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Transient Methods of Thermal Properties Measurement on Fibrous Materials

Fibrous material is a complex porous medium and steady test methods are the main test approaches we currently depend on to study the heat transfer properties. The application of unsteady test methods on fibrous material is still not mature. In this paper, some systematic studies are taken to investigate this problem. By analyzing the main factors impacting the test results, it is found that the local heat convection potentially excited by imposing test temperature can be avoided by limiting the internal temperature gradient and the so-called dual-phase lagging effects are negligible so that the feasibility of the unsteady test method is verified via both theoretical analysis and experimental data. [DOI: 10.1115/1.4000049]

1 Introduction

Fibrous material has excellent thermal insulation property in addition to its flexibility, low density, and formability [1]. As a result, their applications are no longer limited in apparel, but also increasingly in various engineering heat insulation areas.

The basic constituents of a fibrous material include fiber and often-moistured air forming an intricate multiphase and multiscale system. The fiber were arranged in the space by certain porous forms yielding numerous interconnected voids that are filled by the air. Once the heat flow passing through the material, a complex thermal transfer process will take place in the material. From the microview, the heat flow is delivered alternately between the air and the fiber. The microheat flows seem to be random and even chaotic. But at macrosystem level, the heat flow transferring from one side to the other side is both regular and continuous, which are the so-called effective behaviors [2–8].

Therefore, for practical engineering applications, the complex microthermal processes are often not the major interest when we describe the material heat transfer performance. Instead, we focus chiefly on the effective thermal behavior with the macroview.

Over the years, lots of researches have been reported investigations on heat transport in porous fibrous materials. As in many other cases, such investigations largely follow two tracks either theoretical prediction or experimental examination or both, which generated a rich body of knowledge in the effective thermal behaviors of fibrous material [2,3,6,7,9–17]. Needless to say, much remains to be done.

In terms of instrumental measurement, the effective thermal conductivity of fibrous sheets (fabrics) is tested by the guarded hot plate method as recommended by the ASME Standard [18,19]. However the guarded hot plate is based on the principle of thermal equilibrium and it works best when the tested specimen can reach the steady-state quickly. For porous materials such as fabrics, where the multiphase renders the heat equalizing process slow and unstable, the conventional steady-state techniques become ineffective and even inaccurate. Since 1987, Martin and Lamb [20], Schneider and Hoschke [21], and Jirsak et al. [22] successively explored the application of unsteady transient methods to fibrous materials.

However, researchers held controversial opinions on whether fibrous material can be tested through the unsteady method. Jirsak et al. [22] pointed out in his paper that the test result of effective thermal conductivity (by using unsteady method) was unreliable due to the heat convection inside the material invoked by the temperature gradient applied during testing. All such transient methods are based on thermal conduction theories and, hence, unable to deal with the coupling of conduction and convection [23–25] and lead to non-negligible testing errors. Another recent issue has to do with the so-called dual-phase lagging (DPL) effects in porous materials [26,27], i.e., temperature change and heat wave flow both take time yet the classic Fourier's law implies an instantaneous local thermal equilibrium (zero transfer time). Based on a new testing scheme we developed recently [28], the aim of this paper is to examine the influences of such issues so as to establish the unsteady methods as a viable and preferred testing approach to fibrous materials.

2 The Hypothesis of Local Thermal Equilibrium

Fibrous material is a two-phase system with solid and gas composition. If the assumption of *local thermal equilibrium* is valid, then we can use the one-equation model in Eq. (1) to express the heat transfer process [26,27]

$$\langle \rho \rangle c \frac{\partial \langle T \rangle}{\partial t} = \nabla \cdot [k_{\text{eff}} \cdot \nabla \langle T \rangle] \tag{1}$$

where k_{eff} is the equivalent (or effective) thermal conductivity. This one-equation model is necessary for analyzing the thermal properties testing. The factors affecting the hypothesis of local thermal equilibrium include the difference in physical properties of the two phases, the volume fraction of each phase, the heat transfer coefficient, and the heat exchange area between the two phases. According to the research of Minkowycz et al. [29], the local thermal equilibrium, if the *Sp* number $\text{Nu}_{r_h}(k_f/k_{\text{eff}})(L/r_h)^2$ is great than 100, the condition of the local thermal equilibrium is satisfied for all practical applications where h, L, and r_h are the interstitial heat transfer coefficient, porous layer thickness, and the hydraulic radius, respectively. The Nusselt number Nu_{r_h} is nearly constant: $\sim$10 for conduction case and $\sim$0.9 for incompressible laminar flow in the pores. For most fibrous materials, the ratio of $k_{\text{air}}/k_{\text{eff}}$ is usually greater than 1/4, so if the test is designed in such that $L/r_h > 20$ the local thermal equilibrium will be valid in fibrous material.

3 Selection of Transient Method

Among the unsteady thermal tests, transient method is the most preferred in which a thermal perturbation is imposed at a given location of the measured material; the thermal response to this

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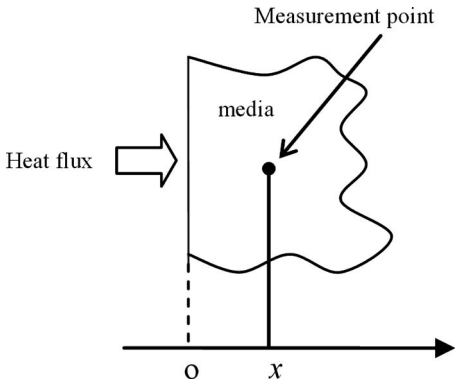

Fig. 1 Measuring principle of stepwise transient method

disturbance is recorded in another designated location. The corresponding thermal properties parameters can thus be calculated using the established theoretical law. According to the form of the heat source, it can be subdivided into a variety of testing methods so we must choose a testing method suitable to fibrous materials.

In terms of the heat source type, linear and surface heat source shapes are usually the available options in transient method. The linear option offers a very large aspect ratio in order to reduce the influence of heat loss at both ends. The thin slender shape however often causes the heat probe to bend just under its own weight. If we apply a tension to maintain a straight state, there may form a local stress concentration at the interface between the heat source and the material. Fibrous materials are very soft and easily deform under a small press themselves; the linear heat probe may not be a good choice and the testing probe in planner shape would at least alleviate such problems.

The heating mode of the heat source is also an important parameter. The pores inside the fibrous material are connected together. If the heating rate is too abrupt, it will cause a dramatic expansion of air in the material so as to generate forced local convection, which will alter the property of the material. Therefore, we selected the stepwise mode, a relatively smooth way, over other pulse profiles.

In summary, this study chose the stepwise transient heating mode with a metal foil probe to form the measurement apparatus for testing the fibrous materials. The stepwise transient method was examined in several studies [30,31] for its several advantages: In theory at least, the stepwise transient method can measure the thermal conductivity and thermal diffusivity of the materials simultaneously. It used a thin surface heat source, which can generate constant heat flow in testing. Furthermore, the stepwise transient method brings much less impact on the sample tested, compared to other unsteady methods [5,32–41].

4 Measurement Principle

The measuring principle for the stepwise transient method is shown in Fig. 1. Assuming the local thermal equilibrium, and a specimen with infinite size and uniform initial temperature T_0 when a constant heat flux starts at $x=0$ and $t>0$, the temperature distribution inside any point in the sample will depend only on the distance x between the measurement point and the heat source and the time t, and can thus be treated as a one-dimensional problem. Equation (1) will reduce into the classic Fourier's law with the solution for the prescribed boundary and initial conditions as

$$T(x,t) = T_0 + \frac{q}{k}\left\{\left(\frac{at}{\pi}\right)^{1/2}\exp\left(-\frac{x^2}{4at}\right) - \frac{x}{2}erfc\left(\frac{x}{\sqrt{4at}}\right)\right\} \quad (2)$$

$$k\left.\frac{\partial T}{\partial x}\right|_{x=0} = \begin{cases} q & t>0 \\ 0 & t\le 0 \end{cases} \quad (3)$$

where $T(x,t)$ is the temperature at position x and time t, q is the flux of heat source, k is the thermal conductivity, and a is the thermal diffusivity.

The temperature profile $T(x,t)$ in Eq. (2) is a time-domain function, which can be measured by the thermometer and recorded by a computer. The thermal conductivity k and the thermal diffusivity a of the sample can be found by superimposing Eq. (2) on the recorded temperature-time curve using appropriate fitting techniques.

5 The Test Apparatus

The schematic diagram shown in Fig. 2 is the test apparatus we recently developed [28]. The main framework of the testing apparatus consists of two plates with guard-bars. These guard-bars are fixed on *plate B* and *plate A* can be moved up and down along with the guard-bars. Multiple specimens are required in one test to form two stacks of the same thickness, which are placed between the plate A and plate B with the heat source located at the center as shown. The sheet heat source made of metal foil with 17.3 Ω electric resistance. The size of the heat source is 90×90 mm^2 and thickness less than 0.1 mm. Owing to the tiny thickness of the heat source, its volume heat capacity can be ignored so that the output power of the heat source can be considered as equal to the input electric power. Given the symmetry of the system, the thermal flow generated from the heat source will be uniformly distributed to the up and down sample stacks provided that, first, the buoyant influence is small and only takes place after a certain time.

The sample temperature response is measured and recorded by a computer data acquisition modules through the temperature sensor placed inside the sample in the figure. In our testing, the sampling frequency is four times per second.

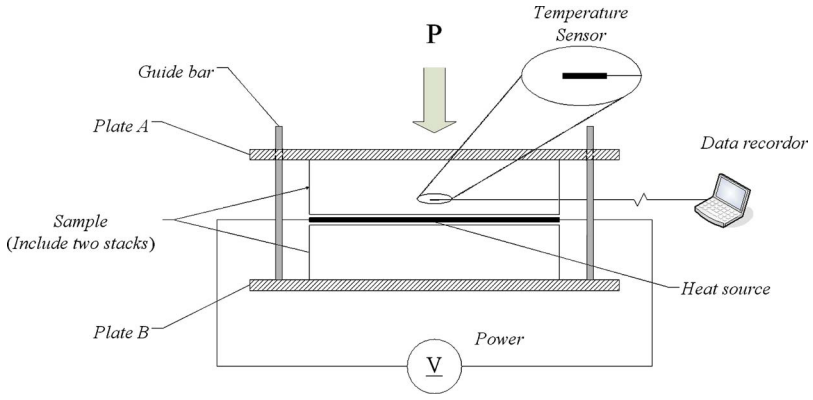

Fig. 2 The schematic diagram of test apparatus

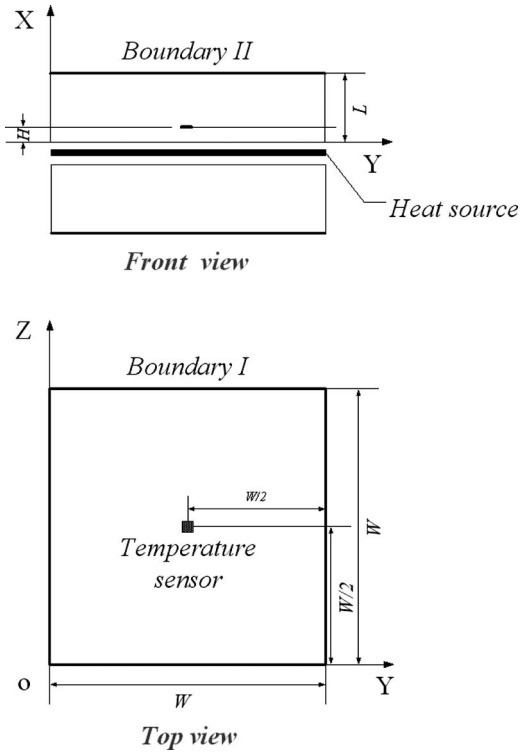

Fig. 3 The actual sample in the experiment

The test specimens are all in sheet form and are stacked up to make up the required total thickness up to 3.5 cm to fill the space. Furthermore, additional air residing in between the fabric layers poses collectively as a potential error source. Still, due to the porous and flexible nature of the fabrics, the density and thus the thermophysical properties of the fibrous material are closely related to the external pressure [23]. As a result, an appropriately defined pressure has to be applied on the sample stacks to stabilize/standardize the thickness of the sample piles. A constant pressure P of 792 Pa is exerted onto the samples uniformly through plate A for all tests in this study.

6 Estimating the Measurement Time

The sample size in establishing Eq. (2) of heat conduction is assumed to be infinite and, obviously, this assumption cannot be realized in an actual experiment. Comparing with the theory, the actual sample with limited size has additional boundaries (*boundary I* and *boundary II*), as illustrated in Fig. 3. For easier treatment without losing generality, we assume the YZ plane as the actual square sample of equal sides W with sensor located at the center and the XZ plane represents the thickness L with sensor at distance H from the heat source. Because of the planer symmetry, all the edges in the YZ plane will be of the boundary I type and in the thickness direction, the boundary II type.

Because of its limited size, the temperature distribution in an actual sample cannot be described by Eq. (2). However, it is easily conceivable that upon heating, it will take some time t_m before the heat can reach the boundaries for the influence caused by limited sample size to realize. That is to say, if we take the measurement within the period $t < t_m$, the difference Δ_f between the actual experiment and theory will be small enough to be negligible and then Eq. (2) becomes valid to use in estimating the sample thermal properties k and a.

In general, the difference Δ_f is a function related to sample type, size, testing time, etc., as expressed in Eq. (4).

$$\Delta_f = (T_E - T_T)/(T_T - T_0) = f(L, W, H, k, a, q, \beta_I, \beta_{II}, t) \quad (4)$$

where T_E is the temperature in the actual sample and T_T is the corresponding temperature in infinite medium defined in Eq. (2), at given (x,t), β_I and β_{II} are the heat transfer coefficients at boundary I and boundary II, respectively. When $|\Delta_f|$ is small enough than a critical value Δ_{fa}, T_E will be close enough to T_T such that we can use Eq. (2) in the test. Therefore $|\Delta_{fm}| < \Delta_{fa}$ is a logical criterion to be used for the t_m determination, where $|\Delta_{fm}|$ is the maximum value of $|\Delta_f|$ at time $t = t_m$ and Δ_{fa} is the allowable testing error.

In calculation of Δ_{fm}, T_T and T_E must be obtained first. T_T can be calculated from Eq. (2) and T_E can be estimated here by numerical approaches as the following. For heat transfer in a finite sample in 3D mode, the temperature field will be governed by Eq. (5), which can be solved under certain boundary conditions using either the finite difference method (FDM) or the finite element method (FEM) to obtain T_E. Once the temperature field is solved and Δ_{fm} value can be calculated from Eq. (4) at $t = t_m$

$$\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \quad (5)$$

Boundary I leads to the heat transfer between sample and air and according to the natural convection conditions, we can take the convective heat transfer coefficient as 10 W m^{-2} C^{-1} [42]. Boundary II reflects the heat transfer between the sample and the plates as the plate is made of metal, which has much greater thermal conductivity and heat capacity than the polymeric samples tested, so it can be considered that there is no temperature gradient at the interface between the sample and the plate, i.e., sample has little disturbance on the temperature field of the plate.

However the distance between the sensor and heat source has to be carefully chosen, for the farther away the sensor from heat source, the greater impact is caused by boundary II on temperature measured. In this article the distance between sensors and heat source will not be more than 5 mm. So in the calculations we assume that the distance between the sensor and the heat source $H = 5$ nm in order to ensure that the calculation result can be valid on all tests. The thickness for each stack of the samples is $L = 35$ nm.

The value of T_E in 3D heat transfer mode can be calculated by using ANSYS finite element software and the impact of material thermal properties on system Δ_{fm} is analyzed and shown in Fig. 4. From the results, the smaller the thermal conductivity and/or the greater the thermal diffusion coefficient, the greater the deviation of $|\Delta_{fm}|$. According to the range of fiber thermophysical parameters, we use $k = 0.025$ W/m°C and $a = 5 \times 10^{-7}$ m^2 s^{-1} in the calculation of t_m in order to suit most fibrous samples tested.

Next we are to determine the maximum testing time t_m, which will allow $|\Delta_{fm}| < \Delta_{fa}$. As shown in Fig. 5, we calculated $|\Delta_f|$ versus time according to the chosen k and a. The flux of the heat source used in the calculation is $q = 20.0$ wm^{-2}. From Fig. 5, we know as expected that $|\Delta_f|$ increases monotonically with the measurement time. If we take $\Delta_{fa} = 0.05\%$, then t_m will be about 202 s.

The next question is whether the magnitude of q has any impact on t_m, so we again conducted the abovementioned numerical analysis by using different q values. Based on the result in Fig. 5, we used the value of $|\Delta_f|$ at time point 202 s in Fig. 6 and see that the impact of q on $|\Delta_f|$ is very limited that it can be ignored. From $q = 20$ W m^{-2} to 20 W m^{-2}, all the calculated results of $|\Delta_f|$ are less than the given threshold Δ_{fa}. We thus come to the conclusion that t_m can be treated as independent of the power of the heat source in our test conditions. In order to simplify the test, we used $t_m = 200$ s for all the samples in the study.

7 The Accuracy of Test Apparatus

In order to check the reliability of the test apparatus, we chose perspex as a standard sample for the validation. The size of per-

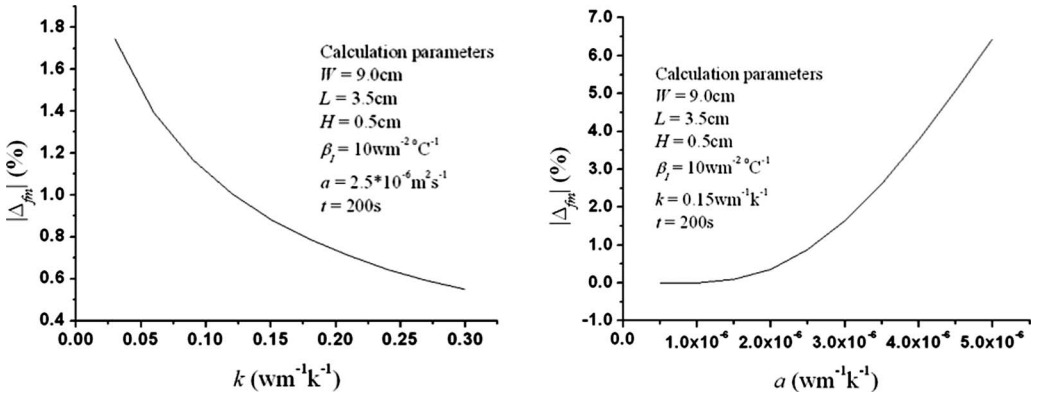

Fig. 4 The impact of material thermophysical properties on Δ_{fm}

spex is $90\times90\times35$ mm^3 and the distance H is 4.53 mm. Through the fitting method mentioned in Ref. [30], we obtained the thermal property parameters of the perspex samples as shown in Table 1.

Both thermal properties for the perspex samples from our tests agree well with the reference values from literature and the errors range from 2% to 3.94%. The reliability of our test device for solid sheets materials are thus confirmed.

8 Apply Stepwise Transient Method on Fiber Materials

The additional difficulty in measuring the thermal properties of fibrous materials or any porous media with interconnected pores, lies in the fact that a fibrous material is a mixed multiphase system of fiber and air residing in the pores. Once the temperature gradient gets large enough in the testing process, the air inside the fibrous material will begin to move around and the convective heat transfer takes place, which completely changes the nature of the heat transfer and renders Eq. (2) for thermal conductivity only no longer valid [25]. In other words, two issues have to be dealt with in testing a fibrous material—the boundary influence and convective heat loss.

In this paper, three kinds of fibrous material (nonwoven, twill, and knit velvet) are used in the testing. All samples are balanced for 24 h under standard environment with temperature of 20°C and relative humidity of 65%.

For the thickness of the fabrics is very small, in order to achieve the required thickness for testing, fabric samples must be stacked together to 35 mm on both sides of the heat source and the temperature sensor is placed inside the upper stack as discussed before. The samples and test parameters are shown in Table 2.

To further examine the potential convective heat transfer, we tested the samples under two different temperature gradients. If there is no convection, then the parameters k and a, as derived by fitting Eq. (2), should remain constant with time. We used two different flux values of heat source in the testing of the nonwoven fabric samples as shown in Fig. 7. Since the sample resistant is given, different heat flux will generate different temperature gradients, in this case by nine times. When the heat density q $=20.6$ W m^{-2}, both effective thermal conductivity and thermal diffusivity, largely remain the same with some random fluctuation around the mean value in different fitting time sections $\bar{t}$. Note that each fitting time is $t<t_m$ so as to eliminate the boundary influ-

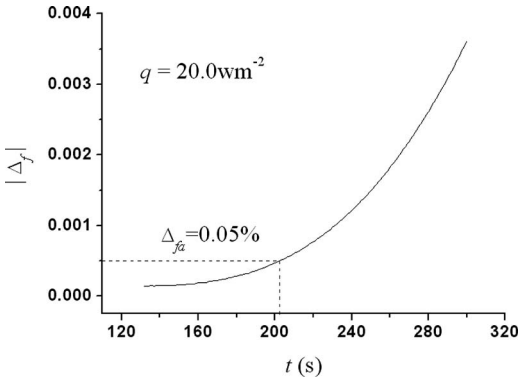

Fig. 5 The influence of t on $|\Delta_f|$

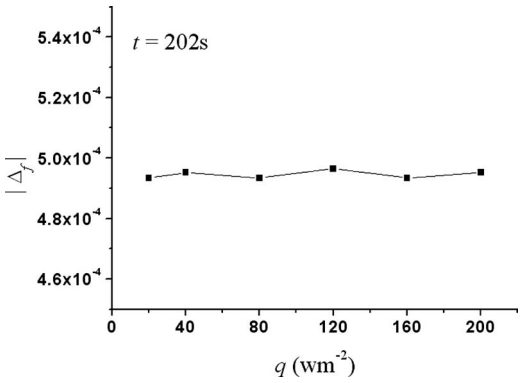

Fig. 6 The influence of q on $|\Delta_f|$

Table 1 Results comparison of thermal property parameters for perspex

	k (W m^{-1} K^{-1})	c_v (J g^{-1} K^{-1})	a (m^2 s^{-1})
Measured value	0.195	1.37	1.22×10^{-7}
Reference value[1]	0.191	1.35	1.22×10^{-7}
Relative error (%)[2]	2.09	1.71	3.94

(1) Reference value is under 20°C from Ref. [43].
(2) Relative error=|measured value−reference value|/reference value (%). The atmosphere temperature is 18°C.

Table 2 The samples and test parameters

Sample	Fabric weight (g/m^2)	H[1] (mm)
Nonwoven	4.852	3.38
Twill	143.1	3.08
Knit velvet	203.5	3.30

(1) H is the distance in Fig. 3, averaged over several measurements.

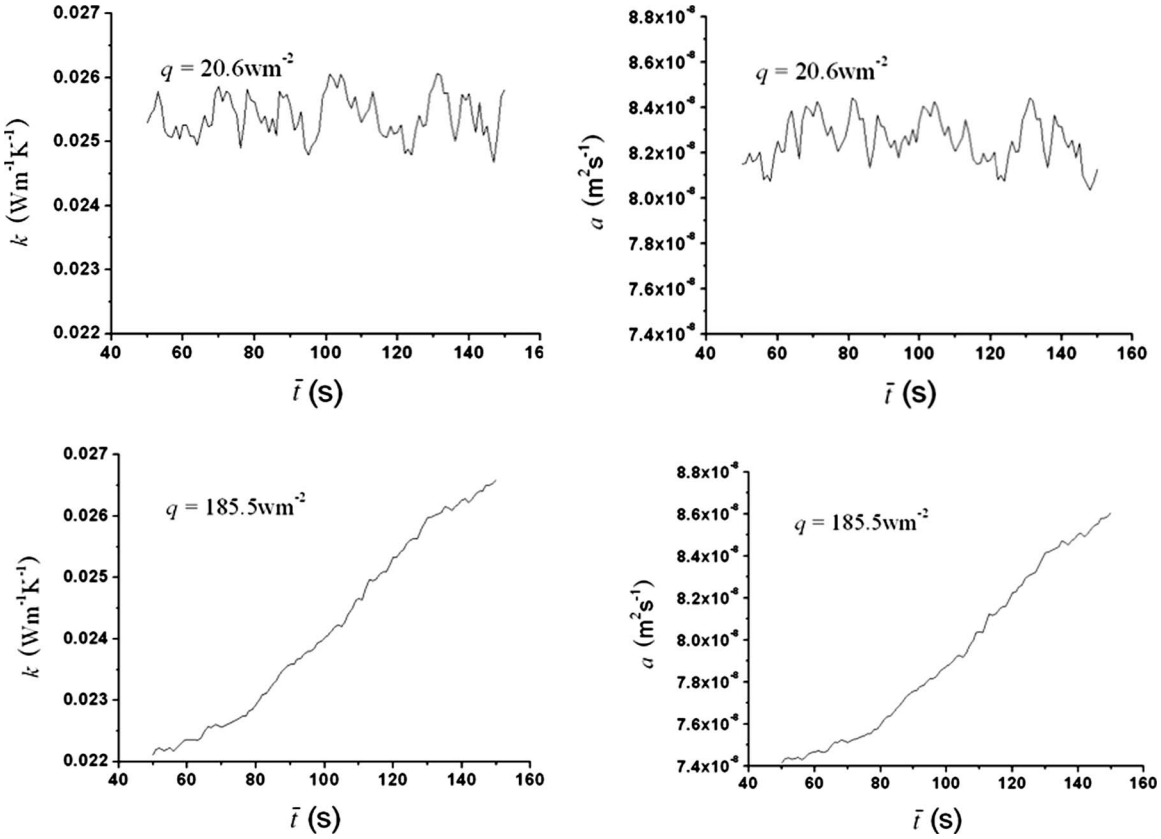

Fig. 7 The testing results for nonwoven fabric under different heat source power

ence. However, these properties now increase monotonously and exceed those at low heat load under a much higher heat load $q = 185.5$ wm^{-2} showing an increase in heat loss due ostensibly to convection. It is interesting that the initial values of the properties in this case would be smaller than those at low heat flux: This may reveal that when the sample is still at room temperature, which is too high a heat impact that actually impedes the heat transfer until the sample temperature rises to a certain level.

In conclusion, to avoid both the sample boundary and heat convection influence, the testing conditions for fibrous materials include appropriately low heat flux $q=20.6$ W m^{-2} and within a time limit $t<t_m$.

The test results of all three fibrous samples are given in Fig. 8 and each data point is a result of five repeats. From the results we can see the nonwoven fabric has the smallest effective thermal conductivity k and thermal diffusivity a among the three fabrics. Whereas the twill fabric exhibits higher effective thermal conductivity k yet lower thermal diffusion coefficient a than the knit velvet. Parameter k describes the medium's thermal conduction performance under the steady-state condition but $a=k/c_v$ describes the temperature diffusion ratio under the unsteady-state condition, so these two parameters have different application fields. In our test, both k and a are simultaneously measured, which can completely describe the fabric sample thermal performance in all cases.

Different fabric samples have different dispersion of test results. In effective thermal conductivity aspect, the coefficient of variation (CV) value for nonwoven fabric and knitting velvet are 12.0% and 6.9%, respectively, which are bigger than twill fabric (CV=3.2%). However in the thermal diffusion coefficient aspect, the CV value for nonwoven fabric and knitting velvet are larger than twill fabric with 9.8%, 9.5%, and 4.3%, respectively, which explains twill fabric has better uniform structure and stability than nonwoven fabric and knitting velvet.

9 Conclusion

In this paper, we have studied the application of unsteady thermal properties methods on fiber material. We first demonstrated that the local heat convection potentially excited by imposing test temperature can be avoided by controlling the heat density q and the DPL effects are normally negligible in practical measurements of fibrous materials. By both numerical analysis and experimental validation, we have demonstrated that our unsteady measurement approach, the stepwise transient heating mode with a metal foil probe, can be used to test the effective thermal conductivity and thermal diffusion coefficient of various fibrous materials.

Nomenclature

a = thermal diffusivity, m^2 s^{-1}
β = heat transfer coefficient
c = heat capacity, J kg^{-1} C^{-1}
c_v = volume heat capacity, J m^{-3} C^{-1}
h = heat transfer coefficient, W m^{-2} C^{-1}
k = thermal conductivity, W m^{-1} C^{-1}
k_{air} = thermal conductivity of air, W m^{-1} C^{-1}
k_{eff} = equivalent (or effective) thermal conductivity, W m^{-1} C^{-1}
H = distance between the sensor and the heat source, m
L = thickness, m
Nu_{r_h} = Nusselt number
ρ = density, kg m^{-3}
q = heat flux, W m^{-2}
r_h = hydraulic radius, m
T = temperature, C
T_0 = initial temperature, C
T_E = temperature in the actual sample

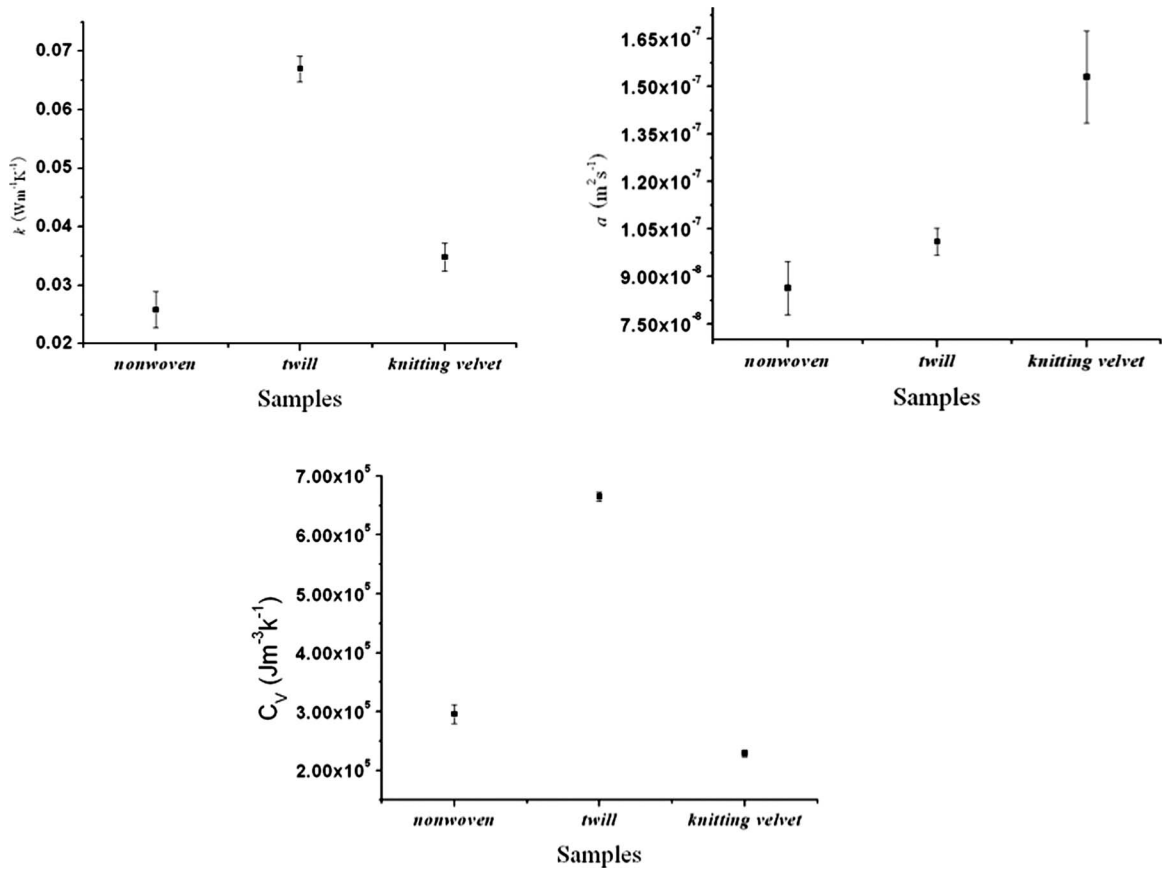

Fig. 8 The test result of fiber materials (the range is +/− standard deviation of the test result)

T_T = temperature in infinite medium
t = time, s
t_m = maximum test time, s
$\bar{t}$ = mean value in different fitting time sections
x = distance between the measurement point and the heat source, m
Δ_f = difference between the actual experiment and theory
Δ_{fa} = critical value of Δ_f
$|\Delta_{fm}|$ = maximum value of $|\Delta_f|$

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