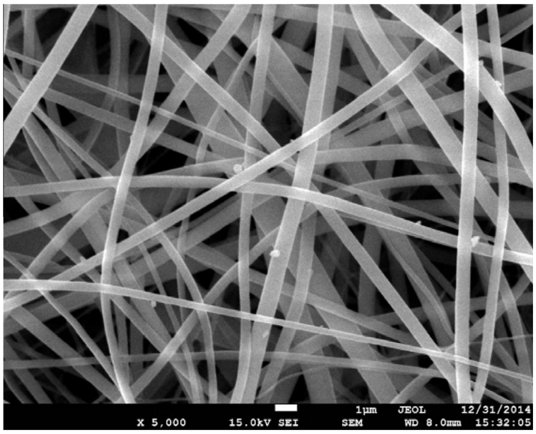

Fig. 1. SEM image of PVDF fibrous insulations.

Extinction efficiency ($Q_{e\lambda}$) is a non-dimensional and temperature-independent parameter indicating the ability of absorbing and scattering the light as the light goes through fibrous insulation. It can be calculated by Mie scattering theory [23] for infinite cylindrical fibers

$$Q_{e\lambda} = \frac{1}{x} Re\left[(a_{0\Pi} + b_{0\mathrm{I}}) + 2\sum_{n=1}^{\infty}(a_{n\Pi} + b_{n\mathrm{I}})\right] \tag{1}$$

where Re is the symbol of real part, $x = \pi d/\lambda$ is the size factor, a_n and b_n are Mie coefficients. As the radiation heat flux vertically incidence on infinite cylinder fibers Mie coefficients can be expressed as

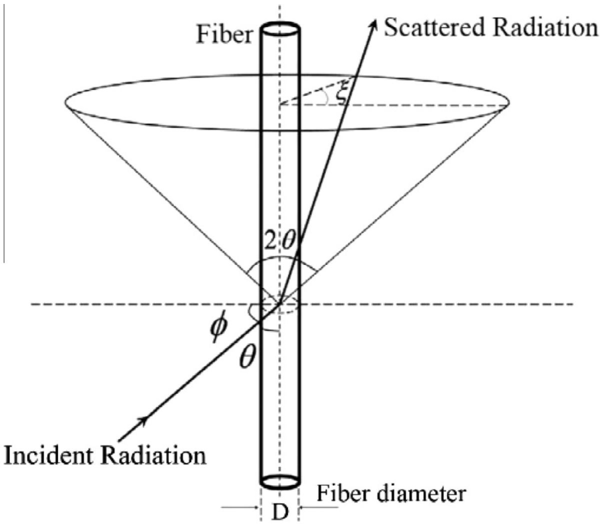

Fig. 2. Scattering geometry for a fiber with incident radiation.