J Therm Anal Calorim (2011) 103:785–790
DOI 10.1007/s10973-010-1025-0

Study on radiative heat transfer property of fiber assemblies using FTIR

W. F. Song · W. D. Yu

Received: 18 July 2010 / Accepted: 26 August 2010 / Published online: 21 September 2010

Abstract Radiative heat transfer could be a significant contribution to the total heat transfer within the highly porous materials. This article reports on the use of a conventional instrument, viz. Fourier transform infrared (FTIR) spectroscopy, for the characterization of radiative heat properties of fiber assemblies with low bulk densities. Experimental measurements on spectral transmission with FTIR were performed on five types of fiber assemblies commonly used for insulating materials. From the measurements, radiative heat conductivity was determined by calculating extinction coefficient using Beer's Law and applying the diffusion approximation approach. Bulk density, fiber arrangement, and temperature influences to radiative heat transfer were discussed. Results show that radiative heat conductivity decreases with bulk density and that of the random arranged fiber assemblies shows lower radiative heat conductivity than the random ball and parallel arranged fiber assemblies. Radiative heat conductivity is proportional to the cubic temperature. The existing theoretical model was modified by comparing theoretical and experimental radiative heat conductivity results.

Keywords Radiative heat transfer · FTIR · Fiber assembly · Bulk density · Arrangement · Temperature

W. F. Song · W. D. Yu
Textile Materials and Technology Laboratory, Donghua University, Shanghai 201620, People's Republic of China

W. D. Yu (✉)
College of Garment & Art Design, Jiaxing University, Jiaxing, Zhejiang 314001, People's Republic of China
e-mail: wdyu@dhu.edu.cn

Introduction

In the fibrous materials, it is well known that heat energy can be transferred by several ways: conduction, convection, and radiation [1]. Many researchers [2–4] have proved by experiments that no convection occurs even at the very low material density, as the small size of the pores and tortuous nature of air channels prevent heat convection effectively. Therefore, with the absence of heat convection, conduction, and radiation are the two modes of heat transfer through fiber assemblies. Heat radiation takes a great proportion at high temperatures [4–6] or at very low material densities [7–10].

Models developed by some researchers [2, 11–13] predict that radiation through fiber assemblies is affected by several factors, which are fiber volume percentage, fiber radius, temperature, and fiber emissivity. Wu et al. [14] investigated the influence of the above parameters on radiative heat transfer systematically based on the model of Farnworth [2], and observed that fiber volume percentage, fiber radius, and temperature are the most important factors affecting radiative heat transfer. Du et al. [15] discussed porosity distribution effect on radiative heat transfer of fiber assemblies by applying a BFGS quasi-Newton optimization procedure. Strong et al. [16] and Davis et al. [17] considered the fiber orientation influence on radiation heat transfer in their models.

There are generally two ways for measuring radiative heat transfer of fiber assemblies. They are indirect and direct methods. Mohammadi et al. [18] obtained the radiative conductivity by subtracting the solid and air conductivity, calculated from the previous model developed by Frick [3], from the total effective conductivity measured by the hot plate method. Hu et al. [19] reported a testing apparatus to characterize the infrared radiation properties by measuring the infrared intensity changes on the two surfaces of fabrics. Zhang et al. [20] developed a Fourier transform infrared spectral radiometer to measure the infrared radiation through fabrics. The latter two direct methods can not get the common index of radiative heat conductivity.

Fourier transform infrared spectroscopy is the most widely used techniques in the polymer industry for its characterization of polymers [21–23]. Recently, FTIR has also been applied to evaluate radiative heat transfer property of foams [24], films [25] or nonwovens [26]. In this article, we will utilize the method to investigate radiative heat transfer of fiber assemblies with low densities, commonly used as filling materials.

Experimental

Materials

Five types of fiber assemblies were selected for the experiment, listed in Table 1. They were all commercial battings. The materials were uniformly filled in identical aluminum hollow cylinders. These cylinders were 10 mm thick and 20 mm in inner diameter. Before testing, the fiber assemblies were conditioned in an air conditioned room with the temperature at 20 ± 0.5 °C and humidity at 65 ± 5% for at least 24 h. The following measurements were conducted at the temperature of 20 °C, except for when studying temperature influence on radiative heat transfer.

Theory

For intermediate temperature (200–500 K) applications, most heat energy radiates in the spectral range between approximately 2 and 15 µm. Usually, a Fourier transform infrared spectrometer (FTIR) was used to measure the transmittance spectrum of an insulation sample. The measuring schematic diagram is shown in Fig. 1. According to Beer's law [28], for a homogeneous sample, the spectral extinction coefficient can be got from the transmittance percentage.

$$C_{e\lambda} = \frac{-\ln(\tau_\lambda)}{L} \qquad (1)$$

where $C_{e,\lambda}$ is the spectral extinction coefficient, L is the thickness of the sample, and τ_λ is the spectral transmittance percentage.

The spectral transmission percentage (τ_λ) is the ratio of the intensity transmitted through the sample (I_λ) to the intensity incident ($I_{o\lambda}$) on the sample.

$$\tau_\lambda = \frac{I_\lambda}{I_{o\lambda}} \qquad (2)$$

Then, the Rosseland approximation can be used to calculate the Rosseland mean extinction coefficient ($\sigma_{e,R}$):

$$\frac{1}{\sigma_{e,R}} = \frac{\int_0^\infty \frac{1}{C_{e,\lambda}} \frac{\partial e_{b\lambda}}{\partial T} \mathrm{d}\lambda}{\int_0^\infty \frac{\partial e_b}{\partial T} \mathrm{d}\lambda} = \int_0^\infty \frac{1}{C_{e,\lambda}} \frac{\partial e_{b\lambda}}{\partial e_b} \mathrm{d}\lambda = \int_0^\infty \frac{1}{C_{e,\lambda}} \frac{\partial e_{b\lambda}}{\partial e_b} \mathrm{d}\lambda \qquad (3)$$

where $e_{b,\lambda}$ is the spectral blackbody emissive power, e_b is the total emissive power of a black body, and T is the medium temperature.

Finally, the radiative heat conductivity is derived from the following analysis. In practical applications, the optical thickness of heat insulation is typically very large. The optical thickness (τ) is defined as the extinction coefficient times the physical thickness of the insulation. For an optically thick medium ($\tau \gg 1$), radiation travels only a short distance before being scattered or absorbed. The local intensity is the result of radiation from the neighboring area. Then, the energy transfer can be approximated as diffusion process. The radiative heat flux (q_r) can be written as:

$$q_r(x) = -\frac{4}{3\sigma_{e,R}} \frac{\partial e_b}{\partial x} = -\frac{4}{3\sigma_{e,R}} \frac{\partial(\sigma T^4)}{\partial x} = -\frac{16\sigma T^3 \partial T}{3\sigma_{e,R}\, \partial x} = -k_r \frac{\partial T}{\partial x} \qquad (4)$$

Table 1 Information of the chosen materials

Fibers	Average fineness/µm	Curl density/unit/cm	Fiber density/g/cm^3	Fiber emissivity[a]
Wool	23.5	4.68	1.32	0.8
Cashmere	15.6	3.5	1.28	0.8
Polyester	33.5	2.5	1.38	0.8
Goose Down	–	–	0.98	0.8
Kapok	19	–	0.029	0.8

[a] We assume the thermal emissivities of wool, goose down, and cashmere are the same as that of keratin, the emissivity of which was reported to be 0.8 (http://www.optotherm.com/emiss-table.htm), the thermal emissivity of kapok is regarded as the same as that of cotton as that of cellulose [27]. Polyester fiber is reported to be between 0.75 and 0.85 [27] (a middle value of 0.8 is used for later analysis)

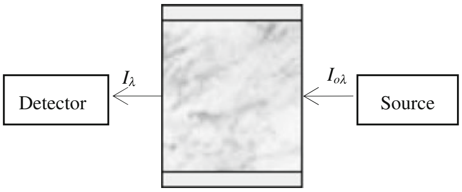

Fig. 1 Schematic of infrared radiation transmission through a sample

where e_b is the blackbody emissive power, σ is the Stefan–Boltzmann constant, and k_r is the radiative heat conductivity.

From the Eqs. 1–4, it can be seen that the radiative heat conductivity can be obtained by measuring the spectral transmission percentage.

FTIR method

Fourier transform infrared spectral transmission was measured on a Nicolet 5700 FTIR spectrometer. First, H_2O and CO_2 influences were eliminated from the background. All the samples were measured over a wave number range from 4000 to 400 cm^{-1}, corresponding to the wavelength range from 2.5 to 25 μm. The spectral transmittance was registered at a revolution of 4 cm^{-1}, and the number of scans was 16.

Results and discussion

Spectral transmission

The five types of fiber assemblies with three levels of bulk density (0.0032, 0.0064, and 0.0096 g/cm^3) were filled in the hollow cylinders. The spectral transmission percentages of the fibrous assemblies at the three bulk densities are plotted in Figs. 2, 3, and 4, and the results are the average of five tests. We can observe the following:

(1) Goose down and kapok have much lower spectral transmission than other fibers. For example, at the bulk density of 0.0032 g/cm^3, the spectral transmission of goose down and kapok range from 0 to 3%, however, that of wool and polyester show the variation between 1.7 and 30.6%.

(2) The spectral transmission decreases with increasing bulk density of the fiber assemblies, and the rate of the decrease slows down at higher bulk density. For instance, at the bulk density of 0.0032 g/cm^3, the spectral transmission of wool ranges from 1.4 to 13.2%; at 0.0064 g/cm^3 bulk density, it ranges from 0.05 to 3.8%; while at 0.0094 g/cm^3 bulk density, it only varies from 0.0001 to 1.5%.

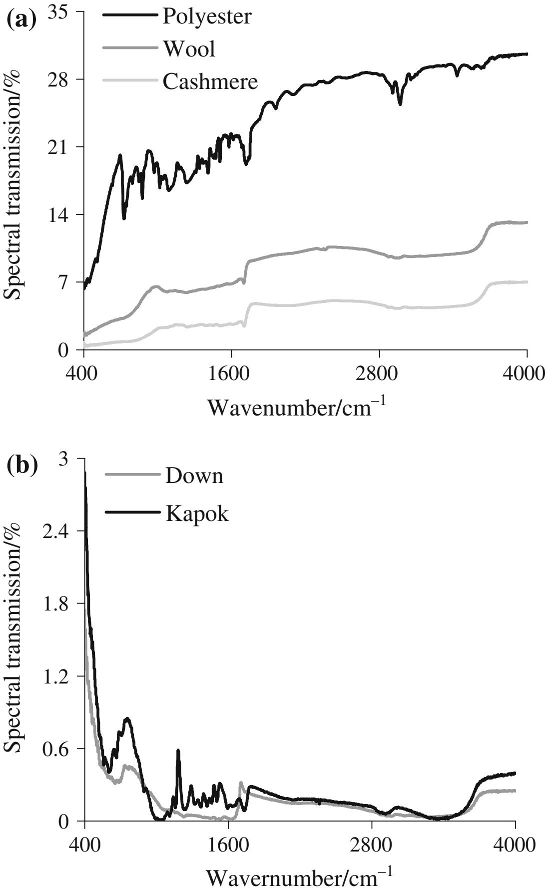

Fig. 2 Spectral transmission at the bulk density of 0.0032 g/cm^3: **a** for polyester, wool, and cashmere; **b** for down and kapok

(3) The spectral transmission ranking of polyester, wool, and cashmere shows direct relation with their fineness. The coarser the fiber, the higher is the spectral transmission. Kapok and goose down show the lowest spectral transmission.

Radiative heat conductivity

Bulk density influence on radiative heat conductivity of fiber assemblies

As shown in Fig. 5, radiative heat conductivity decreases with the increase of bulk density and the decrease rate is slower at higher bulk density. The radiative heat conductivity ranking of polyester, wool, and cashmere shows direct relation with their fineness. The finer the fiber, the lower is the radiative heat conductivity. It is also noted that kapok and goose down display the lowest and approximately equal radiative heat conductivity values. The lower value of kapok is due to its super low fiber density shown in Table 1, resulting in higher fiber volume fraction, preventing radiative heat transfer, while that of goose down is

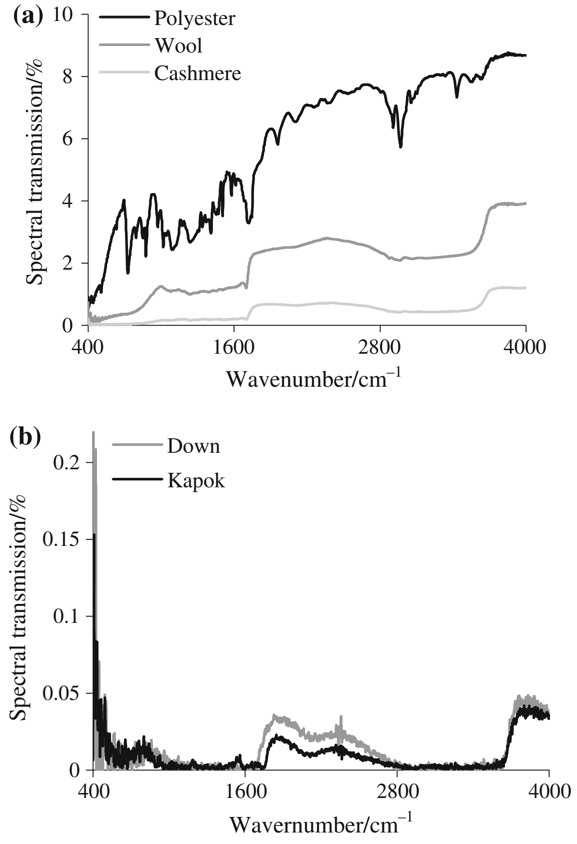

Fig. 3 Spectral transmission at the bulk density of 0.0064 g/cm^3: **a** for polyester, wool, and cashmere; **b** for down and kapok

attributed to its special structure, consisted of plenty of interconnected velvet flowers and the flowers have large quality of down branches, which subdivides the fiber assembly porosity into sufficient small pores, preventing the transfer of radiative heat effectively.

Fiber arrangement influence on radiative heat conductivity of fiber assemblies

Radiative heat transfer property of wool fiber assembly in three forms of arrangements was investigated as well. Figure 6 shows the preparation of the samples, made by hand. In order to get the uniform fiber assemblies, higher densities (0.016, 0.019, and 0.022 g/cm^3) were chosen in this experiment. The random ball arranged fiber assembly is made of balls within the diameter of 1 mm. As shown in Fig. 7, the random ball arranged fiber assembly shows the highest radiative heat conductivity, as the large pores between the balls lead to higher spectral transmission. That the parallel arranged fiber assembly shows higher radiative heat conductivity than the random arranged one can be explained from the aspect that the straight air channels exist in the former one, which is also beneficial for spectral transmission. The above indicates that random arrangement is still the best way to prevent radiative heat transfer. The investigation also reveals that radiative heat transfer is not only dependent on fiber volume fraction, but also related to the property of porosity, such as shape, tortuous nature, and distribution.

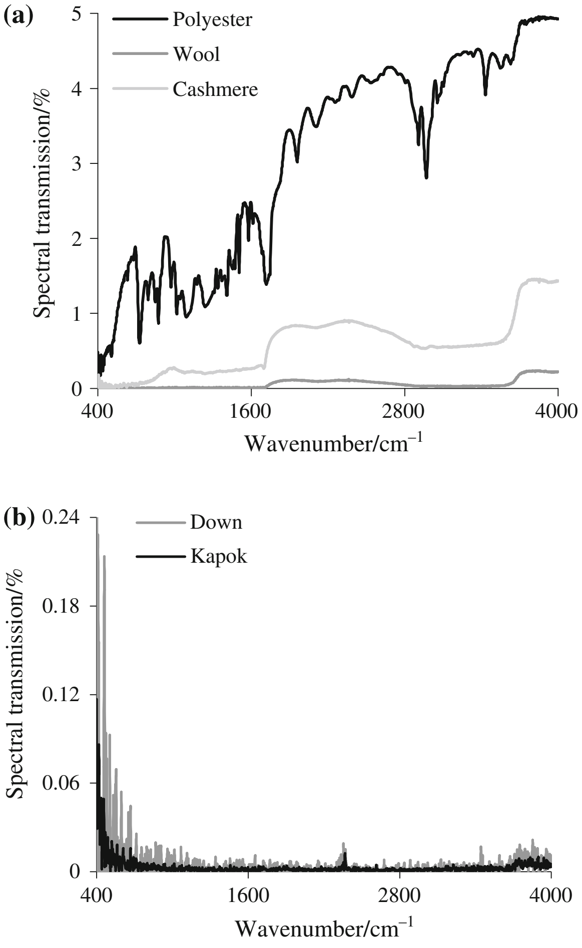

Fig. 4 Spectral transmission at the bulk density of 0.0096 g/cm^3: **a** for polyester, wool, and cashmere; **b** for down and kapok

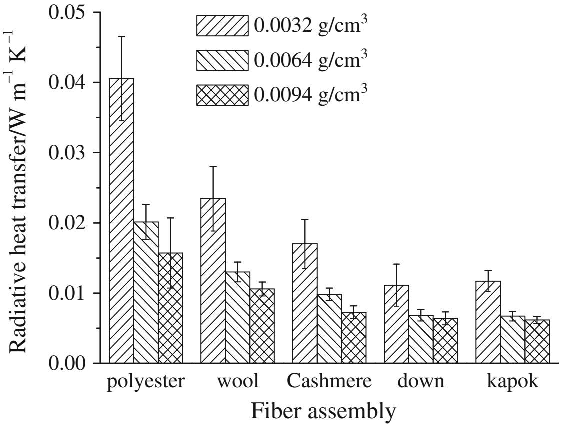

Fig. 5 Radiative heat conductivity of the five types of fiber assemblies

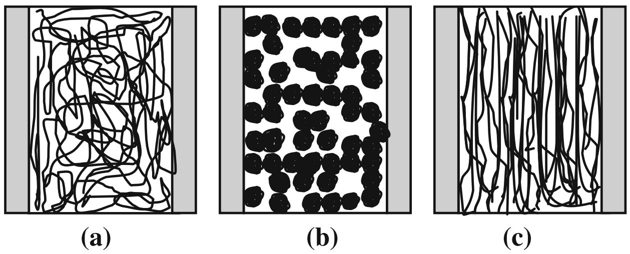

Fig. 6 Wool fiber assembly in three forms of arrangements: **a** random arranged, **b** random ball arranged, and **c** parallel arranged.

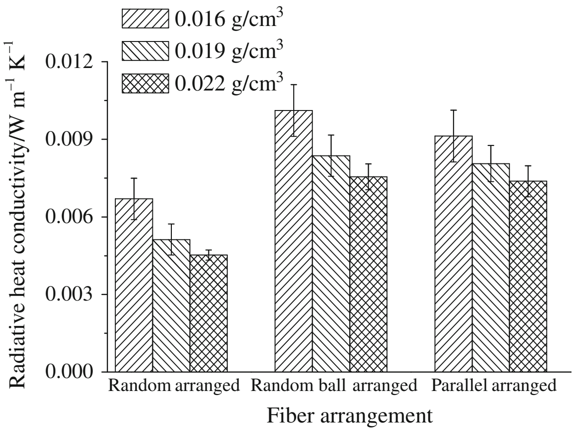

Fig. 7 Radiative heat conductivity of the wool fiber assembly in three forms of arrangements

Temperature influence on radiative heat conductivity of fiber assemblies

Figure 8 plots the radiative heat conductivity at various temperatures for the five types of fiber assemblies at the bulk density of 0.0064 g/cm^3. It can be seen that the radiative heat conductivity rises faster and faster with the increase of temperature. Since the Rosseland mean extinction coefficient is almost independent of temperature according to Eq. 4, the radiative heat conductivity is approximately proportional to the cubic temperature.

Theoretical model modification

The radiative heat conductivity can be obtained from the following equation, according to the studies by previous researchers [2, 17, 18].

$$K_r = C\sigma T^3 \frac{R}{\varepsilon f} \tag{5}$$

$$f = \frac{\rho}{\rho_f} \tag{6}$$

where R is the radius of fiber, ε is the emissivity of the fiber, f is the volume fraction of fiber assembly, ρ is the bulk density of fiber assembly, ρ_f is the fiber density, σ is the Boltzmann constant, T is the temperature, and C is the constant determined by fiber orientation.

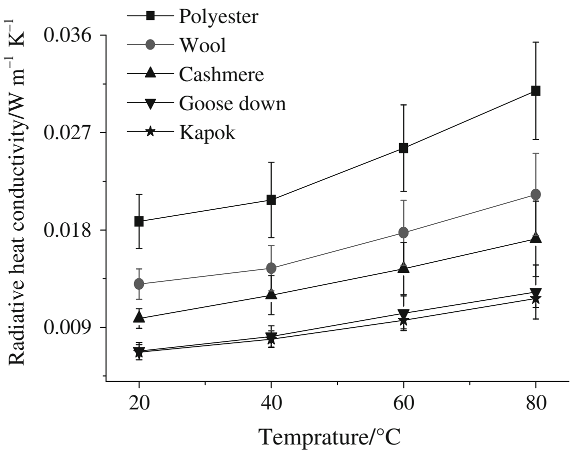

Fig. 8 Radiative heat conductivity of the five types of fiber assemblies vs. temperature

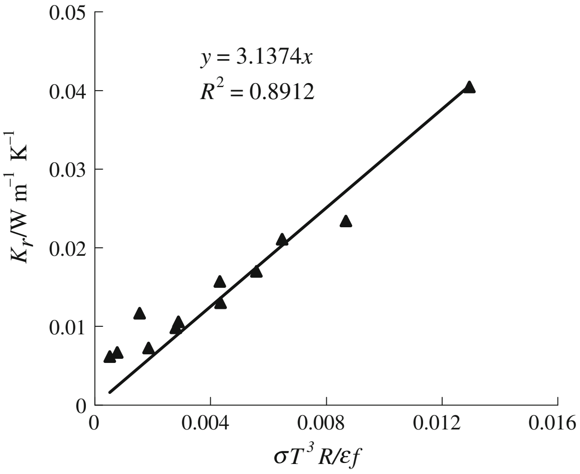

Fig. 9 Thermal radiative conductivity vs. σT^3 ($R/\varepsilon f$)

Farnworth [2] derived the constant $C = 8$ for random arranged fiber assemblies. In Strong et al.'s model [17], the constant $C = 8.38$ and $C = 10.17$ are determined for three-dimensional random-oriented fibers and for the case in which the fibers are randomly oriented in planes perpendicular to the temperature gradient, respectively. In Davis and Birkebak's model [18], the constant C ranges from 10.8 to 13.6, when the material is optically thick and the angle between axis of the fiber and the direction normal to the material surface is 45°.

In this study, we determined the value of C in Eq. 5 by plotting the value of radiative heat conductivity (K_r) obtained from the FTIR method against $\sigma T^3 (R/\varepsilon f)$, as shown in Fig. 9. The data of goose down are not used here as it is difficult to determine the radius of it for calculation. We can get the best linear fitting with $C = 3.135$. The value is smaller than the theoretical value got by previous researchers. The reason is that the measurement involves the effect of scattering of radiation, while this effect was neglected by the previous studies.

Conclusions

Fourier transform infrared spectroscopy technique was applied to measure radiative heat transfer properties of fiber assemblies for applications in an intermediate temperature range. Spectral transmission was obtained with FTIR for five types of fiber assemblies with low densities. From the measurements, the radiative heat conductivity was calculated. Based on the results, the following conclusions can be obtained:

1. Bulk density was found to be a significant factor influencing the radiation heat transfer of fiber assemblies. The radiative thermal conductivity was found to decrease with the increase of bulk density.
2. The radiative thermal conductivity was also found to depend significantly on the fiber arrangement of fiber assemblies. Random arranged fiber assemblies can prevent radiative heat transfer more effectively than the random ball and parallel arranged fiber assemblies.
3. The radiative heat conductivity increases with the increase of temperature and is approximately proportional to the cubic temperature.
4. The constant item in the previous model was modified to be 3.14 by comparing experimental and theoretical radiative heat conductivity results, smaller than the values got by previous researchers.

References

1. Holcombe BV, Hoschke N. Dry heat transfer characteristics of underwear fabrics. Text Res J. 1983;53:368–74.
2. Farnworth B. Mechanisms of heat flow through clothing insulation. Text Res J. 1983;53:717–25.
3. Fricke J, Stark C. Improved heat-transfer models for fibrous insulations. J Heat Mass Transf. 1993;36:617–25.
4. Tong TW, Yang QS, Tien CL. Radiative heat transfer in fibrous insulations—part II: experimental analytic study. J Heat Transf. 1983;105:76–81.
5. Daryabeigi K. Heat transfer in high temperature fibrous insulation. J Thermophys Heat Transf. 2003;17:10–20.
6. Zhao SY, Zhang BM, He XD. Temperature and pressure dependent effective thermal conductivity of fibrous insulation. Int J Heat Mass Transf. 2009;48:440–8.
7. Lee SC, Cunnington GR. Conduction and radiation heat transfer in high porosity fiber thermal insulation. J Thermophys Heat Transf. 2000;44:121–36.
8. Yuen WW. Radiative heat transfer analysis of fibrous insulation materials using the Zonal-GEF method. J Thermophys Heat Transf. 2007;21:105–13.
9. Coquard R, Baillis D, Quenard D. Experimental and theoretical study of the hot-ring method applied to low-density thermal insulators. Int J Heat Transf. 2008;47:324–38.
10. Wu HJ, Fan JT, Du N. Porous materials with thin interlayers for optimal thermal insulation. Int J Nonlinear Sci. 2009;10:291–300.
11. Stuart IM, Holcombe BV. Heat transfer through fiber beds by radiation with shading and conduction. Text Res J. 1984;54: 149–57.
12. Skelton J, Dent R, Donovan JG. Thermal and mechanical properties of down. In: Proceedings of the 7th international wool textile research conference, vol III; 1985. p. 264–73.
13. Fl Zhu, Li KJ. Determining effective thermal conductivity of fabrics by using fractal method. Int J Thermophys. 2010;31: 612–9.
14. Wu HJ, Fan JT, Du N. Thermal energy transport within porous polymer materials: effects of fiber characteristics. Appl Polym Sci. 2007;106:576–83.
15. Du N, Fan JT, Wu HJ, Sun WW. Optimal porosity distribution of fibrous insulation. Int J Heat Mass Transf. 2009;52:4350–7.
16. Strong HM, Bundy FP, Bovenkerk HP. Flat panel vacuum thermal insulation. J Appl Phys. 1960;31:39–50.
17. Davis LB, Birkebak RC. On the transfer of energy in layers of fur. Biophys J. 1974;14:249–68.
18. Mohammadi M. PhD thesis, University of North Carolina State University, America; 1998.
19. Hu JY, Li Y, Yeung KW, Wang SX. Characterization of thermal radiation properties of polymeric materials. Polym Test. 2006; 25:405–12.
20. Zhang H, Hu TL, Zhang JC. Transmittance of infrared radiation through fabric in the range 8–14 μm. Text Res J. 2010;0:1–6.
21. Capek P, Drábik M, Turjan J. Characterization of starch and its mono and hybrid derivatives by thermal analysis and FTIR spectroscopy. J Therm Anal Calorim. 2009;99:667–73.
22. Mothé CG, de Miranda IC. Characterization of sugarcane and coconut fibers by thermal analysis and FTIR. J Therm Anal Calorim. 2009;97:661–5.
23. Bernazzani P, Sanchez RF. Structural and thermal behavior of polystyrene thin films using ATR–FTIR–Nano DSC measurements. J Therm Anal Calorim. 2009;96:727–32.
24. Tseng CJ, K KT. Thermal radiative properties of phenolic foam insulation. J Quant Spectrosc Radiat. 2002;72:349–59.
25. Wu HJ, Fan JT. Measurement of radiative thermal properties of thin polymer films by FTIR. Test Method. 2008;27:122–8.
26. Vallabh R, Lee PB, Mohammadi M. Determination of radiative thermal conductivity in needlepunched nonwovens. J Eng Fibers Fabr. 2008;3:46–52.
27. Bejan A. Convective heat transfer. 2nd ed. New York: Wiley; 1993.
28. Siegel R, Howell JR. Thermal radiation heat transfer. 2nd ed. London: Taylor & Francis; 1992.