Thermal Energy Transport Within Porous Polymer Materials: Effects of Fiber Characteristics

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ABSTRACT: A theoretical model integrating the radiative and conductive heat transfer is presented and applied to evaluate the thermal energy transport within porous polymer materials. The model was first validated by comparing the computed thermal energy flux with the experimental measurements of two porous polymer materials made of wool and polyester. The model was then used to predict the effects of the polymer fiber characteristics (viz. fiber fractional volume, fiber emissivity, fiber radius, and fiber thermal conductivity) on the thermal energy flux within the porous polymer materials. It was found that decreasing fiber radius would significantly reduce the total thermal energy flux through the porous polymer materials, whereas increasing fibre emissivity or decreasing the thermal conductivity would cause a just slight reduction of the total thermal energy flux. The fiber fractional volume had a significant influence on the thermal energy flux, and thereby the fiber fractional volume can be optimized in view of improving the thermal insulating performance of the porous polymer materials. © 2007 Wiley Periodicals, Inc. J Appl Polym Sci 106: 576–583, 2007

Key words: fibers; thermal properties; radiation; modeling; polyesters

INTRODUCTION

Most porous polymer materials are thermally insulating. Increasing the thermal insulation of the porous polymer materials allows them to be used in many applications. One emerging market for thermally insulating polymer materials is for functional cold protective clothing, sleeping bags, etc.[1–3] Recently, various types of polymer fibers, such as polyester and polypropylene, have been developed for thermal insulation in functional cold protective clothing.[4–6]

Although many natural porous materials such as wool and down feather are the most popular thermal insulating materials for these functional clothing, they are expensive and tend to have the problems in quilting and animal or bird flu disease. Polymer fibers have several advantages, relative to natural porous materials, which include high quilting and abundance in supply. Moreover, it is interesting that the thermal insulating performance of the porous polymer materials is strongly dependent upon the properties of the polymer fiber.[7,8] Therefore, understanding the mechanisms of thermal energy transport within porous polymer materials and the effects of polymer fiber characteristics on the thermal energy transport are essential to the improvement of the thermal insulating performance of such materials.

Within porous polymer materials, thermal energy transport involves heat conduction by the solid material of the polymer fibers and intervening air, as well as thermal radiation by an electromagnet.[3,9,10] A significant amount of work on porous polymer materials had shown that radiative thermal energy transfer could be significant in these porous media. It was extremely difficult to obtain exact solution because of the complexity in the integral radiative and conductive equations. Earlier studies[11] dealt with the combined thermal energy transfer mostly by separating the radiation from the other thermal contributions using a radiative conductivity method. However, the separated treatment may be inappropriate for many cases, such as in the thermal energy transport in thin layer media. A great deal of research effort concerning the integrated thermal energy transport has recently been directed applying various effective approximation techniques such as the moment method,[12] successive approximation method,[13] as well as the two-flux method,[3,14,15] which was regarded as an effective and simple means to consider the radiative flux in the integral energy transport.

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Farnworth[3] applied the two-flux radiative model in studying thermal resistance of several fibrous insulations. Sadooghi and Aghanajafi[14,15] evaluated the effects of optical material properties on the thermal response of the polymer fiber subjected to high temperature boundaries. Coupled heat and moisture transfer within moist fabrics or porous insulation have also been extensively studied.[16–22]

Despite of the considerable work carried out in the related area, little work has been carried out on how the properties of porous polymer materials affect the radiant and conductive thermal energy transport through the materials. Such understanding would be of great importance both for the development of special polymer fibers and for the optimization of thermal insulting performance of porous materials. Therefore, this report is aimed at analyzing the effects of fiber fractional volume, fiber emissivity, fiber radius, and fiber thermal conductivity on the radiative and conductive thermal energy flux within porous polymer materials. For this purpose, a simple theoretical model based on radiative two-flux method combined with the conductive heat transfer equation is presented and applied in the analysis.

THEORETICAL ANALYSIS

Energy equations

Figure 1 shows a piece of porous polymer slab of thickness L held between two plates at temperatures T_0 and T_1, where x is the distance from the hot plate. To obtain a simplified model of thermal energy transfer, the porous slab consisting of polymer fibers oriented randomly is considered to be isotropic in terms of structure and thermal properties. As the convective heat transfer is small enough in the cases of a porous polymer material between the plates and since the scattering radiation by the fibers can be ignored,[3,11] the problem is simplified to estimate the combined conductive and radiative thermal energy transport in the direction of the thermal gradient (x). The one-dimensional conservation equation of thermal energy under a steady-state condition can be written as

$$\frac{d}{dx}\left(k_{\text{eff}}\frac{dT}{dx}\right)+\frac{dq_r(x)}{dx}=0 \tag{1}$$

where the effective thermal conductivity (k_{eff}) of the porous polymer slab is considered as the combination of the conductivities of the air (k_a) and of the fiber (k_f) concerning the fiber fractional volume (f),

$$k_{\text{eff}}(x,t)=(1-f)k_a+fk_f \tag{2}$$

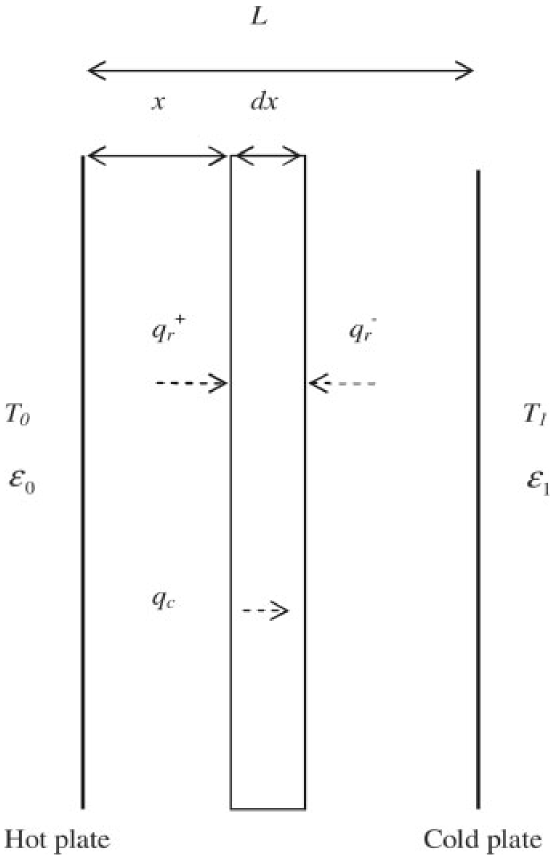


Figure 1 Geometry for thermal energy transport within porous polymer materials between two plates.

$q_r(x)$ is the net radiative thermal energy flux at the position x,

$$q_r(x)=q_r^+(x)-q_r^-(x) \tag{3}$$

where $q_r^+(x)$ and $q_r^-(x)$ are the radiative thermal energy flux to the right and the left, respectively. The attenuations of the two radiative energy fluxes are given by

$$\frac{\partial q_r^+(x)}{\partial x}=-\beta q_r^+(x)+\beta\sigma T^4(x) \tag{4}$$

$$\frac{\partial q_r^-(x)}{\partial x}=-\beta q_r^-(x)+\beta\sigma T^4(x) \tag{5}$$

where, β is the absorption constant of the porous material slab, which is an average over all angles of incidence and independent of position. On the above assumption that the polymer slab consists of fibers randomly oriented, the absorption constant can be expressed by[3,9]

$$\beta=\frac{f\varepsilon}{R} \tag{6}$$

where ε and R are the emissivity and radius of the polymer fiber, respectively.

Boundary and initial conditions

The temperatures on the boundaries close to the hot plate ($x = 0$) and the cold plate ($x = L$) are preset constant as T_0 and T_1, respectively. The radiative thermal energy flux on the boundaries can be expressed as

$$(1 - \varepsilon_1)q_r^-(0) + \varepsilon_1\sigma T_0^4 = q_r^-(0) \tag{7}$$

$$(1 - \varepsilon_2)q_r^+(L) + \varepsilon_2\sigma T_1^4 = q_r^+(L) \tag{8}$$

where, ε_1 and ε_2 are the emissivities of the hot plate and cold plate, respectively.

Numerical solution

A finite difference method is used to construct the numerical scheme. Along the direction of thickness L, the porous polymer slab is divided into the cells with equal interval size. Each cell is regarded as being composed of fiber and air.

EXPERIMENTAL

The porous slab samples were tested for the total thermal energy flux between a hot plate and a cold plate using the thermal prosperity measurement instrument, KES-F7 Thermo Labo II (Kato Tech. Co., Ltd. Japan)[23] as illustrated in Figure 2. In the experimental tests, the temperatures of the hot plate (i.e., BT-box in Fig. 2) and cold plate (i.e., water box in Fig. 2) were controlled at (30 ± 0.3)°C and (20 ± 0.3)°C, respectively. The weight of the hot plate on the material samples of a size (5 cm × 5 cm) was 150 g, which indicted that the load pressure on the porous slab samples was 588 Pa. Three repeated measures on the Thermo Labo II instrument were carried out at each sample for the error analysis of the experimental tests.

Two porous slab samples (i.e., polyester and wool) were investigated on the Thermo Labo II instrument. Table I lists the properties of the porous polyester and wool slab samples below the load pressure of 588 Pa. The morphology of the porous polyester and wool samples were observed with a scanning electron microscope (Leica Stereoscan 440, Leica Cambrige Ltd., Germany). The characteristics of the polyester and wool fibers are presented in Table II.

TABLE I
Properties of Porous Samples Tested on Thermal Labo II Instrument

Property	Wool	Polyester
Weight (g/m^2)	79.6	48.7
Thickness (mm at 588 Pa)	1.75	1.50
Fiber fractional volume (%)	3.5	2.3

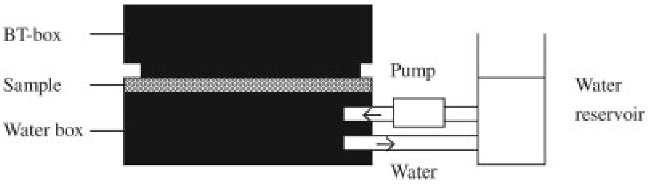


Figure 2 Schematic of Thermo Labo II instrument.

RESULTS AND DISCUSSION

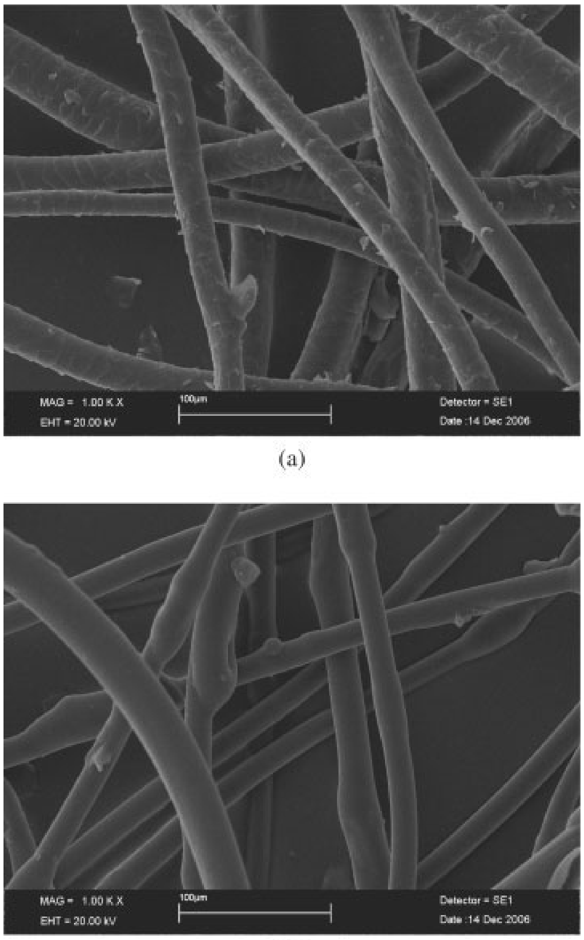
Comparison between experimental and computational results

In the numerical solution of the theoretical model, the absorption constant (β) and the effective thermal conductivity (k_{eff}) are two of the most important input parameters. Figure 3 shows SEM photomicrographs of the porous wool and polyester samples. From Figure 3, the average fibers diameters of wool and polyester are about 36 μm [Fig. 3(a)] and 17 μm [Fig. 3(b)], respectively. As shown in Table II, the emissivity (ε) of wool and polyester fibers are 0.78 and 0.62, respectively. From Table I, the fiber fractional volumes (f) of the porous wool and polyester samples at the pressure of 588 Pa are 3.5% and 2.3%, respectively. According to eq. (6), the absorption constants (β) of the porous wool and polyester samples can be obtained as 1517 and 1678, respectively. According to eq. (3), the effective thermal conductivity (k_{eff}) of the porous wool and polyester samples can be obtained as 0.0298 and 0.0267 W m^{-1} K^{-1}, respectively.

Figure 4(a) shows the computational results of the conductive and radiative thermal energy flux within the porous wool and polyester samples. It can be observed that there are almost the same distributions of the radiative thermal energy flux within the two porous samples. However, the conductive thermal energy flux within the porous polyester sample was slightly larger than that within the porous wool sample. The conductive thermal energy flux ($k_{\text{eff}}\frac{dT}{dx}$) is dependent on both the effective thermal conductivity and the gradient of temperature at the position x. The average thermal energy flux through the whole porous samples can be approximately expressed as

TABLE II
Properties of Polyester and Wool Fiber

Property	Wool	polyester
Density (kg/m^3)	1310	1390
Thermal conductivity (W m^{-1} K^{-1})	0.19	0.14
Volumetric heat capacity (kJ m^{-3} K^{-1})	1600	1300
Emissivity	0.78	0.62



(a)

(b)

Figure 3 SEM photomicrograph of porous samples: (a) wool; (b) polyester.

$\frac{\Delta T}{L/k_{\text{eff}}}$. Table I shows that the thicknesses for the porous wool and samples are 1.75 and 1.50 mm, respectively. The thermal resistances (L/k_{eff}) to conductive thermal energy transport were 0.0587 m^2 K W^{-1} for the porous wool sample and 0.0562 m^2 K W^{-1} for the porous polyester sample, respectively. Therefore, a slightly lower conductive thermal resistance yields slightly greater conductive thermal energy flux within the porous polyester samples.

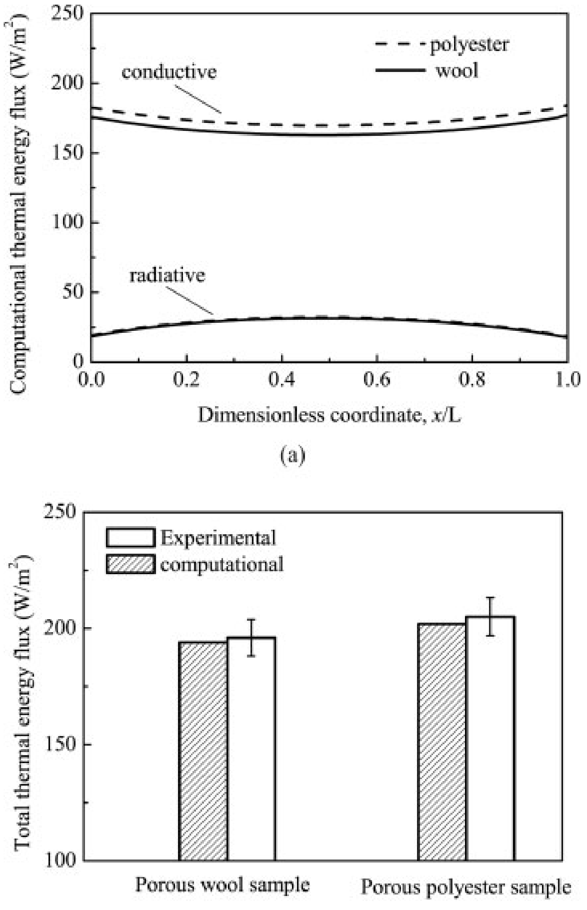
Figure 4(b) shows the comparison of the total thermal energy flux within the two porous polymer samples between the computational results using the theoretical model and the experimental measurements on the Thermo Labo II instrument. The error bars in Figure 4(b) for the experimental results are the standard deviations of the three repeated measures. Good agreement in terms of the total thermal energy flux can be observed between the theoretical and experimental results (the differences are below 4%).

The presented theoretical model was then applied to predict the thermal energy flux through the porous polymer materials, and consequently evaluate how the fiber characteristics affect the thermal insulating performance of the porous polymer materials.

In the following numerical tests using the theoretical model, the thermal energy flux was calculated within different porous polymer materials with various fiber characteristics. The numerical tests were performed based on the porous polymer slab of thickness 3 cm between a hot plate of 30°C and a cold plate of 20°C. The input values of the polymer fiber characteristics were $f = 1\%$, $\varepsilon = 0.6$, $R = 8.5$ μm, and $k = 0.14$ W m^{-1} K^{-1}. When one parameter was considered as a changing variable, the rest were kept unchanged.

Effect of fiber fractional volume

The distributions of the conductive and radiative thermal energy flux within the porous polymer materials are shown in Figure 5(a,b), respectively, in the cases that fiber fractional volume (f) varies from 2 to 10%. As can be observed, with the increase of the fiber fractional volume, the conductive thermal



(a)

(b)

Figure 4 Comparison of thermal energy flux between experimental and simulated results: (a) calculated conductive and radiative; (b) total.

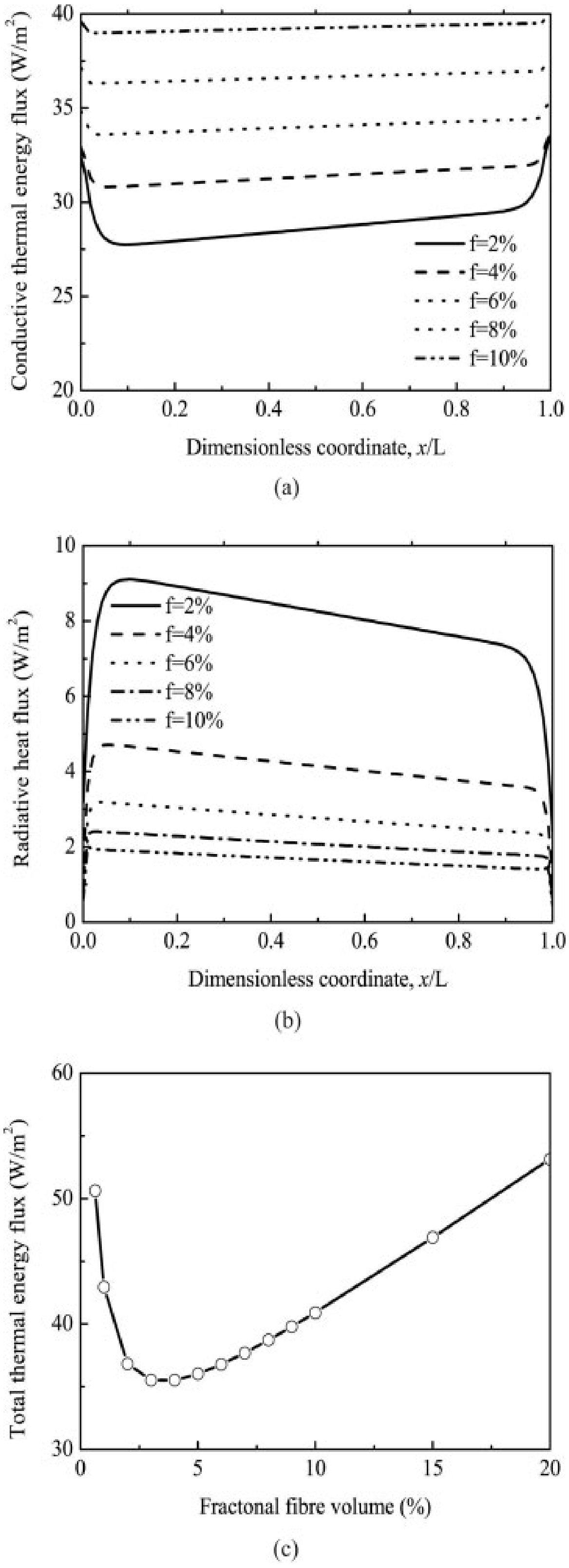


Figure 5 Effect of fractional fiber volume on thermal energy flux within porous polymer material: (a) conductive; (b) radiative; (c) total.

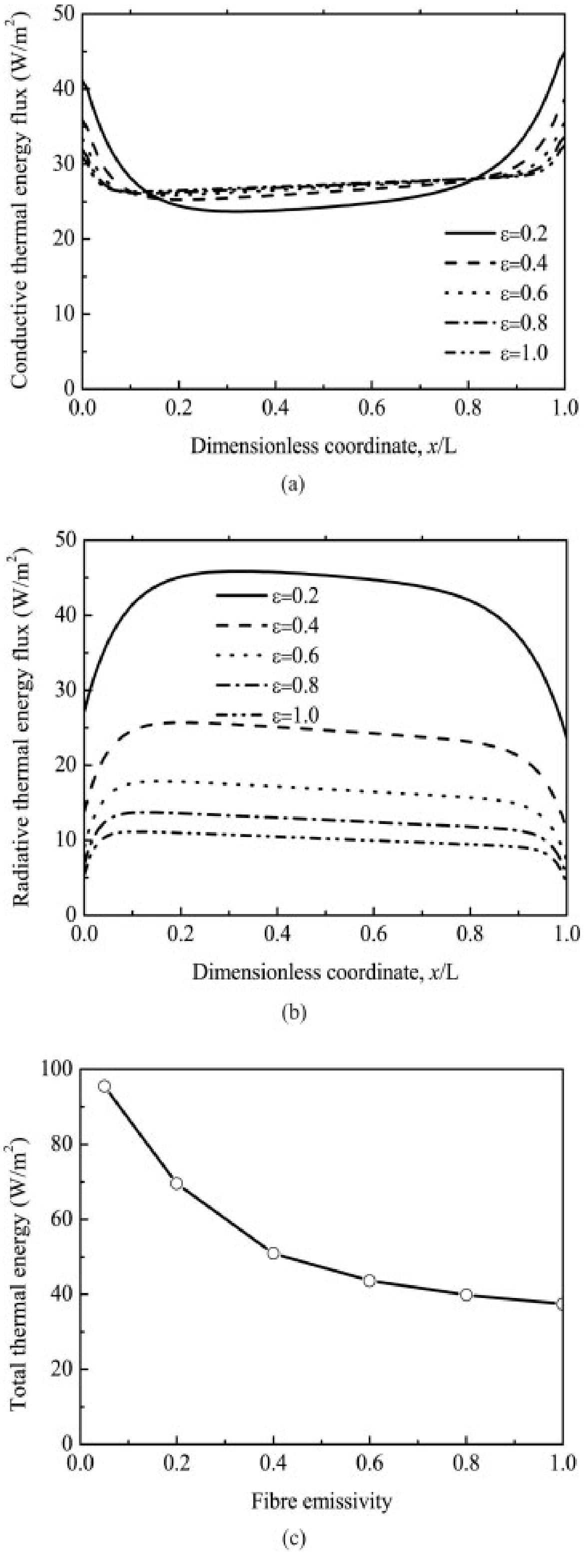
energy flux significantly increased, but the radiative thermal energy flux significantly decreased. The increase of the conductive thermal energy flux within the porous polymer material is because a greater fiber fractional volume yields a higher effective thermal conductivity according to eq. (2). As a comparison, a greater fiber fractional volume yields a higher adsorption constant according to eq. (6), which reduces the radiative thermal energy flux within the porous polymer material. Therefore, the changes of the total thermal energy flux as the fiber fractional volume increases is dependent on the comparison of the increase of the conductive thermal energy flux and the decrease of the radiative thermal energy flux.

Figure 5(c) shows the effect of fiber fractional volume on the total thermal energy flux through the porous polymer materials. It can be observed that the total thermal energy flux first significantly decreased and then significantly increased with the increase of the fiber fractional volume. Moreover, there is a minimum total thermal energy flux, which is advantageous to cold protective clothing materials. For the given parameters in the numerical computation, the optimal value of fiber fractional volume for the thermal insulating performance is approximately 4% and the corresponding minimum total thermal energy flux is 35.5 W/m^2.

Effect of fiber emissivity

The effect of fiber emissivity (ε) on the thermal energy flux within the porous polymer materials is shown in Figure 6. Little change of the conductive thermal energy flux was observed in Figure 6(a) when the fiber emissivity varied in the range of 0.2 and 1.0. It is understandable that there is no effect of fiber emissivity on the effective thermal conductivity (k_{eff}) according to eq. (3). As a comparison, Figure 6(b) shows that the radiative thermal energy flux significantly decreased when the fiber emissivity increased from 0.2 to 1.0. According to eq. (6), the increase of fiber emissivity improved the adsorptive capacity of the porous polymer materials and accordingly reduced the flux of radiative thermal energy through the material.

Concerning Figure 6(a,b), the total thermal energy flux versus fiber emissivity is illustrated in Figure 6(c). From Figure 6(c), the total thermal energy flux significantly decreased as the fiber emissivity increased from 0.2 to 0.6 and slightly decreased as the fiber emissivity increased from 0.6 to 1.0. Since most of polymer materials used for thermal insulating have fiber emissivity larger than 0.6, further increasing fiber emissivity from 0.6 has small effect on the total energy flux as well as the thermal insulating performance of the porous polymer material.



(a)

(b)

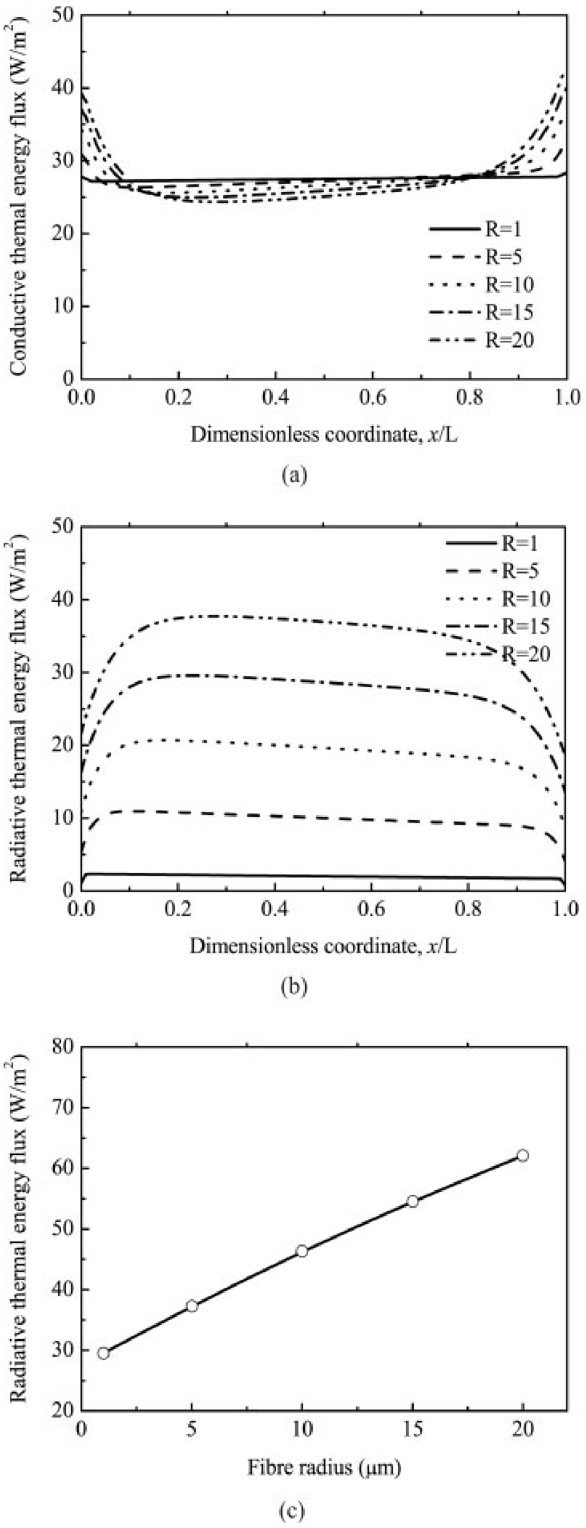
(c)

Figure 6 Effect of fiber emissivity on thermal energy flux within porous polymer material: (a) conductive; (b) radiative; (c) total.

It indicates that increasing fiber emissivity of polymer material is not an effective means to upgrade the thermal insulating performance of the porous polymer material.

Effect of fiber radius

Figure 7 shows the comparisons of the conductive, radiative, and total thermal energy flux within the porous polymer materials when the fiber radius (*R*)



(a)

(b)

(c)

Figure 7 Effect of fiber radius on thermal energy flux within porous polymer material: (a) conductive; (b) radiative; (c) total.

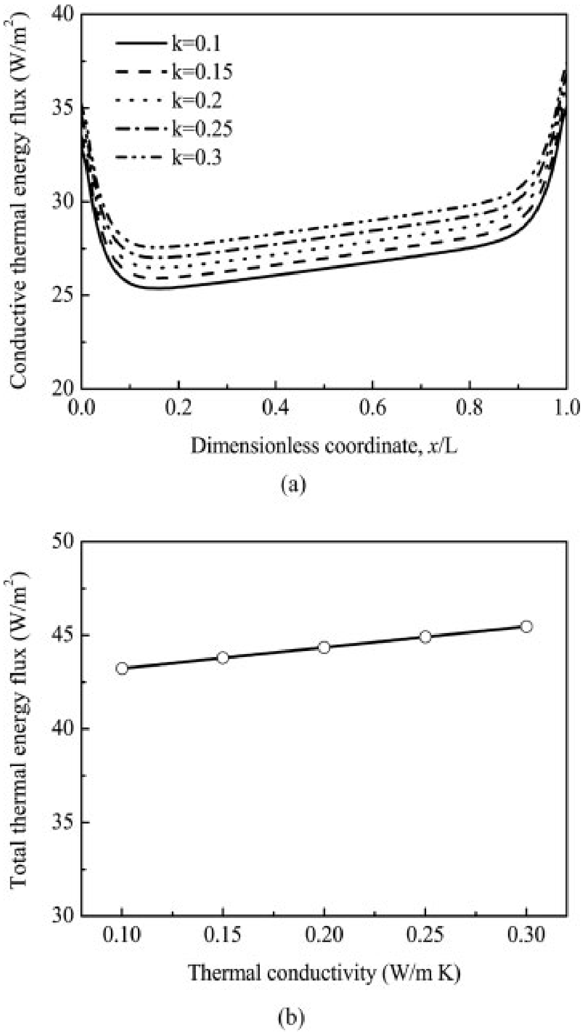


Figure 8 Effect of fiber thermal conductivity on thermal energy flux within porous polymer material: (a) conductive; (b) total.

varies in the range of 1–20 μm. According to eq. (3), the effective thermal conductivity is dependent on the thermal conductivity and fractional volume of the fibers and independent on the fiber radius. Therefore, the conductive thermal energy flux remained approximately unchanged for different fiber radius, which can be observed in Figure 7(a).

Figure 7(b) shows that the radiative thermal energy flux noticeably increased when the fiber radius increased from 1 to 20 μm. For porous material with a constant fiber fractional volume, the fibers with larger radius have smaller effective surface area to absorb radiant thermal energy. According to eq. (6), larger radius of fibers yields a smaller adsorption constant to radiative thermal energy, which results in greater radiative thermal energy flux through the porous polymer material.

Concerning Figure 7(a,b), the total thermal energy flux noticeably increased with the increase of the fiber radius as shown in Figure 7(c). It can be concluded that the finer fiber is preferable to the thermal insulating performance of the porous polymer materials. In fact, many porous polymer materials with superfine fibers have been developed recently to be used in porous cold protective clothing.[22]

Effect of fiber thermal conductivity

Figure 8 shows the effect of the fiber thermal conductivity on the thermal energy flux within the porous polymer materials. It is well understandable that the radiative thermal energy flux does not vary, and the conductive thermal energy increases with the increase of the fiber thermal conductivity. As shown in Figure 8(a), it can be observed that the conductive thermal energy flux increases slightly when the fiber thermal conductivity increases from 0.1 to 0.3 W m^{-1} K^{-1}. The small increase of the conductive thermal energy was because of the low fiber fractional volume in the porous polymer materials (i.e., 1% in the numerically tested case). Therefore, as shown in Figure 8(b), the total thermal energy flux slightly increases when the fiber conductivity increases from 0.1 to 0.3 W m^{-1} K^{-1}. It indicates that reducing the thermal conductivity of polymer fiber can upgrade the thermal insulating performance of the porous material but the improvement is very limited.

CONCLUSIONS

A theoretical model integrating radiative and conductive heat transfer was applied in studying the thermal energy transport in porous polymer material. The model was first validated with the experimental measurements for thermal energy flux within porous wool and polyester samples on the Thermo Labo II instrument. Numerical tests using the theoretical model were then performed to evaluate the effects of the fiber characteristics on thermal energy transport within porous polymer material. Conclusions are drawn as following:

1. The fiber fractional volume in the range of 2–10% significantly influences the thermal energy transport within porous polymer materials. As the fiber fractional volume increased, the total thermal energy flux first significantly decreased and then significantly increased. The minimum total thermal energy flux of 35.5 W/m^2 took place at the fiber fractional volume of $\sim$ 4%, which could be considered as the optimum fiber fractional volume for thermal insulating performance with given other parameters in the present article.
2. The total thermal energy flux slightly decreased either with increase of the fiber emissivity from

0.6 to 1.0 or with the decrease of the fiber conductivity from 0.3 to 0.1 W m^{-1} K^{-1}. Therefore, the upgrade of the thermal insulating performance by improving fiber emissivity or reducing fiber thermal conductivity is very limited to porous polymer materials.

3. The total thermal energy flux could be significantly reduced by decreasing fiber radius of porous polymer materials. Developing finer fiber is a promising means to enhance thermal insulting performance of porous polymer material for its application in cold protective clothing or devices.

NOMENCLATURE

f	Fractional fibre volume of porous polymer material
k_a	Thermal conductivity of air (W m^{-1} K^{-1})
k_{eff}	Effective thermal conductivity of porous polymer material (W m^{-1} K^{-1})
k_f	Thermal conductivity of fibre (W m^{-1} K^{-1})
L	Thickness of porous polymer material (m)
q_c	Conductive thermal energy flux (W/m^2)
q_r	Net radiative thermal energy flux (W/m^2)
q_r^+	Radiative thermal energy flux to the right (W/m^2)
q_r^-	Radiative thermal energy flux to the left (W/m^2)
T	Temperature (K)
T_0	Temperature of hot plate (K)
T_1	Temperature of cold plate (K)
x	Distance from the hot plate (m)

Greek Letters

β	Radiative sorption constant of porous polymer material (m^{-1})
ε	Emissivity of fibre
ε_1	Emissivity of hot plate surface
ε_2	Emissivity of cold plate surface
σ	Stefan-Boltzmann constant (5.67×10^{-8} W K^{-4} m^{-2})

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